

## Propagation of tides in the Cochin estuarine system, southwest coast of India

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Analysis of hourly data on sea level collected at four stations in the Cochin estuarine system has been made to understand the tidal and non-tidal sea level variations inside the estuary, for spring and neap phases during March 2000. Spring phase was dominated by semi-diurnal tides whereas neap phase was dominated by diurnal tides. Diurnal and semi-diurnal bands were together responsible for a high percentage of variance of the observed sea level. The dominance of shallow water tides was seen with increasing distance from the mouth. The sea level variance was dominated mainly by tidal signals, but the tidal influence decreased rapidly inside the estuary. Doodson's  $X_0$  filter appears to be efficient for de-tiding the observed sea level time series.

[ **Key words:** Sea level, tides, meteorological residuals, estuary, Cochin ]

A proper knowledge of tidal dynamics is necessary for understanding many general oceanographic phenomena at any station, particularly at coastal and estuarine locations, because tide is one of the most important forcings governing the mixing, circulation and other processes. Cochin ( $9^{\circ} 58'N$ ;  $76^{\circ} 15'E$ ), a growing city located on the southwest coast of India, is the main port of Kerala State in South India and a major port of the country. It is located on the western side of Vembanad lake (Willingdon Island) and is surrounded by a number of islands, the most important ones being Vallarpadam, Vypin and Bolgatty in the north (Fig. 1). Nettoor, Kumbalam and Panangad are the islands in the south (not shown in the figure). Cochin estuarine complex, approximately  $320 \text{ km}^2$  in area, consisting of the Vembanad lake, the rivers flowing into the lake and the surrounding islands, is a very important estuarine ecosystem, in this part of India. It is used extensively for transport of goods, fishing and dumping of industrial as well as domestic wastes. There are numerous studies on variation of physical, chemical, biological and geological properties with respect to time (duration of about 12 or 24 hours), mainly to understand tidal influence on the parameters, in this estuary<sup>1,2</sup>. However, studies concerning tidal propagation have not been attempted so far. In this study, an attempt has been made to understand the spring-neap variations of the tides at some selected stations in the Cochin estuarine system. The main aim of the present study is to understand the changes of the tidal

constituents as they propagate in the estuary. These, in turn, have important implications for mixing, circulation and flushing characteristics.

### Materials and Methods

The sea level data pertaining to this study were collected during the month of March, 2000. The auto-

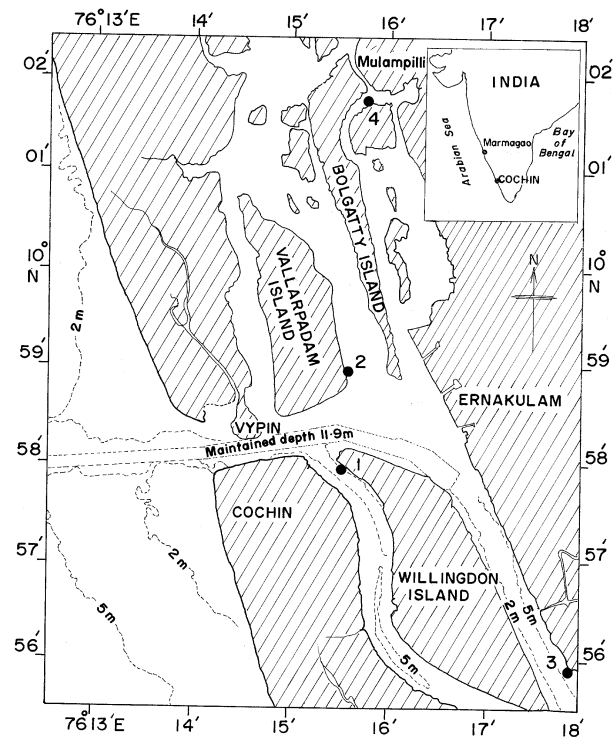


Fig. 1 — Location map

matic tide gauge and tide pole were the instruments used for collecting observations on water level. The hourly data on sea level obtained from the permanent automatic tide gauge maintained by the Cochin Port Trust (station 1) and temporarily installed tide poles at stations 2-4 were utilised in the study (Fig. 1). The data were collected during two phases of the tide i.e., spring and neap, based on lunar data given in the Indian Tide Tables<sup>3</sup>, each of four days duration, viz. Phase I: 20-24 March, 2000 and Phase II: 27-31 March, 2000. Detailed analysis was made on the observed sea level to understand tidal as well as non-tidal variability. The presence of a travelling wave and its periodicity can be revealed by cross-correlation between the sea level at the two stations, specifically by the maximum correlation occurring at some lagged time.

Harmonic analysis of observed sea level provides the basis for the prediction of tides<sup>4-6</sup>. The harmonic tidal constituents which enable us to recognise the characteristic features of tides at a particular location are  $N_2$  (Larger lunar elliptic),  $M_2$  (Principal lunar),  $S_2$  (Principal solar),  $K_2$  (Luni-solar) and  $O_1$  (Principal lunar),  $P_1$  (Principal solar) and  $K_1$  (Luni-solar). Tide filtering is necessary to study non-tidal signals, and harmonic analysis provides a technique for computing the meteorological residuals. This is important as the tidal signal is strong in most of the coastal regions. A new time series comprising of only tides can be constructed, and the time series can be de-tided by subtraction.

In the present study, eight constituents (amplitudes and phases) were resolved using the least squares method<sup>4</sup> on hourly data of 4 days. They are the  $K_1$ ,  $M_2$ ,  $M_3$ ,  $M_4$ ,  $2MK_5$ ,  $M_6$ ,  $3MK_7$  and  $M_8$ , respectively. These constituents actually represent a band, because

of the Rayleigh Criterion (Table 1). The Rayleigh Criterion implies that we cannot resolve two constituents whose frequencies are separated by less than 0.0104 cph. The frequencies of the dominant constituents (diurnal or semi-diurnal) all lie within 0.0104 cph of one another. The Rayleigh Criterion thus prevents us from distinguishing between the amplitudes of the three constituents in the diurnal species and of the four constituents in the semi-diurnal species. Thus,  $K_1$  constituent determined using harmonic analysis will contain energy from  $O_1$  and  $P_1$  constituents also. Similarly,  $M_2$  constituent will contain energy from  $N_2$ ,  $S_2$  and  $K_2$  also. Therefore, in the present analysis,  $K_1$  refers to the “diurnal band”,  $M_2$  refers to the “semi-diurnal band” and the other bands are third-, fourth-, fifth-, sixth-, seventh- and eighth-diurnal bands, respectively. Because of the limited duration of observations (96 hours), there are two difficulties. The first one is the result of Rayleigh Criterion and the second is that we cannot get any information on constituents whose periods are more than 96 hours. The tidal analysis (for the determination of the amplitudes and phases of the constituents) was carried out using the software of the University of Hawaii Sea Level Center, USA. The paper largely follows the techniques described in Shetye *et al.*<sup>7</sup>, wherein the propagation of tides in the Mandovi-Zuari estuarine network at Marmagao ( $15^\circ 25'N$ ;  $73^\circ 48'E$ ) was made using water level data collected at 15 stations during dry and wet seasons of 1993.

