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# Geomorphologic and physical characteristics of a human impacted estuary: Quequén Grande River Estuary, Argentina

Gerardo M.E. Perillo[a,b,*], Daniel E. Pérez[c], M. Cintia Piccolo[a,d], Elbio D. Palma[a,e], Diana G. Cuadrado[a,b]

[a]Instituto Argentino de Oceanografía, CC 804, Florida 4000 Edificio E1, 8000 Bahía Blanca, Argentina
[b]Departamento de Geología, Universidad Nacional del Sur, San Juan 670, 8000 Bahía Blanca, Argentina
[c]Departamento de Ingeniería, Universidad Nacional del Sur, Av. Alem 1253, 8000 Bahía Blanca, Argentina
[d]Departamento de Geografía, Universidad Nacional del Sur, 12 de Octubre y San Juan, 8000 Bahía Blanca, Argentina
[e]Departamento de Física, Universidad Nacional del Sur, Av. Alem 1253, 8000 Bahía Blanca, Argentina

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**Abstract**

Even though the Quequén Grande River Estuary has economic and strategic importance from an oceanographic point of view, it has been ignored until recently. Nevertheless, many anthropogenic modifications (i.e., dredging, jetty and harbour construction, etc.) have taken place in the last 100 years which, most of them, have resulted in significative economic expenses to the harbour and city authorities due to the lack of adequate prior studies. The purpose of this article is to provide a review of the present status of the geomorphology and main physical characteristics of the estuary and describe the effects of these man-made modifications upon the estuary. Data were gathered in several field cruises from 1994 to 2000 plus from continuous recording devices installed at or near the estuary directed to define the present geomorphologic and oceanographic conditions of the estuary and to establish a monitoring program. The ultimate goal is to provide some practical solutions in diminishing the maintenance of the harbour and to provide pollution-control devices.

The estuary is classified as a microtidal, primary, coastal-plain system. It can be considered as a partly-mixed system 2 km from the mouth up to its head (15 km inland). Artificial dredging to accommodate the Quequén harbour in the last 2 km of the estuary has induced a highly stratified water column where the upper 2–3 m concentrates low salinity water and the lower layer is filled by water of the same or slightly higher salinity than the inner shelf waters. Due to the presence of a step at the head of the harbour, water circulation is very reduced and in some cases nonexistent, producing strong reductive and even anoxic conditions. The foot of the step is a sediment and organic matter trap that must be dredged periodically to insure adequate navigability.


*Keywords:* anthropogenic impact; estuarine geomorphology; Quequén Grande Estuary; Argentina

## 1. Introduction

In general, estuaries occupy the coastal areas least exposed to marine action allowing the development of harbours, recreational facilities, or aquiculture initiatives (Perillo, 1995). These same circumstances have induced human occupation along estuarine shores. In fact, most coastal cities in the world are located along an estuary having the multiple advantage of allowing communications both to the hinterland, through the river, and overseas. Even though there are historical

* Corresponding author.
*E-mail address:* perillo@criba.edu.ar (G.M.E. Perillo).

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examples in where some estuaries have been modified by, for instance, diking (i.e., Bay of Fundy), filling of tidal flats and salt marshes (Seine River, France, Avoine et al., 1981) or merging of lagoon–marsh systems (Manzala Lagoon, Egypt, Randazzo et al., 1998), most of the geomorphological and physical changes that occurred in human impacted estuaries started at the end of the 19th Century and increased exponentially to the present.

Anthropogenic changes in estuaries have been mostly influenced by the shipping industry as cargo vessels have increased their sizes by several orders of magnitude since 1800s. The increment in length and tonnage is concomitant with larger draft and, consequently, the need of deeper navigation channels and harbours. Then dredging becomes a major necessity for port authorities who have also been compelled to find ways to dispose off the material. Sometimes these sediments could be polluted and require special treatment rising the maintenance cost of the harbour.

The Charleston Harbour (US) is a clear example that human modifications in the fluvial discharge into an estuary can have a strong impact of the estuarine circulation and hence on the sedimentation rate within the harbour. Either reducing river input by damming upstream (Syvistki et al., in press) or increasing river outflow, as in the indicated case, have major impacts on the geomorphological, physical, chemical and ultimately, on the biological characteristics of an estuary. Most of the anthropogenic changes are rather drastic in time. The slow evolving equilibrium that exists in an estuary suffers the impact and can hardly react to accommodate to the new conditions. Therefore, in most cases, the impact is negative and results in more inconveniences than originally expected.

In areas where littoral sediment transport is very active, preservation of the inlet from both drifting and infilling requires the construction of jetties, a fact commonly found along the southeastern coast of the Unites States. Furthermore, inlets protect the harbour entrance from wave activity. However, jetties have the disadvantage of disrupting the littoral circulation inducing sedimentation on the net upstream side and erosion on the net downstream one.

The Quequén Grande River Estuary (Fig. 1) is an example where all of the human impacts described before converge in the modification of the original estuarine characteristics. It is our objective to describe the geomorphologic and physical characteristics of the Quequén Grande River Estuary, Argentina, and focus attention on the salient processes and their variability on this particular environment.

### *1.1. Description of the Quequén Grande River Estuary*

The Quequén Grande River Estuary (QGE henceforth) is the third largest estuary in the Buenos Aires Province, second only to the Río de la Plata and Bahía Blanca (Piccolo and Perillo, 1999). In spite of its economic and strategic importance, from an oceanographic point of view, it has been ignored. Nevertheless, many anthropogenic modifications were effected in the last 100 years and have resulted in significative economic expenses in maintenance and pollution control to the harbour and city authorities due to the lack of adequate prior studies.

The Necochea–Quequén (Fig. 1) area has received an extraordinary economic advance within the last 20 years due to a strong touristic influence and the improvement of the Quequén harbour. Although there are no major industries located along the Quequén Grande River, most of the city sewages are discharged directly into the system, especially those derived from the cities of Necochea and Quequén. The latter do so within the estuarine part of the river. Also on the Necochea (SW) side of the estuary, there is a large thermoelectric plant that uses the estuary water for the cooling system.

The Quequén harbour (Fig. 1B) is located in the last 2 km of the estuary and covers both margins modifying the original geomorphology of the mouth completely. Because of its activity and draft, the harbour is the second largest deep water system in Argentina. Most of its activities are related to the exportation of grains (especially wheat, corn and sunflower) and to coastal and inner shelf fisheries. During ship loading, it is common to see wind-blown grains that are dispersed on the estuarine surface which then settle at the bottom, developing the basis for a reduction zone at the bottom.

