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Tidal Prediction for Complex Waterways in the Bangladesh Region

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The navigational aspects of marine transport and its manoeuvrability require precise knowledge on tides. Information on time varying water levels, magnitude and direction of tidal currents is quite critical in coastal waterways and estuarine environment. Real-time water levels along with other hydrodynamic parameters are used in almost all major ports for effective operations throughout the year. Also various coastal engineering projects require precise information on site-specific water level elevations. There is a rapid expansion of coastal infrastructure in the recent times, and therefore it is very essential to have reliable water level prediction system that caters the need for coastal engineers, port and harbour activities etc. The Sea Level Processing Package (SLPR2) developed by the University of Hawaii Sea Level Center in collaboration with National Oceanographic Data Center (NODC) provides reliable estimate of location specific sea level information. SLPR2 performs three primary tasks that include tidal analysis and prediction, quality control, and filtering. Harmonic tidal analysis using linear least square produces the relevant tidal constituents of a specific region. High frequency data (preferably one-hour duration) for a minimum duration of one complete year would suffice the tidal analysis phase in SLPR2. The tide prediction algorithm used in the present study uses a maximum of 68 harmonic constituents. The region of interest is the head Bay of Bengal region located along the east coast of India. Preliminary analysis of measured sea level data indicate that tide gauges located along Bangladesh has research quality data, and therefore used in this study. Station data from seven locations viz; Hiron Point, Khepupara, Charchanga, Chittagong, Khal No.10, Cox's Bazaar, and Teknaf all located in Bangladesh were used for tidal analysis, and thereafter the predictive capability of SLPR2 for one-year period was investigated. There are exceptions at two stations, Teknaf (comprising of 87% observed data) and Khal No.10 (99% of observed data), and remaining five stations are free from data gaps. In a hydrographic perspective, the Bangladesh region has complex network of waterways, and bottom topography have several detached shoals. Tides enter the Bangladesh coast through two submarine canyons, reaching Hiron Point and Cox Bazaar at almost the same time. Amongst the principal constituents, dominant modes are exhibited by M_2 and S_2 whose natural oscillation periods are 12 h 25 min, and 12 h respectively. The results from SLPR2 indicate considerable seasonal variation in water level prediction during the monsoon season, attributable to meteorological reasons and excess river discharge, at stations Cox Bazaar and Charchanga. The locations Hiron Point and Khepupara show elevated predicted tides after the onset of monsoon, indicating the presence of seasonal signature resulting from large amplitude of the annual tidal component 'Sa'. Residual time series produce the de-tidal water level variations attributed due to meteorological effects such as wind, atmospheric pressure and river discharge. Inspection of residual can help to quality control measured data such as datum level correction, and replacement of data voids. The effective shallow nature in North-Eastern Bay produces partial reflections thereby increasing the tidal range. In addition, the seasonal

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effects of meteorological forcing along with non-linear shallow water interaction can result in number of higher harmonics. Finally, the correlation of tidal prediction between SLPR2 and measurement show a reasonable good match.

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1. Introduction

Bangladesh has numerous streams, canals, and riverine system that together cover about 7% of the country's surface. One can find complex network of waterways in the low lying deltaic region that reaches its extensive size during the monsoon period. The river system in Bangladesh is highly complex, and dominated by three major rivers namely the Ganges, Brahmaputra and Meghna that forms the world's largest delta and making this area extremely low-lying. Bottom topography of the coastal region in Bangladesh is very shallow comprising several detached shoals with shifting sand banks. As such navigation by ocean-going ships in these waters is quite hazardous and demands regular hydrographic surveys and studies of the area. Regular publications of up-to-date nautical charts and tide tables for the waterways and port are therefore required for the safety of navigation.

The Ganges, Brahmaputra, and Meghna/Barak river system occupies about 175 million hectares of South Asia (Fig. 1) supporting more than 500 million people (Verghese and Iyer, 1993). They are unique in the world with respect to water and sediment supplies, channel processes, and instability. While the Brahmaputra ranks fourth amongst the largest rivers in the world with regards to mean annual discharge, the Ganges ranks thirteenth (Mirza, 1997). The estimated annual sediment yield of the Brahmaputra is 1028 tons km^{-2}, the highest among the world's largest rivers. On the other hand, the sediment yield from Ganges is only 502 tons km^{-2} although its basin area is twice that of the Brahmaputra (Barua, 1994). In the recent years the change in course of Ganges and Brahmaputra rivers has significant influence on the morphology of their alluvial flood plains (Rahman, 1993; Brammer, 1996). They are characterized by high flow during the monsoon and low flow during the dry season.

