TIDE AND RIVER RUNOFF INTERACTIONS IN THE COCHIN ESTUARY

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By

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Certificate

This is to certify that this thesis entitled "**TIDE AND RIVER RUNOFF INTERACTIONS IN THE COCHIN ESTUARY**" is an authentic record of the research carried out by Shri. **SHIVAPRASAD AMARAVAYAL** (Reg: NO: 4010), under my supervision and guidance in National Institute of Oceanography, Regional centre, Cochin- 18, in partial fulfillment of the requirement for the Ph.D degree of the Cochin University of science and Technology and that no part thereof has been presented before for any other degree, diploma or associateship in any University.

Kochi -18
May, 2013

Dr. C. Revichandran,
(Supervising Guide)

DECLARATION

I hereby declare that this thesis entitled **"TIDE AND RIVER RUNOFF INTERACTIONS IN THE COCHIN ESTUARY"** is an authentic record of the research carried out by me, under the guidance of Dr. C. Revichandran, Senior Principle Scientist of National Institute of Oceanography, Regional centre, Cochin- 18, in partial fulfillment of the requirement for the Ph.D degree of the Cochin University of Science and Technology and that no part thereof has been presented before for any other degree diploma or associateship in any University.

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I dedicate this thesis to my parents

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Acronyms and Abbreviations

1D	**One Dimensional**
1DNN-Model	**One Dimensional Network Numerical Model**
2D	**Two Dimensional**
ANOVA	**Analysis Of Variance**
CTD	**Conductivity Temperature Depth Profiler**
DO	**Dissolved Oxygen**
HHW	**Highest High Water**
ISM	**Indian Summer Monsoon**
LHW	**Lowest High Water**
MA	**Moving Average**
MSL	**Mean Sea Level**
NEM	**North East Monsoon**
PEA	**Potential Energy Anomaly**
PSU	**Practical Salinity Unit**
RCM	**Recording Current Meter**
S.C.C.C	**South Carolina Coastal Council**
SPSS	**Statistical Product and Service Solutions**
TASK2000	**Tidal Analysis Software Kit 2000**
TB	**Thannermukkam Barrier**
U.S.E.P.A	***United States Environmental Protection Agency***
IDS	**Idealized Scenario**
RLS	**Realistic Scenario**

CONTENTS

Chapter 6. Classification of Cochin Estuary

Chapter 1

Introduction

Estuaries are always providing an alternative or additional livelihood to mankind. An estuary is both a source of food and a transport link between a river and a sea. This system is often popular as resorts for humans, whereas high biological productivity with marsh wetlands and mangroves swamps makes them popular breeding grounds for various fish and shellfish. Trade and industry find this system attractive location to develop fine seaports and inland navigations. In many cases, this has generated large scale alteration of the natural balance with in the estuary through dredging, construction of barrages and pollution. Almost every large estuary in the world is a site of a major city, especially for port and transport. In estuaries, freshwater collected over vast regions of the land pours into a sea or an ocean, which sends salt water upstream far beyond the river mouth. Vigorous mixing between the two fluids creates a unique environment, with large potential for life forms able to handle the associated large variability in environmental conditions. This chapter provides the major definitions, classification of estuaries, physical processes in estuaries, description of the study area, objectives of the present study and outline of the thesis.

1.1 Definition and classification of estuaries

In the most basic sense, estuaries can be described as the boundaries between terrestrial fresh water, and the salty expanse of the ocean. An estuary has characteristics of both a river and a sea. ; And certainly an estuary is a transition zone between the river and the sea. Savenije, 2005 showed a clear linkage between an estuary, a river and a sea (see Table 1.1). The sea and the river exchange their water, substances and sediments. The estuary is, therefore, a unique environment that is mainly influenced by tides from the sea and freshwater runoff from the river. The action of winds and other physical processes can also influence this complex system. According to Cameron and Pritchard (1963), *an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which, sea water is measurably diluted with fresh water from land drainage.* Freshwater entering a semienclosed basin establishes longitudinal density gradient that results in long-term surface outflow and net inflow underneath. In classical estuaries, freshwater input is the main driver of the long-term (order of months) circulation through the addition of buoyancy. The above definition of an estuary applies to temperate (classical) estuaries but is irrelevant for arid, tropical and subtropical basins. Arid basins and those forced intermittently by freshwater exhibit hydrodynamics that are consistent with those of classical estuaries and yet have little or no freshwater influence. The loss of freshwater through evaporation is the primary forcing agent in some arid systems, and causes the development of longitudinal density gradients, in analogy to temperate estuaries. Estuaries described by this definition are known as positive estuaries. Another definition can be derived that does not have this limitation. The new definition includes situations where intermittent closure of the estuary to the sea can happen and where evaporation exceeds the fresh water supply from rivers and rain. These are called inverse estuaries and have been classified by

Tomczak (2002) as: *"An estuary is a narrow, semi-enclosed coastal body of water which has a free connection with the open sea at least intermittently and within which, the salinity of the water is measurably different from the salinity in the open ocean."* These are broad definitions, and under these general definitions, estuaries may be further separated into various classifications. Estuaries have been long studied and classified based on their stratification or vertical structure of salinity, water balance, geomorphology, tidal characteristics and combination of characteristics. In addition to this classification schemes Indian estuaries have a special flavour that is derived from occurrence of monsoon and they are referred as monsoonal estuaries (see section 1.2).Although a number of excellent reviews are available (Fischer *et al.*, 1979; Dyer, 1997; or Savenije, 2005), it is worthwhile to mention some main classification schemes of estuaries herein, as it is important to understand their general characteristics and to see how the present study fits in to these schemes.

	Sea	**Estuary**	**River**
Shape	Basin	Funnel	Prismatic
Main hydraulic function	Storage	Storage and transport	Transport of water and sediments
Flow direction	No dominant direction	Dual direction	Single downstream direction
Bottom slope	No slope	Very small or virtually no slope	Downward slope
Salinity	Saline	Brackish	Fresh
Wave type	Standing	Mixed	Progressive
Ecosystem	Nutrient poor, marine	High biomass productivity, high biodiversity	Nutrient rich, riverine

Table 1.1 Characteristics of a sea, estuary and a river (Savenije, 2005)

1.1.1 Classification of estuaries based on stratification or vertical structure of salinity

Pritchard (1955), Cameron and Pritchard (1963), and later Dyer (1973, 1997) classified estuaries by their stratification and the characteristics of their salinity distributions. This classification considers the competition between buoyancy forcing from river runoff and mixing from tidal forcing (Fig. 1.1). Mixing from tidal forcing is proportional to the volume of oceanic water entering the estuary during every tidal cycle, which is also known as the tidal prism. Large river runoff and weak tidal forcing results in salt wedge estuaries such as the Mississippi (USA), Rio de la Plata (Argentina), Vellar (India), Ebro (Spain), Pánuco (Mexico), and Itajaí-Açu (Brazil). These systems are strongly stratified during flood tides, when the ocean water intrudes in a wedge shape. Some of these systems lose their salt wedge nature during dry periods. Typical tidally averaged salinity profiles exhibit a sharp pycnocline (or halocline), with mean flows dominated by outflow throughout most of the water column and weak inflow in a near-bottom layer. The mean flow pattern results from relatively weak mixing between the inflowing ocean water and the river water. Moderate to large river runoff and weak to moderate tidal forcing result in strongly stratified estuaries (Fig.1.1). These estuaries are similar to salt wedge estuaries, but the stratification remains strong throughout the tidal cycle as in fjords and other deep (typically >20m deep) estuaries. The tidally averaged salinity profiles have a well-developed pycnocline with weak vertical variations above and below the pycnocline. The mean flow exhibits well-established outflows and inflows, but the inflows are weak because of weak mixing with freshwater and weak horizontal density gradients.

Weakly stratified or partially mixed estuaries result from moderate to strong tidal forcing and weak to moderate river runoff. Many temperate estuaries, such as Chesapeake Bay, Delware Bay and James River (all in the eastern United States) fit into this category. The mean salinity profile either has a weak pycnocline or continuous stratification from surface to bottom, except near the bottom mixed layer. The mean exchange flow is most vigorous (when compared to other types of estuaries) because of the mixing between riverine and oceanic waters. Strong tidal forcing and weak river runoff result in vertically mixed estuaries. Mean salinity profiles in mixed estuaries are practically uniform and mean flows are unidirectional with depth. In wide (and shallow) estuaries, inflows may develop on one side across the estuary and outflow on the other side, especially during the dry season. Parts of the lower Chesapeake Bay may exhibit this behavior in early autumn. In narrow well-mixed estuaries, inflow of salinity may only occur during the flood tide because the mean flow will be seaward. Examples of this type of estuary are scarce because, under well-mixed conditions, the mean (as in the tidally averaged sense) flow will most likely be driven by wind or tidal forcing.

This probably is the most common classification for estuaries due to its physical appeal. The advantages of this classification type are to have a better understanding of how the circulation of water in the estuaries is maintained and to get quantification, which should enhance and assist prediction. Four main estuarine types are defined: (**i**) highly stratified or salt wedge estuaries; (**ii**) fjords; (**iii**) partially mixed estuaries; and (**iv**) well-mixed estuaries (see Table 1.2). Two points should be emphasised that: (**i**) a given estuary can be well mixed during the dry period but be partially mixed during high runoff periods; and (**ii**) a given estuary can consist of several classes, for example it can be well mixed in the lower part and partially mixed in the upper part.

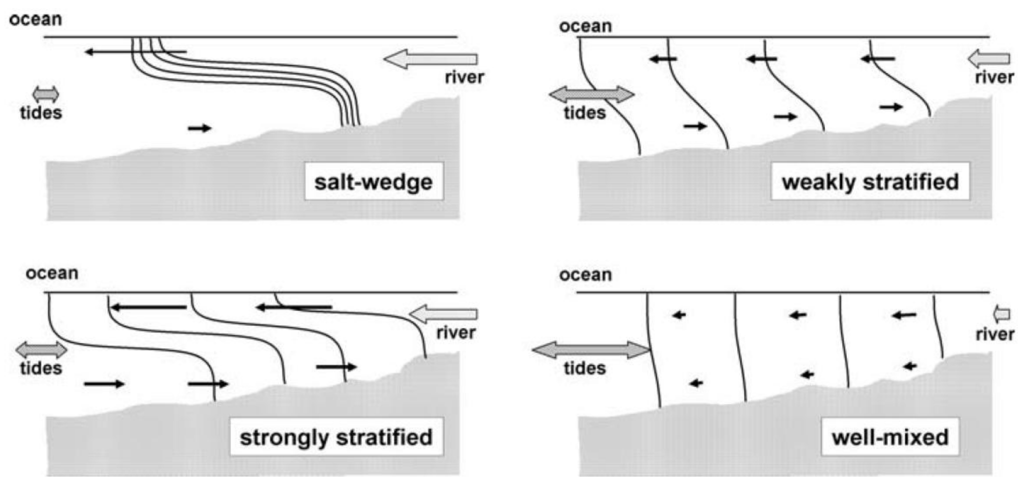


Fig. 1.1. Classification of estuaries on the basis of vertical structure of salinity.

Name	**Characteristic**	**Example**
Highly stratified or salt wedge estuaries	Two layers: Upper fresh layer and lower saline layer	Mississippi(USA) and Vellar estuary (India) , Mekong (Vietnam – in flood season)
Fjords	Two layers: Fresh upper- intermediate layer and saline deep lower layer	Silver Bay (USA), Alberni inlet(British Columbia)
Partially mixed estuaries	Horizontal and vertical gradually varying density	Rotterdam Waterway (Netherlands), Columbia (USA), Mersey (UK)
Well-mixed estuaries	Vertical constant density	Mekong (Vietnam – in dry season), Scheldt (Netherlands), Pungue, Incomati, Limpopo (Mozambique), Elbe (Germany)

Table 1.2 Stratification classification of estuaries (Dyer, 1997)

1.1.2 Classification based on the water balance

Based on their water balance, estuaries can be classified as three types: positive, inverse and low-inflow estuaries. Positive estuaries are those in which, freshwater additions from river runoff, rain and ice melting exceed freshwater losses from evaporation or freezing to establish a longitudinal density gradient. In positive estuaries, the longitudinal density gradient drives a net volume outflow to the ocean, as denoted by stronger surface outflow than near-bottom inflow, in response to the supplementary freshwater flow. Inverse estuaries are typically found in arid regions where freshwater losses from evaporation exceed freshwater additions from precipitation. There is no or scant river runoff into these systems. They are called inverse, or negative, because the longitudinal density gradient has the opposite sign to that in positive estuaries

1.1.3 Classification based on the geomorphology

Although many scientists have used Pritchard's definition, studies in the tidal freshwater regions of estuaries have suggested that the definition of Fairbridge (1980) is also applicable. Fairbridge (1980) stated that: "*An estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: a) a marine or lower estuary, in free connections with the open sea; b) a middle estuary subject to strong salt and freshwater mixing; and c) an upper or fluvial estuary, characterized by freshwater but subject to strong tidal action. The limits between these sectors are variable and subject to constant changes in the river runoff* ". Fairbridge proposed estuary classification in seven types (See Table 1.3). The slightly different classification based on geomorphology characteristics can be found in Dyer (1997), namely "Classification by topography"; and Savenije (2005), namely "Classification based on geology".

Type	Name	Remarks	Example
1			
1a	Fjord	High relief - Shallow sill, constriction in the inlet	Sogne Fjord (Norway), Milford Sound (New Zealand)
1b	Fjard	Low relief – Emerged strandlines	Solway Firth (England/Scotland)
2	Ria	Drowned meanders in the estuary middle sections.	Kingsbridge estuary (UK), Ria de Ribadeo (Portugal), Swan river (Australia)
3	Coastal Plain type – funnel shape	Sea dominant estuary	Chesapeake Bay (USA), Scheldt (Netherlands), Pungue (Mozambique)
4	Bar-built estuary – flask shape	Split bar along coastal line	Vellar estuary (India), Roanoke river (USA)
5	Blind estuary	Ephemeral bar at inlet. Stagnation in dry season.	Balcombe Creek (Australia), Thuan An Inlet (Vietnam)
6	Delta-front estuary	River dominated estuary	Mekong (Vietnam), Nile (Egypt), Mississippi (USA)
7	Tectonic estuary – compound type	Ria (high relief) type at the inlet, Lagoon (low relief) type landward.	San Francisco Bay (USA)

Table 1.3 Classification of estuaries based on geomorphology (Fairbridge, 1980)

1.1.4 Classification by tides

There are two common classifications for estuaries based on tidal characteristics. The first is based on the tidal range values and the second is based on the tidal propagation.

1.1.4.1Classification by tidal range

The tides and freshwater runoff control the type of mixing, circulation and salinity distribution. The tidal range can roughly be used to indicate the type of estuaries. Hayes (1975), who followed the classification proposed by Davies (1964), stated that "*The tidal range has the broadest effect in determining large-scale differences in morphology of sand accumulation*" and that "*a classification of estuaries could best be based on the tidal range*". Table 1.4 presents classification based on the tidal range. However, it does not seem to be a good definition, especially for micro-tidal estuaries, since we can find a number of estuaries having a tidal range smaller than two meters but being partially-mixed or well-mixed (e.g. Limpopo or Gambia).

1.1.4.2 Classification by tidal propagation

The interaction between the tidal wave and the topography of an estuary causes variations in the range of the tide and the strength of the tidal currents. By means of the spatial development of the tidal range, Nichols and Biggs (1985) divided estuaries into hypersynchronous (amplified then damped tidal range), synchronous (un-damped), and hyposynchronous (damped) estuaries. Dyer (1995) indicated that in an ideal estuary, the amount of energy lost by friction is balanced by the amount of energy that is gained by the converging of the riverbanks. This causes the tidal range to be constant along the estuarine axis. In an amplified estuary, the tidal range increases in the upstream direction. It is obvious that this process cannot continue indefinitely, at some points the friction becomes dominant which leads to a reduction of the tidal amplification and subsequently to tidal damping. In a damped estuary, the friction is larger than the converging of the riverbanks and this leads to a decrease of the tidal range in the upstream direction. Table 1.5 shows the classification based on the tidal propagation characteristics.

Name	**Tidal range (m)**	**Characteristic**	**Example**
Micro-tidal estuaries	< 2	Mostly highly stratified during high flows	Tampa Bay, Apalachicola Bay, Mississippi (USA), Limfjord, Isefjord (Denmark)
Meso-tidal estuaries	2 - 4	Mostly mixed to partially mixed	Mae Klong (Thailand), Mekong (Vietnam), Lalang (Indonesia), Columbia (USA)
Macro-tidal estuaries	4 - 6	Generally well mixed	Thames, Mersey, Tees (UK), Scheldt (Netherlands), Delaware (USA), Pungue (Mozambique)
Hyper-tidal estuaries	> 6	Generally well mixed	Seine, Somme (France), Severn (UK), Bay of Fundy (Canada)

Table 1.4 Tidal range classification of estuaries (Hayes, 1975)

Name	Characteristic	Reason	Example
Amplified (Hypersynchronous) estuaries	Tidal range increases toward the head until the riverine section	Convergence > friction	Scheldt (Netherlands), Seine estuary (France), Humber, - Thames (UK)
Ideal (Synchronous) estuaries	Tidal range is almost constant until the riverine section	Convergence = friction	Elbe (Germany), Delaware (UK), Limpopo, Maputo (Mozambique), Gambia
Damped (Hyposynchronous) estuaries	Tidal range decreases toward the estuary head	Convergence < friction	Mekong (Vietnam), Rotterdam Waterway (Netherlands), Incomati, Pungue (Mozambique)

Table 1.5 Tidal propagation classification of estuaries (Dyer, 1995)

1.1.5 Classification of estuaries based on combination of estuarine characteristics

Besides these classifications, there are other types of classification schemes, for example classifications based on the stratification-circulation diagram (Hansen and Rattray, 1966), morphology (Dalrymple *et al.*, 1992) or river influence (Savenije, 2005). It can be seen that there are many ways to classify estuaries on the basis of their diverse and abundant characteristics. Each classification method is based on one single characteristic or at best, two characteristics of estuaries, with an exceptional case of Cameron and Pritchard, 1963. However, this classification mainly follows the mixing pattern of estuaries. Savenije (2005) summarized a combined overview of different estuary types based on their main characteristics related to tide, river influence, geology, salinity and stratification (See Table 1.6).

Type	Shape	Tidal wave type	River influence	Geology	Salinity
1	Bay	Standing wave	No river runoff	Compound type	Sea salinity
2	Ria	Mixed wave	Small river runoff	Drowned drainage system	High salinity, often hypersaline
3	Fjord	Mixed wave	Modest river runoff	Drowned glacier valley	Partially mixed to stratified
4	Funnel	Mixed wave; large tidal range	Seasonal river runoff	Alluvial in coastal plain	Well-mixed
5	Delta	Mixed wave; small/large tidal range	Seasonal river runoff	Alluvial in coastal plain	Partially mixed to well-mixed
6	Infinite prismatic channel	Progressive wave	Seasonal river runoff	Man-made	Partially mixed to stratified

Table 1.6 Classification based on combination of estuarine characteristics (Savenije, 2005).

It is essential to keep in mind that many systems may change from one type to another in consecutive tidal cycles, or from month to month, or from season to season, or from one location to another inside the same estuary. For instance, the Hudson River, in the eastern United States, changes from highly stratified during neap tides to weakly stratified during spring tides. The Columbia River, in the western United States, may be strongly stratified under weak runoff conditions and similar to a salt-wedge estuary during high runoff conditions.

1.2 Monsoonal estuaries

The processes that control distribution of salinity in an estuary can be grouped into two classes, salinity-ingress and salinity egress (Vijith *et al.*, 2009). The salinity egress is associated with runoff into the estuary. The total salt within the estuary gets reduced as the freshwater brought by the runoff mixes with the estuarine water. Salinity-ingress, which leads to increase of salinity in the estuary, arises from the following processes: horizontal diffusion, gravity current formation and impact of spring-neap tidal asymmetry, and tidal straining or impact of ebb-flood tidal asymmetry. When the magnitude of salinity-ingress is equal to that of salinity-egress, the estuary attains a steady state. This steady state has been the hallmark of many estuarine theoretical frameworks and classification schemes. An example is the well-known estuarine model given by Hansen and Rattray (1965, 1966). Many estuaries that do not always have a balance between salinity ingress and egress due to time-dependence in the freshwater runoff. Estuaries that come under the influence of Indian Summer Monsoon (ISM) cannot be treated as being in a steady state at any time. These estuaries are located along the coastline of the Indian subcontinent, and their essential unsteadiness arises due to the runoff. The runoff is very high during the ISM, that usually occurs during June–September. This high runoff is followed by little runoff during the dry season. Most of these estuaries are shallow, with depth at the mouth of 10 m and at the head of the order of a metre. They are convergent, i.e. the width decreases rapidly from mouth to head. Width at the mouth is typically few kilometres and at the head is about a tenth of a kilometre. These estuaries are partially mixed during the dry season. Such estuaries are referred as “monsoonal estuaries” (Vijith *et al.*, 2009).

1.3 Physical processes in an estuary

Although estuaries are diversified due to their unique characteristics, it can be clearly seen in Section 1.1 that the two dominant drivers of an estuary are its tide and river runoff. Moreover, the shape of an estuary certainly defines its characteristics. The interaction between tide, river runoff (and wind to some extent) and topography causes mixing. Mixing in estuaries is the main reason why a sea and a river can exchange their water, substances and sediments.

Tides often dominate the mixing in estuaries (Gross, 1972). Ocean tides are defined as the periodic rise and fall of sea surface caused by the gravitational attraction of moon and sun on earth. The gravitational attraction of other planets on earth is negligible because of their distant locations. Tide created in the ocean penetrates into rivers as a disturbance, the shape and size of rivers being such that they do not respond directly to the tidal forces. The disturbance takes the form of a progressive wave, markedly affected by friction and completely damped eventually (Godin, 1988). Tide, river runoff, bathymetry, wind, Coriolis force, etc. control the processes in an estuary (Fischer *et al.*, 1979). Circulation and transport mechanisms in estuaries are complex and subject to a large spatial and temporal variability derived from the interaction of river runoff, tides and winds. These forces drive the gravitational circulation and turbulent diffusion which are the main processes controlling the transport of properties in estuaries (Mantovanelli *et al.*, 2004). Bathymetry also regulates the propagation of tides. Shallow regions of estuaries enable vertical mixing more effective than that of deeper regions.Freshwater inflow into an estuary normally has a significant impact on mixing and the increased freshwater inflow can change the character of an estuary from well mixed to partially mixed or stratified (Martin and McCutcheon, 1999).Tide is probably the most important factor. Tidal flow is considered as a source of kinetic energy. Savenije (2005) identified seven types of mixing due to tidal influence (i.e. tide-driven mixing).

The river flow provides potential energy (though buoyancy) that drives density-driven circulation (or gravitational circulation). River runoff determines the volume of freshwater in an estuary and the distribution of the salinity (density) field. They will therefore determine the magnitude of the salinity gradients along the axis of the estuary. In this thesis, we do not pay further attention to wind-driven mixing due to its minor contribution to salt intrusion.

1.4 Study area

There are more than 100 major and medium estuarine channels along the east and west coast of India (Manoj, 2008). The estuaries along the east coast of India are long and wide whereas the estuaries along the west coast are smaller. Ganges-Brahmaputra Delta region along the east coast of India is the largest estuarine network in India. Since ancient times, estuaries in India have been a focal point of activities for human settlement, development of ports and harbours, transportation of men and material and for trade and commerce (Qasim, 2003).The estuaries along the west coast of India are unique in their physical and bio- geochemical features. Cochin Estuary is one of the largest estuarine systems along this region and the other important estuarine systems along this coast are Ashtamudi estuary, Kali river, Mandovi and Zuari estuarine system, Mumbai Harbour and Thane Creek system and a number of small estuaries like Sabarmati, Tapti, Narmada etc. These water bodies are fed by rivers that originate in the Western Ghats (Mountain ranges on the west coast of India). For the present study, Cochin estuary is chosen. It is one of the above types of water bodies with two openings to Arabian Sea. This system extending from Munambam (10°10'N, 76°15' E) in the north, to Thanneermukkam (09°30' N, 76°25' E) in the south over a length of ~80 km.

Over the years, Cochin estuary has undergone lot of anthropogenic modifications such as reclamation for agricultural activities at Kuttanad known as rice bowl of Kerala state (1888 onwards), deepening of Cochin inlet for harbour development (1920-36), industrial revolution (1940 onwards), human settlement (1940 onwards), construction of several dams across the perennial rivers

(~1950s), hydraulic barriers (1976-82), all of which lead to eutrophication of the estuary (1980 onwards). The area of this system in 1912 was 315 km^2 and shrunk to 180 km^2 (43% of original) in 1983 (Gopalan *et al.*, 1983) .Of the 130 km^2 surveyed in 1998, nearly 14% (18 km^2) has been observed to be reclaimed by both natural and artificial processes (Asharaf, 1998).

This system is declared as one of the three Ramsar sites in Kerala in November 2002. It is a part of Vembanad-kol wetland system and it has great socio-economic importance.The Cochin estuary is important from the point of view of its flora and fauna, supporting a population of over 20,000 water-fowls in India. It is renowned for its live clam resources and sub-fossil. The soft organically rich sedimentary substratum of the inshore region is an ideal habitat for shrimps. It serves as a habitat for a variety of fin and shell fish, and a nursery of several species of aquatic life. Mangrove ecosystem is found to grow in and around of this largest estuarine system provide unique environment of great ecological value.

For centuries, the system have provided a safe and efficient means of transportation for goods and people moving between the interior and the port towns along the coast. The major commercial and economic activities in this system include agriculture, fisheries, lime shell mining and backwater tourism. Cochin Port with its glorious maritime tradition is the fastest growing maritime gateway to peninsular India is situating in the Willington Island of this estuarine system. Now, with the commissioning of India's first International Container Transshipment Terminal (ICTT) at Vallarpadam Island, Cochin Port asserts its unique advantage in the global maritime trade routes.

1.4.1 Physiographic setting of Cochin estuary

The estuary (Fig. 1.2a) is characterized by its major axis lying parallel to the coastline, with several small islands and interconnected waterways. It was primarily a marine environment bounded by an alluvial bar parallel to the coast line and interrupted by Arabian Sea at intervals (Gopalan *et al.,* 1983). For the establishment of Cochin Port in 1936, the "natural bar" is dredged out while deepening the channel to make the basin accessible for ocean going vessels (Strikwerda., 2004). The width of the estuary varies from 450m to 4km and the depths range from 15m at Cochin inlet to 3m near the head with an average depth of 1.5m (depths are reduced to chart datum). The system is separated from the Arabian Sea by barrier spits interrupted by tidal inlets at two places, namely (i) Munambam in the north (inlet 1) and (ii) Cochin inlet in the middle (inlet 2). The Cochin Port, situated on the Willingdon Island, is near the inlet 2, which provides the main entrance channel to this system. Tides in the estuary are mixed, predominantly semi-diurnal type with an average tidal range of 1m (Qasim and Gopinathan., 1969). Freshwater into estuary is primarily contributed by six rivers. The branch of Periyar River feeds 30% of its runoff into the northern parts of the estuary. The remaining 70% discharges directly into the Arabian Sea through the inlet 1. Muvattupuzha River joins along the length of the channel whereas Pampa, Achankovil, Manimala, and Meenachil join at the upstream end. During the dry season, the runoff originating upstream is minimal which ensures strong saline intrusion to the low-lying paddy fields located further upstream (Shivaprasad *et al.*, 2012). Thannermukkam barrage (TB) in the south was made functional in 1976 to prevent salt-water incursion and to promote cultivation in the low-lying fields. The widest (about 5 km) and the shallowest (1 m) areas of the backwaters are seen in this region. The overall length of the structure (approach road, sluice gates and masonry) is of about 1.5 km. The actual width of the TB portion alone is around 800-850 m and the sill is at an elevation of 3.38 m below MSL. There are around 63 sluice gates; each gate is of around 12.5 m in width. The opening and closing process of the 63 gates of TB is gradual, taking place over a time frame of around 3-4 days. It remains closed from January to May every year.

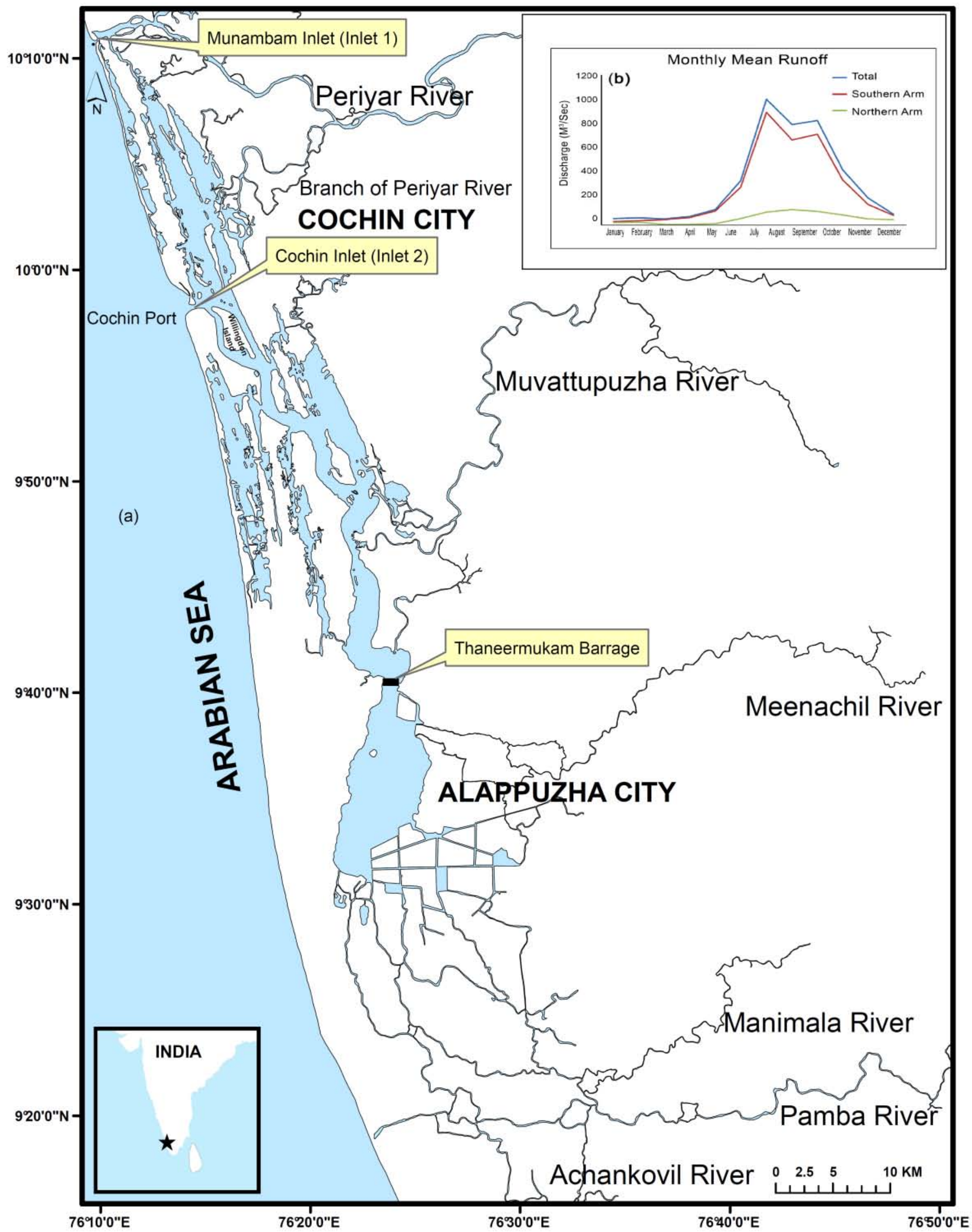


Fig.1.2 (a) The Cochin estuary (b) Monthly mean river runoff

1.4.2 Climatological setting

The domain experiences humid tropical climate with the mean daily temperatures ranging from 19.8 °C to 36.7 °C. Mean annual temperature ranges from 25.0–27.5 °C in the coastal lowlands (Government of Kerala, General features 2005b; Brenkert and Malone 2003). The average monthly rainfall for the year 1978 to 2002 at the different physiographic zones of the river basin is as shown in Fig. 1.2a. In most years, pre-monsoon (March–May) experiences the lowest recorded rainfall with a combined average of only 386mm month^{-1}, thus defining the peak of the "dry" season. In contrast, southwest monsoon (June–September) receives the most rainfall with an average and maximum of 1400 mm month^{-1} and 1891 mm month^{-1}, respectively; thus defining the peak of the "wet" season (Krishnakumar *et al.* 2009). The river runoff data (Fig. 1.2b) for the year 2008 to 2009 is obtained from Central Water Commission. About 60% to 70% of the total runoff occurred during June–September and the least (6.82%) occurred during December-February.

1.5 Previous studies

The Cochin estuary experiences large spring- neap, flood- ebb, seasonal variations in tidal elevations and tidal currents (Rama Raju *et al.*, 1979, Udaya Varma *et al.*, 1981, Joseph et al., 1990, Srinivas et al., 2003a) Studies on currents and tidal propagation (Srinivas *et al.*, 2003b, Revichandran *et al.*, 2011) have been reported earlier in the Cochin estuary. The system has been identified as one of the most productive estuarine systems along the west coast of India by Menon *et al.*, 2000. Further, the sediment heavy metal contamination of this estuary has placed the region among the impacted estuaries in the world (Balachandran *et al.,* 2005). The run-off components like municipal waste discharge from the surrounding city, and riverine water carrying industrial and agricultural wastes are responsible for nutrient enrichment influencing the estuarine water quality (Joseph. S and Ouseph. P. P., 2010).

According to Srinivas *et al.*, 2003b the relative importance of the semi-diurnal and the diurnal components keeps changing throughout the month. Spring phase is dominated by semi-diurnal tides and neap phase by diurnal tides. There is a rapid decay in the amplitudes of the principal tidal constituents as they propagate upstream. The Cochin harbour region has undergone many changes and is still witnessing many engineering modifications like land reclamation, waterways development, construction of bridges and deepening of the shipping channels, which have from time to time influenced the hydrodynamic aspects of this system (Srinivas *et al.*, 2003b). Menon *et al.,* 2000 have exhaustively reviewed the literature concerning the physico-chemical as well as biological aspects of this water body. Based on the data for 1988-'93,Srinivas *et al.,* 1999 reported that the sea level variance is dominated mainly by tidal signals, which accounted for nearly 90-95% of the observed sea level. Srinivas *et al 2003b* described the spring-neap variation of tides at some selected locations in the lower reaches of the Cochin estuarine system. Varma *et al.*, 1981 Concentrated on understanding the structure of currents in the lower reaches of the estuary during different seasons, and discussed the current patterns with respect to tidal rhythm and its effect on salinity changes in the inlet region.

Varma *et al.*, 2002 suggested that signatures of low frequency coastal trapped waves are seen in the southern part of the estuary. The variance in sea level at the lower reaches is dominated mainly by tidal signals (nearly 93.7% of variance of the observed sea level). Mean amplitudes of the tidal constituents based on annual analyses (1988-1993) showed that M_2 (Principal lunar) is maximum, followed by K_1 (Luni-solar), O_1 (Principal lunar) and S_2 (Principal solar) . The amplitudes of the M_2, K_1, O_1 and S_2 tides are 20.4, 17.6, 9.3 and 7.5 cm, respectively (Srinivas *et al.*, 2004).

The published reports on salinity distributions are limited to the lower reaches of Cochin estuary. Udaya Varma *et al.*, 1981 and Joseph *et al.*, 1990 had found that during high runoff periods, the saline waters intrude only through the bottom layers.Flood- ebb variation in salinity gradients of two locations in the middle estuary were studied by Qasim and Gopinathan (1969). However, the salinity observations are limited to in and around inlet regions.

In Cochin estuary, currents are dominated by tidal signals; semi-diurnal tidal regimes experience swift tidal currents than diurnal tidal regimes (Srinivas *et al.*, 2003b). Balachandran *et al.*, 2008, with the help of a model showed that strong currents prevail at the central estuary (from Cochin inlet to 22km south) whereas weak and slow currents are found in the north and south estuary. Strong current velocity of magnitude 130 cm/s was also reported by Varma *et al.*, 1981 in the Cochin inlet region. Therefore the central estuary maintains an effective flushing (Balachandran *et al.*, 2008).

The construction of TB has resulted in drastic and ecological changes in Cochin estuary. The barrage has reduced the extent of backwater nursery grounds by 25% which led to the total collapse of the juvenile shrimp fishery of Kuttanad region (Kannan, 1979). An area of 69 km^2 of brackish water lying south of TB has been economically cut off from backwaters (Gopalan, 1991). The periodical opening and closing TB has seriously deteriorated the ecology of the Cochin estuary especially in the southern part of the barrage as evidenced by the depletion of clam beds (Arun *et al.*, 2009). Construction of TB across Cochin estuary altered the flow patterns and hence enhanced the growth of prevalence of indicator and pathogenic bacteria within the region (Hatha *et al.*, 2008). Tidal flushing is restricted due to closure of TB in summer which has eventually resulted in the accumulation of toxic contaminants like heavy metals in the sediments in the area (Harikumar *et al.*, 2009). Proliferation of weeds and water hyacinths upstream has affected the navigation and severely restricts the natural flushing of pollutants (Revichandran *et al.*, 2011).

Studies on tides and river runoff interactions in this entire estuarine system, using sufficiently long time series data has not been attempted so far. However, a few workers have attempted to understand the tidal characteristics near to the mouth of the Cochin backwater system. Generally estuaries exhibit large spatial variability due to different conditions that exist around the world to form them. While at the same time the estuaries also exhibit quite a bit of temporal variability – as a result of changing river runoff, tidal fluctuations, and climatic conditions. The study of the circulation within estuaries is therefore a complex one, as generally no two estuaries are the same. However, as with most physical oceanographic studies, it is still possible to understand the tide and river runoff interactions. Hydrodynamic characteristics of an estuary resulting from interaction of tide and river runoff are important since problems regarding flood, salinity intrusion, water quality, ecosystem and sedimentation are ubiquitous. The present study focuses on such hydrodynamic aspects in the Cochin estuary.

Considerable effort with aid of sophisticated instruments and systematic observation has not been put forth toward to understand the characteristics due to tide and river runoff interactions in the Cochin estuary. Knowledge of these linkages is important, as estuarine circulation patterns which can influence ecosystem structure and function.

1.6 Objectives

Hydrodynamic characteristics of an estuary resulting from interaction of tide and river runoff are important since problems regarding flood, salinity intrusion, water quality, ecosystem and sedimentation are ubiquitous. The present study focuses on such hydrodynamic aspects in the Cochin estuary.

Most of the estuaries that come under the influence of Indian Summer Monsoon and for which the salinity is never in a steady state at any time of the year are generally shallow and convergent, i.e. the width decreases rapidly from mouth to head. In contrast, Cochin estuary is wider towards the upstream and has no typical river mouth, where the rivers are joining the estuary along the length of its channel .Adding to the complexity it has dual inlets and the tidal range is 1 m which is lower than other Indian estuaries along west coast. These typical physical features lead to its unique hydrodynamic characteristics. Therefore the thesis objectives are: **I**) to study the influence of river runoff on tidal propagation using observations and a numerical model **ii**) to study stratification and property distributions in Cochin estuary **iii**) to understand salinity distributions and flushing characteristics **iv)** to understand the influence of saltwater barrage on tides and salinity **v**) To evaluate several classification schemes for the estuary.

1.7 Outline of the thesis

The chapters in the thesis are structured as follows. Chapter 2 deals with the data and methodology, where the different data sets used, equations used in the numerical model, etc. are described. In Chapter 3, the simulation of tides and freshwater influence on tides are described in detail. The model results are analysed to understand the interaction between tides and river runoff. The results shows high river runoff raises the mean water level but damps the tide. The results of simulations are carried out for two realistic and two idealized scenarios are also explained.

Chapter 4 deals with the seasonal stratification and property distributions in Cochin estuary. The intratidal, spring-neap and seasonal variations in stratification are examined in detail. The influence of tides and river runoff forcing in water column stability are quantified using potential energy anomaly and stratification parameter. Partially mixed (neap) and well-mixed (spring) conditions during low runoff period are altered in high runoff by the salt wedge intrusions. The Chapter 4 also presents the results of longitudinal measurements of salinity profiles made throughout the length of the Cochin Estuary during a 1-year period. The estuary lost about 48% of its salt from June to July due to high spells and a successive gain of about 9% occurred. As a result of peak dry season (Jan-April) the salt content increased steadily despite the variations in runoff.

Chapter 5 describes the Thanneermukkam barrage at the upstream end of the estuary influences tides and salinity. The characteristics of the estuary when the barrage was opened and closed are discussed. The analysis showed that the closure of the barrage caused amplification of tides in the immediate vicinity and up to 10 km farther downstream. During dry period, the reduction in river flow compounded with the closure of barrage resulted in the increase of salinity concentration downstream. The hydrodynamic control on phytoplankton biomass is also evident.

Chapter 6 deals with the results of evaluation of several estuarine classification schemes for this unique system. Statistical analysis shows river runoff is controlled by short term variations rather than long term variations. The results show existing methods proved to be insufficient to represent the real salient features of this typical estuary.

Chapter 7 Provides summary and conclusion.

Chapter 2

Data and methodology

Data collection from Cochin estuary is carried out as part of a major programme on Ecosystem Modeling of the Cochin Backwaters funded by Integrated Coastal and Marine Area Management (ICMAM-Ministry of Earth Sciences, Government of India). Details of the data sets used and methodology employed in accomplishing the objectives are provided in the corresponding sections.

2.1 Influence of river runoff on tidal propagation

2.1.1 Numerical model

Numerical models have a variety of applications in scientific and engineering fields. Numerical models are widely used for the simulations of physical processes in ocean and have many applications in the coastal regions and estuaries. To simulate tidal circulation, sedimentation, salinity distribution etc. in an estuary, various modelling techniques such as physical modelling, analytical modelling etc. are used. Though physical modelling techniques are useful for the predictions of the estuarine processes, this approach is expensive and has limitations in scaling some physical parameters. Analytical modelling is another tool to study the estuarine systems and many studies were carried out in estuaries using analytical models (Ketchum, 1950, 1951a, b, 1954, 1955; Ippen and Harleman, 1961; Hansen and Rattray, 1965, etc.)

Simulation of estuarine processes requires proper representation of bottom topography, irregular coastline etc. The limitations of analytical modelling are that it assumes a regular geometry of systems. The geometry of an estuarine system has an important role on circulation and phase speed of waves. An improper representation of geometry does not show the important characteristics of estuarine dynamics.Advances in computer technology in 1950s made the solution of equations, which represent the systems easy and fast and many models were developed using one dimensional equations of motion, continuity and advection diffusion equation of salinity (Lamoen, 1949; Hansen, 1956; Harleman *et al.*, 1968; Bella and Dobbins, 1968; Dronkers, 1969, etc.).

Lamoen (1949) used a one dimensional numerical model to simulate tides and tidal currents in the Panama Canal. Hansen (1956) proposed a numerical model for the non- linear tidal propagation in Ems estuary, Germany. The finite difference explicit numerical scheme was used in the model. Later on, a one dimensional numerical approach was proposed by Harleman *et al.* (1968) to simulate dispersion coefficient in Potomac estuary. Posmentier and Raymont (1979) used a one dimensional model and the coefficient of lon- gitudinal diffusion for salt was calculated from the distribution of salinity observed in the Hudson estuary. A one dimensional hydrodynamical model was used by Uncles and Jordan (1980) to describe the crosssectionally averaged Stokes drift and Eulerian residual (tidally averaged) currents in a section of the Severn estuary between Porthcawl and Sharpness.

Shetye and Murty (1987) used a one dimensional model to estimate the annual salt budget in the Zuari estuary on the west coast of India. Giese and Jay (1989) used a one dimensional harmonic transport model, which provides a qualitative explanation for and accurate quantitative predictions of along channel variations in tidal properties in terms of the momentum balance. Li and Elliot (1993) used an array of one dimensional model to simulate the vertical structure of tidal currents and temperature of North Sea.

Unnikrishnan *et al.* (1997) and Manoj, 2009 used a network numerical model in the Mandovi and Zuari estuaries to simulate the tidal decay during wet season. Most of these studies were carried out to understand the basic dynamical processes in the estuarine systems. Though one dimensional model are successful in simulating tidal hydrodynamics to a great extent, its inability to represent the changes of circulation and mixing in the lateral and vertical directions, which are significant in many of the estuarine systems, are the major limitations of this modelling approach. But for studying tidal propagation and influence of river runoff on tides, a 1D modelling approach is sufficient. One-dimensional modelling is applicable for estuaries with well defined channels and for bays with single or multiple inlets. In the present study, for the simulation of tides, a one dimensional network numerical model (hereafter 1DNN-model) is used. The resolution is 1km grid (segment) along the channel distance using the formulation given by Manoj *et al.* (2009).

2.1.1.1 Equations in the model

The equations governing motion in channel of the network are, the momentum and continuity equations that are as follow.

The one dimensional momentum equation can be written as

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A} q - \frac{2bQ}{A} \frac{\partial \eta}{\partial t} = -gA \frac{\partial (Z_0 + h + \eta)}{\partial x} - g \frac{Q|Q|}{AC^2 R} \text{.............(1)}$$

The continuity equation is written s follows

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \text{...(2)}$$

Chezy coefficient is calculated using the formula given below

$$C = \frac{(1.49)}{n} R^{\frac{1}{6}} \text{...(3)}$$

where *t, x, Q, h, q, g, d, R* and *n* are, respectively, time, along-channel coordinate (increasing in upstream direction), along-channel transport, elevation with respect to mean water level, freshwater influx per unit channel length, acceleration due to gravity, depth and hydraulic radius, manning coefficient; Z_0 is the height between bottom of the channel and an arbitrary datum below the bottom; b_s is the width in which along-channel flow occurs whereas width b includes mud flats which act as storage; R is equal to (A/P_r), P_r being the wetted perimeter and A is the area of cross section excluding mud flats.

2.1.1.2 Model Setup

The model domain of Cochin estuary is a network of five channels with two open boundaries (Fig. 2.1). The main channel of this network consists of northern and southern channels. The northern channel has 27 segments (1^{st} segment of northern channel is first open boundary of the model domain). The southern channel has 43 segments. Fortkochi channel has 4 segments (1^{st} segment of Fortkochi channel is the second open boundary of the model domain). The 4^{th} segment of Fortkochi channel is connected to the 1^{st} segment of southern channel and 27^{th} grid of northern channel. The Vallarpadam channel and Mattanchery channels have 8 segments each. The 1^{st} segment of Vallarpadam channel is connected to 21^{st} segment of northern channel and the 8^{th} segment is connected to the 3^{rd} segment of Fortkochi channel. The 1^{st} segment of Mattanchery channel is connected to the 3^{rd} segment of Fortkochi channel, and the 8^{th} segment is connected to 8^{th} segment of southern channel.

The model is calibrated and verified using time series measurements of tides mentioned in section 2.1.2.3**.** The observed tides at Munambam are used for forcing the model at open boundary 1 (inlet 1) and at inlet 2, the observed tides at Fortkochi are used.

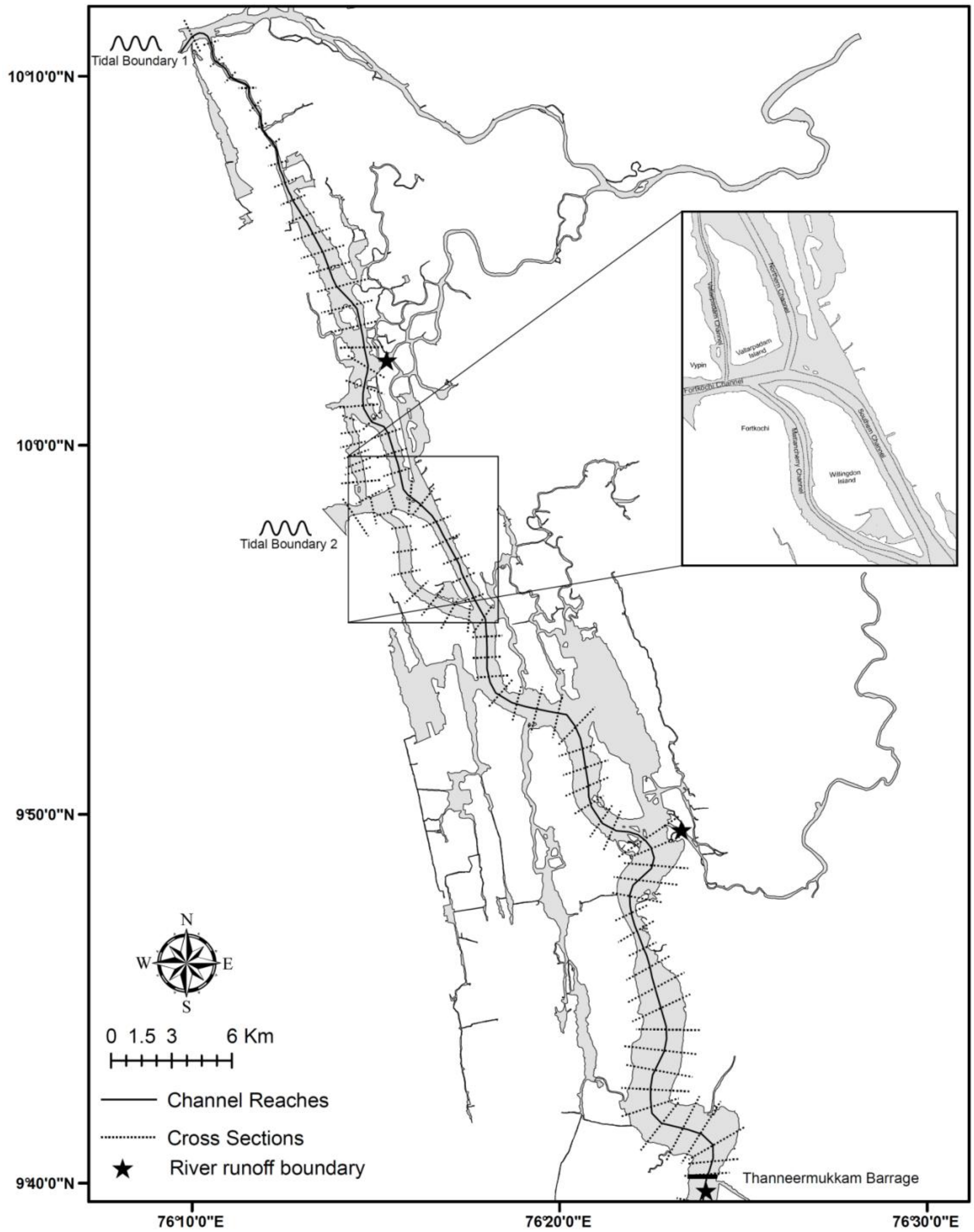


Fig. 2.1. Map shows the schematized channels, tidal boundaries and runoff boundaries of Cochin Estuary

2.1.2 Data sets

Numerical modelling of physical phenomena such as tidal circulation in an estuary require a number of data sets, which include river runoff , bathymetry and sea surface elevation (here after “tide data”) for prescribing open boundary conditions, model validation.

2.1.2.1 River runoff

The daily and monthly mean river runoff data are obtained for six gauging stations corresponding to six major rivers emptying into the Cochin estuarine system, for the period of one year (2008-2009) from Central Water Commission, New Delhi, Government of India. About 73 % of the total river runoff occurred during high runoff characterized by monsoon. The mean runoff to the estuary varied from a maximum of 1008m^3/s in July to a minimum of 49.54m^3/s in March during low runoff (Table 2.1). Based on river runoff, the annual seasonal cycle is distinguished as high runoff months characterised by Indian summer monsoon or ISM (June-September), moderate runoff months characterised by north-east monsoon or NEM (October-December) and low runoff months or characterised by pre-monsoon dry period (January-May).In the present study model simulations are conducted during low run off and high run off.

2.1.2.1.1 River runoff inclusion in the model

The monthly mean runoff of March and September are used to prescribe river runoff conditions in the model. River runoff of rivers Pamba, Meenachil, Achankovil, Manimala are included in the model by calculating transport at the TB, the upstream end of the model domain. The branch of Periyar River feeds 30% of its runoff into the northern parts of the estuary, which is prescribed in the middle of northern arm. Muvattupuzha River joins along the length of the channel which is also prescribed. Transport at the runoff boundary is calculated as follows.

$$q = \frac{Discharge}{\Delta x} \qquad (4)$$

where q is river runoff per unit channel length (m^2s^{-1})

2.1.2.2 Bathymetry data

Bathymetry data of the Cochin estuary are obtained by digitization of recently developed bathymetry charts of The Inland Waterways Authority of India (IWAI NW-3 Planning chart, IWAI NW-3 Subcharts-21Nos), using 3D Analysis tools in ArcGIS software. The one dimensional upstream regions in the Cochin estuary are schematized into segments respectively based on the description given by (Harleman and Lee, 1969).

2.1.2.3 Tide data

Two data sets of tide data are obtained from one month long continuous time series observations under two runoff conditions during 2009-2010 from 7 stations (Fig. 2.2). A SBE 26plus Tide Recorder (Fig. 2.3) with accuracy 0.1% of full scale (Strain Gauge Pressure) is used for the observations at all stations at 10 minute intervals. Stations 2-3 are along northern arm and stations 5 and 7 are along southern arm. Station 1&4 represents inlet 1 and inlet 2 respectively. Sampling is conducted in the months September-October (20/09/2009 16:00hrs to 20/10/2009 8:00hrs) and February-March (22/2/2010 00:00hrs to 22/3/2010 08:00hrs) (Figs. 2.4 & 2.5). These months are representative of high runoff, and low runoff periods respectively.

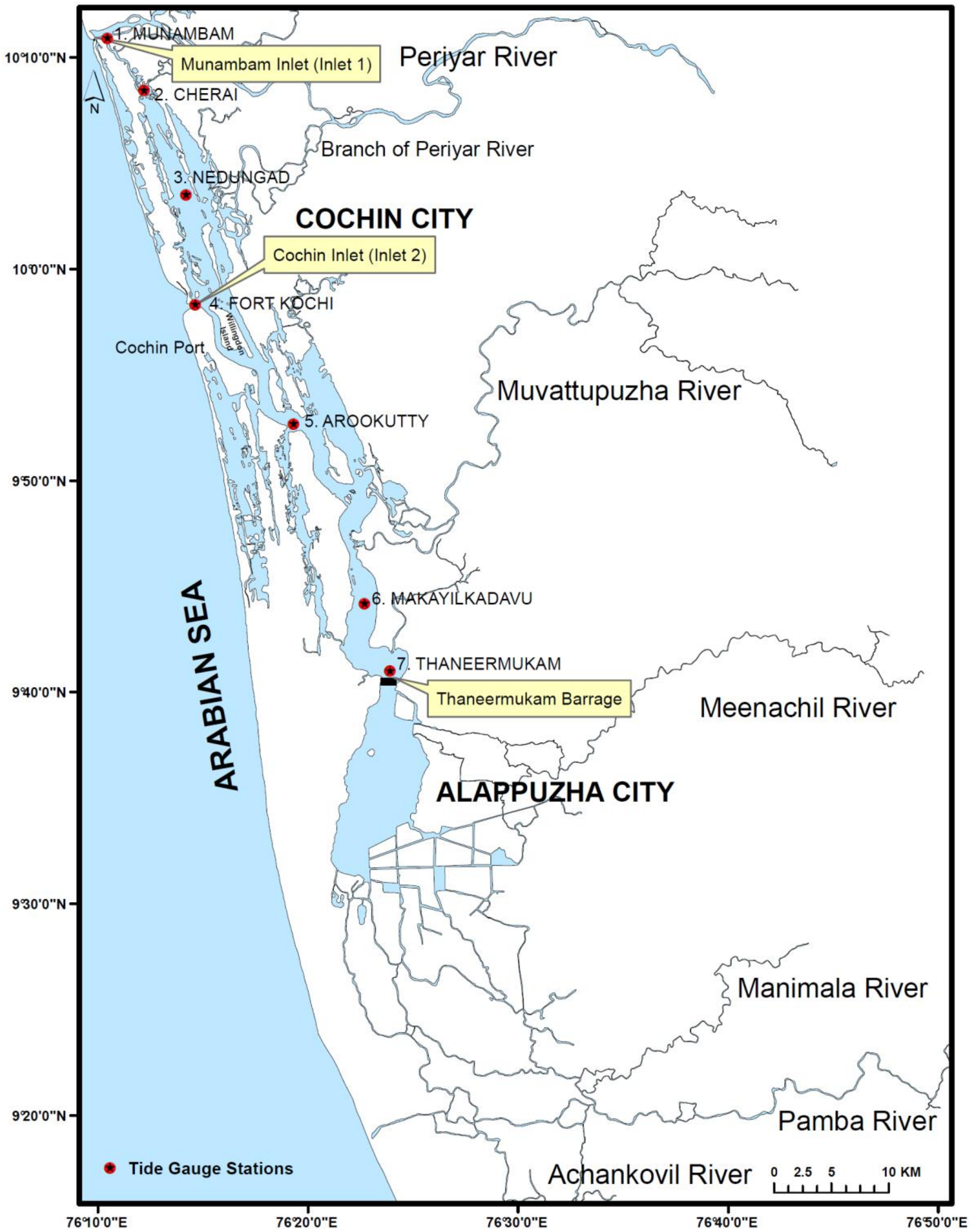


Fig. 2.2. Location map of tidal measurements at seven stations in Cochin estuary. The station name is associated with the station number.

