Hydrol. Earth Syst. Sci. Discuss., 10, 3595–3628, 2013
www.hydrol-earth-syst-sci-discuss.net/10/3595/2013/
doi:10.5194/hessd-10-3595-2013

Hydrology and Earth System Sciences Discussions
Open Access

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

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Received: 18 February 2013 – Accepted: 20 February 2013 – Published: 19 March 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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.

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 $S m^{-1}$) 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

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

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

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

for 1978–2001 and

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

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,

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

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 $\mathrm{m^3\,s^{-1}}$ 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 $\mathrm{m^3\,s^{-1}}$), 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 $\mathrm{m^3\,s^{-1}}$) 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:

$$\eta_\mathrm{R} = \frac{R_\mathrm{a}}{V_\mathrm{e}} \tag{11}$$

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

$$\eta_T = \frac{\text{Maximum monthly runoff}}{\text{Mean monthly runoff}}. \tag{12}$$

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 $200\,\mathrm{m^3\,s^{-1}}$ 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 ($Z_R \sim 5$ 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:

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

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

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.

Acknowledgement. The authors are thankful to the Director, National Institute of Oceanography, Goa, and also to the Scientist-in-Charge of the Regional Center, for encouragement. Shivaprasad Amaravayal is also grateful to CSIR, New Delhi, for financial support in the form of Senior Research fellowship. This work is a part of A. Shivaprasad's doctoral research. Manoj, N. T. is thankful to DST, Govt. of India for financial support under SERC-fast track scheme. This study would not have been possible without the active support of the project team; we express our sincere thanks to them. This work forms part of project "Ecosystem modeling of Cochin Estuary" funded by ICMAM. This is NIO contribution no. 5349.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

References

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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.

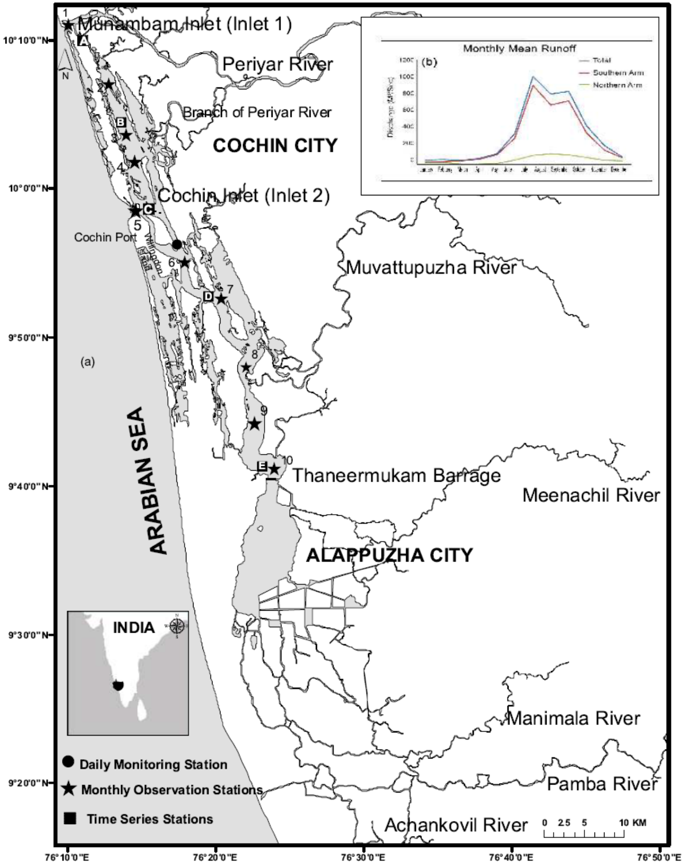


Fig. 1. (a) The Cochin Estuary (West coast, India), showing rivers and extent of the system, having two inlets to Arabian Sea, Munambam Inlet (north) and Cochin inlet (middle of the extent of the system). Daily station is located 5 km away from Cochin inlet. Monthly longitudinal and time series stations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