Geomorphologic and physical studies on this estuary (and the whole river as well) are very few. Sediment grain size distributions were described originally by Wright (1968) indicating that bottom sediments along the thalweg were constituted by sands, silty sands and silty clays with mean grain size decreasing inland. 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. However, at the head of the harbour, and due to its particular dynamics, sediments are very fine and the conditions are highly reductive (Piccolo and Perillo, 1999).

The first references to salinity distribution were provided by Boltovskoy and Boltovskoy (1968) and Wright (1968) as a complement to their study of *foraminifera*. Wright (1968) indicated that maximum salinities ($>30$) were found in the first 2–3 km of the estuary whereas at 15 km from the mouth values diminish to only 1 or less.

The Franzius Institut (1964) made a study of the harbour area prior to its last major dredging. Its findings, published in a technical report, were complete for that time but physical data were gathered at variable tide phases which made it very difficult to correlate the various information. However, it provided some ideas of

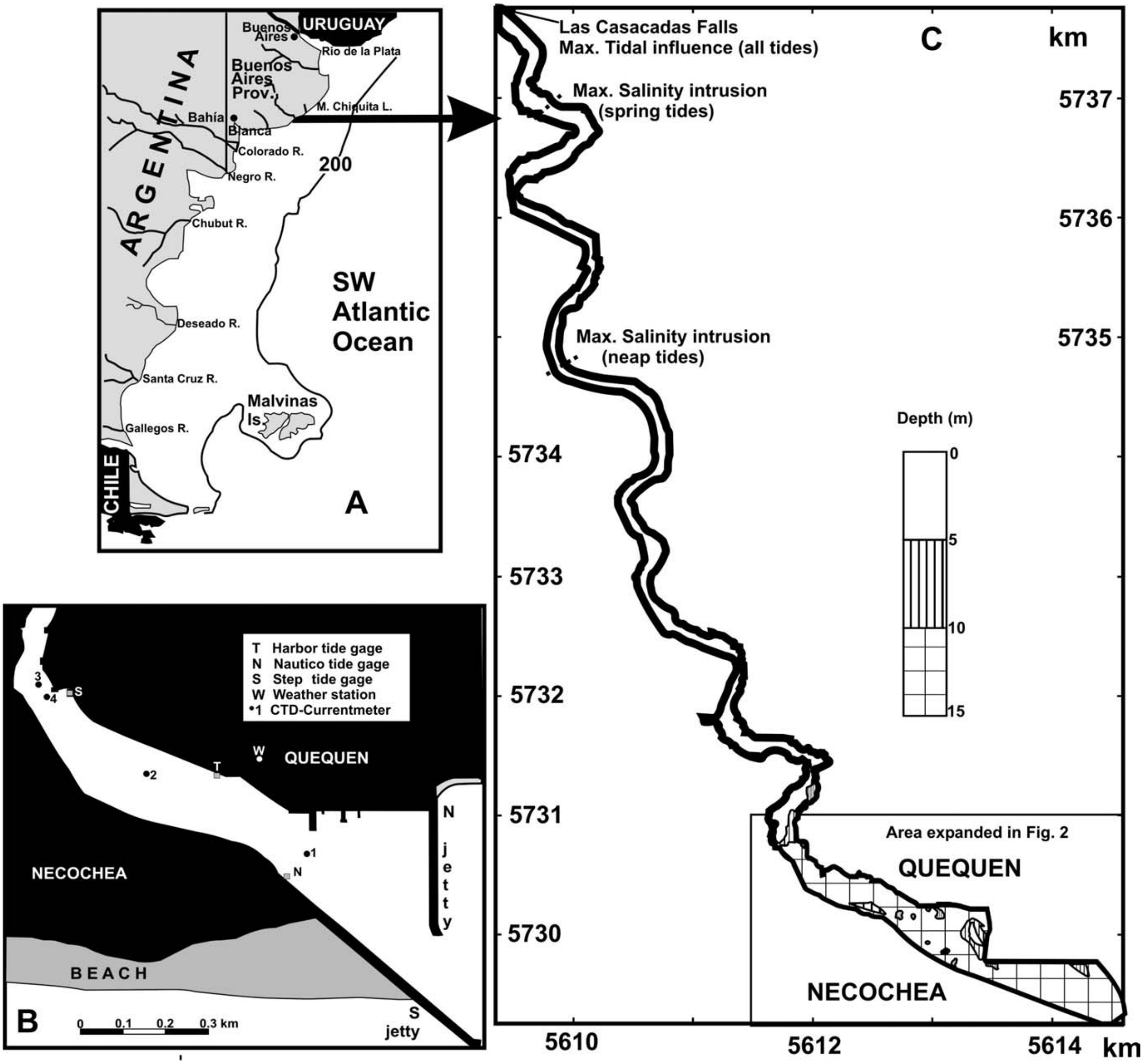


Fig. 1. General morphology of the Quequén Grande River Estuary (B) on the coast of Argentina (A). The last portion of the estuary (C) corresponds to the harbour. The location of the various stations is indicated. Coordinates in Gauss–Kruger projection are in km.

water and sediment circulation when the harbour had completely different characteristics from the present one. Also the Area Hidráulica Marítima (1988) made a statistical study and numerical modelling of the wave conditions at the mouth of the harbour to design the extension of the southwestern jetty.

A brief description of the general hydrography of the estuary was provided by Piccolo and Perillo (1997a, 1999). A preliminary analysis of the tidal characteristics in the harbour area was presented by Piccolo and Perillo (1997b). Campo de Ferrera (1998) described in detail for the first time the general river basin.

Despite the reported studies, the basic properties of the geomorphology and physical oceanography of the QGE and their relation with the mixing processes are poorly understood. Thus, a review of the present status of knowledge of these variables is provided. A number of salient features of the estuarine dynamics is presented especially relative to salinity and current distributions and tidal behaviour. A better understanding of both, geomorphology and hydrography of the estuary will certainly be useful in solving its pollution and dredging problems.

### 1.2. General setting

The Quequén Grande River basin is located in a highly developed farming zone of Argentina and it has a total area of 9370 $km^2$. The river is 173 km long with a dendritic pattern (Campo de Ferrera, 1998). All tributaries, except the Arroyo Seco Creek, join the river upstream at a distance of 36 km from the mouth. The Arroyo Seco Creek does it at 15 km from the mouth coinciding with the last minor falls (Las Cascadas) observed. This point is also where the maximum tidal propagation is detected. Thus, Las Cascadas Falls (Fig. 1C) marks the head of the estuary following the estuarine definition criteria proposed by Perillo (1995).

