Research Article

Caspian Sea Tidal Modelling Using Coastal Tide Gauge Data

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The purpose of this paper is to model tidal conditions in the Caspian Sea using data from coastal tide gauges of Anzali, Noshahr, and Neka Ports. Harmonic analysis method was used to identify and examine 40 tidal components. The results illustrate that the annual (Sa) and semiannual solar (Ssa) components on all of the ports listed have the highest range in comparison with the other components which are, respectively, 16 cm, 18 cm, and 15 cm for annual components and 2.8 cm, 5.4 cm, and 3.7 cm for semiannual components.

1. Introduction

The gravitational attraction between Earth, moon, and sun has a well-known influence on Earth's ocean levels [1].

Tidal analysis and prediction are the primary steps in the studies of each hydrodynamic and coastal management matter. It is dealing with the analysis of the sea level heights observations using physical and geophysical approaches advanced from experiences or physical reasoning and based on spectral analysis [2, 3].

In general, for the modelling of tides, there are three main ways: first is using hydrodynamic models (Laplace differential equations (LTE)), second is empirical modelling, and third is combination of hydrodynamic models and empirical models [4].

Knowing the causes of water level fluctuations of the seas has been one of the major challenges in all scientific fields and attracts the attention of many researches. Oceanic effects, aerologic effects, tides, climate change, and vertical movement of Earth's shell can be noted as five factors that contribute to the impacts of climate change on the water level fluctuations [5].

The prediction is used in science and engineering to confirm the sympathetic of a given phenomenon by stating

what its behavior has been till now and will be at a given time and then verifying that it is so [3], although without considering the physical effects of the large events (e.g., tsunami, storms, and seabed earthquake) the prediction of water levels can be achieved [6].

Not only the tides currently are exactly identified in the most global ocean, but also we have learned and computed new features of tidal dynamics [7].

Tidal effects due to their significant impacts on sea water level are of a great importance and researchers have always been looking forward to modelling them [8].

However, numerous undesirable natural events may have an effect on the predictions, but still there are determinable parameters which are essential to handle them exactly; for example, astronomical arguments and nodal corrections are singing the important parts in dealing with tidal analysis and prediction [9].

In this study, the effectiveness of tidal components by the use of coastal tide gauge's observations is surveyed. Harmonic analysis method was used to determine tidal amplitude and phase of 40 components.

(1) *Study Area and Relevant Data.* Caspian Sea is surrounded by five countries, including Iran, Russia, Azerbaijan,

FIGURE 1: Caspian Sea location.

Turkmenistan, and Kazakhstan (Figure 1). The Caspian Sea is the largest remaining section of the old Tethys Sea breakdown that was spread from the Arctic to Indian Ocean through the first to third geological period. In third geological period, appearance of Caucasus and Asian mountains leads to this big Sea dividing, so rise of European continent and construction of Iranian plateau were the main reasons of creation of Caspian Sea. Having the length of about 1030 km and the width of 435 to 196 km, the Caspian Sea locates between the $47^{\circ}57'$ an $36^{\circ}33'$ circuits and $46^{\circ}43'$ and $54^{\circ}53'$ hour circles [10].

2. Tides

Tides are the regular ebbing and flowing movement of the sea happening as the result of attractions of celestial near-earth bodies such as the sun and the moon. Tidal acceleration of celestial objects such as the moon at one point is the difference between the gravity acceleration of that celestial body and the mass centre of the Earth at that point. Viscoelastic earth changes due to tidal forces are roughly one-third of the surface international water. The vector field of these forces can be replaced with a scalar field named potential of tides [11].

In each point of Earth, this potential can be computed by [12]

$$U(R_e, \lambda, \phi) = \frac{GM}{R} \sum_{i=2}^{\infty} \left(\frac{R_e}{R} \right)^i P_i(\cos \theta), \quad (1)$$

where G is the universal constant of gravity, M is the mass of absorbing body (moon or sun), R_e is the average radius

of Earth, R is the geocentric distance, and θ is the geological distance of a point with (R_e, λ, ϕ) coordinates [1]. Main course of this relation is achieved when $i = 2$. However, in some cases, $i = 3$ is also used for the moon. Thus, the main indicator term of tidal potential is described as follows:

$$U_2(R_e, \lambda, \phi) = \frac{3GMR_e^2}{4R^3} \left(\cos 2\theta + \frac{1}{3} \right). \quad (2)$$

