Characterization of tidal and non-tidal variations in the Chilika lagoon on the east coast of India

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Abstract- Analysis of water level data collected at two locations (Chilika inlet and INS) in the Chilika lagoon has been made to understand monsoonal variation of tidal and non-tidal characteristics based on the WTR tide gauge. Observation shows the variation of major tidal harmonic constituents (M_2, S_2) is caused by wind force, river discharge as well as bottom topography, whereas the variation of constituent is significantly related to seasonal climate change. The study results revealed that during the summer, the water level variation by wind force significantly occurs at INS compared to Chilika inlet, however, during monsoon the water level at both locations is controlled by river discharge. The amplitudes of tidal constituents are comparatively higher at Chilika inlet than at INS, and the tides are perfect semidiurnal at Chilika inlet, whereas tides are mixed, mainly semidiurnal at INS. Further study exhibited that the water level variation is dominated by tidal signal at Chilika inlet than at INS. The non-tidal water level varies seasonally at the both locations that caused by river discharge during monsoon and that by wind force during summer. Analysis of the water level data indicated that the variation in seasonal tidal propagation at the INS and Chilika inlet is due to the different bottom topography. Spectral analysis of water level revealed peak energy was at higher frequencies with lower amplitude during summer due to the wind effect, whereas the peak energy was at lower frequency with higher amplitude during monsoon due to river discharge.

Index Terms: Water level, tidal and non-tidal variation, Chilika inlet, INS, wind, river discharge, spectral analysis

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1. Introduction

The exchange of water between the coastal lagoon and sea through tidal inlets occurs in response to a variety of forces [1]. Various forcings such as wind, tide, fluvial discharges plays significant role simultaneously on these water bodies [2] and lead to considerable spatial and temporal variations in water levels, currents, circulation, flushing characteristics, which in turn affect the biological production [3], [4]. The tidal and non-tidal nature is the important features for lagoon shelf exchanges. Tides in coastal lagoons are driven by tides, give rise to non-linear flow dynamics within the entrance channel(s) [5]. The periodic diurnal and semidiurnal tidal exchanges are continuing as they are systematically predictable. They comprise a consistent baseline level of flushing. Non-tidal processes, particularly those arising in response to meteorological forcing, especially the wind stress, play a variable role depending on characteristics of the wind speeds [6]. They may occur as discrete events or quasi-periodic over time scales on the order of a few days to a few weeks. Over longer time scales, meteorological forcing in response to exchanges may exhibit a distinct seasonality. Meteorological forcing plays an important role for mixing within the lagoon. The non-tidal fluxes thought of as a random position of the oscillating discharge of altered periods and amplitudes, do not display the periodicity of the tidal discharges [1]. For a given velocity amplitude, the displacement of water mass is inversely proportional to the frequency. Sub-tidal frequencies may have greater influence than the tides and play an important role in the displacement [7,8].

Yamano et al. (1998)[9] investigated the influence of seasonal variation of wind on the circulation in shallow water lagoons. Al-Ramadhan (1988)[10] has studied the spatio-temporal variations in residual water circulations resulted from non-linear interactions, density gradients, wind stress and freshwater influx into the lagoon. Assuming complete mixing within the estuary and a stationary distribution of fresh and salty water for a constant river flux, Ketchum (1950)[11] has developed simplified mixing models for flushing time which were later improved by Dyer & Taylor (1973)[12]. Perlas Lagoon and Bluefields Bay are estuarine lagoon systems which have been studied for over five years in relation to biological, oceanographic, and fishing issues [13], [14], [15]. Seasonal variability of tidal and non-tidal currents off Beypore, SW coast of India was studied by dinesh et al (2004a)[16] and concluded that strong seasonal dominance was noticed in non-tidal currents. Panda et al

(2008)[17] have investigated the spatial and inter-annual variability in hydrographic parameters after opening of a new inlet, i.e., during 2001-04. There are many indications that the dredged inlet getting silted up by natural processes and migrating northward in its due course [18]. In view of these changing scenarios of inlets, a systematic, data collection with simultaneous recording at two locations were initiated and the results were presented in the paper. This study focused on the seasonal variability of tide and non-tidal level in the Chilika lagoon.

