

Sea level and currents in the upper reaches of the Cochin estuarine system during October 2000

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Data on sea level, currents, salinity and water temperature collected in the upper reaches of the Cochin estuarine system (southwest coast of India) during October 2000 have been analysed to understand their variability. The tides near to the mouth of the Cochin estuarine system were found to be of a mixed, predominantly semi-diurnal form during the month. The non-tidal sea level at the same location, showed an overall drop of nearly 9 cm during the period. Spectral analysis of the non-tidal sea level revealed the presence of 4 and 21 day period wave phenomena. The study showed that the sea level as well as currents are dominated by tidal signals (diurnal and semi-diurnal bands) even in the upper reaches. However, the amplitudes were seen to decrease with increasing distance from the mouth of the estuarine system. Conspicuous dominance of the shallow water components was noticed in the currents as compared to the sea level. The data on salinity showed tidal signatures whereas that on the water temperature showed strong solar forcing.

[Key words: Sea level, currents, salinity, water temperature, estuarine system, upper reaches, Cochin]

Introduction

One of the largest estuarine systems on the west coast of India, the Cochin estuarine system (*ca.* 320 km² in area), consisting of Vembanad Lake, and the rivers flowing into the estuary, forms an important estuarine ecosystem in this part of the country, supporting a variety of flora and fauna. It is used extensively for fishing, local transport of goods and also as an outlet for industrial and domestic wastes. The Cochin Port Trust, one of the major ports along the west coast of India, is situated on the banks of this estuarine system. The lower reaches of this system has undergone 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 hydrodynamics of this waterbody. The tides enter the Cochin estuary through a narrow inlet, the cross-sectional area of which is only 4234 m².

Menon *et al.*¹ have recently reviewed the literature on physico-chemical as well as biological aspects of this water body. Based on temperature and salinity data collected during 1982-'83, Varma *et al.*² 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 signals³ (nearly 93.7% of

variance of the observed sea level). Mean amplitudes of the tidal constituents based on annual analyses (1988-1993) showed that M₂ (Principal lunar) is maximum, followed by K₁ (Luni-solar), O₁ (Principal lunar) and S₂ (Principal solar)⁴. The amplitudes of the M₂, K₁, O₁ and S₂ tides are 20.4, 17.6, 9.3 and 7.5 cm, respectively. The tides are of a mixed, predominantly semi-diurnal form.

Tidal variations of physical, chemical, biological and geological parameters of the estuary have been studied earlier³⁻⁸. The present study (conducted during October 2000), attempts to understand the characteristics of sea level, currents, salinity and water temperature in the upper reaches of the estuarine complex (Fig. 1). There are practically no studies in this arm of the estuarine system whereas some information on the sea level and currents are available for other arms of the system, especially at the lower reaches^{3-4,7,8}.

Materials and Methods

Hourly data on sea level recorded by an automatic stilling-well tide gauge located near the mouth of the Cochin estuarine system (station 1) during October, 2000 (0000 hrs of October 1 to 2300 hrs of October 28) were provided by the Marine Surveyor's Office, Cochin Port Trust, Cochin. The data on sea level at

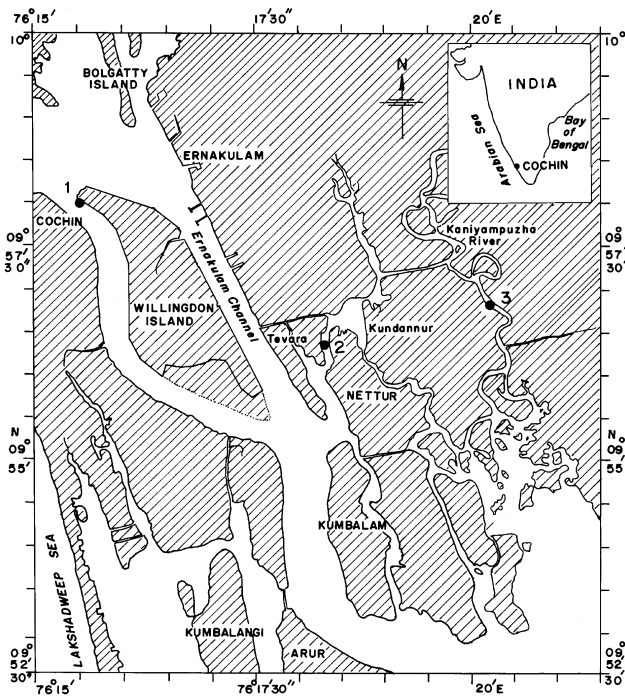


Fig. 1—Station location map

hourly intervals during 16-18 October, 2000 were obtained from different sources *viz.* tide gauge at station 1, and tide poles at stations 2 and 3. Station 1 is deep, because it is quite close to the shipping channel (Mattancherry channel - approximate depth is around 12 m). The depths at stations 2 and 3 are approximately 5 m.

