Tidal analysis and prediction for the Gangra location, Hooghly estuary in the Bay of Bengal

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The Hooghly estuary located in the head Bay of Bengal region is a part of the highly dynamic deltaic environment. Tidal variations are pre-dominant in this estuary, and tides propagate considerable distance through a complex network of various riverine systems, inlets, bays and creeks having vital implications on water mass exchange, reworking of deltaic sediments and the mixing process. The Hooghly River houses two major ports of national importance, viz. Kolkata Dock System and Haldia Dock Complex. Tidal forcing is primarily semi-diurnal in nature and with the presence of complex riverine morphology, the tidal characteristics are substantially modified causing various tidal constituents of compound tides. The present study performs location-specific tidal analysis and prediction utilizing one-hourly tide data with SLPR2 harmonic tidal analysis tool for Gangra situated upstream of the Hooghly River. In a geomorphologic perspective, the water-level elevation at Gangra results from natural tidal flow, as well as refracted effects from cross-flow due to the presence of two natural island barriers, namely Sagar Island situated southward off Gangra and Nayachara in the east. The Hooghly channel comprises of complex bathymetric features and tidal analysis at Gangra reveals the presence of Msf (luni-solar synodic fortnightly) tidal constituent. Very few locations in India have reported on the existence of the Msf tides, and Gangra is one among them. This study also performs a comprehensive validation between the computed monthly tidal prediction from SLPR2 and measured water level at Gangra. The skill level of prediction exhibits a good match. This study also investigates the influence of atmospheric effects on sea-level pressure variations and the resultant water-level elevation from extreme weather events such as depressions and severe cyclonic storms that occurred during 2013. The study signifies the importance of tidal analysis and prediction for operational needs.

Keywords: Estuary, numerical models, tide prediction and analysis, water-level elevation.

THE variations in sea-level attributes arise from various factors such as astronomical tides and currents, atmospheric forcing and hydrological aspects of river discharge[1,2]. These in turn govern the water-level elevation in estuaries and river channels[3]. One can find increasing concerns on the sea-level rise and its variability in the recent literature. The vulnerability aspects due to sea-level rise have implications on livelihood in several coastal areas around the globe. In this context, the Sunderbans situated in the head Bay of Bengal is a low-lying deltaic environment that is highly vulnerable to threat from sea-level rise. In the recent years, one can find several studies on projections for sea-level rise due to global warming and climate change. The subject of sea-level rise and its implications has a direct bearing on socio-economic aspects. Rapid industrialization with increased emission of greenhouse gases has increased the mean global temperature. Estimates show that global sea-level rise is in the order of about 15 cm over the past century. Several studies have been conducted based on measurements and projections from numerical models that portray increased atmospheric temperature in the near future. This indicates that coastal areas and especially the low-lying regions (such as near-shore areas in the head Bay region) have a direct risk from increased total water-level elevation (TWLE). TWLE is a combined effect due to increased storm-surge activity from high intense cyclones, wave-induced set-up, and astronomical tides that happen during landfall of energetic cyclones. In other words, a paradigm shift in climate change during the recent decades has resulted in an increased probability of high-energetic events like cyclones that cause increased storm surge and flooding, as well increased wave set-up along near-shore areas. This coupled with a permanent rise in sea level is a subject of major concern, especially for low-lying coastal areas. Tidal variation forms an integral component of TWLE. Therefore, tidal analysis in coastal/near-shore waters is important to understand the residual effects. The present study is confined only to tidal analysis and prediction for a specific location, Gangra, which is a part of the Hooghly riverine system adjoining the head Bay region in the Bay of Bengal (Figure 1). The study demands quality data; in addition, the measured data should be free from data gaps and spurious noise. Therefore, in the present study we develop a tide prediction system specifically for Gangra, with subsequent scope to extend such work to other regions in the head Bay of Bengal.

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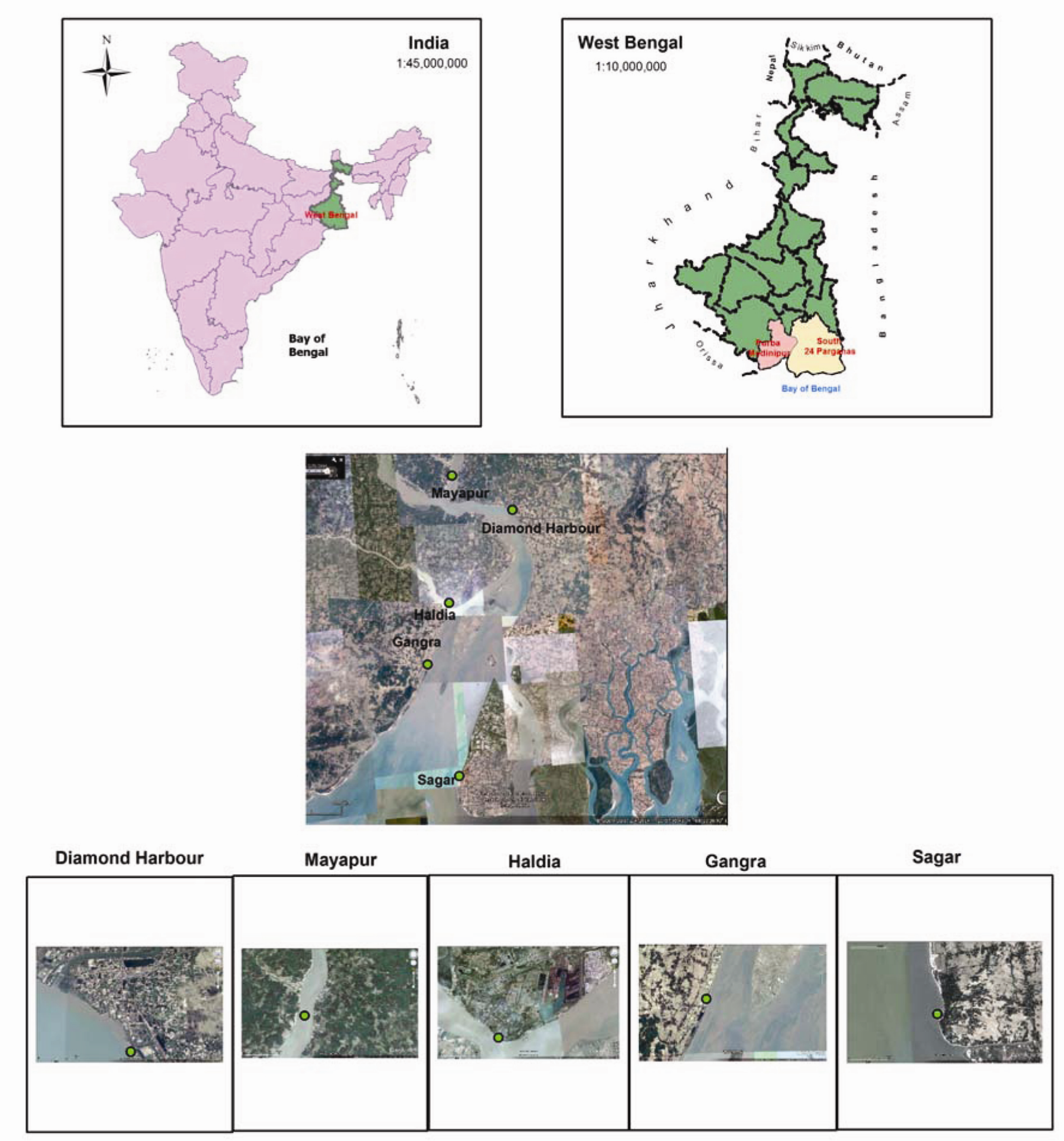

Figure 1. Study area with the network of tide-gauge observatories and the region of interest, Gangra in the Hooghly River.