2. Study area, data and methods

Chilika lagoon, the tropical coastal lagoon, (Fig.1) located on the east coast of India (Lat 19°.19N to 19°.54N, Lon 85°.06E to 85°.35E). The lagoon expands over an area of 950 km^2 during summer and 1165 km^2 during monsoon [19] and oriented in SW-NE direction. Maximum length and breadth of the lagoon are 65 km and 20 km respectively. The lagoon is shallow with a mean depth of 1.7m.Topographically the lagoon is distinguishable into two major regions, namely, the outer channel and the main area. The lagoon comprises four distinctive areas 1) the North Sector- influenced mainly by fresh water most of the year, 2) the central sector corresponds to mixing of both fresh and saline water, 3) the Southern sector is isolated with deep waters constituted of mixed waters of fresh, saline and wind, and 4) the Outer channel completely renewed by oceanic waters during dry season and flooded with fresh water during rainy season. Most of these studies were undertaken based on field measurements in a limited time period. The outer channel is the core conduit through which neritic incursion takes place and floodwater leaves the lagoon, whereas main area of the Chilika lagoon is influenced by the wind forcing. Earlier studies revealed that the sand bar has been widened, the position of inlets constantly shifting, moving generally towards the northeast [20].

Hourly water level data obtained from the tide gauge at two locations, the Chilika inlet and the INS by deploying Valeport Wave and Tide Recorder (WTR) were used for the present analysis (Fig.1). The data were recorded over a period of one year i.e, during 2009 and segmented into two contrasting seasons, namely summer (dry) and monsoon (wet) period. The WTR has an accuracy of ±1cm for water level. Wind speed and direction were recorded at hourly intervals continuously from a fixed platform at Satapada by installing Automatic Weather Station(AWS), by the Chilika Development Authority (CDA), Bhubaneswar. The wind speed has an accuracy of ±0.3 m/s and direction ±5°. Bathymetry in the Chilika lagoon was surveyed using CEEDUCER echosounder integrated with DGPS and heave sensor. The echosounder has an accuracy of ± 2 cm in depth measurements, the DGPS has ± 1m in position accuracy and heave sensor has ± 2cm in pitch and roll movements in height. The freshwater runoff into the lagoon has been estimated based on the field measurements of cross-sectional depth profiles and flow velocities recorded by CDA at each of the river input locations. Tide filtering was necessary to study non-tidal signals, and harmonic analysis provides a basis for computing the residuals. The non-tidal variation which may have oceanographical, meteorological and hydrological signatures.

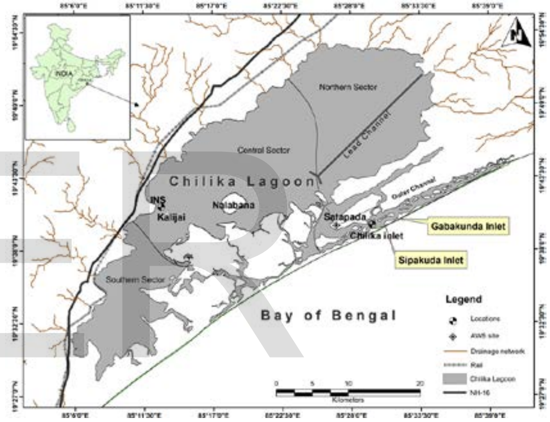

Fig.1 Map of Chilika lagoon, showing sampling locations.

3. Results and discussion

3.1. Bathymetry of Chilika lagoon

In this study the bathymetry and toposheets (prepared by Survey of India) which reflects the geometry of the Chilika region (Fig.2). The bathymetry data from field survey have been used in the Mike21 model (flexible triangular or rectangular grids) with grid resolution of 50 m x 50 m to generate bathymetry. Inside Chilika, the bathymetry is highly variable from one sector to another. The northern sector was the shallowest region where depths are ranging between 0.5 and 1.5m. The central sector was occupied with moderate depths of order of 1 to 2.5 m. The southern sector was the deepest sector with depths varies between 2.5 and 4.0 m. However the outer channel is also deeper region having depths varied between 2.5 and 5.5 m. The Chilika inlet position indicates that, inlets were continuous variations in its position with time [20].