Sea level variations attribute from various factors such as astronomical tides and currents, atmospheric forcing, and hydrological aspects from river discharge (Chen et al., 2000; Douglas et al., 2001). Currently, there is an increasing concern on sea-level rise due to climate change, as vulnerability aspects have implications on livelihood in several coastal areas around the globe. In this context, the Sunderbans in the Head Bay region located in Bay of Bengal is a low-lying deltaic environment and highly vulnerable zone to the threat from sea-level rise. The highest tidal range in the east coast of Indian peninsula pertains to the Head Bay region, and strong currents with reversing tides play an important role on the suspended sediment concentration and sediment transport mechanisms.

Information about tides is essential for coastal engineering works, port and harbour activities, and shoreline management plan to understand near shore ocean-dynamics. The objective in this study is to develop a real-time water-level prediction system for the head Bay of Bengal. Research-quality hourly data available from University of Hawaii Sea Level Center (UHSLC) was used for tidal analysis and prediction at few stations in Bangladesh region namely Hiron Point, Khepupara, Charchanga, Chittagong, Khal No-10, Cox's Bazaar, and Teknaf. A comprehensive validation study between observed data with the prediction was carried out to analyse the efficiency and performance of SLPR2.

2. Data and methodology

SLPR2 is a Sea Level Processing software package developed by the University of Hawaii Sea Level Center in collaboration with the National Oceanographic Data Center to produce quality controlled sea level data sets. The SLPR2 package developed by the UHSLC in collaboration with the National Oceanographic Data Centre (NODC) provides quality controlled sea level data sets for scientific use. This package had its genesis from the existing routines used by Tropical Ocean Global Atmosphere (TOGA) Sea Level Centre (TSLC) for data processing. One of the major efforts under the TOGA program is the maintenance of archived sea level data in one hourly mode. The TOGA program ended in 1995, and thereafter the Joint Archive for Sea Level (JASL) in collaboration with UHSLC had taken this program forward. The JASL prepares the Research Quality Data Set (RQDS) of hourly and daily values from several tide gauge stations around the globe, and archived by the UHSLC.

SLPR2 package performs three primary tasks: tidal analysis and prediction, quality control, and filtering. The method used for estimation of tidal constituents is harmonic tidal analysis using linear least squares, after applying nodal correction. The package utilizes routines by Mike Forman (Foreman, 1977). An equilibrium response to astronomical forcing is predicted and the tidal response at a particular location is modeled as a sum of sinusoids of known frequencies, which are a linear combination of astronomical frequencies. Then the amplitude and phase of the sinusoids are estimated by minimizing the sum of the square of the difference between the observed and predicted water level. SLPR2 uses only hourly data grouped in years as input to generate a maximum of 68 harmonic constituents. These constituents serve as input for tide prediction and SLPR2 predicts the water level due to astronomical tides only. The residual signal-which is the difference between observed water level and predicted tides-contains non-tidal water level variations due to meteorological effects such as wind, atmospheric pressure, and river discharge. An inspection of residual is helpful in quality control of the source data namely, datum level correction, inspection of timing errors and replacement of short gaps and spikes.

Table 1.Details of Tide Gauge station and data availability

Station name	Latitude	Longitude	Duration of available observed data	Year chosen for analysis	Year chosen for prediction
Hiron Point	21 47.0 N	89 28.0 E	1978-2003	2000	1995
Khepupara	21 50.0 N	89 50.0 E	1987-2000	1996	1995
Charchanga	22 13.0 N	91 03.0 E	1980-2000	1999	1995
Chittagong	22 14.8 N	91 49.5 E	2008-2009	2008	2009
Khal No-10	22 16.0 N	91 49.0 E	1983-1992	1992	1990
Cox’s Bazaar	21 27.0 N	91 50.0 E	1983-2006	2005	1995
Teknaf	20 53.0 N	92 18.0 E	1983-1988	1987	1987