The head Bay region located in the northern Bay of Bengal has river discharge from the Ganges, Brahmaputra and Meghna river systems occupying an area of around 175 m ha and supporting the lives of 500 million people[4]. These rivers are unique, known for their freshwater discharge and sediment supply along various cross-sections of the river channels. Amongst the largest river discharges in the world, the Brahmaputra ranks fourth and the Ganges ranks 13th (ref. 5). The estimated annual sediment load from the Brahmaputra is about 1028 tonnes/sq. km, while discharge from the Ganges is about 502 tonnes/sq. km in spite of the basin area being almost two times large compared to that of the Brahmaputra[6]. The highest tidal range in the east coast of India 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. Attempts to understand the dynamics of tides in the Bay of Bengal are limited. Numerical models led to the development of co-tidal charts of major tidal constituents M_2, S_2, K_1 and O_1 for the Bay region[7]. More recently, developments were made on vertically integrated 2D numerical models for the simulation of major tidal constituents (M_2, S_2, N_2, K_1 and O_1) for the Bay of Bengal[8]. In India, the Hooghly River channel is the only location that has two major national ports, viz. Kolkata Dock System (KDS) and Haldia Dock Complex (HDC). The high rates of sediment loads in this channel give rise to severe navigational problems for ship traffic[9]. Due to complex variations in the river channel bed, one can experience tidal asymmetry along various locations upstream of the Hooghly River. The tidal analysis and prediction for Gangra conducted in this study pertain to the area south of HDC. Keeping in view the importance on the variability of water-level elevation and its prediction, there is a need to have a real-time prediction system that provides realistic tidal information to port operators, inland waterways and marine authorities. The work has wide practical application in coastal engineering and habitat restoration projects.

The Geodetic and Research Branch (GRB) in the Survey of India (SOI) maintains the tide data collected from various tide-gauge networks located in the mainland and island locations of the country. The SOI provides tidal prediction for about 30 Indian ports and 14 foreign ports. In addition, the GRB also publishes the tide table for India comprising information for 76 ports, of which the prediction for 44 ports is reported by the GRB, and the remaining published based on exchange programmes with other countries. In addition, the GRB publishes the tide tables for Hooghly River containing information of varying water levels each day at six locations – Sagar, Gangra, Haldia, Diamond Harbour, Mayapur and Garden Reach (Kolkata). Being a riverine port, relevant information for mariners such as signals for dredging and storm warning also forms a part of the service. As noticed, the tide tables exist only for limited number of stations and only for selected areas. In an estuarine environment and especially in the head Bay region, tidal propagation is quite complex due to the presence of numerous inlets, creeks and sand bars. For example, even when an inlet is in close proximity to a tidal observatory, one can expect varying water levels that are difficult to predict. In this study, we demonstrate the methodology for tidal prediction at a specific sampling station using the SLPR2 (Sea Level Processing Software) tide prediction tool developed by the University of Hawaii Sea Level Centre (UHSLC) and tide-gauge data for Gangra as a case study. Such prediction provides an opportunity for the researchers to obtain information and enable refinement of field-sampling schedules relevant for many practical applications.

Practical relevance of tidal prediction and analysis

Several research and practical applications covering a wide range of scientific use depend on the sea-level data analysis. In the discipline of coastal engineering, information on instantaneous water levels is required for planning and design of coastal structures that have a life expectancy of several decades. Long-term data on extreme water levels and their statistics are an essential pre-requisite for many coastal engineering applications. For daily operations, vessel traffic and movement of ships in the port and harbour require real-time data on tides. In addition, information on TWLE during extreme weather events like cyclones is an essential pre-requisite for effective disaster management. Also in a riverine environment, the operation of sluices and barrages requires instantaneous information of water levels. In certain coastal belts, studies on erosion and depositional patterns demand long-term water-level data from measurements or numerical models to gain better insight regarding the mechanisms of coastal processes. In coastal waters, water-level information is required for protection of barriers and coral reefs. Numerical models also require precise information on water levels as model inputs to estimate pollutant trajectories, forecast water quality, identify disposal sites of pollutants and reclamation measures. In coastal waters, varying water levels from tides have application in physical processes such as upwelling that has a direct linkage to the biological food chain. In the context to marine policy, sea-level data are required to establish national datum levels as well as location-specific datum levels for hydrographic charts. In addition, sea-level data are also widely used for assimilation into numerical ocean models and to calibrate and validate the satellite altimeter products. Tidal prediction is based on harmonic analysis. Therefore, location-specific tide prediction models require quality measured data as input field for training purpose.

Sea-level trends and observations relevant to the Indian coast

During the year 1985, the Intergovernmental Oceanographic Commission (IOC) had set up GLOSS (Global Sea Level Observing System) to understand the growing concerns on mean sea-level rise around the globe. In this context, GLOSS had an objective to disseminate high-quality standardized data of sea-level used widely by the scientific community for oceanographic research. Several international programmes resulted from the usage of GLOSS data, such as World Ocean Circulation Experiment (WOCE), Tropical Oceans Global Atmosphere (TOGA), University of Hawaii Sea Level Centre (UHSLC), and Permanent service for Mean Sea Level (PSMSL). At present, there are about 931 water-level monitoring stations throughout the globe, of which 257 stations are under the GLOSS sea-level monitoring facility. Readers can find more information in the website, http://www.ioc-sealevelmonitoring.org. The Indian National

Centre for Ocean Information Services (INCOIS) under the Ministry of Earth Sciences, Government of India, located at Hyderabad, is the local contact for sea-level data pertaining to the Indian Ocean. As part of the WOCE, the British Oceanographic Data Centre (BODC, http://www.bodc.ac.uk) maintains the delayed-mode sea-level data used for climate variability studies. The BODC is also an archiving centre for GLOSS data. As part of the WOCE programme, the BODC maintains voluminous amount of water-level data for about 160 stations covering 20 countries. Readers can refer to the BODC website for more details.

Very few studies are available on the sea-level trends for the Indian coast. A recent study highlights the pattern of sea-level change in a warming climate for the Indian Ocean[10]. This study by Han *et al.*[10], based on observational sea-level trends and Hybrid Coordinate Ocean Model (HYCOM) showed that sea level along all the Indian Ocean coasts has increased since 1960s. The observed trends in sea-level rise are about 13 cm per century, and HYCOM simulations show the rise as 10.1 cm per century. This observation is in close proximity with the reported regional averaged value of 12.9 cm per century corrected with global isostatic adjustment[11]. The results of the study Han *et al.*[10] suggest that anthropogenic forcing combined with natural variability resulted in the sea-level variation for the Indian coasts. It is still debatable open question as to whether this rise in sea level is seen everywhere in the Indian Ocean. Unnikrishnan and Shankar[11] also found that areas in the northeastern part of the head Bay region experienced sea-level rise more than 0.4 cm yr^{-1}, abnormally high compared to other regions in the Indian coast.

Study area

The study area, Gangra (shown in Figure 1), is located in the Ganges River where tides enter the riverine channel through the Hooghly estuary. This channel serves as a navigable waterway to Kolkata and Haldia ports[12]. The influence of tidal effects are felt in the upstream reaches of the Hooghly estuary up to a distance of nearly 295 km covering the districts of Nadia, Hooghly, North and South 24 Parganas, Howrah and East Midnapore in West Bengal[13]. The tides are semi-diurnal in nature with neap–spring variations ranging from 2.0 to 5.0 m at the open boundary. The inter-tidal variation and tidal amplitude are important parameters for fishery and hilsa *Tenualosa ilisha* is one of the important commercial fish yields from this riverine system. Rahman and Cowx[14] found that the growth and behaviour of hilsa fish follows the rhythmic phenomenon of the lunar cycle. In addition, the aquatic organisms in this estuarine environment are acclimatized with the bio-tidal environment associated with geomorphological dynamism[15].