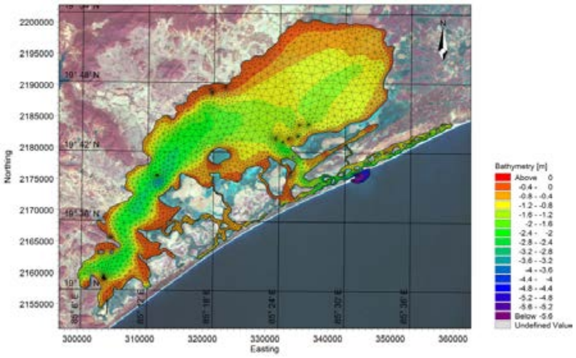

Fig. 2-Bathymetry of the Chilika lagoon

3.2. Freshwater discharge

The drainage basin of Chilika covers an area of over 4,300 km^2 [21]. The upland freshwater drainage into the lagoon has mainly two different hydrological sources such as: (1) drainage from the unregulated and degraded catchment basin lying on the western and southern boundaries [20]; (2) discharge from the distributaries of Mahanadi River to the north, including runoff from both the delta itself and the upper Mahanadi catchments [22]. The rivers and other distributaries that flow into the lagoon show significant seasonal variability in the flow pattern. The discharge of freshwater into the lagoon is quite high during monsoon, while it is negligible or absent during summer period [23]. The lagoon displays a net positive water balance from monsoon to winter season [24]. This decides the intensity and discharge of water from the lagoon to the sea through the inlet. According to Chilika Development Authority (http://www.chilika.com), 52 rivers and rivulets drain into Chilika lagoon and about 0.65 million cubic meter of silt is said to get into the lagoon every year. With the onset of rains, the 52 rivers and rivulets go into spate, causing freshwater currents, which gradually push the seawater out. The major rivers that discharge significant volumes of fresh water are Makara, Daya, Bhargavi, Luna and Kusumi. Based on observation, the total freshwater discharge from different upland rivers during monsoon is calculated to be about 1727 million m^3 (Fig.3). Figure shows the maximum river discharge during the period from 14-26th July 2009 (12 days), that was changed the water level characteristics of the Chilika lagoon.

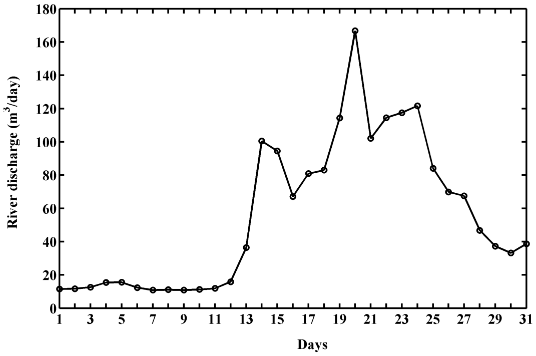

Fig.3-Freshwater discharge pattern into Chilika lagoon during monsoon.

3.3. Wind Pattern

The lagoon experiences seasonal reversible of winds. Figure-4 shows the wind pattern during summer and monsoon period in the Chilika lagoon. Wind speeds are high (6.5 to 9 m/s) during monsoon and low (4.8 to 6.4 m/s) during winter. Wind direction is SE, S and SW during monsoon, whereas N, NE and SE during summer. In Chilika, the winds are influenced by seasonal reversal of monsoons, whereas they are predominantly influenced by onshore and offshore driven by land and sea breezes. The effect of wind components at the INS is more as compared to the Chilika inlet because of variation in bottom topography.

