ORIGINAL ARTICLE

Environmental set-up and tidal propagation in a tropical estuary with dual connection to the sea (SW Coast of India)

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Abstract The Kochi Backwater (KB) is the second largest wetland system in India. It is connected to the sea at Fort Kochi and Munambam (Pallipuram) (30 km north of Kochi). As the tide is forced through two openings, its propagation in the backwater system is very complicated, particularly in the northern arm of the estuary. Using synchronous water level (WL) and current measurements in the KB from a network of stations during 2007–2008, it was convenient to demarcate the northern KB into two distinct regions according to the tidal forcing from the north (Pallipuram) and south (Vallarpadam). This demarcation is useful for computing the propagation speeds of the dominant tidal constituents in the northern branch of the KB with dual opening for opposing tides. WL variations indicated that M_2 tide (Principal lunar semidiurnal constituent) dominated in the sea level variance, followed by the K_1 constituent (Luni-solar declinational diurnal constituent). The M_2 tidal influence was the strongest near the mouth and decayed in the upstream direction. The propagation speed of the M_2 tide in the southern estuary was ∼3.14 m/s. The ratio of the total annual runoff to the estuarine volume is ∼42 that indicates the estuary will be flushed 42 times in a year. KB can be classified as a monsoonal estuary where the river discharge exhibits large seasonal variation.

Introduction

Kerala has a chain of lagoons or backwaters along its coastal region, which is fed by rivers, and drain into the Lakshadweep Sea. The Kochi backwater (KB), a part of the Vembanad wetland system is located in the humid tropical region between 09°40′–10°40′N and 76°00′–77°30′E. It is unique in terms of physiography, geology, climate, hydrology, land use and flora and fauna. KB is bordered by Alappuzha (Alleppy), Kottayam and Ernakulam districts of Kerala covering an area of about 200 km² and extending 80 km in a NW–SE direction from Pallipuram at north to Thaneermukkam at south (Fig. 1). The width of the lake varies from 500 m to 4 km and the depth from <1–12 m. The Kochi backwaters are a very important estuarine ecosystem, supporting rich flora and fauna, in the state of Kerala. It is used extensively for transport of goods, fishing and dumping of industrial as well as domestic wastes. In the recent times, the Kerala backwaters have witnessed increased levels of stress due to a variety of intense infrastructural development activities, such as land reclamation, bridge construction, and more recently the development of Vallarpadam International Container Transshipment Terminal (ICTT). These anthropogenic activities have eventually led to the shrinkage of the estuarine area as well as to other negative environmental impacts. Of 36,500 ha of backwater that existed in the middle of 19th century, only 12,700 ha (34.8%) remains

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Fig. 1 Map of the Kochi backwater. Pallipuram (station 1) and Fort Kochi (station 6) are the openings to the Arabian Sea at west. Thaneermukkam (station 8) at south represents the artificial barrage station in the estuary
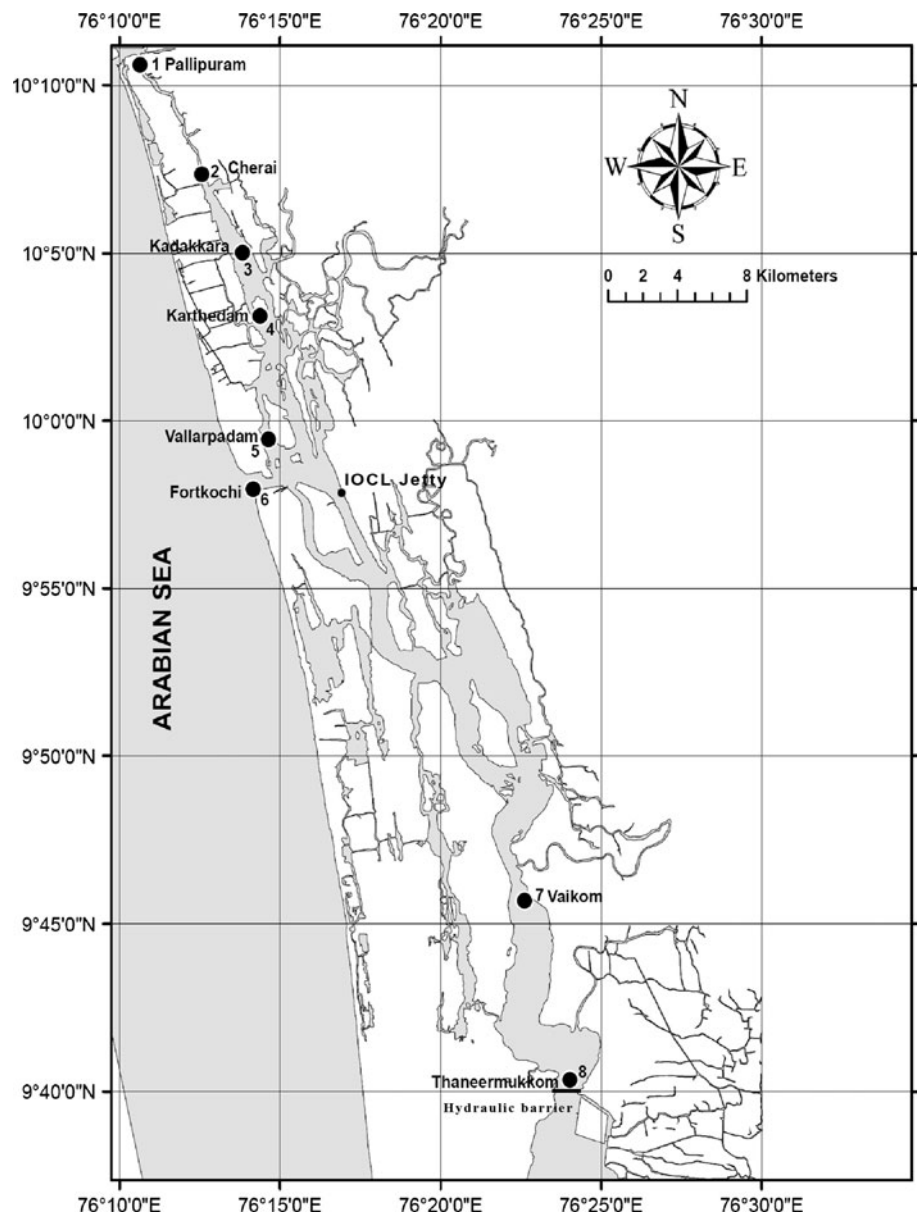