And regarding spherical trigonometry relations [4],

$$U_2(R_e, \lambda, \phi) = \sum_{i=0}^2 U_{2m}(R_e, \lambda, \theta) \cdot \frac{3GMR_e^2}{4R^3} \left\{ \cos^2 \phi \cos^2 \delta \cos 2H + \sin 2\phi \sin 2\delta \cos H + \left(1 - 3\sin^2 \phi \right) \left(\frac{1}{3} - \sin^2 \delta \right) \right\}. \quad (3)$$

It can be seen clearly from this relation that the first parameter of the relation relates to the half-daily effects and the second and third parameters, respectively, show the effects of daily and long period of tides. This relationship suggests that the tidal potential is a function of the absorbent body (moon and sun). It should be noted that, except for the gravitational forces mentioned above, other factors may be effective in producing and intensifying the tides [13].

In general, the sea water level fluctuations can be obtained as the result of the interaction of following dynamic processes: tides, changes in atmospheric pressure, the dynamic effects of ocean circulation, wind effects, the effects of temperature, water salinity changes, the effects of river discharge into the oceans, and melting of polar ices.

3. Tidal Harmonic Analysis

In this study, the Fourier harmonic analysis method is used to determine the effect of tidal components. As tidal components frequency, water level in each moment and time was given, and the amplitude and phase of needed component were determined [14]:

$$u(\varphi, \lambda, t) = \text{MSL}(\phi, \lambda) + \sum_{i=1}^n a_i(\Phi, \lambda) \cos \omega_i t + b_i(\varphi, \lambda) \sin \omega_i t, \quad (4)$$

where $u(\varphi, \lambda, t)$ is water level in t moment obtained by tide gauge, $\text{MSL}(\phi, \lambda)$ is mean sea level, $\omega_i = 2\pi f_i$ is angular frequency derived from tidal components frequency, t is the observation time, and a_i and b_i are the Fourier coefficients we need to determine. Considering (4) and proration, the amplitude and the phase are calculated as

$$\underbrace{\begin{bmatrix} u(\varphi, \lambda, t_1) \\ u(\varphi, \lambda, t_2) \\ \vdots \\ u(\varphi, \lambda, t_m) \end{bmatrix}}_{L_{m \times 1}} = \underbrace{\begin{bmatrix} 1 & \cos \omega_1 t_1 & \sin \omega_1 t_1 & \cdots & \cos \omega_n t_1 & \sin \omega_n t_1 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ 1 & \cos \omega_1 t_m & \sin \omega_1 t_m & \cdots & \cos \omega_n t_m & \sin \omega_n t_m \end{bmatrix}}_{A_{m \times (2n+1)}} \underbrace{\begin{bmatrix} a_1 \\ b_1 \\ \vdots \\ a_n \\ b_n \end{bmatrix}}_{(2n+1) \times 1}^{\text{MSL}} \quad (5)$$

If m was observed value from tide gauge and n was the tidal component, then

$$A_{m \times (2n+1)} X_{(2n+1) \times 1} = L_{m \times 1}. \quad (6)$$

A is Vandermonde (pattern) matrices [15]. As the result,

$$\hat{X} = (A^T A)^{-1} A^T L. \quad (7)$$

And the amplitude and phase of tidal components are determined from the following equation [16, 17]:

Amplitude:

$$A_{(i)} = \sqrt{a(i)^2 + b(i)^2}. \quad (8)$$

Phase:

$$\begin{aligned} \Phi(i) &= \tan^{-1} \left(\frac{b(i)}{a(i)} \right) \\ \text{or } \Phi(i) &= 2 \tan^{-1} \left(\frac{b(i)}{A_{(i)} + a(i)} \right). \end{aligned} \quad (9)$$

4. Tide Modelling

The following equation is used to analyze and predict the tide [18, 19]:

$$\begin{aligned} h(t) &= Z_0 \\ &+ \sum [f_n(t) H_n \cos(\delta_n t - g_n + V_n(t_0) + u_n(t))]. \end{aligned} \quad (10)$$

And $n = 1, 2, \dots, N$ tidal components.

In the above equation, Z_0 is the average sea level, N is the number of tidal components, δ_n is angular frequency or speed (degree per hour), $V_n(t_0)$ is astronomical argument, $f_n(t)$ is nodal factor, $u_n(t)$ is nodal phase, H_n is the component amplitude, and g_n is the phase lag.