The Doodson's  $X_0$  filter<sup>4</sup> was used to de-tide the observed sea level. Unlike the other filters, it involves a data loss of 38 points only, and discriminates strongly against tidal periods. Spectral analysis for determining predominant periodicities was computed following Stull<sup>8</sup>. Principal Component Analysis was used to understand the variance structure of the observed and filtered sea level at the different stations following Cooper & Weekes<sup>9</sup>.

## Results and Discussion

The hourly march of the observed sea level and the predicted sea level (high and low waters<sup>3</sup>) are presented in Fig. 2. The lunar phases are also indicated, to appreciate their forcings on the observed sea level. The lunar phenomena, having a superior effect on the tides are the perigee, new moon, full moon, maximum north and south declination, while those having relatively smaller effects are the apogee, first quarter, last quarter and moon on equator. The observed sea level is uniformly lower than the predicted sea level during

Table 1—Characteristics of the frequencies used in the analysis

Sl. no	Constituent	Frequency (cph)	Range of frequencies the constituent represents (cph)	Bands represented
1	$K_1$	0.0418	0.0314 – 0.0522	Diurnal
2	$M_2$	0.0805	0.0701 – 0.0909	Semi-diurnal
3	$M_3$	0.1208	0.1104 – 0.1312	Third-diurnal
4	$M_4$	0.1610	0.1506 – 0.1714	Fourth-diurnal
5	$2MK_5$	0.2028	0.1924 – 0.2132	Fifth-diurnal
6	$M_6$	0.2415	0.2311 – 0.2519	Sixth-diurnal
7	$3MK_7$	0.2833	0.2729 – 0.2937	Seventh-diurnal
8	$M_8$	0.3220	0.3116 – 0.3324	Eighth-diurnal

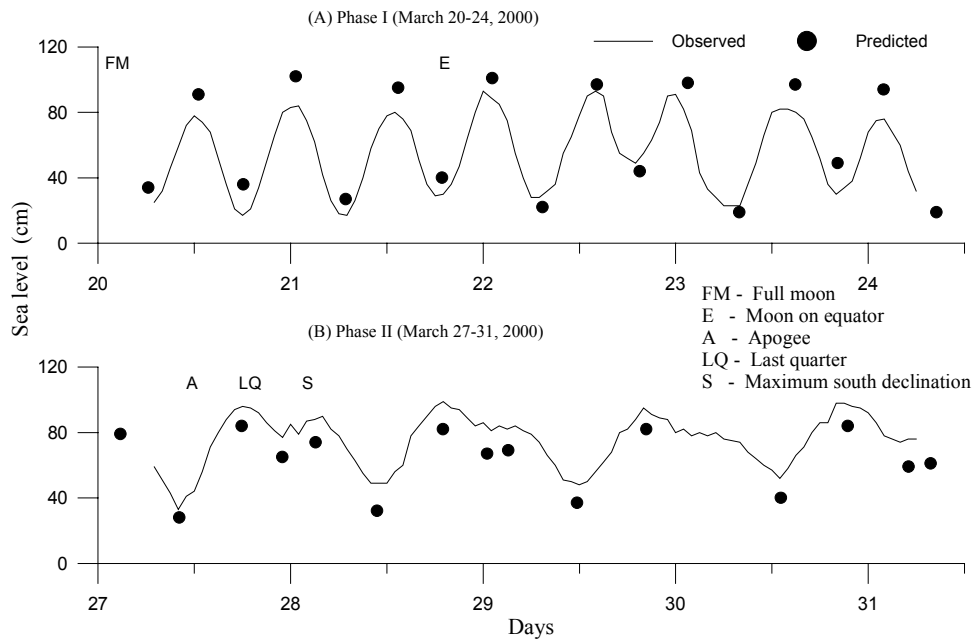


Fig. 2 — Observed and predicted sea level (cm) during (A) Phase I and (B) Phase II of the data collection at station 1. The lunar phases are also indicated.