Most of the river runs on Pleistocene, partly-cemented ($CaCO_3$) loess sediments. Due to the sediment characteristics, large portions of the river flows within a canyon whose walls may reach up to 12 m high (Campo de Ferrera, 1998). The cemented sediments that cut across the river channel provide the conditions to develop small falls and rapids of which Las Cascadas Falls is the last example. Along the estuarine reach of the river, navigation at low tide allowed us to observe several of these rock-crossing that on occasions made navigation risky.

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 last features have been lost with the development of the harbour in 1908 and the initial construction of the jetties in 1915. Due to the prevailing SW–NE littoral drift along the coast, the effect of the jetties was to impound sand on the Necochea side and to provoke a strong erosion process of the Quequén beaches. The situation nowadays is such that Quequén (which was the original resort for the area) has lost practically all its beaches and dunes, and presently its coast is formed by 1–8 m cliffs that are in continuous retreat. Descriptions made by Suarez García (1940) indicated the presence of an outer shoal (maybe a spit) that shifted the estuary mouth northeastward following the typical littoral drift.

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. Even today, high waves may affect harbour activity (specially for the fishing fleet) even 48 h after a storm hits the coast (Campo de Ferrera 1998). Also, a bank still forms at the tip of the southern (S) jetty (Fig. 1B) that requires periodic dredging to maintain adequate navigability conditions. Plans are being made to prolong the S jetty a further 500 m.

Mean river discharge has varied along the years from 20 $m^3 s^{-1}$ (1918) to 5.25 $m^3 s^{-1}$ (1992). Campo de Ferrera (1998) has estimated that the mean annual runoff at the Las Cascadas gauging station is 8.1 $m^3 s^{-1}$. However, mean monthly values vary along the year from a minimum of 5.3 $m^3 s^{-1}$ in February to a maximum of 11.4 $m^3 s^{-1}$ in November. Nevertheless, very large flash floods have been registered during the last century; the most important ones in 1905, 1913, 1915, and the largest one ever in 1980, which reached over 200 $m^3 s^{-1}$, and destroyed three major bridges within the estuarine reach. Unfortunately, the gauging station at Las Cascadas was discontinued in 2000, so data concerning a very large flood that occurred in November 2002 were not available, but unpublished data gathered at the peak of the flood let us estimate it to be on the order of 150 $m^3 s^{-1}$.

To provide deep water conditions for the harbour activities, the last 2 km of the estuary are kept at 12 m depth to the Tidal Datum by continuous dredging (Fig. 2). However, further upstream the thalweg has a depth of 2–4 m (Fig. 1C).

Lanfredi et al. (1988) have studied the variations of the mean sea level in Quequén harbour. They analysed 64 years of hourly tidal heights and obtained the positive long term trend of 1.6 mm $yr^{-1}$, which is in general agreement with similar variations worldwide. The tide is mixed, predominantly semi-diurnal (Formzhal Number = 0.72), with a mean tidal range of 1.03 m. With an estimated total surface of 1.99 $km^2$, the mean tidal prism is $2.05 \times 10^6$ $m^3$. Yearly maximum tides were analysed by Piccolo and Perillo (1997a) for the period 1958–1994. The highest values were registered in 1962 and 1979 with 3.1 m. The most important astronomical components are the $M_2$, $O_1$ and $K_1$. Restricting the analysis to the period 1989–1993 and to the three main constants, Table 1 shows significant annual variations in amplitude and phase.

Piccolo and Perillo (1997a) have also studied the hourly departures of observed tides from predicted ones (storm surges). They presented maximum values of 1.5 m and −1.66 m in the period 1989–1994. Spectral analysis of the storm surges showed significant energy peaks in 60, 21, 10, 5.6 and 0.5 days. These periods indicate that the fluctuations are produced by meteorological processes in macro, synoptic and microscales. The 10-day peak corresponds to the frequency of storm passage for the study zone and the 5.6 days peak characterizes the synoptic scale. These periods are typical of high and mid-latitudes. The 12-h peak corresponds to the local wind circulation: the sea breeze. Therefore, the sea level variations of the QGE are mostly due to the effect of meteorological forcing.

Wave action along the coast is very high. In fact, almost 100 days a year the harbour does not present adequate navigation conditions and must be closed by the harbour authorities. Combined visual-estimation and wave gage data obtained from 1929 to 1969 provided by the harbour authorities showed a mean significative wave height of 1.4 m with a maximum height of 5 m, a mean period of 5.8 s and maximum of 10.8 s. Although significative wave height seems small, peak

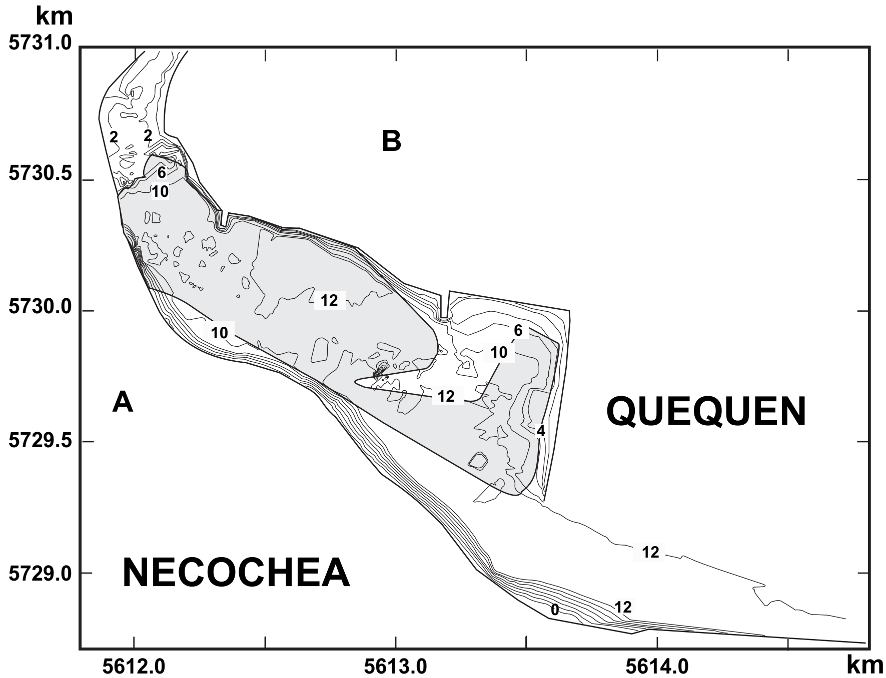


Fig. 2. Bathymetric and sedimentologic map of the harbour area (last 2 km of the estuary). Notice the strong step from the river to the harbour vessel. Insert is a bathymetric profile along the center line of the map. Coordinates in Gauss–Kruger are in km.

waves of the order of 5 m are very common, especially during the typical southeastern winds that hit the coast of the Buenos Aires Province frequently (on average 5–10 times a year during late summer and autumn) with high intensity winds (up to 100 $km\ h^{-1}$).