nowadays as open waters (Gopalan et al. 1983). The Cochin Port, one of the major ports along the west coast of India, is situated on the banks of this estuarine system. There are numerous studies related to the salinity distribution, stratification, and sediment transport in the KB (Josanto 1971; Rama Raju et al. 1979, Udaya Varma et al. 1981; Sankaranarayanan et al. 1986; Joseph 1974). Rasheed and Balchand (2001) studied the short-term impacts of dredging on salinity in the estuary. Studies on the tidal propagation and currents in the KB are scarce; a few workers have made efforts to understand the characteristic of tides in the KB (Srinivas and Dinesh Kumar 2002; Srinivas et al. 2003; Antony et al. 2007, 2009. Balachandran et al. (2008) has developed a two dimensional hydrodynamical model for the KB focusing on the

pollution dispersion characteristics. The present paper is an attempt to comprehend the tidal propagation in the KB particularly in northern arm of the estuary in the wake of its dual connection to the sea by deploying WL recorders and current meters at very closely spaced intervals.

Rainfall

There are seven main rivers and numerous small streams that flow into this lake. Chalakudy, Periyar, Muvattupuzha, Achencoil, Pamba, Meenachil and Manimala are the main rivers which bring freshets into the Kochi backwaters. These rivers have their catchment in the western Ghats (Fig. 2) and discharges large volume of fresh water during

Fig. 2 Map of the major river basins which emptying to the Kochi backwater. *Dotted lines* represent river basin boundary, *solid line* represents rivers and *its branches and triangle* shows the gauging stations
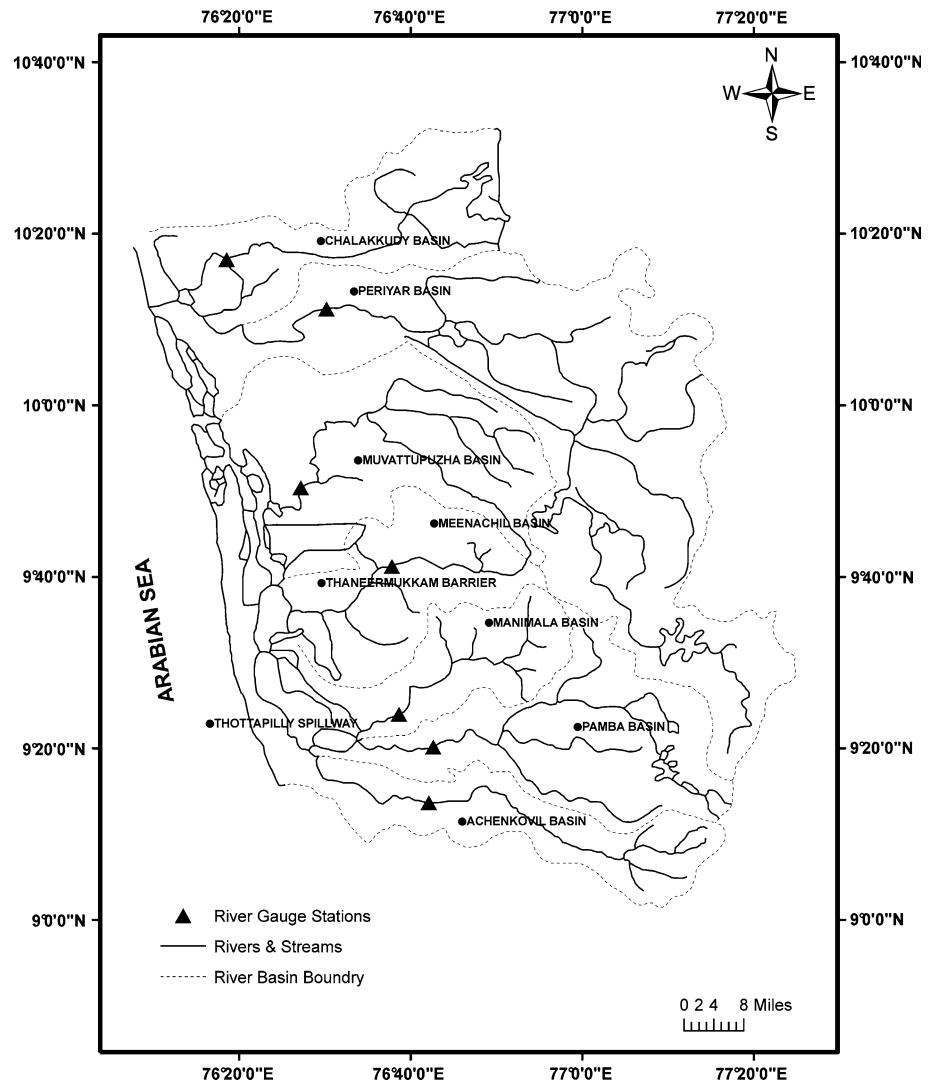
the summer monsoon. Table 1 lists the average monthly rainfall of the different river basins comprising the study area. For the present discussion, we are considering only the integrated annual mean rainfall at the river basins. Nearly 60% of the rainfall at all the basins occurred during June–September. Annual precipitation in the river basin varied between 630 and 916 mm. The highest annual rainfall was recorded at the Meenachil river basin, followed by the Pamba River basin.

Drainage into the system

Climatology of the river discharge into the Kochi backwater was constructed using the data provided by the Central Water Commission (Table 2) from seven gauging stations corresponding to the rivers emptying into the backwater. Monthly discharge data exhibited high seasonality, 60–70% of the total discharge occurring during the SW monsoon periods. The maximum annual net

discharge (6,795 Mm^3) was recorded at Periyar, whereas the minimum discharge (1,250 Mm^3) was recorded at Achencoil. A first order estimate of the annual drainage into the Kochi backwater can be obtained by summing up the annual discharge from the above rivers, the value thus arrived at is 22×10^3 Mm^3/year. Freshwater from these rivers become saltier during the passage to sea through two openings one at Cochin (Fort Kochi) inlet and other at Munambam (Pallipuram) with alongshore separation of 30 km. The cross-sectional area of the Kochi inlet is ~4,234 m^2 (Joseph 1996) whereas that of the Pallipuram inlet, situated to the north of the Cochin inlet is relatively much smaller 900 m^2 (Revichandran 1993), ~20% that of Cochin inlet.