Fig. 2.3. A SBE 26plus Tide Recorder

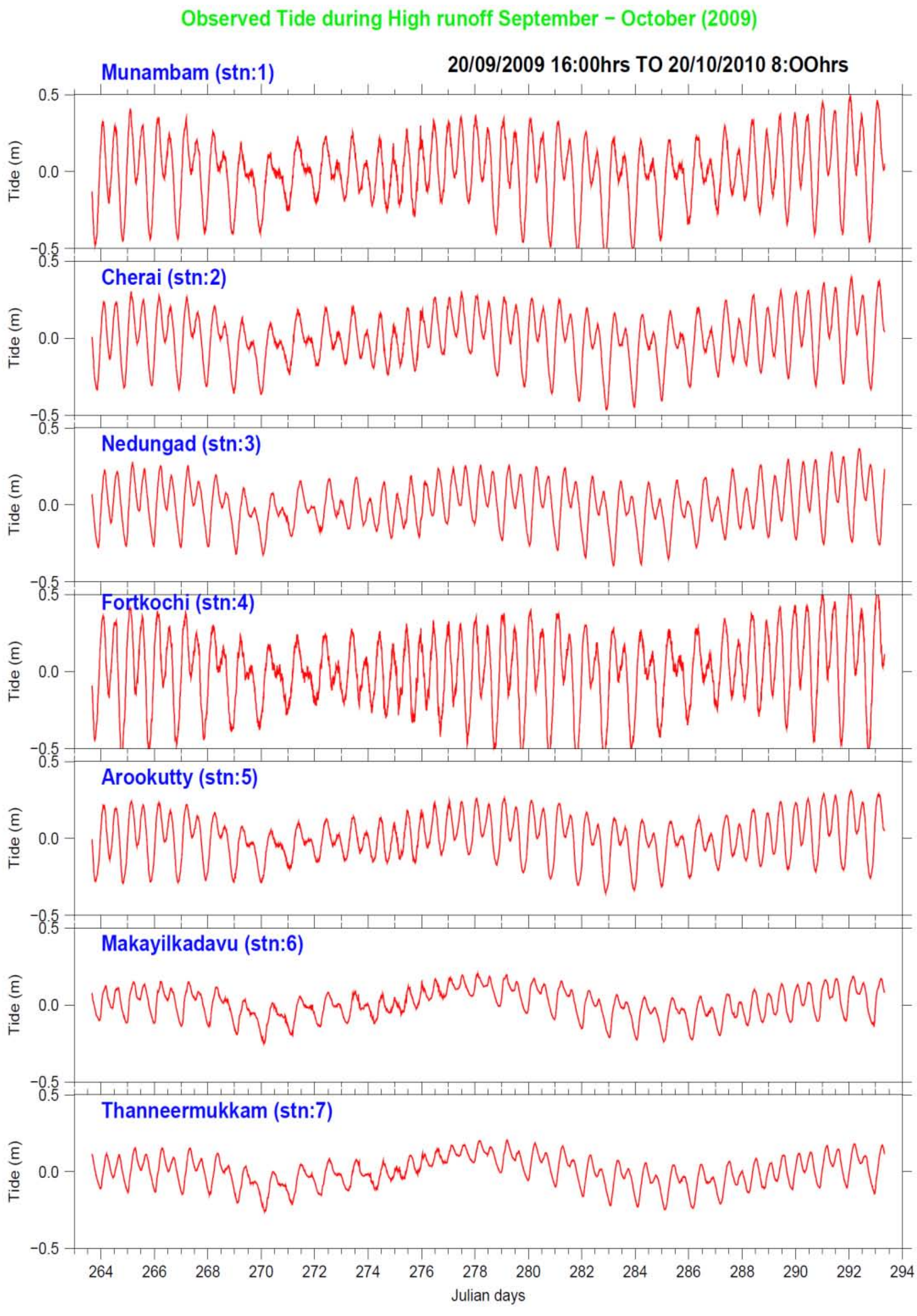


Fig. 2.4. Observed Tide during high runoff (20/09/2009 16:00hrs to 20/10/2009 8:00hrs) shows mixed semidiurnal nature of tide with decaying amplitude towards upstream. Tide is at its maximum amplitudes in the inlets (Stn1&4)

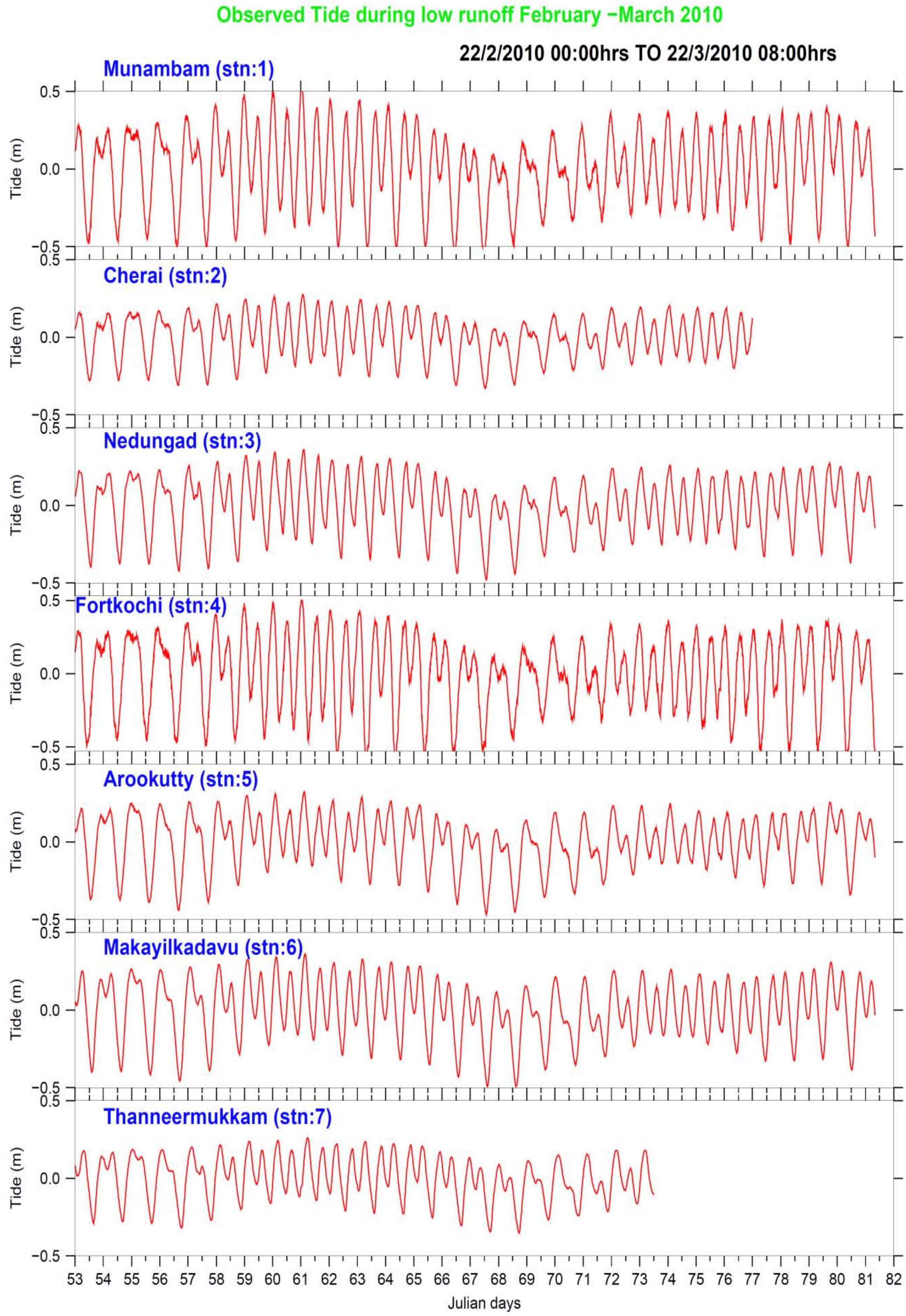


Fig. 2.5. Observed Tide during Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs).Few days data missing is there at Stn 2&7.

2.1.3 Stability criterion of the numerical scheme

The time step is related to the model stability and its appropriated selection is crucial to the total computational time. It is possible to determine a maximum value to this parameter applying the Courant-Friedrichs-Lewy stability criterion,which can be written as follows;

$$\Delta t = \frac{\Delta x}{\sqrt{2g(h+\eta)}} \qquad (5)$$

A range of time steps are used to stabilize the model and the model is stabilized for the time step of 30s. Δx is space increments in x direction which is chosen as 1km. The grid spacing between x direction should be minimised so that it can resolve the effect of irregular coastlines of the estuaries and bays better, but the reduction in grid spacing leads to small time step and this in turn consumes more computational time. In the present model, the grid resolution chosen is sufficient to represent islands, embayments and channels of Cochin estuary.

2.1.4 Finite difference scheme

There are many numerical methods such as finite difference method, finite element method etc. for solving the partial differential equations. Finite difference schemes are widely used numerical schemes because they give less complexity compared to other numerical schemes. Hydrodynamic modelling of estuaries normally requires the physical dimensions to be approximated by a computational grid (Martin and McCutcheon, 1999). There are various types of model grids and a grid is selected for approximating the solutions of differential equations based on what kind of numerical scheme is used. In the present model, an Arakawa C grid (Arakawa and lamb, 1977; Thubum, 2007) is used for approximating the solutions of differential equations. The advantage of using this grid is that it enables the user to include barriers, across which no flow is allowed. Also, a zero velocity boundary condition can be applied at the closed boundaries (Grzechnik, 2000).

2.2 Stratification and property distributions

2.2.1 Salinity observations

Intensive series of hydrographic surveys comprising three different time scales of observations are carried out in the Cochin estuary to achieve this objective: a) time-series at a single station positioned close to the main inlet of the system b) synoptic observations and c) monthly observations

2.2.1.1 Time series observations

Time series data are collected from a station, 5 km upstream of Cochin inlet during four surveys in 2007 (Fig. 2.6). Since the environmental behaviour and dynamics of the Cochin estuarine system is highly influenced by monsoonal rainfall and the associated runoff, we have ideally chosen both extreme conditions of seasons for data collection; low runoff (and high runoff months. Significantly, the observational coverage included two spring (May 2-3^{rd,} July 16-17th, 2007) and two neap (April 25-26^{th,} July 24-25th, 2007) tidal phases. The time series measurements are conducted during low runoff (April-May) and high runoff (July) months for 30 hours and 27 hours respectively covering two consecutive semidiurnal cycles. A SBE 19*plus* V2 SeaCAT Profiler CTD (Fig. 2.7) is used for recording temperature (accuracy +- 0.001C) and salinity (conductivity +- 0.001 S/m) profiles with a bin size 0.2m for every 30 minutes interval. The water level measurements throughout the observations are collected using tide pole and it is crosschecked with the tide table (Published by Survey of India) and the tide is predicted using TASK-2000 software. Water samples collected from surface, mid-depth (~4 m) and close to bottom at 3 hour intervals are utilised to determine the nutrient and chlorophyll *a* concentrations.

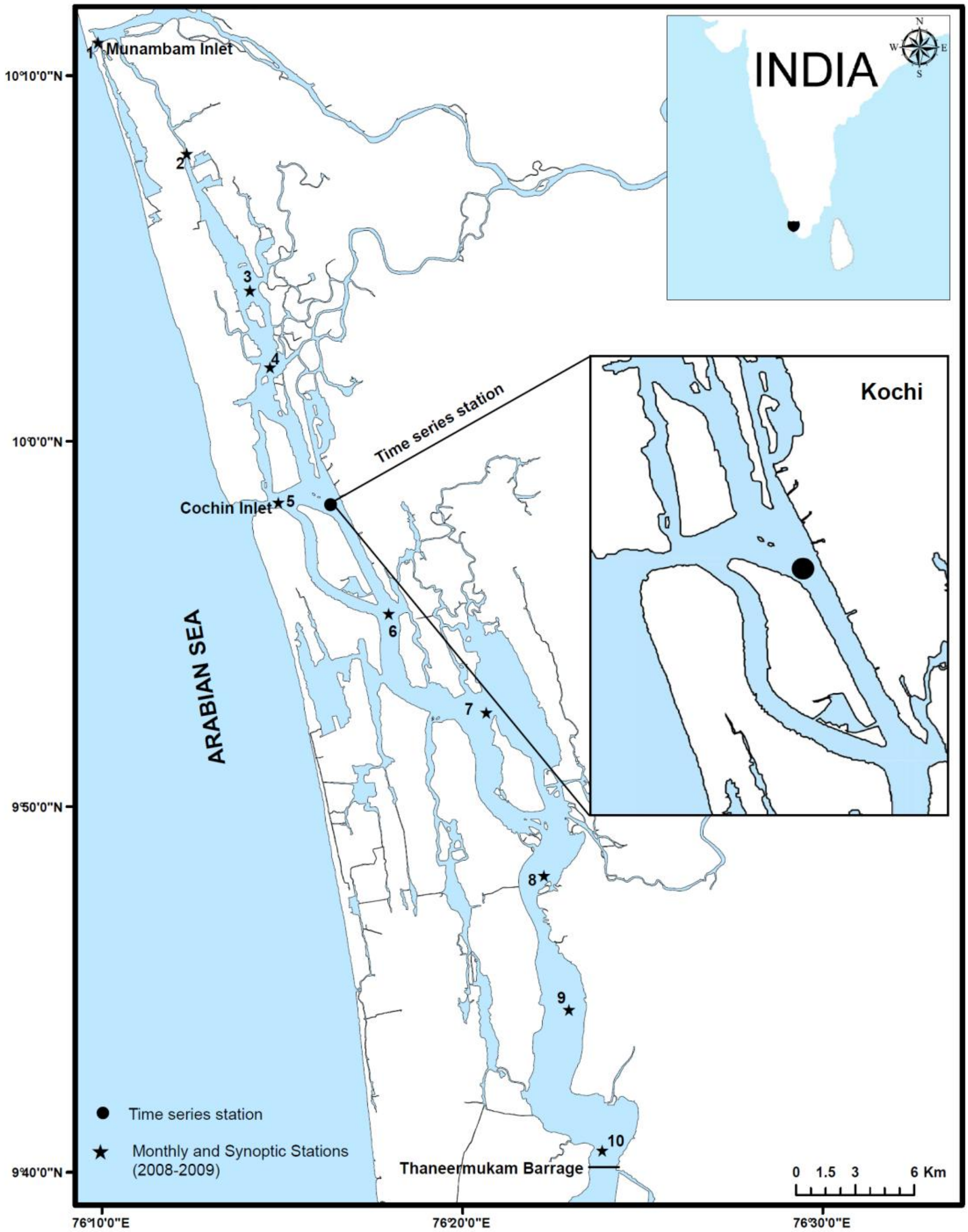


Fig. 2.6. The Cochin estuary (West coast, India), showing stations to study Stratification and property distributions. The time series stations and monthly stations are discerningly marked.

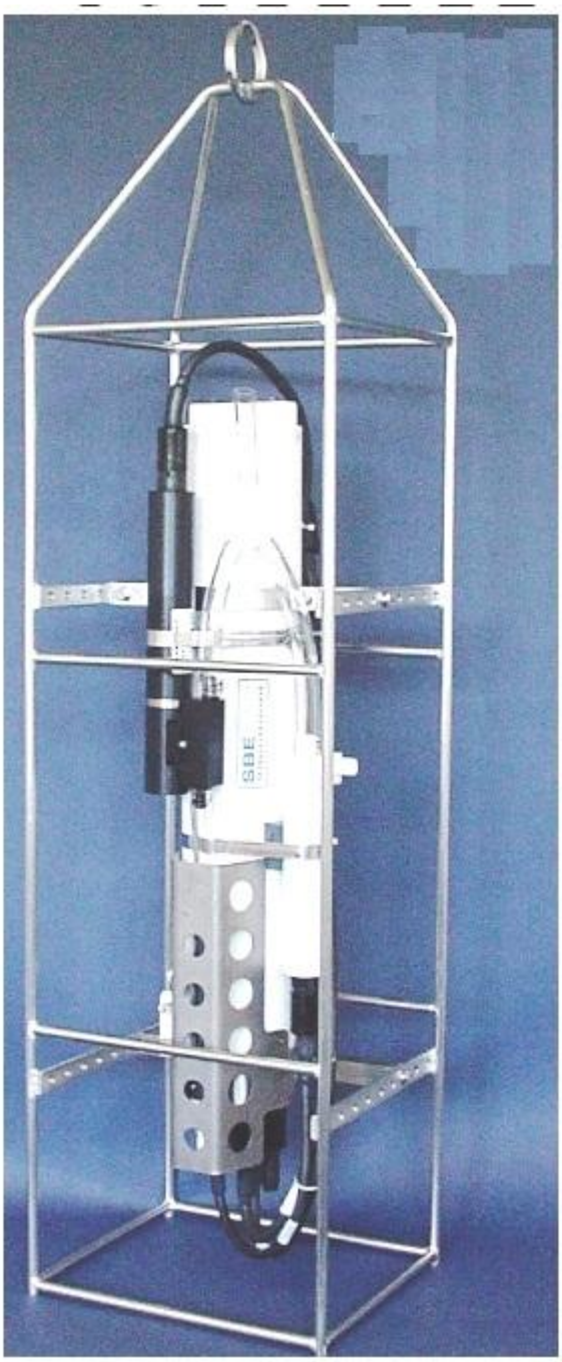


Fig. 2.7. SBE 19*plus* V2 SeaCAT Profiler CTD

2.2.1.1.1 Potential energy anomaly (PEA)

To mix the water column, kinetic energy has to be converted to potential energy so mixing increases the potential energy anomaly of the water column .The energy difference between a mixed and a stratified water column is PEA is the energy required to mix the water column completely.Simpson (1981) defined PEA as the amount of mechanical Energy (per m^3) required to instantaneously homogenize the water column completely. As a convenient measure of water column stability, PEA is calculated for the entire water column for each time series CTD profile using the equation:

$$\varphi = \frac{1}{h}\int_{-h}^{0}(\bar{\rho} - \rho)gzdz \text{ ....(6)}$$

$$where\ \bar{\rho} = \int_{-h}^{0}\rho dz \text{ ....(7)}$$

Here g is gravitational acceleration (m/s^2), ρ is water density (kg/m^3), h is water depth (m) and z is depth interval (m).

Potential energy arguments are found to be an excellent means with which to study the competing influences of stratification and mixing. The method has proved crucial for quantifying the mixing efficiency in numerous stratification studies in coastal seas and estuaries (Nunes Vaz *et al.*, 1989; 5 Rippeth and Simpson, 1996; Lund-Hansen *et al.*, 1996; Ranasinghe and Pattiaratchi, 1999). The spatial variation in the potential energy anomaly at low and high tides has been documented by Shaha *et al.*, 2011.

Although the meteorological phenomena like wind are possible sources of mixing energy, they are overshadowed by the constancy of tidal action (Blanton., 1969) and are therefore not treated in this study.

2.2.1.1.2 Stratification parameter (n_s)

Water column stratification for each profile in time series observation is assessed using the stratification parameter, n_s defined as:

$$n_s = \frac{\delta S}{s'_m} \text{ ....(8)}$$

where $\delta S = S_{bott} - S_{surf}$, $S'_m = 1/2\ (S_{bott} + S_{surf})$,with S_{surf} and S_{bott} the salinity at the surface and bottom of the water column, respectively. In case $n_s < 0.1$, then the water column is well mixed, when $0.1 < n_s < 1.0$ then partial mixing occurs, while if $n_s > 1.0$ stratification with the presence of salt-wedge is evident (Haralambidou K. *et al.*, 2010).

2.2.1.2 Synoptic observations

The results of the time series measurements conducted in the most dynamical zone of Cochin estuary (Balachandran *et al.*, 2008) inspired us to proceed longitudinal transect measurements further along estuary to explore the longitudinal salinity dynamics. Hence, synoptic survey are undertaken from June 2008 to May 2009 during spring and neap tidal phases of each month by casting SBE 19*plus* V2 SeaCAT Profiler CTD every 8 km intervals from Munambam (Inlet 1) to TB using a speed boat (40 km/hr-High speed up-estuary transects) covering ten stations along the estuary (Fig. 2.6). Morphology, tides and runoff are the deciding factors for the selection of sampling stations. Extensive data are gathered from stations 1 and 5, 6, 7 located at the proximity of northern and Cochin inlets respectively, stations 2, 3, 4 at the middle of northern arm and 8, 9, 10 comprising of southern arm. Occasionally, there are technical problems, such that the measurements obtained with CTD did not reach bottom due to strong water currents in January and also a missing data of station 10 in June measurements.

2.2.1.2.1 Salt budget

Data analysed here is the subset of data obtained from synoptic observation (Section 2.2.1.2). Annual variation in salinity is monitored from the spring phase of each month. According to Shetye and Murty*,* 1987 and Jyothi *et al.,* 2000, the total salt content of an estuary can be expressed as:

$$S_{tot} = \int_0^x S_{(x)} A_{(x)} dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

where $S_{(x)}$ is the depth-averaged salinity along the horizontal channel (x), and A is the cross sectional area. The estuarine length (80 km) is divided at every 8 km distance and the salt content of each segment is obtained separately. The integrated salt content for each month is the sum total of the salt content of each cross section.

2.2.1.3 Monthly observations

In order to relate the physical forcing (tide and river runoff) to chemical and biological property distributions, additional surveys are conducted at the mid of every month from June 2008 to May 2009 (similar to the period of synoptic survey). SBE 19*plus* V2 SeaCAT Profiler CTD is used to measure temperature and salinity. Nutrients, chlorophyll *a* and DO concentrations are determined from the bottle samples collected from the surface.

2.2.1.3.1 Chemical and Biological parameters measurements

For the analysis of chlorophyll *a*, one litre of water sample from each depth is filtered through Whatmann GF/F filter and measured according to Strickland and Parsons (1972) using flourometer (Turner designs Instruments, Trilogy, USA). Pheophytin (acidified 0.1N HCL) concentrations are determined and deducted. Dissolved oxygen is analyzed by the Winkler's titrimeteric method. Dissolved inorganic nutrients such as nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (SiO_4^{4-}) are estimated following standard colorimetric techniques (Grasshoff *et al* ., 1983).

2.2.1.3.2 Statistical analysis

The Pearson correlation coefficients are calculated using SPSS 17 statistical software to find out the linear relationship of salinity with all chemical and biological parameters. Two-way ANOVA is carried out on the monthly surface discrete samples to examine the difference in water quality variables among the along-estuary sampling stations (spatial) or through the different sampling months (temporal) with factors of interest being season, river runoff and tidal activity.

2.2.2 Flushing time

The flushing time defined as the time taken to replace the existing freshwater in the estuary, at a rate equal to river runoff (Dyer, 1997a), is calculated by Fresh water fraction method (Ketchum B.H., 1983) as follows;

$$T_F = \frac{F}{Q} \qquad (10)$$

Flushing time (T_F) is the time required to renew existing volume (F) of water in an estuary at a volumetric flow rate (Q) through the estuary (Monsen *et al.,* 2002), i.e,

Here, Q is taken as the monthly mean river runoff.

When tides exclusively flush the system, then tidal prism method can be used to compute flushing time (Dyer 1973) given by:

$$T_F' = \frac{V_e T}{(1-b)P} \qquad (11)$$

Where T is the lunar tidal period (12.42 h), b is the return flow factor taken as 0.5 (Vijith *et al.*, 2009) and P is the tidal prism. The tidal prism of each section is estimated as tidal range multiplied by the surface area at mean sea level (Monsen *et al.,* 2002). Considering the complexity of the bathymetry, we divided the estuarine sections into several polygons for the estimation of area and volume using GIS software (Ensigna, Hallsb, and Mallina, 2004).

2.3 Influence of TB in tides and salinity

2.3.1 Tide

The tide data obtained from major measurements conducted during the period 2007-2008. In the year 2007**,** 40 days long field efforts are designed to characterize variations in tidal levels. Tide data are measured at 15 minute intervals at three locations (A,B,C) (Fig. 2.8) in the southern arm of Cochin backwaters during 30 March, 2007, 0000 hrs to 8 May, 2007, 2345 hrs (Julian day 89-128). Station C is located about 1.5 km away from TB. TB is kept closed during the measurements from 30 March, 2007 to 4 April, 2007 (Julian day 89-94). During the period 5 April, 2007 to 8 April, 2007 (Julian day 95-98), the sluice gates (63 in number) are gradually opened resulting in intrusion of sea water into the southern backwaters. From 9 April, 2007 to 8 May, 2007 (Julian day 99-128), the sluice gates were completely open and as a result the tides forced from the Cochin inlet were felt even in the southern most region. Out of the 40 days data, the first six days pertain to 'completely closed' condition, next four days to 'being opened' condition and the remaining thirty days to 'completely open' condition (Fig. 2.9).

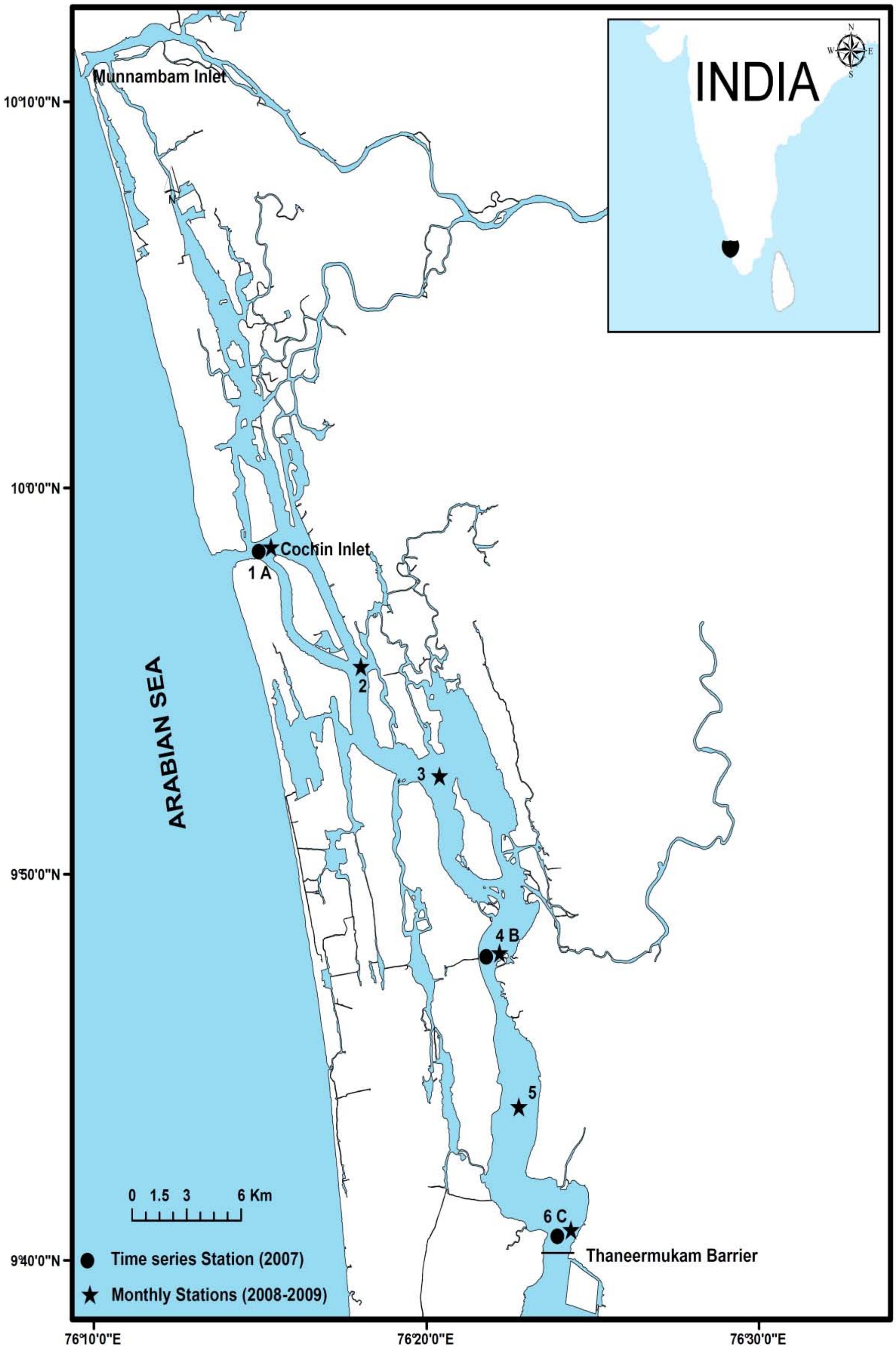


Fig. 2.8. The Cochin estuary, showing stations monitored in the southern arm of Cochin estuary to understand the influence of TB.

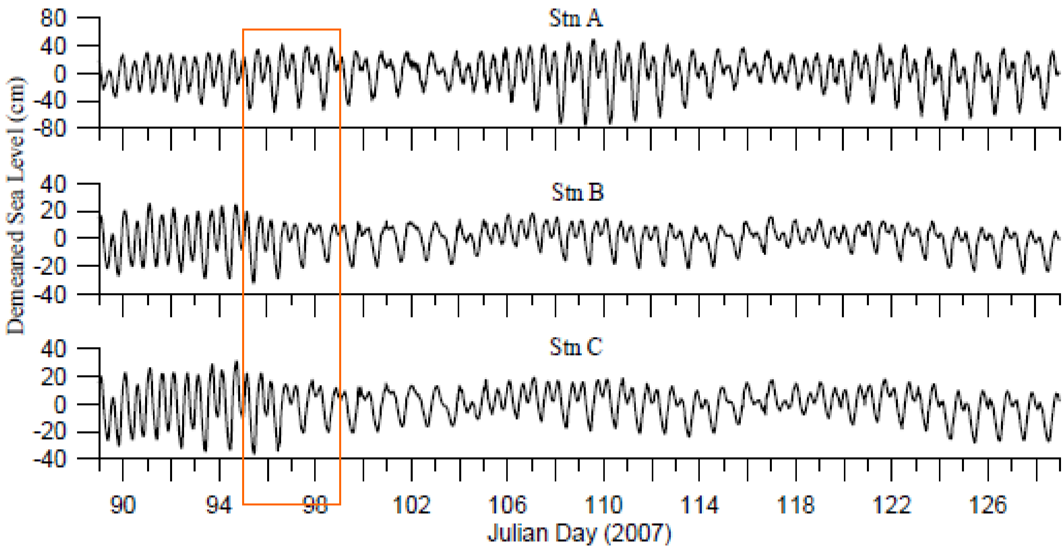


Fig. 2.9. Tide for the period Julian day 89 - 128 (March), 2007 at Stations A-C. The ordinate scale for Station A is different. The box indicates the period during which the barrage was in "being opened" condition (5th April, 2007 to 8th April, 2007 (Julian day 95-98)

2.3.1.1 Harmonic analysis

Tide is the all-weather rising and lowering of water level, produced by a combination of varying astronomical forces and earth's rotation; and is considered to be one of the most regular and rhythmic motions in nature. As the astronomical setting of a given location on earth relative to sun and moon is rather complex, similar complexities are present in the tidal oscillations as well. Although tides have an astronomical origin, the response of a given location to the tidal forces is influenced considerably by a myriad of complex topographical influences (varying depths, boundaries and resonance (Antony *et al.,* 2009).

Thus, the tidal oscillation at a place can be represented by a sum of astronomical constituents and its over-tides and compound-tides. Therefore, a Fourier description (i.e. various cosine series of partial tides) well represents the features of tidal motion at a place. The harmonic analysis of tidal observations consists essentially in the dissection of the aggregate tidal oscillations into a number of partial constituent waves. The tidal constituents obtained from harmonic analysis. Time series records of the tidal measurements at a given location represent the purely astronomical as well as the topographically induced influences on the tidal motion experienced at that location. From this, it is possible to determine the amplitude and phase (known as 'tidal constants') of each tidal constituent (i.e. partial tide). These constants remain unaltered as long as the geometry of the water body and the bed materials that contribute to the bottom friction remain unaltered (Antony *et al.,* 2009). Prediction of tidal oscillation for a given location involves a process of synthesis by summing up an adequate number of harmonic constituents (i.e. various cosine series of partial tides), of different amplitudes and phases, for that location.

Harmonic analysis is conducted on the tide data for the open period (30 days), to extract the amplitudes and phases of 26 independent constituents and 8 related constituents using the software TASK2000 (Tidal Analysis Software Kit). These constituents are used to predict the tides for the six days 'closed' period of TB. Due to short tidal records, the observed ('closed' period) and predicted ('if open' period) data for six days are analyzed to extract the amplitudes and phases of only two constituent bands – centered on semi-diurnal (M_2) and diurnal (K_1). M_2 and K_1 constituents contain energy from other semi-diurnal constituents (egg., N_2, S_2 and K_2) and diurnal constituents (egg., O_1, P_1) respectively (Pugh, 1987; Shetye *et. al.*, 1995).

2.3.2 River runoff

The daily and monthly mean river runoff data for the year 2008-2009 are sourced from the Central Water Commission, Government of India, for six gauging stations corresponding to six major rivers. The runoff is high during ISM with little runoff during dry periods. For the present analyses, the river runoff is the sum total of the runoff of rivers flowing into the southern arm of the estuary. The daily mean runoff is used for statistical analysis and for computation of residence time.

2.3.3 Salinity

The salinity data collected is a subset synoptic observation described in the section 2.2. To understand the influence of TB the data is taken only from the stations in the southern part of the estuary. The stations are marked as 1 to 6 for the convenience (Fig. 2.8). The closing of barrage began on 27 Dec, 2008 and by 31 Dec, 2008 it was fully closed. The sluice gates were partially opened on 29 Mar, 2009 and the barrage was fully opened by 31 Mar, 2009. For the present study, the salt intrusion length L_2 is taken as the upstream distance (in km) of 2 PSU isohaline (length from Cochin inlet along the river channel to the point where the bottom salinity is 2 PSU).

2.3.4 Chlorophyll *a*

The chlorophyll *a* data considered is a subset of monthly observations described in section 2.4. To understand the influence of TB the data is taken only from the stations in the southern part of the estuary stations 1 to 6 (Fig. 2.8). Discrete bottle samples of surface water is taken for the measurement of salinity and chlorophyll *a*. Water samples are filltered for the subsequent determination of chlorophyll *a* and phaeopigment concentration. Surface salinity is measured with salinometer.

2.3.5 The residence time

The residence time *Tr,* defined as the time required for the total mass of a conservative tracer originally within the whole or a segment of the estuary to be reduced by a factor of e^{-1} (i.e., 0.37), is given by (Luketina *et al.*, 1998):

$$T_r = \frac{(V+P)T}{(1-b)P+RT/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where V is the low tide volume of the whole or a segment of the estuary, P is tidal prism, T is the tidal period, R is the river runoff, b is the return flow factor. The tidal prism of Cochin inlet is estimated at 107.8 x $10^6 m^3$ during Indian Summer Monsoon(ISM) (June - September), 18.6 x 10^6 during moderate runoff months (October to December) and 31.5 x $10^6 m^3$ during dry season (Rama Raju *et al.*, 1979). Semi-diurnal period (12.42 h) is the predominant tidal period. Return flow factor (b) is the fraction of ebb water returning to the estuary during the subsequent flood tide and can be taken as 0.5 following S.C.C.C. (1985) and U.S.E.P.A. (1985). The volume of southern arm of the estuary is taken as 360 million m^3.

2.4 Classification

For the present study, the region is divided into two parts (Fig. 2.10): the northern arm extends from Cochin to Munambam and the southern arm extends from Cochin to Thanneermukkam. Both the arms of the estuary receive significant amount of freshwater throughout the year; larger in southern arm than the northern arm. When the TB is closed, Muvattupuzha River contributes to the freshening of the southern arm. The two arms behave differently in physiographical and hydrographical aspects and hence treated separately.

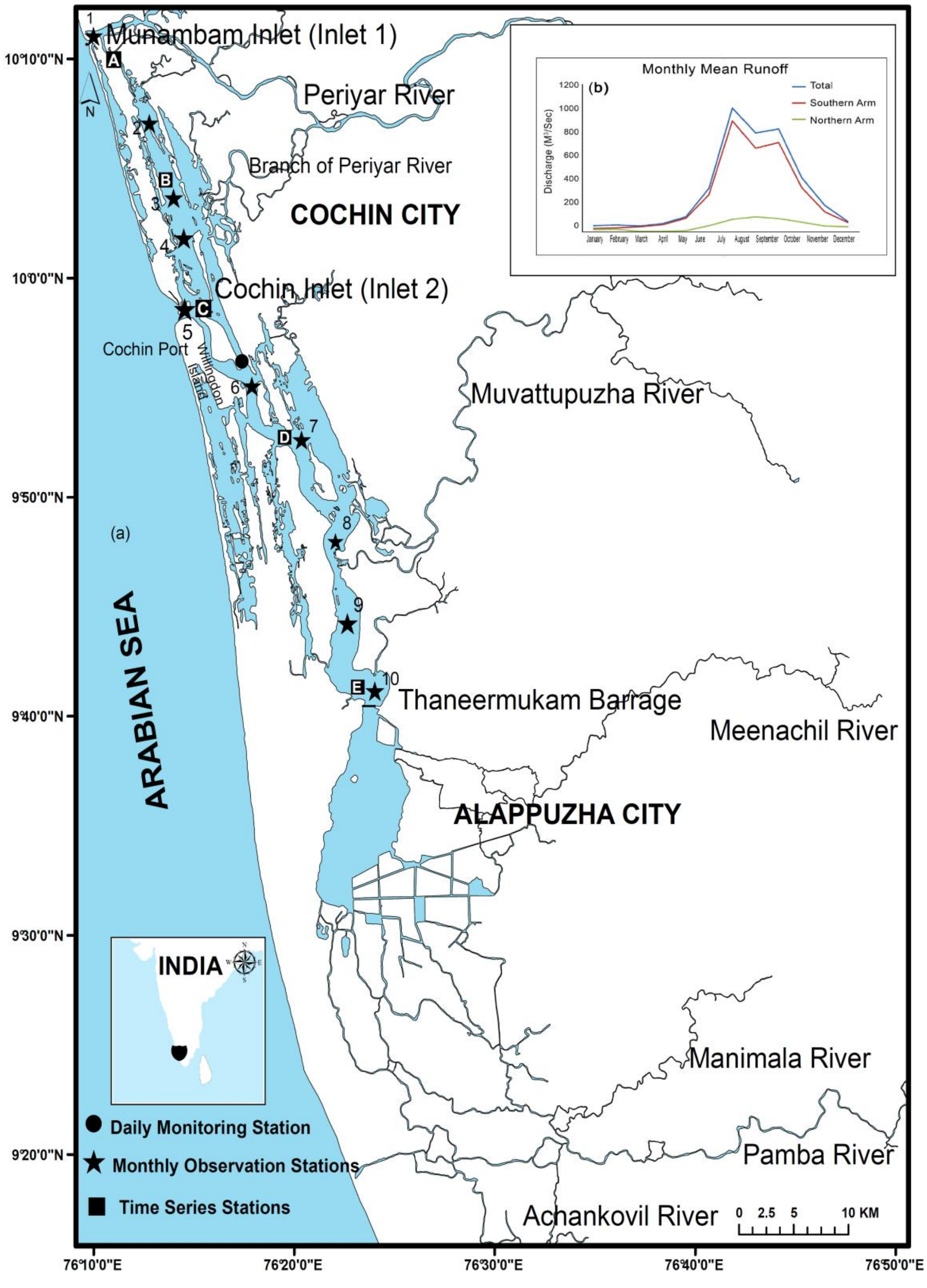


Fig. 2.10. (a) The Cochin estuary (West coast, India), showing rivers and extent of the system. Daily station is located 5 km away from Cochin inlet. Monthly longitudinal and time series stations are discerningly marked. (b) Runoff from 6 rivers for the period of 1year (June 2008 to May 2009).

2.4.1 River Runoff

Three sets of daily runoff data of six rivers are obtained from Central Water Commission, government of India for six gauging stations: Viz, 1978 – 2001; 1985-1989 and 2008-2009. The first two sets are long term data and they are used for the validation, sufficiency and completeness of the runoff data for the year (2008-2009) of the present study. This is the most detailed climatology of this estuary published to date.

2.4.1.1 Statistical analysis on river runoff

The main objective of the statistical analyses is to substantiate the credibility of the objectives studied based on the runoff data for a single year 2008-2009. For this purpose, the data of average monthly runoff for 1978-2001 and 1985-1989 is obtained by calculating the arithmetic means of daily runoff data. Utilizing these past sets of data, monthly total runoff for the year 2008-2009 is predicted using the best polynomial fitted for the average monthly runoff of past data sets among a set of different polynomials (Fig. 2.11a). For the period of 23 years (1978 to 2001), there are some missing data of four rivers but for the period 1985-1989 the data from all the six rivers are obtained. Hence the river runoff is analyzed for time series components using the two data sets for the periods: 1978 – 2001 and 1985-1989 and to determine the type of variations which influences the river runoff of 2008-2009.

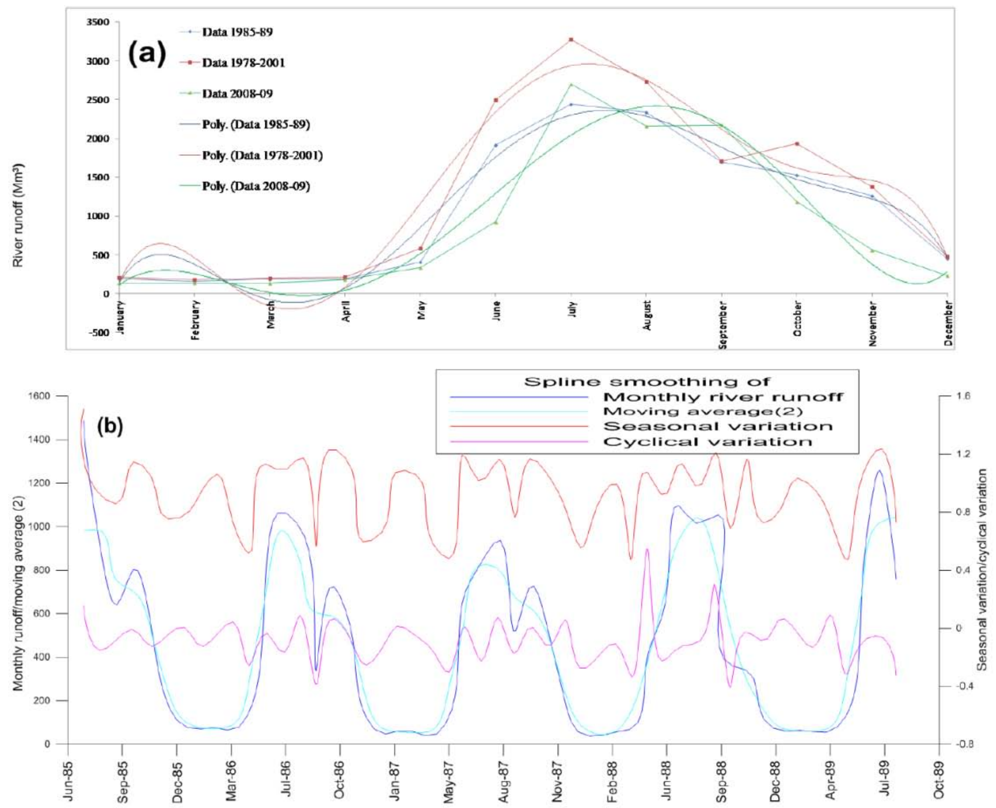


Fig. 2.11 (a) Polynomials of different degrees for the monthly total runoff (b) Spline smoothing of Time series components of the river runoff data.

To determine the main contributing components to the river runoff, a multiplicative time series model is fitted. Since the data sets are complete for the period 1985-1989, time series analyses is carried out for this period only. The multiplicative model (Holt winter) is chosen in which the observed monthly runoff is equal to product of long term trend (T), seasonal variation (S), cyclical component (C) and irregular variation (I) in the runoff

i.e., $O = T * S * C * I$.......................(13)

Trend, 'T' is identified by centered moving average (MA) of period 2. Centered MA of period 2 implied that river runoff at a time point 't' is determined by runoff at t-1, t and runoff at t+1 with weights 1,2 and 1 respectively. This triplet is the best preferred one, since the plots of other periods (3 to 12) explained the observed runoff very poorly. River runoff is observed to follow the moving average trend of period 2 very precisely (Fig. 2.11b). Seasonal variation, 'S' in each month is explained by the seasonal index computed as the simple average of (O/T) over all the years for each month. Cyclical variation is computed as a percentage of moving average as

$$C = \left[\left(\frac{O}{SI}\right) - MA(2)\right] * 100/MA(2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where SI is the average variation adjusted to 12 as

$$SI = \left[Average\ monthly\ \left(\frac{O}{T}\right) * 12\right] /Total\ of\ all\ average\ monthly\ \left(\frac{O}{T}\right) \ldots\ldots (15)$$

and MA (2) is the moving average of period 2. Cycles in the variation is clearly explained by the cyclical variation with a period of 12 months for repeated cycle (Fig. 2.11b). Irregular variation gets removed while averaging at different stages. Then these three time series components are used as independent variables to determine the regression of runoff on these components.

The river runoff (Y) is regressed on moving average of period 2 (X_1), seasonal variation (X_2) and cyclical variation (X_3) and their first order interactive effects. Step up multiple regression method is applied to determine the 2^3*6 models (Snedecor and Cochran, 1967, Jayalakshmy, 1998).

Multiple regression model fitted is of the form

$$Y = a_0 + \sum_{i=1}^{i=k} a_i X_i + \sum_{i=1}^{i=k} \sum_{j=1, i<j}^{j=k} b_{ij} X_i X_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where $a_i, b_{ij}, i, j = 1,2,3, \ldots and\, i < j$ are the regression coefficients of the individual effects and the corresponding interaction effects respectively. To determine the contribution levels of the components uniquely, first order and second order partial correlation coefficients are calculated (Snedecor and Cochran, 1967). First order partial correlation coefficient is

$$r_{ij.k} = \frac{r_{ij} - r_{ik} r_{jk}}{\sqrt{(1-r^2_{ik})(1-r^2_{jk})}} \qquad \text{i, j, k} = 1, 2, 3, 4 \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Where 1 = river runoff

2= MA (2)

3= Seasonal variation 'S'

4= Cyclical variation 'C'

Second order partial correlation coefficient is

$$r_{ij.kl} = \frac{r_{ij.k} - r_{il.k} r_{rl.k}}{\sqrt{(1-r^2_{il.k})(1-r^2_{jl.k})}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

or

$$r_{ij.kl} = \frac{r_{ij.l} - r_{ik.l} r_{jk.l}}{\sqrt{(1-r^2_{ik.l})(1-r^2_{jk.l})}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Three partial correlations have (n-3) and (n-4) degrees of freedom respectively for first order and second order.

2.4.2 Salinity

The first data set of salinity comes from the synoptic observations (see section 2.2.1.2) covering ten stations from June 2008 to May 2009.

2.4.2.1 Daily monitoring of salinity for a period of 1year

This is second data set of salinity is obtained from a daily monitoring station near to the inlet 2 (Fig. 2.10) where the vertical profiles of salinity are collected every day at 11.00 AM local time during the same year (May 2008 to April 2009).

2.4.3 Data set for Hansen Rattray characterisation

This data set is obtained from time series observations under three runoff conditions during 2009-2010. Salinity and velocity are measured during the spring phases of tides at five stations distributed along the channel axis (Fig. 2.10a). Stations A and B are along northern arm and stations D and E are along southern arm. Station C represented inlet 2. Sampling is conducted on spring phases of October 2009, February 2010 and August 2010. These months are representative of moderate runoff, low runoff and high runoff periods respectively. Each observation started at 9.00AM and finished at 9:00 AM of the next day. For every 24 hours observation, CTD is lowered at 30 minutes interval. Current meters (RCM-9 (Fig. 2.12) are moored and velocity is measured at 10 minutes interval from near surface and bottom. The RCM9 speed sensor has an accuracy of ±2% of the recorded speed.

Fig. 2.12. The RCM-9 Self Recording Current Meter

2.4.4 Water level and Volume

Water level data for the five stations in February 2010 is obtained from permanent mooring stations of the Ecosystem modelling program (see section 2.1.2.3). The estuarine volume is estimated from digitization of recently developed bathymetry charts using 3D Analysis tools in ArcGIS software.

Chapter 3

Influence of river runoff on tidal propagation

3.1Introduction

The Cochin estuary has prominent place in the tropical Indian Ocean region for commercial and tourism activities as one of the major ports of India. Recognizing its socioeconomic importance, the Cochin estuary has been included in the Ramsar site of vulnerable wetlands to be protected, in the year 2002. Bio-geochemical aspects of the estuary are well studied compared to many other estuarine systems in India, but there are only a few numerical model studies carried out in the estuary to understand the hydrodynamics. The state of art of modelling in the Cochin Estuary is limited to an estimation using the Delft Hydraulics model (ESTMORF), which was less sensitive due to the neglect of bathymetry and river runoff (Strikwerda 2004). The two other modeling studies (Eldho and Navin 2004; Paul and Cvetkovic 2007) were also limited to the Cochin harbour area and, hence, do not contribute much to the tidal dynamics of the estuary. Many of these studies were carried out for industrial and commercial purposes. A study has been carried out to understand the tide-driven currents of the Cochin Estuary during pre-monsoon and post-monsoon seasons using the model Hydrodyn-FLOSOFT (Babu *et al.* 2005).Later Balachandran *et al.* (2008) used a

2D model to study residual currents and particle trajectories in the whole estuary .However these studies also do not contribute much to the hydrodynamics of tide and river runoff interactions.

In general, tide generated in the ocean penetrates into estuaries as a disturbance; numerous physical factors including river runoff, bathymetry, geometric of channel, and coriolis force can influence the propagation of tide (Dyer, 1997b; Friedrichs and Aubrey, 1994). Estuaries are intrinsically complex, as tidal propagation is influenced by river runoff and vice-versa. According to Godin (1999), tidal waves propagating upstream become distorted and damped, which is caused both by bottom friction and by the river flow. The Cochin estuary, being in the region of the monsoon, experiences large river runoff during south west monsoon and low runoff after its withdrawal. Tides entering into the estuary from the two inlets coupled with seasonally varying river runoff make the tidal propagation characteristics distinct in this system.

Keeping the above facts in mind, a one dimensional network numerical model hereafter, 1DNN-model, is developed to get more insights in to the influence of river runoff on tidal propagation. A 2D or 3D model in an estuary can give more accurate simulations of estuarine dynamics vis-a'-vis circulation, temperature and salinity. But for studying influence of river runoff on tidal, a one dimensional modelling approach is sufficient as it can give accurate simulations of tides even in complex estuarine networks. Besides, a 1D-model is cost effective, easy to set up, and more importantly, fast delivery of results as it does not need a super computing facility.

The 1DNN-Model is simulated for two realistic scenarios (RLS) and four idealized scenarios (IDS). The purpose of model simulation for RLS is to reproduce the observed tides in the Cochin estuary for the low river runoff and high river runoff conditions. Whereas, model simulation for IDS is to delineate the role of river runoff in determining the region of interaction from these two inlets. The IDS also analyses the role of river runoff on tides from each inlet separately. The model is initialized with zero velocity and surface elevation. At the open boundaries, the observed tides are defined as a function of time. The mean monthly river runoff is introduced at the respective grids, where the rivers adjoin. For all the RLS and IDS, the model is simulated for 40 days. The first 10 days of the simulations are considered as spin up period and the remaining 30 days of the simulations are used for analysis. Details of boundary conditions, river runoff, coefficient values and model results are given below under the respective sub-sections.

3.2. Results

3.2.1Tides and river runoff forcing in realistic scenarios (RLS)

3.2.1.1Simulation of tides during high river runoff (RLS-1)

In RLS-1, the observed tides at the two inlets during the high runoff (September-October 2009) period are used to force the model at the open boundaries. The river runoff introduced to the respective grids of the rivers joins in the system (see Fig. 2.1 and section 2.1.2.1.1 in Chapter 2). River runoff of 505.6 m^3s^{-1}, 109.96 m^3s^{-1} and 222.9 m^3s^{-1} is introduced at Thanneermukkam, middle of the northern, middle of the southern arm respectively. The manning coefficient used in this scenario ranges from 0.075 to 0.095. The simulation shows that the model has captured the observed signals (Fig. 3.1) at all the stations except Stations 6-7. The possible reasons for the simulated tides lag behind the observed at station 2 and slight overestimates of observed tides at stations 6 and 7 during the neap phases are explained in the forth coming section 3. 3. The Figure 3.1 shows that tidal amplitudes decay more toward the upstream regions of the southern arm. Whereas in the northern arm, tides from the two inlets do not decay much until the middle of the northern arm. There is no region in the southern and northern arms where tides remain unchanged during this high runoff period. The model results also show that the mean water level rises in both the arms during the high runoff.

3.2.1.2 Simulation of tides during low river runoff (RLS-2)

In RLS-2, the model is forced at the open boundaries using the observed tides during low runoff (February–March, 2010). River runoff of 1.2 m^3s^{-1}, 5.4 m^3s^{-1} and 42.83 m^3s^{-1} is introduced at Thanneermukkam, middle of the northern, middle of southern arm respectively. The manning coefficient used in this scenario ranges from 0.065 to 0.075. In this case, the model simulates the observed signals accurately at all the stations (Fig. 3.2). During this low runoff period, tidal amplitude gets successively decayed toward the upstream regions of the southern arm except from stations Arookutty to Makayilkadavu. (See also Fig. 2.2 in Chapter 2) where tidal amplitudes remain unchanged. It is to be noted that the tides are perfectly simulated by the model in the northern arm. In the northern arm, tide from the two inlets decays to the middle of this arm.

