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SEA LEVEL CHARACTERISTICS IN PUERTO QUEQUÉN

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ABSTRACT

Sea level observations at the mouth of the Quequén Grande river, Puerto Quequén station, are used to study the sea level variation in different time scales: tidal and subtidal fluctuations, sea level variation and seiches in the estuary. Four tidal constituents are found to be the most active in Puerto Quequén, with M_2 being the most important. At subtidal frequencies, the sea level variations are primarily forced by atmospheric forcing on the adjacent shelf. Spectral analysis evidenced atmospheric forcing into the estuary at macro, synoptic and local scale.

RESUMEN

Se estudian las fluctuaciones mareales y submareales, las variaciones del nivel del mar y los seiches en el estuario del río Quequén Grande mediante observaciones del nivel de mar en la estación mareográfica de Puerto Quequén, Cuatro componentes astronómicas son las más activas en el estuario, siendo M_2 la más importante. Las fluctuaciones submareales son originadas primariamente por fluctuaciones en el nivel del mar generadas por el forzamiento atmosférico en la plataforma continental interior adyacente al estuario. El análisis espectral de las variaciones del nivel del mar muestra evidencia de forzamiento atmosférico en escala local, sinóptica y macroescala.

1. INTRODUCTION

Water level variations are known to occur in response to a variety of forces, including the periodic astronomical forces of the Earth-Moon-Sun system, the aperiodic or periodic meteorological forces, and dynamic or thermodynamic forces associated with the motion or properties of seawater. The relative magnitude of these forces are highly variable both in space and time. Therefore, sea level variations have been extensively studied in different time scales.

Many authors have analyzed the large scales tidal features ranging from yearly to monthly values (ie; Balay, 1958; Hicks and Shofnos, 1965; Hicks, 1968; Church, 1980; D'Onofrio *et al*, 1981; Seim, 1987; Bongers and Wyrtki, 1987; Woodworth *et al*, 1991) and they proved that every place presents its own and particular variability. On the other hand, subtidal sea level variations have been extensively examined for evidence of wind-driven coastal circulation and the seasonal variation of oceanic circulation (ie., Wang, 1979; Chao and Pietrafesa, 1980; Schwing, 1989).

In coastal areas, especially those with a relatively small astronomical tide, meteorological forces can play a significant and sometimes dominant role in creating water level variations over time scales ranging from a few hours to several days. This is especially true in estuaries or semi-enclosed coastal bays, where the constricting effects of narrow channels and shallow water serve both to damp progressive tidal waves of astronomical origin and to amplify meteorological effects (Smith, 1974). Storm surges are one of the major processes that have been extensively studied in those environments (i.e., Proudman, 1955; Provis and Radok, 1979; Murty and El-Sabh, 1981).

Little is known about the tides and sea level variations in the Quequén river estuary. The estuary is situated in the SE of the Buenos Aires province (38° 33' S - 58° 43' W), Argentina. In the mouth of the estuary is located the Quequén harbor. The harbor is a very active commercial and industrial site, where many of the main products of Argentina are exported. The knowledge of the circulation and dynamics of the area is useful. However, few works have been performed on the subject.

Lanfredi *et al.* (1988) have studied the variations of the mean sea level in Puerto Quequén. They analyzed 64 years of hourly tidal heights and obtained the long term trend of 16.09 cm/100 yr. The mean tidal range in Puerto Quequén is 0.8866 m. The most important astronomical components are the M_2, O_1 and K_1 (Piccolo et al., 1995). The objective of the present study is to describe and analyze the characteristics of the sea level in the Quequén Grande estuary in different time scales.

2. METHODOLOGY

The tidal data were supplied by Dirección Nacional de Construcciones Portuarias and Vías Navegables of Puerto Quequén, Argentina. The data consisted of daily, monthly and hourly values, in different periods that are mentioned along the present work. Five years (1989-1993) of hourly data were use to calculate the astronomical tides by the methods of Godin (1972) and Foreman (1978).

Non tidal sea level variations were calculated for the period 1989-1993. For operational purposes, storm surges are defined as the difference between the recorded water level and the predicted astronomical tide. This traditional method of subtracting the astronomical tide from the observed water level and treating the residue as storm surge assumes that tide and surge are linearly additive and there is no nonlinear interaction (Murty and El-Sabh, 1981). This form of nontidal sea level fluctuation were calculated from the study period with the purpose of determine its magnitude in the estuary. Standard statistical analysis were performed with the surge information.