There are about six tidal observatories in the Hooghly River (Figure 1) used for navigational purpose, viz. Sagar, Gangra, Haldia, Diamond Harbor, Mayapur and Garden Reach (Kolkata). The Kolkata Port Trust (KoPT) maintains these tidal observatories. After the commissioning of Farakka barrage project, the distribution of river water also occurs through the west bank tributaries such as Mor, Ajay, Damodar and Kansai that drain the Chhotanagpur highlands of Jharkhand[16]. The Farakka barrage was constructed across the Ganges in 1975 to improve navigability in the riverine system on the northern side of Diamond harbour. The barrage diverts certain amount of water from the Ganges about 426 km upstream of its confluence at Sagar Island[17]. The Hooghly estuarine system is a macro-tidal estuary with a tidal range of about 6.5 m. The present study area is Gangra and this observatory is located close to the Nayachara Island that is a part of the macro-tidal estuary in the Hooghly River, a complex environmental setting of the Bengal deltaic system. The tidal data used in the present study were obtained from the Gangra Tidal Observatory maintained by KoPT.

Data and methodology

The Balari–Gangra section occupies a strategic location with respect to navigation. It occupies the southern extremity of low water crossing for vessels departing from Kolkata Port as well as the Haldia Dock that stand as a backbone for trade and tourism in the eastern part of India. The geographic location of Gangra is 21°57′N; 88°01′E, and the tidal observatory is situated 31.4 km from the open boundary adjoining the Bay of Bengal. The channel width at this location is 17.25 km and observed tidal range is 4.77 m. The KoPT maintains and archives data from the Gangra Tidal Observatory, which is a mechanical float-type tide gauge, installed and monitored by SoI. The tide-gauge benchmark or the chart datum is in accordance with the benchmark precision levelling postulated by SoI. The monthly sea-level variations at Gangra closely resemble the seasonal weather pattern in the northern Bay of Bengal. The monsoonal weather system prevails, and the overall trends of monthly sea-level variation are different compared to other tidal stations in India. The hydrographical features for Gangra station have the lowest mean water level from mean sea level value of 0.34 m, and the sea-level change due to glacio-isostatic rise is about –0.51 mm yr^{-1}. The present study uses the daily tide data at one-hour interval and for one complete year during the period of 2013. The SLPR2 uses the data for harmonic tidal analysis and prediction. There are several tidal analysis and prediction software available, and for the present study, the SLPR2 package (more details given below) was used. The other tidal analysis software include TASK-2000 developed by Permanent

Service for Mean Sea Level (PSMSL) and T-TIDE developed by the University of British Columbia.

The SLPR2 package was developed by UHSLC in collaboration with the National Oceanographic Data Centre (NODC), with the objective to provide quality-controlled sea-level datasets for scientific use. This package has 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 programme is maintenance of the archived sea-level data in one-hourly mode. The TOGA programme ended in 1995 and thereafter, the Joint Archive for Sea Level (JASL) in collaboration with the UHSLC had taken this programme forward. The SLPR2 utilizes sea level datasets that have an interval of 1 h. It performs three primary tasks, viz. tidal analysis and prediction, quality control and filtering. The quality control module includes: (i) linking the data to reference level or datum level; (ii) inspection of timing errors in the data record, and (iii) replacing short data gaps and spurious values through linear interpolation. The tidal analysis is based on Foreman Tidal Analysis and Prediction program[18]. It utilizes the harmonic tidal analysis using linear least square coupled with nodal correction. The amplitude and phase of various tidal constituents are resolved using tidal analysis and utilized to construct the tidal prediction for a specific location. The output of tidal analysis thereby serves as the input for tidal prediction. The capability of SLPR2 is its ability to hindcast and forecast tidal amplitude and phase for a specific location. The predictive skill of SLPR2 was evaluated through a comprehensive correlation between SLPR2 prediction and observation for a one-year period. Ascertaining the reliability of tide prediction, this information can be used for planning purpose by the marine authorities.

Tidal analysis and prediction

Tide prediction using SLPR2 is executed in the form of equally spaced (in time) hourly water level either in the UHSLC processing format, or high–low water-level values specified according to the tide-table format. In addition to tide prediction capability, SLPR2 can also estimate the 'residual', that is, the difference between measured and predicted water levels. The SLPR2 theory involves harmonic analysis, where the tidal forcing is modelled as the sum of a finite number of sinusoids at specific frequencies. The specified frequencies result from various combinations comprising the sum and difference of integer multiple of six fundamental frequencies arising from planetary motions. The fundamental frequency represents the effects due to rotation of the earth (lunar day of 24.8 h), the orbit of the moon around the earth (lunar month of 27 days), the earth around the sun (tropical year), periodicities in the location of lunar perigee (8.85 years), the lunar orbit tilt (18.6 years), and location of perihelion (21,000 years). Based on these fundamental frequencies, a set of six integers are assigned, also called 'Doodson numbers', that describe a particular frequency. Different linear combinations of these frequencies appear as different harmonic constituents in the tide data. The most important frequencies (main constituents) have names such as M_2, S_2, O_2, K_1, etc. In addition to these main constituents, the shallow-water constituents also play a role when tides propagate to shallow waters. Their frequencies depend on the sum/difference of major components. During tidal propagation in shallow waters, the nonlinear effects modulate as well masking the main constituents. In such cases, their frequencies are not a linear combination of major constituents that makes it difficult to resolve in tidal analysis.

Consider s and h as the mean longitude of the moon and sun, wherein p and p' are the longitude of perigee and perihelion respectively. N' is the negative longitude of ascending node. Using the Doodson number set for a particular constituent $\{i', j', k', l', m', n'\}$, the astronomical argument V_j is expressed in the form

$$V_j = i't + j's + k'h + l'p + m'N' + n'p'. \tag{1}$$

The sets with common i' are termed as 'species', meaning $i' = 0, 1, 2$ represents the slow, diurnal and semi-diurnal components respectively. The sets with common i', j', k' are termed as sub-groups. The frequency of a particular constituent is $2\pi\, \mathrm{d}V_j/\mathrm{d}t$. If $G(\theta)$ is the geodetic function, the tidal potential is expressed in the form

$$\sum_{i'=0}^{a} \left\{ G_{i'}(\theta) \sum_{j'k'l'm'n'} [(A)'_{j'k'l'm'n'} \cos(2\pi V_j)] + G_{i'}(\theta) \sum_{j'k'l'm'n'} (B)'_{j'k'l'm'n'} \sin(2\pi V_j) \right\}. \tag{2}$$

Assuming that the ocean is in a state of equilibrium with tidal forcing, an equilibrium response is predicted from astronomical considerations. Further, under the assumption that tidal dynamics is nearly linear, a linear least square fit exists between the measured water level at a particular location and the predicted equilibrium tide. The amplitude and phase of the harmonic constituent can thus be determined. Consider $y(t_i)$ as the time series of observed water levels for which $i = 1, 2,\dots, N$. Assuming that $N > 2M + 1$, the equilibrium tidal response can be modelled in the form

$$x(t_i) = C_0 + \sum_{j=1}^{M} [A_j \cos(2\pi\sigma_j t_i) + B_j \sin(2\pi\sigma_j t_i)]. \tag{3}$$

The amplitude (S_j) and phase (ϕ_j) of the tidal constituent are expressed in the form

$$S_j = \sqrt{A_j^2 + B_j^2};\ 2\pi\phi_j = \arctan(B_j / A_j). \tag{4}$$

The set of $2M + 1$ simultaneous equations is solved by matrix method using the minimizing function $|x(t_i) - y(t_i)|^2$, where the coefficients A_j and B_j in eq. (3) are calculated. The tidal height $h(t)$ at a particular location is represented by harmonic summation as

$$h(t) = \sum_{j=1}^{k} f_j(t) S_j \cos[2\pi V_j(t) + u_j(t) - g_j]. \tag{5}$$

In eq. (5) V_j represents the astronomical argument and g_j the Greenwich phase lag corresponding to the constituent j. The term $f_j(t)$ is the nodal correction factor for the amplitude and $u_j(t)$ is the corresponding nodal correction factor for the phase. The index k in the summation term (eq. (5)) represents the total number of constituents chosen to construct the tidal wave. SLPR2 uses a maximum of 68 constituents, including the shallow-water constituents.