Mid-latitude westerly winds and the influence of the Subtropical South Atlantic High dominate the typical weather pattern of the region. The resulting circulation induces strong NW and N winds with a mean velocity of 15.7 $km\ h^{-1}$. Since the installation of the weather station, the maximum gust measured reached 158.8 $km\ h^{-1}$. Average temperature at the harbour area is 11.8 °C varying from maximum values of the order of 35 °C in summer (December–February) to 0 °C in winter (June–August). Mean annual precipitation for the period 1995–2002 is 743 mm.

Table 1
Amplitude and local phase angles for the principal tidal component at QGE

| Year | $M_2$ | | $K_1$ | | $O_1$ | |
|---|---|---|---|---|---|---|
| | A (m) | G (°) | A (m) | G (°) | A (m) | G (°) |
| 1989 | 0.4378 | 178 | 0.1738 | 74.7 | 0.1755 | 3.7 |
| 1990 | 0.4387 | 75.1 | 0.1725 | 72.2 | 0.169 | 265.1 |
| 1991 | 0.4401 | 333 | 0.1607 | 69.5 | 0.1642 | 169 |
| 1992 | 0.4001 | 249 | 0.1434 | 258 | 0.1372 | 266.2 |
| 1993 | 0.3626 | 165 | 0.1452 | 78.7 | 0.1366 | 3.4 |

Significant changes occur in both variables.

## 2. Methodology

Within the period April 1994–August 1998, six surveys covering all seasons and spring–neap conditions were carried out in the QGE to provide basic information to characterize the system. These surveys comprised geomorphological, hydrographic and meteorologic data gathering. The bathymetry was carried out using a 208-kHz Raytheon echosounder and a Differential, real time GPS (DGPS) for positioning. The coasts of the estuary were mapped in detail by walking along the edge of the water or the cliffs with a DGPS. In all cases, coordinates were logged at 1 s/position. Depth data were later corrected in the office to the local Datum Plane with tidal data obtained at the harbour tide gage (Fig. 1B) and a bathymetric chart of the whole estuary was drawn (Figs. 1C and 2). Furthermore, a side scan sonar (SSS) was used to map the geomorphology of the harbour area including the entrance channel.

A total of 40 sediment samples was taken with a Snapper grab sampler at a series of cross-sections along the estuary to describe the general sediment distribution on the system. In each cross-section three samples were gathered from both sides and the centre of the channel and positioned by DGPS. Within the harbour, 20 samples were also taken as a function of the information gathered by the SSS. Samples were analysed for grain size following standard laboratory procedures.

Physical information consisted in tide, salinity, temperature, current velocity and direction as well as meteorological data. A standard tide gage (Fig. 1B) has been operational since 1918 within the harbour area. This gage has been considered by Lanfredi et al. (1988) as the only long term tide series in the country that allow the adequate conditions to estimate mean sea level variations. A specific study of short term sea level fluctuations within the harbour was made by placing two InterOcean WTG904/2 tide/wave gages at two extreme points within the harbour (Sites S and N, Fig. 1B). Water level data were sampled at 1-min interval for a total of two months (August and September 1998).

Salinity and temperature information was obtained following a series of longitudinal surveys at high and low water in each cruise to determine maximum salinity intrusion within the estuary compared to river discharge. In every survey, 13–15 stations were sampled by making continuous vertical profiles using an InterOcean MiniCTD. Unfortunately, during the field work periods river discharge did not vary significantly from the mean value.

Within the harbour area, four stations (1 through 4, Fig. 1B) were monitored for over one tidal cycle each (14 h) in every cruise. At half hour intervals vertical profiles of salinity and temperature were obtained using the MiniCTD InterOcean and current velocity and direction using a Valeport BMF108 current metre. In the case of the current metre data, five levels at 0.6, 1.2, 2.0 m above the bottom, at 1.8 m below the surface and at mid level between the 2 m above the bottom and 1.8 m below the surface were sampled. Obviously this intermediate level varied with tidal conditions. Further details on the methodology employed are described elsewhere (Perillo and Piccolo, 1993). Data processing to insure error-free estimation of residual fluxes were made by employing the method proposed by Perillo and Piccolo (1991, 1993, 1998). An automatic weather station was installed within 200 m of the harbour in August 1995. All data including wind, air temperature and pressure, and precipitation are being registered since then at half hour intervals.

## 3. Results

### 3.1. Geomorphology

Based on the surveys made with echosounder and DGPS, a bathymetric map (Fig. 1) of the whole estuary up to Las Cascadas Falls was drawn. Fig. 2 shows the map of the last portion of the estuary that includes the harbour and a portion of the river. The width of the channel upstream of the harbour is quite regular on the order of 200–220 m. Only in the harbour does it increase to about 250 m, reaching its maximum of 900 m in the ship maneuvering portion near the mouth.

Cross-section profiles have, in general, a rather wide V-shape. Since the channel is meandering, the thalweg follows the standard meander pattern. Maximum thalweg depths are 2–4 m. However, depth in the last reach of the estuary changes dramatically (Fig. 2). Within the harbour, depth is maintained artificially at 12 m by periodical dredging. This depth is kept up to a distance of 1950 m from the mouth. Between the harbour and the river reaches the difference in depth is of the order of 8 m with a slope of 2.6°. We further refer to this abrupt depth difference as "the step". A survey made with SSS of the harbour and the entrance channel did not show any bedforms except for those originated by the dredging.

The step was made artificially by dredging which modified the original morphology of the coastal-plain estuary. A small channel cuts through the step on the Quequén side but there is no clear reason as to how it was formed since the strongest currents in the last meander occurs along the outer (Necochea side) bank. Although there is no official information from the Port Authorities, we suspect that this channel was formed artificially during the dredging. Depth reductions are observed in the ship maneuvering area behind the N jetty and along the coast at the start of the S jetty. Meanwhile, in the other much smaller sector, a sandy beach has developed by littoral transport along the S jetty (waves actually diffract and move inshore along the jetty) and its expansion is controlled by dredging.