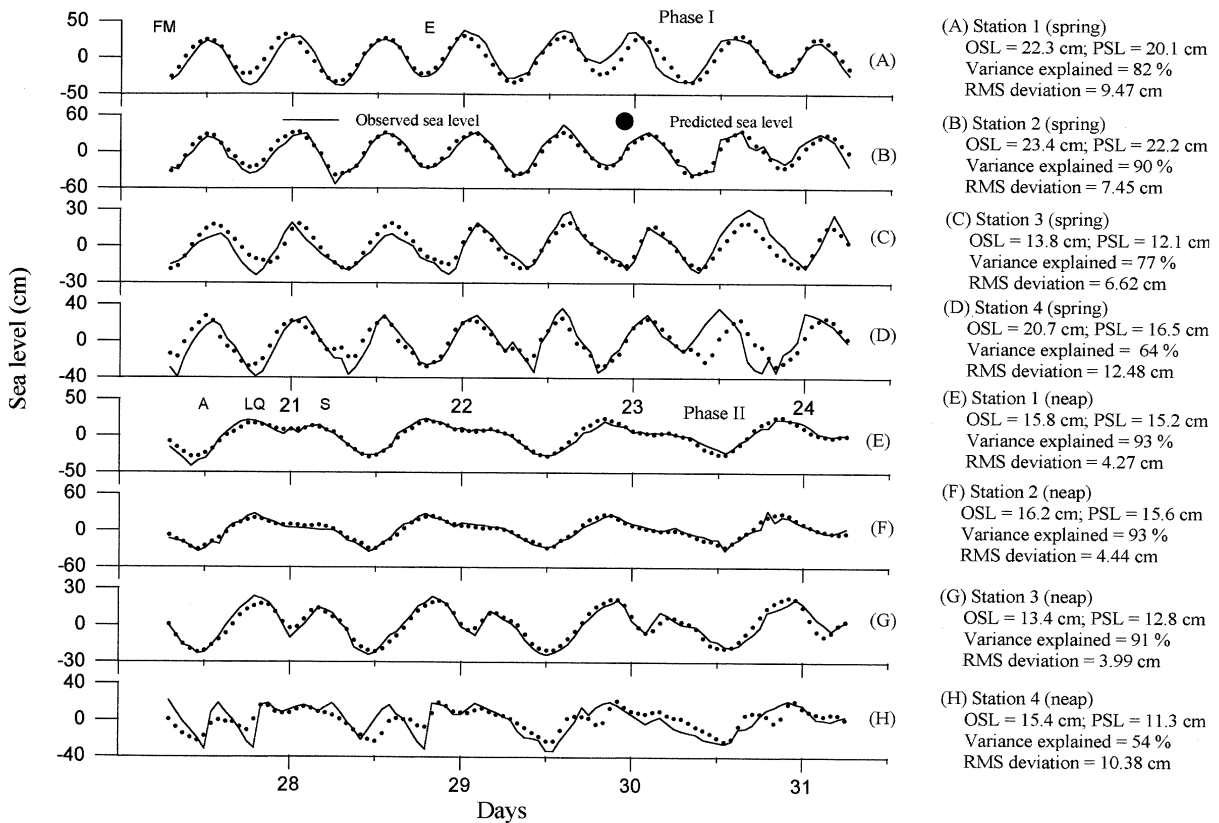


Fig. 3 — Hourly march of the de-meaned observed and predicted sea level (cm) during Phase I (A,B,C,D) and Phase II (E,F,G,H) at the four stations. [FM=full moon, E=moon on equator, A=apogee, LQ=last quarter, S=maximum south declination. OSL=standard deviation of the observed sea level (cm), PSL= standard deviation of the predicted sea level (cm), variance explained=variance explained by the relationship between the observed and predicted sea levels, RMS deviation=root mean square deviation between the observed and predicted sea level (cm)]

Phase I and higher during Phase II. The hourly march of the de-meaned sea level at the four stations for Phases I and II is shown in Fig. 3. The variation of the daily inequality with the moon's declination as well as the variation in range with the phases of the moon at Cochin, can be appreciated in Figs. 2 and 3. In a mixed tide with very large diurnal inequality, the higher low water (or lower high water) frequently becomes indistinct at the time of extreme declinations. During these periods, the diurnal tide has such overriding dominance that the semi-diurnal, although still present, cannot be seen on the tidal curve. This is seen in Figs. 2B and 3E-F.

In the case of mixed tides, the magnitude of the diurnal tides is similar to that of semi-diurnal tides. In this tidal regime, the relative importance of the semi-diurnal and diurnal components keeps changing throughout the month. The diurnal tides have large magnitudes when the moon's declination is greatest but reduce to low values when the moon is passing through the equatorial plane. Semi-diurnal tides are most important after full and new moon (Fig 3A-D) and are only partly reduced during the period of neap tides (Fig 3E-H).

A conspicuous feature seen in the observed sea level series is the lack of coherence of the maxima and minima beyond 23 March 2000 for Phase I and a

similar feature during 27-29 March 2000, for Phase II (Fig. 3). The standard deviation of the observed sea level was found to be higher during Phase I as compared to Phase II for all the stations. The standard deviation of sea level during Phase II at stations 1 to 4 were 71, 69, 97 and 74% of that of Phase I, respectively. Stations 2 and 3 showed the highest and lowest standard deviations for both the phases.

The cross-correlograms between station 1 and the three other stations for the observed sea levels are presented in Fig. 4. Maximum cross-correlation occurs slightly to the right of zero lag, which shows that station 1 marginally leads the three other stations, and is seen for both the phases. Waves with a period of about 12 hours are present in Phase I and about 24 hours in Phase II, the amplitudes and phases of which can be determined from harmonic analysis.

#### Tidal constituents

When presenting the results of a tidal analysis, it is usual to refer to tidal "constituents" rather than tidal "constants". The constituents may have slight changes if a different period of sea level data is analysed for the same place. Reasons for the variability include inconsistencies in the measuring instruments, analysis limitations due to non-tidal energy at tidal frequencies and real oceanographic modulations of the tidal

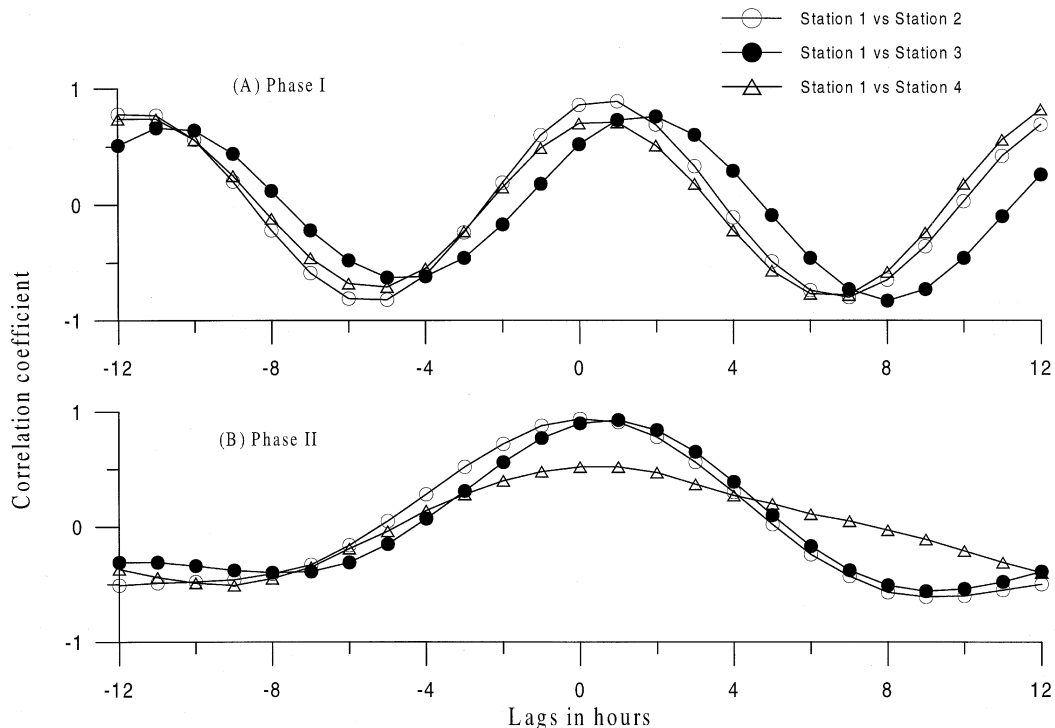


Fig. 4 — Cross-correlograms between the sea level at station 1 against that at other stations during (A) Phase I and (B) Phase II. Positive lags indicate that station 1 leads the other stations.

behaviour. Accuracy of the estimates of harmonic tidal constituents is highly dependent on the record length, total number of harmonic constituents sought and variance of the non-tidal signal in the record<sup>4</sup>.