The tide data used for training SLPR2 in the present study utilized a data record of 1 year length, wherein the effects from the last three fundamental frequencies are marginal. Therefore, the constituents resolved by harmonic analysis appear as large peaks surrounded by smaller subsidiary peaks in the frequency space. These are called 'nodal modulations' or precisely satellite modulations to the main peak. The total signal with a combination of these tidal modulations will be a sinusoid whose amplitude and phase vary slowly with time. These changes are slow enough to consider as effectively constant for record lengths up to one year. In order to avoid this inconsistency, the study considers that the phase and amplitude of true response sinusoids have similar frequency (cases when the first three Doodson numbers are identical) and in the same proportion as the equilibrium response. Under this assumption, the ocean response should be the same at similar frequencies. This takes care of the nodal corrections computed from equilibrium response.

In addition, there are some drawbacks using SLPR2 that require special attention of the readers. In large estuaries, one can experience seasonal changes in river discharge that may vary on a yearly basis. In such situations, the tidal process is not stationary. One can expect broadening of spectral peaks in the harmonic analysis. In smaller estuaries, the tidal height variations are significant compared to water column depth that leads to a variety of nonlinear effects. For such cases, one expects tidal asymmetry between the ebb and flood phases of the tidal cycle. Sometimes the tidal interaction with complex, varying topography produces internal waves and bores, and these characteristics cannot be determined from SLPR2 analysis. The residual plot may not always reflect the inaccuracies in either the measured data or tide prediction. The ability of tidal analysis to model satisfactorily the tidal species depends greatly on the site location. In a general sense, the SLPR2 tide prediction for deeper waters normally has a good predictive skill. Prediction for tidal observatories located in regions with influence of rivers and very shallow coastal shelf or complex basin bathymetry requires caution. The long-term tidal analysis and prediction for such cases will be of moderate quality.

Quality control

The residual signal obtained during tidal analysis can serve the purpose of quality control of the tide gauge data. One can assess the shift in datum level through close inspection of the residual data. This shift arises due to improper calibration of the tide gauge data. In addition, timing errors in measured data occur due to error in data processing, incorrect setting of timer on tide gauge or inaccuracies accounted in the gauge time clock. These anomalies can be checked from residuals during the initial stage of tide data analysis in SLPR2. The algorithms in SLPR2 also handle the correction for timing errors as well as the shift in datum levels. Additional information from the tide residuals can be used to identify data gaps and spurious signals in the tide gauge data.

Data filtering

SLPR2 has a data filtering routine that creates daily and monthly means from the input daily data (interval of 1 h water-level elevation data). To obtain daily values, there is a two-step operation in the filter routine. In the first stage, the dominant diurnal and semi-diurnal tidal components are removed from the quality-controlled hourly values. During the second stage, a 119-point convolution filter centred at noon is applied, which removes the remaining high-frequency components and prevents aliasing for daily computed values. In the final step, monthly values are calculated from daily data with a simple average of all daily values that occur during a particular month.

Results and discussion

The Hooghly River is a tide-dominated environment and Kolkata, the most important metropolis is located along its hinterland. The tidal effects are quite strong in this region and deep draft vessels take advantage of varying water levels for navigation. The location of Gangra, the area of interest in the present study, is close to the Nayachara Island situated in the south proximity of low water crossing that results from tidal variations. The tidal wave propagates up to Nabadwip located approximately 282 km, where two non-perennial rivers, viz. the Bhagirathi and Jalangi meet. Between Sagar Island and Diamond

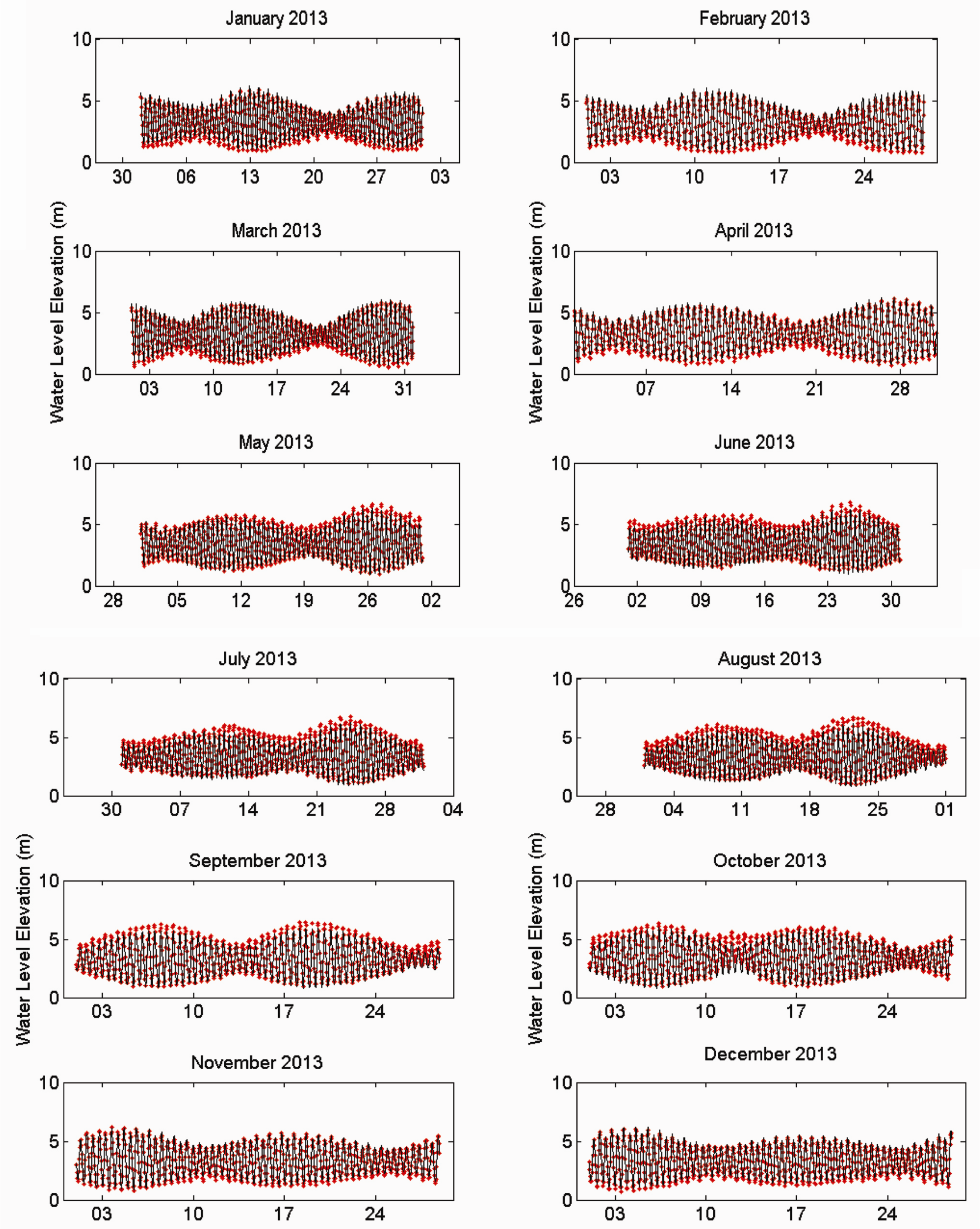

Figure 2. Comparison between measured and predicted monthly water-level elevation from SLPR2 for the year 2013.

Harbour located in the downstream/upstream reaches of the Hooghly River respectively, and separated by a distance of approximately 67 km, the mean tidal range increases from 3.0 (Sagar) to 3.6 m (Diamond Harbour) respectively. The average speed of tidal wave propagation is about 9.95 m s^{-1} during the flood cycle, and 7.17 m s^{-1} during ebb between Hooghly Point and Sagar.