The data on water currents were collected at stations 2 and 3, each of two days duration during October 23-25, 2000 and October 16-18, 2000. It was not possible to collect simultaneous data on currents at the two sites because of instrument failure during October 16-18, 2000, and consequently station 2 was occupied at a later date. The data on speed and direction were recorded at 10 minute intervals using an Aanderaa recording current meter, moored at mid-depth. The currents at each station were resolved into north-south (*v*-component) and east-west (*u*-component) directions, with the flow to the north and to the east being defined as positive. Eulerian and Lagrangian methods were used to describe the water movements. Progressive Vector Diagram is a presentation of the cumulative speed and direction of flow at the meter during deployment. It is a Lagrangian display of Eulerian measurements. These diagrams were constructed for the 48 hour data on currents available at stations 2 and 3. The current

meter moored at station 2 had sensors for salinity and temperature and hence, the tidal influence on these parameters were also studied.

The data on sea level as well as current components were subjected to harmonic analysis to determine the amplitudes and Greenwich phases of the tidal constituents⁹. The tidal analysis (for the determination of amplitudes and phases of the constituents) was carried out using the software of the Sea Level Centre, University of Hawaii.

In the present study, eight constituents were resolved using the least square method on hourly data of 2 days. These constituents actually represent a band, because of the Rayleigh criterion^{9,10}. The Rayleigh criterion implies that we cannot resolve two constituents whose frequencies are separated by less than 0.0208 cph. The bands are diurnal, semi-, third-, fourth-, fifth-, sixth-, seventh- and eighth-diurnal, respectively. The sea level data at station 1, however, gave information on all the four principal tidal constituents O_1 , K_1 , M_2 and S_2 as well as other constituents too, because of its length (twenty eight days). X_0 filter⁹ was used for removing the tides from the original sea level record (for station 1 only), as a fairly long time series was available in this case. Spectral analysis was used to determine the predominant periodicities in the time series data for the observed, predicted, residual and filtered sea level using the Cooley-Tukey FFT algorithm¹¹.

Results and Discussion

The hourly march of the observed sea level at station 1 for the period 1-28 October, 2000 is presented in Fig. 2A. The lunar phases are also indicated, to appreciate their forcings on the tides. These data are taken from the Indian Tide Tables¹². Results of the harmonic analysis (amplitudes and phases of the tidal constituents) for the sea level at station 1 are presented in Table 1. The M_2 constituent shows the maximum amplitude, followed by K_1 , S_2 and O_1 . The mean spring and neap ranges are 61.7 and 20.3 cm, giving a mean range of 41 cm. Spring-neap variation is large: the mean spring range being more than twice the mean neap range. The type of tides at a given location can be determined using the Form Number, which is the ratio of the sums of the amplitudes of the diurnal constituents (K_1 and O_1) to that of the semi-diurnal constituents (M_2 and S_2). Based on the above information, the tides are classified as mixed and predominantly semi-diurnal in