Averaging of hourly sea level values over the study period permitted the calculation of monthly mean sea level. Lanfredi *et al* (1988) presented the monthly and annual mean sea level in Puerto Quequén from 1918 to 1982. The data was completed and analyzed with new information. Spectral analysis was performed using the Fast Fourier Transform technique.

3. RESULTS AND DISCUSSION

3.1 General characteristics

Considering the last twenty years, the mean annual value of the tide in Quequén Grande estuary is 0.88 m. However, the former value changes if a longer period is considered. For the period 1918-1994, the mean annual tide is 0.97 m. Fig. 1 shows the spectral analysis of the hourly data for all 1993. The main harmonic tidal constituents are the M_2, K_1 and O_1. The shallow water constituent, M_4, is also significant.

The harmonic constituents of a particular location are called tidal constants, however it is known that they change from year to year. Restricting the analysis to the period 1989-1993 and to the three main constants, in Table 1 is shown their change in amplitude and phase. An important change in amplitude and phase is found during the

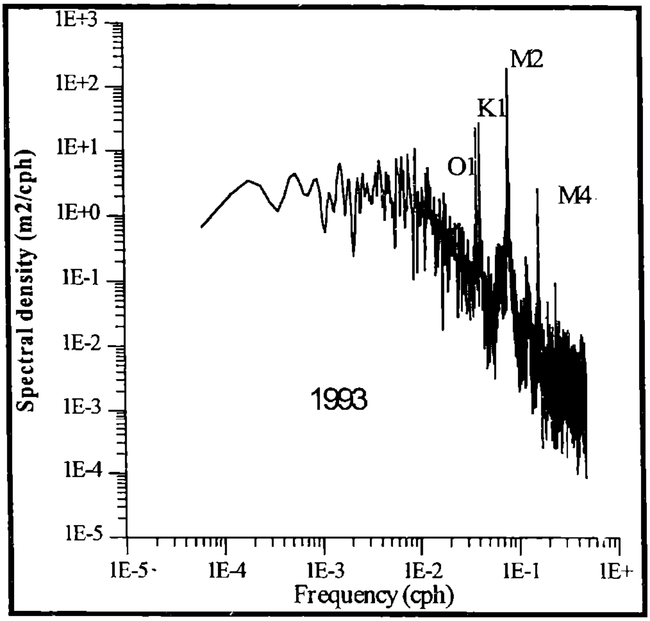

Figure 1. Energy density spectra for Puerto Quequén water level.

study period for all the astronomical constituents. The observed annual variations are significant according to the results presented in Pugh and Faull (1982). Therefore, a more complete study should be made taking decades or centuries to analyze the trends in the tidal constants, but that is beyond the purpose of the present work. An example of the sea level variation during June 1992 is presented in Figure 2. An important semidiurnal inequality is present in the record.

Year	M_2		K_1		O_1	
	A (m)	G (°)	A (m)	G (°)	A (m)	G (°)
1989	0.438	178	0.174	74.73	0.176	3.66
1990	0.439	75.13	0.173	72.21	0.169	265
1991	0.44	333	0.161	69.46	0.164	168.8
1992	0.401	248.9	0.143	257.6	0.137	265.8
1993	0.363	165.2	0.145	78.71	0.137	3.44

Table 1. Amplitude and local phase angles for the principal diurnal and semi-diurnal tidal constituents at Puerto Quequén.

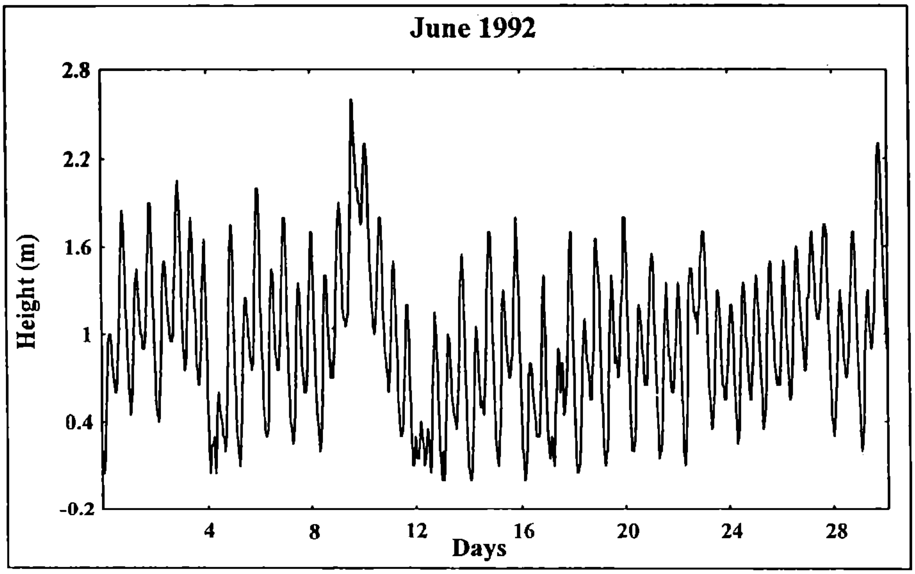

Figura 2. Example of a monthly sea level record.