Bangladesh Inland Water Transport Authority (BIWTA), under the Department of Hydrography, provided the tide-gauge data set for Bangladesh to JASL. Chittagong Port Authority maintains the Chittagong tide gauge station. The Chittagong is a recent water level observing station, whereas Teknaf is relatively an old station that provides data up to 1988 only. The yearly data used for analysis was chosen as the best among the list of available data with minimal gaps and spurious values. Exceptions were at Teknaf having 87% complete data for 1987, and Khal No.10 with 99% complete data for 1990. Information on the location of tide gauge stations and data availability is presented in Table 1. The year chosen for tide prediction was set up as 1995, since for this year actual observations are available at most of the stations that aids in validation of prediction. However, Chittagong being a new station, tidal prediction was attempted for 2009, whereas for Khal No-10 station the year 1990 was chosen, and 1987 for Teknaf. The amplitude and phase of various tidal constituents are resolved using the tidal analysis, and used to construct the tidal prediction for a specific location. The output of tidal analysis thereby serves as input for tidal prediction. The capability of SLPR2 is its ability to hindcast and forecast water level due to tides, for a specific location. The predictive skill of SLPR2 is evaluated through a comprehensive correlation conducted between computation and observation typically for a long period (one year).

3. Results and discussion

The geographical location of all individual stations and their composite are shown in Figure 1. The stations Hiron Point and Khepupara are located within the Sundarban region, surrounded by a large number of tidal river creeks that form the Ganga-Brahmaputra delta. Hiron point is situated at a larger mouth of the river system close to shoals of shallow depth. Khepupara is located in a shallow region west of Dimer Char Island. The Charchanga is at the mouth of Meghna river on the western side of Hatia Island, facing Manpura Island and surrounded by several other small island groups. The stations Chittagong and Khal No-10 are on the western bank of river Karnaphuli. The station Cox's Bazaar is nearly 10 km offshore from the mouth of MaheshKhali Channel on the southern part of Bangladesh. Teknaf, the southernmost station, is on the western bank of Naf River, borderd by Teknaf Game Reserve on the north and Naf River Wildlife Sanctuary in the south.

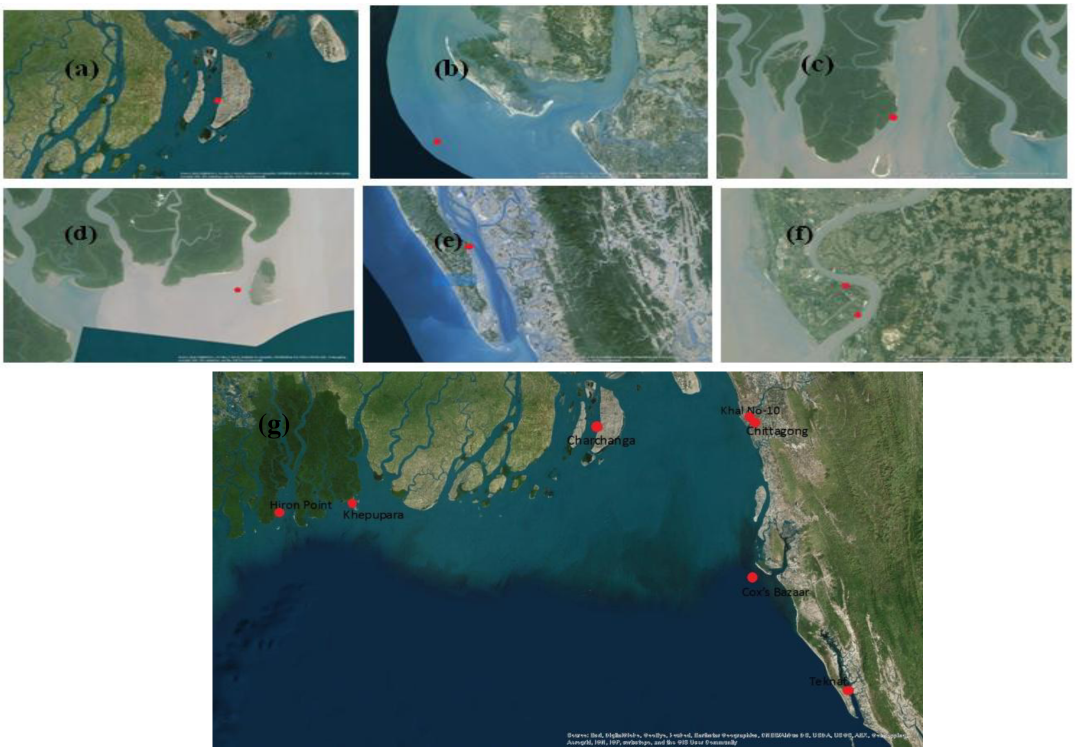

Fig. 1. Location of individual tide stations (a) Charchanga; (b) Cox's Bazaar; (c) Hiron Point; (d) Khepupara; (e) Teknaf; (f) Khal No-10 (north) and Chittagong (south); (g) Location of all seven stations in the Head Bay region.