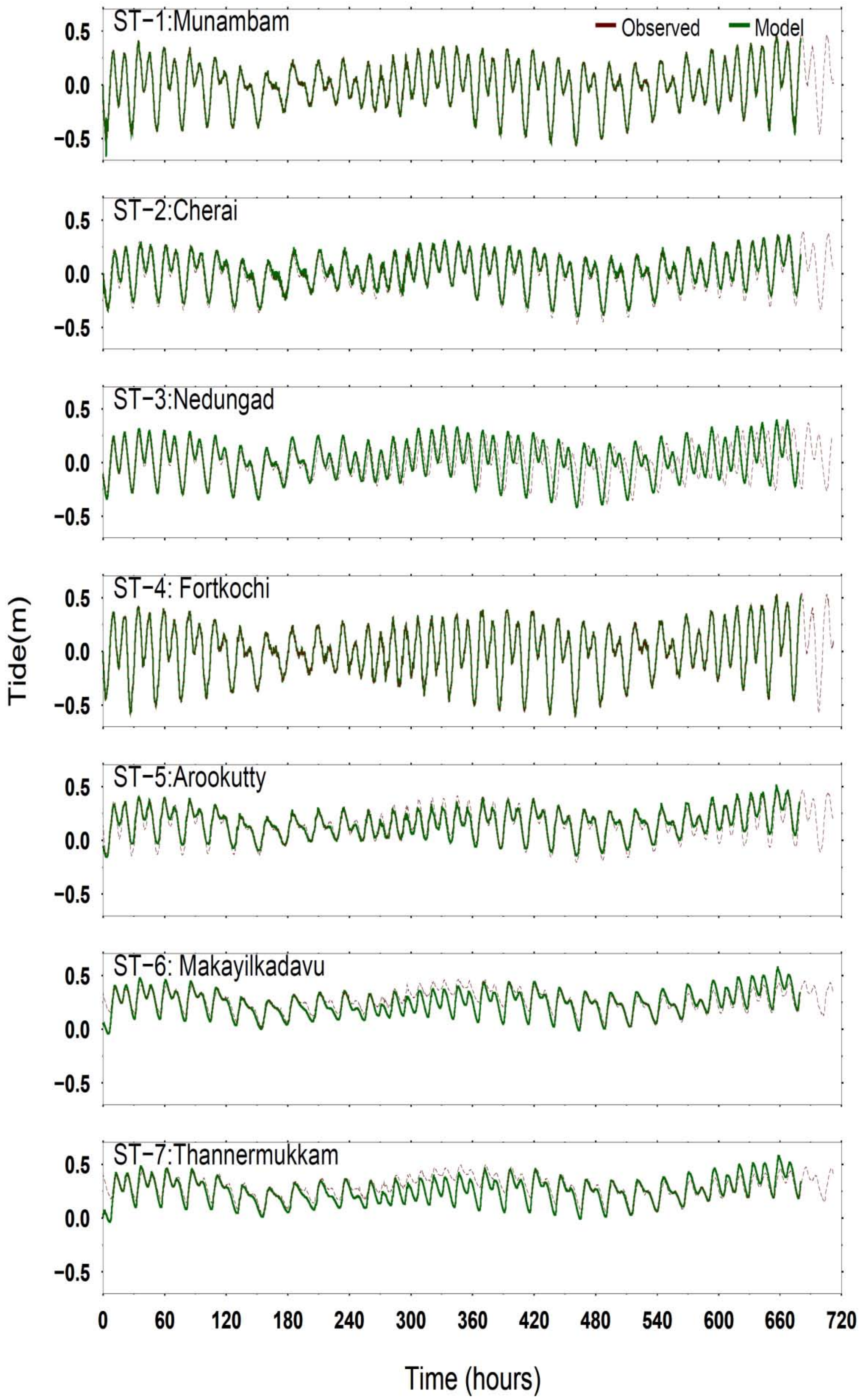


Fig. 3.1. Observed and simulated tides during high runoff (RLS-1) (20/09/2009 16:00hrs to 20/10/2009 8:00hrs) (0 hrs corresponds to 16:00hrs on 20/09/2009)

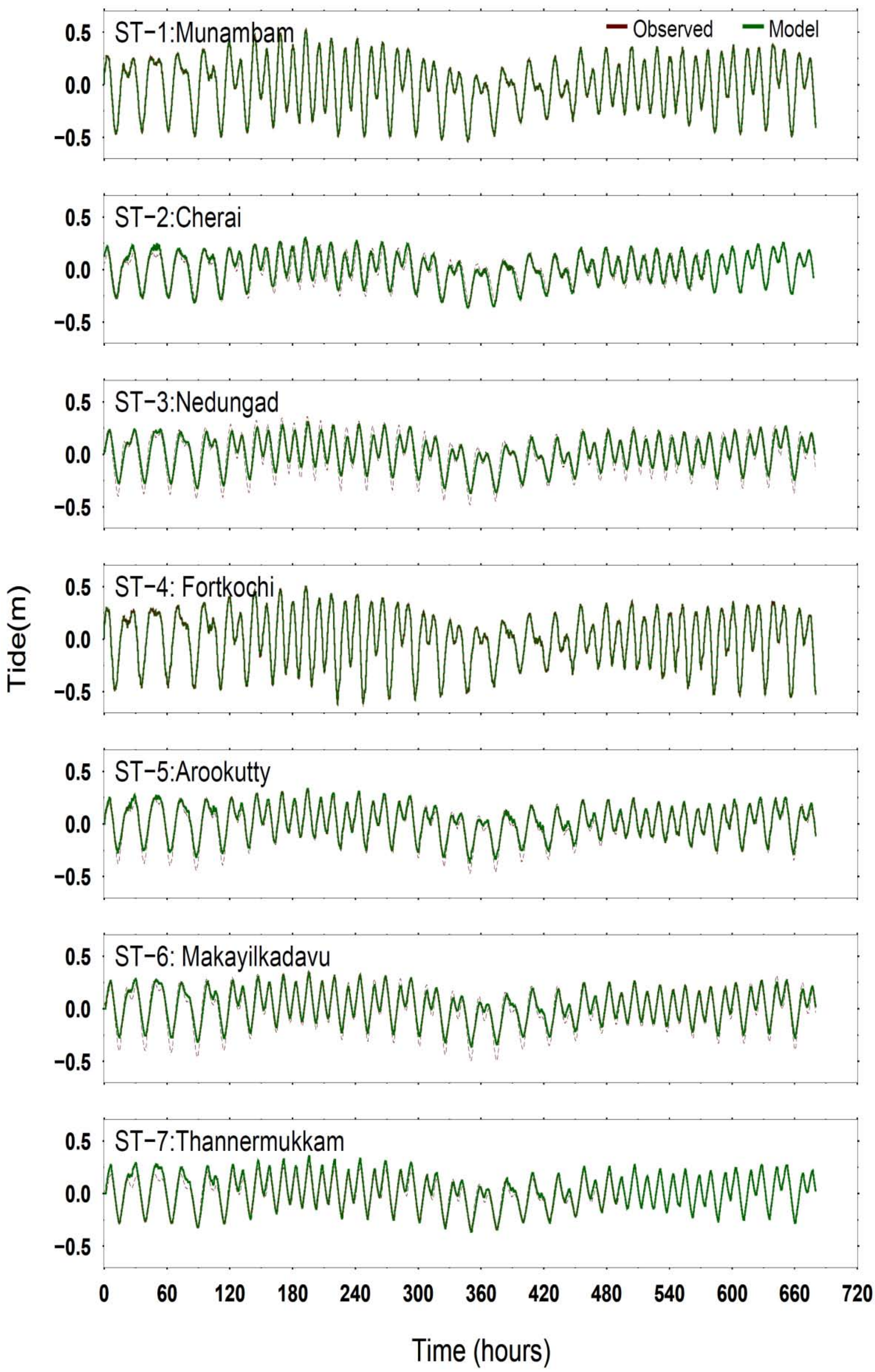


Fig. 3.2. Observed and simulated Tide during Low runoff (RLS-2) (22/2/2010 00:00hrs to 22/3/2010 08:00hrs). (0 hrs corresponds to 16:00hrs on 22/2/2010)

3.2.2 Tides and river runoff forcing in idealized scenarios (IDS)

3.2.2.1 Simulation of tides during inlet 2 closed and zero river runoff (IDS-1)

In IDS-1, the inlet 2 is closed, and the tide is forced from inlet 1(see Fig. 2.2 in chapter 2) using the observed tides during the low river runoff, no river runoff is introduced in this simulation. The manning coefficient used in RLS-2 is applied for all the idealistic simulations. The model simulations show that tides get decayed toward southern arm (Fig. 3.3). The tidal amplitude at Thanneermukkam becomes roughly 1/10th of the amplitude of Munambam.

3.2.2.2 Simulation of tides during inlet 2 closed and low river runoff (IDS-2)

In IDS-2 the inlets are opened and closed as described in IDS-1. However, freshwater is introduced similar to that in RLS-2.The simulation shows that tidal amplitudes get damped (Fig. 3.4) toward the southern arm due to the influence of river runoff. The tidal amplitude at Thanneermukkam becomes negligible. The mean water level rises in the upstream direction due to the inclusion of river runoff.

3.2.2.3 Simulation of tides during inlet 1 closed and zero river runoff (IDS-3)

In IDS-3, the inlet 1 is closed and tide forced from inlet 2 using the observed tides during the low river runoff, zero river runoff is introduced in this simulation. The tidal amplitudes get amplified (Fig. 3.5) from inlet 2 to the upstream regions in the northern arm. The tidal amplitude at northern end is about one and half times of the observed tide at inlet 1.On the contrary in southern arm the simulated tides are perfectly matching with the observed.

3.2.2.4 Simulation of tides during inlet 1 closed and low river runoff (IDS-4)

In this scenario inlets are closed and opened like IDS-3 with low river runoff of RLS-2. The amplified tides during the zero river runoff period get damped (Fig. 3.6) little when the river runoff is introduced in the model. In southern arm, the simulated tides are perfectly matching the observed as in the case of IDS-3. The mean water level rise is also found in the upstream direction.

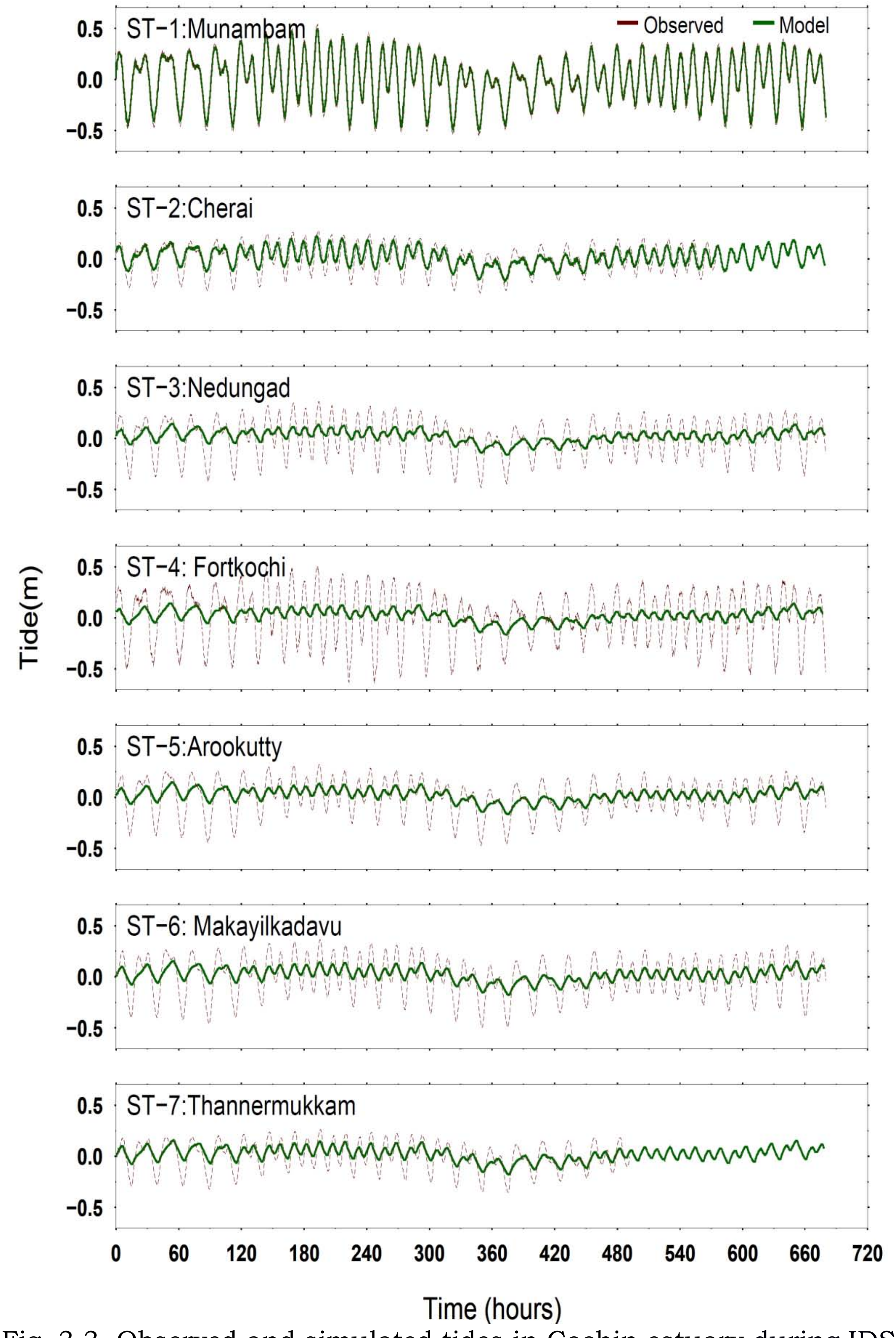


Fig. 3.3. Observed and simulated tides in Cochin estuary during IDS-1 when inlet 2 closed and zero river runoff. (During Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs)). 0 hrs corresponds to 16:00hrs on 22/2/2010

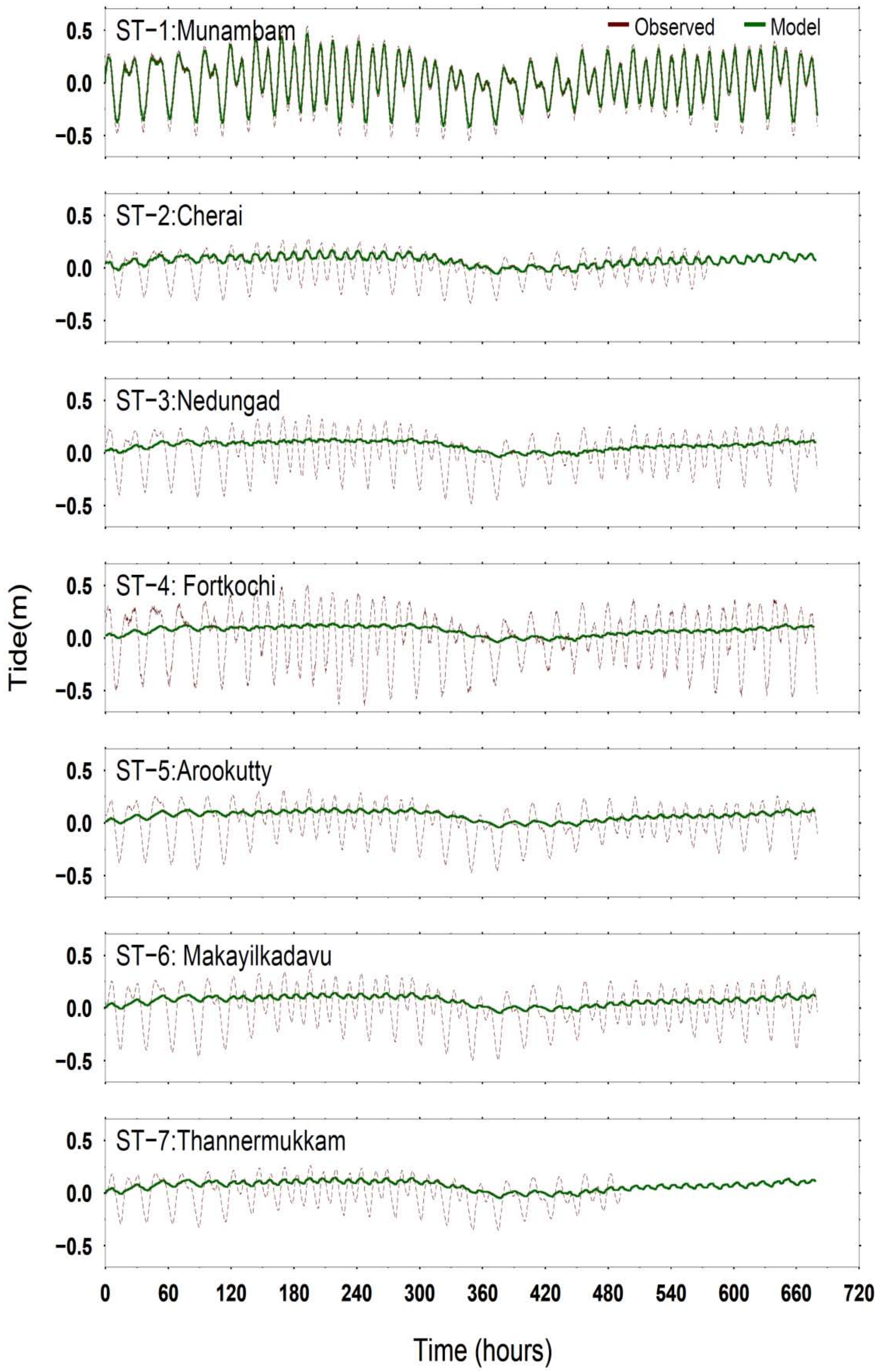


Fig. 3.4. Observed and simulated tides in Cochin estuary during IDS-2 when inlet 2 closed and low river runoff is introduced. (During Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs)). 0 hrs corresponds to 16:00hrs on 22/2/2010

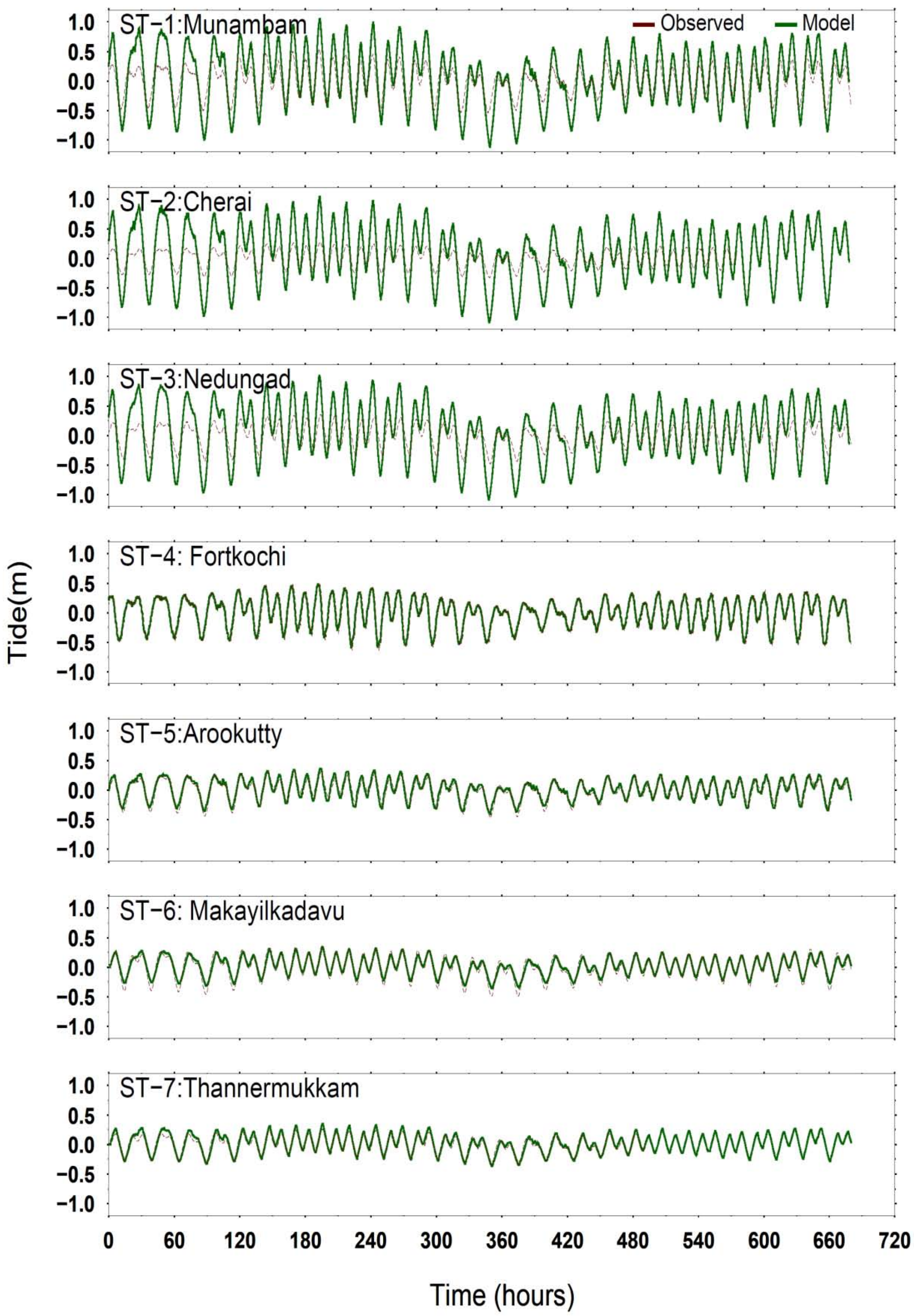


Fig. 3.5. Observed and simulated tides in Cochin estuary during IDS-3 when inlet 1 closed and zero river runoff. (During Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs)). 0 hrs corresponds to 16:00hrs on 22/2/2010

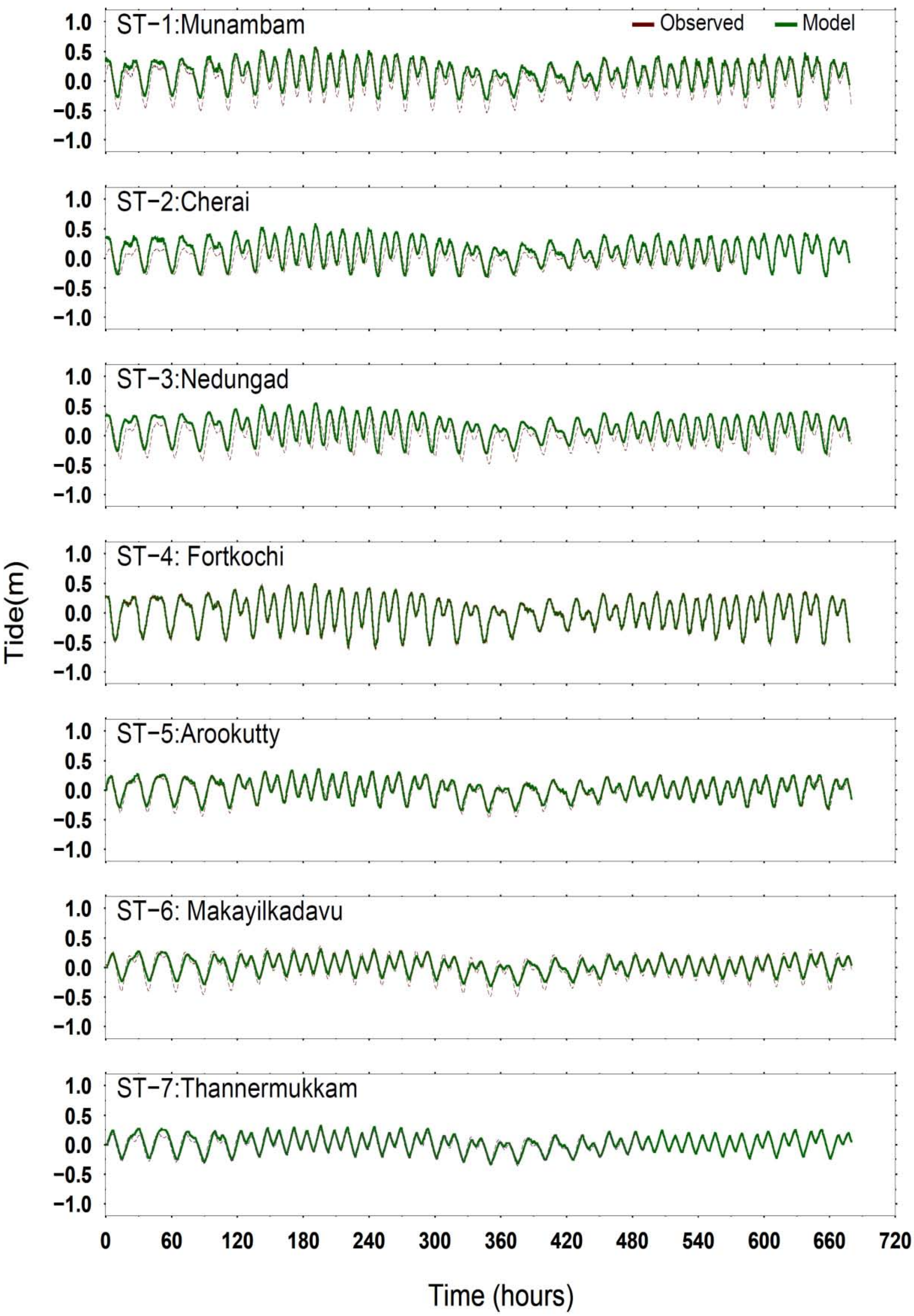


Fig. 3.6. Observed and simulated tides in Cochin estuary during IDS-4 when inlet 1 closed and low river runoff is introduced. (During Low runoff (22/2/2010 00:00hrs to 22/3/2010 08:00hrs)). 0 hrs corresponds to 16:00hrs on 22/2/2010

3.3 Discussion

The observations and the model results for the RLS and IDS reveal many interesting characteristics of tidal propagation and its response to varying river runoff conditions in the Cochin estuary. During low runoff, the observed data show that the tidal amplitudes gradually decay from the inlets of the main channels to the head of the estuary except Arookuty to Makayilkadavu, where the amplitudes remain unchanged. However during high runoff, the tide rapidly decays toward the upstream regions. In this study A1DNN -model model is developed for simulating and analyzing these hydrodynamic processes.

The primitive equations in 1DNN -model are momentum and continuity. In many estuaries, pressure gradient and frictional balance leave the tidal amplitude unchanged in the channel. This balance breaks either due to the large friction or due to the river runoff (change in pressure gradient). Even though, the above terms in the momentum equation are not quantified separately in this study, the model results indicate that the momentum balance in this estuary is mainly between the pressure gradient and friction. The model simulations did not show any significant changes with and without the advection term of the momentum equation. The river runoff plays a major role for the rapid decay of tidal amplitudes toward the upstream regions during the high runoff periods. The downstream velocity of river runoff during this period is sufficiently large enough to decay the tidal amplitudes toward the upstream regions whereas, during the low runoff periods, frictional effect is more dominant than the river runoff as evidenced from the simulations of tides shown in Fig. 3.2. Tidal amplitudes remain unchanged from Arookutty to Makayilkadavu during low river runoff indicates that geometric amplification balances the friction decay leaving the tidal amplitudes unchanged from station 5 to station 6.

But this balance breaks down when the runoff increases (RLS-1). The above results also indicate that the balance between friction and pressure gradient in the estuary breaks up during high river runoff conditions. In estuaries like Mandovi estuary where tidal amplitude remains unchanged for a longer distance from the mouth due to the geometrical amplification which balanced by friction (Unnikrishnan *et al.* 1997; Manoj *et al.* 2009).

Generally, in an estuary manning coefficient values typically range from 0.01 to 0.35 (Howes *et al.*, 2004). But these values are found to be very high in the Cochin estuary even during low runoff periods. The friction is a very dominating factor in the whole estuary during low run off period. The northern arm does not have any region where the tidal amplitude remains unchanged. In addition the tidal decay in the region is independent of river runoff even during the high runoff period. From Periyar River its branch carries only 30% of the water volume to this arm; therefore the frictional decay is present in low and high runoff periods. This entails the overestimated tides at stations 5 to 7 during the neap phases of RLS-1. The lag behind the observed tide at Station 3 during RLS-1 is due to the misconception with regards to the manning coefficient. It concludes that during high runoff, friction is important in northern arm but not in southern arm.

The simulations for IDS-1 shows successively damped tides reach up to Thanneermukkam in the absence of tides from inlet 2 and river runoff (see figure 3.3).When the simulations are carried out with river runoff (IDS-2 see figure 3.4) tide from the inlet 1 is negligible in southern arm. It is therefore possible that the interaction of tides from these two inlets can take place in the northern region in both low and high runoff conditions. Thus, the amount of runoff in the low runoff period has significant role in determining the region of interaction of tides from two inlets.

IDS-3 and IDS-4 show that tide gets amplified towards the north from inlet 2 (Fortkochi to Munambam)and it is irrespective of river runoff (see figures 3.5-3.6).This geometrical amplification is due to the tidal propagation towards converged regions from the wider region in the model. In the in situ data, geometrical amplification does not take place in the Cochin estuary. The model results presented here are good enough to address the tide and river runoff interactions in various runoff scenarios in the estuary and can be applicable to similar kind of systems.

Chapter 4

Seasonal stratification and property distributions

4.1 Introduction

Understanding stratification and de-stratification processes in different time scales (intra-tidal, spring-neap, seasonal) has gained the most attention during the last decades due to its tremendous relevance to the estuarine ecosystem. Estuaries can be classified into three types based on their longitudinal salinity distribution: partially mixed, vertically homogeneous or well-mixed and highly stratified or salt wedge type (Dyer, 1973). The type of the estuary essentially depends on river runoff and tidal regime which have pronounced effect on the distributions of several physical, chemical, and biotic processes within the estuary. The differential advection of salinity creates stratification which inhibits vertical mixing of momentum. With the increase in turbulent energy, stratification is reduced by mixing directly and indirectly by reduced shear (Nepf and Geyer., 1996). Stratification diminishes vertical fluxes of ecologically important variables (Uncles 1990) like heat, salt, oxygen and nutrients. Physical dynamics play a critical role in estuarine biological production, material transport and water quality (Kasai *et al.*, 2010).

For an ecological study, an interdisciplinary approach linking the physical phenomena with chemical and biological properties is essential in Cochin estuary.The physical processes (stratification, advection and flushing) that govern the ecological parameters have not been rigorously investigated in the region to date. For the efficient implementation of estuarine management plans, an imperative study of the impact of stratified systems on water quality and ecosystem ecology is essential. The present chapter assess (1) the intratidal and spring-neap variations in stratification of water column and property distribution in low runoff and high runoff conditions (2) the horizontal extent of salt distribution and the relation between salinity and property distributions.

4.2 Results

4.2.1 Temporal variations at single station

4.2.1.1 Tidal characteristics

Figs. 4.1A-4.1D gives the water level and predicted tide of spring and neap phases during the observation period. The maximum range of the spring tide is 1 m while the neap tides do not exceed 0.59 m. The diurnal inequality is quite evident in all observations; it is prominent in low runoff neap with 0.2 m (Fig. 4.1A). Unlike all other tidal observations which are semi-diurnal in nature, the neap tide of high runoff observation is diurnal (Fig. 4.1D).

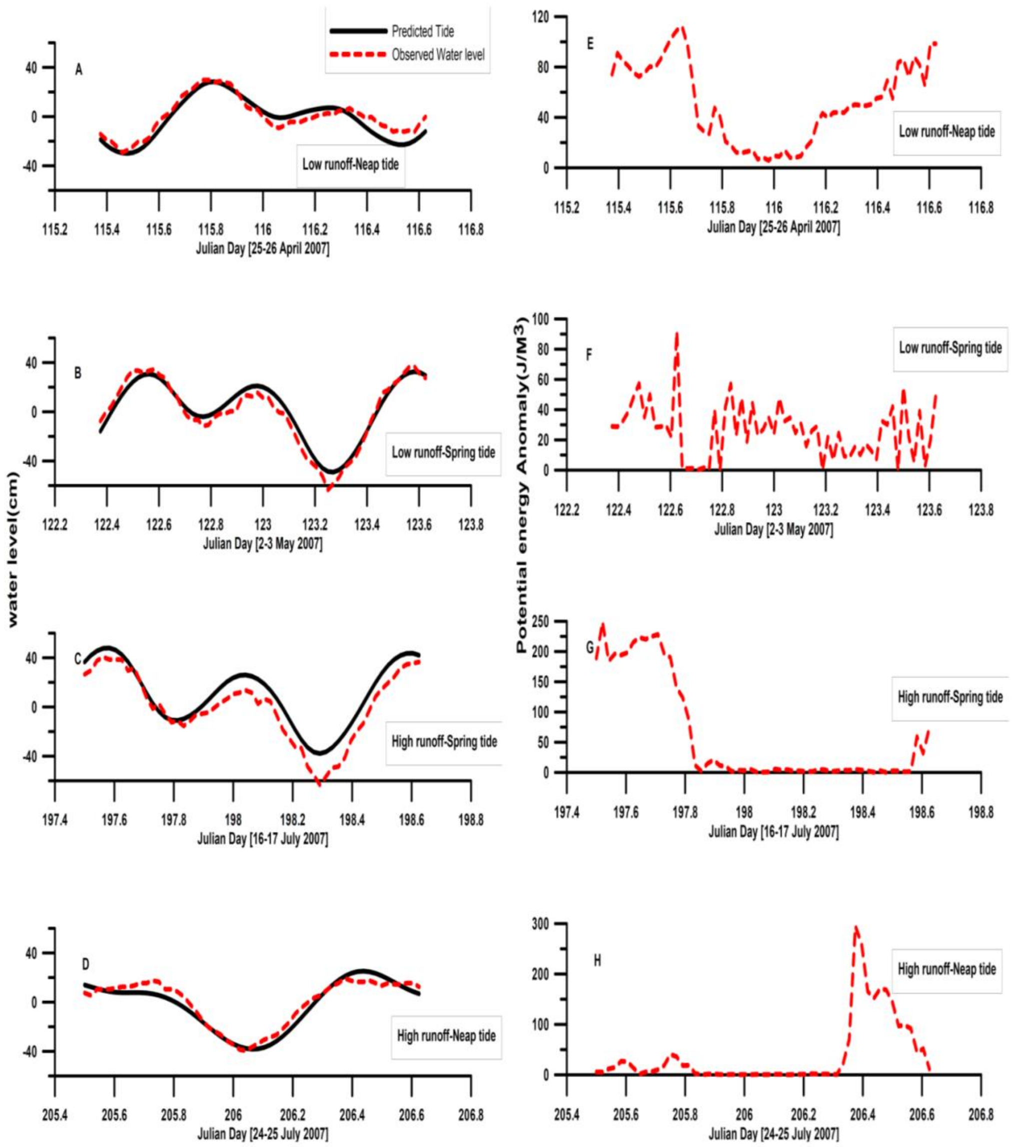


Fig. 4.1. Semi-Diurnal variations of observed water level and predicted tide at the time series location (A-D); Time series of potential energy anomaly (φ) (J/m^3) computed from the 30 minute density profiles (E-F). (3A,3E) 25th April 9.00AM to 26th April 3.00 PM (neap-Low runoff); (3B,3F) 2nd May 9.00 AM to 3rd May 3.00 PM (spring-Low runoff); (3C,3G) 16th July 12.00 AM to 17th July 3.00 PM (spring-High runoff); (3D,3H) 24th July 12.00 AM to 25th July 3.00 PM (neap- High runoff)

4.2.1.2 Temperature

The vertical distribution of temperature is as shown in Figs. 4.2-4.5. A pronounced surface to bottom difference in temperature is absent during both spring and neap tidal phases in low runoff. Even though, during the period when solar forcing is at its peak created a vertical difference of ~1.5°C (Figs. 4.2B, 4.3B). However, the high tides of both the tidal phases of monsoon season (high runoff) experiences substantially lower temperature (~24.5°C) (Figs. 4.4B, 4.5B) at the bottom layers when compared with surface temperature (~27.5°C).

4.2.1.3 Salinity

The seasonally varying river flow and the tidal rhythm affect the vertical distribution of salinity as shown in Figs. 4.2-4.5. During the period April –May, low river runoff (Figs. 4.2A, 4.3A) causes weaker salinity stratification (difference between the surface and near bottom salinities) relative to ISM. In low runoff neap (April), the stratification is observed during flood with maximum of 16.35. With the arrival of ebb phase of the first tidal cycle, stratification declines to a remarkably low value of 0.19. Again, it increases with the upcoming flood tide. During spring phase of low runoff (May), stratification of the entire water column over the tidal cycles is less and the depth averaged salinity ranges from 31.64 to 32.09. The stratification is higher in flood (12.5) than in ebb (0.15) either due to differential advection of salinity or vertical mixing. On the other hand, during both tidal phases of high runoff (Figs. 4.4A, 4.5A) large quantities of fresh water enters the estuary resulting in very low saline water at the surface and denser water at the bottom. Evolution of salinity stratification in water column (spring 33.24; neap 33.03) is associated with advection of salt wedge. The isopycnals are evenly spaced and flattened during HHW. Notably the entire station is flushed with fresh water of salinity ~0.05 during low tides and LHW.

The pycnocline becomes unstable during ebb and the saline wedge disappears.

4.2.1.4 Potential energy anomaly (PEA)

The pattern of distribution of observed water column stability (Figs. 4.1E-4.1H) corresponded well with the salinity distribution notwithstanding seasons and tidal cycles. The spring-neap cycles of stabilization and destabilization of water column are prominent which is having relative importance as far as tidal estuaries are concerned. During low runoff, the average PEA value computed from all density profiles is 25.9 J/m3 in neap which almost doubled to 52.0 J/m3 during spring phase. This implies that the average energy required to mix the water column is about two-fold higher in neap than spring phase. It should also be noted that during neap phase of low runoff the minimum PEA value of 5.0 J/m^3 is obtained during the ebb period whereas during spring phase of low runoff the PEA values neared to zero for many of the density profiles over the tidal cycle. During monsoon the highest values of PEA (>200 J/m^3) in spring and neap phases indicates stratification evolved due to the advancement of the salt wedge. However, for spring, on the arrival of ebb phase, PEA values gradually decline corresponding to the retreat of salt wedge and went as low as < 1 J/m^3, this low value sustained until the next tidal cycle and again the stratification began to develop at HHW. For high runoff neap, the water level is diurnal in nature. The observations of neap begin with low PEA values (~10 J/m^3) and the advancement of salt wedge occurs at the flood phase of the tidal cycle. Again, it begins to retreat during ebb.

4.2.1.5 Stratification parameter (n_s)

During low runoff, stratification parameter fluctuates from 0.5 to 0.8 (partially mixed) in neap phase whereas for spring phase, most of the observations over the tidal cycle show stratification number varying from 0 to 0.1 (well-mixed). During high runoff, stratification parameter calculated from profiles during high tides shows values ranging from 1.3 to 1.9. This is due to the temporary stratification developed due to salt wedge intrusion. Once fresh water conditions prevail and as the saline layer is pushed out of the estuary, stratification number becomes almost zero. The stratification parameter varies depending on the phase of tide and river runoff indicating that Cochin estuary experiences a transition from partially mixed (neap) or well mixed (spring) in low runoff to periodically stratified state during high runoff.

4.2.1.6 Dissolved Oxygen and nutrients

The distribution of chemical properties is shown in Figs. 4.2-4.5. During low runoff neap, the average surface DO value (7.74 ml/l) is higher than bottom (4.37 ml/l). In contrast, the average nutrient concentration (except for PO_4^{3-}) is higher at the bottom than at the surface for both spring and neap phases during low runoff; NO_2 (surface 0.55 µM; bottom 1.55 µM), NO_3 (surface 1.79 µM; bottom 4.10 µM), PO_4^{3-} (surface 0.88 µM; bottom 0.60 µM) and SiO_4 (surface 12.02 µM; bottom 15.73 µM). Unlike neap, the water column property distributions are homogeneous over much of the tidal cycle in spring phase (Figs. 4.3C, 4.3E-4.3H). During high runoff, the incursion of hypoxic water (<1.06 ml/l) through bottom layers (Figs. 4.4C, 4.5C) on flood tides is discernible during both spring and neap tidal phases. The near-bottom intruding water is characterised by high NO_2 (spring, 1.02 µM; neap, 1.84 µM), NO_3 (spring, 12.29 µM; neap, 17.5 µM), PO_4^{3-} (spring, 3.68 µM; neap, 3.24 µM) and low SiO_4 (spring, 39.65µM; neap 38.03 µM) values. However, elevated levels of silicate (120.66 µM) which is a land derived nutrient are found at the surface indicating that river runoff is the principal source of silicate inputs. This is substantiated by the higher silicate concentrations in high runoff than during the low runoff surveys.

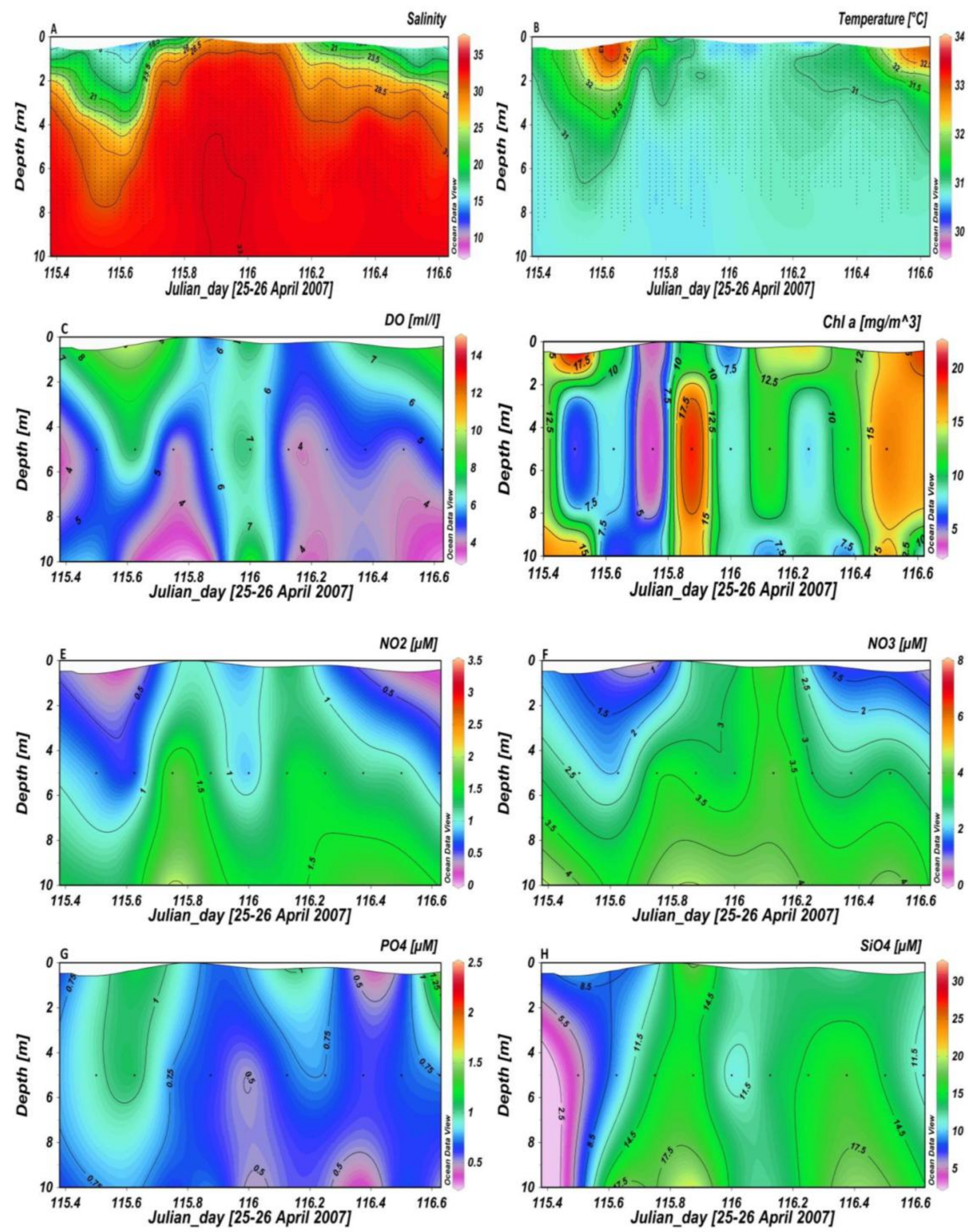


Fig. 4.2. Depth-time contours of salinity, temperature DO, chlorophyll *a*, NO_2^-, NO_3^-, PO_4^{3-}, SiO_4^{4-} for every three hours from surface, mid-depth and bottom during neap tides of low river runoff observation

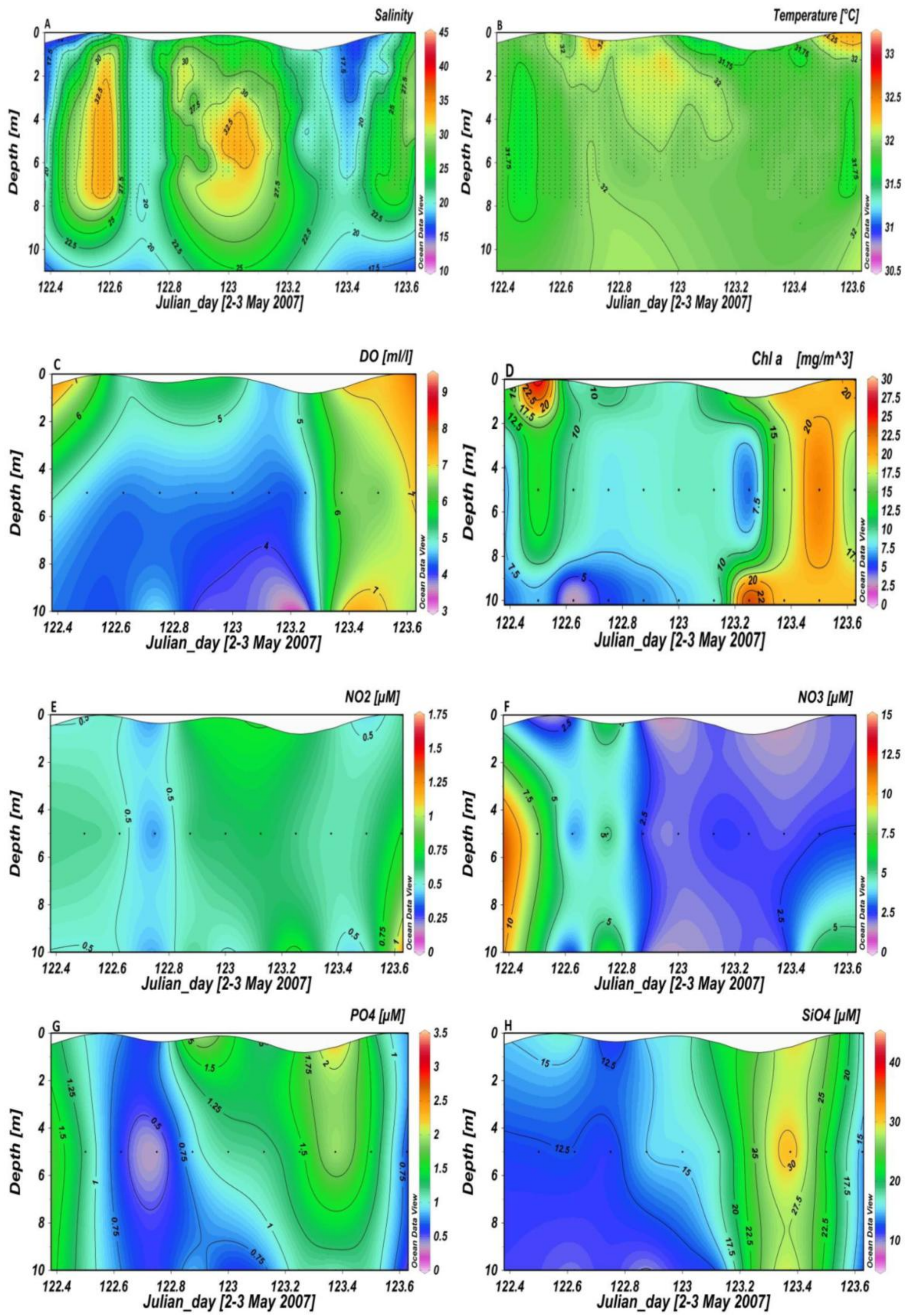


Fig. 4.3. Depth-time contours of salinity, temperature, DO, chlorophyll *a*, NO_2^-, NO_3^-, PO_4^{3-}, SiO_4^{4-} for every three hours from surface, mid-depth and bottom during spring tide of low river runoff observation

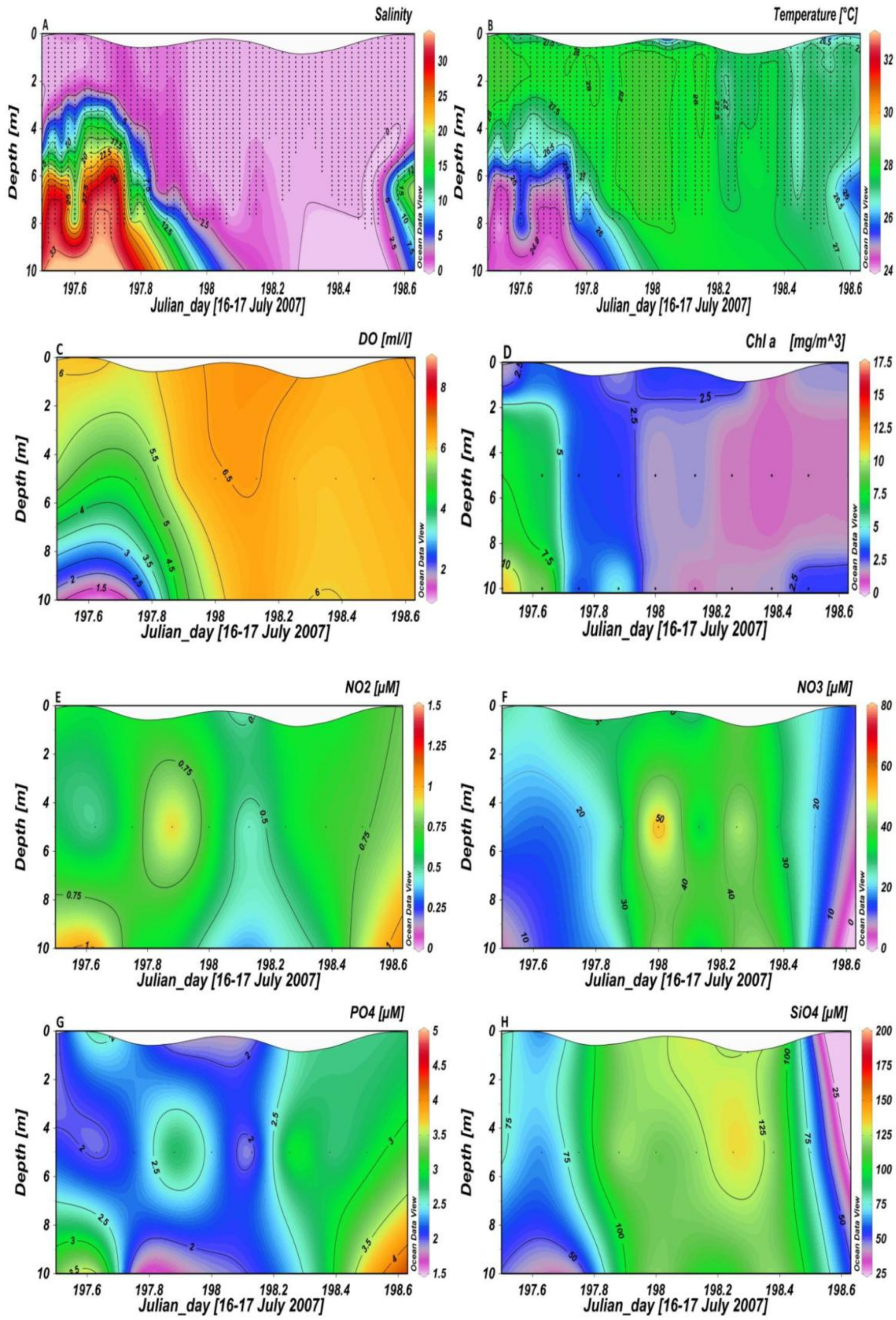


Fig. 4.4.Depth-time contours of salinity, temperature DO, chlorophyll *a*, NO_2^-, NO_3^-, PO_4^{3-}, $SiO_4^{4-}$for every three hours from surface, mid-depth and bottom during spring tide of high river runoff observation

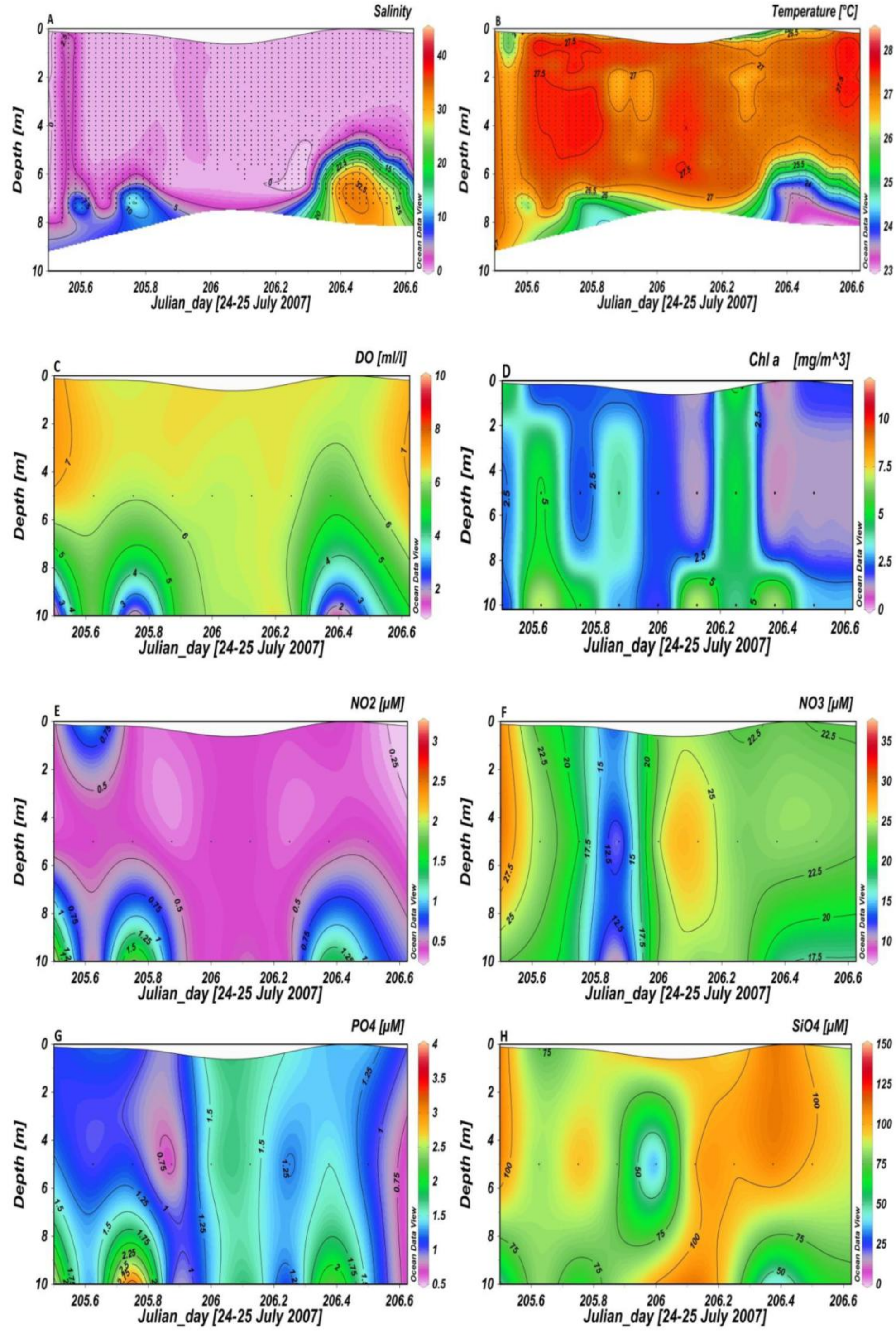


Fig. 4.5. Depth-time contours of salinity, temperature DO, chlorophyll *a*, NO_2^-, $NO3^-$, PO_4^{3-}, SiO_4^{4-} for every three hours from surface, mid-depth and bottom during neap tide of high river runoff observation

4.2.1.7 Chlorophyll *a*

The distribution of chlorophyll *a* pigments which is a reliable measure of phytoplankton biomass is shown in Figs. 4.2-4.5. Seasonal variations in chlorophyll *a* distribution are observed with relatively higher values in low runoff (on an average 12 mg/m^3). The chlorophyll *a* concentration is higher at the surface with its peak (Figs. 4.2D, 4.3D) during 12:00hrs to 15:00hrs owing to the vertical migration of light-sensitive phytoplankton species to the surface. During low runoff, the maximum surface chlorophyll *a* observed for neap and spring is 20.1 mg/m^3 and 26.7 mg/m^3 respectively. During salt wedge formation associated with the high runoff (Figs. 4.4D, 4.5D), chlorophyll *a* maxima layer is formed at the bottom ocean water [salinity 33.29; chl-*a* 11mg/m^3 (spring), salinity 33.04; chl-*a* 6.8mg/m^3 (neap)] and minimum layer at the surface fresh water [salinity 0.05; chl-*a* 1.1mg/m^3(spring), salinity 0.01; chl-*a* 0.9 mg/m^3(neap)].

4.2.2 Longitudinal salinity distributions (synoptic survey)

The results of longitudinal transect measurements (synoptic observation Figs.4.6 and 4.7) are very valuable to insight in the salinity dynamics of the Cochin estuary.

The survey began from June 2008 (Figs 4.6A, B). In the year 2008, with the onset of monsoon on May 31, the river runoff peaked with 8.7% of the total occurring in the month of June. The depth averaged salinity of the southern arm stations (8, 9, 10) and of the stations (2, 3, 4) at the middle of northern arm presents low values averaging to 1.76-spring; 0.17-neap and 8.22-spring; 5.19-neap respectively. Stations near Cochin inlet (5, 6, and 7) exhibited high salinity unlike the station 1 near northern inlet with tidal amplitudes having some influence. Stations 1, 2 are prone to fresh water influence due to Periyar river adjoining northern inlet which is the major river contributing to the total river runoff of the estuary. Overall, the freshening of the estuary is initiated by the monsoon.

By the end of June, the monsoon peaked and July experiences the maximum river runoff amounting to 22.04% of the total. The salt wedge formation which begins in neap of June (Fig. 4.6B) becomes more prominent in July transforming the status of the system to that of a salt wedge type (Fig. 4.6C, 4.6D). A weaker salt wedge front originating from northern inlet, which is visible only in spring phase of July, persists in all other monsoon months. Hence, higher salinities (18-34) are restricted to the bottom waters of the stations adjacent to the inlets (5, 6, 7-Cochin inlet; 1, 2- northern inlet). All the other stations remained well mixed with depth averaged salinity reaching salinity values as low as 0.05.

The salt intrusion length during both spring and neap tides of the synoptic survey has been defined as the length from the river mouth (Cochin inlet) along the river channel to the point where the bottom salinity is 2 PSU. On an average, the intrusion length from the Cochin inlet to south averages to 15 km and 11 km during spring and neap phases respectively of high runoff months (Figs. 4.6D-4.6H). Distinctly, the results in August differs with the intrusion greater in neap (15 km) than spring (13 km) (Fig. 4.6E, 4.6F) since the neap observations are carried out during high tides whereas for spring it is during low tides. This entails the significance of the observation time with respect to tidal cycles denoting the relevance of time series measurements in the system. The depth of the interface (defined as the height of 2 PSU isohaline from the bottom) decreases gradually towards the outer end of the estuary. This depth which is also the thickness of the bottom saline water layer is greater in spring compared to neap phase at the mouth for the time series measurements (Fig. 4.4A, 4.5A) implying that saline intrusion is more during spring phase.

As the river runoff decreases from July to September (Fig. 4.9), coincidently the salt wedge advected further upstream suggesting an inverse relationship of salt intrusion with river runoff. The withdrawal of monsoon concurred with the reduction in river runoff. This results in the longitudinal dispersion of the salinity field (Fig. 4.6I- 4.6L). From 11.81% in October, the river runoff is reduced to 3.34% in December. During the period, though the salinity at stations near Cochin inlet (5, 6, 7) are invariably high over the vertical, there is a consistent increase in the salinity at all other stations. However, the upper most station (10) remains far away from the influence of marine water irrespective of tidal phases. Later when the low runoff period (Figs. 4.7C-4.7J) (from January to April average runoff is only 1.4% of total), commences the tidal actions dominates in the system. The salinity field extends up to station 10 with maximum depth averaged salinity (15.12) attains in spring phase of March. In May, there is a slight increase in runoff to 2.5% of the yearly runoff. The aftermath of an anomalous rainfall in the catchment of Periyar during our spring observation causes station 1 at the northern inlet to be fresh water dominated (Fig. 4.7K).