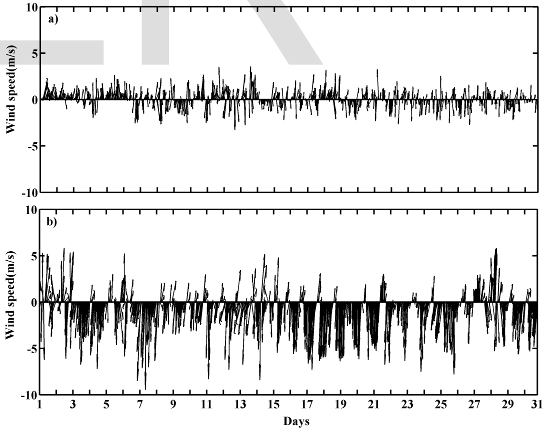

Fig. 4-Wind pattern during a) summer, and b) monsoon period in Chilika lagoon.

3.4. Tides and tidal propagation

A coastal lagoon is a distinct dynamic environment, where the interaction of different energy forces from land-sea operates in a shallow body of water which is partly enclosed by a barrier, and has restricted communication with the sea through one or more inlets. The inlet is a critical element affecting the exchange of water between the sea and lagoon. The position of an entrance controls current patterns and therefore determines the pathways of transport. The size and number of inlets determine the amount of water exchange with the ocean and in turn the exchange of suspended sediments. Tidal flow plays an active role in the evolutionary changes of lagoon morphology.

Information on tidal propagation into the Chilika lagoon was negligible almost until studies carried out by Reddy (1962)[25]. It was found that while high tides near the inlet drive in salt water through the channel during summer, freshwater dominates during active monsoon period. Chandramohan and Nayak (1994) [26] noted that the lagoon is hydraulically poor with little exchange of water between the sea and the lagoon, and the shorefront is exposed to a high degree of littoral drift. Their study also indicated migration of the inlet to approximately 500m northward. However, recent tide recordings reveal that there is a significant improvement in the water level during a tidal cycle, which has turned the lagoon into flushing mode [27]. The recorded water level during summer and monsoon at the Chilika inlet and INS are shown in figures 5&6.

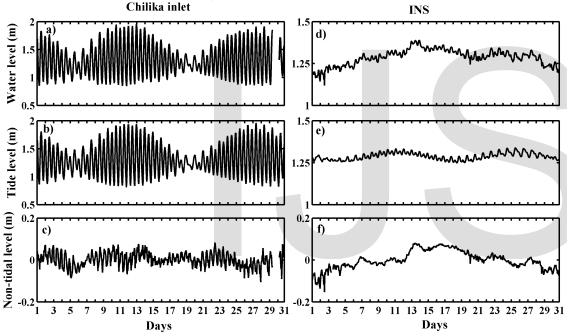

Fig. 5-Seasonal variation of water level, tidal and residual level at Chilika inlet and INS during summer period.

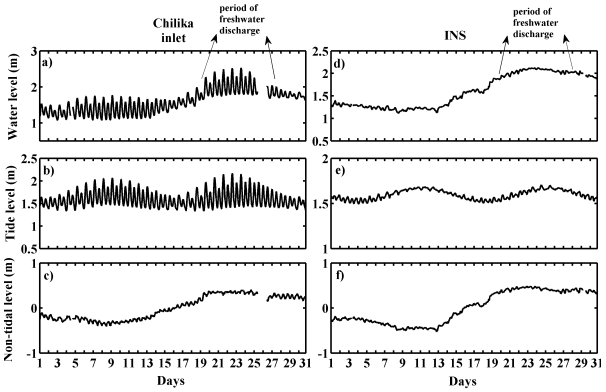

Fig.6-Seasonal variation of water level, tidal and residual level at Chilika inlet and INS during monsoon period.

The water level data were analyzed and the tidal characteristics (harmonic analysis) were calculated. The water level varies between Chilika inlet and INS. During summer, observed water levels were lower as compared to the monsoon. The water level varies between 0.84 to 1.95m at Chilika inlet (Fig.5a) and between 1.14 to 1.34m at INS during summer (Fig.5d). Similarly, during monsoon, the observed water level found between 1.07 to 2.53m (Fig.6a) and 1.13 to 2.12m (Fig.6d) at the Chilika inlet and INS respectively. Maximum water levels were observed in both locations during the monsoon period. Tidal constituents (23 nos.) were computed by analyzing the water level variations at the Chilika inlet and INS during summer and monsoon, presented in Table1 & 2 respectively.