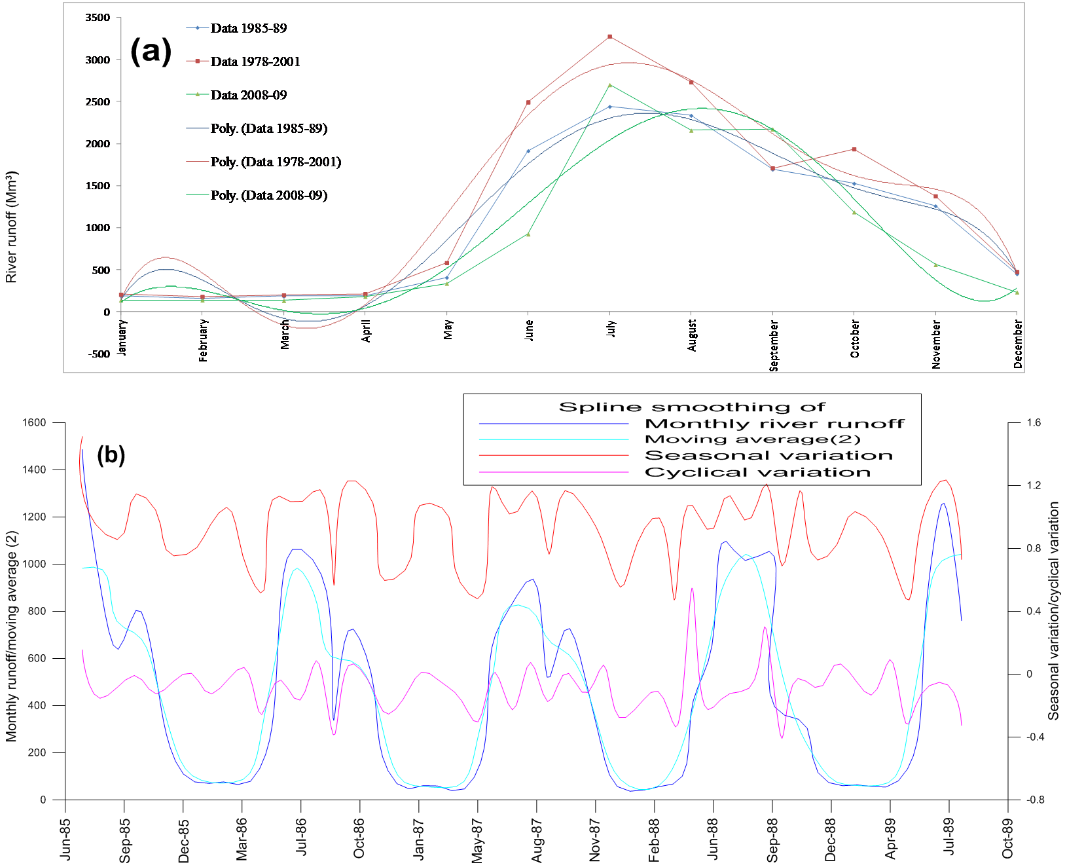
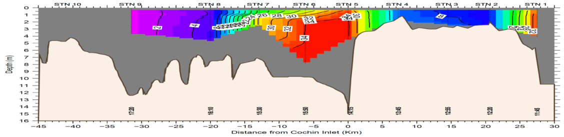
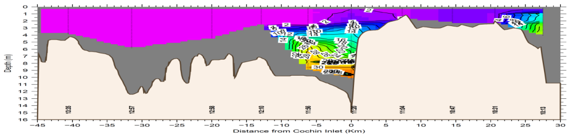


Fig. 2. (a) Polynomials of different degrees for the monthly total runoff. **(b)** Spline smoothing of Time series components of the river runoff data.