Anthropogenic interventions/barrages

At Thaneermukkom near Chertalai, there is a major artificial salt barrier (barrage/regulator) constructed during the

Table 1 Average monthly rainfall (mm) of river basins in this study region

River basin	Chalakudy	Periyar	Muvatupuzha	Meenachil	Manimala	Pamba	Achancoil
January	34.54	50.19	33.00	35.82	43.89	79.19	45.25
February	18.29	55.32	45.26	84.83	58.84	131.48	73.21
March	57.05	94.39	120.15	245.28	104.21	350.67	191.84
April	252.15	249.83	316.34	481.60	329.62	563.46	490.65
May	488.85	515.28	453.48	888.03	472.66	765.71	691.41
June	2,275.08	2,057.13	1,625.35	2,740.91	1,198.40	1,910.71	1,436.38
July	2,163.34	1,783.75	1,539.16	2,050.08	1,070.22	1,745.13	1,321.80
August	1,491.20	1,265.15	1,286.82	1,391.38	839.64	1,453.85	878.74
September	838.24	756.87	804.53	504.03	710.52	1,147.93	937.78
October	848.81	810.35	721.13	1,578.79	643.38	1,172.42	892.67
November	455.03	472.76	526.17	870.65	436.34	752.66	518.37
December	85.65	109.40	114.46	121.80	92.45	211.54	120.72
Average	750.69	685.04	632.15	916.10	500.01	857.06	633.24

Table 2 Average monthly river discharge (Mm^3)

	Muvattupuzha	Chalakudy	Periyar	Meenachilar	Pamba	Achankoil	Manimalayar	Average
January	179.49	25.76	93.75	5.19	63.56	9.59	5.46	54.69
February	157.36	16.02	81.15	1.21	38.57	4.56	4.66	43.36
March	172.50	17.03	90.71	5.25	42.65	3.55	3.15	47.84
April	179.06	17.81	116.95	34.20	68.87	13.16	22.44	64.64
May	230.23	40.13	169.32	48.68	155.40	31.45	67.00	106.03
June	694.65	259.08	990.66	273.46	673.09	199.63	356.72	492.47
July	984.52	543.21	1,654.09	312.30	836.50	247.06	400.67	711.19
August	809.34	471.27	1,500.37	286.75	677.47	203.62	305.37	607.74
September	460.90	223.72	814.82	169.39	480.64	152.61	202.39	357.78
October	540.80	173.77	684.87	166.93	563.97	199.16	260.44	369.99
November	399.60	109.60	440.88	172.30	356.79	158.09	158.65	256.56
December	220.64	41.52	157.71	37.31	113.45	30.13	29.22	90.00
Total	5,029.11	1,938.92	6,795.29	1,512.97	4,070.96	1,252.61	1,816.15	3,202.29

1970s for regulating salt water from entering the southern most areas and adversely affecting the agricultural operation in the low-lying Kuttanad, which is the rice bowl of the state. The barrage is about 1,250 m long with 93 vent ways, each 12.2 m wide and 5.5 m high, and the sill is at an elevation of 3.38 m below MSL. For navigation purposes, a twin-lock has been provided. The barrage is kept closed all through summer (January–May), and there is no flushing possible in the upper reaches, so much so that the nonpoint discharge of water containing insecticides and pesticides from the rice field is trapped on the upstream side of the barrage. The structure has been relatively successful in keeping the water in Kuttanad free from salinity, enabling increased cropping in the dry season. However, these structural measures taken to prevent salinity intrusion without carrying out sufficient detailed study have caused problems to the estuarine ecosystem and overall ecology of the region. Several drawbacks have been noticed; the major

ones are: reduction of upstream migration of marine fish and prawns, increased weed growth at upstream which affects the navigation and severely restricts the natural flushing of pollutants. Another hydraulic intervention is the Thottapally spillway, completed in early 1955, and built in the southernmost part of Kuttanad to divert a part of the combined flood waters of Achencoil, Pamba and Manimala along an easier and more direct outlet to the sea, which would otherwise exit through the mouth at Kochi, after travelling about 75 km. The structure is located at Thottapally 27 km south of Alappuzha (CWRDM, Report on Carrying capacity-based developmental plan for Greater Kochi Region 1999).

Highly complex geometry and bathymetry of the KB along with high freshwater influx may have great influence on mixing and flushing characteristics. Present study focuses on the propagation of tide along the estuary and influence of the fresh water discharge on the flushing efficiency.

Materials and methods

The data on water level (WL) variations were collected at eight locations (Fig. 1) between April 2007 and April–May 2008. All the measurements were of 1 month duration. Stations were positioned to cover adequately the northern and southern arm of the KB. Daily river discharge data (1978–2001) has been collected from Central water commission and computed monthly climatology using objective analysis. In order to study the influence of rainfall and river discharge to the estuarine dynamics, CTD profiles were gathered from a fixed station everyday from at ICOL jetty (Fig. 1) 11:00 h from May 2008 to April 2009. Figure 3 a two peaks, characterize rainfall pattern, the first one during June–September, representing the southwest monsoon and secondary peak during October–November (northeast monsoon). WL variations at the station for the above period is shown in Fig. 3b, the red line indicates the phase of the tide at the time of salinity profiling. Figure 3c depicts the salinity profiles gathered during the above period. Water column is partially stratified during most of the observation period. Dominance of fresh water prevailed during the wet seasons (summer monsoon and northeast monsoon) while during the dry season tides overwhelms the river flow and entire water column was high saline with reduced stratification. Spring–neap variation also was observed in the salinity profiles as a fortnightly pattern. The reason for collecting WL data during April–May period is justified by the fact that these months represent the dry season with negligible river discharge. Hence the estuarine (KB) dynamics during the above periods is controlled by the tides and the tide-induced dynamics can be well captured in the WL data. One month WL data at a location during any time is sufficient to derive the tidal constituents at that location. These constituents remain invariant as long as the geological setting (i.e., bathymetry, topography, bed materials, etc.) of a sufficiently large region in the vicinity of the given location remains unchanged. Between 2007 and 2008, there were no major changes in the geometry of the Channel in the immediate vicinity of the WL recording stations and for discussion purposes data gathering exercise may be treated synoptic. Harmonic analysis of observed WL provides the foundation for the prediction of tides (Pugh 1987; Emery and Thomson 1998; Martin and McCutcheon 1999). Harmonic analysis (to determine the amplitude and phase of constituents) was carried out using the software TASK 2000 developed at the Proudman Oceanographic Laboratory, UK (Bell et al. 1998). The present paper largely follows the techniques described in Sunder and Shetye 2005, where the tidal propagation in Mandovi–Zuari estuarine network was studied using 1 month WL data at 13 locations.