The semi-diurnal, diurnal or mixed nature of the tide is defined by the ratio of the principal diurnal and semidiurnal constituents: $F = (O_1+K_1)/(M_2+S_2)$. The magnitude of this ratio at Puerto Quequén is 0.68, indicating that the tide is a predominantly semi-diurnal, mixed tide.

Yearly maximum tides were analyzed for the period 1958-1994. The highest values were registered in 1962 and 1979 with 3.10 m. However, in 1975 the maximum tide reached the value of 2.30 m.

3.2 Time variance

The seasonal departures from the annual mean differ considerably from one year to the next, due largely to anomalies in weather (atmosphere and ocean). Table 2 shows the

Month	Mean (cm)	Minimum departure	Maximum departure	SD
January	4.7	-7	16	5.2
February	6.5	-9	19	5.3
March	4.4	-13	17	6.2
April	5.3	-12	28	7.2
May	3.9	-20	17	6.4
June	2.4	-11	24	6.7
July	-3	-34	9	6.7
August	-6.3	-21	8	5.9
September	-10.5	-28	6	5.9
October	-7.1	-20	7	5.1
November	-2.2	-21	16	5.6
December	2.2	-15	15	5.9

Table 2. Standard deviation per year for each month.

standard deviation, SD, of a monthly departure from the annual average, taken year by year, based on the procedure by Patullo et al. (1955). The study period was 76 years.

There is a significant seasonal variation. From January to June the monthly values were greater than the annual one. On the contrary from July to November the monthly values were smaller. The standard deviation calculated for the Quequén Grande estuary is smallest in October and greatest in April. According to Patullo et al. (1955) the April SD for La Plata, Buenos Aires and Montevideo are 8.0, 6.3 and 6.2 respectively. Therefore, the calculated standard deviations are similar to the ones calculated for the Río de la Plata estuary. Both estuaries are located in the Buenos Aires province and they present similar tidal ranges.

3.3 Low Frequency Perturbations of the Tide

In many harbors is common to find a series of oscillations superimposed to the normal astronomical tidal record; however, their presence is observed only a small percentage of the time. In the case of Puerto Quequén Tide Gage records (Fig. 3) these oscillations are practically continuous having amplitudes of few tens of a meter. In certain occasions the oscillations become strongly enhanced reaching amplitudes up to 1.5 m within 5 to 20 minutes. Such significant changes in water level occurring within short times induce rapid modifications in the harbor depth affecting the navigation in it. In fact, this analysis was initiated due to two major incidents that happened in March and May, 1992 in which two loaded cargo vessels were leaving the harbor when events of 1.2 and 1.5 m, respectively, produced that their hulls touched the bottom. Fortunately there were no damages nor injuries because the vessels were relatively small compared with the ones that operate there normally.

Balay (1961) and Inman et al. (1962) have mentioned the occurrence of typical oscillations in tidal records both in Quequén and Mar del Plata (in two nearby tide stations), both places are separated by 124 km. In the latter article the authors tried unsuccessfully to correlate the fluctuations to edge wave propagating along the broad Argentine continental shelf. Also, the sampling rate employed by them was 5 minutes; therefore, they were looking for large scale processes beyond the resonance period of small harbors.

Balay (1961) commented about a storm surge that produced the flooding of all downtown Mar del Plata beaches causing panic and damage on the tourist that were on the beach January 21, 1954. Similar events repeated several times in the last decades. Those that have been reported in the press were associated to very good weather conditions on the coast that helped large concentrations of beach goers. In all cases the tourist were surprised because no previous warning was possible. According to Balay (1961) these events can be related to rapid changes on the atmospheric pressure over the