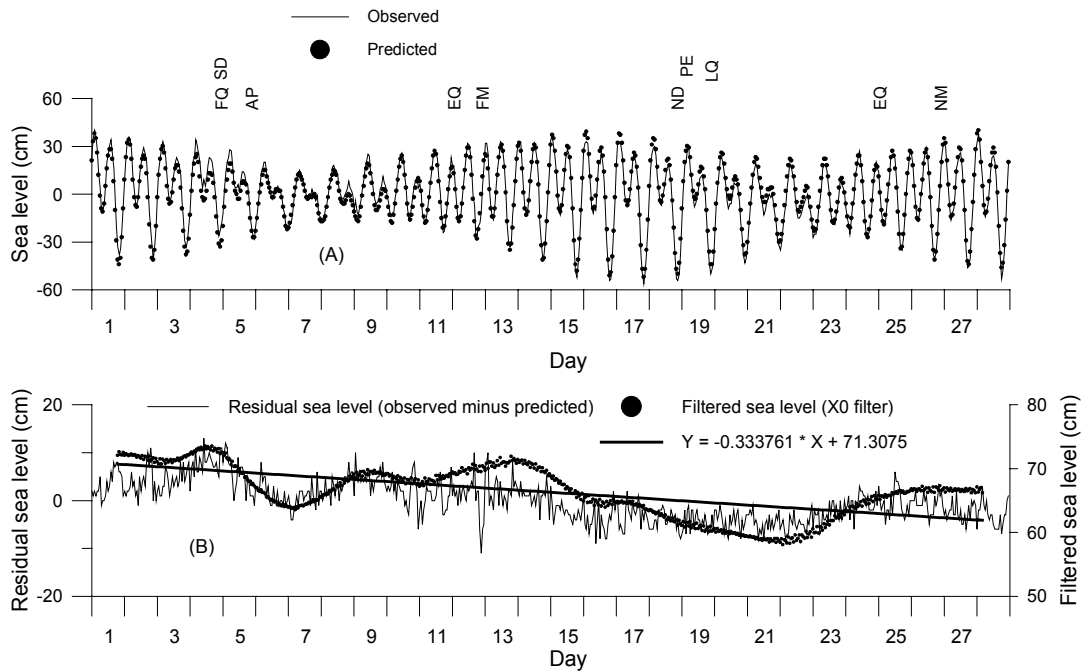


Fig. 2—Observed, predicted, residual and filtered sea level during October, 2000 at station 1. The lunar phases are also indicated. AP - Apogee, NM- New moon, FQ- First quarter, FM- Full moon, LQ - Last quarter, ND - Maximum north declination, SD - Maximum south declination, PE - Perigee, EQ- Moon on equator.

Table 1—Details of the tidal constituents analysed in the present study, based on sea level data of October 1-28, 2000 at station 1

Sl. No	Constituent	Frequency (cph)	Amplitude (cm)	Phase (°)	Amplitud** (1988-'93)
1	M _{sf}	0.0028	3.03	35.3	0.88
2	O ₁	0.0387	7.11	67.9	9.32
3	K ₁	0.0418	12.94	45.4	17.58
4	N ₂	0.0790	3.99	297.0	4.54
5	M ₂	0.0805	20.51	340.2	20.36
6	S ₂	0.0833	10.35	28.8	7.52
8	M ₃	0.1208	0.08	196.8	0.32
9	M ₄	0.1610	0.99	91.0	0.68
10	2MK ₅	0.2028	0.08	274.2	0.30
11	M ₆	0.2415	0.19	33.6	0.20
12	3MK ₇	0.2833	0.16	115.8	0.08
13	M ₈	0.3220	0.17	227.0	0.12

**Srinivas *et al.*⁴

nature, having a Form Number of 0.65. In such regimes, two high and two low waters occur daily with large inequalities in range and time. The maxima in inequalities occur when the moon's declination passes its maximum values. The predicted sea levels

were determined using the values of amplitudes and phases presented in Table 1.

Shallow water tidal constituents arise from the distortion of the main constituent tidal oscillations by bottom friction and other physical processes^{13,14}. The

amplitudes of the short period shallow water constituents were all less than 1.0 cm. The contribution of the shallow water tides was not found to be important, with the ratio of the amplitudes of quarter-diurnal to the semi-diurnal constituent of tide being 0.05 and 0.03, respectively for the data analysed at station 1 for October, 2000 as well as that for 1988-1993 period. The long period shallow water constituent M_{sf} has an amplitude of 3.0 cm, suggesting a strong spring-neap tidal cycle.

The residual sea levels were determined from the observed and predicted sea levels (Fig. 2B). The standard deviation of the observed sea level series was 19.9 cm, whereas that of the residual series was 4.3 cm, indicating that the predictions have been fairly successful (over 95% of the variance of the observed sea level is due to the tides). However, using a digital filter is always more efficient as it discriminates strongly against the tidal periodicities and also removes noise. In order to understand the low frequency characteristics of the sea level, the X_0 filter was deployed. This filter strongly discriminates against tidal frequencies, but its application leaves the original record short of 38 hours of data (Fig. 2B). In general, there is a decreasing trend in the non-tidal sea level for the period under consideration, caused by the incursion of cool and dense upwelled coastal water into the estuary⁷. The drop in sea level during the dates 6-7 and 21-22 are particularly conspicuous. The non-tidal sea level showed an overall drop of nearly

9 cm during the period 1- 28 October, 2000. From climatological data on sea level for Cochin³, the most conspicuous feature was the sharp rise in sea level from September to December (nearly 19 cm). In the present study, however, the sea level was found to be decreasing during the month, suggesting a rather delayed upwelling phase. The lowering in sea levels combined with high river discharge are favourable in the context of flushing of pollutants from the estuarine region.