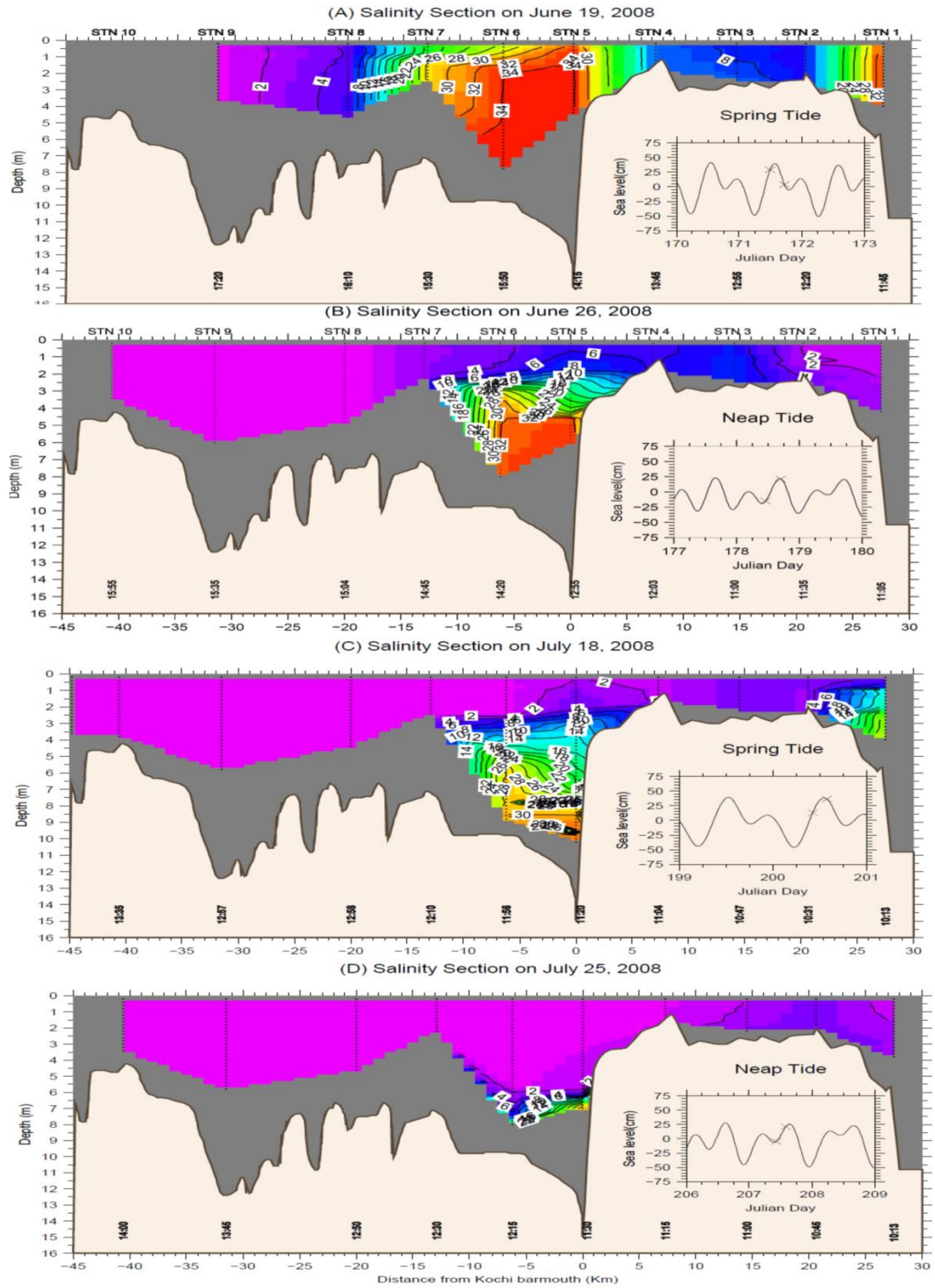


Fig. 4.6. Longitudinal synoptic distribution of salinity measured twice monthly (during spring and neap tides) from June 2008 to November 2008. The Cochin inlet is at the coordinate origin. The northern / southern arm stations are at positive /negative distances, respectively. The insets show the tidal amplitude and the times (as X's) when each survey began and ended. Times of each station appear along the lower x-axis

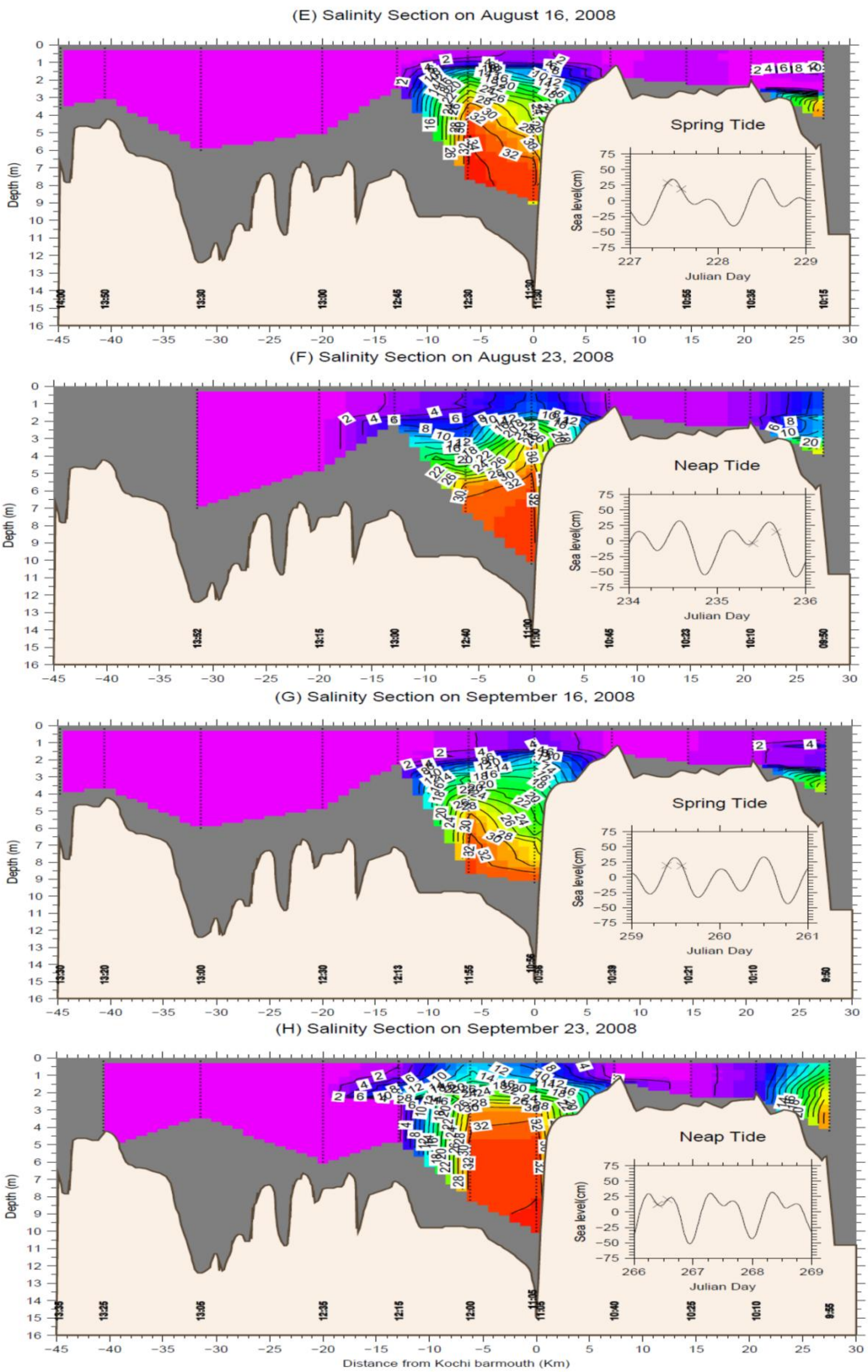
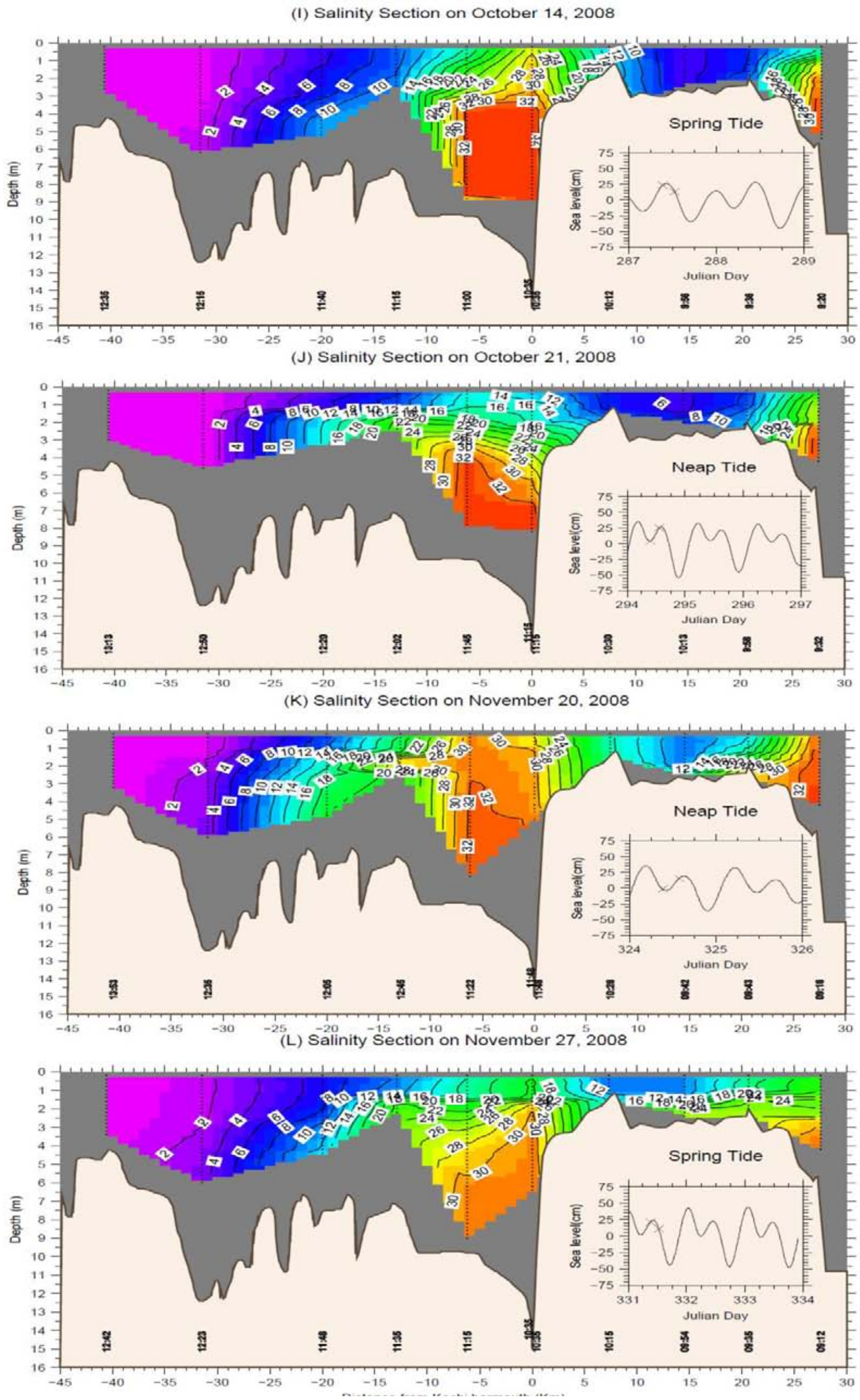


Fig. 4.6(Continued)



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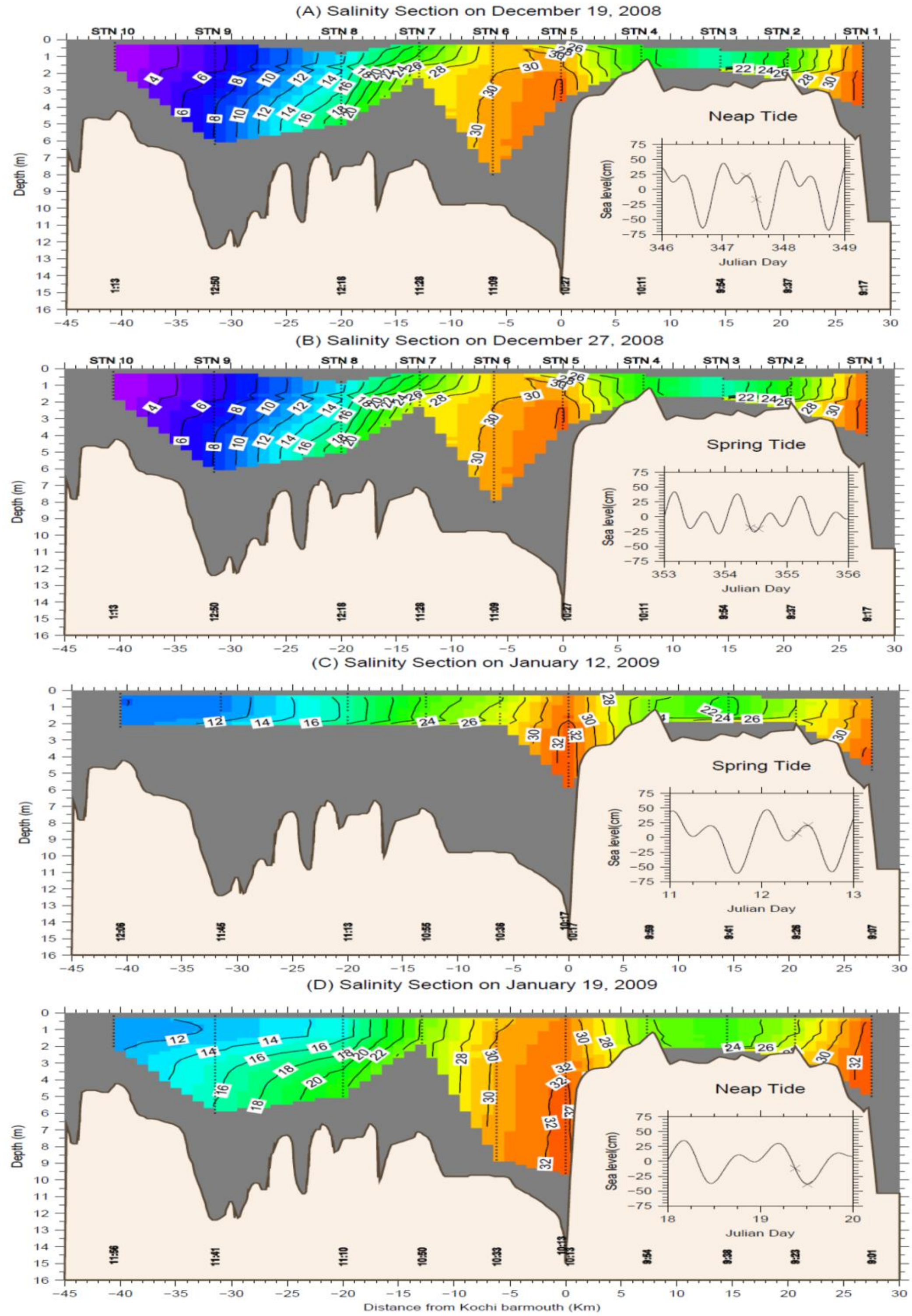

Fig. 4.7. Longitudinal synoptic distribution of salinity measured twice monthly (during spring and neap tides) from December 2008 to May 2009. The Cochin inlet is at the coordinate origin. The northern / southern arm stations are at positive /negative distances, respectively. The insets show the tidal amplitude and the times (as X's) when each survey began and ended. Times of each station appear along the lower x-axis

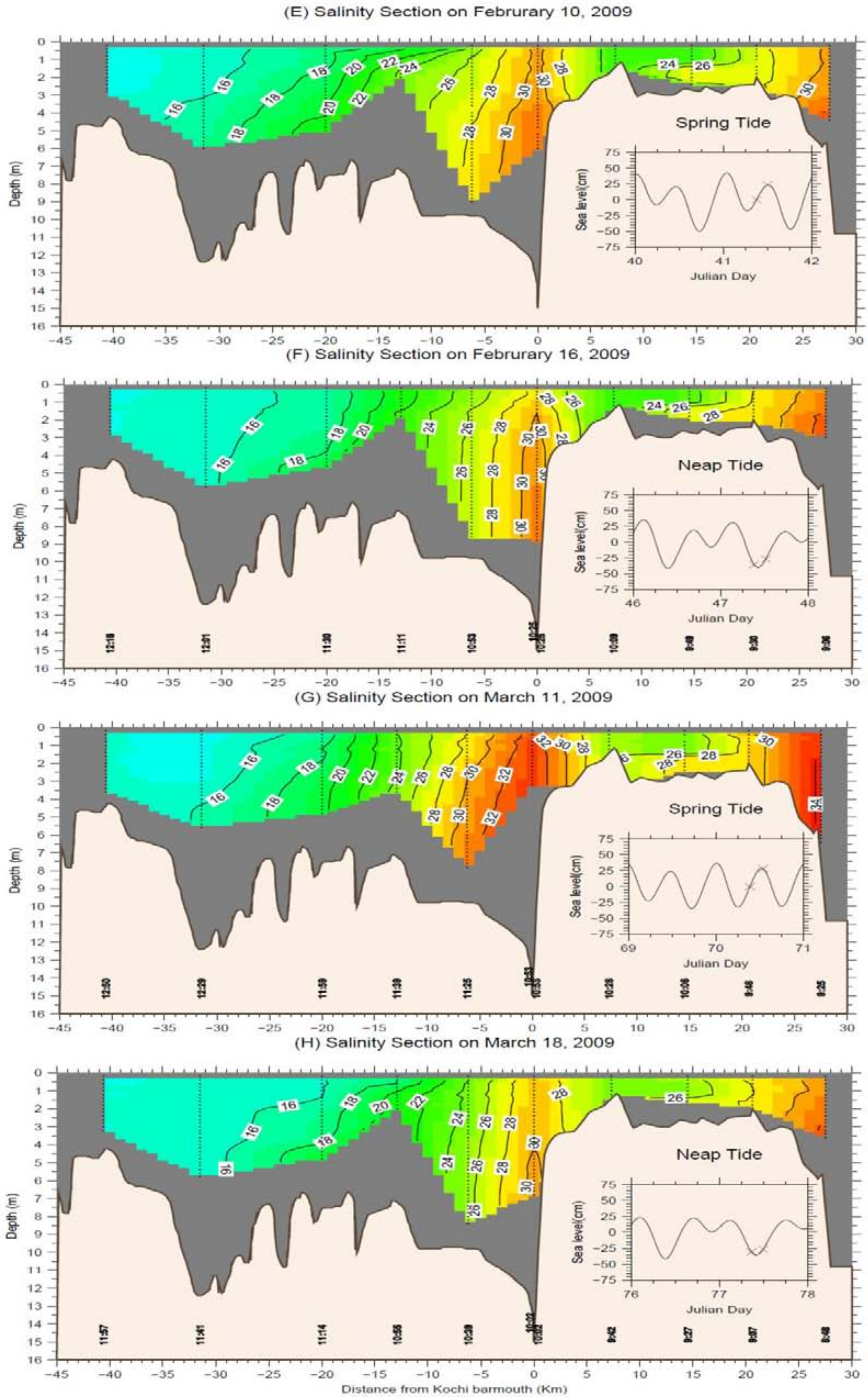

Fig. 4.7. (Continued)

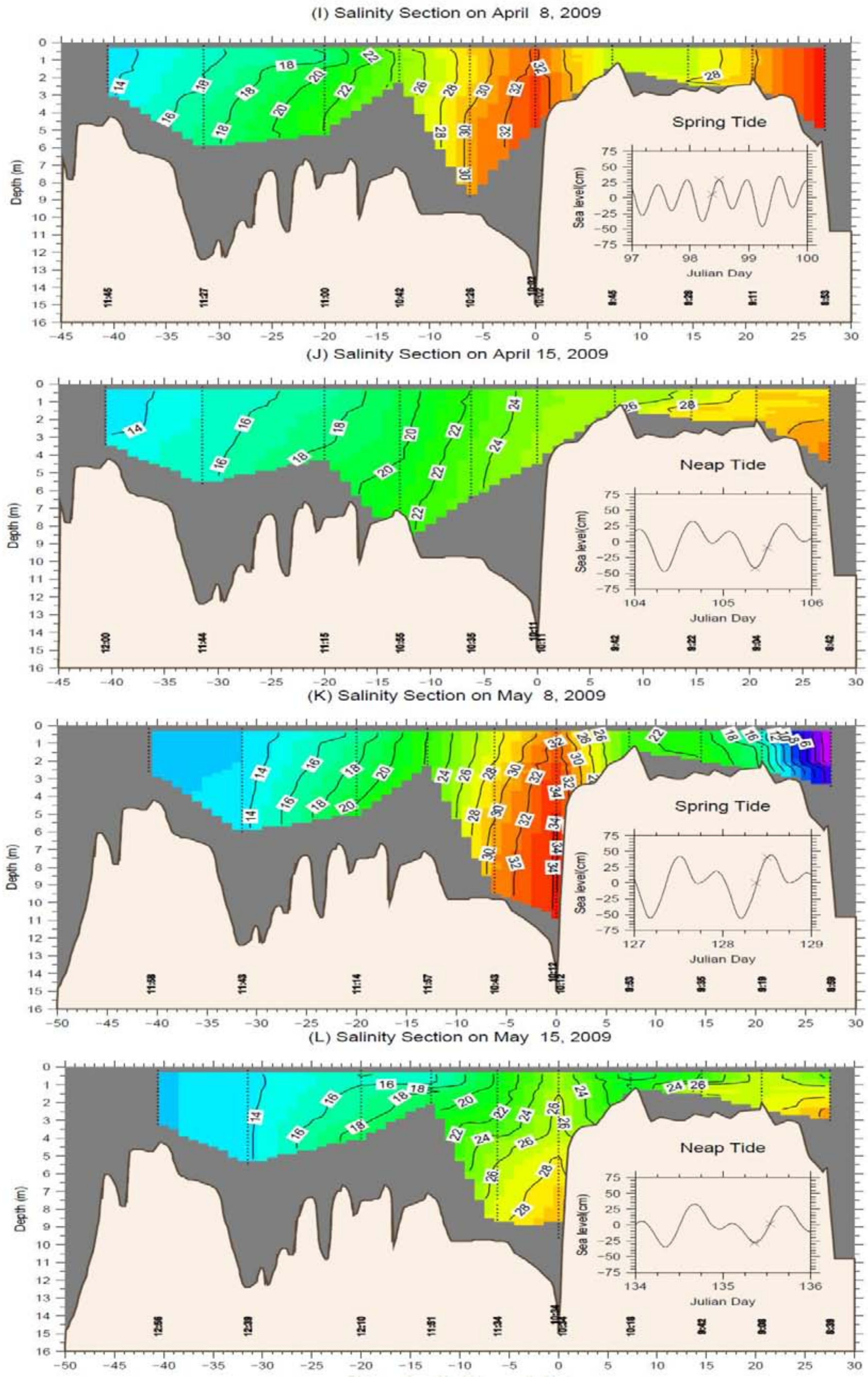

Fig.4.7.(Continued)

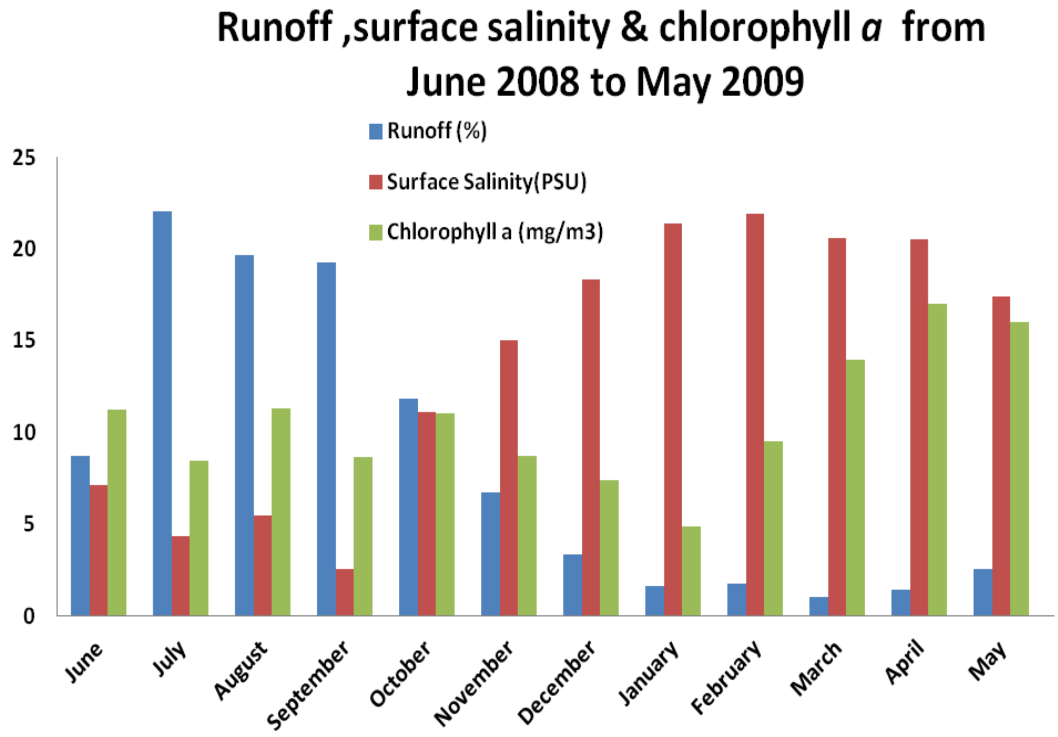

Fig. 4.8. Monthly river runoff, surface salinity, surface chlorophyll *a* starting from June 2008 and finishing May 2009

4.2.2.1Salt budget

The annual variation of salt content against the monthly-mean runoff for the one year synoptic survey is shown in Fig. 4.9. Drastic variations in salt content are observed during high runoff months. Thereafter a steady increase occurred in salt content during later months and from February to April the salt content shows little variations. The estuary loses about 48% of its salt from June to July due to high spells of rainfall. In the following month, a gain of about 9% occurs, owing to a decrease of about 200 m^3s^{-1} of runoff from July-August. From August–September there is again a decrease in salt content when monsoon regained its strength after the break. Thereafter, until December, salinity ingress or egress is observed in accordance with the prevailing monthly runoff. In contrast, from January-April, the mean monthly runoff is fluctuating by 10-20 m^3s^-

^{1} which is not reflected in the salt content of the region. Despite the increase or decrease in the runoff, the total salt content of the estuary increases during this period. The annual cycle of salinity ended with the observation in May. During the period, freshening of the estuary is initiated and the salt content decreases.

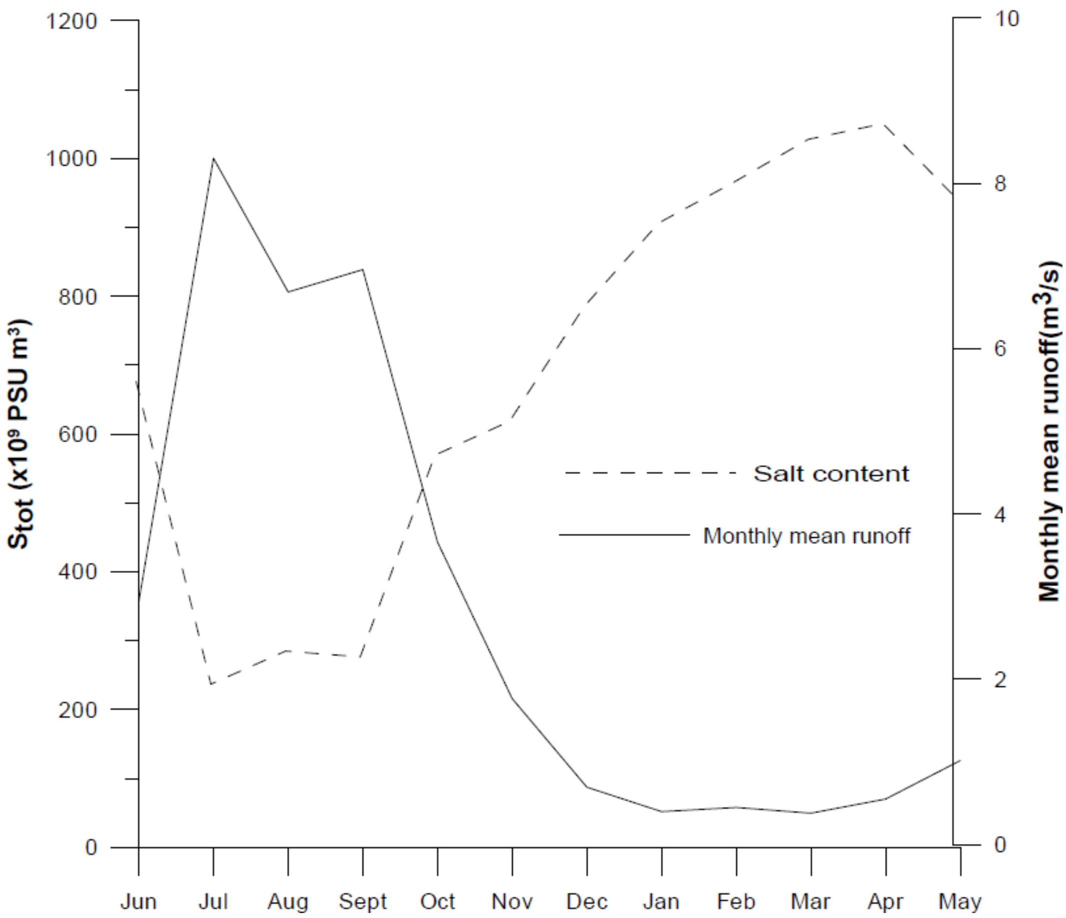

Fig. 4.9. Total salt content and monthly-mean runoff during the year 2008-2009

4.2.3 Flushing Time

The river runoff peaked with 8.7% of the total occurring in the month of June and flushing time (T_F) calculated is 5.8 days. July experiences the maximum river runoff amounting to 22.04% of the total and flushing time (T_F) decreases to 2.8 days when the runoff is 1008 m^3s^{-1}. From 11.81% in October, the river runoff is reduced to 3.34% in December. Consequently, flushing time (T_F) also increases from 3.5 days in October to 8.4 days in December. The flushing time is 9.3 days in January which increases to 13 days in April. In May, there is a slight increase in runoff to 2.5% of the yearly runoff and the flushing time (T_F) is 14.7 days. Among the high runoff months, the longest T_F occurred in June. This is substantiated by the results of salinity distribution in June (Fig. 4.6a). Stratification is not fully evolved during the period and hence relatively low flushing rate. During low runoff, tidal actions are predominant and tide driven flushing time (T'_F) is 8.7 days.

4.2.4 Statistical analysis of monthly observation

The Pearson correlations between the surface values of ecologically important variables are shown in Table. 4.1. Salinity shows significant positive correlation with P^H ($R=-0.524$, $P<0.01$). Relevantly, it is negatively correlated with nitrate ($R=-0.308$, $P<0.01$), DO ($R=-0.370$, $P<0.01$) and silicate ($R=-0.650$, $P<0.01$) indicating freshwater as their source of inputs. Chlorophyll *a* is highly correlated with phosphate ($R=0.455$, $P<0.01$), with no significant correlation with salinity. Also, there is no distinct correlation between salinity and phosphate. Although DO is inversely correlated with chlorophyll *a*, it is not significant indicating that biological processes are not the only factor influencing DO in the estuary. Negative correlations between salinity and DO are highly significant ($R=-0.370$, $P<0.001$).

The two-way analysis of variance carried out on monthly samples is shown in Table. 4.2. Salinity variations are found to be significant spatially ($F=7.88$, $P<0.001$) and temporarily ($F=6.37$, $P<0.001$). However, temperature varies more temporarily ($F=2.29$, $P<0.01$) than spatially ($F=0.88$, $P<0.01$) owing to the seasonal changes in the domain. Among the different nutrient species, only phosphate manifests fluctuations spatially ($F=9.87$, $P<0.001$) and temporarily ($F=2.66$, $P<0.005$). Chlorophyll *a* marks remarkably significant variations spatially (F=4.35, P<0.001) than temporarily (F=1.23, P<0.5).

Parameters	Salinity	Temp	DO	pH	Nitrate	Nitrite	Ammonia	Silicate	Phosphate	Chl *a*
Salinity	1									
Temp	0.028	1								
DO	**-0.370****	0.375**	1							
pH	0.524**	0.690**	0.203*	1						
Nitrate	**-0.308****	-0.027	0.173	-0.122	1					
Nitrite	0.106	0.059	**-0.209***	-0.017	0.139	1				
Ammonia	-0.027	0.054	-0.092	0.064	-0.068	**-0.204***	1			
Silicate	**-0.650****	0.168	0.290**	**-0.231***	0.251**	**-0.186***	0.247**	1		
Phosphate	0.117	0.117	-0.127	0.168	0.125	-0.027	0.055	0.032	1	
Chl *a*	0.086	0.158	-0.038	0.16	0.014	-0.038	-0.048	-0.029	**0.455****	1

Table 4.1. Results of Pearson correlation analysis (R) for the investigated physical and chemical variables during monthly observation. *: P<0.05[1], **: P<0.01[2], bold values indicate negative correlation

Variables	*Station*		*Year*	
	F	P	F	P
Salniity	7.883679	0.000065***	6.370352	0.00047**
Temperature	0.884074	0.541915	2.291627	0.014651
DO	3.411882	0.000984**	2.104926	0.025726
pH	3.836676	0.000301**	3.082916	0.001237*
Nitrate	0.419885	0.922091	12.94469	0.00002***
Nitrite	0.971728	0.4674	9.793611	0.00042**
Ammonia	1.006034	0.439704	8.134114	0.00032**
Silicate	1.843739	0.068204	7.809754	0.00008***
Phosphate	9.872694	0.0005**	2.662658	0.004654*
Chl a	4.357485	0.00007***	1.233476	0.273961

Table 4.2 Two-way analysis of variance for differences of ecologically important parameters on sampling stations and sampling months for the survey (June 2008 to May 2009). F indicates the likelihood ratio; P indicates the probability. *** indicates statistically significant differences < 0.0001, ** indicates < 0.001 and * indicates <0.01

[1] Correlation significant at 0.05 level
[2] Correlation significant at 0.01 level

4.3 Discussion

Temperature has lesser influence in density stratification than salinity because the salinity range is larger than temperature in estuaries (Dyer, 1973). Thus, an attempt is made to analyze the variations in stratification considering salinity as the major determining factor. The data presented from this survey suggest that salinity fluctuates at different timescales, including intratidal, fortnightly of spring and neap tidal cycle, and seasonal (high runoff and low runoff periods). It is evident from this study that Cochin estuary transform from partially mixed (neap) or well mixed (spring) in low runoff to a periodically stratified state during high runoff (monsoon). Results of the longitudinal transect measurements show salt intrusion recedes with increasing river runoff and rebounds with decreasing river runoff. During high runoff, the intense flushing and reduction in salinity field expansion are seen. The salt content also varies drastically during high runoff. The estimated flushing time is also varies with the river runoff.

The approach of linking the physical phenomena with chemical and biological properties has been carried out. The Arabian Sea, one of the major upwelling zones of the world, experiences upwelling from June to October (Banse, 1968, Naqvi *et al.*, 2000). Srinivas *et al.*, 2006 claims that the increased intensity of upwelling processes in off Cochin in July is instrumental in generating drop in sea level and surface temperature. Whilst this process aids in quicker flushing of the estuarine water through the bar mouth (Udaya Varma,1981), low tidal amplitudes and increasing number of oscillations in the south west coast may lead to small inter-tidal expanses, which reduce flushing (Qasim, 2003). Coastal upwelling in the Arabian Sea induces anomalies in the distribution of physiochemical properties characterized by a rapid decrease in temperature and DO concomitant with an increase in salinity and surface nutrients, particularly nitrates (Rotchord, 1975) which could foster enhanced primary productivity of the area (Mann and Lazier, 1996).The upwelled water area is situated just off the shelf break (Shetye *et al.*, 1990), where the predominant tidal circulation is responsible in advecting these waters in to the estuaries. In this present study the intruding water mass at the bottom layers during monsoon season (high runoff) is identified as upwelled water from the adjacent shelf with its peculiar characteristics of low temperature, high salinity, severely oxygen depleted, nutrient rich and high chlorophyll *a*.

Dynamics of salt wedge play an important role in the distribution of chemical and biological variables that have profound impacts on water quality (Haralambiduo *et al.*, 2010). Coastal hypoxia (defined here as <1.42 ml L) develops seasonally in many estuaries, fjords, and along open coasts as a result of natural upwelling (Levin L.A. *et al.*, 2009).The upwelled water incursion and the stratification induced by river runoff of monsoon season fuels the oxygen depletion at the bottom layer. Under persistent stratification, the probability of the shift of hypoxic to anoxic condition in the intruding frontal system cannot be ruled out. Detailed hydrological analysis of present study suggests that the dynamic and energetic environment of Cochin estuary hinder the sustainability of this front at the bottom. The onset of strong ebb phase and high flushing of monsoon flushes the estuary from top to bottom with well oxygenated waters by pushing the saline wedge seaward. The duration of the existence of this front in our system is greatly determined dynamics by the tidal range and duration of flood-ebb cycles. The dependence of the salt wedge advancement on tidal range is clearly identifiable in spring phase as the tidal amplitude of 26.05 cm is not sufficient to force the transient stratified flow. The diurnal inequality of the neap phase contributes well to the flushing period (12 hrs) as when compared with the semi-diurnal spring phase (9 hrs 30 min). The time dependent nature of salt wedge has also been justified in Fraser estuary (Geyer *et al.*, 1989), where during ebb the saline structure was eroded due to local enhancement of shear instability. Therefore, the periodic advance and retreat of the salinity wedge front is inevitable in preserving the ecosystem functioning and maintaining the health of the estuary.

Cochin estuary is reported to be a eutrophic estuary (Qasim *et al.*, 2003). During high runoff surveys, an increase in the overall nutrient concentrations is noticed when compared to low runoff surveys. However, the salt wedge intrusion affected its distributions in the water column. Higher concentrations of phosphate and nitrite are restricted to the near bottom saline intrusions, but extreme levels of silicate and nitrate are observed in low salinities. Although the near-bottom seawater intrudes with high nutrients, river runoff is the principal source of silicate and nitrate supply. This is further substantiated by the statistical results which revealed that silicate and nitrate are highly negatively correlated with surface salinity whereas phosphate and nitrite which do not manifest a significant relationship. Phosphorous shows both seasonal and spatial variability. The surface phosphate concentrations are moderately high in the stations with high salinity whereas concentration decreases in low saline regions. The previous work on the fractionation of phosphorous in Cochin estuary (Balchand *et al.*, 1994) also concluded that enhanced amounts of exchangeable P appeared in high saline waters, signifying the presence of biologically available nutrient phosphorus.

In Cochin estuary nutrients are not a limiting factor for the optimum phytoplankton growth at any time of the year (Balachandran *et al.*, 2005) and also transient variations in the water quality play a significant role on phytoplankton behaviour (Madhu *et al.*, 2009). Prior experimental studies had found that generally Cochin estuary exhibits high chlorophyll *a* when intermediate salinity (10-25) conditions prevail (Qasim and Sankaranarayanan *et al.*, 1972). The present study substantiated the above statements such that increased chlorophyll *a* distribution is observed during low runoff than high runoff. The increased flushing during high runoff resulted in low chlorophyll concentration in surface layers where salinity is low. The effect of river runoff and surface salinity on the surface chlorophyll *a* distribution is clearly depicts in Fig. 2B such that the maximum chlorophyll concentrations are observed during lean-river runoff months when the surface salinity is high. High river runoff leads to reduced residence time, leading to increased flushing of phytoplankton biomass out of the estuary (Lane *et al.*, 2007). Further, the overall surface distribution of chlorophyll *a* during monsoon is affected when the increased river runoff restricted the salinity dispersion and hence the saline waters with biologically available phosphorous is limited in some areas along the estuary. Phosphorous is being attributed as a limiting nutrient in fresh water-dominated systems (Neil 2005). The river pulses impede the salinity field expansion affecting the nutrient distributions. However, salinity could not be considered as the only determining factor for triggering phytoplankton growth. Unravelling these evidences is henceforth a major task to be accomplished through sustained research. Although the linking between temporal stratification of the water column with chlorophyll *a* distributions is a question of some subtlety, this study reveals the persuasive evidence of its critical importance in Cochin estuary.

The advancement in understanding of time-dependent nature of water column stabilization and destabilization mechanisms can be achieved through continuous monitoring of multiple stations along with supporting flow field to define various processes in spatial and time scales.

Chapter 5

Influence of Thanneermukkam Barrage on tides and salinity

5.1Introduction

Thanneermukkam Barrage (TB) is a salinity barrier (commissioned in 1976) in the upstream part (~40.6 km away from Cochin inlet) of Cochin estuary. It was constructed to prevent the entry of saline water into the polders of Kuttanad region of Kerala coast to facilitate agriculture of paddy fields during summer season. Among the six rivers flowing into cochin estuary , four rivers viz., Meenachil, Manimala, Achankovil and Pamba drain to south of TB. When TB is closed during the dry season (January-April), although river runoff is minimal (low runoff), the river supply from these rivers is hindered to north of TB. However, the shallow regions, south of the TB becomes freshwater dominated due to runoff from the rivers. Thus, TB acts as a river runoff regulator in the system. Therefore, TB when closed separates freshwater regions south of it from brackish water regions of Cochin estuary. The exact date of closure of TB is decided based on salinity increase in the area adjacent to TB and the barrage is opened when the river runoff sufficient to prevent salt intrusion. Prior to the commissioning of TB, it was possible to cultivate only one crop of paddy a year. A second crop in about 300 ha of the paddy area, cultivation of cocoa, plantain, and vegetables as inter-crops in coconut garden become feasible after the construction of TB with the availability of fresh water round the year at the upstream.

In this study efforts are made to understand the influence of TB on the hydrodynamics of the estuary using in-situ data. The study discusses the tidal amplitude variations, tidal asymmetry, salinity and chlorophyll *a* distribution in the southern arm (from Cochin inlet to TB) of the estuary during the 'open' and 'closed' conditions of TB. An attempt is also made to investigate the residence time of Cochin estuary for different river runoff conditions. This attempt enables to assess the hydrodynamic controls on phytoplankton biomass.

5.2 Results

5.2.1Tidal propagation

The observed de-meaned sea level data at the three stations for 40 days (Julian days 89-129) are presented in Figure. 2.9(Chapter 2). The sea level (tide) variability is found to be higher at the Cochin inlet (station A) and decreased towards the upstream direction. The spring-neap variability in the sea level is obvious at stations A and B. Evidently, during the barrage closed period; the tides get amplified very much at C and to a lesser extent at B too. It is interesting to point out that the observed tidal range at neap phase during the TB 'closed' period is found to be much higher than the spring phase for the TB 'open' condition.

Constituents	Stations Closed Period A	B	C	Stations Open Period A	B	C
O_1	8.8 (55.8)	5.3 (89.3)	5.9 (89.8)	9.3 (61.6)	3.6 (91.6)	3.7 (107.2)
K_1	18.1 (62.5)	12.8 (106.3)	14.8 (96.9)	17.8 (61.8)	6.9 (127.8)	8.7 (131.0)
N_2	4.9 (303.6)	1.6 (25.0)	1.6 (49.8)	4.9 (303.6)	1.6 (25.0)	1.6 (49.8)
M_2	27.0 (341.4)	17.2 (63.0)	19.5 (65.7)	23.8 (339.5)	7.0 (59.2)	7.4 (89.9)
S_2	8.6 (37.6)	6.2 (125.6)	7.5 (125.9)	8.5 (36.1)	2.0 (115.0)	2.5 (146.8)
M_4	2.3 (140.3)	0.7 (108.3)	0.9 (85.1)	1.17 (98.3)	0.15 (325.2)	0.33 (352.7)
Form number†	0.41	0.77	0.77	0.84	1.17	1.25
Mean spring range (cm)‡	71.2	46.8	53.0	64.6	18.0	19.8
Mean neap range (cm)§	36.8	22.0	24.0	30.6	10.0	9.8
$2M_2$–M_4 (degrees)	182.6	17.8	46.0	220.7	153.2	187.1
M_4/M_2 (cm)	0.08	0.04	0.05	0.05	0.02	0.04

* Values in brackets are the phase angles.
† Form number $= (O_1 + K_1)/(M_2 + S_2)$.
‡ Mean spring range $= 2(M_2 + S_2)$.
§ Mean neap range $= 2(M_2 - S_2)$.

Table 5.1. Amplitudes (cm) and phases (°) during "closed" (March 30- April 4, 2007; Julian day 89-94) and "open" periods (April 9-May 8, 2007; Julian day 99-128) at stations A-C

The amplitude and phases of major tidal constituents derived from one month data at three stations are shown in Table 5.1. The amplitude of the tidal constituents is higher at station A compared to stations B and C. M_2 tide dominated the K_1 tide at A whereas at B and C these two constituents are almost comparable in magnitude. The mean spring range is higher at A than neap range but they are comparable at B and C. The form number indicates that there is a slighter increase of dominance in diurnal constituents in the upstream stations when compared to the lower station. When the duration of the falling tide exceeds that of the rising tide, leading to stronger flood currents, the system is defined as `Flood-dominant', while it is defined as `Ebb-dominant' when the duration of the falling tide is smaller than that of the rising tide, leading to stronger ebb currents (Speer and Aubrey, 1985; Speer *et al.*, 1991). The downstream and farther most upstream regions of this estuary is ebb dominant mainly due to the large width of the channel in these regions where large volume of water is stored during the high tide. The ebb and flood dominance remain the same at stations A and B respectively during both the open and closed period of TB.

Interestingly, the station C is transforms from ebb dominant to flood dominant during the closed period of TB. The increase of M_4/M_2 amplitude ratio at this station also indicated higher degree of distortion of tides when the TB is closed (Table. 5.1). Flood-dominant systems infill the estuary, while ebb-dominant systems flush sediment seaward (Boon and Byrne, 1981; Aubrey and Speer, 1985; Manoj *et al.,* 2009). Change in ebb and flood dominance in this region due to the opening and closure of TB can influence sediment transport pathways and the morphological evolution.

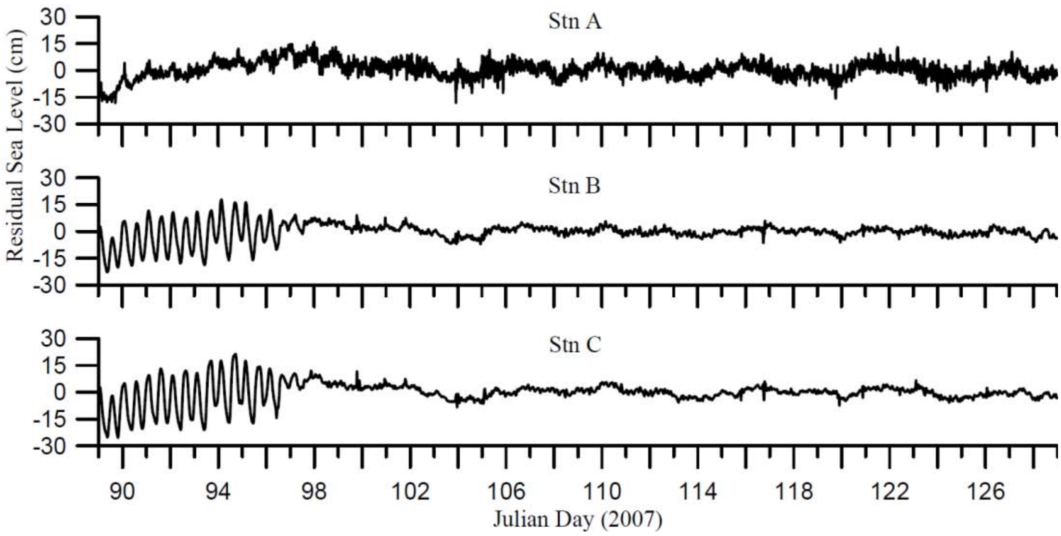

Fig. 5.1 Residual sea level for the period Julian day 89 – 128 (March), 2007 at Stations A-C.The period 99-128 is used for obtaining the tidal constituents.

The residuals (difference between the observed tide and the predicted tide) for the 40 days period (including the 6 days ‘closed’ period) are presented in Fig. 5.1. During the TB ‘closed’ period, even though one do not observe any conspicuous feature at A, distinct wave like patterns are observed at B and C. It shows that the periodicity of this wave is not effectively filtered by tidal analysis. The amplification of these signals is most likely as a result of standing wave formation. To understand this aspect, in detail, and to quantify the amplification, performed harmonic analysis of tidal signals during the ‘closed period’ and the ‘if open’ period (Table 5.2 and Fig. 5.2). The analysis shows that diurnal and semi-diurnal tidal bands got amplified by a factor of 2.6 and 1.6 times at station C when TB was kept closed. The strong amplification signatures of the above two bands are also seen at station B.

	Diurnal				Semidiurnal			
Station	C	O	Amplification	Change in Phase (°) (O–C)	C	O	Amplification	Change in Phase (°) (O–C)
A	7.5	5.8	1.3		25.7	25.8	1.0	
B	5.6	2.6	2.2		18.8	7.4	2.5	
C	6.8	4.3	1.6		22.1	8.6	2.6	
A	45.2	36.2		−9.0	9.8	8.2		−1.6
B	94.8	112.0		17.2	101.9	89.6		−12.3
C	78.9	104.5		25.6	102.2	121.2		19.0

C, closed period; O, if-open period.

Table 5.2. Changes in the tidal bands (amplitudes /phases) caused by the ‘closed barrage vis-à-vis “if open” barrage during the six day period (Julian day 89-94).

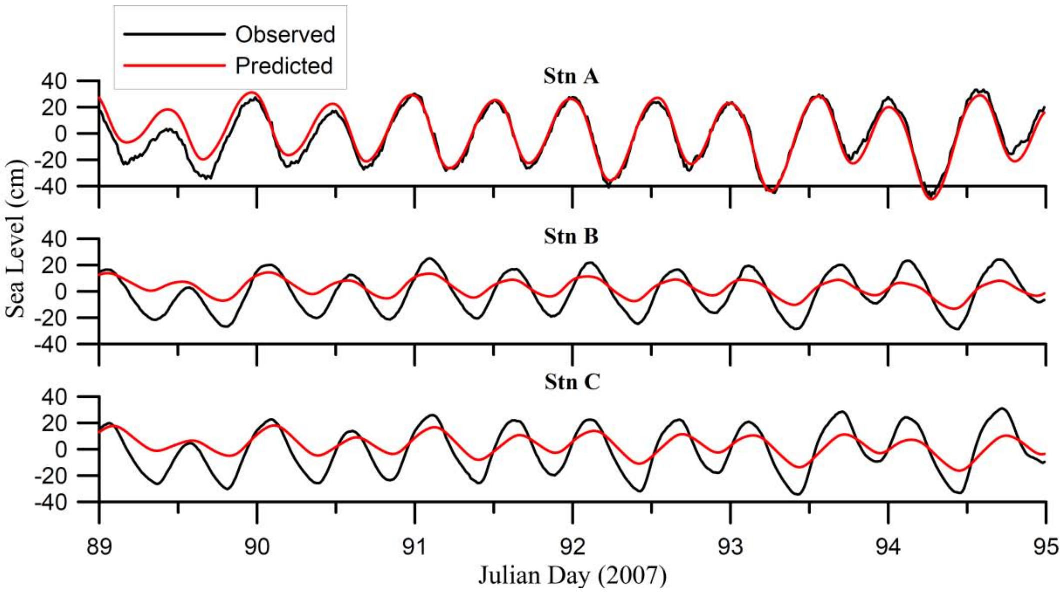

Fig. 5.2. Observed and predicted sea level for the period Julian day 89 – 94 (March), 2007 at Stations A-C. The predictions are based on one month data during which the Thanneermukkam barrage was open (Julian Day 99-128 (March)).

5.2.2 Salinity distributions and variability

The salinity transects reveal the dynamics of salinity intrusion under various river runoff conditions and tidal phases. The monthly mean runoff into the southern arm of Cochin estuary during the observation is presented in Fig. 5.5a. The observations begin on 19, June 2008 when the barrage was open. The maximum salinity gradient is marked at station 1 near the inlet and it declined to zero at the station 6 near TB. The salt wedge formation which begins in neap of June (Fig. 5.3b) becomes more prominent in July as a consequence of high runoff (Fig. 5.3c). Stratification evolves in the water column of the estuary allows the low saline river water at the surface to flow over the high dense water at the bottom. During ISM, salinity (18-34) is intrudes into the estuary only through the bottom waters of near inlet stations. All the other stations remains well mixed and salinity are as low as 0.05 until September.

From October to December (Fig. 5.3i-5.3m), with the decreasing trend in river runoff, the saline water is pushed further upstream hence active displacement of isohalines are observed. A consistent increase in the salinity (~ 3) is discernible towards upstream. The river runoff conditions prevent the intrusion of salinity to station 6. However, during the spring phase of December (Fig. 5.3m) the river runoff decreases further and the salinity at station 6 is 2.

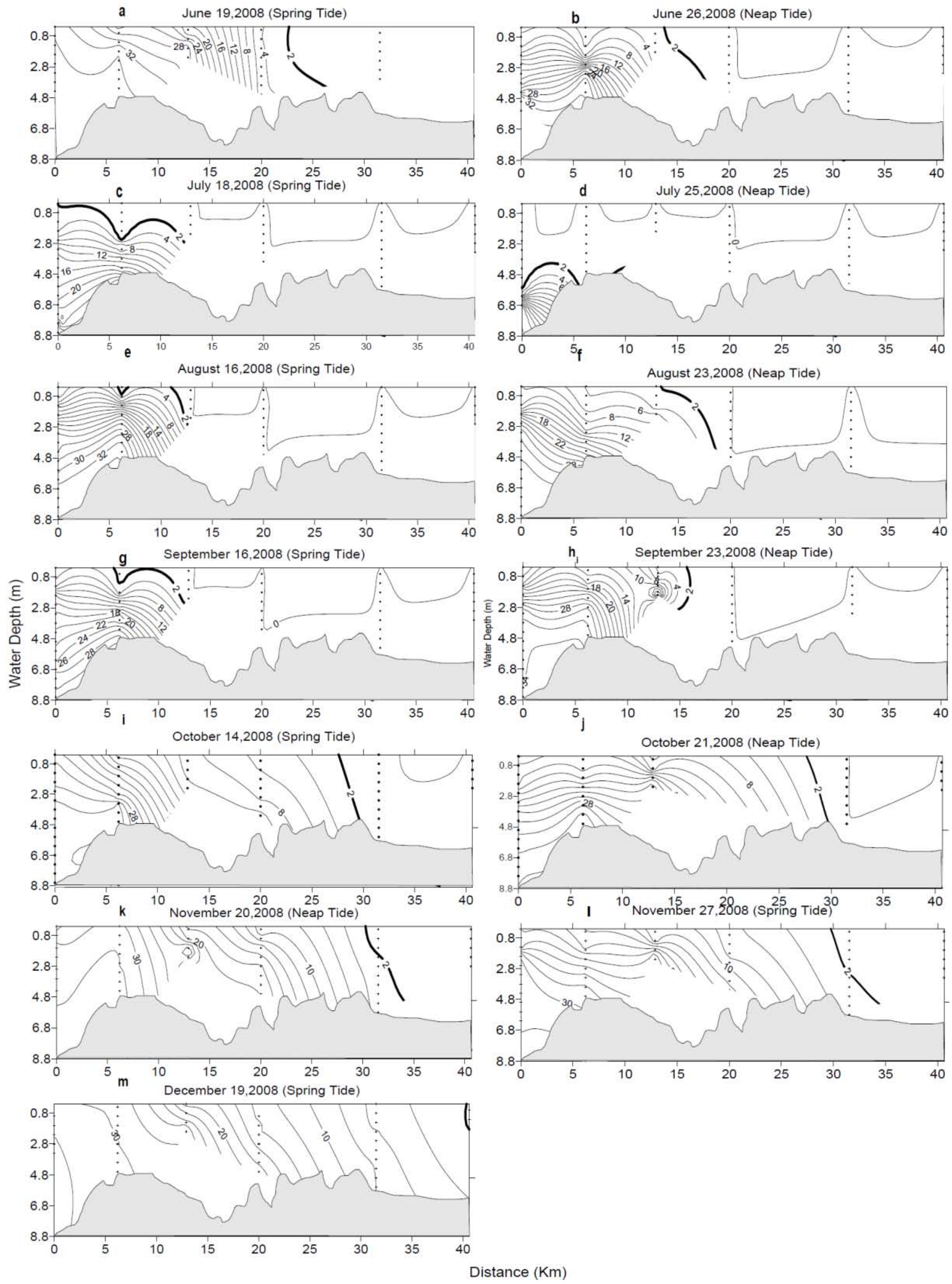

Fig. 5.3. Longitudinal synoptic distribution of salinity measured monthly twice (one spring, one neap) during TB is opened condition starting from June 2008 to December 2008. The Cochin inlet is pointed at "0". The 2 PSU isohaline is highlighted.