Table1: Amplitudes and phases of the 23 harmonic tidal constituents at Chilika inlet and INS during summer period.

Sl. No.	Name of constituents	Chilika inlet		INS	
		Amplitude (m)	Phase(degree)	Amplitude (m)	Phase(degree)
1	MSF	0.0468	54.41	0.0289	80.5
2	$2Q_1$	0.0024	215.89	0.0023	268.93
3	Q_1	0.0036	269.66	0.0026	198.77
4	O_1	0.0364	316.22	0.0043	159.31
5	NO_1	0.0003	158.71	0.0023	5.15
6	K_1	0.0642	325.17	0.0116	301.22
7	N_2	0.0371	234.68	0.0004	124.19
8	M_2	0.3045	249.66	0.0021	88.31

9	L_2	0.0081	291.17	0.0011	121.63
10	S_2	0.16	288.06	0.0102	311.65
11	MO_3	0.0034	262.57	0.0005	347.51
12	M_3	0.001	203.07	0.0005	292.46
13	MK_3	0.0092	200.84	0.0003	225.62
14	SK_3	0.0021	261.04	0.0014	108.38
15	MN_4	0.0052	97.34	0.0009	270.13
16	M_4	0.0199	95.29	0.0002	77.62
17	SN_4	0.0052	143.28	0.0006	71.3
18	MS_4	0.0223	132.33	0.0008	100.49
19	$2MK_5$	0.0028	172.4	0.0004	230.94
20	$2SK_5$	0.0009	91.02	0.0003	239.95
21	$2MN_6$	0.0025	119.38	0.0003	18.2
22	M_6	0.0071	119.41	0.0004	120.15
23	$2MS_6$	0.0118	154.84	0.0005	335.96

Table2: Amplitudes and phases of the 23 harmonic tidal constituents at Chilika inlet and INS during monsoon period.

Sl. No.	Name of constituents	Chilika inlet		INS	
		Amplitude (m)	Phase(degree)	Amplitude (m)	Phase(degree)
1	MSF	0.068	2.13	0.0087	125.96
2	$2Q_1$	0.0028	23.2	0.002	16.66
3	Q_1	0.0084	345.3	0.0057	164.87
4	O_1	0.0321	355.36	0.0029	62.3
5	NO_1	0.0002	69.22	0.0008	7.16
6	K_1	0.0602	11.44	0.0069	37.71
7	N_2	0.0452	304.35	0.0009	268.25
8	M_2	0.2499	310.17	0.0062	48.33
9	L_2	0.0134	0.3	0.001	113.95
10	S_2	0.1307	329.91	0.012	300.46
11	MO_3	0.0041	333.51	0.0016	73.42
12	M_3	0.0025	185.76	0.001	182.38
13	MK_3	0.0096	280.45	0.0005	74.55
14	SK_3	0.0027	273.97	0.0004	228.47

15	MN_4	0.0121	222.94	0.0005	239
16	M_4	0.0304	216.44	0.0002	174.19
17	SN_4	0.0027	266.3	0.0014	325.72
18	MS_4	0.0273	241.11	0.0004	88.24
19	$2MK_5$	0.0017	49.83	0.0005	306
20	$2SK_5$	0.0009	215.73	0.0004	19.12
21	$2MN_6$	0.0013	86.64	0.0012	261.38
22	M_6	0.0017	339.37	0.0006	4.86
23	$2MS_6$	0.0043	342.91	0.0007	177.75