The spectra of the observed, predicted, residual and filtered sea level series at station 1 are presented in Fig. 3. The spectra of the observed and predicted sea level showed a strong dominance of the semi-diurnal signal (period - 12.2 hrs) as compared to the diurnal (period - 23.3 hrs). The spectra of the residual sea level series showed a dominance of 4.3 days and 10.7 days. Frequencies at the higher end of the

spectrum, with relatively less energy were also seen. The energy at 4.3 days and 10.7 days, however, were not very high. The spectra of the filtered sea level, on the other hand, show a distinct maxima at 20.8 days followed by a relatively minor peak at 4.3 days. There is no energy at the higher end of the spectrum which shows that the filter has been quite effective in removing the tidal signals, as well as noise. The 4 day and 21 day period waves could be signatures of a coastally trapped phenomena¹⁵.

The hourly march of the observed sea level at stations 1-3 during October 16-18, 2000 are presented in Fig. 4. The overall mean has been removed from the observed time series for each station to enable comparisons between the three of them. In general,

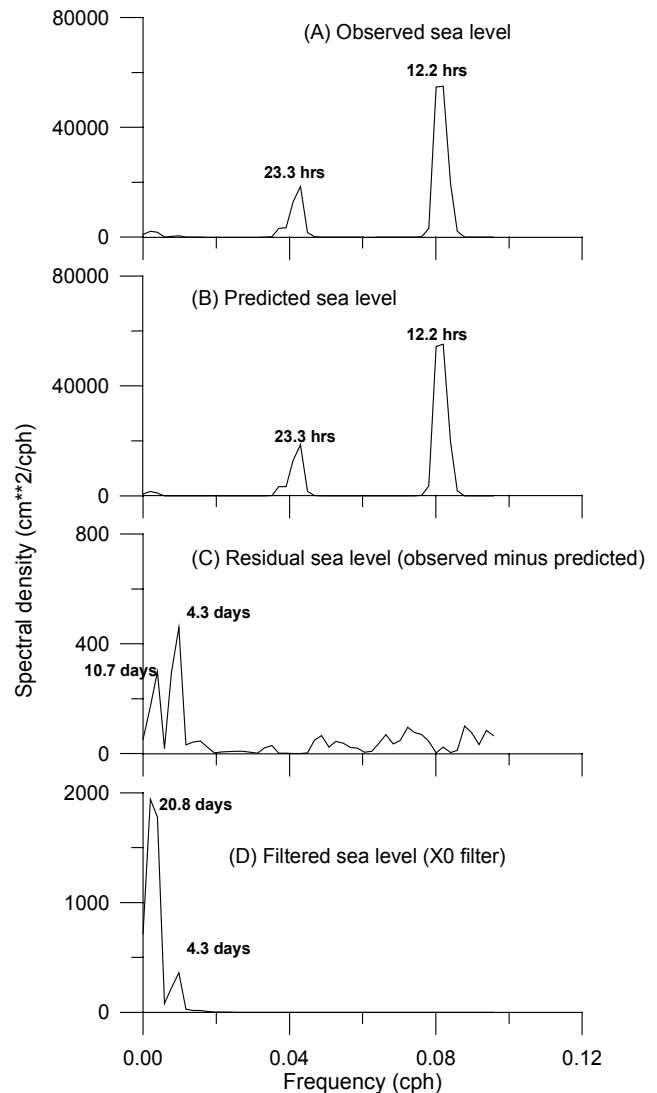


Fig. 3—Spectra of the (A) Observed, (B) Predicted, (C) Residual and (D) Filtered sea level at station 1, during October, 2000.

the three time series have a similar movement, but the highs and lows appear progressively later at stations 2 and 3. The standard deviations of the sea level at the three stations were 26.1, 19.4 and 17.1 cm, respectively, which indicate that there is a reduction in energy in the upstream direction. The semi-diurnal band is very dominant, followed by diurnal band for October 16-18 period at all the three stations (Table 2). The amplitudes of semi-diurnal band were 28.5, 21.3 and 18.6 cm whereas that of the diurnal band were 22.8, 17.3 and 13.7 cm, respectively. In general, station 2 shows the least amplitudes among the three stations for third-diurnal to eighth-diurnal bands. The diurnal inequality caused by the mixed tides is clearly seen in the sea level series. The contribution of the shallow water tides was not found to be important, with the ratio of the amplitudes of quarter-diurnal to the semi-diurnal bands of tide being 0.05, 0.02 and 0.04, respectively at the three stations.