As mentioned above, a minimum period of 1 year tide data is required for harmonic tidal analysis using SLPR2 for a specific location. Using 1 year trained data as the input field, SLPR2 can predict the water-level variations both in hindcast and forecast mode. In the present study, one-hourly tide-gauge data free from data gaps for the year 2013 were used to train SLPR2, and predictions were made both for the years 2013 and 2014. Figure 2

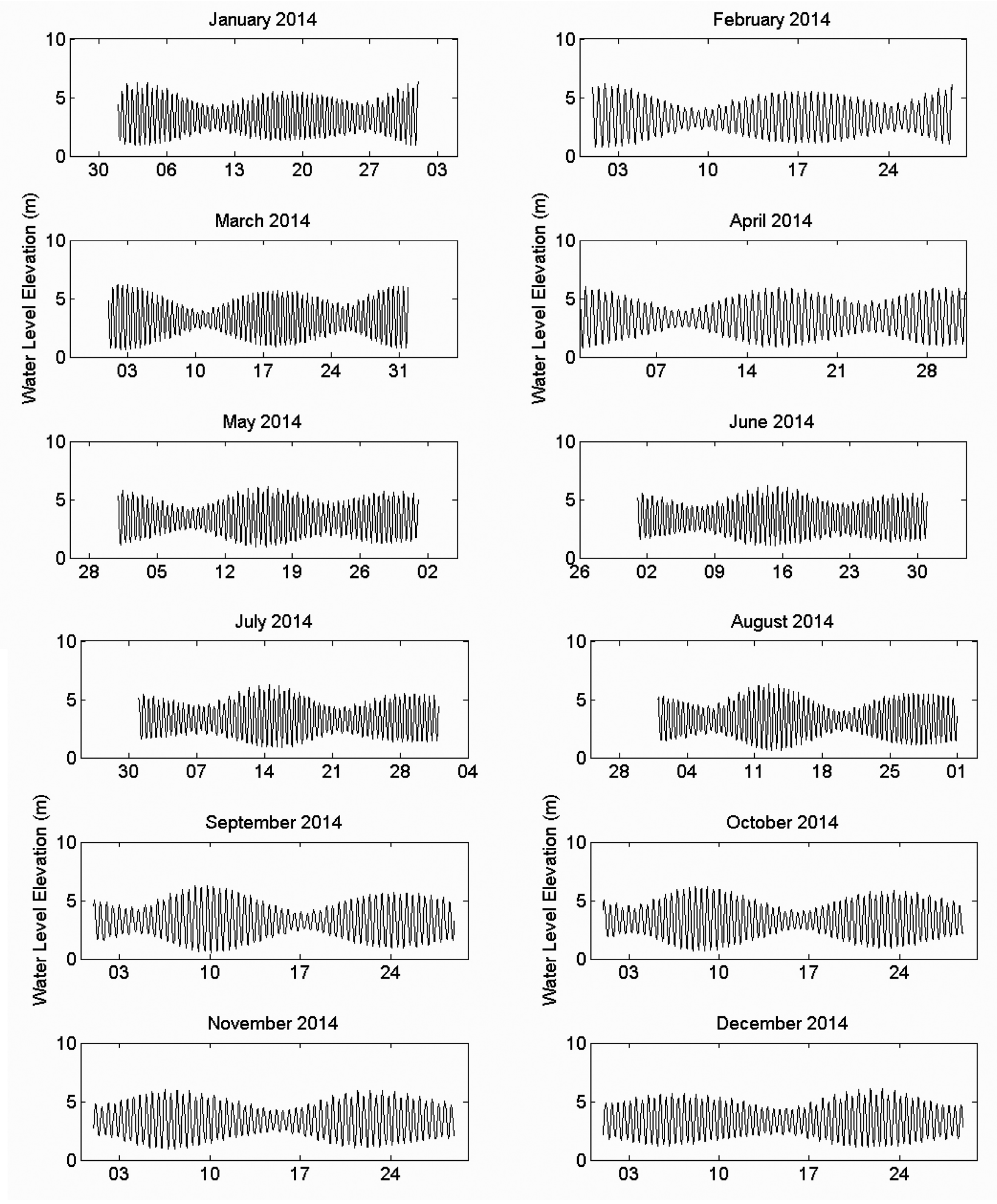

Figure 3. Predicted monthly tidal elevation from SLPR2 for the year 2014.

shows the comparison between observed and SLPR2-predicted tides for the year 2013, whereas Figure 3 shows the prediction during 2014. The skill assessment from SLPR2 predictions shows that both amplitude and phase of the tidal cycle during different months of the year exhibit a good match. This clearly demonstrates that the overall skill level of SLPR2 prediction is highly satisfactory. During end-July 2013, a low-pressure system classified as 'depression' by India Meteorological Department (IMD) had its landfall between Balasore in Odisha and Digha in West Bengal. The tidal amplitudes predicted by SLPR2 show slight underestimation during this period from end-July until the first week of August. The mismatch in tidal amplitude is accountable due to the presence of low pressure system in the head Bay region. Similarly, during the period from 20 to 23 August 2013, a depression developed over the land in coastal West Bengal. It covered the northern portions of Odisha and Jharkhand, and this phenomenon resulted in the marginal underestimation of tidal amplitudes in SLPR2 prediction. In addition, considering the winter months of October and November 2013, the SLPR2 prediction during certain days in these months was also underestimated. One such case is the period 8–14 October 2013, that coincides with the occurrence of extreme weather event '*Phailin*', a very severe cyclonic storm that developed in the Bay of Bengal and had landfall in Odisha. Very clear signatures of extreme water levels at Gangra were noticed, that resulted from extreme waves generated during the movement of *Phailin*. The underestimated water levels from SLPR2 (prediction that is purely based on various tidal constituents) are accounted due to reduced atmospheric sea-level pressure. The differences in predicted water levels during the *Phailin* event are in the order of about 1 m. In addition, for the corresponding period from 13 to 17 November 2013 the remnants of a tropical depression that developed over the Pacific Ocean entered the Bay of Bengal on 8 November 2013. This transformed into a deep depression and finally made landfall close to Nagapattinam in Tamil Nadu. Compared to the previous cases discussed above on depressions and severe cyclonic storms, the depression in the Bay of Bengal that occurred during November 2013 had its landfall very far away from the Gangra site in West Bengal. The far-field landfall location in Tamil Nadu resulted in no significant variability in the sea-level pressure at Gangra.

Therefore, as noticed from Figure 2, the predicted water-level variation for November 2013 is in close accordance with the measured water levels. A similar reason holds good for the '*Lehar*' cyclone (23–28 November 2013) that had landfall near Machilipatnam in Andhra Pradesh. During this period no significant water-level variation occurred at Gangra from atmospheric effects (Figure 2). The objective of the present study was to understand the predicted skill level of SLPR2, and therefore a comprehensive validation exercise was made for the year 2013. Due to limitation of data availability for 2014, Figure 3 shows only the predicted water levels at Gangra.

Figure 4 depicts overall prediction skills based on comparison between measured and observed tidal amplitudes in terms of statistical measures such as correlation coefficient. It provides an overall view on the prediction skill of SLPR2 for a particular location. One can find a consistent, good correlation for all the months, with relatively lower correlation for October. The reason for this is the effect of lower sea-level pressure due to *Phailin*. Long waves such as 'swells' generated from extreme weather events can travel long distances, and in their course of propagation modulate and modify the local wind-waves of a region. A peculiar characteristic noticed in the head Bay region (where Gangra is located) is the presence of bottom soft mud brought to the estuarine environment by river discharge. The wave attenuation characteristics are known to be significantly affected by the presence of mud[19], and therefore the role of long swells influencing tidal waves is marginal. In a complex sea-state over-ridden by swells, the role and influence of swells through nonlinear interaction mechanisms on tidal propagation characteristics in the presence of heterogeneous muddy bottom is an active area of research, and proper knowledge on the underlying physical mechanism is still lacking. Therefore, it is important to understand the effect of tidal constituents in a complex bathymetric setting such as the head Bay region, and more discussions on this issue are presented below.