In Chilika lagoon, tide in Chilika inlet experiences purely semi-diurnal micro tide in summer having tidal form number 0.18 and mixed semi-diurnal during monsoon with the tidal form number 0.30.The form number is the ratio of the tidal constituent amplitudes, $(K_1+O_1)/(M_2+S_2)$ and an indicator of the tidal type [28].The Semi-diurnal constituents that are a consequence of the earth's rotation, causing two high waters and two low waters to occur during one complete revolution at a certain place on the surface. The lunar principal constituent M_2, observed to be dominant at the Chilika inlet. The M_2 represents the tide due to a fictitious moon circling the equator in the mean lunar distance and with constant speed. The tides transform into mixed mainly semi-diurnal inside the lagoon, especially when the complex bottom topography inside the shallow lagoon and dry period reduces the semi-diurnal component amplitudes through friction and non-linear effects. INS exhibits mixed mainly semidiurnal tides with the tidal form number shifts from 1.40 during dry to 1.51 during monsoon period.

Spectral analysis was performed in order to analyze the data for partitioning the variation of a time series into a function of frequency. The study of the energy spectrum provides an alternative way of estimating the attenuation of the tidal and non-tidal signals in different frequencies. Spectral density plots are generated using the spectrum function of MATLAB to determine the power spectrum as energy per unit time. Figure 7 shows the energy spectra oscillations for the Chilika inlet and INS during summer and monsoon respectively. The spectral density of water levels indicates a peak at 0.08 cycles per hour (cph) suggesting a form of tidal effect (Fig.7).

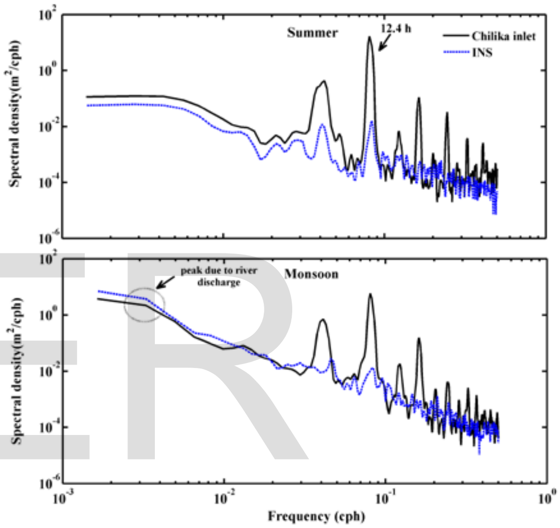

Fig.7. Spectral analysis of water level at Chilika inlet and INS during summer and monsoon period.

The most energetic peaks are dominated during semidiurnal (12.4h). Semidiurnal component is stronger than the diurnal peaks observed at both locations. The high energy content of tidal components present at Chilika inlet, as compared to the INS. This strong reduction of tidal amplitude in the interior of the lagoon is a common feature observed in choked coastal systems, where the narrow channel that connects them to the ocean acts as a low pass filter mechanism decreases tidal amplitude [29].The tidal propagation from Chilika inlet to INS is drastically controlled by the bottom topography. Thus, it clearly shows that the tidal propagation is taking place predominantly in the open channel, and inside Chilika the propagation is very much reduced.

3.5. Non-tidal variation

The non-tidal variation result from unequal ebb and flood during a complete tidal cycle. This unequal arise from the phase relationship of tidal fluctuation in water level. The non-linear interactive exhibits between the tidal flow and bottom topography, wind stress and net freshwater discharge [30]. Figures 5 (c, f) & 6(c, f) shows the effect of non-tidal variation at the Chilika inlet and INS respectively. During summer, the freshwater discharge was negligible; wind force plays a significant role. Similarly, during monsoon, the upland freshwater discharge was high, which exhibits to change in the water level of about 1 m more than dry period and affect the water level characteristics in the Chilika lagoon. Figure7 shows spectral energy peak during the summer and monsoon period. The wind has an effect on oscillation with higher frequency and lower amplitude during summer. The spectral density of the water levels indicates a maximum peak at 0.00329 cph (12 days) signifies freshwater discharge during monsoon (Fig.7). The non-tidal components forced by the wind and river discharge play a significant role to change the characteristics of the tide in Chilika lagoon.