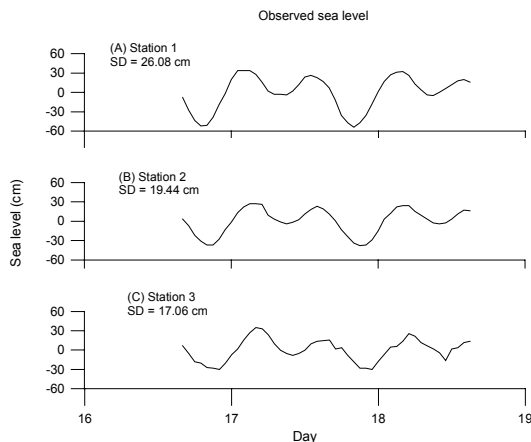


Fig. 4—Observed sea level (demeaned) at (A) station 1 (B) station 2 (C) station 3 during 16-18 October, 2000.

The standard deviations of the residual sea level (the difference between observed and predicted tides) were 2.6, 2.2 and 4.2 cm, respectively at the three stations. The residuals are normally high when there is nonlinear influence from the shallow depth, interaction with river discharge, irregular estuarine geometry and bottom topography (siltation effects are important) on the tides. The tides dominate these regions, accounting for 99.0, 98.7 and 93.9% of the observed sea level variance.

The time series of current speeds at stations 2 and 3 are presented in Fig. 5 A, B. The mean and standard deviation of the current speeds at station 2 were high compared to those at station 3. Station 2 was occupied during the neap phase of the tide (Fig. 2A) whereas station 3 was occupied during spring phase. This suggests a strong tidal forcing at station 2. The time series of u-component of currents are displayed in Fig. 5 C, D and that for v-component of currents in Fig. 5 E, F, along with associated statistics. The v-component of current at station 2 very much dominated that of the u-component whereas such a strong dominance was not seen in the case of station 3.

Dot plots of the currents are displayed in Fig. 5 G, H. Each point represents the speed and direction at a particular instant of time. A strong rectilinear nature in the currents was seen for both the stations. At station 3, a strong directionality was seen for ebb currents, which was absent for the flood currents. Concentration of the dots near zero suggests that slack water conditions occur with little flow. Steadiness (or persistence) - the ratio of vector mean speed to the scalar mean speed, a measure of

Table 2—Amplitude (cm) and phase (°) of the tidal bands at stations 1 to 3 for sea level

Band	Frequency band (cph)	Station 1		Station 2		Station 3	
		Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)
Diurnal	0.0210 – 0.0626	22.84	22.9	17.26	37.9	13.71	37.8
Semi-diurnal	0.0597 – 0.1013	28.54	281.4	21.32	308.7	18.56	333.8
Third-diurnal	0.1000 – 0.1416	1.99	157.1	0.14	246.3	2.40	37.8
Fourth-diurnal	0.1402 – 0.1818	1.30	345.0	0.38	146.8	0.78	114.2
Fifth-diurnal	0.1820 – 0.2236	0.48	133.5	0.62	317.1	1.13	16.9
Sixth-diurnal	0.2207 – 0.2623	1.27	332.1	0.65	1.4	1.50	354.1
Seventh-diurnal	0.2625 – 0.3041	0.50	29.2	0.06	33.9	1.07	9.8
Eighth-diurnal	0.3012 – 0.3428	0.73	292.1	0.35	42.9	0.24	157.9