Harmonic analysis of the hourly sea levels was performed to determine the amplitudes and phases of the tidal bands for the four stations, for both the phases and the results are presented in Table 2.

*Phase I:* The semi-diurnal band was very dominant, followed by diurnal. The ratio of the amplitudes of the semi-diurnal to the diurnal band were 3.5, 4.6, 4.4 and 4.3, respectively. The amplitudes of the diurnal band varied from 8.00 cm (at station 1) to 3.72 cm (at station 3), whereas that for the semi-diurnal band varied from 31.06 cm (at station 2) to 16.21 cm (at station 3). Station 4 showed the highest amplitudes, among the four stations for third-diurnal to eighth diurnal bands.

*Phase II:* The diurnal band dominated, followed by semi-diurnal. The ratio of the amplitudes of the diurnal to the semi-diurnal band were 1.8, 1.9, 1.3 and 3.5, respectively. The amplitude of the diurnal band varied from 19.03 cm (at station 2) to 13.42 cm (at station 4), whereas that of the semi-diurnal band varied from 10.58 cm (at station 3) to 3.83 cm (at station 4). The highest amplitudes among the 4 stations for third-diurnal to eighth-diurnal bands were seen at station 4.

#### Shallow water tides

Shallow water tidal constituents arise from the distortion of the main constituent tidal oscillations<sup>4</sup>. The percentage contributions of the sum of the amplitudes of the shallow water bands (third-diurnal to eighth-diurnal) to that of the sum of amplitudes of the principal tidal bands (diurnal and semi-diurnal) are presented in Table 3. It is evident that shallow water contributions are important, and their importance increases in the upstream direction. Their contribution as a percentage of the sum of the diurnal and semi-diurnal constituents was found to be particularly high at station 4, during both the phases. However, it must be emphasized that these computations are highly sensitive to the period of the study.

#### Tides at Cochin and Marmagao

Srinivas<sup>10</sup> used observed hourly data on sea levels at Cochin for each year, for the period 1988-1993 to determine the amplitudes of the tidal constituents. Harmonic analysis of the yearly record gave amplitudes and phases of 67 tidal constituents. The relevant portion of those results is reproduced in Table 4. From the table, it is seen that diurnal and semi-diurnal constituents dominated the tide. Amplitudes of the harmonic constituents showed that  $M_2$  is maximum, followed by  $K_1$ ,  $O_1$  and  $S_2$ .

Table 2 — Amplitude (cm) and phase (°) of the tidal bands at stations 1 to 4 during Phase I and II

Band	Station 1		Station 2		Station 3		Station 4	
	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)
Diurnal	8.00 (18.36)	192.7 (247.7)	6.76 (19.03)	213.3 (244.2)	3.72 (13.70)	153.9 (255.5)	5.02 (13.42)	344.0 (269.7)
Semi-diurnal	27.69 (10.42)	206.7 (3.4)	31.06 (10.03)	225.4 (16.7)	16.21 (10.58)	255.3 (29.3)	21.54 (3.83)	224.6 (335.0)
Third-diurnal	2.91 (0.55)	43.3 (20.9)	1.57 (0.41)	305.3 (177.0)	2.15 (3.23)	204.6 (333.1)	3.29 (4.77)	20.0 (43.2)
Fourth-diurnal	0.74 (0.52)	283.8 (173.8)	0.77 (0.38)	300.7 (143.6)	2.09 (1.67)	106.5 (241.1)	3.33 (5.15)	47.4 (208.1)
Fifth-diurnal	0.78 (0.29)	290.9 (331.2)	1.31 (1.03)	156.4 (320.3)	1.47 (1.26)	13.0 (176.7)	2.08 (2.04)	136.9 (57.6)
Sixth-diurnal	0.62 (0.41)	122.1 (144.7)	0.36 (0.82)	294.5 (341.9)	0.50 (0.39)	319.7 (138.4)	0.66 (1.11)	132.0 (346.2)
Seventh-diurnal	0.09 (0.08)	153.8 (60.3)	1.13 (0.95)	213.9 (106.5)	0.52 (0.55)	153.8 (196.6)	1.97 (1.63)	131.1 (145.3)
Eighth-diurnal	0.40 (0.98)	188.8 (132.8)	1.81 (0.67)	241.4 (213.5)	0.09 (0.16)	311.5 (258.1)	2.26 (1.22)	226.3 (342.1)

\*Values within brackets are for Phase II

A comparison has been made to understand the tidal characteristics at Cochin, with that at Marmagao, for the principal tidal constituents to bring out the salient features of Cochin estuarine system. Cochin and Marmagao are two estuarine systems on the west coast of India, separated by 660 km. The data for Marmagao estuarine system were taken from Shetye *et al.*<sup>7</sup>. The tidal amplitudes are much higher at Marmagao, than at Cochin. The amplitudes of the  $M_2$ ,  $K_1$ ,  $O_1$  and  $S_2$  tides are reported to be 55.65, 31.98, 16.17 and 20.23 cm at Marmagao whereas the same are 20.36, 17.58, 9.32 and 7.52 cm at Cochin, respectively. The mean spring range was 152 cm and the mean neap range was 71 cm, giving a mean range of 112 cm at Marmagao, whereas that at Cochin for the same are 56, 26, and 41 cm, respectively. A large

spring-neap variation is seen at both the stations, the mean spring range being more than twice the mean neap range. The Form Numbers are 0.63 and 0.96, at Marmagao and Cochin, indicating that the tide is of a mixed, predominantly semi-diurnal form for both the systems. 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 has passed its maximum values. Relative amplitude (in percentage) with respect to  $M_2$  of  $K_1$ ,  $O_1$  and  $S_2$  at Marmagao were 57.5, 29.1 and 36.4 and the corresponding values at Cochin were 86.3, 45.8 and 36.9, respectively.  $M_3$  to  $M_8$  constituents showed a relative amplitude of less than 4% at Cochin. The coefficients of variation are high in the case of the shallow water tides whereas the principal tidal constituents did not show a high coefficient of variation.