4. Conclusion

The results of this study concluded that, during the summer period, tidal propagation at Chilika inlet due to the neritic incursion and excursion of tide, whereas INS is totally controlled by the bottom topography and greatly affected by wind force. The tidal propagation declined more during the monsoon period, which could be generated by the predominantly freshwater discharge. Diurnal and semidiurnal tidal exchanges are predictable as they are periodic and hence, they constitute a reliable baseline for flushing. Meteorological forcing in estuary and lagoon waters provides a relatively important supplement to tidal processes [31]. The depth-topography, length and orientation exert a substantial influence on estuarine response to local meteorological forcing.

Tidal amplitudes are larger at the Chilika Inlet than at INS, whereas the impact of M_2 is more than that observed by S_2 for both the locations. The more seasonal change in water level at INS caused by the substantial affect of wind and river discharge. At the Chilika inlet, tides are perfect semidiurnal, whereas at INS, water level are controlled by non-tidal forces such as wind and freshwater discharge and tides are mixed, mainly semidiurnal. The water level spectral density peaks at 0.08 cph (12.4h) suggesting tidal signal. The oscillation by the non-tidal wind component during summer shows at higher frequency with lower amplitude, whereas during monsoon the spectral density peaks at 0.00329 cph (12 days) signifies freshwater discharge.To have a deeper insight in the propagation of the Chilika lagoon, detailed studies using long term observation of water level, currents and associated met-ocean data.

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REFERENCES

[1] F.Ahmad and S.A.R Sultan, "The Effect of Meteorological Forcing on the Flushing of Shuaiba Lagoon on the Eastern Coast of the Red Sea", J.K.A.U.: Marine Science, Vol.3, pp. 3-9,1992.

[2] G.Symonds,K.P, Black ,I.R, Young, "Wave-driven flow over shallow reefs", Journal of Geophysical Research,Vol.100,pp.2639-2648,1995.

[3] F.A Comin, "Seasonal changes of phytoplankton in three coastal lagoons of the ebro delta in relation to environmental factors", *Oceanol.Acta*,vol.suppl.,actes Symposium international sur Les lagunes cotieries,SCOR/IABO/UNESCO,pp.259-267,1982.

[4] J.H,Simpson,R.Vennel, A.J,Souza,"The salt fluxes in a tidally-energetic estuary",Estuarine, Coastal and Shelf Science,Vol.52,131-142,2001.

[5] Aubrey, D.G and P.E.Speer,"A study of non-linear tidal propagation in shallow inlet/estuarine systems", Part I: Observations. Estuarine, Coastal and Shelf Science, Vol.21, 185-205,1985.

[6] N.P,Smith, "Tidal and nontidal flushing of florida's Indian river lagoon", Esuaries, Vol.16, pp.739-746, 1993.

[7] N.P,Smith,"Meteorological and tidal exchange between Corpus Christi Bay, Texas and the north-Western Gulf of Mexico" Estuarine, Coastal and Marine Science, Vol. 5, pp. 511-520,1977.

[8] N.P,Smith, " Long period estuarine shelf exchanges in response to meteorological forcing" , *In Hydrodynamic of estuarines and Fjords* (Nihoul, J.C.T. ed.), pp. 147-159,1978.

[9] Yamano H, Kayanne H, Yonekura N, Nakamura H, Kudo K "Water circulation in a fringing reef located in a monsoon area: Kabira Reef", Ishigaki Island, Southwest Japan. Coral Reefs Vol.17, pp.89-99, 1998.

[10] B.Al-Ramanadhan," MResidual fluxes of water in an estuarine lagoon" Estuarine, Coastal and Shelf Science,Vol.24, pp.319-330,1988.

[11] B.H.Ketchum,"Circulation in estuaries. Proceedings Third Conference on Coastal Engineering" pp. 65-76, 1952.

[12] K.Dyer and P.A. Taylor, "A simple segmented prism model of tidal mixing in well-mixed estuaries", Estuarine Coastal Marine. Science, Vol.1 pp.411-418,1973.

[13] M,Pérez, M, "Biología pesquera y aspectos ecológicos de la ictiofauna más importante de la cuenca de Laguna de Perlas en la región autónoma del Atlántico sur (RAAS) de Nicaragua", Proyecto DIPAL II, Bluefields, Nicaragua, 142 pp, 1999.