Sediment distribution within the harbour (samples taken 5 months after a dredging) indicated that the central part of the harbour is dominated by very fine sediments, mostly silty clays with low percentages of sand. The distribution of mean size higher than $4\varphi$ (silt-clay, Fig. 2) forms a band that extends from the step to the mouth of the harbour. The only parts that have sand-dominated sediments are at the mouth and along the right margin of the harbour. Finest sediments are found just at the bottom of the step and behind the N jetty on the left margin of the harbour. Above the step, the bottom material is fine to medium sand. The bottom material taken at the lower portion of the step is highly reductive which shows that the sector concentrates organic material and tends to become anoxic.

### 3.2. Longitudinal distribution of salinity

A series of 12 longitudinal profiles was made along the thalweg of the estuary following conditions of high and low tides. As the discharge conditions along the year varies very little, except for exceptional floods, the general distribution was similar in all surveys varying only in the length of the salt intrusion as a function of tidal stage. One example is presented in Fig. 3 for low tide conditions and average runoff. A certain stratification

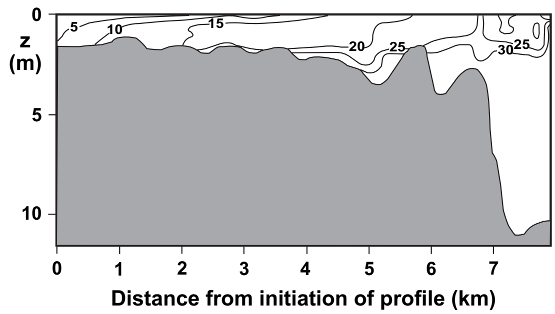


Fig. 3. Longitudinal salinity profile along the thalweg of the Quequén Grande Estuary during low tide and average runoff. The isohalines have a general landward slope similar to a partly-mixed estuary; however, in the harbour vessel they show a strong stratification in the upper water column and homogeneity with marine values in the lower part of the column. Isohalines are every 5 salinity units.

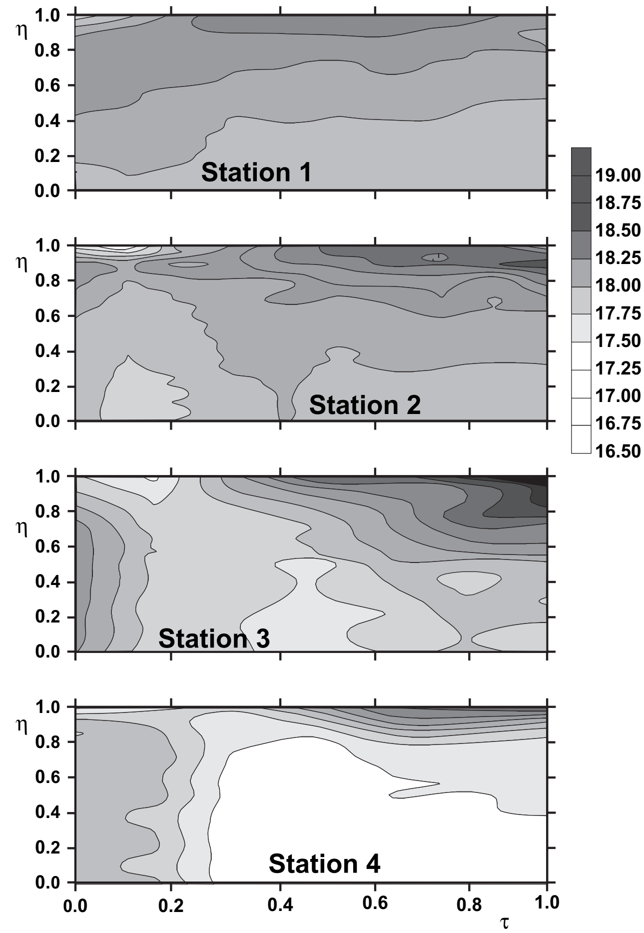


Fig. 4. Time–depth distribution of temperature measured over one tidal cycle for the four stations. Data correspond to the March 1996 cruise.

is evident with fresher water overlying sea water and concentrated toward the head of the estuary. The general salinity structure of the estuary resembles a typical partially mixed estuary and even in the maximum point of salt intrusion the partially mixed structure persists. In no case we found a salt wedge development. However, within the harbour area, we observed in all the longitudinal surveys and tidal-cycle stations that a strong stratification occurs; meaning that the upper 1–3 m of the water column is fresh water and a halocline develops reaching salinities of over 30 being homogeneous down to the bottom. In some surveys, especially those associated with lower river discharge, below halocline salinities reached up to 33 which is the typical value found along the inner continental shelf adjacent to the estuary (Piccolo, 1998; Perillo et al., in press).

### 3.3. Temporal variations of temperature, salinity and density

CTD profiles were measured, and salinity and density (follows almost exactly the salinity curves) were calculated at stations 1–4 (Fig. 1B) over complete tidal cycles during six cruises. Typical examples of depth–time variations of temperature and salinity for the four stations are given in Figs. 4 and 5. Vertical data are presented as normalized depth $\eta = z/d$, where $z$ is the actual measurement or interpolated depth and $d$ is the total depth at the measurement or interpolation time, being 0 at the bottom and 1 at the surface. On the other hand, $\tau$ is the normalized time representing a total of 13 h, being 0 at the beginning of the measurements (low tide) and 1 at the end (next low tide).

At both stations 1 and 2, temperature close to the surface is colder than at the bottom during low tide. At low tides, there exists a clear evidence of stratification within the upper 20% of the column. As tide enters, stratification disappears and vertical profiles turn into uniform density and salinity until the tide ebbs back again showing new signs of stratification (Fig. 4). Station 2 presents similar patterns but the influence of fresh water input remains for longer time at the top of the column, and a slight decrease of salinity (Fig. 5) was registered at high water which was not observed at station 1. It is important to note that at the bottom 80% both salinity and density (not shown here) are homogeneous and of the same order of magnitude found at the inner continental shelf.