In above relations, nodal corrections ($f_n(t)$, $u_n(t)$) for each tidal component and astronomical argument ($V_n(t_0)$)

must be calculated in order to determine the revised amplitude and phase. In this step, $V_n(t_0)$ is computed as

$$\begin{aligned} V_n(t_0) &= i_b \lambda_s(t) + i_c \lambda_h(t) + i_d \lambda_p(t) + i_e \lambda_N(t) \\ &+ i_f \lambda_{p'}(t) + \Phi_n, \end{aligned} \quad (11)$$

where (i_b, i_c, i_d, i_e, i_f) are the constituent's Doodson numbers in which solar coefficients are preferred to lunar coefficients and the desired time is the time data starting in zero hour UT (Universal Time) and remaining terms are as follows:

- (i) $\lambda_s(t)$ or simply “s” is the Mean Longitude of Moon.
- (ii) $\lambda_h(t)$ or simply “h” is the Mean Longitude of Sun.
- (iii) $\lambda_p(t)$ or simply “P” is the Longitude of Lunar Perigee.
- (iv) $\lambda_N(t)$ or simply “N” is the Longitude of Lunar Ascending Node.
- (v) $\lambda_{p'}(t)$ or simply “P’” or “P1” is the Longitude of Perihelion.
- (vi) Φ_n is stationary phase (a multiple of 90°).

Stationary phase exists in most of Doodson numbers' tables. Algebraic formula to determine the geographic Astronomical Longitude (the Celestial Sphere) $\lambda_s(t)$, $\lambda_h(t)$, $\lambda_p(t)$, $\lambda_N(t)$, $\lambda_{p'}(t)$ or in some references in form of (s, h, P, N, P') has been provided [20, 21]. In this study, Task-2000 method has been used.

Task-2000 is based on zero hour epochs UT, January 1900. This formula is accurate at least from 1800 to 2100 [22]:

$$\begin{aligned} \lambda_s(t) &= 277.0247 + 129.38481 \cdot \text{IY} + 13.17639 \cdot \text{DL}, \\ \lambda_h(t) &= 280.1895 - 0.23872 \cdot \text{IY} + 0.98565 \cdot \text{DL}, \\ \lambda_p(t) &= 334.3853 + 40.66490 \cdot \text{IY} + 0.11140 \cdot \text{DL}, \\ \lambda_N(t) &= 259.1568 - 19.32818 \cdot \text{IY} - 0.05295 \cdot \text{DL}, \\ \lambda_{p'}(t) &= 281.2209 + 0.017192 \cdot \text{IY}, \end{aligned} \quad (12)$$

where

$$\begin{aligned} \text{IY} &= \text{year} - 1900, \\ \text{DL} &= \text{IL} + \text{IDAY} - 1. \end{aligned} \quad (13)$$

FIGURE 2: Display studied stations.

FIGURE 3: Time series along with the tidal modelling and residual of Anzali tide gauge station.

TABLE 1: The location of Caspian Sea coastal tide gauge stations.

Station name	Latitude	Longitude	Time spam
Anzali	37.4780°	49.4623°	21/3/2005–20/3/2014
Noshahr	36.6584°	51.5047°	21/3/2006–21/3/2014
Neka	36.8502°	53.3656°	1/1/2000–31/8/2012

In this formula, IL is the number of leap years from 1900 onward that is calculated by the following equation:

$$IL = \frac{(IY - 1)}{4}. \quad (14)$$

IDAY is the number of days from January 1st of that year.

5. Forming the Observations Time Series of Coastal Tide Gauge

Features of tide gauge stations which are formed from their time series data were in Table 1 and geographical position of tide gauge stations could be seen in Figure 2.

The analysis of time series Anzali tide gauge station and modelling time series by (10) could be seen in Figure 3. Residuals are small and acceptable. More amplitude to frequency of 40 tidal components of Anzali tidal gauge station could be seen (Figure 4). The values of time series analysis in Anzali station as well as the values of time series modelling analysis are shown in Table 2. It is shown that the modelling was done well. The same process was continued for stations Noshahr and Neka (Figures 5–8). Also, results of time series analysis

FIGURE 4: Amplitude to frequency of 40 tidal components of Anzali tidal gauge station.

FIGURE 5: Time series along with the tidal modelling and residual of Noshahr tide gauge station.

FIGURE 6: Amplitude to frequency of 40 tidal components of Noshahr tidal gauge station.

FIGURE 7: Time series along with the tidal modelling and residual of Neka tide gauge station.

FIGURE 8: Amplitude to frequency of 40 tidal components of Neka tidal gauge station.

and results of time series modelling in stations Noshahr and Neka are shown in Tables 3-4.

6. Conclusion

Tidal analysis of tide gauge stations illustrates the absence of efficiency in tidal components except for annual and semiannual components. However, unlike other stations, in Anzali station, MS4 components were effective.

