Local flows in the Quequén Grande River Estuary, Argentina

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Abstract. Quequén Grande River is one of the most important water courses of Buenos Aires Province due to the economic and strategic significance of its estuary, where the populous Quequén-Necochea area and Quequén Port are located. The minor Las Cascadas falls, at 15 km from the place where the river meets the sea is the point where the maximum tidal propagation is detected marking the head of the estuary. Artificial dredging is needed to insure the adequate navigability conditions in the Quequén harbour, which has induced a highly stratified water column in the last 2 km of the estuary. Thus, an abrupt step is established at the head of the harbour, implying a much reduced water circulation and in some cases nonexistent, producing strong reductive and even anoxic conditions. The foot of the step is a sediment and organic matter trap and becomes an interesting place of study. The goal of this article is to present the information obtained with Doppler sonar at the neighborhood of the step, which allows distinguishing local turbidity currents that may influence the deposition patterns of the sediments.

1. Introduction

Estuaries are dynamic systems because of the noticeable interaction between the discharge of fresh water and the saline intrusion, which generates the variations of the salinity distribution. Sometimes the mix of the waters produces homogeneous environments, while others estuaries are characterized by the presence of well differenced layers.

The estuaries constitute ideal places to settle harbours, which gives place to two remarkable effects for the particulate material flows: 1) frequent dredging is usually needed to remove the accumulated sediments and provide adequate navigability conditions, and 2) the circulation of ships generates local currents that are important enough to change the patterns of sedimentation.

The Quequén Grande River, one of the most significant water courses in the south-west of Buenos Province, is 173 km long and born in the Tandilia Sierras range. Its drainage basin is located in a highly developed farming zone covering a total area of 9370 km$^2$ (figure 1) in which the conditions to form small falls and rapids along the river are provided. The last minor falls, named Las Cascadas, located at 15 km from the mouth are the point where the maximum tidal propagation is detected, and mark the head of the estuary following the estuarine definition criteria proposed by Perillo [1]. The monthly mean river runoff varied throughout the year since a minimum of 5.3 m$^3$/s in February to a maximum of 11.4 m$^3$/s in November according the files obtained at the Las Cascadas Gauging station. Nevertheless, large flash floods have been registered occasionally; among them the most important

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occurred in 1905, 1913, 1915, 1998, 2002 and the largest one ever in 1980, which reached over 200 m$^3$/s and destroyed three major bridges in the estuarine zone [2].

The Quequén harbour is located in the last 2 km of the estuary and covers both margins modifying the original geomorphology of the river mouth. Because of its activity, mainly related to the exportation of grains coming from an extensive hinterland, the harbour is the second largest deep water system in Argentina. To provide deep water conditions for the harbour activities, this part of the estuary is kept at 12 m depth by continuous dredging. However, further upstream the thalweg has a depth of 2–4 m. In this way, an artificial step is formed and separates the estuary in two parts, being one of them notoriously affected by the tide [2].

The formation of this abrupt depth jump in the harbour head induces flows with different behaviour and a low or even null circulation in the deep lower layer where velocities are extremely small, restricting the estuarine circulation only to the depth of the crest of the step. Thus any sediment particle or contaminant that drops below the interface becomes trapped and settle at the foot of the step. Based on Perillo et al. [2] results, this sector of the harbour is reductive and even anoxic at times, with both reduced circulation and, obviously, oxygenation of the deeper water. Thus, this particular zone of accumulation of particulate material becomes an interesting place of study.

The river itself, and mainly the estuary, has a meandering pattern which originally ended in a coastal plain dominated by a coastal dune system on the Necochea side and a cliffy coast with extended beaches on the Quequén side. However, these features have been lost with the development of the harbour in 1908 and the construction of the jetties in 1915. Due to the prevailing SW–NE littoral drift along the coast, the effect of the jetties was to accumulate sand on the Necochea side and to erode the Quequén beaches. Although the construction of the jetties was prompted by the embankment of the harbour mouth by littoral drift and designed to reduce wave activity within, the results along the years have been very poor [2].

Quequén harbour presents singular man-made structures that have produced major consequences altering the geomorphology and circulation in the estuary. First of all, both jetties, especially the South one, have modified the littoral circulation and sediment transport pattern. Originally, the mouth of the estuary was deflected to the north by a spit that was cut periodically by seasonal peak runoff. The presence of the North jetty reduces the width of the mouth to 165 m developing a basin with low circulation.