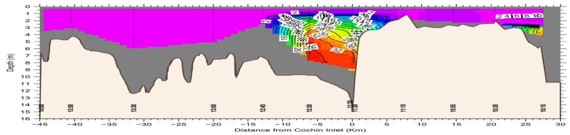
(a) Longitudinal Salinity Section on June 19, 2008



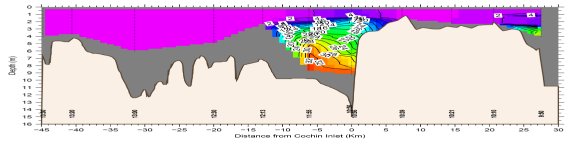
(b) Longitudinal Salinity Section on July 18, 2008



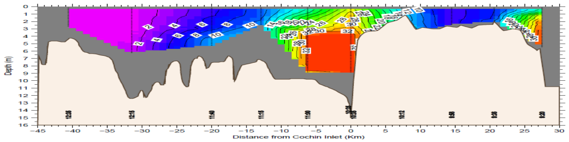
(c) Longitudinal Salinity Section on August 16, 2008



(d) Longitudinal Salinity Section on September 16, 2008



(e) Longitudinal Salinity Section on October 14, 2008



(f) Longitudinal Salinity Section on November 27, 2008

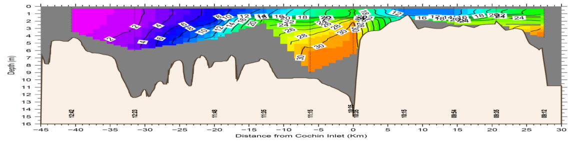


Fig. 3. Longitudinal distribution of salinity measured monthly once during June–November 2008. The Cochin inlet is at the coordinate origin. The northern/southern arm stations are at positive/negative distances, respectively. Times of each station appear along the lower x-axis.

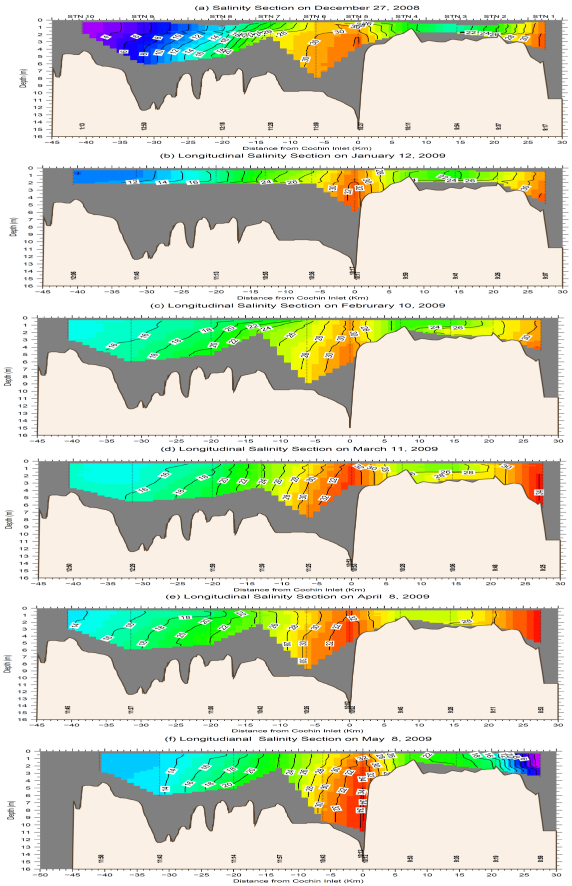


Fig. 4. Longitudinal distribution of salinity measured monthly once during December 2008, to May 2009. The Cochin inlet is at the coordinate origin. The northern/southern arm stations are at positive/negative distances, respectively. Times of each station appear along the lower x-axis.