The results also indicate that the annual (Sa) and semi-annual solar (Ssa) components on all of the ports listed have the highest range in comparison with the other components which are, respectively, 16 cm, 18 cm, and 15 cm for annual

components and 2.8 cm, 5.4 cm, and 3.7 cm for semiannual components.

By comparing the results with other studies [23, 24], the results of tidal analysis of this study are confirmed. The effect of the tides in the Caspian Sea is very small and there are only annual and monthly variations.

In [23], spectral analysis on tide gauge observation of Caspian Sea was done where the annual and semiannual component effect were observed. So it is corresponding with tidal analysis of this study.

Ignoring the modulation of solar perihelion and nodal modulation use can be mentioned as the weak points which were effective in tidal harmonic analysis; 18.6 time series must exist for resolving all frequencies. As for the other defects

TABLE 2: The amplitude and phase of 40 tidal components for Anzali tide gauge station, obtained from observations and modelling.

Constituent	Amp_obs (m)	Phase_obs (deg)	Amp_mod (m)	Phase_mod (deg)
K2	0.003015	295.7626	0.00208	286.43
L2	0.001672	271.2841	0.00171	271.46
M2	0.008682	269.2956	0.0084	269.245
N2	0.003698	158.6862	0.00374	159.22
Ma2	0.003133	296.7903	0.00314	296.79
R2	0.017878	73.22793	0.01812	78.22
S2	0.012064	67.14119	0.01206	67.141
T2	0.005672	144.9542	0.0065	142.954
J1	0.001707	121.5101	0.0017	121.8201
K1	0.022738	11.43623	0.0233	11.3
M1	0.007332	67.24207	0.0073	68.45
O1	0.006945	165.1889	0.00693	165.1923
P1	0.00704	217.9986	0.007245	218.43
Q1	0.008204	232.6201	0.008325	232.56
S1	0.008428	83.31833	0.008267	84.673
M3	0.0072	93.20983	0.00687	93.65
S3	0.002717	119.0538	0.00281	119.487
M4	0.005868	233.6994	0.00589	233.996
S4	0.006028	85.39538	0.006518	85.7
M5	0.015845	21.3593	0.01522	21.487
M6	0.004693	239.5097	0.00467	240.43
S6	0.004883	193.316	0.0049	193.76
M8	0.008275	265.0774	0.00865	265.9
S8	0.003187	159.8985	0.00376	158.34
Mf	0.006459	109.5878	0.006217	107.789
Mm	0.007524	134.4543	0.00776	136.89
Msf	0.000792	77.13807	0.000734	76.54
Oo1	0.006236	355.2012	0.006236	355.34
Ssa	0.028563	55.42608	0.02862	53.56
Ms4	0.070979	15.67987	0.0704	15.456
Mn4	0.018667	186.2534	0.01889	186.789
Mk3	0.02533	282.7036	0.0255	282.408
Sa	0.163234	212.3174	0.163198	212.456
Mo3	0.007534	219.1039	0.007423	218.56
No3	0.026181	8.642835	0.026789	9.43
2N2	0.006548	46.04756	0.006437	47.13
So3	0.028834	137.9187	0.02889	136.67
Sk3	0.006522	44.34284	0.00657	44.389
S01	0.001092	68.53536	0.001034	68.576
Mk4	0.022139	331.8166	0.0234	331.8834

of this study, we can point out that there is no easy way to indicate the significance of amplitude and phase together with lack of appropriate solution for coastal areas that affects the shape of tidal waves.

In this study, the method of modelling and predicting of sea level is explained. With modelling sea level, the trend of sea level in future will be predicted and it helps coastal management. Also, in areas where effect of tide is

high, by having sea level prediction with modelling, tide can be used to assess other factors affecting sea level variations like tsunami, vertical movement of the crust, and so forth.

The main problem with Caspian Sea tide gauge stations data is improper collecting and compiling them. Moreover, the sampling intervals in Anzali and Noshahr tide gauges are daily and each three hours, respectively, that can affect

TABLE 3: The amplitude and phase of 40 tidal components for Noshahr tide gauge station, obtained from observations and modelling.