Results and discussion

Rainfall pattern (Fig. 3) in the study area shows a peak during June–September (summer monsoon) and a second peak during October–November representing the north east monsoon. Annual runoff into KB from all the seven rivers is estimated to be 22.41×10^3 Mm^3. Runoff is not uniformly distributed; 60–70% of the runoff is during the SW monsoon period (June–September), while during the pre-monsoon period (April–May) virtually there was no significant runoff.

Table 3 gives the location and period of observations. Observed WL records of 1 month duration are shown in Fig. 4. Tides experienced in the KB are of mixed, predominantly semidiurnal type, with two high and two low waters of unequal heights occurring every day. Maximum tidal range (difference in the amplitude between lowest low tide and highest high tide) occurred during spring tide with 65.22 cm at Fort Kochi. Tidal range decreased in the upstream stations both in the northern and southern branches. Minimum tidal range of 13.44 cm was observed at Thaneermukkam approximately 40 km south of Fort Kochi. Tidal range during neap tide was comparatively low, maximum tidal range occurred at Fort Kochi (30.64 cm) and minimum at Thaneermukkam (9.4 cm). All the stations exhibited large spring–neap tide variability. The impact of barrage (Fig. 4) on the tidal amplitude can be seen in the WL records at Thaneermukkam for the initial 7 days when the barrage was closed.

Characteristic tidal features at eight locations were determined using harmonic analysis. The dominant constituents were M_2 (Principal lunar semidiurnal (12:25 h) followed by K_2 (luni-solar semidiurnal (11:58 h), O_1 (Principal lunar diurnal (25:49 h), P_1 (Principal solar diurnal (24:04 h) and K_1 (Luni-solar diurnal (23:56 h). The accuracy of the estimates of harmonic tidal constituents is highly dependent on the record length, total number of harmonics constituents sought and variance of the non-tidal signal in the record (Pugh 1987). Information on half a dozen of the most dominant (largest amplitude) constituents will suffice to understand the important characteristics of the tide at that location (Shetye et al. 2007). While studying tide in an estuary, it is generally assumed that tide at the mouth of the estuary is a consequence of global scale dynamics to which the contribution of estuary is negligible. Given the tide at the boundary condition, the characteristics of tide within the estuary are then studied. Amplitude and phase lag of the 32 constituents derived is listed in Tables 4 and 5, respectively.

The KB tides are forced at two locations one at Fort Kochi and another at Pallipuram separated by a distance of 30 km, and so there are inherent difficulties in describing the tidal propagation in the KB as a single entity. For all

Fig. 3 **a** Figure shows the daily rainfall, **b** predicted tide and **c** salinity at fort Kochi from May 2008 to April 2009
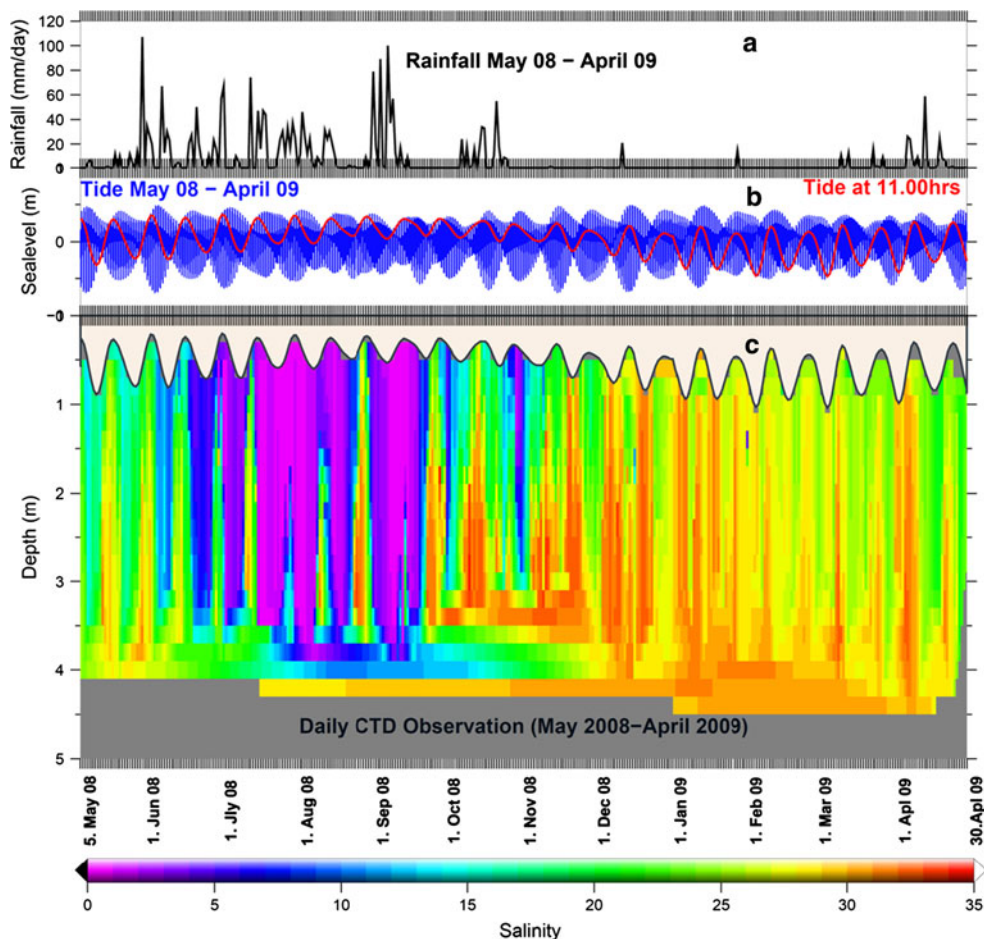