Temporal variations of temperature and salinity at stations 3 and 4 (Figs. 4 and 5) were obtained simultaneously. Station 3 at the top of the step and station 4 just at its foot. The abrupt deepening produced by dredging at the harbour head has a marked influence in the mixing of the water column. Water stratification at station 3 reaches a relative depth of 50% at low tide while at station 4 only the top 20% of the column is affected by the fresh water input having sea water for most of the depth in the harbour vessel. Temperature is lower at the surface during the early hours of the

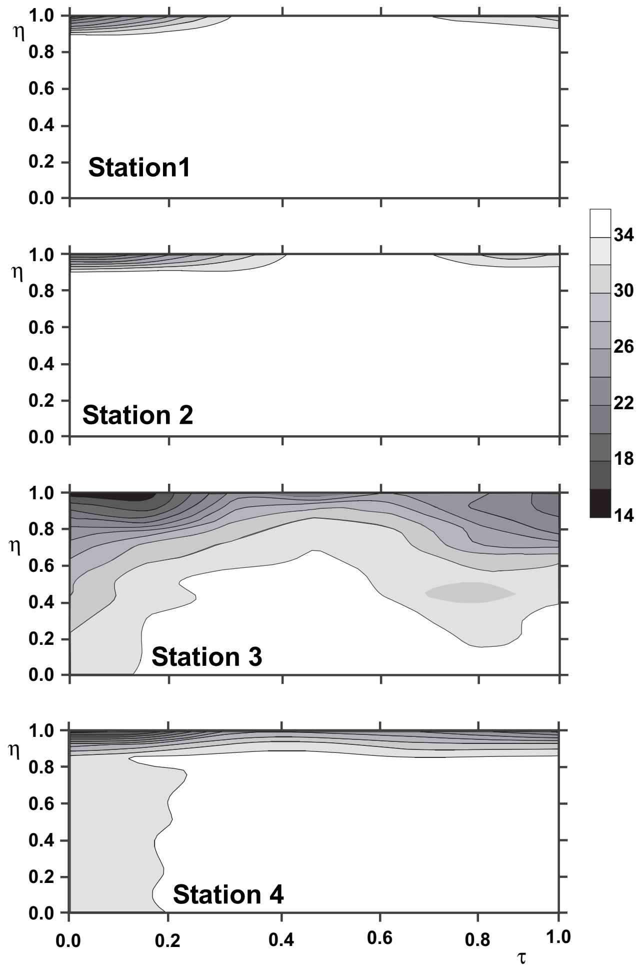


Fig. 5. Time–depth distribution salinity measured over one tidal cycle the four stations. Data correspond to the March 1996 cruise.

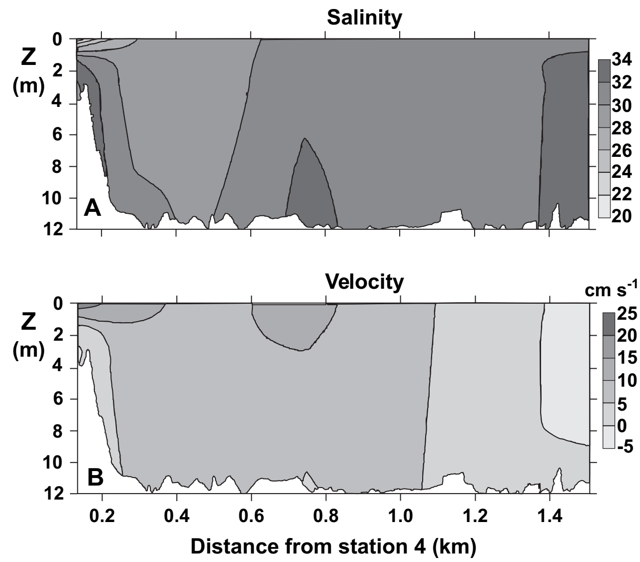


Fig. 6. Tide-averaged distribution along the harbour of the (A) salinity, and (B) longitudinal velocity component. Data correspond to the August 1998 cruise.

morning due to the low temperatures registered during the night before. Similar to stations 1 and 2, this effect disappears as the sun heats the surface. Salinity at each station has strong gradients between bottom and surface. Salinity distribution over station 4 suggests that sea water invades the lower portion of the water column having very little exchange with the fresh water input.

Station 3 has the lowest average salinity which denotes a stronger river fresh water presence but at all stations minimum values of salinity have the same order of magnitude. The distribution of the time-averaged salinity along the harbour is given in Fig. 6a. River input is observed very near the top and there is a downward plume right after the crest of the step. A strong stratification is observed at the river portion of the step, being reduced seaward. Salinity at the step reaches values closer to those at the inner shelf. In the harbour, salinity is rather constant and there is no sign of vertical mixing with the upper layer.

### 3.4. Current velocity

Current velocity profiles were obtained simultaneously with the CTD profiles. Maximum velocities at all stations were measured near the surface reaching up to 0.40 m. In the present analysis we worked mostly with the longitudinal component of velocity ($U$) as the transversal component was very small in most cases. At the surface maximum ebb-directed ($U$ positive) values of the order of $0.35\ m\ s^{-1}$ were observed, but in most cases, values were below $0.1\ m\ s^{-1}$. Depth and time variations of $U$ for stations 3 and 4 are given here (Fig. 7) for the August 1998 cruise. During the first flood measured at station 1 (not shown), $U$ presents an incoming component in all the column but as soon as the high water slack is reached, a stratification becomes evident and is also maintained for the rest of the tidal cycle. The topmost layer of the column has an outward velocity while the bottom layer shows an inward velocity, but with high vertical variability at different depths. This stratification has some concordance with density and salinity (Fig. 5).

At station 2 (not shown), river influence becomes more evident. During the flood period, stratification persists and there is almost a predominant outgoing flow. The proximity to the step concentrates the flux at the topmost (20% from the surface) layer at this station showing a considerable stratification during the flood. For high water and ebb, the whole section has an outgoing component of water until low tide is reached again. Also the lowest speed values were found below the level of the step, creating an area of tranquil waters with velocities very close to zero.