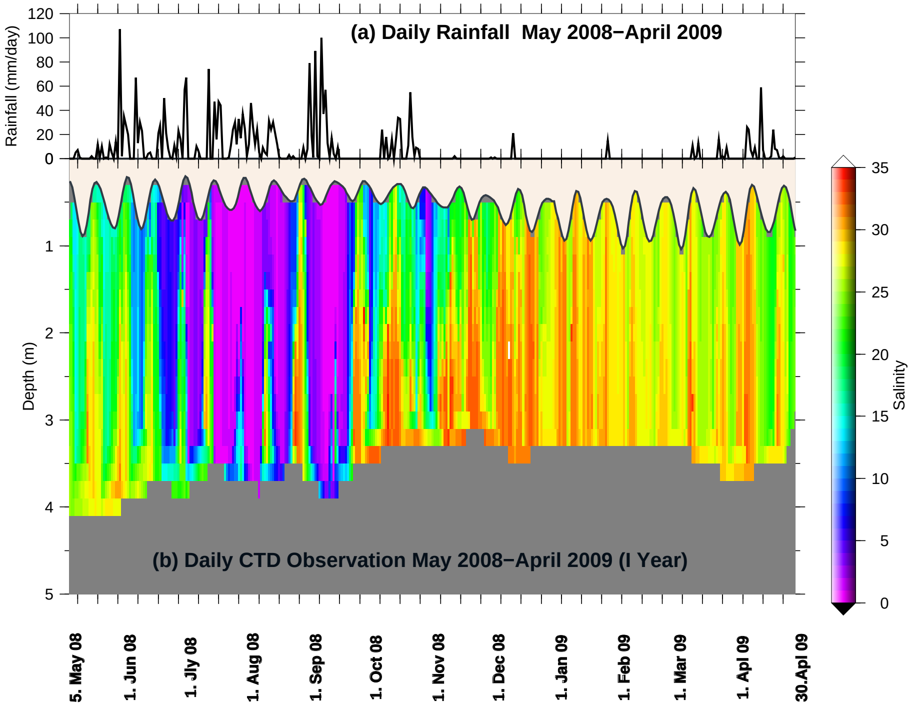


Fig. 5. (a) The daily rainfall pattern (May 2008–June 2009). **(b)** The daily salinity pattern of the station situated 5 km away from Cochin Inlet.