Table 3 Details of observations that were carried out

Station	Station no.	Distance (km)	Start date	End date	Time interval (min)
Pallipuram	1	27	19 March 2008 00:00 h	19 April 2008 23:50 h	10
Cherai	2	20	19 March 2008 00:00 h	19 April 2008 23:50 h	10
Kadakkara	3	15	19 March 2008 00:00 h	19 April 2008 23:50 h	10
Karthedam	4	7.5	19 March 2008 00:00 h	19 April 2008 23:50 h	10
Vallarpadam	5	3	19 March 2008 00:00 h	19 April 2008 23:50 h	10
Fort Kochi	6	0	1 April 2007 00:00 hours	30 April 2007 23:50 h	15
Vaikom	7	32	1 April 2007 00:00 h	30 April 2007 23:50 h	15
Thanneermukkam	8	44	1 April 2007 00:00 h	30 April 2007 23:50 h	15

practical purposes, KB can be divided into two arms: the northern arm (Fort Kochi–Pallipuram) and the southern arm (Fort Kochi–Thannermukkam). Figure 5 follows the variation in the amplitudes of major tidal constituents. The amplitudes of the semi and diurnal constituents decreased in the upstream direction. In which, M_2 amplitude (Major constituent) decreased from 23.8 cm at Fort Kochi to 5.7 cm at Thanneermukkam at a distance of 40 km. The
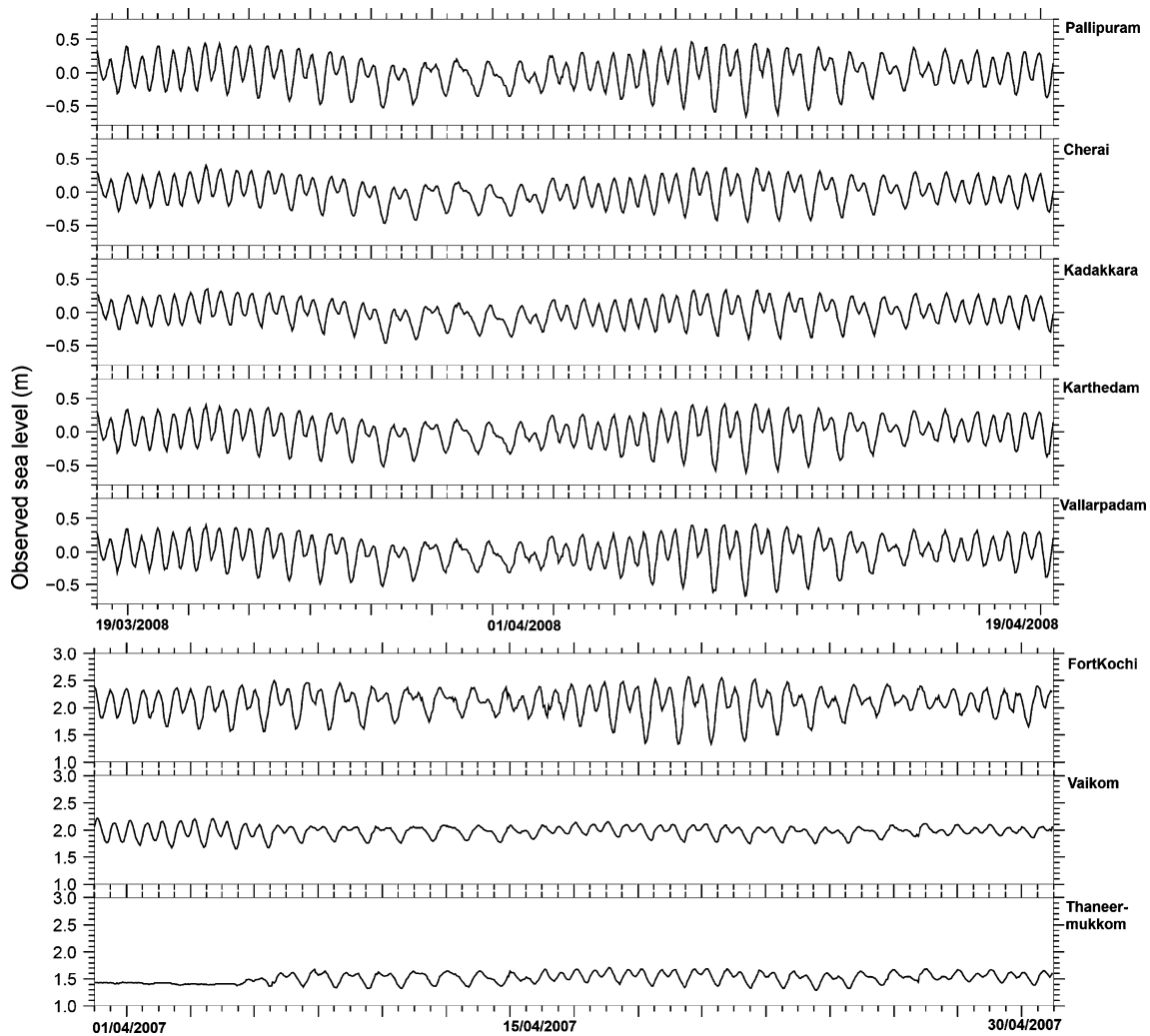
Fig. 4 Sea level (m) shows mixed semidiurnal nature of tide with decaying amplitude towards upstream. In the northern part (Fort Kochi–Pallipuram), tide is decaying from both opening and minimum amplitude can be seen at Kadakkara (station 3). In the southern part (station 8), Thaneermukkam station showed minimum tidal amplitude

variation of amplitude and phase difference along the channel is a function of friction and geometry of the channel. If the estuary is converging, the decrease in amplitude due to friction will be compensated by the increase in amplitude by the channel geometry. The KB decrease in the tidal amplitude can be attributed to the frictional dissipation and partly due to the presence of shallow and wide water bodies in the up streams. In the northern Part of the KB, between Fort Kochi and Pallipuram tides are forced from two open boundaries. So the amplitude of the most predominant M_2 was higher (23.89 cm at Fort Kochi and 23.24 cm at Pallipuram) at the inlets and decrease to the lowest value at 18 cm at Kadakkara.