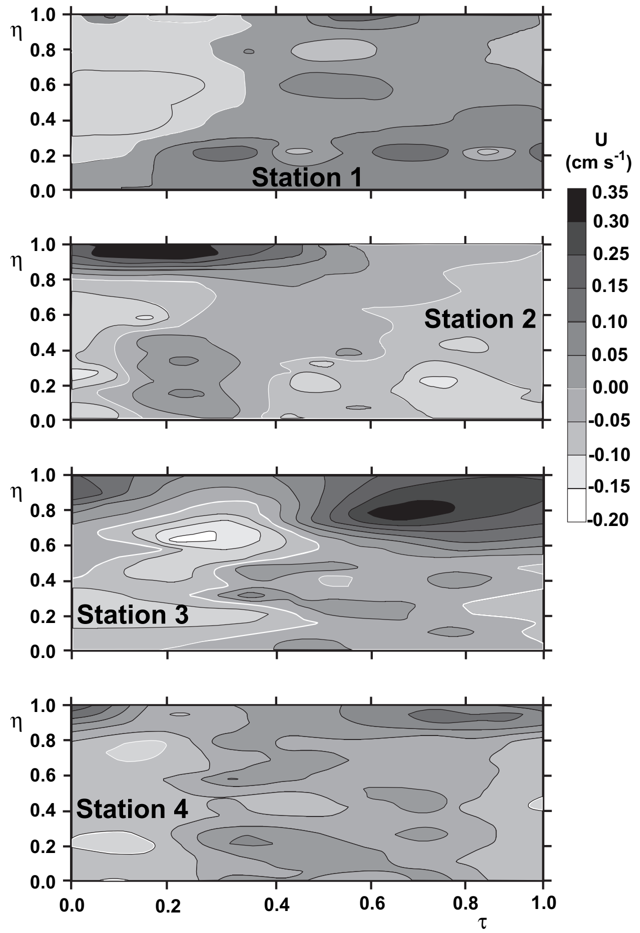


Fig. 7. Time–depth distribution of the longitudinal component of the velocity measured over one tidal cycle for the four stations. Data correspond to the August 1998 cruise.

Station 4, which was measured at the same time as station 3, shows very low velocity values (almost null) for depths below 80% of the total and the 20% topmost have the river freshwater velocity towards the sea (Fig. 7a). Flood-period observations register this kind of behaviour suggesting that sea water close to the step has almost no velocity, with the consequent stratification at the top of the column. During ebb and high tides the column presents a positive outgoing flow until tide turns back again.

As a whole, the presence of the step creates an area of quiet saltier water, over which the fresh water input from the river produces a fair stratification. This stratification persists at least up to station 2 where velocities are always towards the mouth of the estuary. Station 3, located just over the step, shows a marked stratification during flood periods. But even at the highest velocities the top layers move towards the mouth (Fig. 7b). Stratification disappears during high water and ebb again showing a positive outgoing flow.

The distribution of the time-averaged longitudinal current along the harbour (Fig. 6B) only presents stratification (partly-mixed type circulation) above the step. There are very low average velocities near the step increasing towards the middle of the harbour. The outer portion has practically no residual transport or is small headward. This effect may be produced by the artificial constriction due to the N jetty and the maneuvering area behind it that modifies the circulation pattern of the zone.

## 4. Discussion

The Quequén Grande River is a microtidal estuary. According to the morphogenetic classification (Perillo, 1995), it is considered as Primary Estuary and within this division, it is a coastal-plain estuary. As a matter of fact, the original river developed a sandy coastal plain during a lower sea level stand. As the sea level increased, the coastal plain was inundated by the sea reaching up to 2 m above present level about 6000 years BP (Isla, 1989) which is in concordance with similar higher than present sea level stands observed along the Argentina coast (Isla, 1989; Gómez and Perillo, 1995). As the sea level retreated to the present situation, the coastal plain covered only a minor portion of the coast. Although smaller, the Quequén Salado River Estuary (Marini, 2002), located some 100 km to the southwest, presently represents the exact conditions that the QGE had before the anthropogenic influences.

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 N jetty reduces the width of the mouth to 165 m developing a basin with low circulation.

On the other hand, the step at the head of the harbour acts as a wall that may reflect the incoming tidal wave generating a stationary wave. Due to this effect, velocities at and near the step are very low (Fig. 6B) even during the instant of maximum currents at the surface. At the same time, fresh water input from the river does not mix effectively downward since below 2–3 m (about the depth of the top of the step) there is only seawater in all the column. Therefore, starting from the top of the step to the head, the estuary can be considered as a partly-mixed system. However, within the harbour, it becomes highly stratified, much more similar to a fjord-like circulation pattern than a salt wedge one.

Tidal records also show the presence of high frequency oscillations (Fig. 8). Measurement at the two extreme tide gages (S and N in Fig. 1B) during August and September 1998 at 1 min interval were made

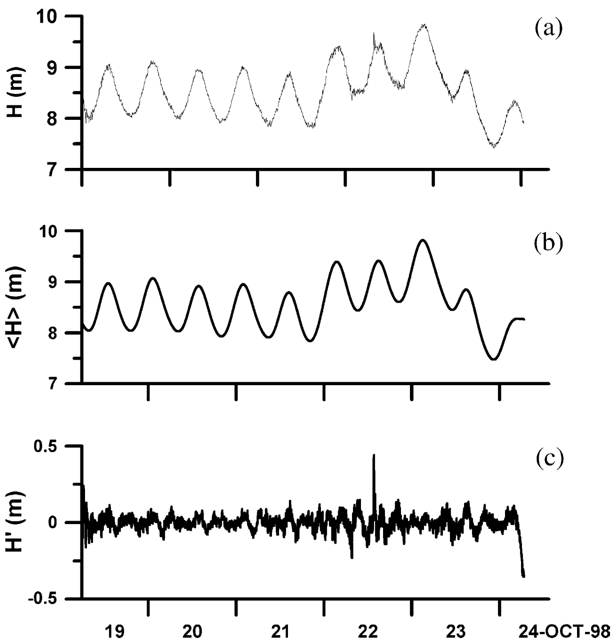


Fig. 8. Typical tidal record from the harbour tide gage (e.g., period 19–24 October 1998). (a) Original record, (b) high-pass filtered, (c) elevation fluctuations ($H' = H - \langle H \rangle$). The oscillations are a common feature in this harbour and strong peaks appear unexpectedly as the one observed in October 22.

to evaluate these oscillations observed originally on the harbour tidal records. The estimated periods for these oscillations are between 3 and 25 min, although the latter are predominant. Even though normal oscillations have amplitudes of the order of 10 cm, oscillations of up to 1.5 m often appear. Normally, the oscillations increase in size suddenly and inexplicably. When they occur, the strong oscillations induce serious consequences for the navigation of large cargo vessels. At least two vessels departing from the harbour with full loads have hit the bottom due to the occurrence of sudden large oscillations; fortunately without damage. The resonance periods for the harbour, calculated with Merian's and Helmholz's equations (Neumann and Pierson, 1966) show theoretical values of 3.3 and 6.4 min, which are well below the typical 25 min.

One possible explanation for the fluctuations is that they are produced by internal waves generated at the interface, a process that is presently under study. On the other hand, preliminary comparison of the data gathered simultaneously at the tide gages located at the mouth (N in Fig. 1B) and at the foot of the step (S in Fig. 1B) show that the phase lag of just the fluctuations is of the order of 1 min but with the S station leading. This means that the fluctuations may be due to a high frequency wave which is propagating from the head of the harbour out produced by the reflection against the step. Trying to identify and possibly predict the cause of the fluctuations, including the meteorological forcing, is a study in progress.