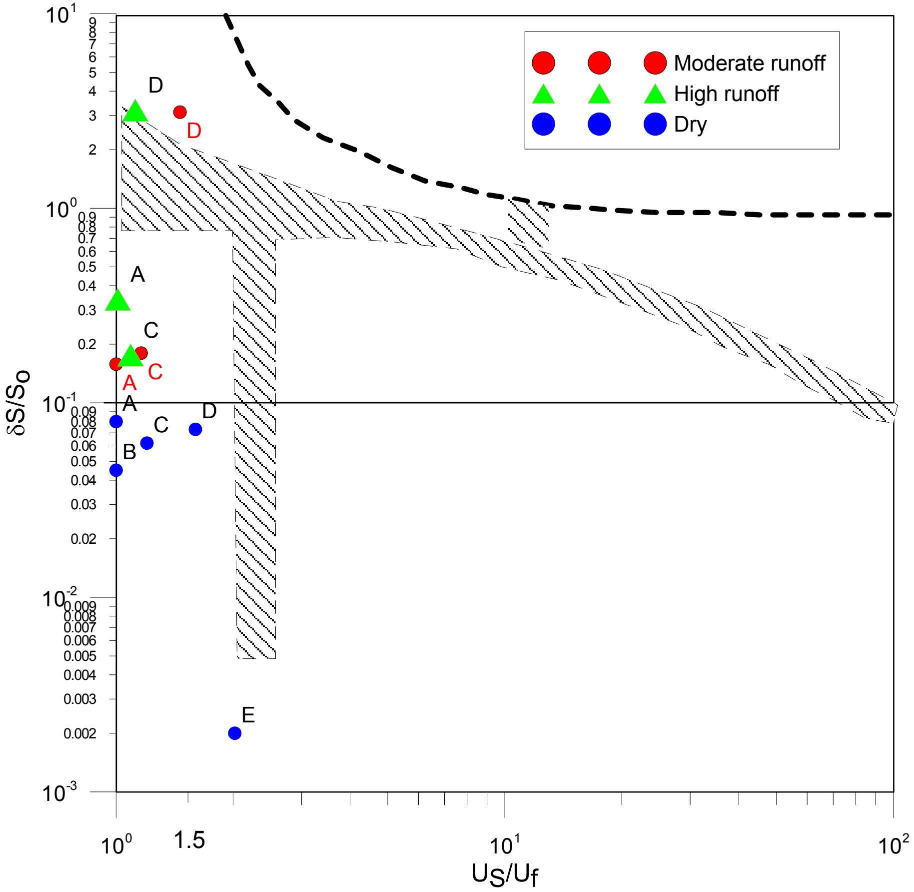


Fig. 6. Hansen–Rattrey classification diagram for Cochin Estuary.

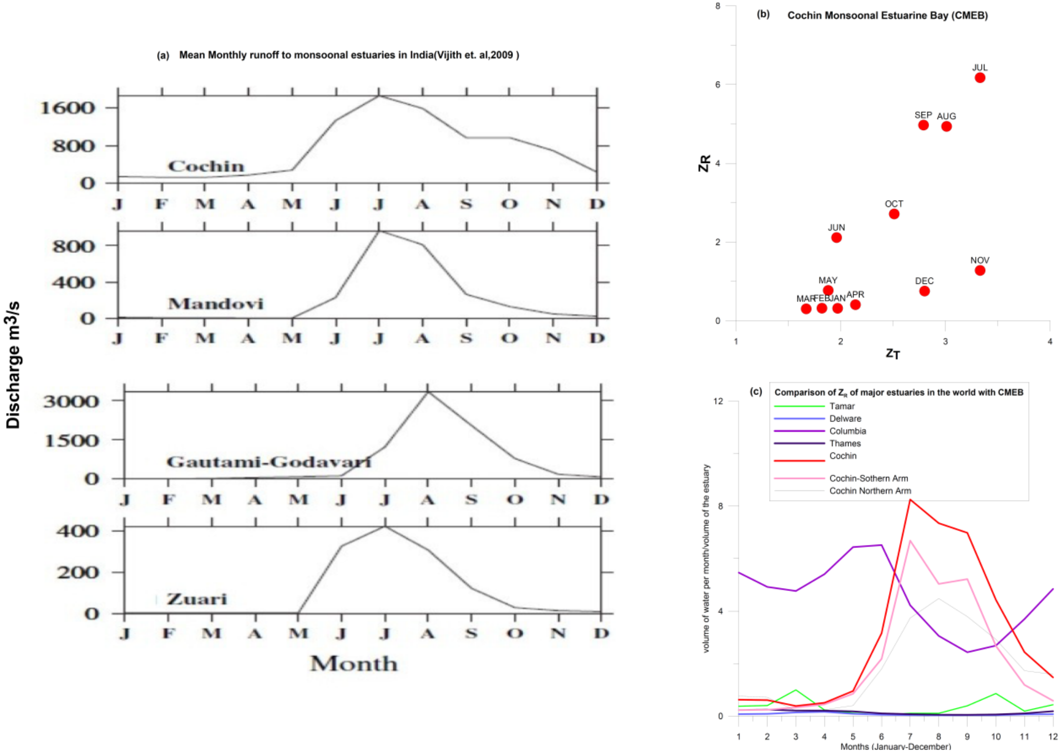


Fig. 7. Seven positions of each month of Cochin Estuary on the (Z_R, Z_T) plane.