An axial plot of the predominant tidal constituents provides prima-face evidence as to the nature of tides in the northern limp of the KB. Generally the amplitude of the

diurnal and semidiurnal tidal constituents decreases as we go upstream. In the northern part, we see that amplitude decreases upstream from both inlets, minimum amplitudes are observed in the vicinity of Kadakkara (station-3). Physically this implies that tides from the opposite ends are reaching this location between Kadakkara and Karthedam. Synchronous current measurements at Kadakkara are needed to further substantiate the argument. Figure 6 shows the time series plot of WL and current sticks during spring and neap tide at Kadakkara. In spring as the WL increases, during the flooding phase of the tide, the currents are directed southward suggesting a forcing from north. A similar trend is also observed during neap tide. This would mean that the tides from the northern inlet (Pallipuram) dictate the circulation dynamics of the region between Pallipuram and Kadakkara. This information is a priori when we attempt to compute the propagation speed of the

Table 4 Amplitude (cm) of the tidal constituents at eight stations during 2007 and 2008

Constituents	2008					2007		
	Pallipuram (1)	Cherai (2)	Kadakkara (3)	Karthedam (4)	Vallarpadam (5)	Fort Kochi (6)	Vaikom (7)	Thanneermukkam (8)
PI_1	0.36	0.29	0.26	0.33	0.35	0.35	0.14	0.15
P_1	6.29	4.99	4.46	5.80	6.06	6.08	2.60	2.61
PSI_1	0.15	0.12	0.11	0.14	0.15	0.14	0.06	0.06
PHI_1	0.27	0.21	0.19	0.25	0.25	0.26	0.11	0.11
$2N_2$	0.56	0.45	0.40	0.51	0.53	0.69	0.17	0.31
NU_2	0.82	0.65	0.58	0.74	0.77	1.01	0.24	0.45
T_2	0.49	0.31	0.26	0.45	0.48	0.51	0.23	0.06
K_2	2.25	1.43	1.20	2.08	2.24	2.37	1.07	0.28
Q_1	1.95	1.58	1.39	1.71	1.87	2.10	0.42	1.05
O_1	9.20	7.23	6.31	8.38	8.94	9.59	3.88	3.41
M_1	0.53	0.49	0.47	0.37	0.34	0.65	0.78	0.33
K_1	19.01	15.09	13.46	17.54	18.31	18.37	7.88	7.89
J_1	0.84	0.53	0.38	0.87	1.12	1.33	0.34	1.16
OO_1	0.56	0.06	0.12	0.61	0.78	1.18	0.79	0.53
MU_2	0.20	0.69	0.93	0.33	0.54	0.86	1.03	1.57
N_2	4.24	3.38	3.02	3.81	4.01	5.20	1.28	2.33
M_2	23.24	18.23	17.04	21.16	21.59	23.89	8.93	5.70
L_2	1.30	1.12	1.08	1.06	1.18	1.41	3.74	1.66
S_2	8.28	5.26	4.43	7.66	8.26	8.72	3.96	1.03
$2SM_2$	0.19	0.34	0.415	0.02	0.16	0.30	0.92	1.07
MO_3	0.35	0.97	1.24	0.63	0.35	0.63	0.35	0.31
M_3	0.16	0.19	0.31	0.16	0.35	0.35	0.48	0.16
MK_3	0.50	1.24	1.91	0.12	0.58	0.26	0.31	0.28
MN_4	0.22	0.09	0.29	0.16	0.31	0.88	0.33	0.12
M_4	0.52	0.39	0.71	0.68	0.87	1.23	0.31	0.35
SN_4	0.19	0.11	0.10	0.16	0.15	0.22	0.21	0.14
MS_4	0.02	0.52	1.11	0.39	0.63	0.88	0.65	0.21
$2MN_6$	0.29	0.26	0.36	0.11	0.17	0.12	0.21	0.13
M_6	0.24	0.09	0.39	0.08	0.25	0.05	0.12	0.12
MSN_6	0.07	0.06	0.05	0.12	0.19	0.11	0.14	0.08
$2MS_6$	0.28	0.07	0.39	0.27	0.45	0.86	0.37	0.15
$2SM_6$	0.43	0.25	0.10	0.12	0.13	0.14	0.11	0.05

diurnal and semidiurnal tidal constituents. Computation of the propagation speed of the major harmonics in the southern estuary is rather direct. Phase lag between Fort Kochi and Thaneermukkam for the various tidal constituents are considered and the speed computed. The speed of M_2 and O_1 computed from the phase shift were 3.13 and 4.15 m/s, respectively. In the northern part, there are inherent difficulties in computing the propagation speed and hence the speed is computed separately for two regions, Region-1 where the forcing is from North (Pallipuram–Kadakkara) and Region-2—between Vallarpadam and Kadakkara, where the tides from south (Fort Kochi) prevail. Table 6 lists the propagation speed of the dominant

tidal constituents between various stations. The speed of M_2 tide was 2.5 m/s between Pallipuram and Kadakkara and 2.32 m/s between Vallarpadam and Kadakkara.

Form number/tidal classification

The nature of tides in a particular location of the study area can be identified using form number, which is defined as $F = (O_1 + K_1)/(M_2 + S_2)$, the ratio of the main diurnal and main semidiurnal component of the tide, where the constituent's symbol indicates its respective amplitude. The form number of the study area varied from 0.85 to 0.91, except for the station at Thaneermukkom where the

Table 5 Phase lag of the tidal constituents at eight stations during 2007 and 2008