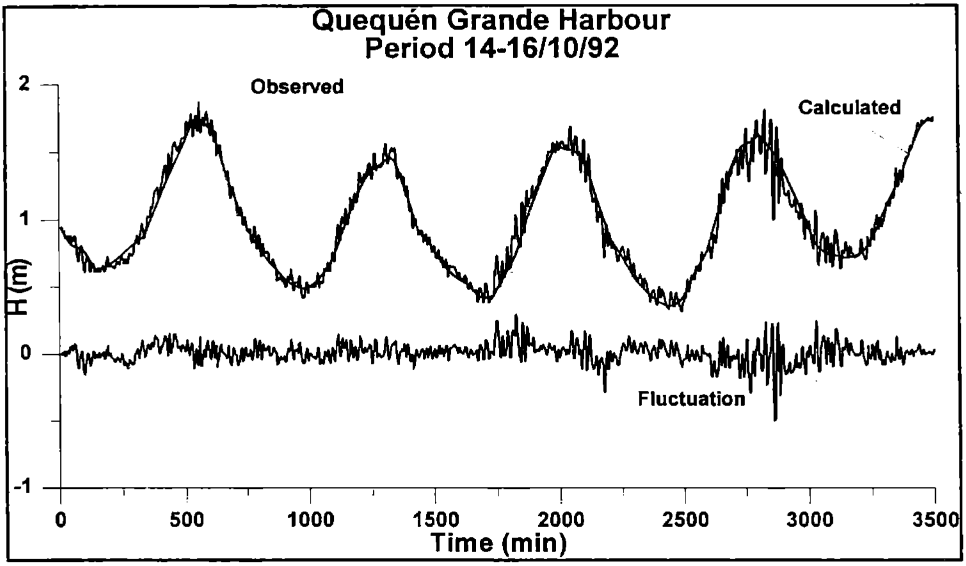

Figure 3. Observed, predicted and perturbacion of the tide .

shelf. In the present case we have analyzed a total of 20 100-hr tidal records from the Quequén tidal station which is located some 1000 m from the mouth of the harbor.

All records were digitized at approximately 1 min intervals. Since the resulting data file presented unequal time intervals, the sampled data was interpolated using the Stineman method (Perillo and Piccolo, 1991) and resampled to $\Delta t = 1$ min. The record for October, 1992 is shown in Fig. 3. The actual tidal curve estimated by sampling every hour was interpolated with the same method at also 1 min interval and subtracted from the original record. The resulting perturbation record is also shown in Fig. 3.

Spectral analysis using FFT of these records (i.e., Fig. 4) show that energy peaks appear at periods 25, 6.5, 5.2, 4.3, 3.4 and 3 min. Also the high frequency part of the spectra is proportional to $f^{-5/3}$. These periods cannot be correlated to atmospheric forcing since there were no meteorological data available for that period. An automatic weather station was installed at only 500 m of the tidal gage only in August 1995.

To establish if the periods could be related to the normal resonance of the harbor. For an open basin with the characteristics of the Quequén harbor, Sorensen (1978) proposed a classical expression for the resonant period (T_n)

$$T_n = \frac{4L}{(2k + 1)\sqrt{gd}} \tag{1}$$

where L is the length of the harbor, g is the acceleration of gravity, d is water depth and k represents the oscillation mode of the basin, being k = 0 the free oscillation mode and higher values the forced ones. Considering that the harbor has a length of almost 2000 m and the water depth is quite homogeneous in 12 m due to the dredging, T_n results in 12.3 min.

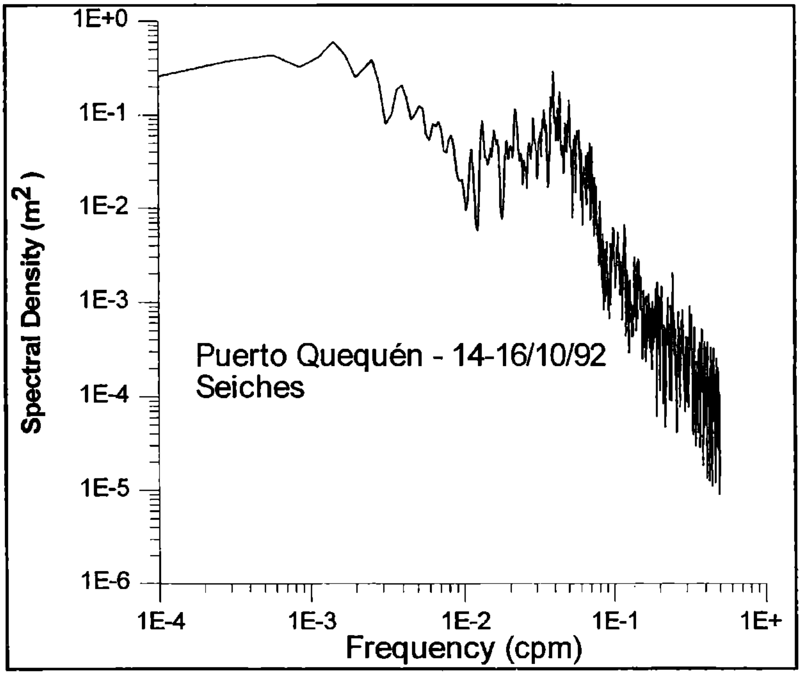

Figure 4. Spectral density of the seiches at Puerto Quequén

In addition to the standing wave mode represented by eq. (1), a basin of the characteristics of Quequén harbor can resonate in the Helmholtz mode, which is analogous to the acoustic resonator by the same name. In this case, the water surface in all the basin moves up and down uniformly, while the water at the inlet oscillates in and out (Sorensen, 1978). The period of the Helmholtz resonance is estimated by