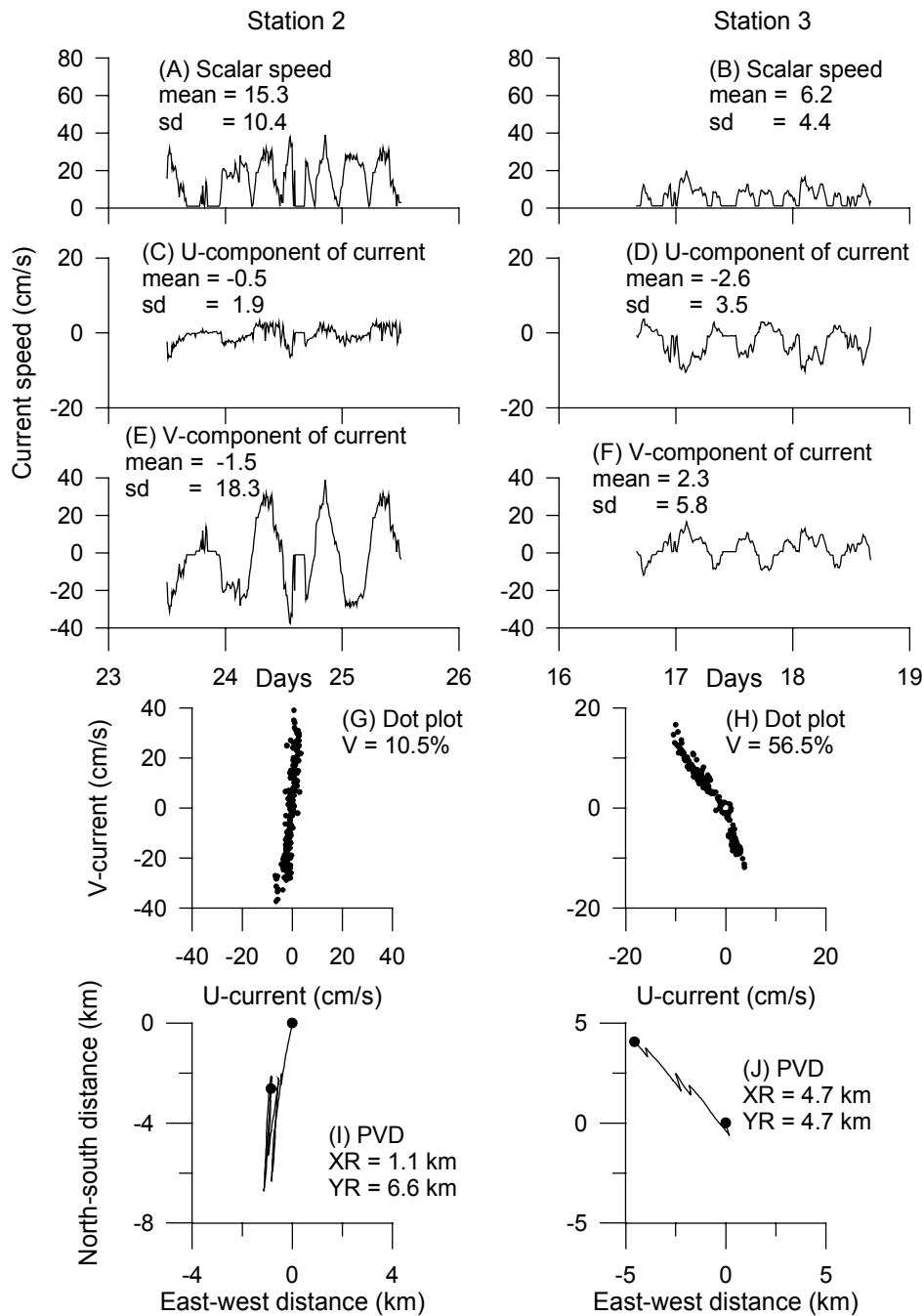


Fig. 5—Variation of current speed at (A) station 2 and (B) station 3. Variation of u-component of current (C) station 2 and (D) station 3. Variation of v-component of current (E) station 2 and (F) station 3. The means and standard deviations are also presented. Scatter diagrams of currents (G) station 2 and (H) station 3. V indicates the steadiness. Progressive vector diagrams of currents (I) station 2 and (J) station 3. XR and YR indicate the maximum ranges (in km) in the east-west and north-south directions.

directionality of the flow, was higher at station 3 than at station 2.