Perillo et al. [2] consider the estuary as a microtidal and partly mixed system from the step to the head, while in the last 2 km the water column is highly stratified meaning that the upper 1-3 m of the water column layer is fresh water and a halocline (or interface of density) develops reaching salinities of over 30 salinity practical units being homogeneous down to the bottom [3]. According to the morphogenetic classification [1], it is considered as a coastal-plain primary estuary. The bottom sediments along the thalweg are constituted by sands, silty sands and silty clays with mean grain size decreasing inland while the bottom sediments within the estuary reflect the influence of the Pleistocene loess sediments of the adjacent area as most of the materials found have a related mineralogical composition [4]. However, at the head of the harbour, and due to its particular dynamics, sediments are very fine and the conditions are highly reductive [5].

There are very few hydrographic studies on the Quequén Grande River estuary and consequently the basic properties of the geomorphology, its physical oceanography and the relation with the mixing processes are poorly understood. Perillo et al. [2] reported a number of salient features of the estuarine dynamics, especially those relative to salinity, temperature and current distributions and tidal behaviour. Within the period April 1994–August 1998, six surveys covering all seasons and spring–neap conditions were carried out in the estuary to provide basic information to characterize the system. Sediment samples were taken at a series of cross-sections along the estuary to describe the general sediment distribution. All measurements were performed before the modification and extension of the jetties started at 2003. Developing gravity currents or arrested wedges have not been detected at all. A better understanding of both, geomorphology and hydrography of the estuary will certainly be useful in solving its pollution and dredging problems.
The preliminary results of a two day-campaign are introduced here, whose purpose was to study the local flows around the step neighbourhood and their influence on the deposition of the suspended material. In the next Section, the methodology is described and the relevant information obtained is introduced. Then some of the results are shown and briefly discussed; finally the conclusions are presented.

Figure 1: Geographic location of the Quequén Grande River estuary.

2. Methology
The field work was performed between the midday on 27 and the dawn on 28 December (2007) during a tide cycle. The figure 2 shows the area where 45 runs were made and that includes the harbour zone located between the step and the jetties. As an example, one of these trajectories is marked with a red line, together a reference frame that indicates the distances to the North and East from the starting point.

An Workhorse Acoustic Doppler Current Profiler (or ADCP), provided by RDInstruments, and a Global Positioning System (GPS) were employed. The ADCP, attached to a side of the IADO 4 boat, measures absolute velocities in three dimensions and maps the bed giving a bathymetry. In addition, the intensity of the reflected acoustic signal (or backscatter) provides information about the suspended material, being possible to determine the evolution of the sediments transport by a given current.

During the time of the campaign, the suction dredger Beachway was operating in the harbour zone. This vessel is 95m long and 16 m wide, has two powerful engines of 810 kW which suck through a pipe of 0.80 m diameter and a storing volume of 3580 m³. Measurements were made during the time in which the dredger went offshore to unload the sediments, which allowed visualizing flows generated under particular conditions as described in the next Section.

The values of the air temperature, humidity and atmospheric pressure, and wind intensity and
direction every 10 min were provided by the meteorological station located in Quequén Port. According to the data reported in Table I, the weather conditions prevailing during the measurements days were stable and the sky was clean. The maximum temperature was reached at 14:00 and its minimum at 00:00. The maximum wind intensity was 32.2 km/h registered between 15:00 and 15:30 on 27 December. According to the wind rose shown in figure 3, it is may be inferred that the East direction is the most frequent and in this direction the most intense intensity was registered.

![Figure 2: Run N° 44 wholly performed in the 2 km long harbour zone.](image)

**Table 1.** Data registered at the meteorological station of the *Consorcio de Gestión de Puerto Quequén* on 27-28 December

| Parameter                  | Value       |
|----------------------------|-------------|
| Mean temperature           | 19.9 °C     |
| Maximum temperature        | 26.9 °C     |
| Minimum temperature        | 15.5        |
| Mean wind velocity         | 21.06 km/h  |
| Maximum mean wind          | 29.2 km/h   |
| Main wind direction        | E           |
| Rain                       | 0 mm        |
| Mean humidity              | 47%         |
| Atmospheric pressure       | 1012.23 bar |