One can notice remarkable transformation in the tidal pattern and its range during its propagation from open-ocean into the shelf region and further into shallower river channels. These transformations result 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, one can expect other phenomena such as wave reflection, resonance, diffraction, etc. due to the presence of natural barriers like islands. These natural barriers can affect the generation of various tidal constituents. In the present study, as seen from Figure 1, the free tidal propagation into the area of interest (Gangra) is affected by the presence of natural islands. In the first place, the presence of Sagar Island impedes the free flow of open-ocean tides upstream in the Hooghly River. Major portion of tidal energy propagates into the Hooghly River (west of Sagar Island), and the remaining into the Barartala River channel (eastern side of Sagar Island). The bifurcation of Hooghly River occurs at Kachuberia situated northward of Sagar Island.

Figure 5 shows a comprehensive tidal analysis of 59 harmonic constituents for Gangra spanning one complete year. The figure clearly signifies that 8 amongst the 59 constituents dominate the water-level elevation of Gangra. The relative influence of eight dominant tidal constituents and their respective periods in ascending order at Gangra are as follows: (i) M_2 (principal-lunar, 12.42 h); (ii) S_2 (principal-solar, 12.00 h); (iii) N_2 (large lunar elliptic, 12.66 h); (iv) K_1 (luni-solar diurnal, 23.93 h), (v) MS_4 (shallow water quarter diurnal, 6.10 h); (vi) M_4 (shallow water overtides of principal lunar, 6.21 h); (vii) Msf (luni-solar synodic fortnightly, 354.36 h) and (viii) O_1 (lunar diurnal, 25.81 h). It is apparent from this distribution that M_2 dominates the water-level elevation at Gangra. In general, the tidal analysis clearly reveals that the tidal pattern in Gangra is a mixture arising from luni-solar diurnal/semi-diurnal components along with varying combinations from over-tides and compound tides. In addition, compound tides like M_4 and MS_4 also have a significant contribution. Table 1 presents the percentage contribution from significant constituents. It is observed that although M_2 is the dominant mode, its percentage contribution is only 36.43, while

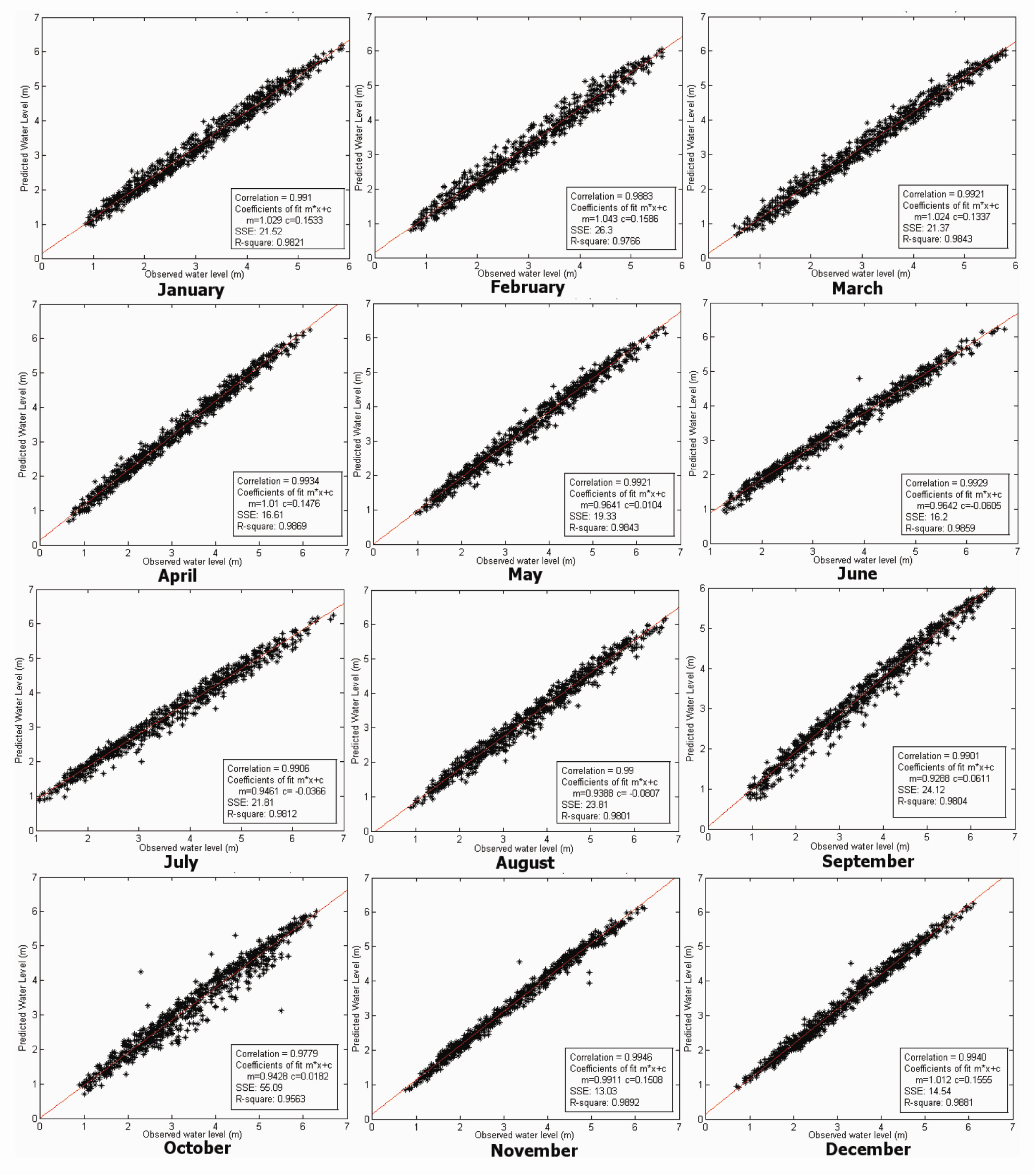

Figure 4. Correlation and statistical relationship between measured water-level elevation and predicted tides (m) from SLPR2 for the year 2013.

those of S_2, N_2, K_2, and K_1 are 16.12, 7.21, 4.51 and 3.25 respectively. The total contribution from diurnal component is 8.44%, while that from semi-diurnal is 72.88%. The higher harmonics like third, fourth, fifth and sixth order have contributions 1.64%, 9.36%, 0.13% and 1.18% respectively. Long-period tides show a contribution of 4.84%, and the remaining is due to shallow-water modifications of diurnal, semi-diurnal and long period tides.

Interestingly, the present study also indicates the presence of a fortnightly tidal characteristic at Gangra arising from the presence of Msf tidal constituent having a periodicity of 14.76 days. In a global perspective, the