The Progressive Vector Diagrams (PVDs) of the currents are presented in Fig. 5 I, J. PVD at station 2 shows a strong north-south movement whereas that at

station 3 shows a northwest-southeast movement. In general, the PVDs indicate flows parallel to the local shoreline. The range of movement in the lagrangian sense, in the x and y directions are 1.1 and 6.6 km in the case of station 2 whereas at station 3, it is 4.7 km

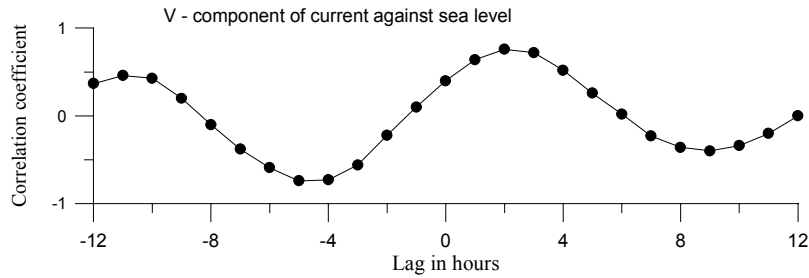


Fig. 6—Lag correlation between v-component of current against sea level at station 3. Positive lag indicates lead by the v-component of current.

Table 3—Results of the harmonic analysis of the u and v component of currents at the two stations

Tidal band	Station 2				Station 3				Station 2 Speed (cm/s)	Station 3 Speed (cm/s)
	U-component		V-component		U-component		V-component			
	Amp (cm/s)	Phase (°)	Amp (cm/s)	Phase (°)	Amp (cm/s)	Phase (°)	Amp (cm/s)	Phase (°)		
Diurnal	0.73	55.3	4.21	82.8	2.22	149.7	3.03	323.2	4.27	3.76
Semi-diurnal	1.82	293.5	21.85	292.2	3.41	110.7	5.62	281.5	21.93	6.57
Third-diurnal	0.26	172.3	4.85	223.0	1.32	222.9	2.43	40.3	4.86	2.77
Fourth-diurnal	0.25	77.1	3.81	257.7	0.65	116.1	1.43	289.8	3.82	1.57
Fifth-diurnal	0.76	136.4	3.81	94.2	0.33	293.1	1.55	99.5	3.89	1.58
Sixth-diurnal	0.73	74.7	3.10	52.3	1.13	325.1	1.40	155.0	3.18	1.80
Seventh-diurnal	0.49	158.9	0.92	197.3	1.10	282.8	1.72	120.8	1.04	2.04
Eighth-diurnal	0.36	99.3	2.40	104.4	0.92	196.9	1.17	14.1	2.43	1.49

in both the directions.

A combination of standing and progressive wave characteristics was seen at station 3, with the maximum of current (v-component) coinciding with the mid-tide¹⁶, approximately. The lag correlation shows a lag of two hours between maximum of v-current and the sea level (Fig. 6). In an estuary with a predominantly semi-diurnal regime, the maximum currents occur at approximately 3 hours after the low or high waters, whereas the salinity is maximum at high water and minimum at low water.

Results of the harmonic analysis of the hourly currents (u- and v- components) at the two stations are presented in Table 3. The semi-diurnal band is very dominant followed by diurnal for station 2 whereas such a strong domination is not seen at station 3. The amplitudes of the semi-diurnal and the diurnal band, in respect of sea level were 20.7 and 7.1 cm, respectively at station 1 during October 23-25, 2000. The results for currents agree with those for the sea level, with respect to the similarity in semi-

diurnal and diurnal forcings. The contribution of the shallow water tides was found to be important, with the ratio of the amplitudes of quarter-diurnal to semi-diurnal currents being 0.17 and 0.24, respectively at stations 2 and 3. In an earlier study on the sea level and currents in some locations at the lower reaches of the Cochin estuarine system, for spring and neap phases^{4,8}, it was seen that the ratio of the amplitudes of the quarter-diurnal to semi-diurnal bands showed high spring-neap variability in respect of currents whereas such a high degree of variability was not seen in the case of sea level.