Table 3 — Percentage contribution of the sum of shallow water bands (third- to eighth-diurnal) to the sum of diurnal and semi-diurnal bands

Station	Phase I			Phase II		
	A	B	C	A	B	C
1	35.70	5.53	15.49	28.78	2.82	9.81
2	37.82	6.95	18.37	29.07	4.25	14.62
3	19.92	6.83	34.27	24.28	7.27	29.93
4	26.56	13.59	51.16	17.26	15.92	92.26

A = Sum of amplitudes of diurnal and semi-diurnal bands (cm)

B = Sum of amplitudes of third-diurnal to eighth-diurnal bands (cm)

C = (B/A) in percentage

#### *Tidal propagation in the Cochin and Marmagao estuaries*

The cross-sectional area of the Cochin inlet is approximately 4234 m<sup>2</sup> below the chart datum<sup>11</sup>. This is very small compared to the cross-sectional area at the mouths of the Mandovi and Zuari estuaries<sup>7</sup>. This area is attained in the Mandovi-Zuari estuaries at approximately 10 km, in the upstream directions. The tides enter the Cochin estuary through this narrow inlet. There is a rapid decay in the amplitudes of the major constituents within less than 10 km or so (Table 2).

Table 4 — Amplitudes of the principal tidal constituents plus the constituents analysed in the present study, based on annual analysis of 1988 - 1993 for Cochin

Sl. no	Constituent	Frequency (cph)	Amplitude (cm)		Coefficient of variation (%)	Relative amplitude (%) $M_2 = 100\%$
			Average	Standard deviation		
1	$O_1$	0.0387	9.32	0.33	3.59	45.8
2	$P_1$	0.0416	5.48	0.50	9.04	26.9
3	$K_1$	0.0418	17.58	0.71	4.06	86.3
4	$N_2$	0.0790	4.54	0.17	3.65	22.3
5	$M_2$	0.0805	20.36	1.26	6.20	100.0
6	$S_2$	0.0833	7.52	0.58	7.77	36.9
7	$K_2$	0.0836	2.17	0.07	3.06	10.7
8	$M_3$	0.1208	0.32	0.03	8.15	1.6
9	$M_4$	0.1610	0.68	0.07	10.52	3.3
10	$2MK_5$	0.2028	0.30	0.12	41.38	1.5
11	$M_6$	0.2415	0.20	0.06	28.85	1.0
12	$3MK_7$	0.2833	0.08	0.03	37.89	0.4
13	$M_8$	0.3220	0.12	0.04	33.10	0.6

The damping of the tidal constituents is particularly conspicuous at station 4, which is located in an area dominated by fresh water effects, complex geometry and shallow depths. The other three stations are located in an area close to the Ernakulam and Mattancherry channels (depths are maintained by frequent dredging at around 10-12 m) and hence damping is not conspicuously seen. Station 3 is also located in a region where shallow water dominates but it is not far from the Ernakulam channel. The most conspicuous difference between the Mandovi-Zuari estuarine system and the Cochin estuarine system is that the former is in a region where tides predominate, as was seen in the last section. Both these estuaries, i.e., Mandovi and Zuari also have a typical funnel shape. Shetye *et al.*<sup>7</sup> and Unnikrishnan *et al.*<sup>12</sup> have suggested that the undamped propagation of the tidal amplitudes in the Mandovi-Zuari estuarine network, is a consequence of the balance between geometric amplification, due to decrease in the cross-sectional area in the upstream direction, and frictional dissipation. The rapid decay of the tidal amplitudes near the upstream end of the channel was attributed to the freshwater efflux. They reported that the amplitudes of the semi-diurnal and diurnal tides remained unchanged over a distance of 40 km from the mouth in the upstream direction and then decayed rapidly over the next 10 km, for both the estuaries - Mandovi and Zuari. The Cochin estuarine system, on the other hand, is a bar-built estuary. It is a very complex system with a number of islands, and a number of rivers debouching into it. Periyar, Muvattupuzha and Pamba are the more important rivers discharging into the Vembanad estuary, the others being Manimala, Minachil and Achankovil. The percentage contribution of each river to the total annual discharge (from climatology) is: Periyar (33.2), Muvattupuzha (24.2), Minachil (8.3), Manimala (8.8), Pamba (19.7) and Achankovil (5.8). The total volume of discharge for these six rivers is approximately 20,000 M<sup>3</sup>/year. The least river discharge is during February-March. The discharge during March (from climatology) is 1.69% of the annual total and that during February is slightly lesser, at 1.61% of the annual total. The month of July has the highest discharge of 21.52% of the annual total. Another conspicuous difference between the Mandovi-Zuari estuarine network and the Cochin estuary, is in terms of depth scales. The Mandovi-Zuari estuarine network has a depth of approximately 5 m in the lower reaches. This is in sharp contrast to that of the Cochin estuary, where the lower reaches, especially the channels (Ernakulam and

Mattancherry) are maintained at depths of around 10-12 m. The major source of sediments to the Cochin harbour are mainly the two large rivers Muvattupuzha and Periyar (and the four smaller rivers to a lesser extent). To counteract sedimentation in the Cochin harbour, dredging of the port area is carried out throughout the year. The Cochin Port Trust maintains three dredged channels: Approach channel (9 km), Ernakulam channel (5 km) and Mattancherry channel (3 km). Approximate depths of these channels are 10-12 m.

#### *Propagation speeds of the diurnal and semi-diurnal waves*

As the diurnal tidal signal was prominent during Phase II as compared to Phase I, and the semi-diurnal tidal signal was prominent in Phase I, as compared to Phase II, these phases were used for the computation of the speeds of the diurnal and semi-diurnal tides. The data on phase (Table 2) pertaining to station 1 and 3 were utilised for the computation of propagation speeds of these waves. The distance between the two stations is approximately 7 km. The computed speed of the diurnal wave was 3.8 m/sec and that of the semi-diurnal wave 1.2 m/sec. The average speed of the diurnal and semi-diurnal waves in the Mandovi-Zuari estuarine network was approximately 5.3 m/sec for the dry season<sup>7</sup>.