$$T_H = \sqrt{\frac{(L_c + L_c^{\prime}) A_b}{g A_c}} \qquad (2)$$

where A_b and A_c are respectively the areas of the basin and the inlet cross-section, L_c is the length of the inlet channel and L_c' is an additional length to account for the water mass outside of each end of the channel that is involved in the resonant oscillation. Sorensen (1978) gives the following expression for the estimation of L_c'

$$L_c^{\prime} = -\frac{W}{\pi} \ln\left(\frac{\pi W}{\sqrt{g d_c} T_H} \right) \qquad (3)$$

where W and d_c are the channel width and depth. Assuming that the width of the channel is 200 m, its depth is 12 m, the area of basin 1.6 10^6 m^2 and the channel cross-section area is 2400 m^2, estimation of T_H and L_c' must be made by an iteration procedure that results in T_H = 2.2 min and L_c' = 51.9 m.

Although there are some peaks at periods similar to those calculated for the normal oscillation and the Helmholtz resonance for the harbor in the spectra, they are small in comparison with those indicated before. The lack of meteorological data preclude some correlations with the atmospheric forcing that may give some light to these behavior. Another possible source for harbor oscillation is the effect induced by waves which are important at the mouth. However,

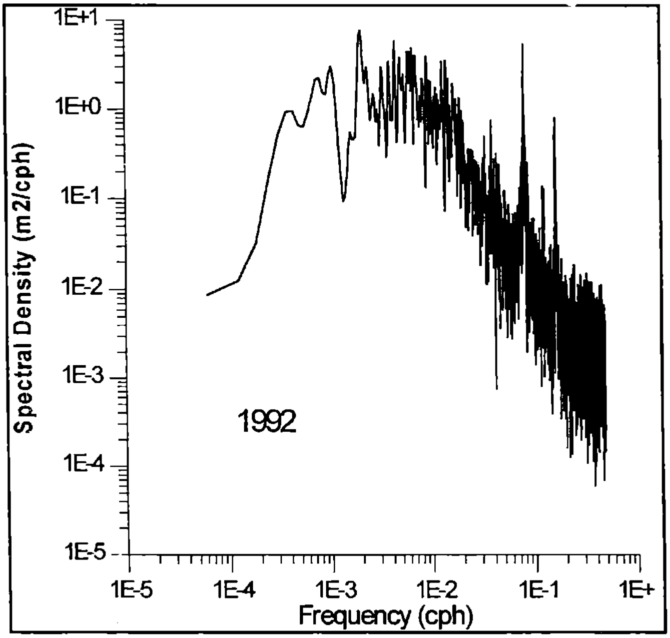

Figure 5. Power spectra of the storm surges.

there is no data available at the presetn time to assess their influence.

3.3 Storm Surges

Hourly departures of observed tides from predicted ones, storm surges, presented maximum values of 1.5 m and -1.66 m in the period 1989-1994. Figure 5 shows the power spectrum for 1992. Significant energy peaks are found in 2 month, 21 days, 10 d, 5.6 d and 12 hs. These periods indicate that the fluctuations are produced by meteorological process in macro, sinoptic and microescales. The 10 days peak corresponds to the frequency of storm passage for the study zone and the 5.6 d characterizes the sinopticscale. These periods are typical of high and mid latitudes. The 12 hs peak corresponds to the local wind circulation, the sea breeze. Therefore, the sea level variations of the Quequén river estuary is due mostly to the effect of the meteorological forcing.

4. CONCLUSION

Sea level and its fluctuations have interested man for many centuries. Historical sea level time-series data are unique among marine data sources. Sea level records include not only periodic fluctuations due to astronomical tides but also nontidal, low frequency fluctuations resulting from various oceanic and atmospheric processes.

Analysis of 5 years of hourly sea levels indicates that the nontidal sea level variations are large compared with the normal tide range in Quequén harbour. The meteorological processes are important in determine the sea level variations in the different time scales.

Acknowledgments

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