Constituents	2008					2007		
	Pallipuram (1)	Cherai (2)	Kadakkara (3)	Karthedam (4)	Vallarpadam (5)	Fort Kochi (6)	Vaikom (7)	Thanneermukkom (8)
PI_1	67	86	96	68	62	62	125	140
P_1	67	86	96	68	62	62	125	140
PSI_1	67	86	96	68	62	62	125	140
PHI_1	67	86	96	68	62	62	125	140
$2N_2$	309	335	344	309	298	305	328	73
NU_2	309	335	344	309	298	305	328	73
T_2	33	58	73	39	30	35	118	175
K_2	33	58	73	39	30	35	118	175
Q_1	64	76	79	68	63	71	88	135
O_1	324	332	333	326	325	61	98	102
M_1	185	235	258	199	170	63	191	160
K_1	67	86	96	68	62	62	125	140
J_1	344	354	358	333	326	73	251	118
OO_1	198	198	30	213	208	125	132	31
MU_2	314	250	260	336	5	185	108	258
N_2	309	335	344	309	298	305	328	73
M_2	244	270	282	250	240	338	65	92
L_2	159	155	157	180	174	33	85	267
S_2	33	58	73	39	30	35	118	175
$2SM_2$	63	31	47	156	195	340	137	347
MO_3	206	254	263	266	281	156	300	252
M_3	233	30	62	265	213	223	103	213
MK_3	246	251	255	288	11	92	58	160
MN_4	270	156	178	261	286	30	338	14
M_4	242	9	68	294	247	92	325	347
SN_4	295	288	318	5	45	335	326	127
MS_4	156	243	264	75	49	137	74	125
$2MN_6$	89	179	233	71	42	339	283	323
M_6	29	162	215	226	210	241	274	307
MSN_6	116	313	12	47	54	61	298	28
$2MS_6$	87	298	14	23	36	199	0	357
$2SM_6$	296	324	282	330	274	266	109	0

Form number is 1.66. This indicates that the tides in the KB are predominantly mixed semidiurnal with diurnal nature at southern most station, probably due to the presence of an artificial barrage in the extreme south of the study area.

Flushing time scale

A cursory information on the flushing characteristic of the system is obtained by the parameter $\eta_r = V_a/V_e$, where V_a is the total annual runoff (22.41×10^3 Mm^3) and V_e is the volume of the estuary (0.51×10^3 Mm^3). For KB, η_r is ~ 42, so estuary would have freshened many times at least

during the monsoon period. Monthly variation of discharge to volume ratio is shown in the Fig. 7, the ratio varied drastically between pre-monsoon (<1) and monsoon (9). Khadkikar (2008) described this type of estuary as being a monsoonal estuary. Vijith et al. (2009) introduced a new parameter (η_t) to quantitatively differentiate the monsoonal estuaries.

$$\eta_t = \frac{\text{Maximum monthly runoff}}{\text{Average monthly runoff}}$$

For KB η_t is ~ 2.6, typical value of a monsoonal estuaries according to the classification scheme suggested above.
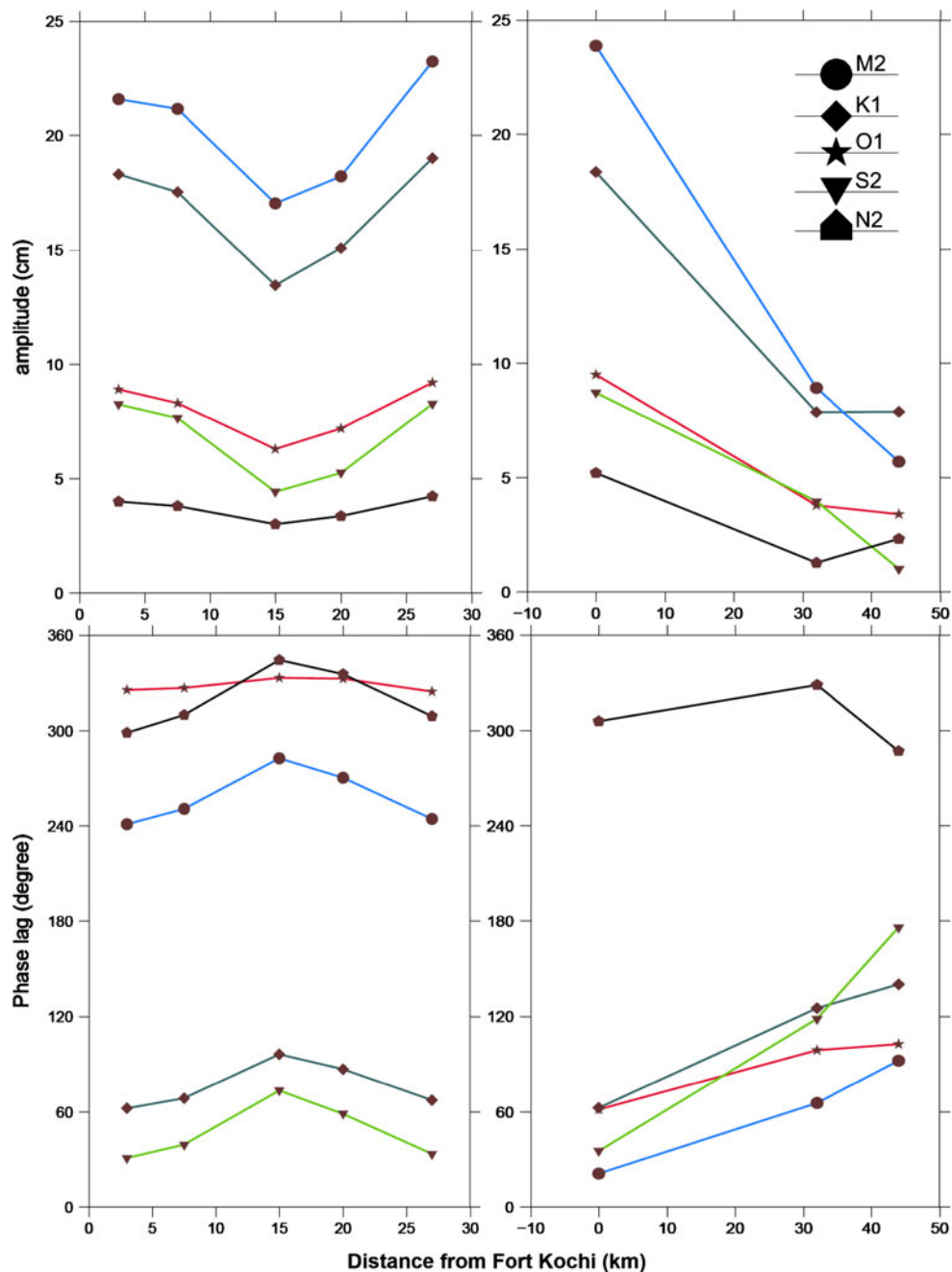
Conclusion