#### *Meteorological residuals*

The regular and predictable tidal movements of the sea are continuously modified to a greater or lesser extent by the effects of the weather. The relative importance of tidal and non-tidal movements depends on the time of the year and the local bathymetry. The meteorological residual (set-up, or non-tidal component) is the difference between the observed and predicted tides. Even though tidal variations can be removed in the analysis, there could be energy in the tidal frequencies because of small timing errors in the gauge and weak interaction between the tides and the surges. The standard deviations of the meteorological residuals (Root Mean Square deviation) were found to be higher during Phase I as compared to Phase II. Further, as compared to other stations, station 4 showed higher standard deviations for both the phases. The meteorological residuals for the stations indicated that the residuals are more noisy inside the estuary due to nonlinear influence from the shallow depth, interaction with the river discharge, irregular estuarine geometry and bottom topography (siltation effects are important) on the tides. The non-tidal circulation is

influenced by the river discharge at station 4, along with the other factors highlighted above.

The percentage variance explained by the curve constructed using diurnal to eighth-diurnal bands (8 bands) for both the phases are presented in Fig. 3. The percentage variance accounted was generally high (excluding station 4). The modelled data had a better fit with the observed data during Phase II, as compared with Phase I. Station 4 showed a very poor percentage variance, as was seen in Phase I and Phase II. The percentage variance during Phase II at station 4 was lower than that during Phase I, unlike that displayed by other three stations. From the data on percentage variance explained, it appears that the tidal influence was particularly high at stations 1 and 2 as compared to station 3, the influence being the least at station 4. Based on the data for 1988-'93, Srinivas<sup>10</sup> showed that the sea level variance is dominated mainly by tidal signals, which accounted for nearly 90-95% of the observed sea level (Table 5).

#### Filtered sea level

The hourly march of the filtered sea level is presented in Fig. 5. During Phase I, in general, there is an increasing trend, whereas during Phase II, there is a decreasing trend at all the stations. The increasing trends seen for Phase I are particularly conspicuous. These could be signatures of a low frequency signal, not resolved in the short record. The variance explained by the relationship between observed sea level and filtered sea level (Table 6) was generally much less than 10%. This suggests that the  $X_0$  filter is fairly effective in removing the tidal signals. The standard deviations of the filtered sea level during Phase II were less than that during Phase I, for the corresponding stations.

Table 5 — Tidal variance (%) in the sea level data for 1988-'93 period at Cochin, based on annual analysis

Year	Standard deviation of observed sea level (cm)	Standard deviation of residual sea level (cm)	Tidal variance (%)
1988	25.34	7.50	91.2
1989	25.39	6.32	93.8
1990	23.97	7.24	90.9
1991	22.62	6.00	93.0
1992	24.39	5.60	94.7
1993	24.02	5.86	94.0

Srinivas<sup>10</sup>

The cross-correlograms between station 1 and the three other stations for the filtered sea levels are presented in Fig. 6. The maximum correlation at zero lag was for station 1 against station 2 and minimum for station 1 against station 3 for Phase I. For Phase II, however, highest correlation at zero lag was maximum for station 1 against station 3 and minimum for station 1 against station 2. The symmetrical distribution seen for Phase I was not seen for Phase II. The cross-correlograms also suggest that during Phase II, riverine influence may be more, especially at stations 3 and 4 (these stations lead the sea level at station 1).

#### Spectral signatures

Results of spectral analysis of the observed sea level are presented in Figs 7A and B for Phase I and Phase II, respectively. During Phase I, the absolute dominance of the semi-diurnal tides is seen in the observed sea level. During Phase II, the dominance of the diurnal tides over the semi-diurnal is clearly seen. The signatures of higher harmonics is seen at station 4. These results are in agreement with that obtained using harmonic analysis (Table 2).

Results of spectral analysis of the filtered sea level are presented in Figs 7C and D for Phase I and Phase II, respectively. The dominance of "red noise" was seen for both the phases. This is because of unresolved low frequency signals. The increasing and decreasing trend seen in Fig. 5 could be part of a low frequency signal. There also appears to be a signal of a 2.5 hour wave in the spectra.

Table 6 — Percentage variance explained by the relationship between the observed sea level and the filtered sea level

Station	SD <sub>OBS</sub> (cm)	SD <sub>FIL</sub> (cm)	RMS <sub>OBS-FIL</sub> (cm)	Variance explained (%)
Phase I				
1	23.02	3.48	22.41	8.31
2	24.96	2.54	24.86	1.09
3	12.71	2.78	12.61	1.11
4	19.27	2.86	18.91	3.79
Phase II				
1	14.40	1.01	14.41	0.06
2	15.39	0.90	15.27	6.17
3	13.06	0.84	13.06	0.13
4	15.32	2.74	14.95	4.73

SD<sub>OBS</sub> – Standard deviation of the observed sea level (cm)

SD<sub>FIL</sub> – Standard deviation of the filtered sea level (cm)

RMS<sub>OBS-FIL</sub> – Root mean square deviation between the observed and filtered sea level (cm)