Tides enter the Bangladesh coast through two submarine canyons, reaching Hiron Point and Cox Bazaar at almost the same time. One of the canyons is in the close proximity of Hiron Point and Khepupara stations as visible from Figure 1(g). The observed water level, tides predicted by SLPR2 and the residual signal for all the seven stations are shown in Figure 2. As most of the stations are located within the vicinity of rivers, seasonal changes tend to affect the water level. These rivers are characterized by high discharge during the monsoon periods and low discharge during the dry season. Since the river bed remains more or less dry during January to May, the elevated river bed causes the observed water level to fall below the predicted tides. Although this effect is seen at most of the stations, it is more conspicuous at Charchanga (Fig. 2), located at the mouth of Meghna river, and near Cox's Bazaar along

Maheshkhali Channel. The water level elevations at Charchanga also show higher residuals during the monsoonal months of July-September owing to excessive river discharge. The amplitudes of the resolved constituents are presented in Table 2. The stations Hiron Point and Khepupara, exhibits an increased predicted tide after the onset of monsoon, which indicates that the low tide levels have increased considerably for Hiron Point and Khepupara during monsoons. The stations Chittagong and Khal No.10 also show elevated values of predicted tide during monsoon (Fig. 2). This is confirmed by the large amplitudes of the solar annual component 'Sa' in these 4 stations (Table 2), usually strongly enhanced by seasonal variations (Pugh, 1996). Sa is the third dominant tidal constituent for stations Hiron Point, Khepupara and Khal No-10 following M_2 and S_2; and the fourth dominant in Chittagong following M_2, S_2, and N_2. Although SLPR2 basically predicts only astronomical tides, the fact that predicted tidal level varies with monsoons, indicate the presence of a seasonal signature in it. The maximum tidal level is between 4 to 5 meters for all the stations except Chittagong. The exception is due to the larger water depth at Chittagong (as is noticeable form the Mean Sea Level values given in table 2). The Form Factor is determined as the ratio of sum of amplitudes of K_1 and O_1 to the sum of amplitudes of M_2 and S_2. The Form Factor for these seven stations Hiron Point, Khepupara, Charchanga, Chittagong, Khal No-10, Cox's Bazaar and Teknaf are estimated as 0.168, 0.156, 0.091, 0.114, 0.127, 0.123, and 0.135 respectively. The value of form factor for all the stations is less than 0.25, which implies the dominance by semidiurnal tides. The tidal analysis module of SLPR2 separates the constituent frequencies, giving their respective amplitudes and phases.