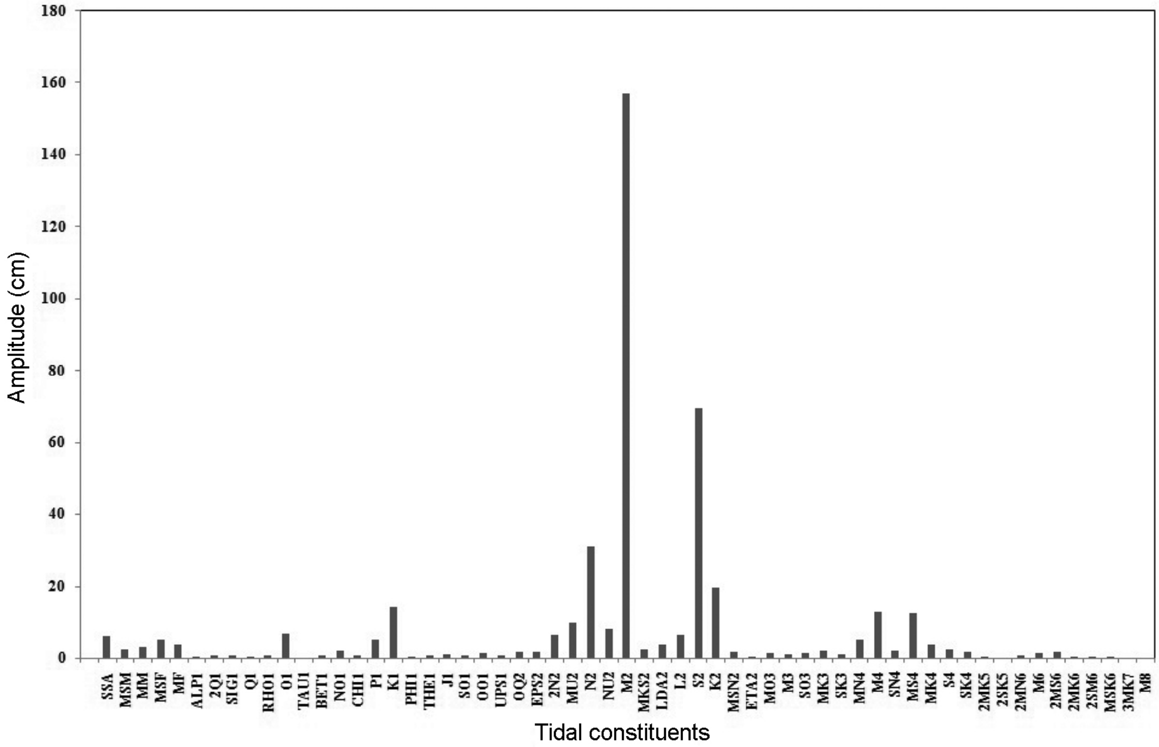

Figure 5. Distribution of various tidal constituents for Gangra.

Table 1. Percentage contribution of significant tidal constituents for Gangra

Tidal constituent	Contribution (%)	Tidal constituent	Contribution (%)
M_2	36.43	Ssa	1.43
S_2	16.12	P_1	1.22
N_2	7.21	Msf	1.22
K_2	4.51	MN_4	1.20
K_1	3.25	Ssa	1.43
M_4	3.00	MK_4	0.88
MS_4	2.90	Mf	0.85
MU_2	2.28	Mm	0.74
NU_2	1.92	Msm	0.59
O_1	1.54	MKS_2	0.54
$2N_2$	1.52	NO_1	0.50
L_2	1.50	MK_3	0.48

Table 2. Comparison of amplitude and percentage contribution of Msf at Gangra with nearby stations

Station	Amplitude of Msf	Contribution from Msf (%)
Gangra	5.2596	1.22
Chittagong	5.9542	1.22
Hiron Point	2.3133	0.86
Khal No. 10	8.0332	1.77
Cox's Bazaar	8.2731	2.88
Teknaf	2.7781	0.92
Charchanga	19.8568	6.1
Khepupara	3.8421	1.21

presence of Msf is reported only at a few places such as the Gulf of Guinea[20], St Lawrence estuary, Canada[21] and Amazon estuary[22]. There are only a few reports on Msf tidal constituent in the Indian waters. One such location is the Kochi backwater in Kerala[23] and the Mandovi and Zuari estuaries in Goa[24]. Mishra *et al.*[25] have reported Msf tides of 3 cm amplitude in Gopalpur port, Odisha. Compared to other harmonics, the Msf tidal motions are relatively weak, and can play an important role in the low-frequency ocean dynamics[26]. Study of Msf constituent at locations near Gangra is difficult due to the non-availability of hourly data required for tidal analysis. The nearest station is Haldia Port, for which monthly and annual mean sea-level data are available from PSMSL. Tidal analysis using SLPR2 for a few locations in the Bangladesh region also shows the presence of Msf constituent. The analysis was carried out using research-quality hourly data from the UHSLC for the stations Hiron Point, Khepupara, Charchanga, Chittagong, Khal No. 10, Cox's Bazaar and Teknaf. Table 2 presents the amplitude of Msf constituent and its percentage contribution at these locations. Charchanga has Msf constituent with amplitude of 19.8 cm, which contributes 6.1% to the total amplitude of all the constituents. However, for other stations, the amplitude of Msf is comparable to that of Gangra. The contribution from Msf at Gangra is 1.22%. Hence, it is can be inferred that the role of Msf constituent has significance in the head Bay region, and its role in the dynamics requires a separate study.

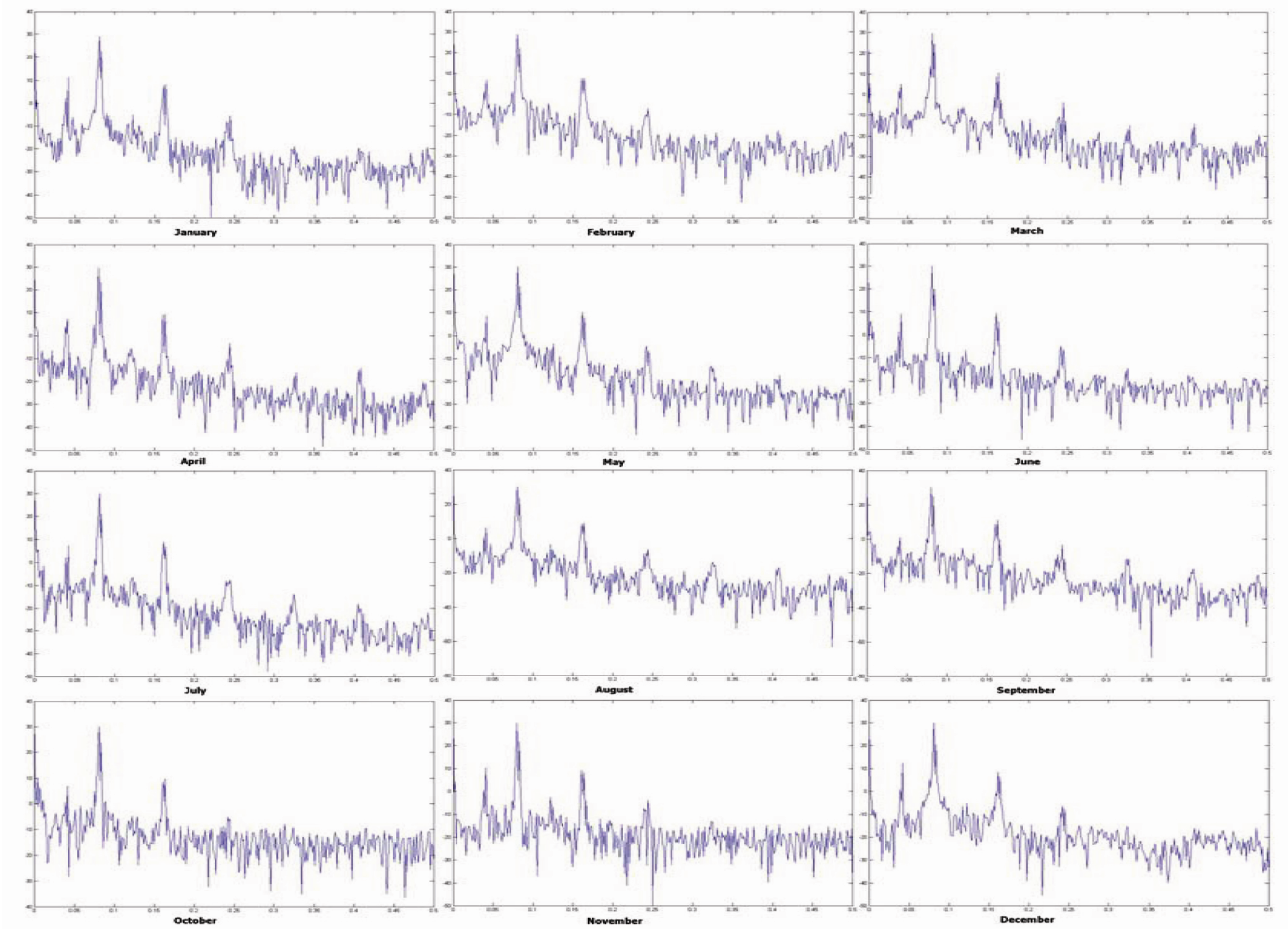

Figure 6. Monthly periodogram distribution of dominant modes in the measured water-level elevation.