The Kochi backwater (KB) is the second largest wetland ecosystem in India. KB is unique by virtue of its dual connection to the sea. Tidal propagation in the estuary is rather complex. In this paper, we have described the changes in the tidal constituents from head to mouth. With concurrent measurement of WL and currents we could demarcate two zones in the northern estuary where the tidal circulation is drastically different. Propagation speed of the most dominant semi diurnal constituent M_2 is 3.0–4.17 m/s in the southern estuary and that of northern estuary was 2.2–2.5 m/s. The ratio of river discharge to the volume of the estuary is ~ 42, suggestive of complete freshening of the estuary during peak monsoon period. Thus, estuary can be grouped into the monsoonal estuaries where the river discharge shows large seasonal variation. Tides in the estuary are predominantly mixed semidiurnal, however, the tides at the southern most station is mixed semidiurnal to diurnal.
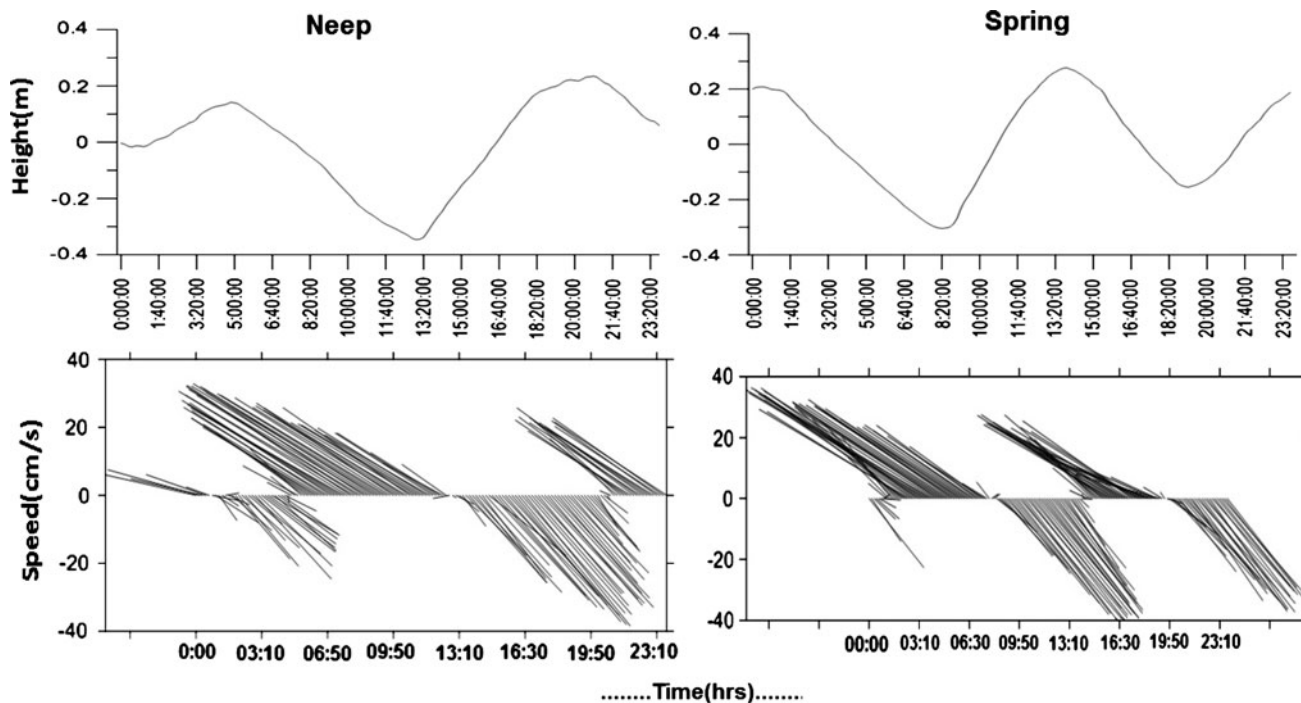
Fig. 6 Water level and currents at Kadakkara (station 3) during spring and neap phases

Table 6 Propagation speed of the dominant tidal constituents at different regions

Stations	O_1		M_2		S_2		K_1	
	Time (h)	Speed (m/s)	Time (h)	Speed (m/s)	Time (h)	Speed (m/s)	Time (h)	Speed (m/s)
Pallipuram–Kadakkara	0.62	5.38	1.32	2.53	1.34	2.50	1.93	1.73
Vallarpadam–Kadakkara	0.54	6.16	1.44	2.32	1.42	2.34	2.26	1.48
Fortkochi–Thaneermukkam	2.94	4.15	3.91	3.13	4.68	1.44	5.17	2.36

Fig. 7 Monthly discharge to volume ratio shown during different months
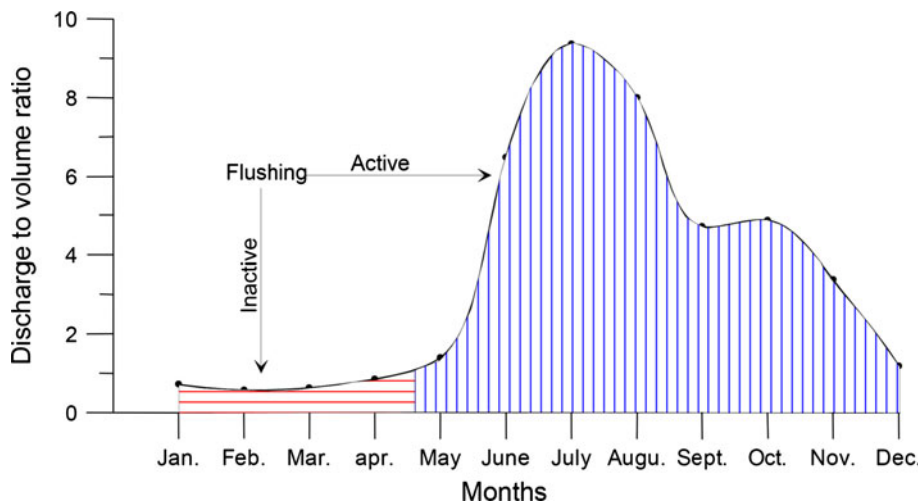
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