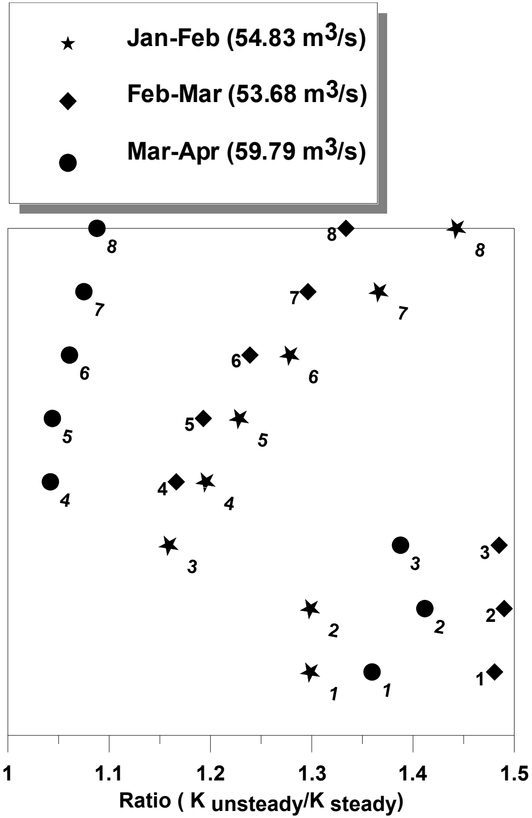


Fig. 8. The ratios of K_{unsteady} to K_{steady} calculated as shown in Eq. (7).

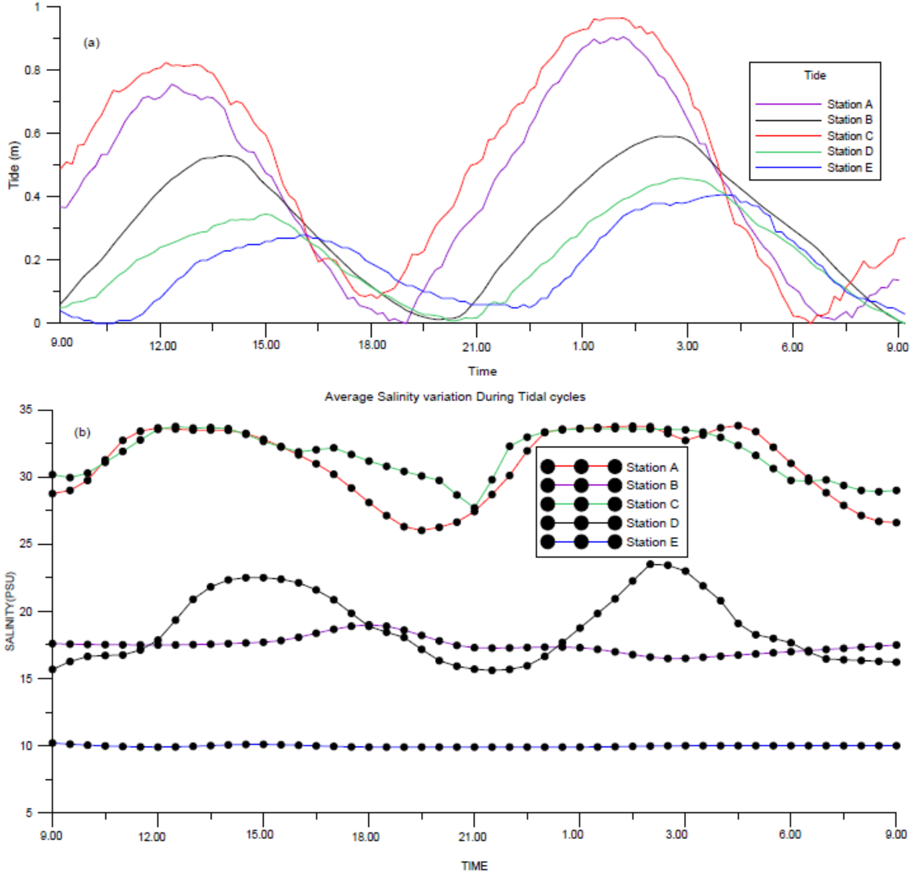


Fig. 9. Average salinity variations during a tidal cycle for monthly time series stations during the dry period.