In general, there is a very good agreement between the observed and predicted currents. The percentage variance accounted by the relationship between the observed and predicted u-component of currents at stations 2 and 3, were 75.3 and 92.9%, respectively. The percentage variance accounted by the relationship between the observed and predicted v-component of currents at stations 2 and 3, were 88.8 and 48.6%, respectively. The phase and amplitude

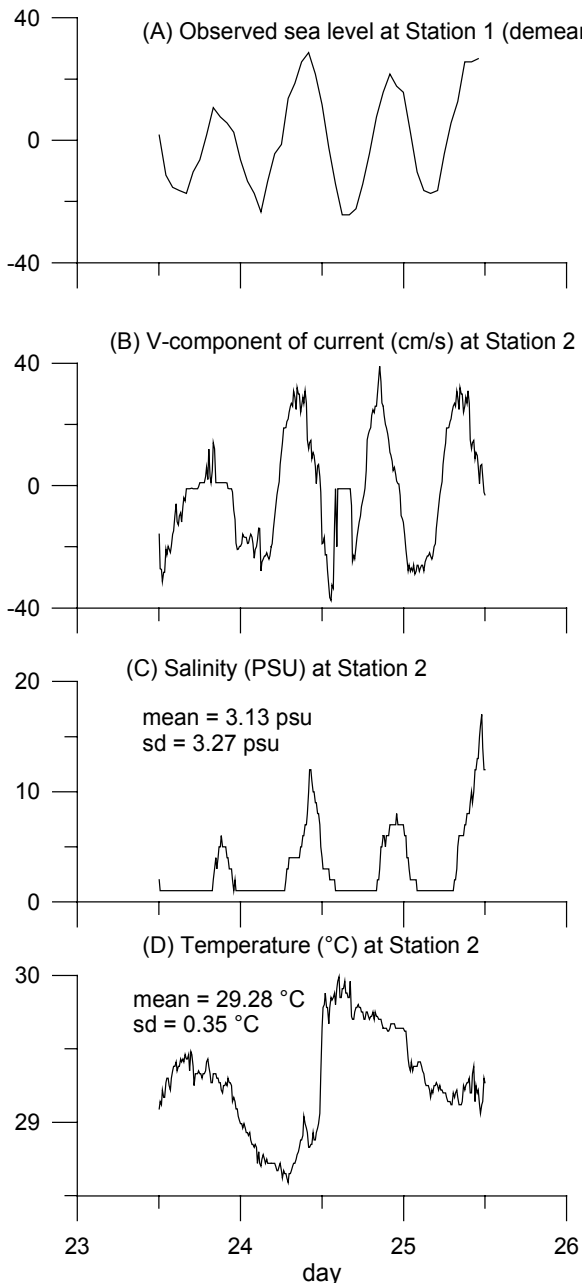


Fig. 7—Time series of (A) Sea level at station 1 (B) V-component of current at station 2 (C) Salinity at station 2 and (D) Temperature at station 2. The means and standard deviations are also presented.

information of all the 8 bands (diurnal to eighth-diurnal bands) have been used for the prediction purposes. This shows that currents are very much dominated by the tidal signals at both the stations.

The time series of sea level at station 1 are plotted against the v-component of current, salinity and temperature data of station 2 (Fig. 7). The data on

salinity also showed a cycle similar to the tides in the region whereas the data on temperature showed peaks corresponding to the solar cycle (maxima during late afternoon). The salinity lags the v-current by 2 hours, at which the correlation coefficient is about 0.80, whereas the synchronous series show a correlation coefficient of only about 0.32. This suggests that the peak in salinity occurs with a lag of about 2 hours after the peak in v-current. The station showed tidal signatures but is predominantly under freshwater influences as evident from the low values of salinity and high values of temperature. The freshwater effects appear to be very dominating, as salinity was seen to increase only during peak flood time from very low values. The coefficient of variation shows a value of 104% for salinity whereas that for temperature is only 1%, showing the dominance of freshwater effects on salinity. The time series of the sea level and currents (v-component) indicate that the flood tides at the two sites are forced from the southern side of the locations.

Limited time series data on sea level, currents, salinity and temperature for two unexplored sites in the upper reaches of the Cochin estuarine system have been subjected to detailed analyses to understand their variability. The sea level variance was dominated mainly by tidal signals, but the tidal influence decreases in the upstream direction. Doodson's X_0 filter appears to be efficient for detiding the observed sea level time series. During spring tides, one can expect stronger currents, thorough mixing and good flushing because of the higher tidal ranges.

There is a need to repeat the observation campaigns with a period of 30 days to resolve amplitudes and phases of all the diurnal and semi-diurnal constituents. The number of stations is also to be increased, especially in the upstream directions and the observations should be conducted during the two contrasting months i.e., April (dry month) and August (wet month). This will enable us to derive a clear picture of the seasonal variability as well as tidal variability.

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