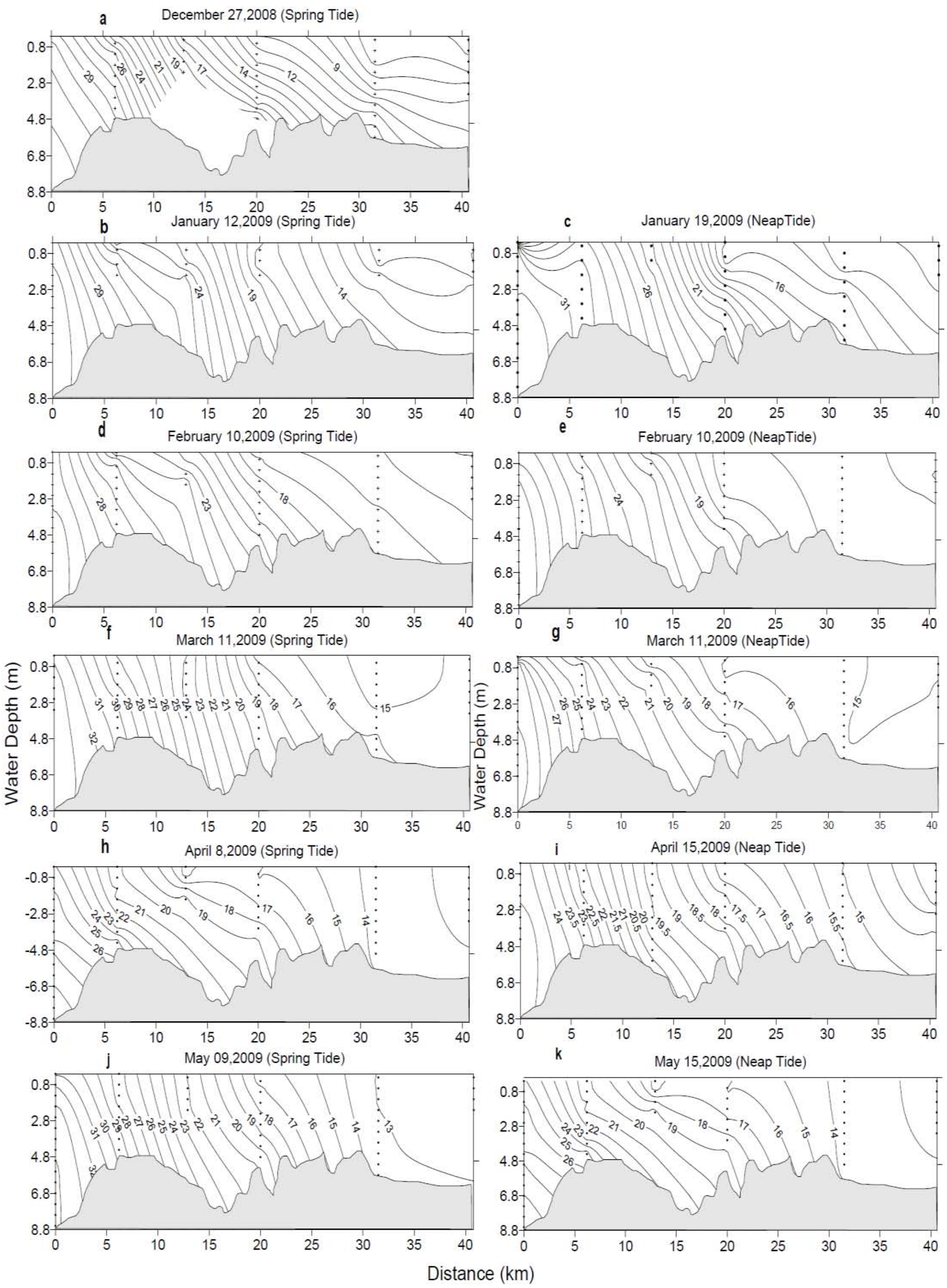

Fig. 5.4. Longitudinal synoptic distribution of salinity measured monthly twice (one spring, one neap) during TB is closed condition starting from december2008 spring observation to May 2009. The Cochin inlet is pointed at “0”.

The closed period survey begins with neap phase of December (Fig. 5.4a). The peak low runoff (January-March) occurs when the river runoff is about 30-40 m^3/s (Fig. 5.4b-5.4g). The gradual closing of the barrage compounded with the reduction in the river runoff and the tides forced from Cochin inlet triggered the horizontal salinity transport. At least salinity of 14 remained at upstream throughout the closed period which indicates the increase of concentration of salinity compared to high runoff period. The TB was opened in April and the runoff from four rivers is allowed to enter the system. Consequently drop in salinity found at station 6, in April and May.

5.2.2.1 Salinity distribution during high and moderate runoff periods

The above results suggest that the salt intrusion in southern arm is strongly dependent on river runoff rather than tide during the high and moderate runoff months (TB open period). Minimum salt intrusion of 10 km is attained during the peak monsoon month July when the river runoff is 1008m^3/s. As the river runoff starts decreasing in the following months, the salinity field begins to expand toward upstream. The maximum salt intrusion is observed under minimum runoff conditions (32m^3/s) on 19 December, 2008. Salinity intrudes until TB achieving an L_2 value of 40.6 km (Fig. 5.3m).

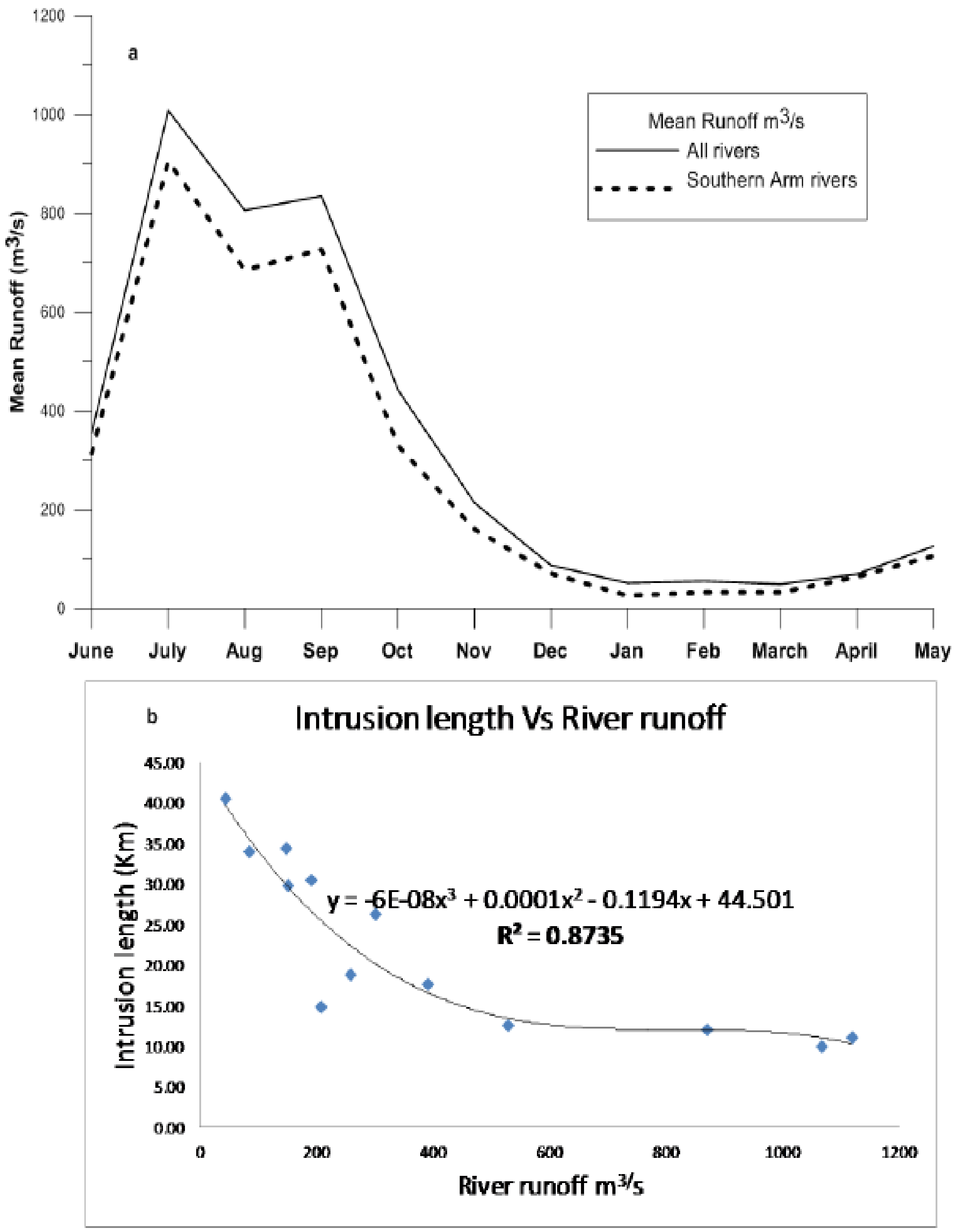

Fig. 5.5 (a) Monthly mean river runoff from June (2008) to May (2009). (b)Polynomial regression between 2PSU isohaline length and river runoff

TB was closed on 23 December 2008. Salinity >2 is observed at all stations from 27 December 2008 (Fig. 5.4a-5.4k). There is appreciable increase in salinity in the upstream close to TB. Several regression equations between salt intrusion and daily mean river runoff is considered. Best results are obtained between L_2 and R using a third order polynomial regression (r^2=0.87, Fig. 5.5b). Similar relationship using a second degree polynomial is found in Strymon River estuary (Haralambiduo *et al.,* 2010). Comparing the results of Strymon River estuary, the salt intrusion in Cochin estuary is much more sensitive to changes in river runoff. This is a typical feature of estuaries along the Indian coast line that are influenced by the ISM (Shetye, 2011). Therefore, the empirical equation relating salt intrusion (L_2 in km) and river runoff (R in m^3/s) during TB open period is determined as:

$$L_2 = -6\times10^{-08}R^3 + 0.000R^2 - 0.119R + 44.50$$

It is obvious that the trend (Fig. 5.5b) in salt intrusion is decreasing with increasing river runoff when R<400 and steadily decreasing when R>400.There is a sudden drop in the intrusion length when R>400 m^3s^{-1}.

5.2.3 Chlorophyll *a*

Figs. 5.6-5.7 illustrate the seasonal surface concentrations of suspended chlorophyll *a* and salinity along the transect stations of southern arm of Cochin estuary. The trend of salinity intrusion discussed above is also reflected in the observations of surface salinity. Longitudinal distributions of surface salinity in all months show the upstream progression from coastal waters to brackish or fluvial waters. During the ISM, very low salinity is observed along the surface of the estuary (Fig. 5.6a-5.6g). The surface salinity is zero throughout the estuary during July owing to the greater freshwater runoff. During the period October –November, the river runoff is relatively low. As a result, surface salinity of > 30 is seen at ocean-end stations and the salinity of river-end stations also increased (Fig. 5.6e-5.6g). From January –March (Fig. 5.7a-5.7c), high surface salinity levels are noted at all stations. The spatially averaged surface salinity is maximum (19.95) in February. During April-May surveys (Fig. 5.7d-5.7e), TB was reopened and the river flux into the estuary increased. Consequently, the salinity decreases relatively throughout the southern arm of the estuary.

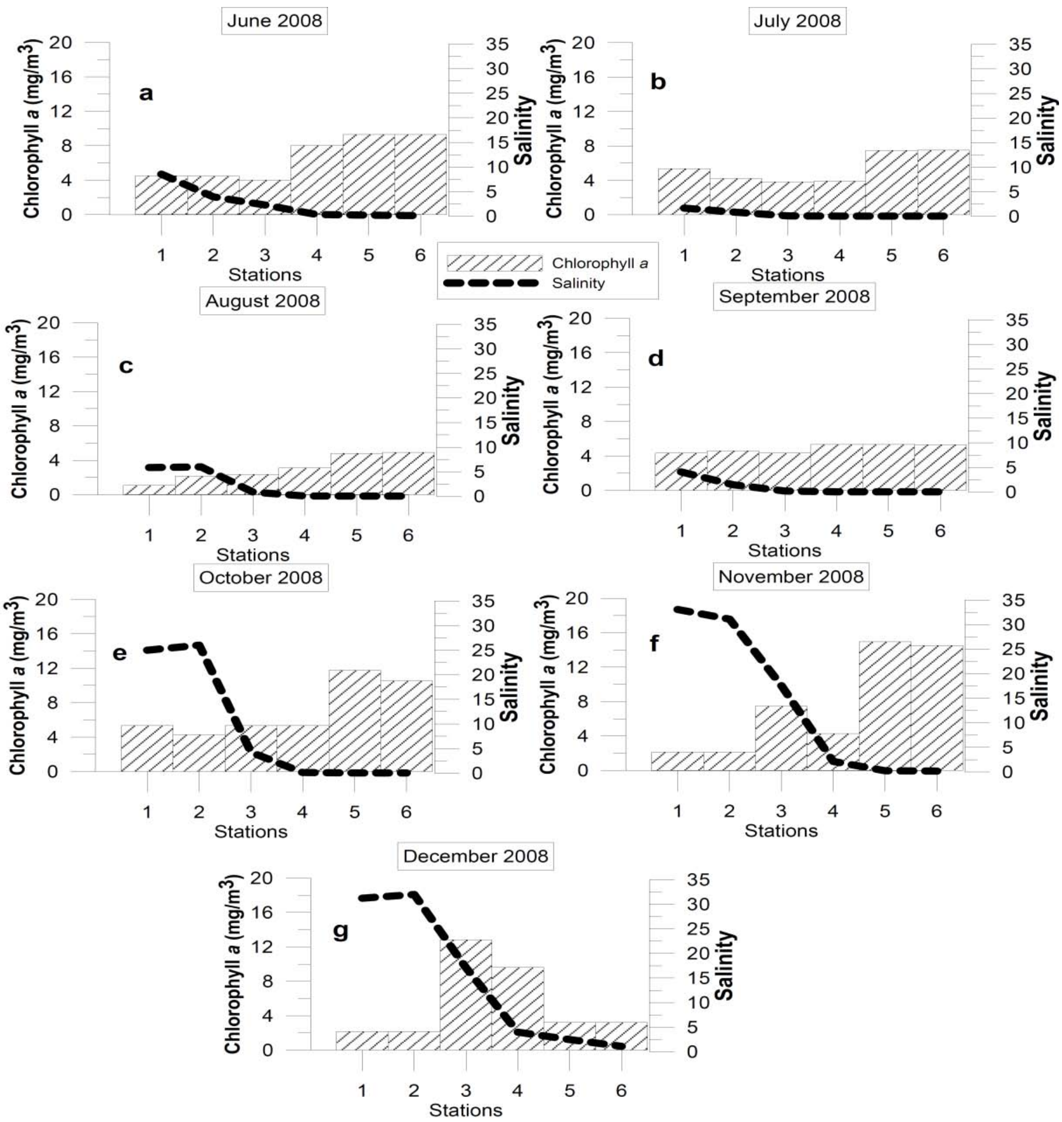

Fig. 5.6. Monthly surface salinity, surface chlorophyll *a* starting from June 2008 and ending December 2008

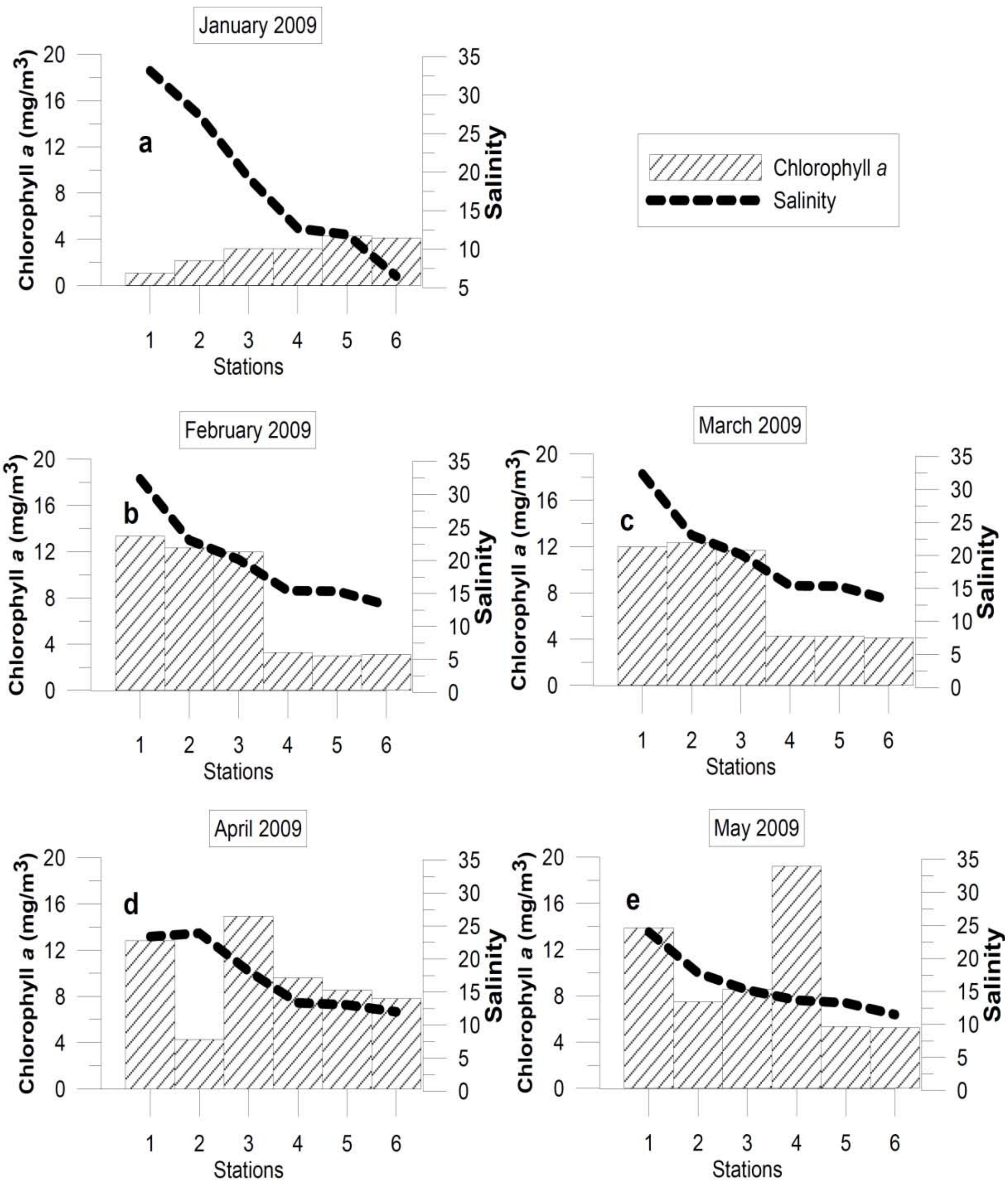

Fig. 9. Monthly surface salinity, surface chlorophyll *a* starting from January 2009 and ending May 2009.

Chlorophyll *a* levels show large spatial variability (Figure. 5.6-5.7). During TB open period, elevated levels of chlorophyll *a* are observed at the river-end stations 5 and 6 (Figure. 5.6a-5.6d). During peak runoff period of July, chlorophyll concentrations of 7.4mg/m^3 are found at upstream end station 6 and of 4mg/m^3 at near inlet station 1. This could signify the dominance of fresh water species advected into the system as a result of freshwater runoff. This situation continued from October to November also but chlorophyll *a* concentrations at stations 5 and 6 increased further to about 14mg/m^3. During December survey, TB was closed. Coincidentally, the surface chlorophyll *a* at stations 5 and 6 drastically decreases (~3mg/m^3). Stations 3 and 4 are brackish and contains high chlorophyll concentrations (Figure. 5.6g). In January, the river runoff is very low and there is an overall decrease of chlorophyll *a* (average of 3 mg/m^3) along the surface of the estuary (Fig. 5.7a). The low runoff ensures strong saline intrusion which may have provided stress to various organisms. However, the biomass increases at the ocean-end stations by February (13 mg/m^3 at Cochin inlet) whereas decreases at stations 5.3 and 5.4 (~3mg/m^3) (Fig. 5.7b). Thus, the distributions of chlorophyll *a* are in converse to the TB open period. The higher chlorophyll *a* levels are observed at oceanic salinity indicating the dominance of marine species. When TB was again opened in April, the little river runoff from the four rivers entered into the system. Although suspended chlorophyll *a* levels are higher at station1 (13 mg/m^3), the concentrations (9mg/m^3) increase at stations 5 and 6 as well. This possibly arises because the different salinity ranges could have supported a more diverse species population with relatively higher biomass (Fig. 5.7d-5.7e).

5.2.3.1 Residence time and Chlorophyll *a*

River runoff is related to the flushing rate and there is a statistically significant negative correlation between runoff and biomass accumulation (Filardo and Dunstan, 1985). The residence time is 3 days during high river runoff period (June-September) and 11 days during moderate river runoff period (October-December). During the low river runoff period (January-May), the residence time is highest and ranges from 13 to 14 days. The above results of chlorophyll *a* clearly depict the hydrodynamic controls on the biomass. Despite the nutrient enrichment of the estuary during ISM as a result of terrestrial runoff (Joseph S. and Ouseph P.P., 2008), the average surface chlorophyll *a* levels are relatively lower during high runoff (June-September) than during peak dry season (low runoff). This study speculated on tentatively that high flushing during monsoon results in low chlorophyll concentration in surface layers where salinity is low. The most likely source for higher chlorophyll *a* concentration in the river-end stations are freshwater runoff from rivers south of TB, although these chlorophyll *a* will also be flushed rapidly once they are discharged into the estuary. However, when the runoff decreases during October-November, the flushing reduces and the more residence times favor the sustainability of species in the estuary. During the low runoff, highest water residence conditions results in relatively higher biomass accumulation.

5.3 Discussion

The study could bring out the amplification effect on tides when TB was kept closed using a limited 6 day data on sea level. The amplification is to such an extent that the neap phase range during the closed condition is more than the spring phase range during the open condition. The study emphasize that TB has significant role in transforming an ebb dominant region to a flood dominant region, and which may lead to morphological modification of the estuary.

TB acts as a salinity barrage for regions south of it but acts as a river runoff regulator to the estuarine region north of it. During the open period, the salt intrusion is strongly dependent on river runoff in high and moderate runoff months. The position of salinity intrusion is highly dynamic with the distance of upstream intrusion inversely related to river runoff. During low runoff, the salinity is regulated by controlled runoff from four rivers south of TB. When TB was completely closed, there is a reduction in the river runoff as the flow from four rivers is impeded. The concentrations of salinity increase throughout the southern arm including the upstream regions.

Chlorophyll *a* levels show large spatial variability and mostly dependent on the hydrodynamics of the estuary. It seems that freshwater species dominated upstream which are higher during high runoff months. During low runoff, the ocean-end stations exhibited high chlorophyll implying the dominance of marine species. The biomass is generally low during high runoff survey whereas relatively higher during low runoff surveys. With the rapid flushing of Cochin estuary in monsoon season, it is hypothesize that it is not possible for several algal cell divisions to occur before algae are flushed. Under the low runoff and the highest water residence, the estuarine environment supported relatively higher biomass accumulation.

Sarma *et al.*, 2009 documented that the river runoff can alter the trophic status of the estuary influencing the plankton metabolic rates. They found that a net heterotrophy with low gross primary production (GPP) occurred during the peak runoff period in the tropical monsoon driven Godavari estuary. Cochin estuary is same kind, however, without complete cessation after monsoon. In Cochin Estuary, the ratio of primary production to community respiration ranges from 0.05 and 8.5 seasonally (Shoji *et al.*, 2008). Since TB regulates the river runoff, this barrage can influence the metabolic activity of the estuary. The present study is a persuasive evidence of the hydrodynamic controls on the accumulation of phytoplankton biomass. These findings highlight the need for future studies focusing on the changes in the phytoplankton metabolic activities associated with the opening and closing of TB using a daily measurement strategy.

Chapter 6

Classification of Cochin Estuary

6.1Introduction

Estuaries are always dynamic and often exhibit a gradient in conditions from absolute riverine to oceanic which makes estuarine classification a complex matter. For a specific estuary, the classifications dealing with one type may change from one type to another in consecutive tidal cycles, or from month to month and from season to season or even from one location to another within the estuary (Valle-Levinson, 2010). Additionally, the system may undergo changes under the influence of natural hazards or even anthropogenic influences. Thus, a realistic classification, representative of its true characteristics can be done only after understanding the dominant dynamic processes of an estuary. This demands rigorous investigation in to the dynamics of each section of the estuary using comprehensive data sets. Then that an estuary can be uniquely placed into the most appropriate category which it deserves. The peculiar behaviour of this estuary at times makes its classification an arduous work. This is clearly revealed by the different names it is being introduced in various literatures.

In this context, present study objective is to evaluate various classification schemes and to classify Cochin estuary. This is achieved by collating past evidences and by examining the present characteristics of the estuary using recently acquired large data sets. Estuarine classification schemes based on relatively easily measurable parameters (Hansen and Rattray, 1966) and climatological factors like river runoff (Vijith *et al.*, 2009) are also evaluated for the estuary to determine how well the classification schemes represents the reality. The constraints imposed by these classification schemes evidences the uniqueness of the region. Due to all these reasons, a new nomenclature is proposed Cochin Monsoonal Estuarine Bay (CMEB) for this estuary. With this nomenclature is comprehended the physiographic, hydrographic and biological characteristics of the system which are elucidated in the following discussions.

6.2 Results

6.2.1 Prediction of runoff from polynomial fitting

A sixth degree polynomial is obtained as the best prediction equation for 1978-2001 and 1985-1989 data sets. The equations are

$$Y= 0.485X^6+19.49X^5-300.3X^4+2205x^3-7802X^2+12214.0X-6191.0 \ldots\ldots\ldots (20)$$

for 1978-2001

and

$$Y=-0.321X^6+13.06X^5-204.3\ X^4+1523\ X^3-5456.X^2+8624.0X-4359.0 \ldots\ldots (21)$$

for 1985-1989

Where Y is the total monthly runoff and X is the month number 1, 2,3....12 from June to July. Equation (20) predicts 2008-2009 runoffs with only 27.36% prediction efficiency whereas equation (21) predicts it with 83.69% prediction efficiency. The lower values for prediction efficiency from the 23 years data may be due to the missing data. Since total monthly runoff is predicted with high efficiency from the past data of 1985-1989, it followed that further analysis made in this study using the 2008-2009 runoff data can be generalised.

For the 1985-1989 monthly runoff data, time series components are calculated and the adjusted seasonal indices for June to July are 130.89, 108.28, 92.67, 115.88, 120.41, 79.58, 76.86, 107.04, 111.85, 69.98, 69.33 and 117.23% respectively. From the $2^3 * 6$ models (Jayalakshmy, 1998), ($2^k * r$, where k is the number of independent parameters and r is the number of transformations for the dependent and independent variables) the one which explained the maximum variability and in which the independent variables are uncorrelated is chosen. The optimal model for this study is the simple model,

$$LOG_{10}Y=-1.4453*10^{-7}+0.8839*LOG_{10}T+0.2405*S+0.002416*C \quad .....(22)$$

It can explain about 99.86% of the variability in the river runoff distribution during 1985-1989. The other models are depicted in Table 6.1. These regression models are fitted assuming that the three components are independent. From the regression models fitted, moving average of period 2 represented the observed runoff with 94.72% of precision (Table 6.1).

Parameters	Explained variability	F statistic (n1, n2)#	P value
X1, 2 period centered MA	94.72	880.5 (1,48)	P<0.001
X2, Seasonal variation,	31.32	23.35 (1,48)	P<0.005
X3, Cyclical variation,	0.9915	1.4907 (1,48)	P<0.005
X1, X2,(X1*X2)	99.89	15501.2 (3,46)	P<0.0001
X1, X3,(X1*X3)	96.83	501.23 (3,46)	P<0.001
X2, X3,(X2*X3)	39.58	11.69 (3,46)	P<0.05
X1, X2,X3,(X1*X2), (X1*X3), (X2*X3)	99.96	26970.85 (6,40)	P<0.001
X1, X2, X3	99.86	12418.5 (3,46)	P<0.001

#n_1 and n_2 are the degrees of freedom of F statistic

Table 6.1. Multiple regression model results based on log transformed runoff, log transformed trend and non transformed seasonal and cyclical variations

Seasonal variation measured by seasonal index indicated up to what level, runoff is affected seasonally (Table 6.1). A seasonal index more than 100 indicated that runoff is increased by an amount equal to that of seasonal index in excess of 100 implying a positive effect of seasonal variation. Similarly, a seasonal index less than 100 implied that runoff is decreased by an amount equal to that of seasonal index in deficit of 100 implying a negative effect of seasonal variation on the runoff. If seasonal index for any month is 100%, then it implied that there is no effect of seasonal variation on the runoff. In this study, seasonal variation can explain only 31.32% of the variability in the runoff. Based on 1985-1989 data sets, seasonal effect is positive on the river runoff of June, July, August, October, November, February and March. For the rest of the months, seasonal effect is negative on the average. The observed runoff is mostly controlled by the trend effects of the optimal period determined.

Cyclical variation provided the period of repetition of the peak of minimal runoff. The period is unique with 12 months approximately (Fig. 2.12b). Cyclical variation could explain only <1% of the variations in the runoff. Hence, it can be stated that the observed runoff is mostly controlled by the trend effect and to some extent by the seasonal variations only. From the graph (Fig. 2.12b), it can be understood that the cycles present are removed along with the trend effect as the observed curve and the trend curves are almost exact. The observed cycles presented for the MA are of period 12 months.

In order to study the contribution of 2 period centered moving average alone on the river runoff, second order partial correlation coefficient using the non transformed data is computed which is 0.96 ($P<0.001$). Similarly, contribution of seasonal variation alone on the river runoff is also high with second order partial correlation coefficient as 0.93 ($P<0.001$). On the other hand, contribution of cyclical variation alone on the river runoff is not significant, 0.30 ($P>0.001$). Hence, river runoff is controlled by short term variations of period 2 months, but not by long term variations with periods >2months.

6.2.2 Salinity distribution

6.2.2.1 Annual variations

Figures (6.1 and 6.2) demonstrate how the stratification evolves in this system .Fig. 6.2 and 6.3 show the longitudinal section of salinity distribution in estuary during one year. With the onset of ISM on May 31, 2008, the mean runoff is 356m^3/s in June 2008 (Fig. 6.1a). As a result, oceanic salinities are confined to near-inlet stations (1, 5, and 6) and the river-end stations (2, 3, 8, and 9) are brackish. When the runoff peaks in July, the estuary transformed to a salt wedge type (Fig. 6.1b). Higher salinities (18-34) are found only in the bottom waters of stations 1, 5, and 6. The wedge formation is more prominent at stations 5 and 6 than station 1 which can be attributed to the greater depths of inlet 2. All the other stations remains well mixed with depth averaged salinity as low as 0.05 (Figs. 6.1b-6.1d).

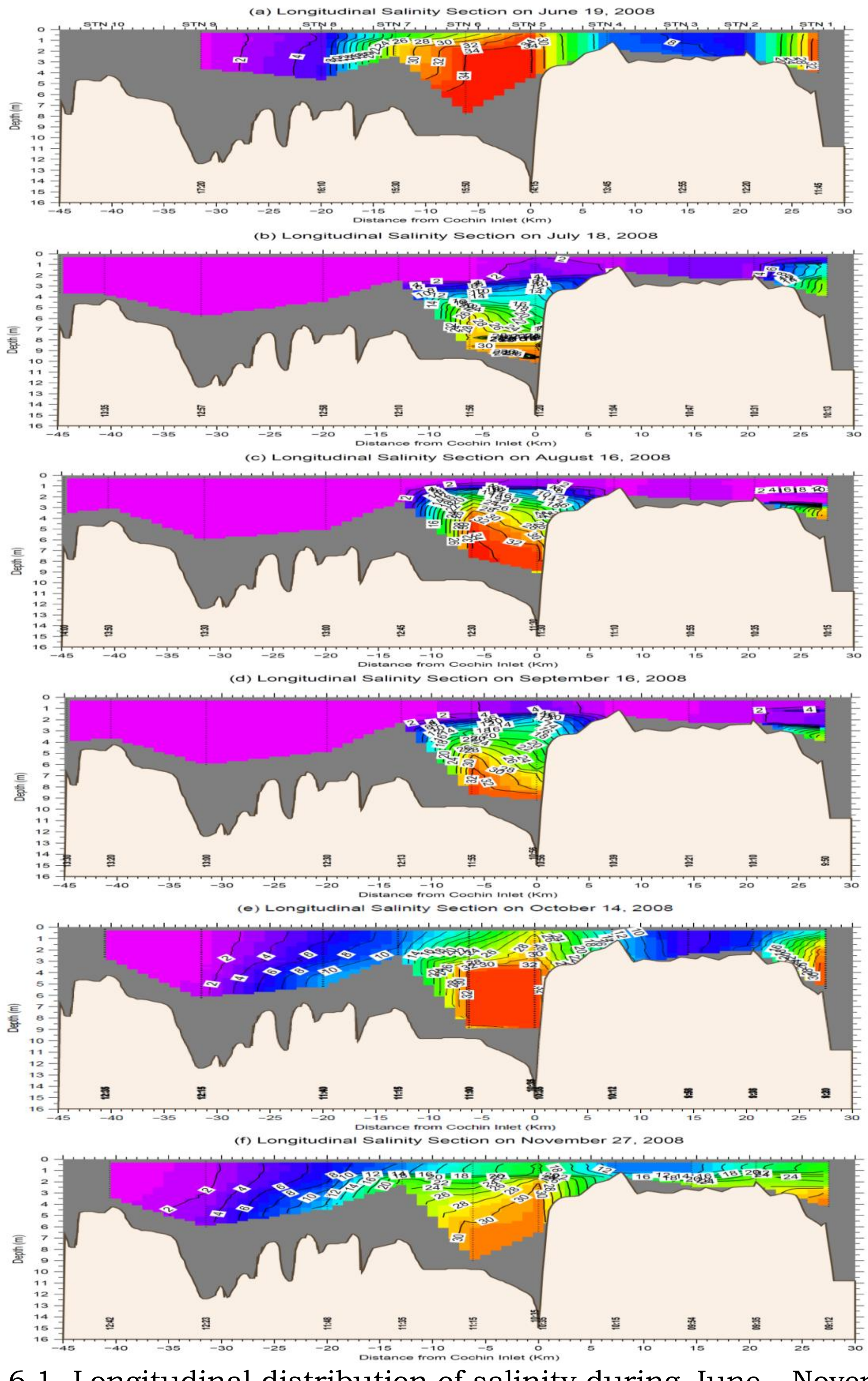

Fig. 6.1. Longitudinal distribution of salinity during June - November 2008. The Cochin inlet is at the coordinate origin. The northern / southern arm stations are at positive /negative distances, respectively. Times of each station appear along the lower x-axis.

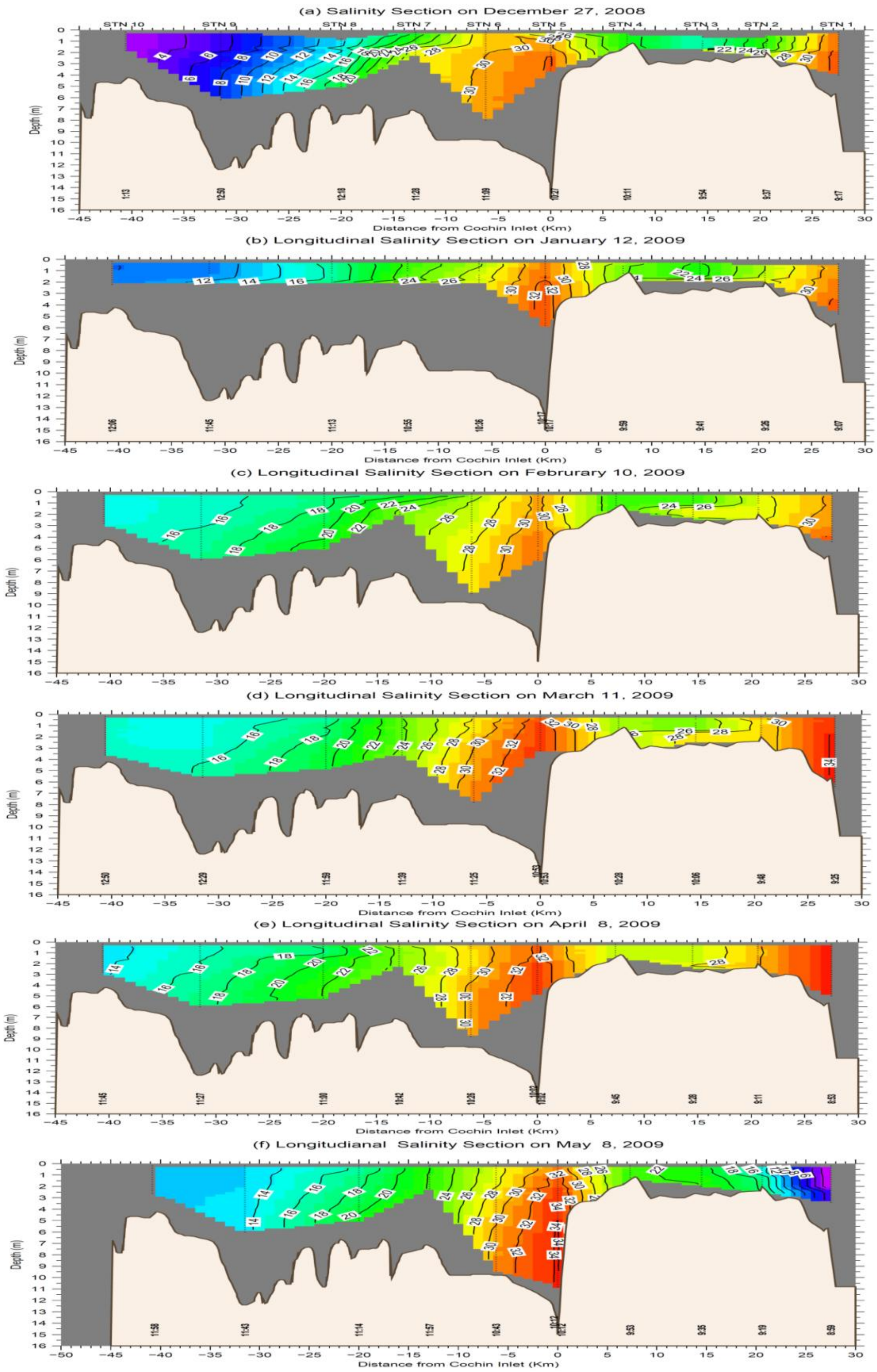

Fig. 6.2. Longitudinal distribution of salinity during December 2008, to May 2009. The Cochin inlet is at the coordinate origin. The northern / southern arm stations are at positive /negative distances, respectively. Times of each station appear along the lower x-axis.

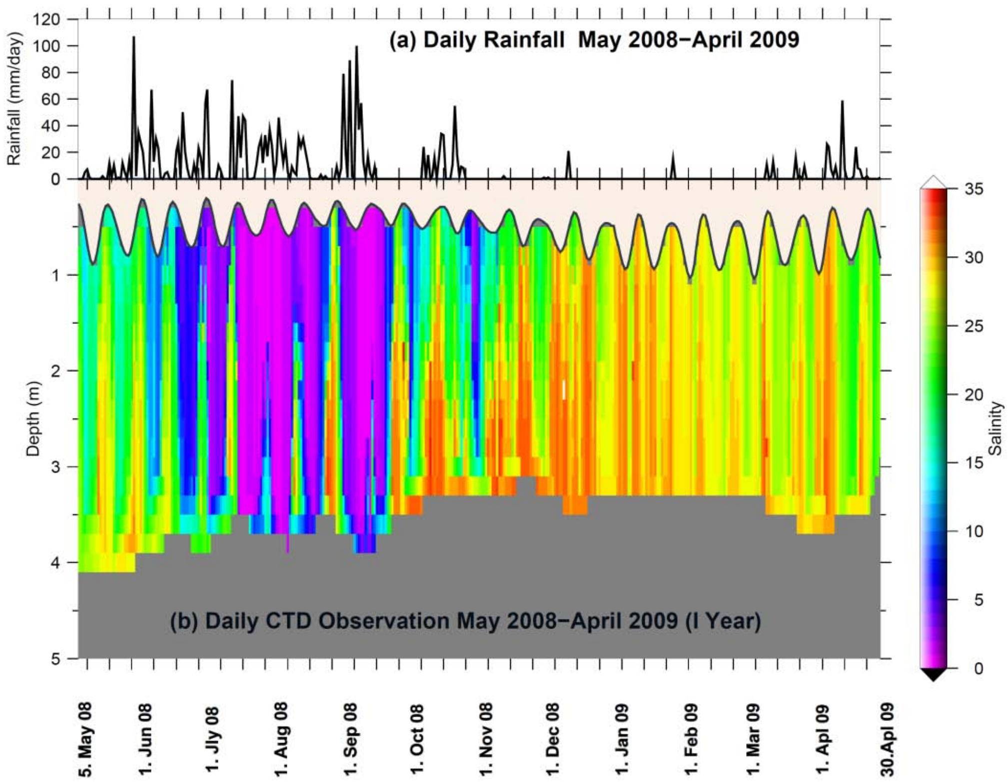

Fig. 6.3.(a) The daily rainfall pattern (May 2008-June 2009). (b) The daily salinity pattern of the station situated 5km away from Cochin Inlet.

By October 2008, the salinity field expansion is established (Fig. 6.1e). From October to December, the runoff is moderate (on average 260m^3/s) and an accumulation of fresh water is observed only at the upstream regions (stations 8, 9, 10). However, during the dry period, the river runoff decreased remarkably such that only 49m^3/s occurred in March. Under limited river flows, the estuarine water column actively mixed and tended towards extremely low horizontal and vertical salinity gradients (Fig. 6.2b-6.2f). The salinity field extended up to station 10 with maximum depth averaged salinity (15.12) attained in March (Fig.6.2d). In May, there is a slight increase in runoff to 2.5% of the annual runoff. The aftermath of an anomalous rainfall in the catchment of Periyar caused station 1 at the inlet 1 to be fresh water dominated (Fig. 6.2f).

6.2.2.2 Daily variations

Figure 6 depicts the daily salinity variations allowing to verify whether the daily rainfall modifies the salinity pattern of the station significantly. The daily rainfall pattern (Fig. 6.3a) is characterised by spikes of high rainfall during the active spells of ISM and NEM. During the ISM, strong spate occurs in July proceeding to the beginning of August too. Fresh water salinities occur for most of the time. Occasionally, high saline waters are also observed at the bottom due to the intrusion of salt wedge. By the end of August, there is a lull in monsoon resulting in intrusion of high saline waters (Fig. 6.3b). Consequently, a single vertical profile of salinity ranging from 25 to 35 is noticed. Again by the second week of September, the monsoon regains its strength causing freshening at the station. The same conditions are again observed only by the end of October–November characterised by NEM. In contrast, during the rest of the year, high saline conditions (23-35) prevailed at the station. However small peaks in rainfall are sighted in April and May which can't however, bring any effect on the salinity of that station.

6.2.3 Estuarine classifications based on hydrodynamics and runoff

6.2.3.1 Hansen and Rattray characterization

Hansen and Rattray (1966) developed a two-parameter system of estuarine classification in which the classes are delineated by the magnitudes of the relative stratification and circulation parameters associated with changes in the salt balance mechanism. The diagrams represent $\partial S/S_0$, where ∂S is the difference in salinity between surface and bottom and S_0 is the depth mean salinity, both averaged over a tidal cycle, as the ordinate. The circulation parameter U_s/U_f , where U_s is the surface velocity averaged over a tidal cycle and U_f is the discharge velocity, that is the rate of river discharge divided by the cross-sectional area, defines the abscissa. In this study these parameters are calculated from the time series observations. The parameters are then plotted in the relevant portion of the stratification-circulation diagram for three runoff conditions (Fig. 6.4).

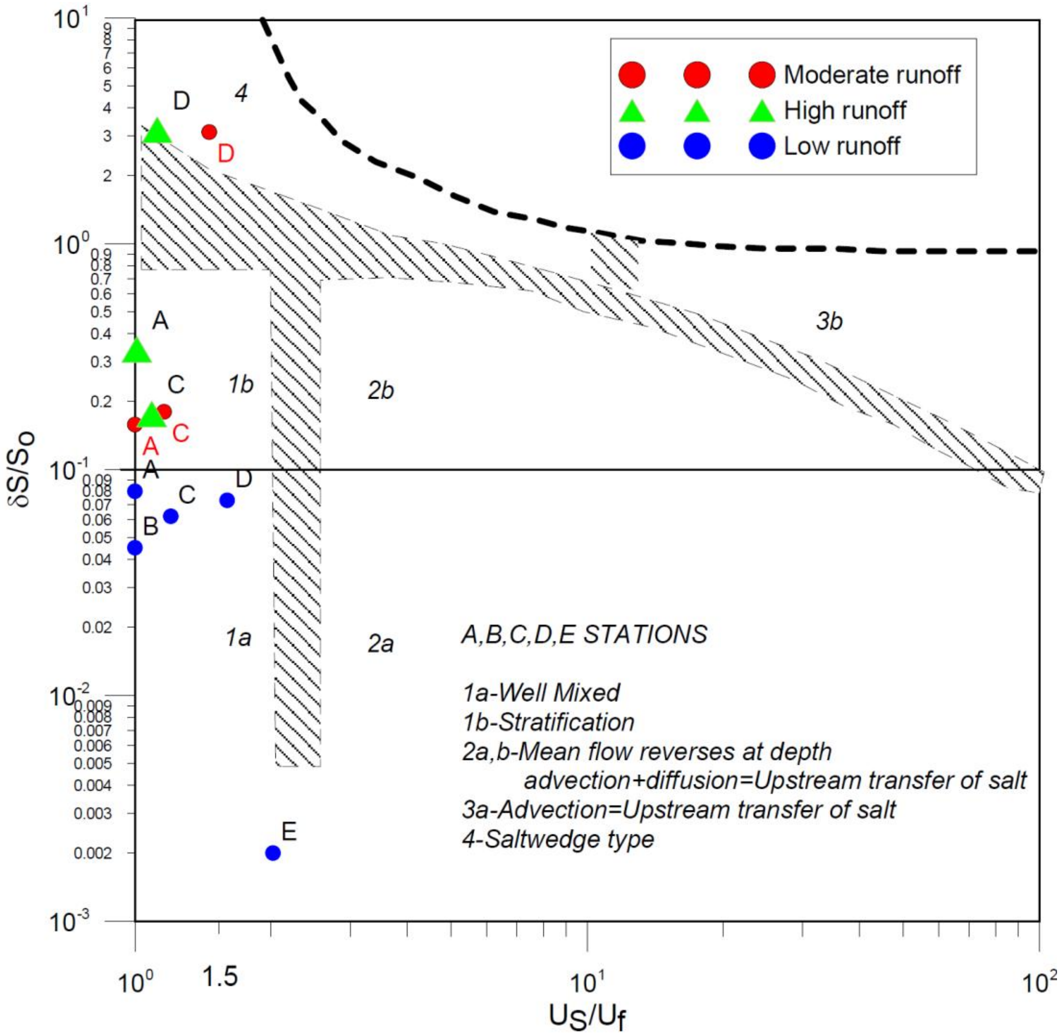

Fig. 6.4. Hansen –Rattrey classification diagram for Cochin Estuary.

The Fig. 6.4 shows reasonable agreement with the longitudinal monthly salinity observations discussed above. For high and moderate runoff months, the estuary exhibited similar characteristics. High $\partial S/S_0$ values are found at station (C) near inlet 2 tending them to fall in class “1b (stratified)” of the classification diagram. Station D occupied class "4" in the diagram suggesting a salt wedge type. This is because of the depth of station C so that the salt wedge thickness is higher reaching almost the surface. However, the wedge tapered towards station D allowing more freshwater to flow over it. Recorded U_s/U_f values are above 1 for all stations. Station B in the middle of the northern arm and upstream station E are fresh water dominated. In contrast, during the dry period, the system is well-mixed (classes "1a"). Whereas the values of $\partial S/S_0$ are below 0.1, U_s/U_f ratio is almost 1. This indicates an upstream transfer of salt by diffusion.

6.2.4 Uniqueness of Cochin estuary among monsoonal estuaries

Vijith *et al.*, (2009) state that estuaries that come under the influence of Indian Summer Monsoon (ISM) and for which the salinity is never in a steady state at any time of the year are generally shallow and convergent, i.e. the width decreases rapidly from mouth to head. In contrast, Cochin estuary is having a widespread area at the upstream and has no typical river mouth entrance (as discussed under section 1.1). Adding to the complexity it has dual inlets and the tidal range is 1 m which is lower than other Indian estuaries along west coast. These typical physical features lead to its uniqueness.

Vijith *et al.*, (2009) had documented that the monsoonal estuaries experience total annual runoff which is many times of the estuarine volume and that there is a high "peakiness" or seasonality in the runoff. They used the following equations to represent the above two features:

$$\eta_R = \frac{R_a}{V_e} \qquad (23)$$

where, R_a is the volume of total annual runoff (m^3) and V_e is the volume (m^3) with respect to mean sea level in the estuary. Higher the value of η_R, higher is the runoff. η_R is calculated as 42 for the Cochin estuary indicating the chance that the estuary turns 'fresh' 42 times(s)/year.

The equation for second parameter is

$$\eta_T = \frac{Maximum\ \ Monthly\ runoff}{Mean\ \ Monthly\ \ runoff} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

Fig. 6.5a shows the mean monthly runoff to monsoonal estuaries in India (Vijith *et al.*, 2009). It can be plainly understood that while the runoff into other estuaries average to zero for about eight month-long dry season, the average runoff into Cochin estuary is never zero. A steady runoff is maintained even during the peak low runoff period $\eta_T \sim 1$.

To zoom in the dynamics of the estuary, this study reduce the above mentioned parameters into monthly scale. This will provide means to examine the seasonal variations in runoff.

The above classification parameters redefine as written below:

$$Z_R = \frac{R_m}{V_e} \ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

$$Z_T = \frac{Total\ \ of\ \ the\ maximum\ \ among\ \ daily\ \ runoff\ \ of\ \ all\ rivers\ \ in\ a\ month}{Total\ \ of\ mean\ \ Daily\ \ runoff\ \ of\ \ all\ rivers\ \ in\ a\ month} \ldots\ldots \quad (26)$$

Where R_m is the volume of total monthly runoff (m^3) and V_e is the volume (m^3) with respect to mean sea level in the system. R_m is computed from daily runoff**.** Z_T represents the daily variations in runoff. The computed values are presented in Fig. 6.5b.

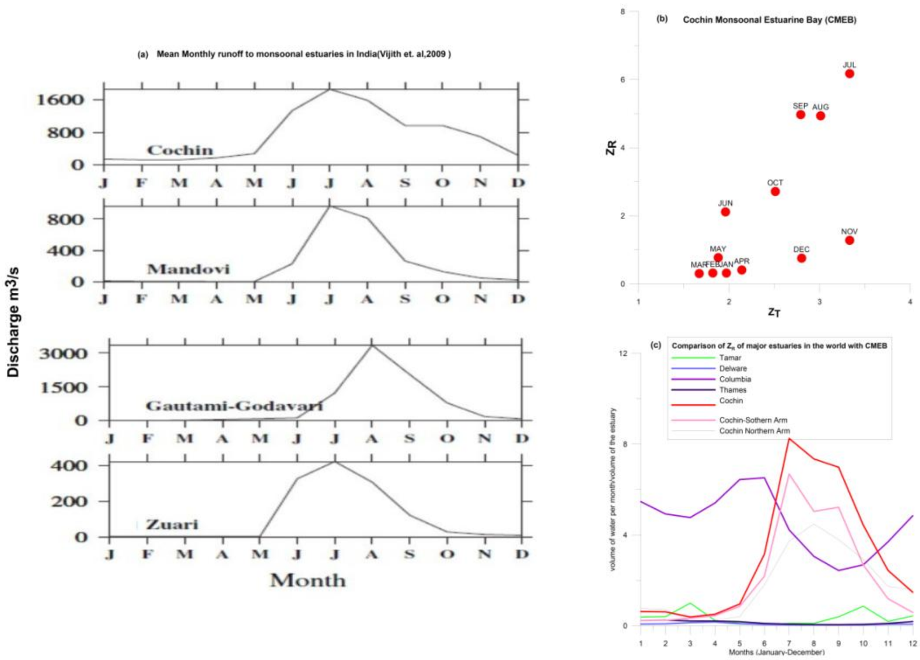

Fig. 6.5. (a) Monthly mean runoff to monsoonal estuaries in India. (b)Positions of each month of Cochin estuary on the (Z_R, Z_T) plane.(c)comparison of Z_R with major estuaries in the world.

During June Z_R is 2.06 when ISM is in the progressing stage whereas for the rest of the months of wet season Z_R >5. The observed maximum monthly runoff of wet season is 3.606×10^9 m^3 in July. For the moderate runoff months (October -December), the values are $1< Z_R<4$ and $1< Z_T<3$ (Fig. 6.5b). From January-April, Z_R is about 0.3 and Z_T is almost 2. This indicates that although there are prominent daily runoff variations, for no single day of each month during the period, the runoff can flush the estuary. For it to occur, the runoff obtained should exceed to above 70% of the estuarine volume. During May, the runoff is higher which completed the annual cycle with Z_R and Z_T showing 0.8 and 2 respectively.

6.2.4.1 Comparison of Z_R of other estuaries with Cochin estuary

Fig. 6.5c, shows the Z_R values of Cochin estuary with other estuaries in the world. The analysis shows that Z_R is an order of less than one for Tamar, Delaware, and Thames estuaries for all months and the standard deviation is 0.3. In the case of Columbia estuary, Z_R values are more or less comparable with Cochin estuary with the standard deviation 1.3. However, the peak runoff in attained by Columbia in June is 6.5 which is less than that of Cochin estuary by 2. For estuary, the peak in July with a value of 8.5 is featured by ISM. The influence of NEM on flushing of the estuary is negligible. The minimum Z_R of 0.3 occurred during peak low runoff condition. The high standard deviation of 3.0 obtained for Cochin estuary suggested that the runoff exhibited large range of values over the months compared to all other estuaries.

To explore the flushing nature more closely, Z_R for the two arms of estuary are calculated separately (Fig. 6.5c). It is found that, for July, with the Periyar River runoff in the northern arm Z_R ratio is 3.7. The runoff from all the other rivers is responsible for Z_R to go as high as 6.7 in the southern arm. The volume of southern arm is about 5 times larger than the northern arm. Notwithstanding this fact, the runoff into the south flushed the volume of the southern arm almost twice as that of northern arm. During August, the lull in monsoon (about 200 m^3/s decrease from July) is characterised by an increase in runoff in the northern arm and a decrease in runoff into the southern arm. Consequently, an equal flushing of both arms (Z_R~5 in both the arms) resulted in transforming the estuary into a river. This implies that the uniform flushing of all the sections of the estuary could not be directly related to the 'peakiness' of monsoonal spell and the subsequent runoff.

6.2.5 Cochin estuary in a quasi-steady state

Implicit in several estuarine classification schemes commonly used for understanding estuarine dynamics is a steady state assumption. By the term "steady state"' is meant that the average of the salinity concentration over a tidal cycle does not change from tide to tide if the river runoff remains constant (Stommel 1953). In such cases, during each tidal cycle the salinity at any location varies with the stage of the tide, but on successively similar tidal stages the salinity returns to substantially the same value (Ketchum *et al.*, 1951). In the Cochin estuary, such a steady state can be expected during the least runoff period (January-April). In order to establish this fact, the study uses the salt balance equations to determine the salinity steadiness in the Cochin estuary.

The general unsteady salt balance is given by:

$$\frac{\partial}{\partial t}\int_{x}^{x_r} S_{(x)}A_{(x)}dx + RS = K_{unst}A\frac{\partial S}{\partial x} \quad \text{...(27)}$$

where $S_{(x)}$ is the salinity integrated over the volume of the estuary, and A is the cross sectional area, R is the river runoff, S is the average salinity. K_{unst} is the unsteady horizontal diffusion coefficient computed in the axial direction from x until the upstream location x_r. With the steady state assumption, the time dependent term of equation (27) vanishes. The equation can then be re-written as:

$$RS = K_{st}A\frac{\partial S}{\partial x} \quad \text{...(28)}$$

K_{st} is the horizontal diffusion coefficient under equilibrium (steady state) conditions.

If the estuary is in a steady state, the total salt content of the estuary does not change, so the same volume *R* will have to leave the estuary at its mouth during one tidal cycle. Thus, by comparing K_{unst} with K_{st}, the steadiness of the salt balance can be diagnosed roughly. Dividing equation (27) by (28), the ratio of K_{unst} to K_{st} can be obtained as:

$$\frac{K_{unst}}{K_{st}} = \frac{\frac{\partial}{\partial t}\int_{x}^{x_r} S_{(x)}A_{(x)}dx}{RS} + 1 \quad \text{.. (29)}$$

$= \Phi + 1$ ....(30)

The steadiness of the salt balance is diagnosed for the months, January-April, when Φ is continuously > 0. The integral term in equation (29) is estimated using longitudinal salinity measurements (Figs. 6.2-6.3) from x to the upstream location x_r for two consecutive months. The averages of salinity S and runoff R for these two months are used. The ratios are computed for all sections from x (station 1) to x_r (station 10).