[14] C.L,Brenes and E. Castillo,"Caracterización hidrográfica de la Laguna de Perlas", Nicaragua. Proyecto DIPAL II, Bluefields, Nicaragua, 46 pp,1999a.

[15] Brenes, C.L. and E. Castillo,"Hidrografía de la bahía de Bluefields", Proyecto DIPAL II, Bluefields, Nicaragua, 22 pp,1999b.

[16] K.P.K, Dinesh., K. Srinivas and N. Anil Kumar, "Seasonal variability of tidal and non-tidal currents off Beypore, SW coast of India", Proceedings of National Symposium on Emerging Trends in the Fields of Meteorology and Oceanography (METOC-2004) (Kochi, India), Paper IV- 12, 401-409,2004a.

[17] U.S,Panda and P.K Mohanty "Monitoring and modelling of Chilika environment using remote sensing data"*In: Proceedings of Taal 2007- The 12th World Lake Conference*. Edited by M. Sengupta and R. Dalwani,2008.

[18] CDA, "The Atlas of Chilika. Chilika Development Authority", Bhubaneswar,pp.133, 2008.

[19] S.R,Pal and P.K Mohanty," Use of IRS-1B data for change detection in water quality and vegetation of Chilika Lagoon, east coast of India", International Journal of Remote Sensing,Vol. 23, pp.1027-1042, 2002.

[20] Samal R.N, "The transport of sediments in the Chilika Lagoon, East Coast of India", Ph.D thesis, Berhampur University,2011.

[21] N.K,Das and R.C, Samal, "Environmental survey of Chilika" *In :Chilika the pride of our wetland heritage*, Edited by S.N.Patro, Orissa Environmental Society pp.96-103,1988.

[22] V,Asthana, "Limnological studies of Lake Chilka, Orissa", Final Report, Indian Programme on Man and Biosphere (M.A.B.), Project No. 112, Department of Science & Technology, Govt. of India, New Delhi,1979.

[23] P.K,Mohanty and U.S Panda," Circulation and mixing processes in Chilika lagoon", Iindian Journal of Geo-Marine Science, Vol.38, pp.205-214, 2009.

[24] G.V.M,Gupta, V.V.S.S Sarma, R.S, Robin, A.V, Raman, M.J Kumar, M. Rakesh, B.R, Subramanian, "Influence of net ecosystem metabolism in transferring riverine organic carbon to atmospheric CO_2 in a tropical coastal lagoon (Chilka Lake, India)", Biogeochemistry, Vol.87,pp.265-285. (DOI 10.1007/s10533-008-9183-x), 2008.

[25] M.P.M, Reddy," Limnological studies of the Chilka lake and wave refraction studies in relation to shoreline development", Ph.D. thesis, Andhra University, Waltair, 1962.

[26] P.Chandramohan and B.U Nayak, "A study for the improvement of the Chilika lake tidal inlet, East Coasts of India", Journal Coastal Research, Vol.10, pp.909-918,1994.

[27] A.K Pattnaik, "Rejuvenation of Chilika Lagoon- A journey from Montreux Record to Ramsar Wetland Conservation Award", The Newsletter-CHILIKA, (CDA, Bhubaneswar),Vol. 4, pp.2-3, 2003.

[28] A.Defant, " Physical Oceanography", Pergamon Press, New York.Vol.2,pp. 598,1960.

[29] B.Kjerfve and K.E Magill, "Geographic and hydrodynamic characteristics of shallow coastal lagoons", Marine Geology, 88, 187-199,1989

[30] J.M Miller, L.J Pietrafesa, N.P Smith "Principles of hydraulic management of coastal lagoons for aquaculture and fisheries", FAO Fisheries Technical Paper. No. 314. Rome, FAO. 88p, 1990.

[31] D.Arief and S.P Murray, "Low frequency fluctuations in the Indonesian throughflow through Lombok Strait", Journal of Geophysical Research, Vol.101,pp.12455-12464, 1996.