Constituent	Amp_obs (m)	Phase_obs (deg)	Amp_mod (m)	Phase_mod (deg)
K2	0.001265	205.3896	0.001276	204.9
L2	0.000134	104.9257	0.000144	103.89
M2	0.010247	275.8484	0.01028	276.896
N2	0.002429	110.3829	0.002534	110.789
Ma2	0.002005	73.94501	0.002007	74.289
R2	0.00083	248.9937	0.00076	249.3397
S2	0.001758	10.64485	0.001777	10.5689
T2	0.00104	252.2587	0.001067	252.678
J1	0.000575	38.258	0.000589	38.378
K1	0.003133	206.5065	0.003145	206.45
M1	0.000804	197.7024	0.000809	197.745
O1	0.001833	74.5144	0.001845	74.78
P1	0.001664	171.5155	0.001643	172.504
Q1	0.000887	255.0884	0.00076	255.56
S1	0.002105	352.2459	0.00167	352.214
M3	0.000044	284.4275	0.000245	284.545
S3	0.000222	10.67813	0.00678	10.63413
M4	0.000773	269.5824	0.00989	269.6724
S4	0.000389	334	0.000567	333.89
M5	0.000592	308.7407	0.000345	308.437
M6	0.000816	107.9719	0.00424	107.901
S6	0.001758	297.3552	0.00987	296.9552
M8	0.001783	300.9042	0.00345	300.405
S8	0.035218	128	0.03789	128.2362
Mf	0.005655	63.45231	0.00679	64.82
Mm	0.008585	157.1591	0.00567	156.2271
Msf	0.000698	171.7511	0.000778	171.842
Oo1	0.001602	126.1866	0.00189	125.731
Ssa	0.054341	86.44686	0.05345	86.461
Ms4	0.000389	142.9945	0.00927	143.18
Mn4	0.000375	12.73982	0.00678	13.7
Mk3	0.000346	67.02355	0.00345	66.425
Sa	0.188683	208.5804	0.18907	208.2541
Mo3	0.000228	52.28991	0.00789	51.75
No3	0.000178	216.8859	0.000845	217.323
2N2	0.000519	37.64077	0.000612	37.772
So3	0.000414	105.4683	0.000432	105.94
Sk3	0.000306	334.2423	0.000351	334.58
S01	0.000225	195.3219	0.000376	194.218
Mk4	0.000424	74.62624	0.000387	74.947

TABLE 4: The amplitude and phase of 40 tidal components for Neka tide gauge station, obtained from observations and modelling.

Constituent	Amp_obs (m)	Phase_obs (deg)	Amp_mod (m)	Phase_mod (deg)
K2	0.000609	248.292	0.00071	248.35
L2	0.000094	210.8618	0.000078	211.23
M2	0.003386	211.6024	0.00421	212.316
N2	0.000451	33.09812	0.000418	33.789
Ma2	0.000203	2.616894	0.000206	3.269
R2	0.00027	266.0452	0.000261	266.169
S2	0.001491	353.4808	0.00152	353.724
T2	0.000322	84.26617	0.000341	83.972
J1	0.0002	222.6129	0.000237	222.7034
K1	0.003984	232.586	0.004112	232.213
M1	0.000075	18.18968	0.000087	18.226
O1	0.001979	22.82131	0.002141	24.718
P1	0.000709	221.6676	0.000801	237.18
Q1	0.000071	199.8688	0.000076	200.1073
S1	0.001333	265.0889	0.001343	265.623
M3	0.000014	238.5899	0.000017	238.3041
S3	0.000127	71.53864	0.000143	70.946
M4	0.000041	106.7546	0.000052	106.9928
S4	0.00007	53.35676	0.000083	53.468
M5	0.000036	289.5994	0.000038	289.783
M6	0.00004	274.9504	0.000047	275.7935
S6	0.000042	59.32671	0.00004	58.87
M8	0.000071	0.493216	0.000082	0.78465
S8	0.000007	343.1489	0.000007	343.1376
Mf	0.003968	358.5273	0.003965	357.5186
Mm	0.001392	37.48796	0.001323	38.418
Msf	0.002203	332.5874	0.002212	333.64
Oo1	0.000043	172.098	0.000043	172.487
Ssa	0.037471	90.08432	0.0375	91.508
Ms4	0.000045	225.9218	0.00005	226.5
Mn4	0.000063	309.734	0.00006	310.47
Mk3	0.000063	168.7787	0.00007	169.681
Sa	0.151559	218.163	0.1518	217.2045
Mo3	0.000028	42.31016	0.000027	43.401
No3	0.000055	308.456	0.000054	307.731
2N2	0.000032	294.6541	0.000034	295.391
So3	0.00005	94.33536	0.00006	95.591
Sk3	0.000114	73.86118	0.000145	74.584
S01	0.000171	47.30391	0.000182	47.835
Mk4	0.000058	116.3563	0.000072	116.2482

the tidal modelling and will decrease the accuracy of the computation.

Competing Interests

The authors declare that they have no competing interests.

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