The figure 4 shows the variation of the tide level during the days of the survey. The height difference reached 2 m and the main period was of about 12 hours (according to a microtidal estuary and a semidiurnal tide). The interference of the different components of the tide causes a significant variation of the maximum and minimum values that coincide with those of the astronomical tide tables provided by the Servicio Hidrológico Nacional, suggesting that the wind did not affect the measurements. The maximum height was 1.75 m at 9:00 on the day 28. Since the dawn of day 28 the wind was more variable, tending later to blow from the south-east, that is perpendicularly to the coast; consistently, the tide height increased about 0.30 m with respect to the astronomic tide. The mean height of the waves was approximately constant, which is consistent with the wind intensity registered.
Figure 3: Wind rose for the days December 27 (left) and 28 (right). The wind direction 0° corresponds to the north, 90° to the east, etc. The wind intensity is given in km/h.

Figure 4. Tide height registered by the gauge of the Consorcio de Gestión de Puerto Quequén (circles). The squares represent the height forecasted by the Servicio de Hidrografía Naval and the triangles represent the main wave height. The wind intensity and direction (the north is upwards) is showed above.
3. Results and discussion

The most interesting findings come from the analysis of the intensity distribution of the ADCP backscatter signal. Particularly, a remarkable sedimentation pattern is observed, which may be understood taking into account the dredging operation and the movement of other ships during the runs. The dredger sucks sediments from the estuary bed and simultaneously generates turbulent flows with suspended sediments, thus increasing the water density in the dredging zone. The density difference between the fluids due to the suspended particles generates horizontal flows on the bed known as turbidity currents and whose dynamics is well described by the gravity currents theory [6].

Briefly, a gravity (or density) current on a rigid bottom is characterized by a frontal zone (or head) of height $h$ that is greater than that of the following flow, and moves forwards with a velocity $V$ that depends on the relative density difference $\Delta \rho / \rho$ and the thickness $h$:

$$V = \sqrt{\frac{g' \cdot h}{1.41}}$$

where $F = 1$ is the Froude number, $g' = g \Delta \rho / \rho$ is the reduced gravity with $g$: gravity acceleration, and $h = \varepsilon h_0$ with $h_0 = 12$ m: total depth of the estuary water column and $0 < \varepsilon < 1$. The density difference between the salt and fresh waters is $\Delta \rho / \rho = 0.025$ for 3.5% of dissolved salts (sea water). If it is possible to measure $V$ and to estimate the values of $g'$ and $h$ independently, the matching between both sides of Eq. (1) suggests the presence of gravity currents.

In the following the backscattering results obtained in some of the 45 trajectories performed during a tidal cycle are presented. The time in which each run occurred is indicated in a tide evolution graph, allowing determining the stage of the flood or ebb tide at that moment. The figure 5 shows the backscatter-intensity distributions near the step obtained on a part of the trajectories initiated at 16:39 and 17:06. The deep blue zone indicates a denser fluid moving to the right. From the leading mark and the time difference it is possible to estimate $V = \Delta x / \Delta t = 1.65$ m/s, while $F \cdot \sqrt{g' \cdot h} = 1.41$ m/s. The figure 6 shows the distributions corresponding to the trajectories initiated at 19:38 and 20:24, giving $V = 1.97$ m/s and $F \cdot \sqrt{g' \cdot h} = 1.55$ m/s. The acoustic signal dispersion corresponding to the trajectories initiated at 20:32 and 20:35 (figure 7) shows a gravity current head moving forwards the step with velocity $V = 2.18$ m/s that is close to the value of $F \cdot \sqrt{g' \cdot h} = 1.73$ m/s.

The trajectories started at 23:20 and 23:30 in figure 8 show a practically arrested gravity current. Its front velocity results $V = -0.15$ m/s despite $F \cdot \sqrt{g' \cdot h} = 1.55$ m/s. In this case the tidal flow towards the sea causes the retreat of the turbidity current when it was advancing to the step.

During the trajectories corresponding to initial times 01:21 and 01:30 a gravity current is observed (figure 9) again traveling forward the step with velocity $V = 2.3$ m/s and $F \cdot \sqrt{g' \cdot h} = 1.73$ m/s.

Other kind of flows also was detected. The backscattering registered during the runs initiated at 0:23 and 0:31 (figure 10) suggest the presence of an homogeneous fluid without sediments on the right (red colour), separated from another fluid containing a significant quantity of suspended material through the whole water column. Here, the sediments are more concentrated near the bottom but no gravity current seems to be produced. The velocity of the separation plane between the two fluids is insignificant.