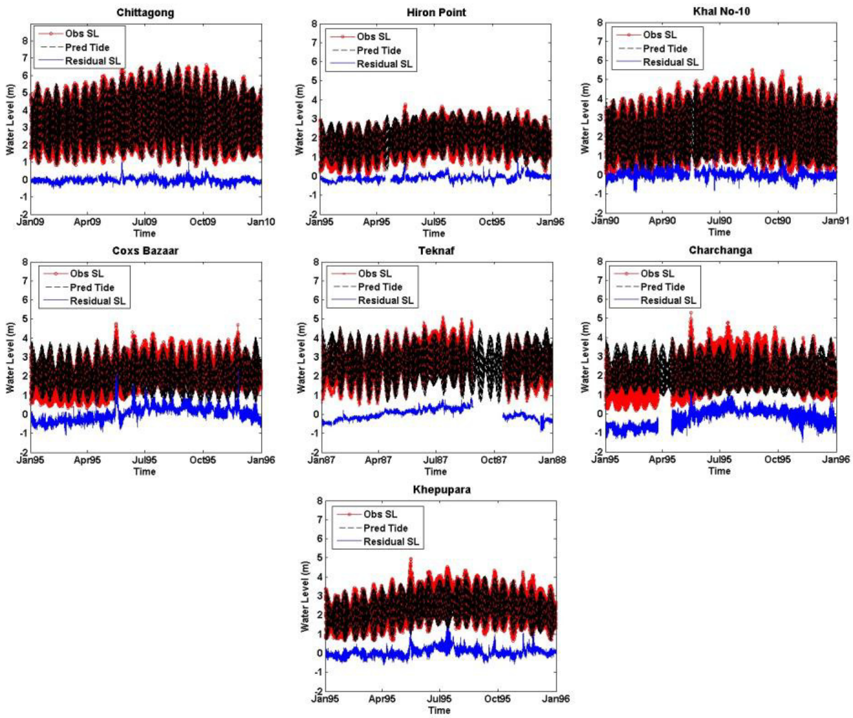

Fig. 2. Observed water level (red), predicted tide (black) and residual water level (blue) in meters for the stations (a) Chittagong; (b) Hiron Point; (c) Khal No-10; (d) Cox's Bazaar; (e) Teknaf; (f) Charchanga; (g) Khepupara

There can be remarkable transformation in the tidal pattern and its range during the course of tidal propagation from open-ocean into the shelf region and further into extremely shallow river channels. It results from a multitude of topographical variations resulting in the presence of over-tides as well compound tides. During the course of tidal propagation into narrow channels, other phenomena such as wave reflection, resonance, and diffraction play their role, due to presence of natural barriers like islands, detached shoals, etc. These natural barriers do affect the various

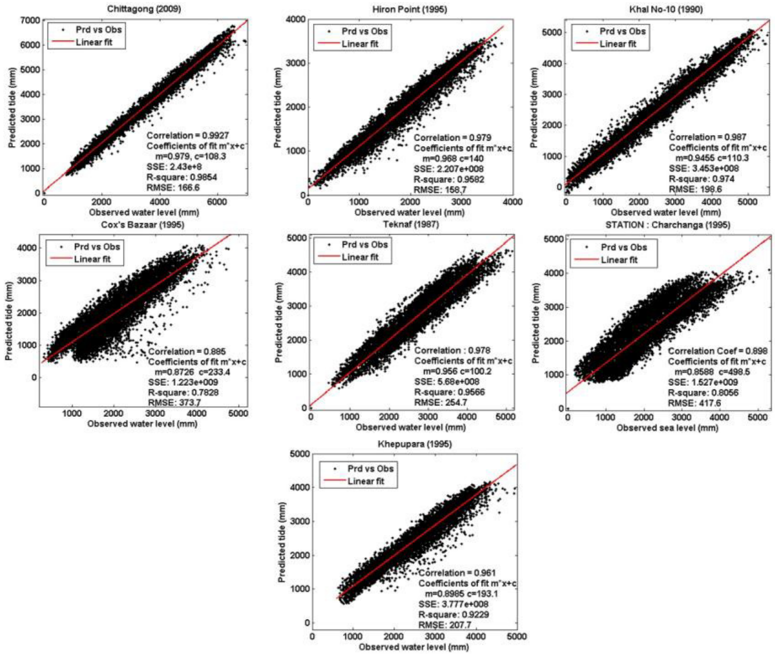

Fig. 3. Scatter plot showing correlation between observed water level and predicted tides for the stations (a) Chittagong; (b) Hiron Point; (c) Khal No-10; (d) Cox's Bazaar; (e) Teknaf; (f) Charchanga; (g) Khepupara

tidal constituents. The present area of study is a highly dynamic region dominated by shallow water processes. This is evident from a close inspection of the tidal stations under consideration. The scatter diagram representing the correlation between observed water level and predicted tide is given in Figure 3. The stations Charchanga and Cox's Bazaar show a wide scatter accounting from river discharge and seasonal effects that SLPR2 is incapable of