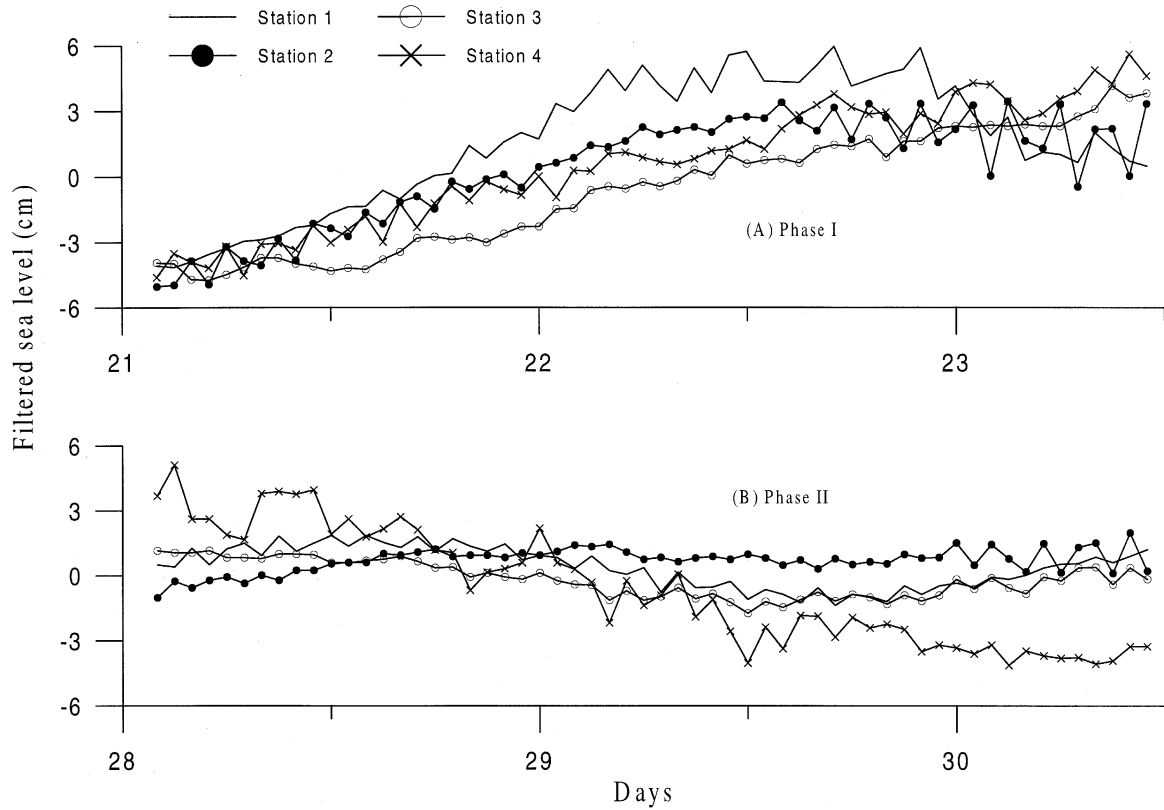


Fig. 5— Hourly march of the filtered sea level (cm) during (A) Phase I and (B) Phase II at the different stations.

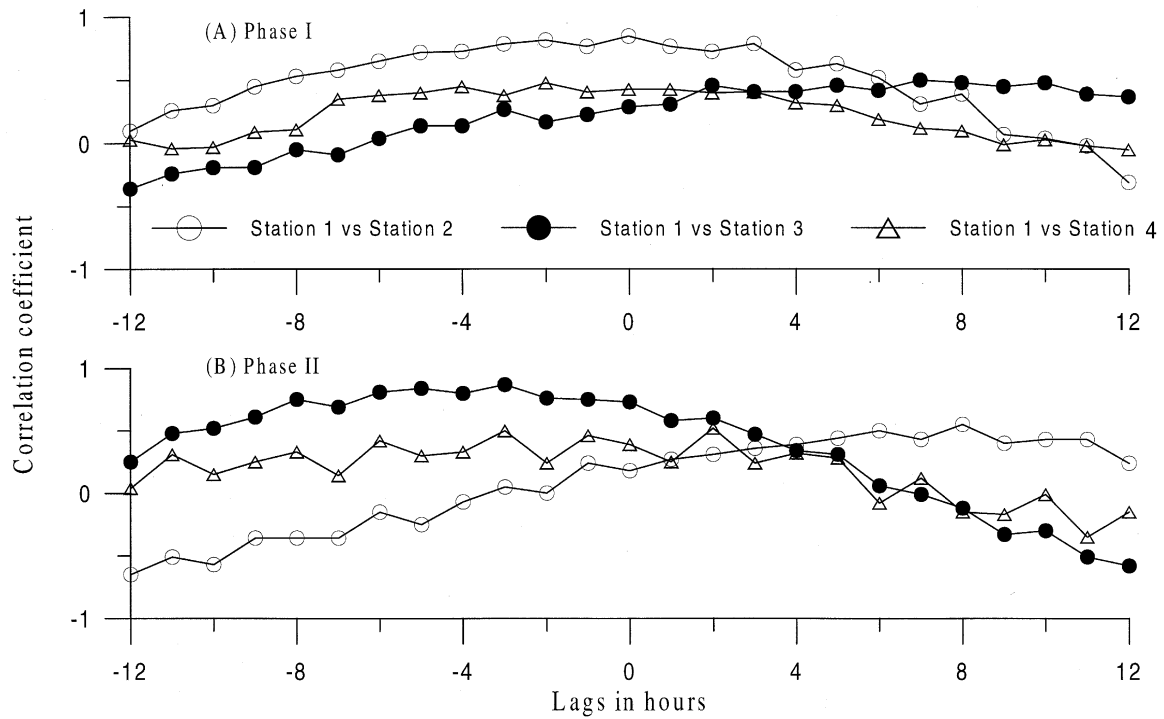


Fig. 6— Cross-correlograms between the filtered sea level at station I against that at other stations during (A) Phase I and (B) Phase II. Positive lags indicate that station I leads the other stations.