The figure 11 shows a bore [6] reaching the step. In the present case, the typical undulations of this kind of flow in a stratified medium are observed behind the frontal zone of the current suggesting a turbulent bore. When an intense enough turbidity current meets a wall, a hydraulic jump as that observed in the figure 12 propagates away from the wall after the interaction.

The velocity values obtained from figures 5-9 allow estimating the time $T = L/V$ that the turbidity current needs to travel along the harbor zone of the estuary. Table 2 presents the values of $T$ for a length $L \approx 2250$ m obtaining times of the order of 20 min.
Figure 5: On the left, intensity registered by the ADCP in a part of the trajectories N° 2 and 5. The vertical lines indicate the gravity current front positions. On the right, the initial time of the trajectories (red point) are marked on the tide variation graph.

Figure 6: Idem figure 5 for trajectories N° 9 and 13.

Figure 7: Idem figure 5 for trajectories N° 15 and 16.
Figure 8: Idem figure 5 for trajectories Nº 25 and 26. An arrested turbidity current is evident.

Figure 9: Idem figure 5 for trajectories Nº 37 and 38

Figure 10: Backscattering registered by the ADCP in a part of the trajectories Nº 28 and 29. It is clear the separation between a zone with a high concentration of suspended materials and another of an homogeneous fluid without sediments.
Figure 11: Turbulent bore moving forwards the frontal zone of a turbidity current.

Figure 12: Hydraulic jump produced by the reflexion of the turbidity current at the step wall.

Table 2: Estimated time during which the turbidity currents travel across the analyzed sector of the estuary.

| Trajectory Nº | Measurement time | T (min) |
|---------------|------------------|---------|
| Intensity     |                  |         |
| 2 - 5         | 17               | 28      |
| 9 - 13        | 20               | 23      |
| 25 - 26       | 23:30            | 23      |
| 37 - 38       | 1:30             | 16      |
| Backscatter    |                  |         |
| 15 - 16       | 20:30            | 17      |

4. Conclusions
The measurements performed in this campaign allow detecting for the first time the occurrence of turbidity currents, bores and hydraulic jumps in the harbour zone of the Quequén Grande river estuary. It is found that the circulation times of these flows are of the order of 15-30 min. Since the time difference between the detection of two consecutives currents is at least a couple of hours, which is similar to the time employed by the dredger in going to offshore, unloading the sediment and coming back to its work section, and also is similar to the time between the exit of two big ships, the detected turbidity currents seem to be generated each in an individual way by the vessels displacement.

Some interesting relationships arise when the results showed here are compared with those reported by Perillo et al. [2] who detected dangerous oscillations over the water surface of about 1 m with respect to that explained by the astronomical tide. As the harbour tidal records used to show the presence of high frequency oscillations, Perillo et al. [2] made specific measurements at the two extreme tide gages during August and September 1998 at 1 min interval to evaluate these oscillations. The periods were estimated resulting between 3 and 25 min, although the latter are predominant. Even though normal oscillations have amplitudes of the order of 0.10 m, oscillations of up to 1.5 m often are observed. Normally, the oscillations increase in size suddenly and inexplicibly. When they occur, the strong oscillations may induce serious consequences for the navigation of large cargo vessels. The theoretical resonance periods of the surface waves for the harbour vary between 3.3 and 6.4 min, which are well below the typical 25 min found during the field measurements. In the present field work those oscillations did not appear, but turbidity currents generated by the dredger action and the
motion of other ships were clearly identified and their velocities of displacement suggest circulation times that coincide with those of the oscillations reported by Perillo et al. (2005).

Perillo et al. [2] also suggested the occurrence of at least two macro vortexes during floods at the harbour, with opposite components of velocity in depth and surface, and such vortexes may create special conditions for the sedimentation process in that place. However, the turbidity currents observed this time might be responsible for such a velocity change.

Thus, the measurements made and the information acquired allow visualizing many interesting aspects of the local flows and the movement of the suspended material in the harbour sector of the estuary. There is a complex interaction between the displacing of vessels, the river discharge, the tide and the sediments transport. Then, conditions for creating an intense sedimentation area at the foot of the step exist and more hydrodynamic information is needed to understand the varied processes that occur.

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