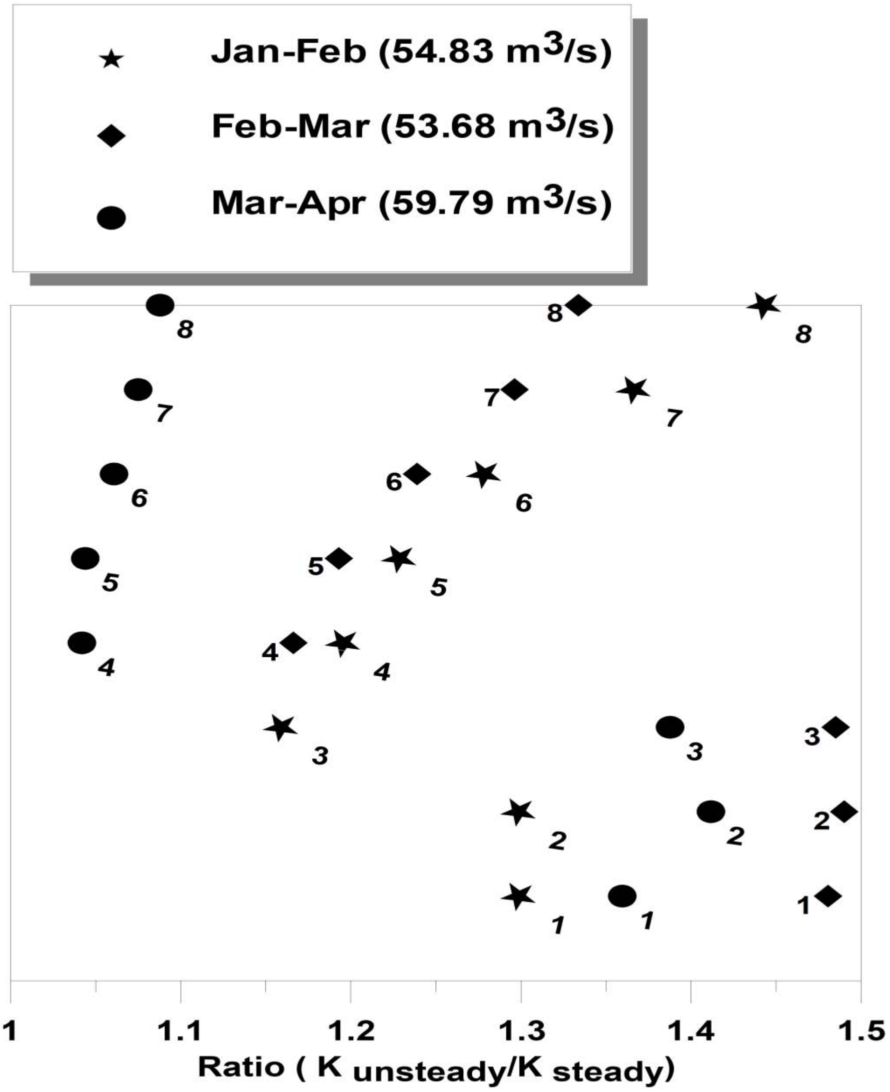

Fig. 6.6. The ratios of $K_{unsteady}$ to K_{steady} calculated as shown in equation (29).

The analyses prove that the ratios approached 1 most of the time throughout the estuary. Occasionally, a maximum value of 1.5 is also obtained (Fig. 6.6). This is possible only if suggesting a steady state or rarely a quasi-steady state. The total salt content remains constant for the peak dry period. The period from March to April is in an acute steady state even at the upstream. Specifically, along sections from stations 5 to 7, the balance is better achieved than the other locations. This is possible as Muvattupuzha joins between the regions which supply a constant runoff. It is the only river that causes freshening in the southern arm during the period. The upstream salt flux is balanced by this runoff induced oceanward advective flux asserting a steadiness in salt balance.

Fig. 6.7 illustrates the water level and salinity variations over a tidal cycle at five stations during February 2010. In each case the salinity at successive high tides returned to the value previously observed approximately. Therefore, Hansen Rattray classification holds well for this particular steady state of the estuary. Whatever be the runoff occurred during the period, it is not sufficient to bring the salinity at the upstream to zero. This typical feature is due to the diverging geometry of the estuarine channel unlike other Indian estuaries such as Mandovi and Zuari channels which are strongly convergent at the upstream regions (Manoj *et al.*, 2009). For the Mandovi and Zuari, although the tidal flushing times are in the order of days during the low runoff, so much of freshwater remains available at the upstream and these systems always lag behind steady state (Vijith *et al.*, 2009).

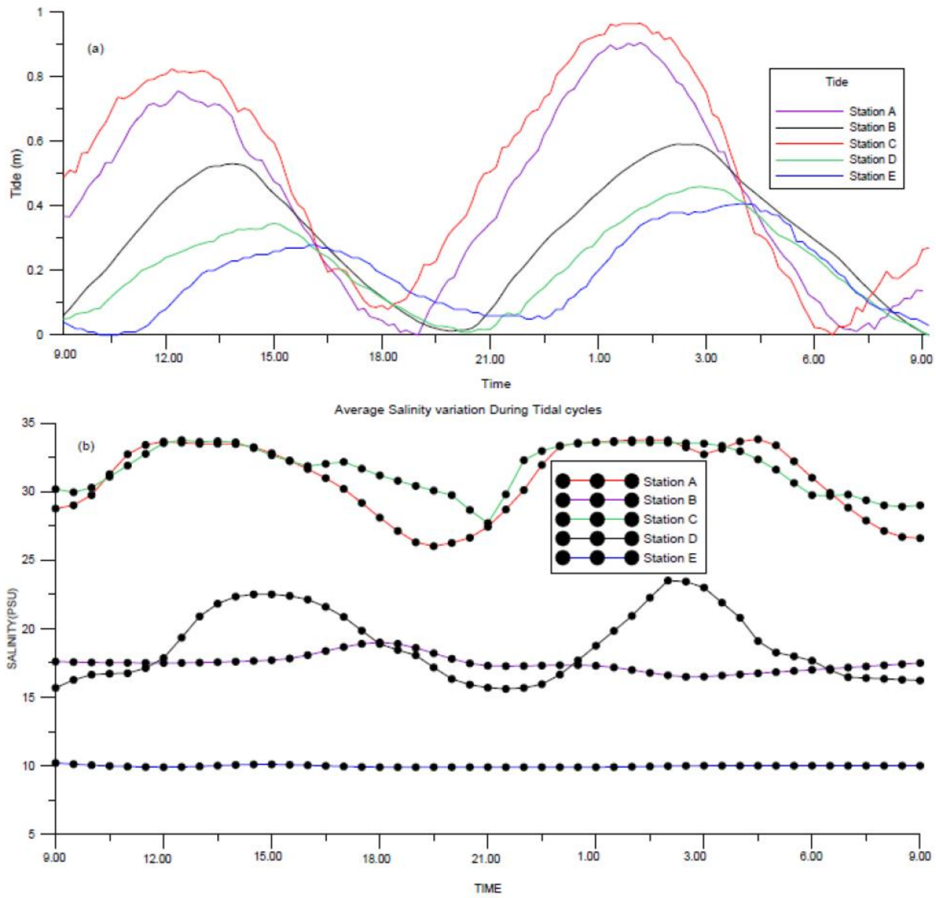

Fig. 6.7. Average salinity variations during a tidal cycle from monthly time series stations during the low runoff period.

The steadiness in salinity during low runoff period is even reflected in the abundance of zooplankton species which showed little variations during tidal cycles (Mathupratap *et al.*, 1977). They had opined that these species appear to develop behavioural mechanisms in response to tidal changes which keep it in the water of same salinity throughout the tidal cycle by having some kind of biological clock or signal. So, this study concludes that estuary is in a steady state for some time during a year and deserves to be placed under a ‘special’ category among the monsoonal estuaries.

6.2.6. The Physical-biological coupling

Cochin estuary is one of the largest productive ecosystems along west coast of India with an estimated annual gross production of nearly 300gC/m2 (Qasim *et al* l969). Its bioceonosis can be recognized as a physically controlled community. It may be called as a "tropical monsoonal estuary" due to the pronounced influence of monsoon on the ecology of the system bringing about a total change in the environment and fauna (Madhupratap *et al.*, 1977). In such estuaries, the seasonality in salinity is a key feature as the ecosystems have to adjust accordingly. Cochin estuary is more productive at all levels during dry season. The salinity gradient during the period favoured large species richness, species diversity and species evenness in zooplankton (Jyothibabu *et al.*, 2006). Whereas in monsoon, the abundance of phytoplankton grazers (zooplankton) is reduced and this altered the trophic food web of the estuary resulting in substantial amount of unconsumed carbon at primary level (Madhu *et al.*, 2010). A qualitative shift in phytoplankton composition (Qasim, 2003) and an increase in its biomass owing to high residence times (Shivaprasad *et al.*, 2012) were also reported during peak low runoff conditions. In essence, the low runoff period provides a biotope supporting the survival of various high species as competitors, expanding their overlapping niches in space with time because of the facility provided by salinity intrusion. The impact of monsoonal effluxes and high flushing evokes its elimination and an 'essential' cleanup of the estuary.

6.2.7 A new nomenclature: Cochin Monsoonal Estuarine Bay

There are several ways in which Cochin estuary was named in earlier studies. The estuary is sometimes called as a "lagoon" (Rao and Balasubramaniam., 1996); or very often referred to as "backwaters" (Sankaranarayanan and Qasim., 1969, Martin *et al.*, 2008, Abhilash *et al.*, 2012). Lagoons are shallow body of water at least intermittently connected with sea or other larger body of water across a beach or barrier (Snead 1982). Cochin estuary is permanently open to sea and is much larger and deeper than a typical lagoon. The Webster dictionary defines 'backwaters' as part of river water backed up in its course by an obstruction, an opposing current, or the tide. Being an extraordinarily energetic and dynamic environment typified by strong tidal currents (1.3m/s) (Udaya Varma *et al.*, 1981, Balachandran *et al.*, 2008), the nomenclature 'backwaters' remains subtle to this estuary.

The present analyses manifests that the assumptions implicit in the classification schemes discussed above limits their applicability to Cochin estuary. There arises a need for a comprehensive classification representing all the dominant conditions of the estuary. Such an approach is suggested by Whitefield (1992) for African estuaries using a combination of physiographic, hydrographic and salinity features. According to him, estuarine bays are estuaries that may be either natural or partly artificial due to dredging activities in the mouth and harbour region. They have a large tidal prism exceeding 10x106 m3 and tides are the dominant force driving mixing of water column. The salinity ranges from 20-35 and near marine conditions may extend even to the upper reaches.

Cochin estuarine system is partly artificial due to the anthropogenic activities like land reclamations (Gopalan *et al.*, 1983) and dredging at inlet 2 (Balchand and Rasheed 2000), frequently modifying its geomorphology. Also, the tidal prism of Cochin inlet is estimated at 107.8 x 106m3 during ISM, 18.6 x 106 m3 during moderate runoff months (October to December) and 31.5 x 106m3 during the dry season (Rama Raju *et al.*, 1979). The salinity conditions of a bay are found in the lower reaches only during low runoff period. Meanwhile, the maximum salinity observed at the upstream is never greater than 15. Hence, a salinity gradient from mouth to head persists throughout the low runoff period. Peak monsoonal spells and runoff may entirely change the estuary from an estuarine bay to a riverine system. This transformation plays a fundamental role in the ecology of the system. Thus, 'Monsoonal Estuarine Bay' seems to be an appropriate name for this estuary.

6.3 Discussion

The runoff into estuary is never zero at any time of the year. It is a unique divergent estuary with a widespread area at the upstream. During the wet season and moderate runoff months, the salinity field is extremely sensitive to the drastic variations in river runoff even on daily time scales. Saline water creeps in slowly during moderate runoff months, but then persists unabatedly in the following peak low runoff condition. During least low runoff period, the salinity values are high throughout the system with a gradient from mouth to head and the variations in runoff is slow. The lower reaches behave like an extension of the coastal waters and salinity ranging from 10-12 is observed at the upstream and the water column is well mixed. The runoff that enters is only 30% of the estuarine volume so that zero salinity is never attained at the upstream. The 'little but constant' runoff is mainly contributed by Muvattupuzha River flowing into southern arm which is not sufficient to flush the large upstream volume.

Fluctuations in the estuary are of extreme nature with regard to salinity. The new terminology 'Monsoonal Estuarine Bay' encapsulates the salinity gradient of the Cochin estuary ranging from completely riverine to completely saline. The term 'Monsoonal' succinctly describes the unsteadiness of salinity of wet season. The possibility of the estuary turning to a river cannot be ruled out. 'Bay' conditions are accomplished during peak low runoff condition when the estuary is in a steady state with little constant runoff. During the rest of the year, the system behaves only as a true estuary. The gist of the previous studies is that the ecosystem and ecology respond well to this varying salinity and environment.

Chapter 7

Summary and Conclusion

The thesis elaborates tide and river runoff interactions in the Cochin estuary through a series of measurements covering the following topics: **I**) the influence of river runoff on tidal propagation using observations and a numerical model **ii**) stratification and property distributions **iii**) salinity distributions and flushing characteristics **iv)** influence of TB (salt water barrage) on tides and salinity, and **v**) Evaluation of classification schemes for the estuary.

This study uses a one dimensional network numerical model of tide and river runoff together with observational data to understand the influence of river runoff on tidal propagation in this dual opened complex estuarine network. The model results are in agreement with the observed field data. The model could skilfully reproduce the observed temporal and spatial variability in tidal elevations during different runoff regimes. The river runoff is found to play a major role in the rapid decay of tidal amplitudes toward the upstream regions during the high runoff periods. The downstream velocity of river runoff during this period is sufficiently large enough to decay the tidal amplitudes toward the upstream regions whereas, during the low runoff periods the frictional effect is more dominant than the river runoff as evidenced from the simulations of tides. Tidal amplitudes remain unchanged from Arookutty to Makayilkadavu during low river runoff indicating that the geometric amplification balances the frictional decay. But this balance breaks down in this region when the runoff increases during the high runoff period. However the runoff does not have much influence on the decay of the tide even in the high runoff in the northern arm.

This study analyzes the stratification considering salinity as the major factor. Salinity fluctuates at different timescales, including intratidal, fortnightly of spring and neap tidal cycle, and seasonal (high runoff and low runoff periods). The tides and river runoff forcing stratification is quantified using potential energy anomaly and stratification parameter. The intra-tidal variations in stratification are greatly governed by the tidal characteristics like flooding-ebbing, diurnal inequality and tidal range. The spring-neap cycles of stabilization and destabilization of water column are prominent in low runoff than high runoff. Partially mixed (neap) and well-mixed (spring) state during low runoff are altered during high runoff when the salt wedge induces periodic stratification. During both tidal phases of high runoff, the salinity stratification in water column is associated with advection of salt wedge during high tide. During high runoff, entire estuary becomes dominant in fresh water of salinity ~0.05. During low tides and LHW, the pycnocline becomes unstable and the saline wedge disappears. The observations establish a strong connection with the distribution of chemical and biological properties. The ecological impact of salt wedge propagation on high tides bringing upwelled water to the system is evident from the bottom hypoxic, high chlorophyll a and nutrient-rich conditions. The strong ebb regime, LHW and high flushing arrested the salt wedge enhancing complete vertical mixing with well oxygenated fresh water in the estuary. The periodic advance and retreat of the salt wedge is inevitable in making the system immune from extended hypoxia/anoxia and maintaining the health of Cochin estuary.

Results are presented from the longitudinal transects measurements of salinity profiles made throughout the length of the Cochin Estuary during a 1-year period, that experience varying runoff conditions. For the seasonally varying river runoff in the estuary, salt intrusion receded with increasing river flow in monsoon and rebounds with decreasing river flow in dry season. During monsoon, the intense flushing and reduction in salinity field expansion are seen. The estuary loses about 48% of its salt from June to July due to high spells of monsoon and a successive gain about 9% in later months. As the runoff slackens, the increase in total salt content of the estuary is well noticed. As a result of peak low runoff (Jan-April) the salt content increases steadily despite the variations in runoff. During the peak runoff (July) the flushing time is 2.8 days when the runoff is 1008 m^3s^{-1}. In low run off (April), there is 1.4% runoff and the flushing time is 13 days. The intense flushing and reduction in salinity field expansion during high runoff seen to be responsible for the limited chlorophyll *a* levels along the surface of Cochin estuary.

The study reveals the influence of TB on the hydrodynamics of the southern arm of the estuary. It shows that the closure of the barrage causes amplification of tides in the immediate vicinity of TB and up to 10 km farther downstream. Harmonic analysis is performed to understand this aspect, in detail, and to quantify the amplification of tidal signals during the 'closed period' and the 'if open' period. The analysis shows that diurnal and semi-diurnal tidal bands got amplified by a factor of 2.6 and 1.6 times at the upstream when TB was kept closed. The strong amplification signatures of the above two bands are also seen at 10 km farther downstream. The flood and ebb-dominance are analysed by the phase relationship between the M_2 and M_4 constituents, which shows that when barrage is closed, the northern region of TB transforms from ebb dominant system into a flood dominant system. During high runoff period, the barrage is opened and salinity intrusion is dependent on river discharge. During dry period, the reduction in river flow compounded with the closure of barrage results in the increase of salinity downstream. An attempt is also made to investigate the residence time of Cochin estuary for different river runoff conditions. This enables in assessing the hydrodynamic controls on phytoplankton biomass. Higher surface chlorophyll *a* levels are observed at higher salinity during the barrage closed period and the residence time is 4 days during this period.

To conclude, rigorous investigation using comprehensive data sets are made so that the estuary is classified into the most appropriate category which it deserves. The statistical analysis performed on river run off data proves that the analysis made in this study using the 2008-2009 runoff data can be generalised, hence the various results during this period also can be generalised. The river runoff is controlled by short term variations of period 2 months, but not by long term variations with periods >2months. Daily monitoring of salinity allow to verify whether the rainfall modifies the salinity pattern of the station significantly. The daily rainfall pattern is characterised by spikes of high rainfall during the active spells of ISM and NEM. During the ISM, strong spate occurred in July proceeding to the beginning of August too. Fresh water occur for most of the time. Occasionally, high saline waters are also observed at the bottom due to the intrusion of salt wedge.

Hansen –Rattray characterisation shows this estuary changes from one type to another in high runoff to low runoff and from one location to another location within the estuary. This estuary is unique in its own way among the Indian estuaries. For most of the Indian estuaries that come under the influence of Indian Summer Monsoon (ISM), the salinity is never in a steady state and the upstream end is with zero salinity at any time of the year. They are generally shallow and convergent. In contrast, Cochin estuary is having a widespread area at the upstream and has no typical river mouth entrance. Adding to the complexity, it has dual inlets and the tidal range is 1 m which is lower than other Indian estuaries along west coast. These typical physical features lead to its uniqueness .This system experience total annual runoff which is many times of the estuarine volume and that there is a high "peakiness" or seasonality in the runoff Cochin estuary indicating the chance that the estuary turns 'fresh' 42 times(s)/year.The runoff to volume ratio is 3.7 for July, with the Periyar River runoff in the northern arm. The runoff from all the other rivers is responsible for ratio to go as high as 6.7 in the southern arm. This implies that the uniform flushing of two arms of the estuary can't be directly related to the 'peakiness' of monsoonal spell and the subsequent runoff. In Cochin estuary, a steady state of salinity found during the peak of low runoff period (January-April). In order to establish the salinity steadiness in the Cochin estuary, the study uses the salt balance equations. This shows that the upstream salt flux is balanced by the runoff induced oceanward advective flux asserting a steadiness in salt balance. Unlike other monsoonal estuaries, whatever be the runoff occurring during the period, is not sufficient to bring the salinity at the upstream to zero. These typical features lead to consider Cochin estuary as a special category among the Indian estuaries.

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Hydrology and Earth System Sciences

Seasonal stratification and property distributions in a tropical estuary (Cochin estuary, west coast, India)

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Abstract. The intratidal, spring–neap and seasonal variations in stratification were examined in the Cochin estuary. The observations established a strong connection with the distribution of chemical and biological properties. The influence of tides and river discharge forcing in water column stability was quantified using potential energy anomaly (PEA) and stratification parameter. Partially mixed (neap) and well-mixed (spring) conditions during low river discharge (dry) period were altered in monsoon by the salt wedge intrusions. The ecological impact of salt wedge propagation on high tides bringing upwelled water to the system was evident from the bottom hypoxic, high chlorophyll *a* and nutrient-rich conditions. Phosphate and nitrite concentrations were higher at the bottom saline conditions but silicate and nitrate were clearly supplied by river water. However, during ebb tide this front was driven out of the estuary. The periodic advance and retreat of the salt wedge was inevitable in making the system immune from extended hypoxia/anoxia and maintaining the health of the Cochin estuary. For the seasonally varying river flow in the estuary, salt intrusion receded with increasing river flow in monsoon and rebounded with decreasing river flow in dry season. During monsoon, the intense flushing and reduction in salinity field expansion seemed to be responsible for the limited chlorophyll *a* levels along the surface of the Cochin estuary.

1 Introduction

The key to understanding stratification and de-stratification processes in different time scales (intra-tidal, spring–neap, seasonal) has gained the most attention during the last decades due to its tremendous relevance to the estuarine ecosystem. Estuaries can be classified into three types based on their longitudinal salinity distribution: partially mixed, vertically homogeneous or well-mixed, and highly stratified or salt wedge type (Dyer, 1973). The type of the estuary essentially depends on the river discharge and tidal regime, which have pronounced effects on the distributions of several physical, chemical, and biotic processes within the estuary. The differential advection of salinity creates stratification, which in turn inhibits vertical mixing of momentum. With the increase in turbulent energy, stratification is reduced by mixing directly and indirectly by reduced shear (Nepf and Geyer, 1996). Stratification diminishes vertical fluxes of ecologically important variables (Uncles et al., 1990) like heat, salt, oxygen and nutrients. Physical dynamics play a critical role in estuarine biological production, material transport and water quality (Kasai et al., 2010).

The Cochin estuary is the largest among many extensive estuarine systems along the southwest coast of India. It has been identified as one of the most productive estuarine systems along the west coast of India by Menon et al. (2000). However, due to anthropogenic interventions, the Cochin estuary has been reported to be on the brink of an ecological disaster by Dinesh Kumar et al. (1994). Further, the sediment heavy metal contamination of this estuary has placed the region among the impacted estuaries in the world (Balachandran et al., 2005). The runoff components like municipal waste discharge from the surrounding city and riverine water carrying industrial and agricultural wastes are responsible for nutrient enrichment influencing the estuarine water quality (Joseph and Ouseph, 2010).

Numerous studies reveal the dynamics of the energetic environment of the Cochin estuary. Tides in the Cochin estuary are of mixed semidiurnal type with an average tidal range

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of 1m (Qasim and Gopinathan, 1969). According to Srinivas et al. (2003b), the relative importance of the semidiurnal and the diurnal components keeps changing throughout the month. Spring phase is dominated by semidiurnal tides and neap phase by diurnal tides. There is a rapid decay in the amplitudes of the principal tidal constituents as they propagate upstream. However, tidal amplification has been observed in the south estuary during pre-monsoon season (March), which is possibly caused by the closure of the hydraulic barrier at Thanneermukkom (upstream) (Balachandran et al., 2008). In the Cochin estuary, currents are dominated by tidal signals; semidiurnal tidal regimes experience swifter tidal currents than diurnal tidal regimes (Srinivas et al., 2003a). Balachandran et al. (2008), with the help of a model, showed that strong currents prevail at the central estuary (from Cochin inlet to 22 km south) whereas weak and slow currents are found in the north and south estuary. The strong ebb velocity of about 130 cm s^{-1} at the Cochin inlet (Udaya Varma et al., 1981), which is comprised in the central estuary, maintains an effective flushing through the channel in this region (Balachandran et al., 2008).

For an ecological study, an interdisciplinary approach linking the physical phenomena with chemical and biological properties is essential, and for the Cochin estuary this study is first of its kind.The physical processes (stratification, horizontal and vertical advection, flushing, etc.) that govern the ecological parameters have not been rigorously investigated in the region to date. For the efficient implementation of estuarine management plans, an imperative study of the impact of stratified systems on water quality and ecosystem ecology is essential. The objective of the present study is to assess (1) the intratidal and spring–neap variations in stratification of water column in dry and wet seasons, and (2) the horizontal extent of salt intrusion and the relation between salinity and property distributions.

1.1 Geomorphology

The Cochin estuary is the largest among many extensive estuarine systems along the southwest coast of India. It extends from Munambam (10°10′ N, 76°15′ E) in the north, to Thanneermukkom (09°30′ N, 76°25′ E) in the south over a length of ∼ 80 km (Fig. 1). The system is characterised by its long axis lying parallel to the coastline, with several small islands and interconnected waterways, and it covers an area of about 300 km^2. The width of this estuarine system varies from 450 m to 4 km, and the depths range from 15m at the Cochin inlet to 3 m near the head with an average depth of 2.5 m (depths are reduced to chart datum). The estuary is separated from the sea by barrier spits interrupted by tidal inlets at Munambam and Cochin. The openings at Cochin, known as the Cochin inlet, with a width of 450 m, and another at Munambam, provide perennial connections to the Arabian Sea. The Cochin Port, situated on the Willington Island, is near the Cochin inlet, which provides the

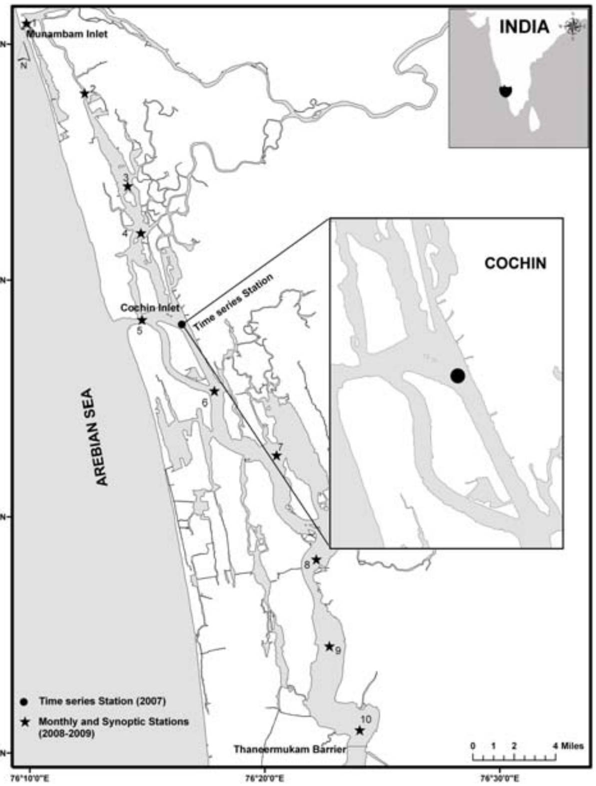

Fig. 1. The Cochin estuary (West coast, India), showing stations and extent of backwaters, having two inlets to Arabian Sea Munambam (north) and Cochin inlet (middle of the extent of backwaters). The time series station which is located 5 km way from Cochin inlet. Synoptic and monthly stations are discerningly marked in the backwaters.

main entrance channel to this harbour. The rivers that discharge freshwater into this estuarine system are Periyar in the north; Pampa, Achankovil, Manimala, and Meenachil in the south; and Muvattupuzha, midway between the two (Srinivas et al., 2003a). Munambam inlet is located further north, through which 70 % of the Periyar River discharges into the Arabian Sea and the rest through the Cochin inlet (unpublished data). The Thannermukkom barrier in the south was made functional in 1976 to prevent saltwater incursion and to promote cultivation in the low-lying fields. It remains closed from January to May every year.

1.2 Climatological setting

The domain experiences humid equatorial tropic climate with the mean daily temperatures ranging from 19.8 °C to 36.7 °C. Mean annual temperature ranges from 25.0–27.5 °C in the coastal lowlands (Government of Kerala, General features, 2005b; Brenkert and Malone, 2003). The average monthly rainfall for the years 1978 to 2002 at the different physiographic zones of the river basin is shown in Fig. 2a. In most years, pre-monsoon (March–May) experiences the

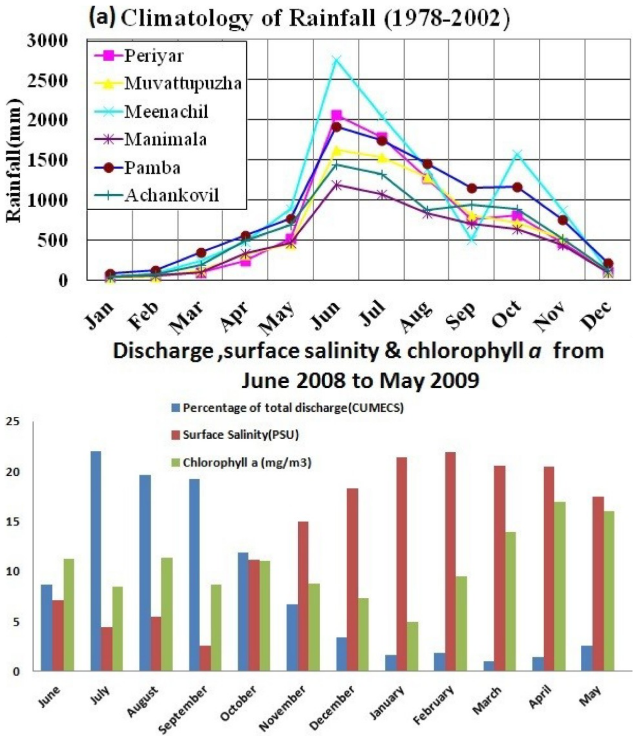

Fig. 2. (a) Climatology of rainfall (1978–2002) in the catchment of Cochin backwaters; **(b)** Monthly river discharge, surface salinity, surface chlorophyll a starting from June 2008 and finishing May 2009.

lowest recorded rainfall with a combined average of only 386 mm month^{-1}, thus defining the peak of the "dry" season. In contrast, southwest monsoon (June–September) receives the most rainfall with an average and maximum of 1400 mm month^{-1} and 1891 mm month^{-1}, respectively, thus defining the peak of the "wet" season (Krishnakumar et al., 2009). The freshwater runoff data (Fig. 2b) for the year 2008 to 2009 was obtained from the Central Water Commission. About 60 % to 70 % of the total discharge occurred during June–September and the least (6.82 %) occurred during December–February.

2 Materials and methods of observation

Intensive series of hydrographic surveys comprising three different time scales of observations were carried out in the Cochin estuary: (a) time-series at a single station positioned close to the main inlet of the system (temporal study of water column stability), (b) synoptic (salt intrusion measurement), and (c) monthly observations (correlation analysis of environmental parameters) at ten stations.

2.1 Time series observations

Time series data were collected from a station 5 km upstream of the Cochin inlet during four surveys in 2007 (Fig. 1). Since the environmental behaviour and dynamics of the Cochin estuarine system is highly influenced by monsoonal rainfall and the associated runoff, we had ideally chosen both extreme conditions of seasons for data collection: pre-monsoon (dry) and monsoon (wet) seasons. Significantly, the observational coverage included two spring (2–3 May, 16–17 July 2007) and two neap (25–26 April, 24–25 July 2007) tidal phases. The measurements were done for dry (April, May) and wet (July) seasons for 30 h and 27 h, respectively, covering two consecutive semidiurnal cycles. A SBE Seabird 19 plus CTD was used for recording temperature (accuracy ± 0.001 °C) and salinity (conductivity ± 0.001 Sm^{-1}) profiles with a bin size 0.2 m for every 30 min interval. The water level measurements throughout the observations were collected using tide pole and it was cross-checked with the tide table (Published by Survey of India) and the tide predicted using TASK-2000 software (POL/PSMSL Tidal Analysis Software Kit 2000, Proudman Oceanographic Laboratory, UK). Water samples collected from surface, mid-depth (~ 4 m) and close to bottom at 3 h intervals were utilised to determine the nutrient and chlorophyll a concentrations.

As a convenient measure of water column stability, potential energy anomaly (PEA, φ) was calculated for the entire water column for each CTD profile using the equation

$$\varphi = \frac{1}{h}\int_{-h}^{0} (\bar{\rho} - \rho)\, gz\mathrm{d}z \text{ where } \bar{\rho} = \frac{1}{h}\int_{-h}^{0} \rho \mathrm{d}z.$$

Here, g is gravitational acceleration (ms^{-2}), ρ is water density (kg m^{-3}), h is water depth (m) and z is depth interval (m).

Simpson (1981) defined PEA as shown in equation above as the amount of mechanical energy (per m^3) required to instantaneously homogenize the water column completely. Thereafter, this method has proved crucial for quantifying the mixing efficiency in numerous stratification studies in coastal seas and estuaries (Nunes Vaz et al., 1989; Rippeth and Simpson, 1996; Lund-Hansen et al., 1996; Ranasinghe and Pattiaratchi, 1999). Although the meteorological phenomena like wind are possible sources of mixing energy, they are overshadowed by the constancy of tidal action (Blanton, 1969) and are therefore not treated in this study.

Water column stratification for each profile in time series observation was assessed using the stratification parameter n_s defined as

$$n_\mathrm{s} = \frac{\delta S}{\mathrm{s'}_\mathrm{m}},$$

where $\delta S = S_\mathrm{bott}$-$S_\mathrm{surf}$, $S'_\mathrm{m} = 1/2\ (S_\mathrm{bott} + \mathrm{S}_\mathrm{surf})$, with S_surf and S_bott the salinity at the surface and bottom of the water column, respectively. In case n_s <0.1, then the water column is well mixed, when $0.1 < n_s < 1.0$ then partial mixing occurs, while if $n_s > 1.0$ stratification with the presence of salt wedge is evident (Haralambidou et al., 2010).

2.2 Synoptic observations

The results of the time series measurements conducted in the most dynamical zone of the Cochin estuary (Balachandran et al., 2008) inspired us to proceed our observations further along the estuary to explore the longitudinal salinity dynamics. Hence, salinity intrusion surveys were undertaken from June 2008 to May 2009 during spring and neap tidal phases of each month by casting CTD-SBE 9^{11} *plus* every 8 km intervals from northern arm to southern arm using a speedboat (40 km h^{-1}) covering ten stations along the estuary (Fig. 1). Morphology, tides and discharge were the deciding factors for the selection of sampling stations. Extensive data were gathered from stations 1 and 5, 6, 7 located at the proximity of northern and Cochin inlets, respectively; stations 2, 3, 4 at the middle of northern arm and 8, 9, 10 comprising the southern arm. Occasionally, we had to face technical problems such that the measurements obtained with CTD did not reach bottom due to strong water currents in January and also missing data of station 10 in June measurements.

The flushing time, defined as the time taken to replace the existing freshwater in the estuary at a rate equal to river discharge (Dyer, 1997), was calculated by the freshwater fraction method (Ketchum, 1983),

i.e. $T = F/Q$,

where F is the total volume of the freshwater in Cochin estuary and Q is the river discharge from the year 2008 to 2009.

2.3 Monthly observations

In order to relate the physical forcing (tide and river discharge) to chemical and biological property distributions, additional surveys were conducted at the middle of every month from June 2008 to May 2009 (similar to the period of synoptic survey). CTD–SBE 9^{11} *plus* was used to measure temperature and salinity. Nutrients, chlorophyll *a* and dissolved oxygen (DO) concentrations were determined from the bottle samples collected from the surface.

2.4 Chemical and biological parameters measurements

For the analysis of chlorophyll *a*, one litre of water sample from each depth was filtered through Whatmann GF/F filter and measured according to Strickland and Parsons (1972) using flourometer (Turner designs Instruments, Trilogy, USA). Pheophytin (acidified 0.1N HCL) concentrations were determined and deducted. Dissolved oxygen was analyzed by the Winkler's titrimeteric method. Dissolved inorganic nutrients such as nitrite (NO_2), nitrate (NO3), phosphate (PO_4^3) and silicate (SiO_4^4) were estimated following standard colorimetric techniques (Grasshoff et al., 1983).

2.5 Statistical data analysis

The Pearson correlation coefficients were calculated using SPSS 17 statistical software to determine the linear relationship of salinity with all chemical and biological parameters. Two-way ANOVA was carried out on the monthly surface discrete samples to examine the difference in water quality variables among the along-estuary sampling stations (spatial) or through the different sampling months (temporal), with factors of interest being season, discharge and tidal activity.

3 Results

3.1 Temporal variations at single station

3.1.1 Tidal characteristics

Figures 3a–d give the water level and predicted tide of spring and neap phases during the observation period. The maximum range of the spring tide was 1 m while the neap tides did not exceed 0.59 m. The diurnal tidal inequality was quite evident in all observations; it was prominent in dry neap with 0.20 m (Fig. 3a). Unlike all other tidal observations which were semidiurnal in nature, the neap tide of wet season was diurnal (Fig. 3d).

3.1.2 Temperature

The vertical distribution of temperature is as shown in Figs. 4–7. A pronounced surface to bottom difference in temperature was absent during spring and neap tidal phases in dry season. Even though, during the period when solar forcing during late afternoon was at its peak created a vertical difference of ∼ 1.5 °C (Figs. 4b, 5b). However, the high tides of both the tidal phases of monsoon season experienced typically substantially lower temperature (∼ 24.5 °C) (Figs. 6b, 7b) at the bottom layers when compared with surface temperature (∼ 27.5 °C).

3.1.3 Salinity

The seasonally varying river flow and the tidal rhythm affected the vertical distribution of salinity is shown in Figs. 4–7. During the period April–May, low freshwater discharge (Figs. 4a, 5a) caused weaker salinity stratification (difference between the surface and near bottom salinities) relative to summer monsoon. In dry neap (April), the stratification was observed during flood with maximum of 16.35. With the arrival of ebb phase of the first tidal cycle, stratification declined to a remarkably low value of 0.19. Again, it increased with the upcoming flood tide. During spring phase of dry season (May), stratification of the entire water column over the

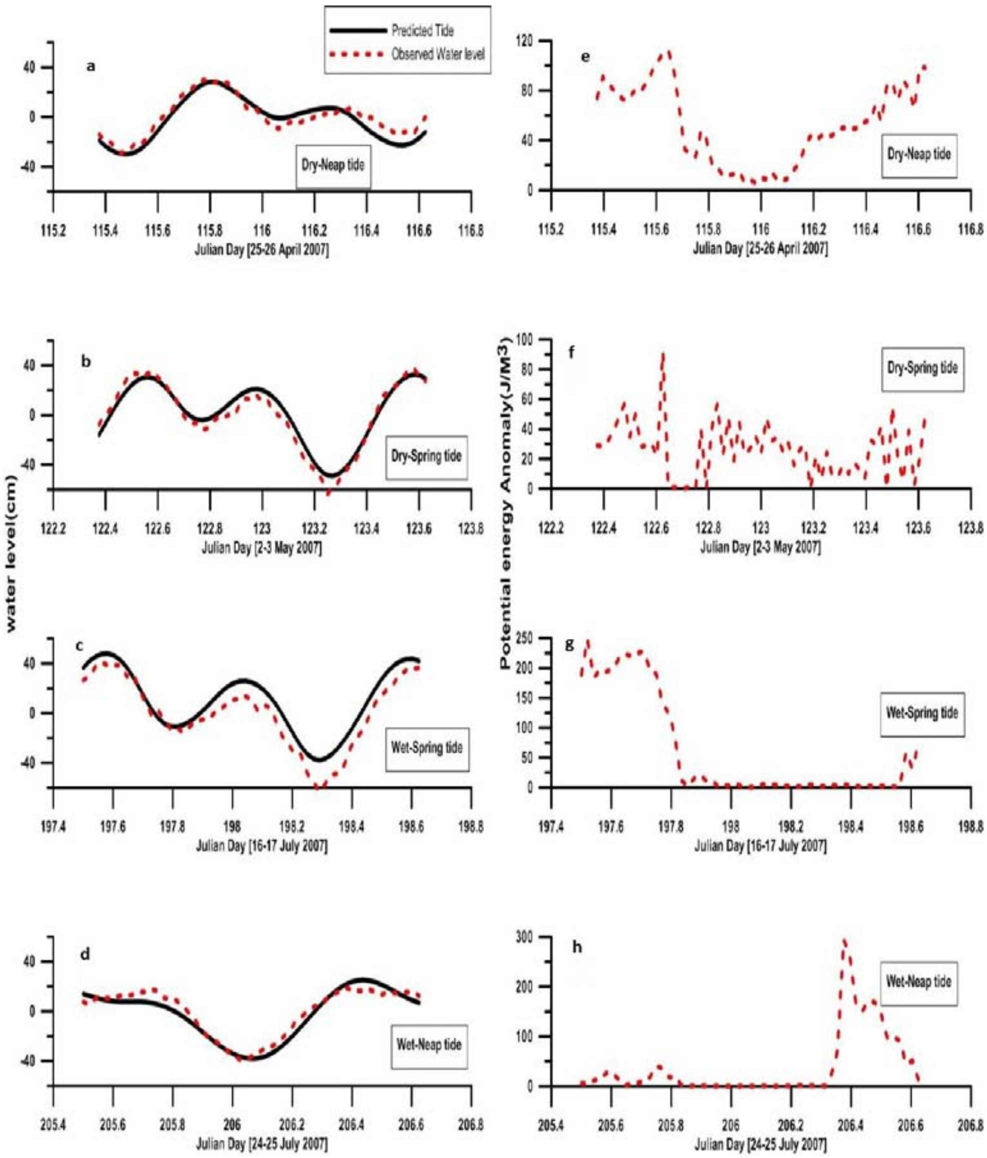

Fig. 3. (a–d) Semidiurnal variations of observed water level and predicted tide at the location; **(e–f)** Time series of potential energy anomaly (φ) ($\mathrm{J\,m^{-3}}$) computed from the 30 min density profiles **(a, e)** 25 April 09:00 LT to 26 April 15:00 LT (neap-dry); **(b, f)** 2 May 09:00 LT to 3 May 15:00 LT (spring-dry); **(c, g)** 16 July 12:00 LT to 17 July 15:00 LT (spring-wet); **(d, h)** 24 July 12:00 LT to 25 July 15:00 LT (neap-wet).

tidal cycles was less and the depth-averaged salinity ranged from 31.64 to 32.09. The stratification was higher in flood (12.5) than in ebb (0.15) either due to differential advection of salinity or vertical mixing. On the other hand, during both tidal phases of monsoon (Figs. 6a, 7a), large quantities of freshwater entered the estuary, resulting in very low saline water at the surface and denser water at the bottom. Evolution of salinity stratification in water column (spring 33.24; neap 33.03) is associated with advection of salt wedge. The isopycnals were evenly spaced and flattened during highest high water (HHW). Notably, the entire station was flushed with freshwater of salinity ~ 0.05 during low tides and lowest high water (LHW). The pycnocline became unstable during ebb and the saline wedge disappeared.

3.1.4 Stability factor and Stratification parameter

The pattern of distribution of observed water column stability (Figs. 3e–h) corresponded well with the salinity distribution, notwithstanding seasons and tidal cycles. The spring–neap cycles of stabilization and destabilization of water column were prominent, which have relative importance as far as tidal estuaries are concerned. During dry season, the average PEA value computed from all density profiles was $52.02\,\mathrm{J\,m^{-3}}$ in neap, which almost reduced to $25.9\,\mathrm{J\,m^{-3}}$

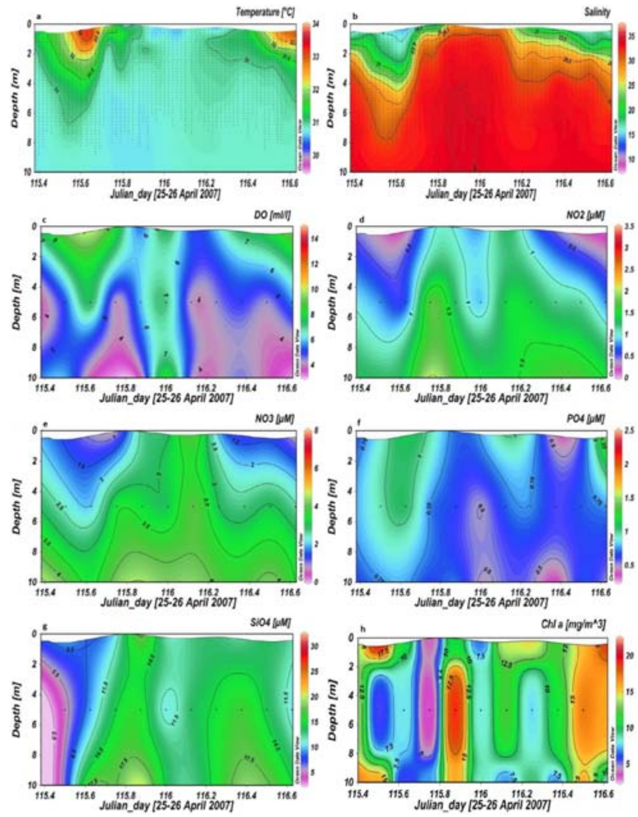

Fig. 4. Depth–time contours of salinity, temperature DO, chlorophyll *a*, NO_2, NO_3, PO_4^3, SiO_4^4 for every three hours from surface, mid-depth and bottom during neap tides of dry season.

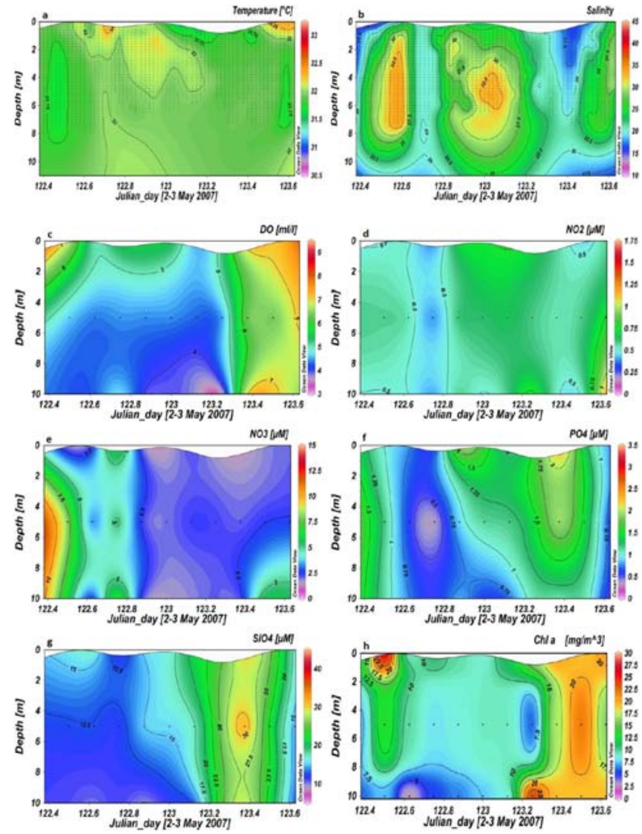

Fig. 5. Depth–time contours of salinity, temperature, DO, chlorophyll *a*, NO_2, NO_3, PO_4^3, $SiO_4^4$for every three hours from surface, mid-depth and bottom during spring tide of dry season.

during spring phase. This implies that the average energy required to mix the water column was about two-fold higher in neap than spring phase. It should also be noted that during dry neap, the minimum PEA value of $5.0\,\mathrm{J\,m^{-3}}$ was obtained during the ebb period. However, during dry spring the PEA values neared to zero for many of the density profiles over the tidal cycle. During wet, the highest values of PEA ($> 200\,\mathrm{J\,m^{-3}}$) in spring and neap phases indicated stratification evolved due to the advancement of the salt wedge. However, for spring, on the arrival of ebb phase, PEA values gradually declined corresponding to the retreat of salt wedge and went as low as $< 1\,\mathrm{J\,m^{-3}}$, this low value sustained until the next tidal cycle and again the stratification began to develop at HHW. For wet neap, the water level was diurnal in nature. The observations of neap began with low PEA values ($\sim 10\,\mathrm{J\,m^{-3}}$) and the advancement of salt wedge occurred at the flood phase of the tidal cycle. Again, it began to retreat during ebb. The computed PEA from the density profiles of spring phase of intrusion survey (Synoptic observation – Sect. 2.2) for the months July 2008, August 2008, November 2008 and March 2009 are shown in (Fig. 9). These months are characterised by southwest monsoon, northeast monsoon and dry period, respectively. The spatial variations in PEA plainly depict the changes in stratification due to bathymetry and seasonal river discharge. During July, the PEA also reached the maximum value of $128.3\,\mathrm{J\,m^{-3}}$ near the inlets whereas all the other stations remained well mixed (PEA ~ 0). In August also, similar character was observed with high values of PEA $113.2\,\mathrm{J\,m^{-3}}$ near the inlets. Then river discharge was reduced to 3.34 % in November. This resulted in the longitudinal dispersion of the salinity field and the PEA in the upstream of the system increased to $68.2\,\mathrm{J\,m^{-3}}$. Later during the dry period (March), discharge was only 1.4 %. Therefore, the tidal actions dominated in the system, which subsequently turned to well mixed and the average energy required to mix the water column in the estuary was $33.8\,\mathrm{J\,m^{-3}}$.

During dry season, stratification parameter fluctuated from 0.5 to 0.8 (partially mixed) in neap phase, whereas for spring phase most of the observations over the tidal cycle showed stratification number varying from 0 to 0.1 (well mixed). During wet season, stratification parameter calculated from profiles during high tides showed values ranging from 1.3 to 1.9. This was due to the temporary stratification developed due to salt wedge intrusion. Once freshwater conditions prevailed and as the saline layer was pushed out of

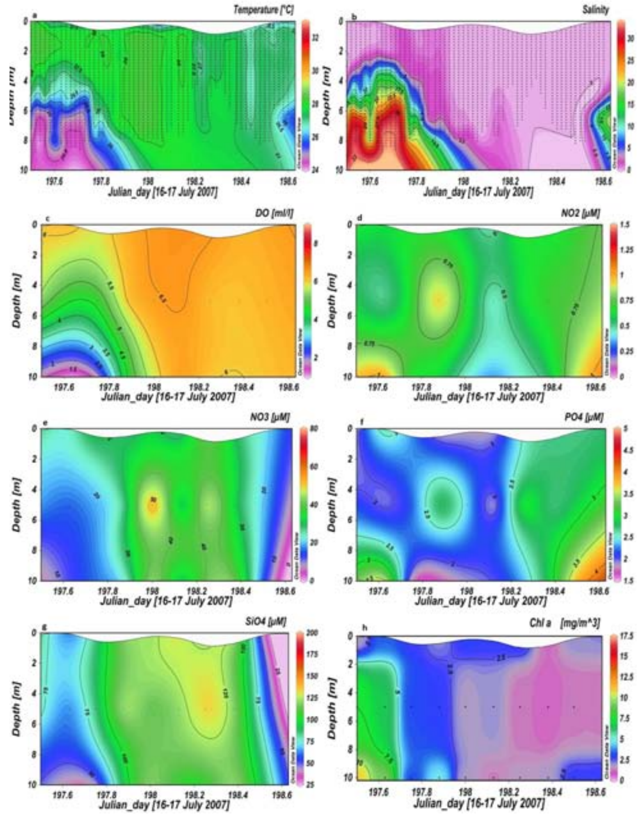

Fig. 6. Depth–time contours of salinity, temperature DO, chlorophyll a, NO_2, NO_3, PO_4^3, SiO_4^4 for every three hours from surface, mid-depth and bottom during spring tide of wet season.

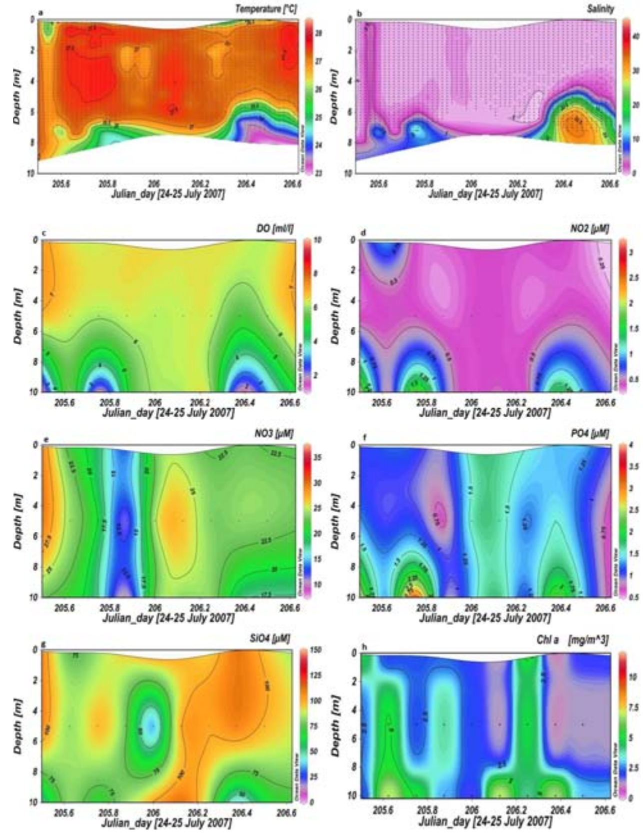

Fig. 7. Depth–time contours of salinity, temperature DO, chlorophyll a, NO_2, NO_3, PO_4^3, SiO_4^4 for every three hours from surface, mid-depth and bottom during neap tide of wet season.

the estuary, stratification number became almost zero. The stratification parameter varies depending on the phase of tide and freshwater discharge, indicating that Cochin estuary experiences a transition from partially mixed (neap) or well mixed (spring) in dry season to periodically stratified state during wet season.

3.1.5 Dissolved oxygen and nutrients

The distribution of chemical properties is shown in Figs. 4–7. During dry neap, the average surface DO value ($7.74 + 1.76\,\mathrm{ml\,l^{-1}}$) was higher than bottom ($4.37 + 1.66\,\mathrm{ml\,l^{-1}}$). In contrast, the average nutrient concentration (except for PO_4^{3-}) was higher at the bottom than at the surface for neap phase during dry season: NO_2 (surface $0.55 + 0.41\,\mu M$; bottom $1.55 + 0.21\,\mu M$), NO_3 (surface $1.79 + 1.10\,\mu M$; bottom $4.10 + 0.50\,\mu M$), PO_4^{3-} (surface $0.88 + 0.30\,\mu M$; bottom $0.60 + 0.13\,\mu M$) and SiO_4 (surface $12.02 + 2.69\,\mu M$; bottom $15.73 + 3.87\,\mu M$). Unlike neap, the water column property distributions were homogeneous over much of the tidal cycle in spring phase (Figs. 5c, e–h). During wet season, the incursion of hypoxic water ($< 1.06\,\mathrm{ml\,l^{-1}}$) through bottom layers (Figs. 6c, 7c) on flood tides was discernible during both spring and neap tidal phases. The near-bottom intruding water was characterised by high NO_2 (spring, $1.02\,\mu M$; neap, $1.84\,\mu M$), NO_3 (spring, $12.29\,\mu M$; neap, $17.5\,\mu M$), PO_4^{3-} (spring, $3.68\,\mu M$; neap, $3.24\,\mu M$) and low SiO_4 (spring, $39.65\,\mu M$; neap $38.03\,\mu M$) values. However, elevated levels of silicate ($120.66\,\mu M$), which is a land-derived nutrient, were found at the surface. Silicate showed a negative relationship with salinity ($r^2 = 0.48$, $n = 31$) during wet season, indicating that freshwater runoff is the principal source of silicate inputs. This is substantiated by the higher silicate concentrations in wet than during the low-runoff surveys.

3.1.6 Chlorophyll *a*

The distribution of chlorophyll a pigments, which is a reliable measure of phytoplankton biomass, is shown in Figs. 4–7. Seasonal variations in chlorophyll a distribution were observed with relatively higher values in dry seasons (on an average $12\,\mathrm{mg\,m^{-3}}$). The chlorophyll a concentration was higher at the surface with its peak (Figs. 4d, 5d) during 12:00 h to 15:00 h which may be attributed to the vertical migration of light-sensitive phytoplankton species to the surface. During dry season, the maximum surface

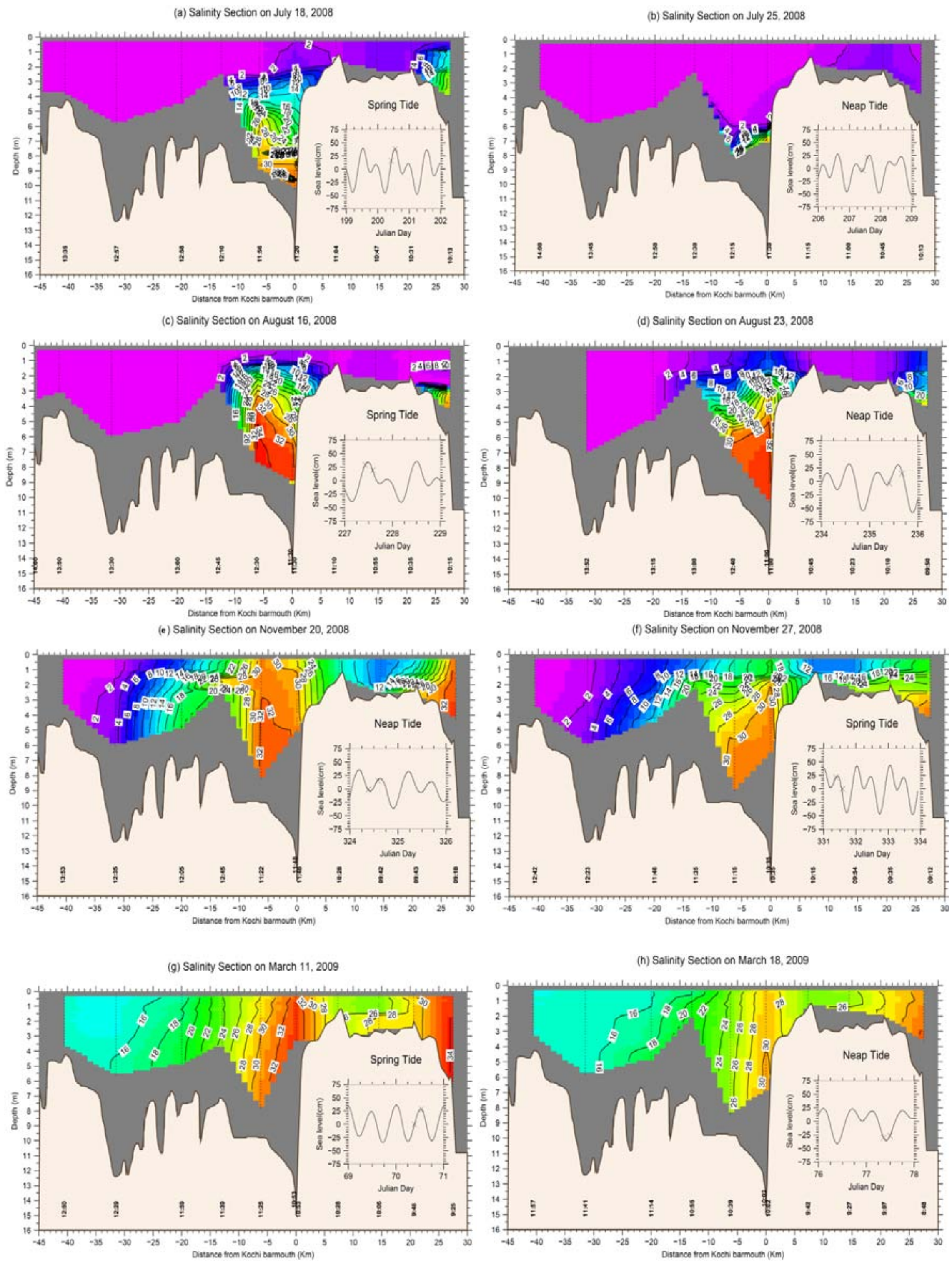

Fig. 8. Longitudinal synoptic distribution of salinity measured twice monthly (during spring and neap tides) During July 2008, August 2008, November 2008 and March 2009. The Cochin inlet is at the coordinate origin. The northern/southern arm stations are at positive /negative distances, respectively. The insets show the tidal amplitude and the times (as X's) when each survey began and ended. Times of each station appear along the lower x-axis.