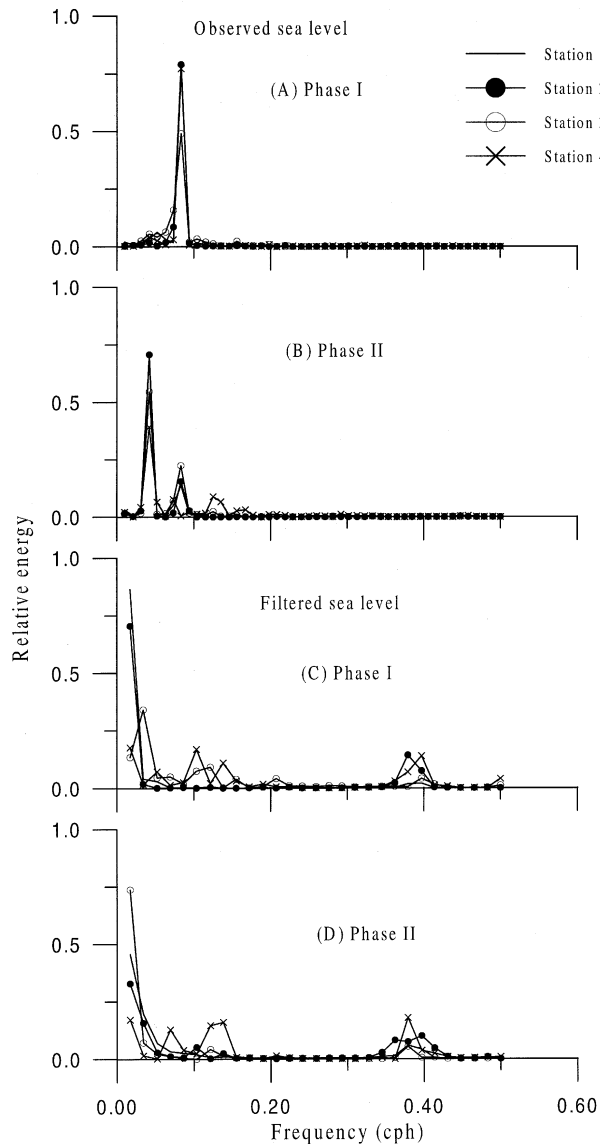


Fig. 7 — Spectra of the observed sea level during (A) Phase I and (B) Phase II and spectra of the filtered sea level during (C) Phase I and (D) Phase II.

#### Principal Component Analysis (PCA)

PCA was performed to understand the variance structure of the observed and filtered sea level. The first two PCs accounted for nearly 75% of the total variance for the observed sea level and 92% of the total variance in the case of the filtered sea level. A plot of PC1 against PC2 for observed and filtered sea level is presented in Fig. 8, to understand the variance structure. For the observed sea level, during Phase I, all the stations are scattered, whereas during Phase II, they occur as one group. For the filtered sea level, during Phase I, all the stations are scattered, whereas during Phase II, the scatter is relatively less. In

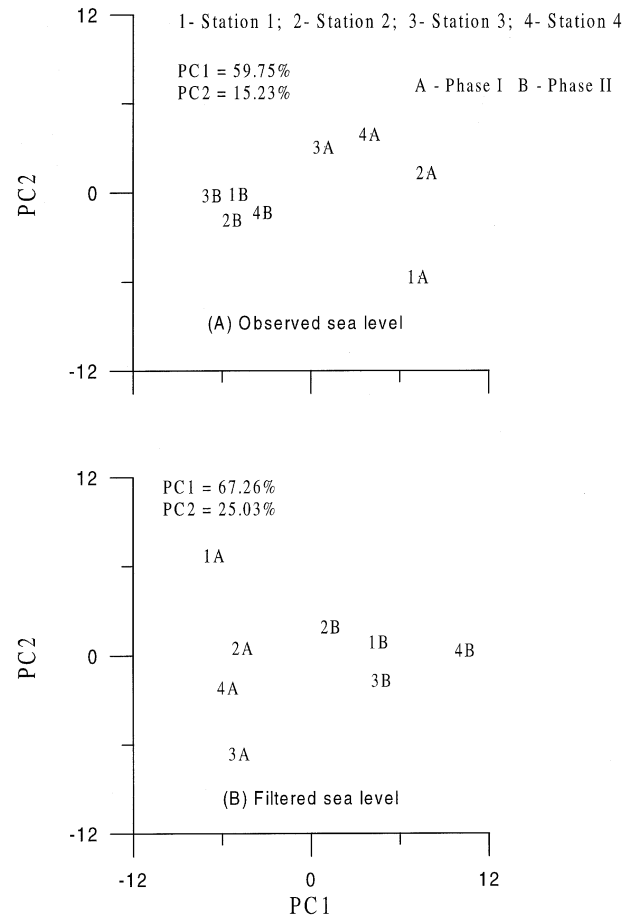


Fig. 8 — Plot of PC1 against PC2 for (A) observed sea level and (B) filtered sea level.

general, for observed sea level and filtered sea level, stations 1 and 4 seem to stand apart. This points out that the observed sea level and the filtered sea level display a markedly different nature at these two stations. Station 1 is near the mouth of the estuary and hence marine influence is more dominating whereas station 4 is much inside and hence freshwater influence could be more dominating.

#### Changes in mean sea level

The tide poles were kept undisturbed during the entire survey (Phase I and Phase II), making it possible to determine the change in mean sea level from Phase I to Phase II. The mean water level was higher during Phase II. The differences in the mean water level (Phase II minus Phase I) were 19.4, 4.5, 4.6 and 0.3 cm for the four stations, respectively. Oceanographic effects (dynamics of large scale currents along the west coast of India) could be responsible for the large drop of sea level at the mouth and a small drop at stations 2 and 3. At station 4 no conspicuous change was seen. The results suggest that the influence of

river discharge could be higher during Phase II as compared to Phase I. The observed sea level at station 1 was uniformly lower than the predicted sea level during Phase I whereas during Phase II, it was higher (Fig. 2) supporting the above results. Further, the changes are stronger where marine influence is stronger, diminishing progressively in the upstream direction.

#### *Practical implications of the findings*

At the times of new moon and full moon (spring tide days), tides are semi-diurnal whereas during the first and last quarters of the moon (neap tide days), they are predominantly diurnal in nature. During an approximately twenty four hour period, there are two high and two low waters at times of new moon and full moon, with a higher tidal range. These cause the associated currents to be stronger and also cause more vertical mixing, and one can expect good flushing. On the other hand, during first and last quarters of the moon, the tidal ranges are much smaller, with one high and one low water during a twenty four hour period. The lower high water and the higher low water are often not discernible in the records, and may not play an important role in the present context *viz.* circulation, mixing and flushing. These spring-neap differences could be appreciable as the spring-neap variation in the tidal forcing is relatively high at Cochin<sup>10</sup> estuarine region has undergone considerable shrinkage 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<sup>13,14</sup>. The results of the present study would be of use for any future comparison of the tidal constituents.

#### *Conclusion*

The sea level variance is dominated mainly by tidal signals, but the tidal influence decreases rapidly inside the estuary. Spring phase was dominated by semi-diurnal tides whereas neap phase was dominated by diurnal tides. Diurnal and semi-diurnal bands were together responsible for a high percentage of variance of the observed sea level. The dominance of shallow water tides was seen with increasing distance from the mouth. Doodson's  $X_0$  filter appears to be efficient for de-tiding the observed sea level time series. During spring tides, one can expect stronger circulation, mixing and flushing because of the higher tidal ranges and more frequent flood and ebb phases as compared to the neap tides.

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).

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