The angular speed of an over-tide is an exact multiple of the angular speed from one of the astronomical constituents. In the case of compound tides, angular speed is equal to sum/difference between the angular speeds of two or more astronomical constituents. This explains the fact that Fourier transform of a tidal signal apart from the major constituents can well represent all features of tidal propagation, including the effects from partial constituents. In this context, the periodogram is a powerful statistical tool to understand the periodic tendencies that occur in a given time series. It provides information on measure of the relative importance of a possible frequency that explains the oscillation pattern in the observed data. Figure 6 shows the monthly periodogram distribution for the year 2013. The *X*- and *Y*-axes represent the frequency and corresponding power spectral density respectively. These figures clearly exhibit the presence of various dominant frequency modes in the water-level elevation for Gangra. The first peak is centred at 0.04 Hz having a corresponding period of 25 h, depicting the importance of K_1 tidal constituent (luni-solar diurnal mode shown in Figure 5). The K_1 mode is dominant during the winter seasons from November to January, and its activity reduces during March and September. The summer month, especially during June shows the dominance of K_1 for this region. Amongst all the major observed peaks, the dominant peak for all months (Figure 6) corresponds to a frequency of 0.083 Hz, representing a diurnal cycle (Figure 6; the second major peak from left for all months).

This peak arises from the resultant contribution of three tidal constituents: M_2 (12.42 h), S_2 (12.00 h) and N_2 (12.66 h). The combination from these three constituents constitutes 53.3% of the total water-level signal. The form factor (*F*) classifies the tides based on their respective amplitude. It depicts the strength of semi-diurnal with the diurnal components. Considering the major tidal constituents K_1, O_1, M_2 and S_2, the form factor is expressed as: $F = \{(K_1 + O_1)/(M_2 + S_2)\}$. Based on this categorization, the value of *F* lying between 0 and 0.25 represents semi-diurnal cycle; 0.25 and 1.5 mixed semi-diurnal and between 1.5 and 3.0 mixed cycle, and $F > 3$ has diurnal characteristics. The maximum value of *F* estimated at Gangra is about 0.14. It clearly signifies that semi-diurnal components of tidal forcing dominate the water-level elevation. September has the highest contribution in this regard. The third peak is centred around

0.125 Hz, and its magnitude is very small compared to the preceding two peaks described above. The fourth peak has a periodicity of 0.165 Hz that corresponds to a period of almost 6 h cycle. This is attributed to the compound tides such as MS_4 (6.21 h) and M_4 (6.10 h) shown in Figure 5. The contribution from both these compound tidal constituents is significant compared to over-tide effects.

In addition, the periodogram also shows the existence of other minor peaks having higher frequencies such as 0.25, 0.33 and 0.4 Hz. These peaks arise due to the reflected waves reaching Gangra during the flood/ebb phases of the tidal cycle. Being a narrow river channel, during the flood phase, in addition to elevated water levels observed by the tide gauge, the reflected waves from Sagar also contribute to the net water-level elevation at Gangra. During the reversing phase (ebb cycle), the refracted waves generated from Nayachara reach Gangra at a shorter timescale compared to the natural tidal cycle. The multiple refractions due to channel geometry and presence of natural islands (Figure 1) produce the minor peaks evidenced from the monthly periodogram of observed water-level elevation at Gangra. The high-frequency waves (0.45 Hz) are those refracted from Nayachara during the various phases of tidal propagation. The amplitude of the periodogram from various tidal constituents also clearly shows that September experienced the highest water levels at Gangra. October and November 2013 experienced three cyclonic storms, viz. very severe cyclonic storm *Phailin* (8–14 October 2013) that had landfall near Gopalpur in Odisha and severe cyclonic storms *Helen* (19–23 November 2013) and *Lehar* (23–28 November 2013) that had landfall at Machilipatnam in Andhra Pradesh. One can observe from the periodogram (Figure 6), and particularly in these two months, significant distortion in the amplitude of high-frequency waves. It is also clearly evidenced from the measured water-level records at Gangra, and this observation requires a separate comprehensive analysis, which is outside the scope of the present study.

Summary and conclusion

The head Bay region in the Bay of Bengal occupies the lower portion of the Gangetic Delta stretching about 274 km from the brackish water environment of the Hooghly estuary. The Indian Sunderbans occupies the lower portion of this delta spread over an area of approximately 19,509 sq. km. UNESCO considers this deltaic environment as a world heritage site owing to its fertile, low-lying alluvial plains. In addition, this region is thickly populated owing to its unique fertile plains and natural resources. Tidal variations are quite high in this region comprising of highest tidal range in the east coast of India. Multiple river channels of varying dimensions and irregular tidal creeks form an integral part of this deltaic region. Tides play an important role and they dominate the hydrodynamic behaviour and gamut of coastal processes. The present study performs comprehensive tidal analysis and prediction for a specific location Gangra, in the upstream reach of the Hooghly River channel. Effects of tidal propagation are felt at a considerable distance upstream leading to vigorous mixing and stratification of the water column. The head Bay region is also highly susceptible to natural disasters such as tropical cyclones and damages that resulted from past cyclones have caused enormous destruction to life and property. The Gangra lies along the eastern side of the Hooghly River encompassed by Sagar Islands to the south, and Nayachara to the north. Tidal cycle is primarily semi-diurnal in nature with an effective form factor of 1.4. The tidal strength is highest during the winter months from December to February. The study uses a location-specific tide prediction tool, SLPR2, to perform tidal analysis and prediction of water levels during 2013 and 2014 at Gangra. Tidal data at 1 h interval, free from data gaps and spurious noise facilitate as input to train SLPR2. The study performs tidal analysis and prediction during the years 2013 and 2014. The correlation coefficient between measurement and prediction shows a good match. A comprehensive periodogram analysis was conducted that utilizes monthly measured tides at Gangra. The analysis clearly demonstrates the presence of various dominant frequency modes. The semi-diurnal component is the dominant mode followed by other high-frequency oscillations. Investigations on all dominant modes of variability in the tidal signal decipher the fact that high-frequency oscillations having frequencies in excess of 0.25 Hz resulted from multiple refractions of tidal wave between Sagar Islands and Nayachara. Interestingly, the compound tidal constituent Msf was also evident from analysis in the Hooghly River channel. It arises due to shallow-water effects and nonlinear interaction of tidal system with the channel topography. The other compound tidal constituent that exists is M_4 generated by the nonlinear self-interaction of M_2 tidal constituent within the tidal system. Tide prediction for 2013 using SLPR2 was compared with the measured water-level elevation at Gangra. The results signify a good match with observed water levels. Further, the influence of atmospheric sea-level pressure variations due to energetic events such as depressions and very severe cyclonic systems during 2013 in the Bay of Bengal was correlated with net water-level elevation at Gangra. The results signify that the effect of *Phailin* during October 2013 had a significant impact on the net water-level elevation at Gangra. The estimated difference between prediction and measurement during this event was about 1 m. Effects from far-field cyclones that had landfall in Andhra Pradesh and Tamil Nadu show insignificant variations in the observed water-level elevation at Gangra. The net water-level elevation resulting from tidal forcing and other external mechanisms is important for the port and harbour departments, coastal zone management authorities, etc. The present study demonstrates tide analysis and water-level prediction skills for Gangra. Similar study may be extended to other areas in the head Bay region that have tidal observatories. This study has wide practical applications and is important for planning in coastal engineering applications.

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