Table 2.Amplitude of tidal constituents in cm for the seven stations

Constituents	Chittagong	Hiron Point	Khal No-10	Cox's Bazaar	Teknaf	Charchanga	Khepupara
Z0 (MSL)	350.3523	193.8535	237.2367	206.7274	265.9221	233.9771	236.9090
LONG PERIOD							
MAIN							
Sa	28.9292	31.9672	38.9932				34.2133
Ssa	1.3991	4.851	1.6516	8.4657	16.2252	4.4186	6.7674
Msm	1.629	3.3859	5.0986	6.2769	3.0948	3.8563	5.2798
Mm	2.873	0.2256	0.9118	6.0867	4.5181	10.5722	0.9808
Mf	2.6182	0.5546	4.2791	6.1245	3.237	6.0734	2.3685
SHALLOW WATER							
Msf	5.9542	2.3133	8.0332	8.2731	2.7781	19.8568	3.8421
DIURNAL							
MAIN							
Alpha1	0.1791	0.0515	0.4976	0.5567	0.1508	0.3789	0.1805
2Q1	0.2512	0.239	0.5011	0.6925	0.2467	0.4892	0.27
Sigma1	1.0198	0.514	0.7769	1.8998	0.2389	1.4541	0.5482
Q1	0.8046	0.715	0.6188	0.7099	0.5349	0.5228	0.1689
Rho1	0.1739	0.421	0.1075	0.7508	0.3166	0.8952	0.2891
O1	8.0795	5.169	8.1798	7.8029	6.0233	6.0586	5.5974
Tau1	3.0582	0.2509	2.2874	3.6629	0.6959	1.3422	0.4165
Beta1	0.6337	0.3037	0.2256	0.4769	0.4136	0.7734	0.5777

Chi1	0.4102	0.0805	0.2618	0.5833	0.4868	0.6325	0.195
Pi1	0.3056	0.3457	0.4835				0.381
P1	5.7133	3.5156	4.7435	4.1762	3.9816	2.2846	4.3842
S1	3.1773	4.1426	4.2213				1.3518
K1	18.9798	14.4222	17.7546	9.2141	15.2969	5.7917	13.303
Psi1	0.6794	0.4233	0.5913				1.1964
Phi1	0.5958	0.4454	0.5596	0.4651	0.3948	0.3964	0.2275
Theta1	0.6524	0.3909	0.5447	0.6523	0.101	0.7525	0.2551
J1	0.5533	0.6341	0.5993	0.4724	0.621	0.6325	0.556
SO1	1.4546	0.5368	2.0324	0.2525	0.3484	0.3026	0.6507
OO1	0.753	0.5398	0.3294	0.2351	0.9736	2.2846	0.2422
Upsilon1	0.7530	0.0633	0.1873	0.3550	0.2081	0.4339	0.8165
SHALLOW WATER							
NO1	0.5011	0.2728	0.3608	1.5643	0.8062	0.2099	1.0548
SEMI-DIURNAL MAIN							
Epsilon2	3.3647	0.9587	4.6616	1.2221	1.2267	3.4027	1.3193
2N2	8.9598	3.7381	2.2177	3.0722	4.5612	2.7925	3.8254
Mu2	11.6642	0.7654	12.0739	6.2649	4.1563	6.9422	4.8082
N2	32.0907	16.2551	29.6544	17.7746	23.0589	16.1097	16.2491
Nu2	9.2478	5.5538	10.076	1.6053	4.9647	6.0659	3.7091
H1	13.4938	4.0482	8.1813				6.7536
M2	173.3768	82.0578	150.9111	98.5113	109.0103	95.4611	84.0905
H2	9.4876	4.7140	5.1136				7.8018
Lambda2	1.9102	2.0964	5.4519	1.1711	3.1367	4.7709	2.4508
L2	9.9645	5.1154	12.267	4.2915	4.6176	9.1728	3.9694
T2	3.2048	1.7562	0.7671				3.8015
S2	64.1211	34.6629	53.4451	39.3367	49.1661	35.297	37.2899
R2	3.6317	1.2733	1.7645				3.4553
K2	18.0616	11.7571	14.4132	9.7896	13.2031	7.4706	11.273
Eta2	0.3597	0.5549	0.2146	0.2677	0.1484	1.0763	0.4144
SHALLOW WATER							
MSN2	3.3942	1.1444	3.7063	1.3245	0.7525	2.0643	1.4467
OQ2	1.9879	1.4516	1.3894	0.8939	0.2109	0.2961	0.7958
MKS2	1.9102	0.6577	3.3765	2.5826	1.8912	8.3196	2.6589
HIGHER HARMONICS							
MO3	1.6876	0.8988	1.8273	1.5217	0.5508	0.8478	1.3468
M3	0.5031	0.4284	1.0968	0.273	1.0251	0.096	0.7755
SO3	1.324	0.8988	1.4886	1.0575	0.7283	0.5106	1.3182
MK3	1.7755	0.4284	1.7585	1.8039	0.4416	0.9248	1.7792
SK3	1.2733	0.5904	1.0662	0.3889	1.0833	0.6885	0.9307
MN4	3.165	1.0281	3.4486	2.2623	1.0882	4.1839	2.5083
M4	8.0582	0.902	8.3826	6.4447	2.0267	14.0573	6.7944
SN4	1.2651	1.2264	1.2467	0.9972	0.4939	2.1849	1.0559
MS4	7.6944	3.1525	7.5568	5.4854	1.7485	12.3922	7.3221
MK4	2.4595	0.6825	2.0103	1.076	0.5317	2.3497	2.9684
S4	1.8102	2.9019	1.5097	1.2578	0.6881	2.3634	1.3873
SK4	1.055	0.9524	0.6835	0.6699	0.3748	1.2825	1.1231
2MK5	0.9148	0.3298	1.0210	0.2715	0.4771	0.2622	1.0661
2SK5	0.2469	0.1296	0.3289	0.1751	0.3185	0.1035	0.3038
2MN6	0.9148	1.0182	1.6767	0.3994	0.859	1.6944	2.375
M6	0.2469	1.6867	2.8017	1.2363	1.6795	4.0344	4.1791
2MS6	1.6048	2.5719	3.7074	1.9107	2.166	5.0764	6.3643
2MK6	2.8003	0.8647	1.1353	0.3595	0.6565	1.1647	2.53
2SM6	3.799	0.7852	0.8234	1.0018	1.04	1.841	1.9425
MSK6	0.6853	0.4054	0.5670	0.3078	0.4524	0.4926	1.1982
3MK7	0.1598	0.0930	0.2381	0.1670	0.0886	0.1960	0.1526
M8	0.3321	0.0216	0.3166	0.4168	0.2866	1.0196	1.0265