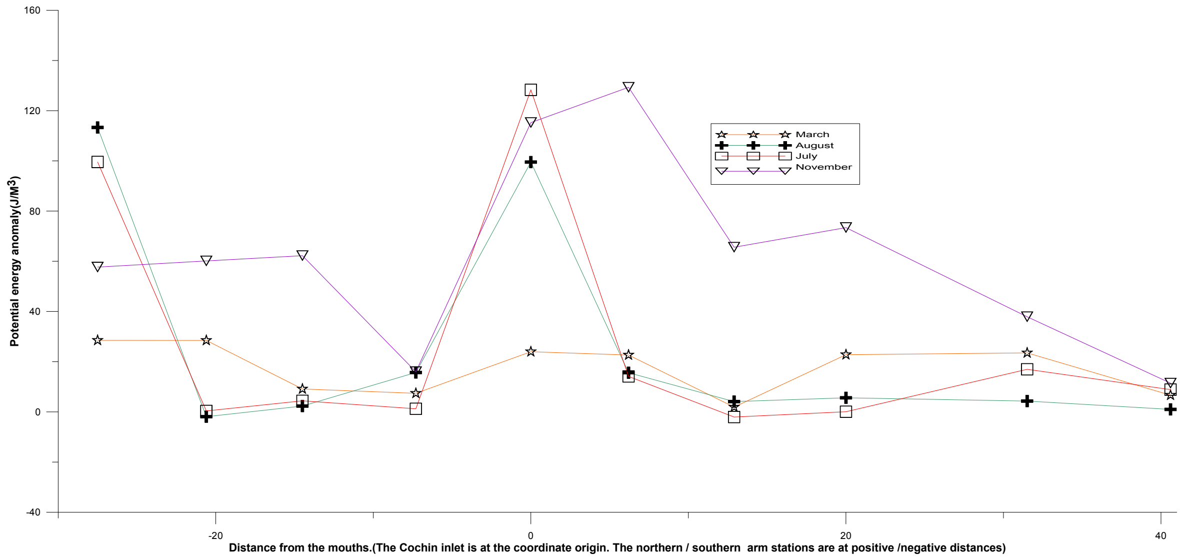

Fig. 9. Spatial variation in the potential energy anomaly (the months are characterised by southwest monsoon (July–August), northeast monsoon (November) and dry period (March)).

chlorophyll *a* attained for neap and spring was 20.1 mg m^{-3} and 26.7 mg m^{-3}, respectively. During salt wedge formation in both tidal phases of wet seasons (Figs. 6d, 7d), chlorophyll *a* maxima layer was formed at the bottom ocean water [salinity 33.29; chl *a* 11 mg m^{-3} (spring), salinity 33.04; chl *a* 6.8 mg m^{-3} (neap)] and minimum layer at the surface freshwater [salinity 0.05; chl *a* 1.1 mg m^{-3} (spring), salinity 0.01; chl *a*0.9 mg m^{-3} (neap)].

3.2 Longitudinal salinity distributions (synoptic survey)

The results of the salinity intrusion survey for the months July 2008, August 2008, November 2008 and March 2009 are shown in Fig. 8. These months are characterised by southwest monsoon, northeast monsoon and dry period, respectively.

In the year 2008, with the onset of monsoon on 31 May, the river discharge peaked with 8.7 % of the total occurring in the month of June and flushing time calculated to be 5.8 days. The depth-averaged salinity of the southern arm stations (8, 9, 10) and of the stations (2, 3, 4) at the middle of northern arm presented low values averaging to 1.76-spring; 0.17-neap and 8.22-spring; 5.19-neap, respectively. Stations near the Cochin inlet (5, 6, 7) exhibited high salinity unlike station 1 near the northern inlet with tidal amplitudes having some influence. Stations 1, 2 were prone to freshwater influence due to the Periyar River adjoining northern inlet, which is the major river contributing to the total discharge of the estuary. Overall, the freshening of the estuary was initiated by the monsoon.

By the end of June, the monsoon peaked and July experienced the maximum freshwater discharge amounting to 22.04 % of the total and flushing time decreased to 2.8 days. The salt wedge became prominent in July, transforming the status of the estuary to that of a salt wedge type (Fig. 8a, b). A weaker salt wedge front originating from northern inlet, which was visible only in spring phase of July, persisted in all other monsoon months. Hence, higher salinities (18–34) were restricted to the bottom waters of the stations adjacent to the inlets (5, 6, 7-Cochin inlet; 1, 2-northern inlet). All the other stations remained well mixed with depth averaged salinity reaching salinity values as low as 0.05.

The salt intrusion length during both spring and neap tides of the synoptic survey has been defined as the length from the river mouth (Cochin inlet) along the river channel to the point where the bottom salinity is 2 PSU. On average, the intrusion length from the Cochin inlet to south averaged to 15 km and 11 km during spring and neap phases, respectively, of monsoon months. The results in August differed distinctly, with the intrusion greater in neap (15 km) than spring (13 km) since the neap observations were carried out during high tides whereas for spring they were during low tides (Fig. 8c, d). This entails the significance of the observation time with respect to tidal cycles denoting the relevance of time series measurements in the system. The depth of the interface (defined as the height of 2 PSU isohaline from the bottom) decreased gradually towards the outer end of the estuary. This depth, which is also the thickness of the bottom saline water layer, was greater in spring compared to neap phase at the mouth for the time series measurements (Figs. 6a, 7a), implying that saline intrusion was more during spring phase.

As the river discharge decreased from July to September (Fig. 2b), coincidently the salt wedge advected further upstream, suggesting an inverse relationship of salt intrusion with river flow. The withdrawal of monsoon concurred with the reduction in freshwater discharge. This resulted in the

Table 1. Results of Pearson correlation analysis (R) for the investigated physical and chemical variables during monthly observation.

Parameters	Salinity	Temp	DO	pH	Nitrate	Nitrite	Ammonia	Silicate	Phosphate	Chl *a*
Salinity	1									
Temp	0.028	1								
DO	**−0.370****	0.375**	1							
pH	0.524**	0.690**	0.203*	1						
Nitrate	**−0.308****	−0.027	0.173	−0.122	1					
Nitrite	0.106	0.059	**−0.209***	−0.017	0.139	1				
Ammonia	−0.027	0.054	−0.092	0.064	−0.068	**−0.204***	1			
Silicate	**−0.650****	0.168	0.290**	**−0.231***	0.251**	**−0.186***	0.247**	1		
Phosphate	0.117	0.117	−0.127	0.168	0.125	−0.027	0.055	0.032	1	
Chl *a*	0.086	0.158	−0.038	0.16	0.014	−0.038	−0.048	−0.029	**0.455****	1

*: $P < 0.051$, **: $P < 0.012$, bold values indicate negative correlation.

longitudinal dispersion of the salinity field. From 11.81 % in October, the river discharge was reduced to 3.34 % in December. Consequently, flushing time also increased from 3.5 days in October to 8.4 days in December. During the period, though the salinity at stations near Cochin inlet (5, 6, 7) were invariably high over the vertical, there was a consistent increase in the salinity at all other stations. However, the uppermost station (10) remained far away from the influence of marine water irrespective of tidal phases. Later when the dry period (from January to April average discharge is only 1.4 % of total) commenced, the tidal actions dominated in the system. The flushing time was 9.3 days in January, which increased to 13 days in April. The salinity field extended up to station 10 with maximum depth-averaged salinity (15.12) attained in spring phase of March. In May, there was a slight increase in discharge to 2.5 % of the yearly discharge and the flushing time was 14.7 days. The aftermath of an anomalous rainfall in the catchment of Periyar during our spring observation caused station 1 at the northern inlet to be freshwater dominated.

3.3 Statistical analysis of monthly observation

The Pearson correlations between the surface values of ecologically important variables are shown in Table 1. Salinity showed significant positive correlation with P^{H} ($R = -0.524$, $P < 0.01$). Relevantly, it was negatively correlated with nitrate ($R = -0.308$, $P < 0.01$), DO ($R = -0.370$, $P < 0.01$) and silicate ($R = -0.650$, $P < 0.01$), indicating freshwater as their source of inputs. Chlorophyll a was highly correlated with phosphate ($R = 0.455$, $P < 0.01$), with no significant correlation with salinity. Also, there was no distinct correlation between salinity and phosphate. Although DO was inversely correlated with chlorophyll a, it was not significant, indicating that biological processes are not the only factor influencing DO in the estuary. Negative correlations between salinity and DO were highly significant ($R = -0.370$, $P < 0.001$).

The two-way analysis of variance carried out on monthly samples is shown in Table 2. Salinity variations were found to be significant spatially ($F = 7.88$, $P < 0.001$) and temporarily ($F = 6.37$, $P < 0.001$). However, temperature varied more temporarily ($F = 2.29$, $P < 0.01$) than spatially ($F = 0.88$, $P < 0.01$) owing to the seasonal changes in the domain. Among the different nutrient species, only phosphate manifested fluctuations spatially ($F = 9.87$, $P < 0.001$) and temporarily ($F = 2.66$, $P < 0.005$). Chlorophyll a marked remarkably more significant variations spatially ($F = 4.35$, $P < 0.001$) than temporarily ($F = 1.23$, $P < 0.5$).

4 Discussions and summary

Temperature has lesser influence in density stratification than salinity because the salinity range is larger than temperature in estuaries (Dyer, 1973). Thus, an attempt was made to analyze the variations in stratification considering salinity as the major determining factor. The data presented from this survey suggests that salinity fluctuates at different timescales, including intratidal, fortnightly of spring and neap tidal cycle, and seasonal wet and dry periods. It is evident from our study that Cochin estuary experiences a transition from partially mixed (neap) or well mixed (spring) in dry season to periodically stratified state during monsoon. The potential energy anomaly (PEA) increases with increasing river discharges, specifically to the inlet regions in the southwest monsoon and northeast monsoon periods.

The Arabian Sea, one of the major upwelling zones of the world, experiences upwelling from June to October (Banse, 1968; Naqvi et al., 2000). Srinivas and Dinesh Kumar (2006) claim that the increased intensity of upwelling processes in Cochin in July is instrumental in generating a drop in sea level and surface temperature. Whilst this process aids in quicker flushing of the estuarine water through the bar mouth (Udaya Varma, 1981), low tidal amplitudes and increasing number of oscillations in the southwest coast may lead to

Table 2. Two-way analysis of variance for differences of ecologically important parameters on sampling stations and sampling months for the survey (June 2008 to May 2009). F indicates the likelihood ratio; P indicates the probability.

Variables	Station		Year	
	F	P	F	P
Salnity	7.883679	0.000065***	6.370352	0.00047**
Temperature	0.884074	0.541915	2.291627	0.014651
DO	3.411882	0.000984**	2.104926	0.025726
pH	3.836676	0.000301**	3.082916	0.001237*
Nitrate	0.419885	0.922091	12.94469	0.00002***
Nitrite	0.971728	0.4674	9.793611	0.00042**
Ammonia	1.006034	0.439704	8.134114	0.00032**
Silicate	1.843739	0.068204	7.809754	0.00008***
Phosphate	9.872694	0.0005**	2.662658	0.004654*
Chl *a*	4.357485	0.00007***	1.233476	0.273961

*** Indicates statistically significant differences < 0.0001, ** indicates < 0.001 and * indicates < 0.01.

small inter-tidal expanses, which reduce flushing (Qasim, 2003). Coastal upwelling in the Arabian Sea induces anomalies in the distribution of physiochemical properties characterised by a rapid decrease in temperature and DO concomitant with an increase in salinity and surface nutrients, particularly nitrates (Rotchord, 1975) that could foster enhanced primary productivity of the area (Mann and Lazier, 1996).The upwelled water area is situated just off the shelf break (Shetye et al., 1990), where the predominant tidal circulation is responsible in advecting these waters into the estuaries. Significantly, the intruding water mass at the bottom layers during monsoon season was identified as upwelled water from the adjacent shelf with its peculiar characteristics of low temperature, high salinity, severe oxygen depletion, nutrient rich and high chlorophyll a.

The salt wedge plays an important role in the distribution of chemical and biological variables that have profound impacts on water quality (Haralambiduo et al., 2010). Coastal hypoxia (defined here as < 1.42 ml l) develops seasonally in many estuaries, fjords, and along open coasts as a result of natural upwelling (Levin et al., 2009). The upwelled water incursion and the stratification induced by freshwater discharge of monsoon season fueled the oxygen depletion at the bottom layer. Under persistent stratification, the probability of the shift of hypoxic to anoxic condition in the intruding frontal system cannot be ruled out. Our detailed hydrological analysis suggests that the dynamic and energetic environment of Cochin estuary hindered the sustainability of this front at the bottom. The onset of strong ebb phase and high flushing of monsoon flushed the estuary from top to bottom with well oxygenated waters by pushing the saline wedge seaward. The duration of the existence of this front in our system was greatly determined by the tidal range and duration of flood–ebb cycles. The dependence of the salt wedge advancement on tidal range was clearly identifiable in spring phase as the tidal amplitude of 26.05 cm was not sufficient to force the transient stratified flow. The diurnal inequality of the neap phase contributed well to the flushing period (12 h) as when compared with the semidiurnal spring phase (9 h 30 min). The time-dependent nature of salt wedge has also been justified in Fraser estuary (Geyer and David, 1989), where during ebb the saline structure was eroded due to local enhancement of shear instability. Therefore, the periodic advance and retreat of the salinity wedge front is inevitable in preserving the ecosystem functioning and maintaining the health of the estuary.

The Cochin estuary is reported to be an eutrophic estuary (Qasim, 2003). During high runoff surveys, an increase in the overall nutrient concentrations was noticed when compared to low runoff surveys. However, the salt wedge intrusion affected its distributions in the water column. Higher concentrations of phosphate and nitrite were restricted to the near bottom saline intrusions, but extreme levels of silicate and nitrate were observed in low salinities. Although the near-bottom seawater intruded with high nutrients, freshwater runoff was the principal source of silicate and nitrate supply. This is further substantiated by the statistical results, which revealed that silicate and nitrate were highly negatively correlated with surface salinity whereas phosphate and nitrite did not manifest a significant relationship. As the river flow weakened after monsoon, the flushing of the estuary diminished and the nitrite, nitrate, ammonia, phosphate and silicate loadings through anthropogenic activities (industries) and sediment re-suspension alter the nutrient stoichiometry substantially (Martin et al., 2008). Phosphorous showed both seasonal and spatial variability. The surface phosphate concentrations were moderately high in the stations with high salinity whereas concentrations decreased in low saline regions. The previous work on the fractionation of phosphorous in the Cochin estuary (Balchand and Nair, 1994) also concluded that enhanced amounts of exchangeable P

appeared in high saline waters, signifying the presence of biologically available nutrient phosphorus.

In the Cochin estuary, nutrients are not a limiting factor for the optimum phytoplankton growth at any time of the year (Balachandran et al., 2005); also, transient variations in the water quality play a significant role on phytoplankton behaviour (Madhu et al., 2010). Prior experimental studies had found that generally Cochin estuary exhibits high chlorophyll *a* when intermediate salinity (10–25) conditions prevail (Qasim and Sankaranarayanan et al., 1972). Our study substantiated the above statements such that increased chlorophyll *a* distribution was observed during dry season compared to wet season. The increased flushing during monsoon resulted in low chlorophyll concentration in surface layers where salinity was low. The effect of river discharge and surface salinity on the surface chlorophyll *a* distribution is clearly depicted in Fig. 2b, such that the maximum chlorophyll concentrations were observed during lean-river flow months when the surface salinity was high. High riverine discharge leads to reduced residence time, leading to increased flushing of phytoplankton biomass out of the estuary (Lane et al., 2007). Further, the overall surface distribution of chlorophyll *a* during monsoon was affected when the increased river discharge restricted the salinity dispersion and hence the saline waters with biologically available phosphorous was limited in some areas along the estuary. Phosphorous is being attributed as a limiting nutrient in freshwater-dominated systems (Neil, 2005). The river pulses impede the salinity field expansion affecting the nutrient distributions. However, salinity could not be considered as the only determining factor for triggering phytoplankton growth. Unravelling these evidences is henceforth a major task to be accomplished through sustained research. Although the linking between temporal stratification of the water column with chlorophyll *a* distributions is a question of some subtlety, this study reveals the persuasive evidence of its critical importance in the Cochin estuary.

The advancement in our understanding of time-dependent nature of water column stabilization and destabilization mechanisms can be achieved through continuous monitoring of multiple stations along with supporting flow field to define various processes in spatial and time scales.

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Influence of Saltwater Barrage on Tides, Salinity, and Chlorophyll *a* in Cochin Estuary, India

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ABSTRACT

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Thanneermukkam Barrage (TB) is constructed in the southern arm of Cochin estuary. It prevents salt intrusion upstream and regulates river discharge downstream. Characteristics of the estuary when the barrage is opened and closed are discussed. The analysis showed that the closure of the barrage caused amplification of tides in the immediate vicinity and up to 10 km farther downstream. When the barrage was closed, the northern region of the TB transformed from an ebb-dominant system into a flood-dominant system. During high discharge periods, the barrage was opened and salinity intrusion was exponentially dependent on river discharge. During the dry period, the reduction in river flow compounded with closure of the barrage resulted in an increased salinity concentration downstream. Whereas oceanic salinity was observed at the ocean-end station, about 13PSU occurred at the river-end station when the barrage was closed. Hydrodynamic control on phytoplankton biomass was also evident. Higher surface chlorophyll *a* levels were observed at higher salinity during the closed barrage period, and residence time was estimated for 4 days during this period.

ADDITIONAL INDEX WORDS: *Estuary, saltwater barrage, tidal amplification, salinity intrusion, chlorophyll* a.

INTRODUCTION

Many estuarine systems of backwaters occur along the west of coast of India. These waterbodies are fed by rivers that originate in the western Ghats (mountain ranges on the west coast of India). The Cochin estuary is one of these types of waterbodies, with two openings to Arabian Sea. This system extends from Munambam (10°10′ N, 76°15′ E) in the north to Thanneermukkam (09°30′ N, 76°25′ E) in the south over a length of ~80 km. The regional tidal regime is microtidal, with an average range of 1 m (Qasim and Gopinathan, 1969). The tides are mixed with semidiurnal dominance, with form number varying from 0.85 to 0.91 (Revichandran *et al*., 2011). The rivers that discharge freshwater in this estuarine system are Periyar in the north; Pampa, Achankovil, Manimala, and Meenachil in the south; and Muvattupuzha at the central estuary. Thanneermukkam Barrage (TB) is a salinity barrier, commissioned in 1976, in the upstream part (~40.6 km from Cochin inlet) of the Cochin estuary. It was constructed to prevent the entry of saline water into the polders of the Kuttanad region of the Kerala coast to facilitate agriculture of paddy fields during the summer season. The widest (about 5 km) and the shallowest (1 m) areas of the backwaters are seen in this region. The overall length of the structure (approach road, sluice gates, masonry, etc.) is about 1.5 km. The actual width of the TB portion alone is around 800–850 m, and the sill is at an elevation of 3.38 m below mean sea level. There are around 63 sluice gates; each gate is about 12.5 m in width. The opening and closing process of the 63 gates of TB is gradual, taking place over a time frame of around 3–4 days.

Among the six rivers mentioned above, four rivers, *viz*., Meenachil, Manimala, Achankovil, and Pamba, drain south of the TB. When the TB is closed during the dry season (January–April), although river discharge is minimal, the river supply from these rivers is hindered north of the barrage. However, the shallow regions south of it become dominated by freshwater because of river runoff. Thus, the TB acts as a river discharge regulator in the system. Therefore, the TB when closed separates freshwater regions south of it from saline water regions of the Cochin estuary. The exact date of closure of the TB is decided on the basis of salinity increases in the area adjacent to the TB, and the barrage is opened when the river flow increases. Before the commissioning of the TB, it was possible to cultivate only one paddy crop a year. A second crop on about 300 ha of the paddy area—cultivation of cocoa, plantain, and vegetables as intercrops in coconut garden—

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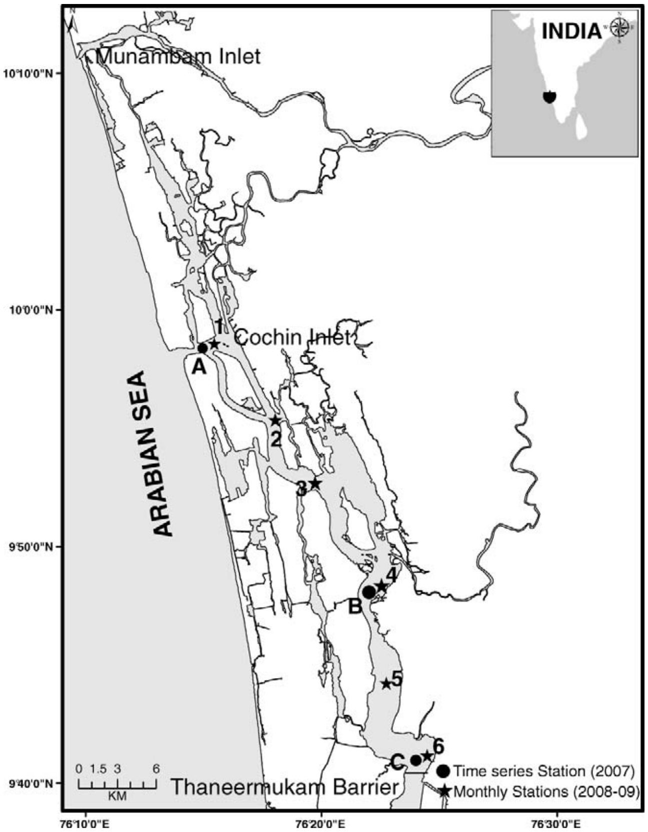

Figure 1. The Cochin estuary (west coast, India), showing stations and extent of backwaters, having two inlets to the Arabian Sea at Munambam (north) and Cochin inlet (middle of the extent of backwaters). The time series stations and monthly stations are discerningly marked in the backwaters.

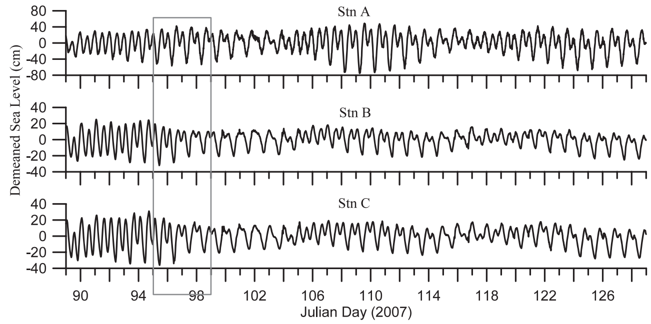

Figure 2. Sea level for the period Julian day 89–128 (March), 2007 at Stations A–C. The ordinate scale for Station A is different. The box indicates the period during which the barrage was in "being opened" condition (5th April, 2007 to 8th April, 2007 [Julian day 95–98].

became feasible upstream with the availability of fresh water year round.

Construction of the TB resulted in drastic and ecological changes in the Cochin estuary. The barrage has reduced the extent of backwater nursery grounds by 25%, which led to the total collapse of the juvenile shrimp fishery of the Kuttanad region (Kannan, 1979). A 69 km^2 area of brackish water lying south of the TB has been economically cut off from backwaters (Gopalan, 1991). The periodical opening and closing of the TB has seriously deteriorated the ecology of the Cochin estuary, especially in the southern part of the barrage, as evidenced by the depletion of clam beds (Arun, 2009). Construction of the TB across the Cochin estuary altered flow patterns and hence enhanced the growth and prevalence of indicator and pathogenic bacteria within the region (Hatha, Abhirosh, and Sherin, 2008). Tidal flushing is restricted by closure of the TB in summer, which has eventually resulted in the accumulation of toxic contaminants like heavy metals in the sediments (Harikumar, Nasir, and Mujeebu Rahman, 2009). Proliferation of weeds and water hyacinths upstream has affected navigation and severely restricts the natural flushing of pollutants (Revichandran *et al.*, 2011).

For the first time, efforts are being made to understand the influence of the TB on the hydrodynamics of the estuary using *in situ* data. Here, we discuss tidal amplitude variations, tidal asymmetry, salinity, and chlorophyll *a* (Chl *a*) distribution in the southern arm (from Cochin inlet to the TB) of the estuary during the "open" and "closed" TB conditions. An attempt is also made to investigate Cochin estuary residence times for different river flow conditions. This enables us to assess the hydrodynamic controls on phytoplankton biomass.

DATA SETS AND ANALYSIS

We obtained data sets of major measurements conducted during the period 2007–2008. In 2007**,** 40-day field efforts were designed to characterize variations in tidal levels. Sea level data were measured at 15-minute intervals at three locations (Figure 1A–C) in the southern arm of Cochin backwaters from time 0000 on 30 March 2007 to time 2345 on 8 May 2007 (Julian days 89–128). Station C is located about 1.5 km from the TB. The TB was kept closed during the measurements from 30 March 2007 to 4 April 2007 (Julian days 89–94). During the period 5 April 2007 to 8 April 2007 (Julian days 95–98), the sluice gates (63 in number) were gradually opened, resulting in intrusion of seawater into the southern backwaters. From 9 April 2007 to 8 May 2007 (Julian days 99–128), the sluice gates were completely open; as a result, the tides forced from the Cochin inlet were felt even in the southernmost region. Out of the 40 days of data, the first 6 days pertain to the "completely closed" condition, the next 4 days to "being opened," and the remaining 30 days to "completely open" (Figure 2). Harmonic analysis was conducted on sea level data for the open period (30 d) to extract amplitudes and phases of 26 independent and eight related constituents with the software TASK2000 (Tidal Analysis Software Kit). These constituents were used to predict the tides for the 6-day TB closed period. Because of short tidal records, the observed (closed period) and predicted ("if-open" period) data for 6 days were analyzed to extract the amplitudes and phases of only two constituent bands, centered on semidiurnal (M_2) and diurnal (K_1). M_2 and K_1 constituents contain energy from other semidiurnal (e.g., N_2, S_2, and K_2)

Table 1. *Amplitudes (cm) and phases (°) during closed (30 March 2007 to 4 April 2007; Julian days 89–94) and open periods (9 April 2007 to 8 May 2007; Julian days 99–128) at stations A–C.**

	Stations Closed Period			Stations Open Period		
Constituents	A	B	C	A	B	C
O_1	8.8 (55.8)	5.3 (89.3)	5.9 (89.8)	9.3 (61.6)	3.6 (91.6)	3.7 (107.2)
K_1	18.1 (62.5)	12.8 (106.3)	14.8 (96.9)	17.8 (61.8)	6.9 (127.8)	8.7 (131.0)
N_2	4.9 (303.6)	1.6 (25.0)	1.6 (49.8)	4.9 (303.6)	1.6 (25.0)	1.6 (49.8)
M_2	27.0 (341.4)	17.2 (63.0)	19.5 (65.7)	23.8 (339.5)	7.0 (59.2)	7.4 (89.9)
S_2	8.6 (37.6)	6.2 (125.6)	7.5 (125.9)	8.5 (36.1)	2.0 (115.0)	2.5 (146.8)
M_4	2.3 (140.3)	0.7 (108.3)	0.9 (85.1)	1.17 (98.3)	0.15 (325.2)	0.33 (352.7)
Form number†	0.41	0.77	0.77	0.84	1.17	1.25
Mean spring range (cm)‡	71.2	46.8	53.0	64.6	18.0	19.8
Mean neap range (cm)§	36.8	22.0	24.0	30.6	10.0	9.8
$2M_2–M_4$ (degrees)	182.6	17.8	46.0	220.7	153.2	187.1
M_4/M_2 (cm)	0.08	0.04	0.05	0.05	0.02	0.04

* Values in brackets are the phase angles.
† Form number = $(O_1 + K_1)/(M_2 + S_2)$.
‡ Mean spring range = $2(M_2 + S_2)$.
§ Mean neap range = $2(M_2 - S_2)$.

and diurnal constituents (e.g., O_1 and P_1), respectively (Pugh, 1987; Shetye *et al.*, 1995).

The second data set comes from the high-speed up-estuary transects (stations 1–6) along the channel's centerline from June 2008 to May 2009 (Figure 1) during the spring and neap tidal phases. The closing of the barrage began on 27 December 2008, and by 31 December 2008 it was fully closed. The sluice gates were partially opened on 29 March 2009, and the barrage was fully opened by 31 March 2009. The conductivity-temperature-depth (CTD) profiler was lowered from a speedboat (40 km/h) at various depths covering six stations along the southern arm of the estuary. An SBE Seabird 19 plus CTD was used for recording salinity (conductivity $\pm$ 0.001 S/m) profiles with a bin size 0.2 m. For the present study, the salt intrusion length (L_2, km) is taken as the upstream distance of 2 PSU isohaline (length from Cochin inlet along the river channel to the point where the bottom salinity was 2 PSU).

Additionally, monthly surveys were conducted at stations 1–6 in the middle of each month from June 2008 to May 2009 (Figure 1). Discrete bottle samples of surface waters were taken for the measurement of salinity and Chl *a*. Water samples were filtered for the subsequent determination of Chl *a* and pheopigment concentration. Surface salinity was measured with a salinometer.

The residence time *Tr,* defined as the time required for the total mass of a conservative tracer originally within the whole or a segment of the estuary to be reduced by a factor of e^{-1} (i.e., 0.37), is given by (Luketina *et al.*, 1998),

$$Tr = \frac{(V + P)T}{(1 - b)P + RT/2}$$

where V is the low-tide volume of the whole or a segment of the estuary, P is the tidal prism, T is the tidal period, R is river discharge, and b is the return flow factor. The tidal prism of Cochin inlet is estimated to be 107.8×10^6 m^3 during Indian Summer Monsoon (ISM, June–September), 18.6×10^6 m^3 during moderate runoff months (October–December), and 31.5 $\times 10^6$ m^3 during dry season (Rama Raju, Udaya Varma, and Pylee, 1979). The semidiurnal period (time 1242) is the predominant tidal period. Return flow factor (b) is the fraction of ebb water returning to the estuary during the subsequent flood tide and can be taken as 0.5 following SCCC (1985) and U.S. EPA (1985). The volume of the southern arm of the estuary is taken as 360 million m^3.

The daily and monthly mean river discharge data for the 2008–2009 year were sourced from the Central Water Commission, Government of India, for six gauging stations corresponding to six major rivers. The discharge was high during ISM with little runoff during dry periods. For the present analyses, river discharge is the sum total of the runoff of rivers flowing into the southern arm of the estuary. The daily mean discharge was used for statistical analysis and for computation of residence time.

RESULTS AND DISCUSSION

Tidal Propagation

The observed de-meaned sea level data at the three stations for 40 days (Julian days 89–129) are presented in Figure 2. The sea level variability was found to be higher at the Cochin inlet (station A) and decreased toward the upstream direction. The spring-neap variability in sea level was obvious at stations A and B. Evidently, during the barrage closed period, tides are much amplified at C and, to a lesser extent, at B, too. It is interesting that the observed tidal range at neap phase during the TB closed period was found to be much higher than the spring phase for the TB open condition.

The amplitude and phases of major tidal constituents derived from 1 month of data at three stations are shown in Table 1. The amplitude of the tidal constituents was higher at station A compared with stations B and C. M_2 tide dominated the K_1 tide at A, whereas at B and C, these two constituents were almost comparable in magnitude. The mean spring range was higher at A than the neap range, but they were comparable at B and C. The form number indicates a slighter increase of dominance in diurnal constituents in the upstream stations when compared with the inlet station. The downstream and farthermost upstream regions of this estuary is ebb dominant, mainly

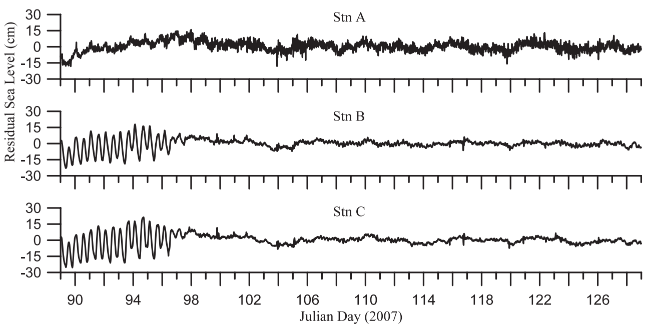

Figure 3. Residual sea level for the period Julian day 89–128 (March), 2007 at Stations A–C. The period 99–128 was used for obtaining the tidal constituents.

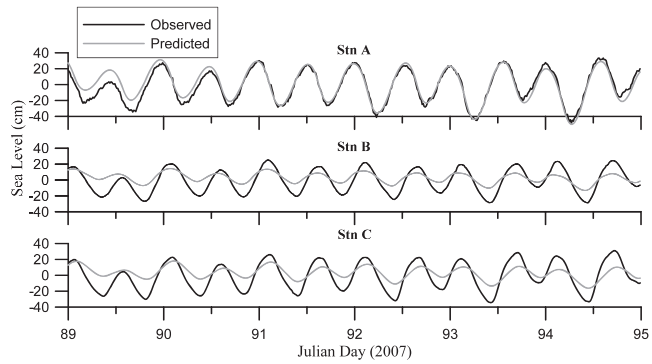

Figure 4. Observed and predicted sea level for the period Julian day 89–94 (March), 2007 at Stations A–C. The predictions are based on one month data during which the Thanneermukkam barrage was open (Julian Day 99–128 (March)).

because of the large width of the channel in those regions where a large volume of water is stored during the high tide. The ebb and flood dominance remain the same at stations A and B, respectively, during both the TB open and closed periods. Interestingly, station C was transformed from ebb dominant to flood dominant during the TB closed period. The increase of M_4/M_2 amplitude ratio at this station also indicated a higher degree of tide distortion when the TB was closed (Table 1). Flood-dominant systems infill the estuary, whereas ebb-dominant systems flush sediment seaward (Aubrey and Speer, 1985; Boon and Byrne, 1981; Manoj, Unnikrishnan, and Sundar, 2009). Changes in ebb and flood dominance in this region because of the opening and closing of the TB can influence sediment transport pathways and morphological evolution.

The residuals (difference between the observed tide and the predicted tide) for the 40-day period (including the 6-day closed period) are presented in Figure 3. During the TB closed period, even though we did not observe any conspicuous feature at A, distinct wave-like patterns were observed at B and C. It shows that the periodicity of this wave is not effectively filtered by tidal analysis. The amplification of these signals was most likely a result of standing wave formation. To understand this aspect in detail and to quantify the amplification, we performed harmonic analysis of tidal signals during the closed period and the if-open period (Table 2; Figure 4). The analysis showed that diurnal and semidiurnal tidal bands were amplified by a factor of 2.6 and 1.6 at station C when the TB was kept closed. The strong amplification signatures of the above two bands were also seen at station B.

Salinity Distributions and Variability

The salinity transects revealed the dynamics of salinity intrusion under various river discharge conditions and tidal phases. The monthly mean discharge into the southern arm of the Cochin estuary during the observation is presented in Figure 7a. The observations began on 19 June 2008 when the barrage was open. The maximum salinity gradient was marked at station 1 near the inlet, and it declined to 0 at station 6 near the TB. The salt wedge formation, which began in neap of June (Figure 5b), became more prominent in July as a consequence of high run-off (Figure 5c). Stratification that evolved in the water column of the estuary allowed the low-saline river water at the surface to flow over the high, dense water at the bottom. During ISM, salinity (18–34) intruded into the estuary only through the bottom waters of near inlet stations. All other stations remained well mixed, and salinity profiles were as low as 0.05 until September.

From October to December (Figure 5i–m), with the decreasing trend in river flow, saline water was pushed farther upstream. The active displacement of isohalines commenced. A consistent increase in salinity (~3 PSU) was discernible toward upstream. The river flow conditions prevented the intrusion of

Table 2. *Changes in the tidal bands (amplitudes/phases) caused by the closed barrage vis-à-vis the if-open barrage during a 6-d period (Julian days 89–94).*

Station	Diurnal C	Diurnal O	Amplification	Change in Phase (°) (O–C)	Semidiurnal C	Semidiurnal O	Amplification	Change in Phase (°) (O–C)
A	7.5	5.8	1.3		25.7	25.8	1.0	
B	5.6	2.6	2.2		18.8	7.4	2.5	
C	6.8	4.3	1.6		22.1	8.6	2.6	
A	45.2	36.2		−9.0	9.8	8.2		−1.6
B	94.8	112.0		17.2	101.9	89.6		−12.3
C	78.9	104.5		25.6	102.2	121.2		19.0

C, closed period; O, if-open period.

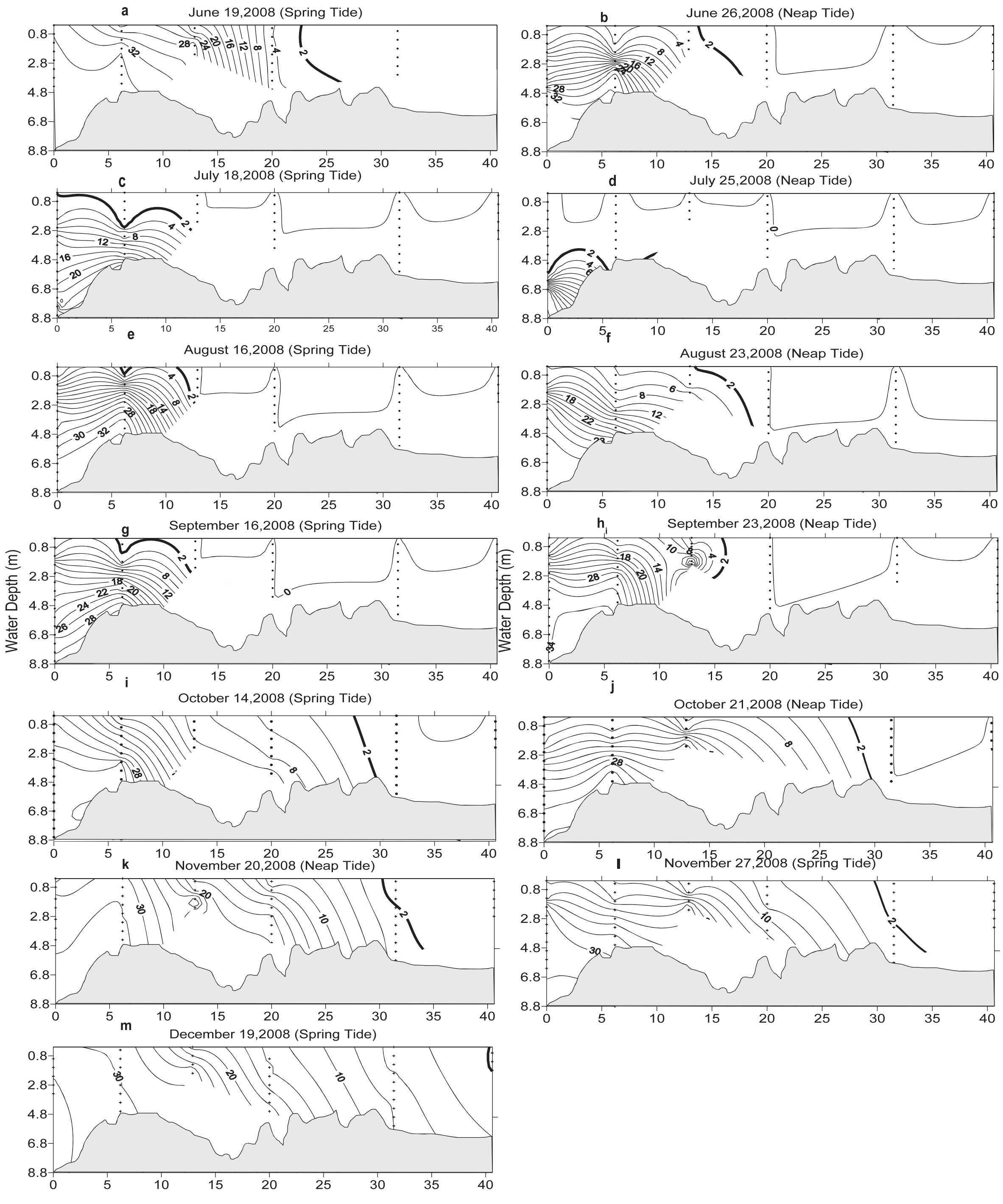

Figure 5. Longitudinal synoptic distribution of salinity measured monthly twice (one spring, one neap) during TB is opened condition starting from June 2008 to December 2008. The Cochin inlet is pointed at "0". The 2 PSU isohaline is highlighted.

salinity to station 6. However, during the spring phase of December (Figure 5m), the river discharge decreased further, and the salinity at station 6 was 2 PSU.

The closed period survey began with the neap phase of December (Figure 6a). The peak dry season (January–March) occurred when river flow was about 30–40 m^3/s (Figure 6b–g). The gradual closing of the barrage, compounded with the reduction in river flow and tides forced from Cochin inlet, triggered the horizontal salinity transport. A salinity of at least 14 PSU remained upstream throughout the closed period,

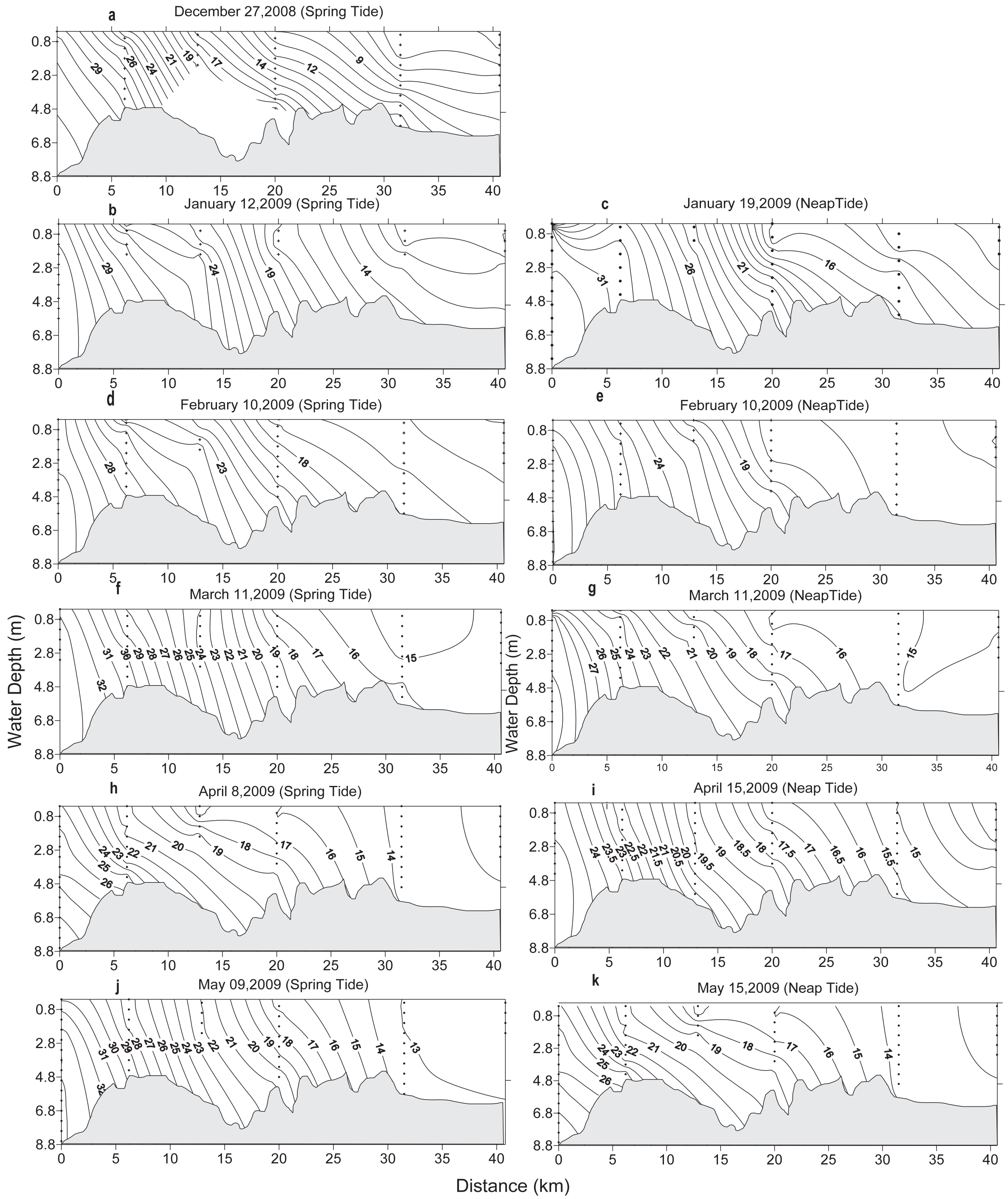

Figure 6. Longitudinal synoptic distribution of salinity measured monthly twice (one spring, one neap) during TB closed condition starting from December 2008 sprint observation to May 2009. The Cochin inlet is pointed at "0."

which indicates an increased salinity concentration compared with the high-discharge period. The TB was opened in April, and flow from the four rivers was allowed to enter the system. Consequently, a drop in salinity was found at station 6 in April and May.

Salinity Intrusion and River Discharge for High and Moderate Runoff Periods

The above results suggest that salt intrusion is strongly dependent on river discharge rather than tide during the high and moderate runoff months (TB open period). A minimum salt intrusion of 10 km was attained during the peak monsoon month of July when river discharge was 1118.2 m^3/s. As the river discharge decreased in the following months, the salinity field began to expand upstream. Maximum salt intrusion was observed under minimum runoff conditions (32 m^3/s) on 19 December 2008. Salinity intruded until TB, achieving an L_2 value of 40.6 km (Figure 5m).

The TB was closed on 23 December 2008. Salinity > 2 PSU was observed at all stations from 27 December 2008 (Figure 6a–k). The salinity increase was seen even in the upstream regions. Several regression equations between salt intrusion and daily mean river discharge were considered. Best results were obtained between L_2 and R using a third-order polynomial regression ($r^2 = 0.87$; Figure 7b). A similar relationship using a second-degree polynomial is found in the Strymon River estuary (Haralambidou, Sylaios, and Tsihrintzis, 2010). Comparing the results with the Strymon River estuary, the salt intrusion in Cochin estuary is much more sensitive to changes in river discharge. This is a feature typical of estuaries along the Indian coastline that are influenced by the ISM (Shetye, 2011). Therefore, the empirical equation relating salt intrusion (L_2, km) and river discharge (R, m^3/s) during the TB open period was determined as:

$$L_2 = -6 \times 10^{-08} R^3 + 0.000R^2 - 0.119R + 44.50$$

From Figure 7b it is obvious that the trend in salt intrusion is exponentially decreasing with increasing river discharge when $R < 400$ and steadily decreasing when $R > 400$.

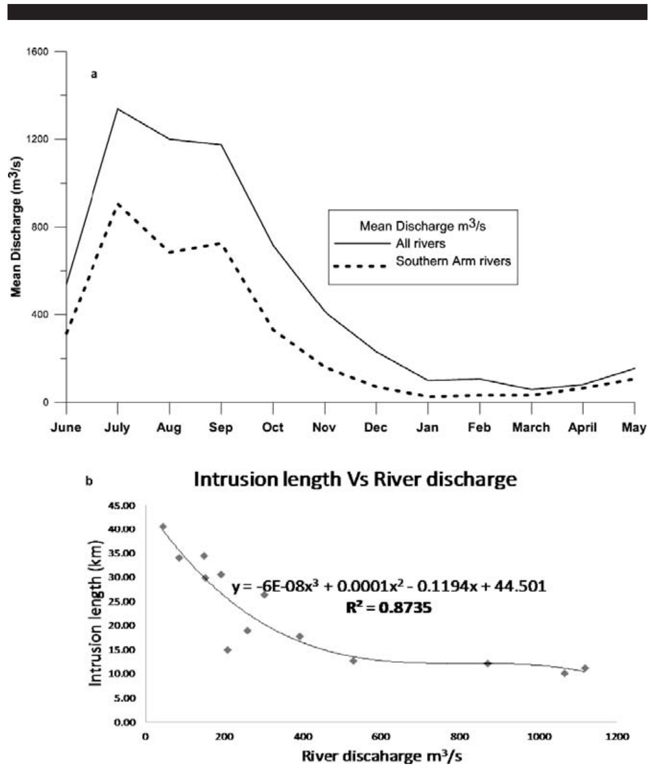

Figure 7. (a) Monthly mean river discharge during the year 2008–2009. (b) Polynomial regression between 2PSU isohaline intrusion length and river discharge.

Chl *a*

Figures 8 and 9 illustrate the seasonal surface concentrations of suspended Chl *a* and salinity along transect stations of the southern arm of the Cochin estuary. The trend of salinity intrusion discussed above was also reflected in the observations of surface salinity. Longitudinal distributions of surface salinity in all months showed the upstream progression from coastal waters to brackish or fluvial waters. During the ISM, very low salinity was observed along the surface of the estuary (Figure 8a–g). Surface salinity was 0 throughout the estuary during July owing to the greater freshwater runoff. During the period October–November, freshwater runoff was relatively low. As a result, a surface salinity > 30 was seen at ocean-end stations, and the salinity of river-end stations also increased (Figure 8e–g). From January–March (Figure 9a–c), high surface salinity levels were noted at all stations. Spatially averaged surface salinity was maximum (19.95) in February. During April–May surveys (Figure 9d and e), the TB was reopened, and the river flux into the estuary increased. Consequently, a relative decrease in salinity was observed throughout the southern arm of the estuary.

Chlorophyll *a* levels showed large spatial variability (Figure 8 and 9). During the TB open period, elevated levels of Chl *a* were observed at river-end stations 5 and 6 (Figure 8a–d). During the peak runoff period of July, chlorophyll concentrations of 7.4 mg/m^3 were found at upstream-end station 6 and 4 mg/m^3 at near-inlet station 1. This could signify the dominance of freshwater species advected into the system as a result of freshwater runoff. This situation continued from October to November as well, but Chl *a* concentrations at stations 5 and 6 increased further to about 14 mg/m^3. During the December survey, the TB was closed. Coincidentally, the surface Chl *a* at stations 5 and 6 drastically decreased (~3 mg/m^3). Stations 3 and 4 were brackish and contained high chlorophyll concentrations (Figure 8g). In January, river flow was very low, with an overall decrease of Chl *a* (average 3 mg/m^3) along the surface of the estuary (Figure 9a). The low runoff ensured strong saline intrusion, which might have provided stress to various organisms. However, biomass increased at ocean-end stations by February (13 mg/m^3 at Cochin inlet), whereas it decreased at stations 5 and 6 (~3 mg/m^3; Figure 9b). Thus, the distributions of Chl *a* were converse to the TB open period. The higher Chl *a* levels were observed at oceanic salinity, indicating the dominance of marine species. When the TB was again opened in April, the little river discharge from the four rivers entered into the system. Although suspended Chl *a* levels were higher at station 1 (13 mg/m^3), the concentrations (9 mg/m^3) increased at stations 5 and 6 as well. This possibly arose because the different salinity ranges could have supported a more diverse species population with relatively higher biomass (Figure 9d and e).

River discharge is related to flushing rate, with a statistically significant negative correlation between discharge and biomass accumulation (Filardo and Dunstan, 1985). Residence time was 3 days during the high–river flow period (June–September) and 11 days during the moderate–

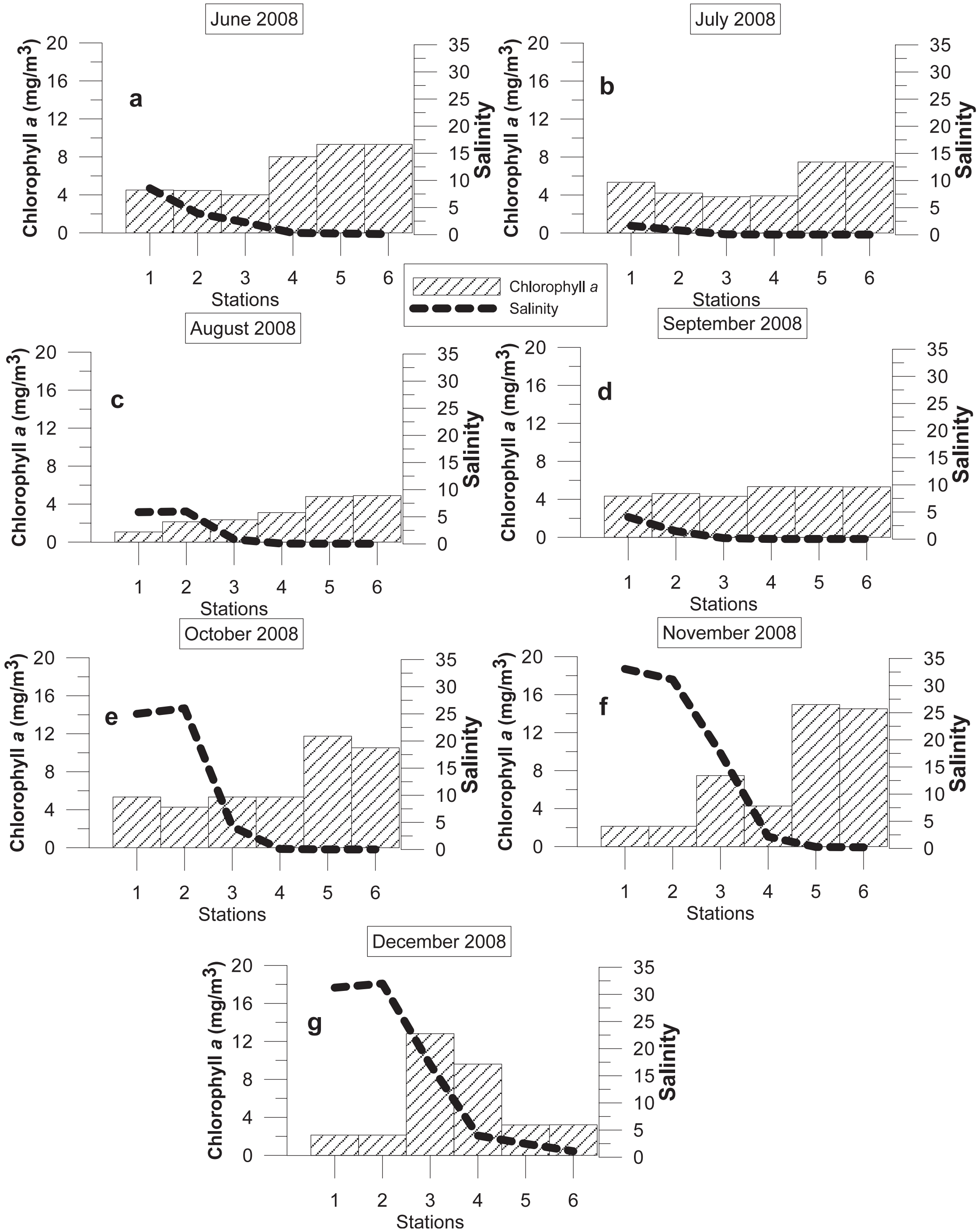

Figure 8. Monthly surface salinity and surface chlorophyll *a* from June 2008 to December 2008.

river flow period (October–December). During the low–river flow period (January–May), residence time was highest and ranged from 13 to 14 days. The above discussions of Chl *a* clearly depict the hydrodynamic controls on biomass. Despite nutrient enrichment of the estuary during ISM as a result of terrestrial runoff (Joseph and Ouseph, 2008), average surface Chl *a* levels were relatively lower during monsoon (June–September) than during peak dry season. We have speculated tentatively that high flushing during monsoon resulted in a low chlorophyll concentration in surface layers where

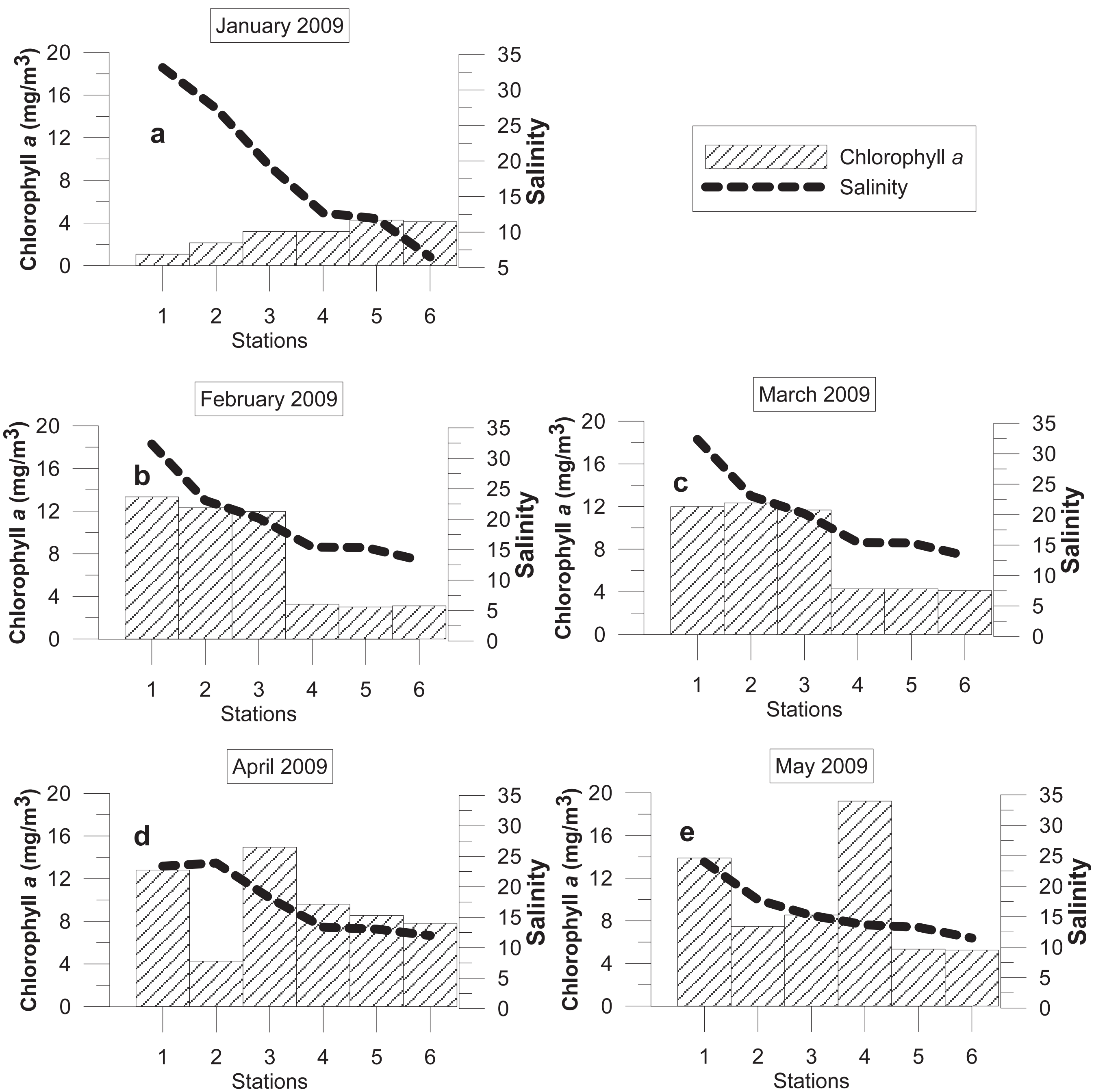

Figure 9. Monthly surface salinity and surface chlorophyll *a* from January 2009 to May 2009.

salinity was low. The most likely source for higher Chl *a* concentration in the river-end stations were freshwater runoff from rivers south of the TB, although these algae would also be flushed rapidly once they were discharged into the estuary. However, when discharge decreased during October–November, reduced flushing and higher residence times favored the sustainability of species in the estuary. During the dry season, low discharge and the highest water residence conditions resulted in relatively higher biomass accumulation.