predicting. The values of correlation coefficient and curve fitting parameters for other stations show that there is a reasonable good match between the observed and predicted water level. The correlation coefficient for the stations Hiron Point, Khepupara, Charchanga, Chittagong, Khal No-10, Cox's Bazaar, and Teknaf are 0.979, 0.961, 0.898, 0.993, 0.987, 0.885, and 0.978 respectively. Hence the study shows that all stations show a correlation factor above 88%.

4. Summary and Conclusion

The coastal stretch of Bangladesh is tidal dominated comprising of numerous tidal creeks and waterway inlets. This region has a high population density owing to its unique fertile plains and natural resources. The region is extremely low-lying and highly vulnerable to floods, cyclones, and sea level rise. Multiple river channels of varying dimensions and irregular tidal creeks form an integral part of this deltaic region. The study covers the world's largest deltaic system formed by the Ganga-Brahmaputra-Meghna Rivers. The study aims to develop a tide-prediction system for the Head Bay of Bengal, thereby providing reliable tide predictions used to train location specific models. The study covers on aspects such as tidal analysis and prediction for seven stations in the Bangladesh coast, using a location specific harmonic tidal analysis tool SLPR2. SLPR2 is Sea Level Processing software package developed by the University of Hawaii Sea Level Center in collaboration with the National Oceanographic Data Center with the goal of quality control of sea level data sets. The method used for estimation of tidal constituents is harmonic tidal analysis using linear least squares, after applying respective nodal correction. Tide-gauge observations from seven locations viz; Hiron Point, Khepupara, Charchanga, Chittagong, Khal No.10, Cox's Bazaar and Teknaf, were used for tidal analysis, and thereafter the predictive capability of SLPR2 for one-year period was investigated. The Form Factor indicates domination by semidiurnal tides, and the dominant mode is M2. Although SLPR2 predicts tides arising from astronomical forcing, seasonal/meteorological signature was found in the predicted tides at four stations, arising from the dominance of the annual component Sa. It indicates that there is considerable seasonal variation in water level prediction during the monsoon season, attributable to meteorological reasons and excess river discharge. The shallow nature in the Bay produces partial reflections thereby increasing the tidal range, and the seasonal effects of meteorological forcing along with non-linear shallow water interaction results in number of higher harmonics with relatively higher amplitude. The skill assessment from SLPR2 predictions show that observed tidal cycle show a good match with the predictions. The correlation analysis between measurement and prediction show a reasonable match with correlation skill level exceeding 88%. Therefore, the tidal analysis shows that the overall prediction skill by SLPR2 is highly satisfactory.

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