SUMMARY AND CONCLUSION

In the present paper, we could bring out the amplification effect on tides when the TB was closed by using a limited 6 days of sea level data. The amplification was of such an extent that the neap phase range during the closed condition was greater than the spring phase range during the open condition. Our study shows that the TB has a significant role in transforming an ebb-dominant region to a flood-dominant region, which can lead to morphological modification of the estuary.

The TB acts as a salinity barrage for regions south of it but acts as a freshwater regulator to the estuarine region north of it. During the open period, salt intrusion was strongly dependent on river discharge during months of high and moderate runoff. Salinity intrusion was highly dynamic, with the distance of upstream intrusion inversely related to river discharge. During the dry season, salinity was regulated by controlled discharges from four rivers south of the TB. When the TB was completely closed, freshwater runoff was reduced as flow from the four rivers was impeded. Salinity concentrations increased throughout the southern arm, including the upstream regions.

Chlorophyll *a* levels showed large spatial variability and were dependent on the hydrodynamics of the estuary. It seems that freshwater species dominated upstream, which were higher during high-runoff months. During dry season, the ocean-end stations exhibited high chlorophyll, implying the dominance of marine species. Biomass was generally low during high runoff surveys, whereas it was relatively higher during low-runoff surveys. With rapid flushing of the Cochin estuary in monsoon season, it is hypothesized that it was not possible for several algal cell divisions to occur before algae were flushed. Under low discharge and the highest water residence, the estuarine environment supported relatively higher biomass accumulation.

Sarma *et al*. (2009) documented that river discharge can alter the trophic status of the estuary, influencing plankton metabolic rates. They found that a net heterotrophy with low gross primary production occurred during the peak discharge period in the tropical monsoon–driven Godavari estuary. Cochin estuary is of the same kind, but without complete cessation after monsoon. In the Cochin estuary, the ratio of primary production to community respiration ranges from 0.05 to 8.5 seasonally (Thottathil *et al*., 2008). Because the TB regulates river discharge, this barrage can influence the metabolic activity of the estuary. The present study is persuasive evidence of hydrodynamic controls on the accumulation of phytoplankton biomass. These findings highlight the need for future studies focusing on changes in phytoplankton metabolic activities associated with the opening and closing of the TB using a daily measurement strategy.

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Discussions

Ambiguities in the classification of Cochin Estuary, West Coast of India

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Abstract

Cochin Estuary is a unique complex system along Indian coastline with a widespread area at the upstream. The fluctuations in salinity are of extreme kind ranging from entirely riverine to entirely saline. The high runoff months are characterized by monsoonal spells causing intense flushing. During the peak dry period, the runoff is less but steady providing a stable environment. River runoff is controlled by short term variations rather than long term variations. Using large comprehensive data sets, an attempt is made to evaluate several classification schemes for the estuary. The existing methods proved to be insufficient to represent the real salient features of this typical estuary. Arguments are also presented to illustrate the confusion in the names by which the estuary is commonly known. Therefore, a new nomenclature is proposed as "Cochin Monsoonal Estuarine Bay" embodying the physiographic, hydrographic and biological features of the estuary.

1 Introduction

Estuaries are always dynamic and often exhibit a gradient in conditions from absolute riverine to oceanic which makes estuarine classification a complex matter. For a specific estuary, the classifications dealing with one type may change from one type to another in consecutive tidal cycles, or from month to month and from season to season or even from one location to another within the estuary. Additionally, the system may undergo changes under the influence of natural hazards or even anthropogenic influences. According to Valle-Levinson (2009), the most widely accepted definition of an estuary was proposed by Cameron and Pritchard (1963). According to their definition, an estuary is a semi-enclosed coastal body of water which has a free connexion with the open sea and within which sea water is measurably diluted with fresh water from land drainage. The above definition of an estuary applies to temperate (classical) estuaries but is irrelevant for arid, tropical and subtropical basins. Arid basins and those forced intermittently by freshwater exhibit hydrodynamics that are consistent with those of classical estuaries and yet have little or no freshwater influence. Under this general definition, estuaries may be further separated into various classifications. Estuaries have been long studied and classified based on their stratification or vertical stricture of salinity (Pritchard, 1955; Cameron and Pritchard, 1963; and later Dyer, 1973, 1997), water balance (Valle-Levinson, 2009), geomorphology (Fairbridge, 1980), tidal characteristics (Hayes, 1975; Dyer, 1995). and combination of characteristics (Savenije, 2005). In addition to this classification schemes Indian estuaries have a special flavour that is derived from occurrence of monsoon and they are referred as monsoonal estuaries (Vijith et al., 2009).

Thus, a realistic classification, representative of its true characteristics can be done only after understanding the dominant dynamic processes of an estuary. This demands rigorous investigation in to the dynamics of each section of the estuary using comprehensive data sets. Then that an estuary can be uniquely placed into the most appropriate category which it deserves.

Cochin Estuary, situated along west coast of India, attained its present configuration as a result of natural and man-made interventions. It was primarily a marine environment bounded by an alluvial bar parallel to the coast line and interrupted by Arabian Sea at intervals (Gopalan et al., 1983). For the establishment of Cochin Port in 1936, the “natural bar” is dredged out while deepening the channel to make the basin accessible for ocean going vessels (Strikwerda, 2004). The peculiar behaviour of this estuary at times makes its classification an arduous work. This is clearly revealed by the different names it is being introduced in various literatures.

In this context, our main objective is to coin a new terminology for Cochin Estuary that is representative of its behaviour as a whole. This is achieved by collating past evidences and by examining the present characteristics of the estuary using recently acquired large data sets. Estuarine classification schemes based on relatively easily measurable parameters (Hansen and Rattray, 1966) and climatological factors like river runoff (Vijith et al., 2009) are also evaluated for the estuary to determine how well the

classification schemes represents the reality. The constraints imposed by these classification schemes evidenced the uniqueness of the region. Due to all these reasons, we propose a new nomenclature Cochin Monsoonal Estuarine Bay (CMEB) for this estuary. With this nomenclature is buried the physiographic, hydrographic and biological characteristics of the system which are elucidated in the following discussions.

Physiographic setting

Cochin Estuary is the largest estuarine system along the west coast of India. It is a part of Vembanad-Kol wetland system, one of the three Ramsar sites in Kerala (November 2002), which extends from Munambam (10°10′ N, 76°15′ E) in the north to Alappuzha (09°30′ N, 76°28′ E) in the south at over 96.5 km in length (Fig. 1a). The estuary is characterized by its major axis lying parallel to the coastline, with several small islands and interconnected waterways, and it covers a surface area of about 300 km^2. The width of the estuary varies from 450 m to 4 km and the depths range from 15 m at Cochin inlet to 3 m near the head with an average depth of 1.5 m (depths are reduced to chart datum). The system is separated from the Arabian Sea by barrier spits interrupted by tidal inlets at two places, namely (i) Munambam in the north (inlet 1) and (ii) Cochin inlet in the middle (inlet 2). The Cochin Port, situated on the Willingdon Island, is near the inlet 2, which provides the main entrance channel to this system. Tides in the estuary are mixed, predominantly semi-diurnal type with an average tidal range of 1 m (Qasim and Gopinathan, 1969). Freshwater into estuary is primarily contributed by six rivers. The branch of Periyar River feeds 30 % of its discharges into the northern parts of the estuary. The remaining 70 % discharges directly into the Arabian Sea through the inlet 1. Muvattupuzha River joins along the length of the channel whereas Pampa, Achankovil, Manimala, and Meenachil join at the upstream end. During the dry season, the runoff originating upstream is minimal which ensures strong saline intrusion to the low-lying paddy fields located further upstream (Shivaprasad et al., 2012) (Fig. 1a). Therefore, a salt water barrage called Thanneermukkam Barrage (TB) was constructed in 1976 which is thereafter kept closed during the dry season to facilitate paddy cultivation.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

For the present study, the region is divided into two parts (Fig. 1a): the northern arm extends from Cochin to Munambam and the southern arm extends from Cochin to Thanneermukkam. Both the arms of the estuary receive significant amount of freshwater throughout the year; larger in southern arm than the northern arm. When the TB is closed, Muvattupuzha River contributes to the freshening of the southern arm. The two arms behave differently in physiographical and hydrographical aspects and hence treated separately.

2 Data sets

Three sets of daily runoff data of six rivers were obtained from Central Water Commission, government of India for six gauging stations: Viz, 1978–2001; 1985–1989 and 2008–2009. The first two sets were long term data were used for the validation, sufficiency and completeness of the runoff data for the year of the present study. This is the most detailed climatology of this estuary published to date. The mean monthly runoff during the year of study (2008–2009) is shown in (Fig. 1b). About 73 % of the total river runoff occurred during (wet season) characterized by monsoon. The mean inflows to the estuary varied from a maximum of 1000 $m^3 s^{-1}$ in July to a minimum of 49 $m^3 s^{-1}$ in March.

Based on river runoff, the annual seasonal cycle is distinguished as high runoff months characterised by Indian summer monsoon or ISM (June–September), moderate runoff months characterised by north-east monsoon or NEM (October–December) and low runoff months or dry period (January–May).

Accordingly a major field campaign under the programme “Ecosystem modelling” was designed and a long term salinity data were acquired so as to cover most of the range over which salt intrudes from the Sea. The first data set of salinity comes from the longitudinal transect measurements covering ten stations from June 2008 to May 2009 (Fig. 1a). CTD (SBE Seabird 19 plus) casts of temperature (accuracy ±0.001 °C) and salinity (conductivity ±0.001 Sm^{-1}) profiles were taken from a small

boat (40 $km h^{-1}$) for every 8 km in the deepest part of the main channel during the spring tides of each month. Stations, 1–4 were located in northern arm and the stations 5–10 were located in the southern arm. The second data set of salinity was obtained from a daily monitoring station near to the inlet 2 (Fig. 1) where the vertical profiles of salinity were collected every day at 11.00 a.m. LT (local time) during the same year (May 2008 to April 2009).

The third data set was obtained from time series observations under three runoff conditions during 2009–2010. Salinity and velocity were measured during the spring phases of tides at five stations distributed along the channel axis (Fig. 1a). Stations A and B were along northern arm and stations D and E were along southern arm. Station C represented inlet 2. Sampling was conducted on spring phases of October 2009, February 2010 and August 2010. These months were representative of moderate runoff, dry and high runoff periods respectively. Each observation started at 09:00 a.m. LT and finished at 09:00 a.m. LT of the next day. For every 24 h observation, CTD was lowered at 30 min interval. Current meters (RCM-9) were moored and velocity was measured at 10 min interval from near surface and bottom. Water level data for the five stations in February 2010 was obtained from permanent mooring stations of the field program. The estuarine volume was estimated from digitization of recently developed bathymetry charts using 3-D Analysis tools in ArcGIS software.

2.1 Statistical analysis on river runoff data

The main objective of the statistical analyses was to substantiate the credibility of the objectives studied based on the runoff data for a single year 2008–2009. For this purpose, the data of average monthly runoff for 1978–2001 and 1985–1989 was obtained by calculating the arithmetic means of daily runoff data. Utilizing these past sets of data, monthly total runoff for the year 2008–2009 was predicted using the best polynomial fitted for the average monthly runoff of past data sets among a set of different polynomials (Fig. 2a). For the period of 23 yr (1978 to 2001), there were some missing data of four rivers but for the period 1985–1989 the data from all the six rivers were obtained. Hence the river runoff was analyzed for time series components using the two data sets for the periods: 1978–2001 and 1985–1989 and to determine the type of variations which influences the river runoff of 2008–2009.

To determine the main contributing components to the river runoff, a multiplicative time series model was fitted. Since the data sets were complete for the period 1985–1989, time series analyses were carried out for this period only. The multiplicative model (Holt winter) was chosen in which the observed monthly runoff is equal to product of long term trend (T), seasonal variation (S), cyclical component (C) and irregular variation (I) in the runoff i.e.,

$$O = T \cdot S \cdot C \cdot I. \tag{1}$$

Trend, "T" was identified by centered moving average (MA) of period 2. Centered MA of period 2 implied that river runoff at a time point "t" was determined by runoff at $t-1$, t and runoff at $t+1$ with weights 1, 2 and 1, respectively. This triplet was the best preferred one, since the plots of other periods (3 to 12) explained the observed runoff very poorly. River runoff was observed to follow the moving average trend of period 2 very precisely (Fig. 2). Seasonal variation, "S" in each month was explained by the seasonal index computed as the simple average of (O/T) over all the years for each month. Cyclical variation was computed as a percentage of moving average as

$$C = \left[\left(\frac{O}{\mathrm{SI}}\right) - \mathrm{MA}(2)\right] \cdot 100/\mathrm{MA}(2) \tag{2}$$

where SI is the average variation adjusted to 12 as

$$\mathrm{SI} = \left[\text{Average monthly } \left(\frac{O}{T}\right) \cdot 12\right] / \text{Total of all average monthly } \left(\frac{O}{T}\right) \tag{3}$$

and MA(2) is the moving average of period 2. Cycles in the variation was clearly explained by the cyclical variation with a period of 12 months for repeated cycle (Fig. 2).

Irregular variation gets removed while averaging at different stages. Then these three time series components were used as independent variables to determine the regression of runoff on these components.

The river runoff (Y) was regressed on moving average of period 2 (X_1), seasonal variation (X_2) and cyclical variation (X_3) and their first order interactive effects. Step up multiple regression method was applied to determine the $2^3 \times 6$ models (Snedecor and Cochran, 1967; Jayalakshmy, 1998).

Multiple regression model fitted is of the form

$$Y = a_0 + \sum_{i=1}^{i=k} a_i X_i + \sum_{i=1}^{i=k} \sum_{j=1, i<j}^{j=k} b_{ij} X_i X_j \tag{4}$$

where $a_i, b_{ij}, i, j = 1, 2, 3, \ldots$ and $i < j$ are the regression coefficients of the individual effects and the corresponding interaction effects, respectively. To determine the contribution levels of the components uniquely, first order and second order partial correlation coefficients were calculated (Snedecor and Cochran, 1967). First order partial correlation coefficient is

$$r_{ij.k} = \frac{r_{ij} - r_{ik} r_{jk}}{\sqrt{(1 - r_{ik}^2)(1 - r_{jk}^2)}} \qquad i, j, k = 1, 2, 3, 4 \tag{5}$$

where 1 = river runoff ,
2 = MA(2),
3 = Seasonal variation "S",
4 = Cyclical variation "C".

Second order partial correlation coefficient is

$$r_{ij.kl} = \frac{r_{ij.k} - r_{il.k} r_{rl.k}}{\sqrt{(1 - r_{il.k}^2)(1 - r_{jl.k}^2)}} \tag{6}$$

or

$$r_{ij.kl} = \frac{r_{ij.l} - r_{ik.l}r_{jk.l}}{\sqrt{(1 - r^2_{ik.l})(1 - r^2_{jk.l})}}. \quad (7)$$

Three partial correlations have (n – 3) and (n – 4) degrees of freedom respectively for first order and second order.

3 Results and discussion

3.1 Prediction from polynomial fitting

A sixth degree polynomial was obtained as the best prediction equation for 1978–2001 and 1985–1989 data sets. The equations were

$$Y = 0.485X^6 + 19.49X^5 - 300.3X^4 + 2205X^3 - 7802X^2 + 12214.0X - 6191.0 \quad (8)$$

for 1978–2001 and

$$Y = -0.321X^6 + 13.06X^5 - 204.3X^4 + 1523X^3 - 5456.X^2 + 8624.0X - 4359.0 \quad (9)$$

for 1985–1989 where Y is the total monthly runoff and X is the month number 1,2,3. . . 12 from June to July.

Equation (8) could predict 2008–2009 runoffs with only 27.36 % prediction efficiency whereas Eq. (9) could predict it with 83.69 % prediction efficiency. The lower values for prediction efficiency from the 23 yr data could be due to the missing data. Since total monthly runoff was predicted with high efficiency from the past data of 1985–1989, it followed that further analysis made in this study using the 2008–2009 runoff data could be generalised.

For the 1985–1989 monthly runoff data, time series components were calculated and the adjusted seasonal indices for June to July are 130.89, 108.28, 92.67, 115.88,

120.41, 79.58, 76.86, 107.04, 111.85, 69.98, 69.33 and 117.23 %, respectively. From the $2^3 \times 6$ models (Jayalakshmy, 1998), ($2^k \times r$, where k is the number of independent parameters and r is the number of transformations for the dependent and independent variables) the one which explained the maximum variability and in which the independent variables were uncorrelated was chosen. The optimal model for this study was the simple model,

$$\mathrm{LOG}_{10}Y = -1.4453 \times 10^{-7} + 0.8839 \cdot \mathrm{LOG}_{10}T + 0.2405 \cdot S + 0.002416 \cdot C. \quad (10)$$

It could explain about 99.86 % of the variability in the river runoff distribution during 1985–1989. The other models were depicted in Table 1. These regression models were fitted assuming that the three components are independent. From the regression models fitted, moving average of period 2 represented the observed runoff with 94.72 % of precision (Table 1).

Seasonal variation measured by seasonal index indicated up to what level, runoff was affected seasonally (Table 1). A seasonal index more than 100 indicated that runoff was increased by an amount equal to that of seasonal index in excess of 100 implying a positive effect of seasonal variation. Similarly, a seasonal index less than 100 implied that runoff was decreased by an amount equal to that of seasonal index in deficit of 100 implying a negative effect of seasonal variation on the runoff. If seasonal index for any month was 100 %, then it implied that there was no effect of seasonal variation on the runoff. In this study, seasonal variation could explain only 31.32 % of the variability in the runoff. Based on 1985–1989 data sets, seasonal effect was positive on the river runoff of June, July, August, October, November, February and March. For the rest of the months, seasonal effect was negative on the average. The observed runoff was mostly controlled by the trend effects of the optimal period determined.

Cyclical variation provided the period of repetition of the peak of minimal runoff. The period was unique with 12 months approximately (Fig. 2b). Cyclical variation could explain only < 1 % of the variations in the runoff. Hence, it could be stated that the observed runoff was mostly controlled by the trend effect and to some extent by the seasonal variations only. From the graph (Fig. 2b), it can be understood that the cycles present were removed along with the trend effect as the observed curve and the trend curves were almost exact. The observed cycles presented for the MA were of period 12 months.

In order to study the contribution of 2 period centered moving average alone on the river runoff, second order partial correlation coefficient using the non transformed data was computed which was 0.96 ($P < 0.001$). Similarly, contribution of seasonal variation alone on the river runoff was also high with second order partial correlation coefficient as 0.93 ($P < 0.001$). On the other hand, contribution of cyclical variation alone on the river runoff was not significant, 0.30 ($P > 0.001$). Hence, river runoff was controlled by short term variations of period 2 months, but not by long term variations with periods > 2 months.

3.2 Salinity distribution

Annual variations

Figures 3 and 4 demonstrate how the stratification evolved in this system. Figures 4 and 5 show the longitudinal section of salinity distribution in estuary during one year. With the onset of ISM on 31 May 2008, the mean runoff was 356 $m^3 s^{-1}$ in June 2008 (Fig. 3a). As a result, oceanic salinities were confined to near-inlet stations (1, 5, and 6) and the river-end stations (2, 3, 8, and 9) were brackish. When the runoff peaked in July (1000 $m^3 s^{-1}$), the estuary transformed to a salt wedge type (Fig. 3b). Higher salinities (18–34) were found only in the bottom waters of stations 1, 5, and 6. The wedge formation was more prominent at stations 5 and 6 than station 1 which could be attributed to the greater depths of inlet 2. All the other stations remained well mixed with depth averaged salinity as low as 0.05 (Fig. 3b–d).

By October 2008, the salinity field expansion was established (Fig. 3e). From October to December, the runoff was moderate (on average 260 $m^3 s^{-1}$) and an accumulation of fresh water was observed only at the upstream regions (stations 8, 9, 10). However,

during the dry period, the river runoff decreased remarkably such that only 49 $m^3 s^{-1}$ occurred in March. Under limited river flows, the estuarine water column actively mixed and tended towards extremely low horizontal and vertical salinity gradients (Fig. 4b–f). The salinity field extended up to station 10 with maximum depth averaged salinity (15.12) attained in March (Fig. 4d). In May, there was a slight increase in runoff to 2.5 % of the annual runoff. The aftermath of an anomalous rainfall in the catchment of Periyar caused station 1 at the inlet 1 to be fresh water dominated (Fig. 4f).

3.3 Daily variations

Figure 6 depicts the daily salinity variations allowing to verify whether the daily rainfall modifies the salinity pattern of the station significantly. The daily rainfall pattern (Fig. 5a) was characterised by spikes of high rainfall during the active spells of ISM and NEM. During the ISM, strong spate occurred in July proceeding to the beginning of August too. Fresh water salinities occurred for most of the time. Occasionally, high saline waters were also observed at the bottom due to the intrusion of salt wedge. By the end of August, there was a lull in monsoon resulting in intrusion of high saline waters. Consequently, a single vertical profile of salinity ranging from 25 to 35 was noticed. Again by the second week of September, the monsoon regained its strength causing freshening at the station. The same conditions were again observed only by the end of October–November characterised by NEM. In contrast, during the rest of the year, high saline conditions (23–35) prevailed at the station. However Small peaks in rainfall were sighted in April and May which could not however, bring any effect on the salinity of that station.

3.4 Estuarine classifications based on hydrodynamics and runoff

3.4.1 Hansen and Rattray characterization

Hansen and Rattray (1966) developed a two-parameter system of estuarine classification in which the classes are delineated by the magnitudes of the relative stratification and circulation parameters associated with changes in the salt balance mechanism. The diagrams represent $\partial S/S_0$, where ∂S is the difference in salinity between surface and bottom and S_0 is the depth mean salinity, both averaged over a tidal cycle, as the ordinate. The circulation parameter U_s/U_f, where U_s is the surface velocity averaged over a tidal cycle and U_f is the discharge velocity, that is the rate of river discharge divided by the cross-sectional area, defines the abscissa. Here, the study exercised these parameters, calculated from the time series observations. These were then plotted on the relevant portion of the stratification-circulation diagram for three runoff conditions (Fig. 6).

The Fig. 6 shows reasonable agreement with the longitudinal monthly salinity observations discussed above. For high and moderate runoff months, the estuary exhibited similar characteristics. High $\partial S/S_0$ values were found at station (C) near inlet 2 tending them to fall in class "1b (stratified)" of the classification diagram. Station D occupied class "4" in the diagram suggesting a salt wedge type. This was because of the depth of station C so that the salt wedge thickness was higher reaching almost the surface. However, the wedge tapered towards station D allowing more freshwater to flow over it. Recorded U_s/U_f values were above 1 for all stations. Station B in the middle of the northern arm and upstream station E were fresh water dominated. In contrast, during the dry period, the system was well-mixed (classes "1a"). Whereas the values of $\partial S/S_0$ were below 0.1, U_s/U_f ratio was almost 1. This indicates an upstream transfer of salt by diffusion.

3.4.2 Uniqueness of Cochin Estuary among monsoonal estuaries

Vijith et al. (2009) state that estuaries that come under the influence of Indian Summer Monsoon (ISM) and for which the salinity is never in a steady state at any time of the year are generally shallow and convergent, i.e. the width decreases rapidly from mouth to head. In contrast, Cochin Estuary is having a widespread area at the upstream and has no typical river mouth entrance (as discussed under Sect. 1.1). Adding to the complexity it has dual inlets and the tidal range is 1 m which is lower than other Indian estuaries along west coast. These typical physical features lead to its uniqueness.

Vijith et al. (2009) had documented that the monsoonal estuaries experience total annual runoff which is many times of the estuarine volume and that there is a high "peakiness" or seasonality in the runoff. They used the following equations to represent the above two features:

$$\eta_R = \frac{R_a}{V_e} \quad (11)$$

where, R_a is the volume of total annual runoff (m^3) and V_e is the volume (m^3) with respect to mean sea level in the estuary. Higher the value of η_R, higher is the runoff. η_R was calculated as 42 for the Cochin Estuary indicating the chance that the estuary turns "fresh" 42 times(s) yr^{-1}.

The equation for second parameter is

$$\eta_T = \frac{\text{Maximum monthly runoff}}{\text{Mean monthly runoff}}. \quad (12)$$

Figure 7a shows the mean monthly runoff to monsoonal estuaries in India (Vijith et al., 2009). It can be plainly understood that while the runoff into other estuaries average to zero for about eight month-long dry season, the average runoff into cochin estuary is never zero. A steady runoff is maintained even during the peak dry period $\eta_T \sim 1$.

To zoom in the dynamics of the estuary, we reduce the above mentioned parameters into monthly scale. This will provide means to examine the seasonal variations in runoff.

We re-define the above classification parameters as written below:

$$Z_\mathrm{R} = \frac{R_\mathrm{m}}{V_\mathrm{e}} \tag{13}$$

$$T_T = \frac{\text{Total of the maximum among daily runoff of all rivers a month}}{\text{Total of mean daily runoff of all rivers in a month}} \tag{14}$$

where R_m is the volume of total monthly runoff (m^3) and V_e is the volume (m^3) with respect to mean sea level in the system. R_m is computed from daily runoff values shown in Fig. 1b. Z_T represents the daily variations in runoff. The computed values are presented in Fig. 7b.

During June Z_R was 2.06 when ISM was in the progressing stage whereas for the rest of the months of wet season $Z_\mathrm{R} > 5$. The observed maximum monthly runoff of wet season was $3.606 \times 10^9\,\mathrm{m}^3$ in July. For the moderate runoff months (October–December), the values were $1 < Z_\mathrm{R} < 4$ and $1 < Z_T < 3$ (Fig. 7b). From January–April, Z_R was about 0.3 and Z_T was almost 2. This indicated that although there were prominent daily runoff variations, for no single day of each month during the period, the runoff could flush the estuary. For it to occur, the runoff obtained should exceed to above 70 % of the estuarine volume. During May, the runoff was higher which completed the annual cycle with Z_R and Z_T showing 0.8 and 2, respectively.

Figure 7c, shows the Z_R values of Cochin Estuary with other estuaries in the world. The analysis showed that Z_R was an order of less than one for Tamar, Delaware, and Thames estuaries for all months and the standard deviation was 0.3. In the case of Columbia estuary, Z_R values were more or less comparable with Cochin Estuary with the standard deviation 1.3. However, the peak runoff in attained by Columbia in June was 6.5 which was less than that of Cochin Estuary by 2. For estuary, the peak in July with a value of 8.5 was featured by ISM. The influence of NEM on flushing of the estuary was negligible. The minimum Z_R of 0.3 occurred during peak dry. The high standard deviation of 3.0 obtained for cochin estuary suggested that the runoff exhibited large range of values over the months compared to all other estuaries.

To explore the flushing nature more closely, Z_R ratio for the two arms of estuary were calculated separately (Fig. 7c). It was found that, for July, with the Periyar River runoff in the northern arm Z_R ratio was 3.7. The runoff from all the other rivers was responsible for Z_R to go as high as 6.7 in the southern arm. The volume of southern arm was about 5 times larger than the northern arm. Notwithstanding this fact, the runoff into the south flushed the volume of the southern arm almost twice as that of northern arm. During August, the lull in monsoon (about $200\,\mathrm{m}^3\,\mathrm{s}^{-1}$ decrease from July) was characterised by an increase in runoff in the northern arm and a decrease in runoff into the southern arm. Consequently, an equal flushing of both arms ($Z_\mathrm{R} \sim 5$ in both the arms) resulted in transforming the estuary into a river. This implied that the uniform flushing of all the sections of the estuary could not be directly related to the “peakiness” of monsoonal spell and the subsequent runoff.

4 Cochin Estuary in a quasi-steady state

Implicit in several estuarine classification schemes commonly used for understanding estuarine dynamics is a steady state assumption. By the term “steady state” is meant that the average of the salinity concentration over a tidal cycle does not change from tide to tide if the river flow remains constant (Stommel, 1953). In such cases, during each tidal cycle the salinity at any location varies with the stage of the tide, but on successively similar tidal stages the salinity returns to substantially the same value (Ketchum, 1951). In an estuary like Cochin Estuary, such a steady state can be expected during the peak dry period (January–April). In order to establish this fact, we use the salt balance equations to determine the salinity steadiness in the Cochin Estuary.

The general unsteady salt balance is given by:

$$\frac{\partial}{\partial t}\int_{x}^{xr} S_{(x)}A_{(x)}\mathrm{d}x + RS = K_\mathrm{unst}A\frac{\partial S}{\partial x} \tag{15}$$

where $S_{(x)}$ is the salinity integrated over the volume of the estuary, and A is the cross sectional area, R is the river runoff, S is the average salinity. K_{unst} is the unsteady horizontal diffusion coefficient computed in the axial direction from x until the upstream location x_r.

With the steady state assumption, the time dependent term of Eq. (15) vanishes. The equation can then be re-written as:

$$RS = K_{\text{st}} A \frac{\partial S}{\partial x}. \tag{16}$$

K_{st} is the horizontal diffusion coefficient under equilibrium (steady state) conditions.

If the estuary is in a steady state, the total salt content of the estuary does not change, so the same volume R will have to leave the estuary at its mouth during one tidal cycle. Thus, by comparing K_{unst} with K_{st}, the steadiness of the salt balance can be diagnosed roughly. Dividing Eqs. (14) by (15), the ratio of K_{unst} to K_{st} can be obtained as:

$$\frac{K_{\text{unst}}}{K_{\text{st}}} = \frac{\frac{\partial}{\partial t}\int_{x}^{xr} S_{(x)} A_{(x)} \mathrm{d}x}{RS} + 1 \tag{17}$$

$$= \Phi + 1. \tag{18}$$

The steadiness of the salt balance was diagnosed for the months, January–April, when Φ was continuously > 0. The integral term in Eq. (17) was estimated using longitudinal salinity measurements (Figs. 4–5) from x to the upstream location x_r for two consecutive months. The averages of salinity S and runoff R for these two months were used. The ratios were computed for all sections from x (station 1) to x_r (station 10).

The analyses proved that the ratios approached 1 most of the time throughout the estuary. Occasionally, a maximum value of 1.5 was also obtained (Fig. 8). This is possible only if suggesting a steady state or rarely a quasi-steady state. The total salt content remains constant for the peak dry period. The period from March to April was in an

acute steady state even at the upstream. Specifically, along sections from stations 5 to 7, the balance was better achieved than the other locations. This is possible as Muvattupuzha joins between the regions which supplied a constant runoff. It is the only river that caused freshening in the southern arm during the period. The upstream salt flux was balanced by this runoff induced oceanward advective flux asserting a steadiness in salt balance.

Figure 9 illustrates the water level and salinity variations over a tidal cycle at five stations during February 2010. In each case the salinity at successive high tides returned to the value previously observed approximately. Therefore, Hansen Rattray classification holds well for this particular steady state of the estuary. Whatever be the runoff occurred during the period, it is not sufficient to bring the salinity at the upstream to zero. This typical feature is due to the diverging geometry of the estuarine channel unlike other Indian estuaries such as Mandovi and Zuari channels which are strongly convergent at the upstream regions (Manoj et al., 2009). For the Mandovi and Zuari, although the tidal flushing times are in the order of days during the dry season, so much of freshwater remains available at the upstream and these systems always lag behind steady state (Vijith et al., 2009).

The steadiness in salinity during dry period is even reflected in the abundance of zooplankton species which showed little variations during tidal cycles (Mathupratap et al., 1977). They had opined that these species appear to develop behavioural mechanisms in response to tidal changes which keep it in the water of same salinity throughout the tidal cycle by having some kind of biological clock or signal. So, we conclude that estuary is in a steady state for some time during a year and deserves to be placed under a "special" category among the monsoonal estuaries.

5 The physical-biological coupling

Cochin Estuary is one of the largest productive ecosystems along west coast of India with an estimated annual gross production of nearly 300 $\mathrm{g\,C\,m^{-2}}$ (Qasim et al., l969).

Its bioceonosis can be recognized as a physically controlled community. It may be called as a “tropical monsoonal estuary” due to the pronounced influence of monsoon on the ecology of the system bringing about a total change in the environment and fauna (Madhupratap et al., 1977). In such estuaries, the seasonality in salinity is a key feature as the ecosystems have to adjust accordingly. CMEB is more productive at all levels during dry season. The salinity gradient during the period favoured large species richness, species diversity and species evenness in zooplankton (Jyothibabu et al., 2006). Whereas in monsoon, the abundance of phytoplankton grazers (zooplankton) is reduced and this altered the trophic food web of the estuary resulting in substantial amount of unconsumed carbon at primary level (Madhu et al., 2010). A qualitative shift in phytoplankton composition (Qasim, 2003) and an increase in its biomass owing to high residence times (Shivaprasad et al., 2012, 2013) were also reported during peak dry conditions. In essence, the dry season provides a biotope supporting the survival of various high species as competitors, expanding their overlapping niches in space with time because of the facility provided by salinity intrusion. The impact of monsoonal effluxes and high flushing evokes its elimination and an “essential” cleanup of the estuary.

6 A new nomenclature: Cochin monsoonal Estuarine Bay

There are several ways in which Cochin Estuary was named in earlier studies. The estuary was sometimes called as a “lagoon” (Rao and Balasubramaniam, 1996); or very often referred to as “backwaters” (Sankaranarayanan and Qasim, 1969; Martin et al., 2008; Abhilash et al., 2012). Lagoons are shallow body of water at least intermittently connected with sea or other larger body of water across a beach or barrier (Snead, 1982). Cochin Estuary is permanently open to sea and is much larger and deeper than a typical lagoon. The Webster dictionary defines “backwaters” as part of river water backed up in its course by an obstruction, an opposing current, or the tide. Being an extraordinarily energetic and dynamic environment typified by strong currents

($1.3\,\mathrm{m\,s^{-1}}$) (Udaya Varma et al., 1981; Balachandran et al., 2008), the nomenclature “backwaters” remains subtle to this estuary.

The present analyses manifested that the assumptions implicit in the classification schemes discussed above limits their applicability to Cochin Estuary. There arises a need for a comprehensive classification system representing all the dominant conditions of the estuary. Such an approach was suggested by Whitefield (1992) for African estuaries using a combination of physiographic, hydrographic and salinity features. According to him, estuarine bays are estuaries that may be either natural or partly artificial due to dredging activities in the mouth and harbour region. They have a large tidal prism exceeding $10 \times 10^6\,\mathrm{m^3}$ and tides are the dominant force driving mixing of water column. The salinity ranges from 20–35 and near marine conditions may extend even to the upper reaches.

Cochin estuarine system is partly artificial due to the anthropogenic activities like land reclamations (Gopalan et al., 1983) and dredging at inlet 2 (Balchand and Rasheed, 2000), frequently modifying its geomorphology. Also, the tidal prism of Cochin inlet is estimated at $107.8 \times 10^6\,\mathrm{m^3}$ during ISM, $18.6 \times 10^6\,\mathrm{m^3}$ during moderate runoff months (October to December) and $31.5 \times 10^6\,\mathrm{m^3}$ during the dry season (Rama Raju et al., 1979). The salinity conditions of a bay are found in the lower reaches only during dry period. Meanwhile, the maximum salinity observed at the upstream is never greater than 15. Hence, a salinity gradient from mouth to head persists throughout the dry period. Peak monsoonal spells and runoff may entirely change the estuary from an estuarine bay to a riverine system. This transformation plays a fundamental role in the ecology of the system. Thus, “Monsoonal Estuarine Bay” seems to be an appropriate term for this estuary.

7 Synthesis and conclusion

The runoff into estuary is never zero at any time of the year. It is a unique divergent estuary with a widespread area at the upstream. During the wet season and moderate runoff months, the salinity field is extremely sensitive to the drastic variations in river runoff even on daily time scales. Saline water creeps in slowly during moderate runoff months, but then persists unabatedly in the following peak dry season. During peak dry period, the salinity values are high throughout the system with a gradient from mouth to head and the variations in runoff is slow. The lower reaches behave like an extension of the coastal waters and salinity ranging from 10–12 is observed at the upstream and the water column is well mixed. The runoff that enters is only 30 % of the estuarine volume so that zero salinity is never attained at the upstream. The "little but constant" runoff is mainly contributed by Muvattupuzha River flowing into southern arm which is not sufficient to flush the large upstream volume.

Fluctuations in the estuary are of extreme nature with regard to salinity. The new terminology "Monsoonal Estuarine Bay" encapsulates the salinity gradient of the Cochin Estuary ranging from completely riverine to completely saline. The term "Monsoonal" succinctly describes the unsteadiness of salinity of wet season. The possibility of the estuary turning to a river cannot be ruled out. "Bay" conditions are accomplished during peak dry season when the estuary is in a steady state with little constant runoff. During the rest of the year, the system behaves only as a true estuary. The gist of the previous studies is that the ecosystem and ecology respond well to this varying salinity and environment. The terminology may be used for future works due to its significance. It provides basic information about the physiographic, hydrographic, salinity and ecological features of the system.

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Table 1. Multiple regression model results based on log transformed runoff, log transformed trend and non transformed seasonal and cyclical variations.

S. no	Parameters	Explained variability	F statistic ($n1$, $n2$)	P valve
1	X_1, 2 period centered MA	94.72	880.5 (1,48)	$P < 0.001$
2	X_2, seasonal variation	31.32	23.35 (1,48)	$P < 0.005$
3	X_3, cyclical variation	0.9915	1.4907 (1,48)	$P < 0.005$
4	X_1, X_2, $(X_1 \cdot X_2)$	99.89	15 501.2 (3,46)	$P < 0.0001$
5	X_1, X_3, $(X_1 \cdot X_3)$	96.83	501.23 (3.46)	$P < 0.001$
6	X_2, X_3, $(X_2 \cdot X_3)$	39.58	11.69 (3,46)	$P < 0.05$
7	X_1, X_2, X_3, $(X_1 \cdot X_2)$, $(X_1 \cdot X_3)$, $(X_2 \cdot X_3)$	99.96	26 970.85 (6,40)	$P < 0.001$
8	X_1, X_2, X_3	99.86	12418.5 (3,46)	$P < 0.001$

n_1 and n_2 are the degrees of freedom of F statistic.

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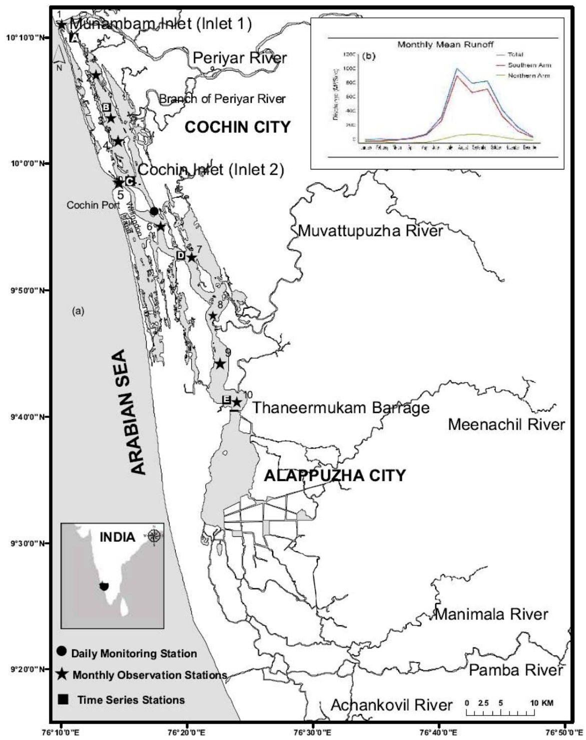

Fig. 1. (a) The Cochin Estuary (West coast, India), showing rivers and extent of the system, having two inlets to Arabian Sea, Munambam Inlet (north) and Cochin inlet (middle of the extent of the system). Daily station is located 5 km away from Cochin inlet. Monthly longitudinal and time series stations are discerningly marked. **(b)** Runoff from 6 rivers for the period of 1 yr (June 2008 to May 2009).

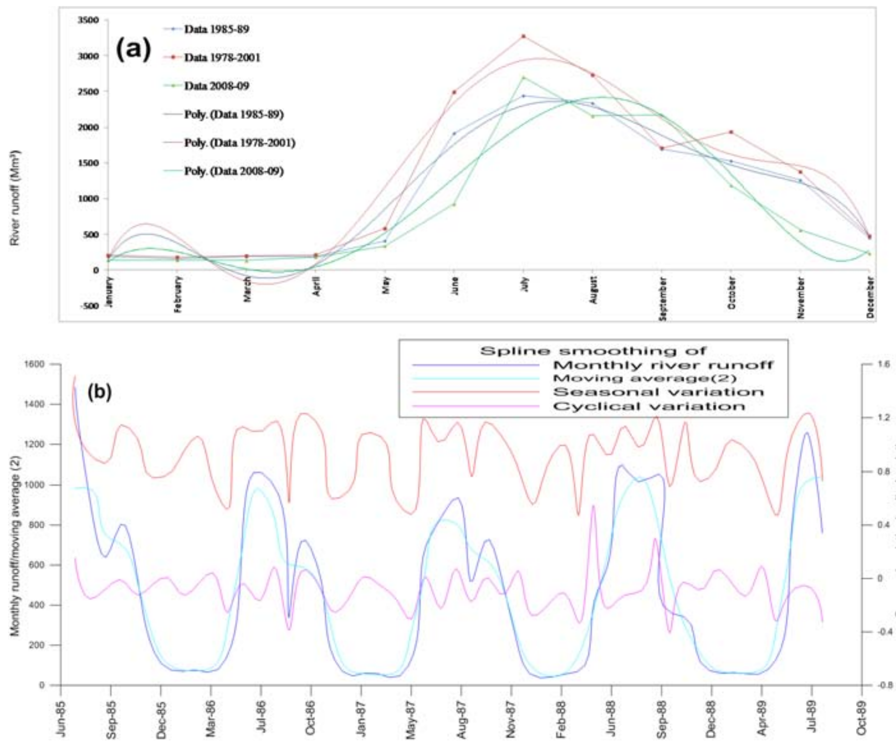

Fig. 2. (a) Polynomials of different degrees for the monthly total runoff. **(b)** Spline smoothing of Time series components of the river runoff data.

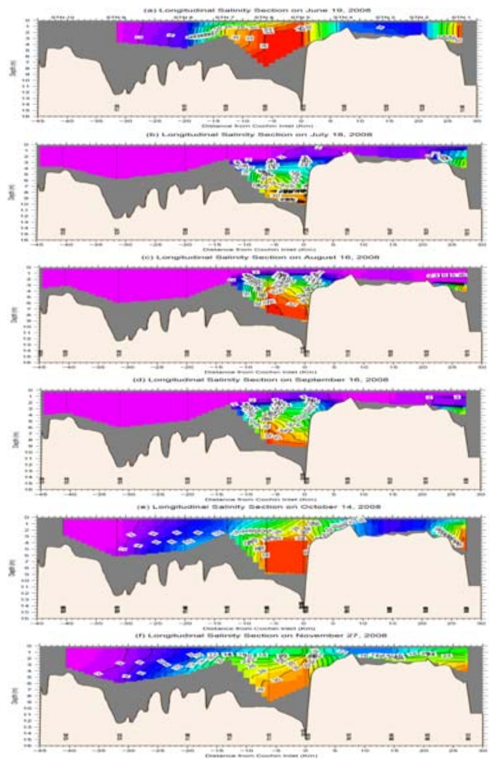

Fig. 3. Longitudinal distribution of salinity measured monthly once during June–November 2008. The Cochin inlet is at the coordinate origin. The northern/southern arm stations are at positive/negative distances, respectively. Times of each station appear along the lower x-axis.

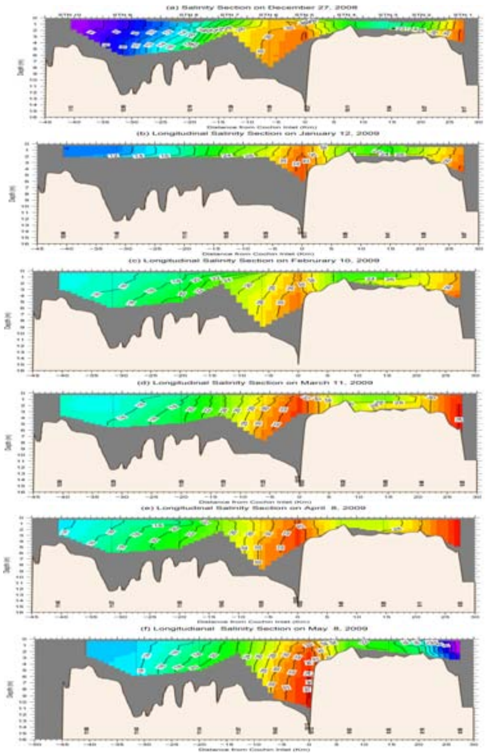

Fig. 4. Longitudinal distribution of salinity measured monthly once during December 2008, to May 2009. The Cochin inlet is at the coordinate origin. The northern/southern arm stations are at positive/negative distances, respectively. Times of each station appear along the lower x-axis.

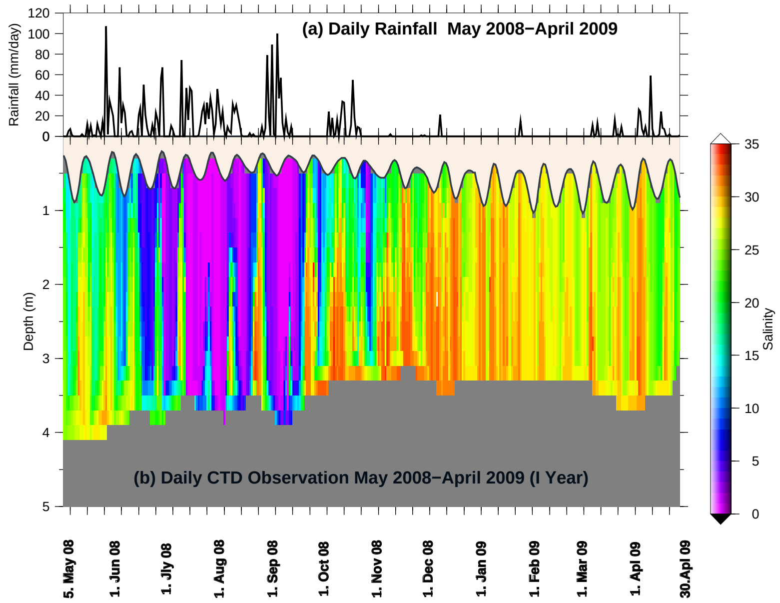

Fig. 5. (a) The daily rainfall pattern (May 2008–June 2009). **(b)** The daily salinity pattern of the station situated 5 km away from Cochin Inlet.

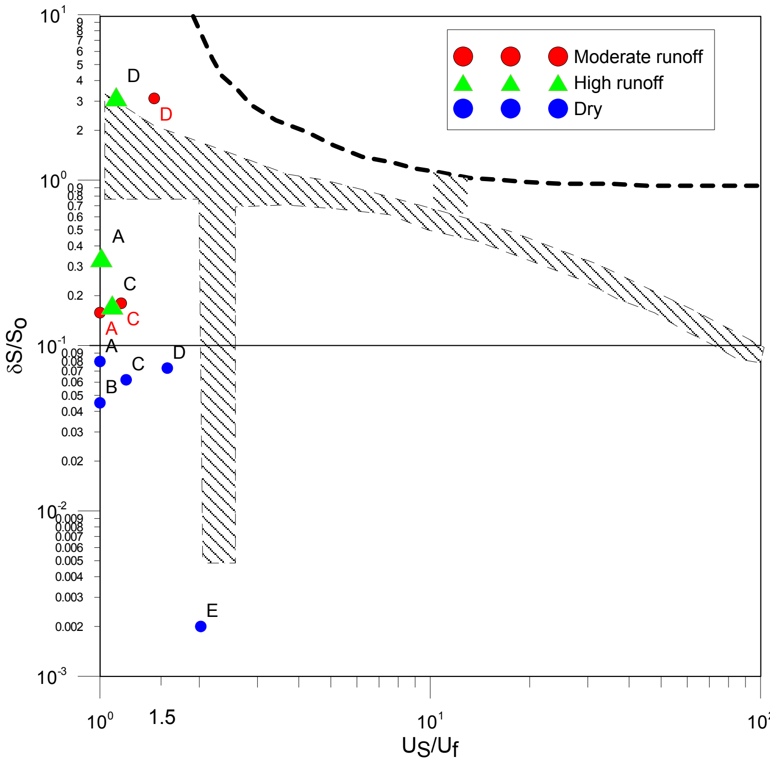

Fig. 6. Hansen–Rattrey classification diagram for Cochin Estuary.

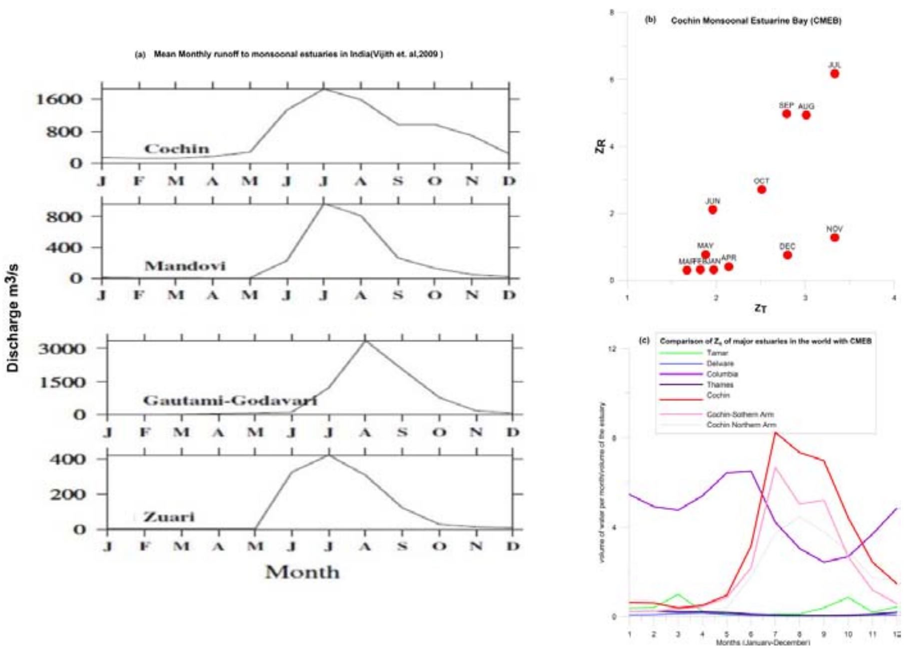

Fig. 7. Seven positions of each month of Cochin Estuary on the (Z_R, Z_T) plane.

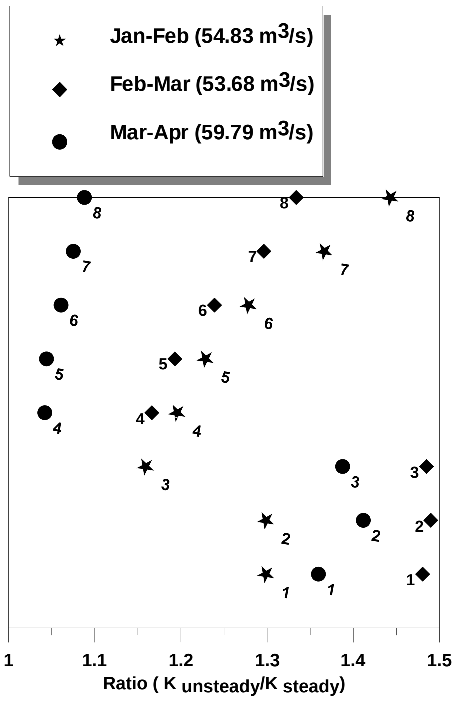

Fig. 8. The ratios of $K_{unsteady}$ to K_{steady} calculated as shown in Eq. (7).

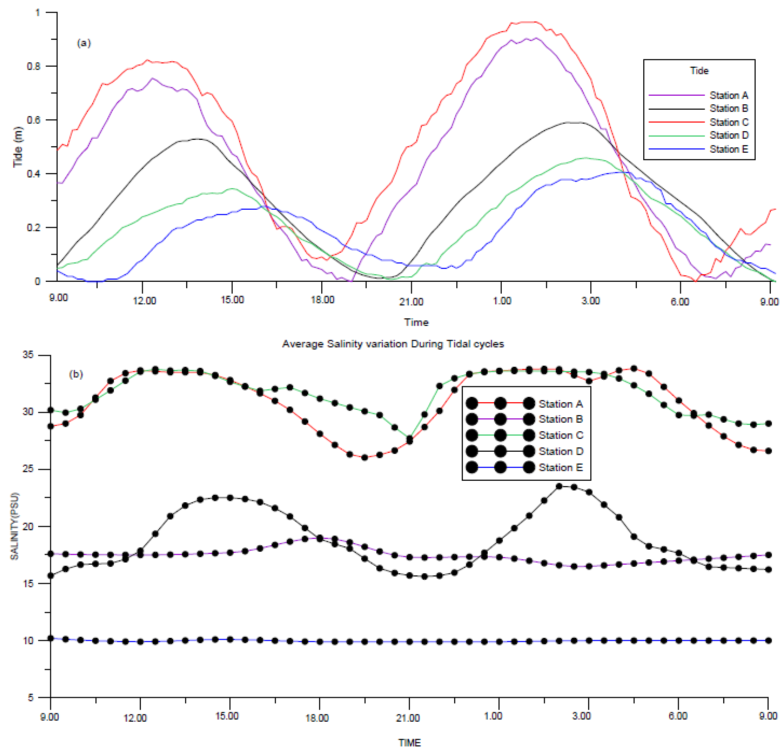

Fig. 9. Average salinity variations during a tidal cycle for monthly time series stations during the dry period.