The extremely low velocities found at the foot of the step create the condition for an intense sedimentation area. This part of the port has to be dredged frequently and the sediments dredged have highly reduced and even anoxic characteristics. The circulation measured suggests that at least two macro vortexes may be occurring during floods at the harbour. Velocity profiles show incoming and outgoing velocities at the same column which correspond to horizontal vortex axes. Part of the water jet coming from the river curls down and produces a contrary velocity component at different heights.

Because of the strong influence of the step, we have modelled the circulation at the head of the harbour. The model employed is a 2D version of the Princeton Ocean Model (POM). The full 3D model has been described in detail by Blumberg and Mellor (1987). Briefly, the model has a free-surface, a bottom that follows a sigma coordinate system and splits the time integration into barotropic and baroclinic modes. It also includes a turbulence closure model (Mellor and Yamada, 1982) to provide vertical-mixing coefficients. In the present study, particular care was given to the incorporation of the freshwater river discharge (Kuorafalou et al., 1996) and the specification of open (seaward) boundary conditions (Palma and Matano, 2000). The model resolution is 100 m in the horizontal and it has 28 levels in the vertical, with variable thicknesses at the surface and bottom boundary layers. To drive the model we prescribed the free-surface elevation at the open boundary and the freshwater river discharge at the head, both obtained from measurements. We started from rest and ran the simulation for 90 days till the area-averaged salinity attained a tidal-average steady state and the following tidal period was used for analysis.

Currents and salinity distribution obtained with the model show a two-layer circulation pattern where relatively low salinity water flows out at the surface and compensating high salinity waters from the shelf flows at the bottom (Fig. 9). However, the model results also show that the presence of the step can generate internal waves that modified the two-layer circulation mode. Sensitivity experiments conducted by changing the step position and depth confirm its strong influence on the harbour dynamics. During slack water time the model results show a re-circulation pattern at the base of the step (Fig. 9). Further numerical experiments including passive tracers in the model (not shown here) indicate that this re-circulation modifies the vertical distribution of dissolved and suspended estuarine constituents.

## 5. Conclusions

Although the original objective of our research was to provide a general overview of the geomorphologic and

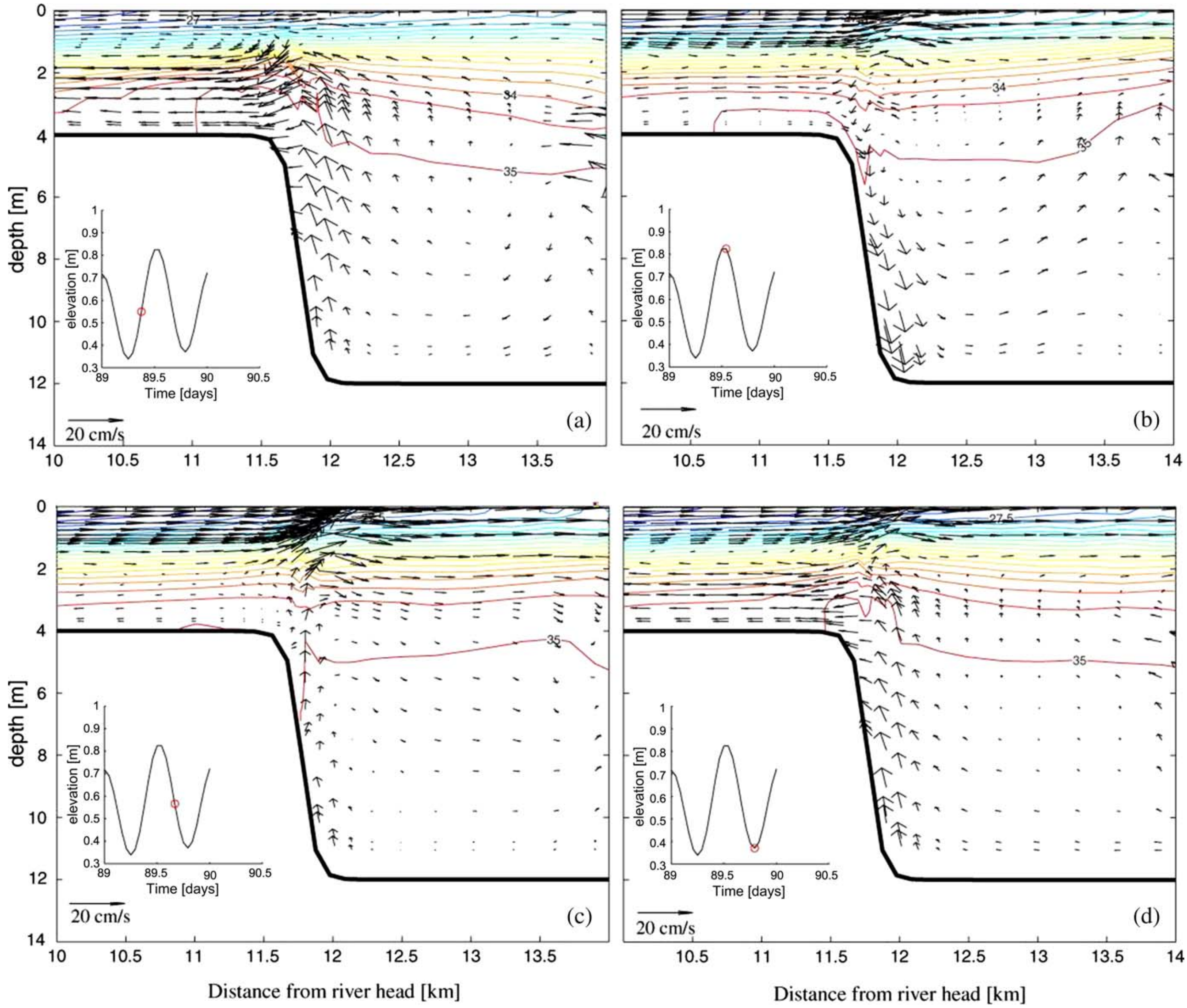


Fig. 9. Salinity field and velocity vectors obtained from the model simulation at day 90. (a) Flood tide, (b) high tide, (c) ebb tide, and (d) low tide. Salinity contour interval is 0.5. Vertical velocity is augmented 1000 times.

physical characteristics of the QGE, our studies have demonstrated that the anthropogenic changes induced at the mouth of the estuary have produced strong modifications in the circulation pattern of the environment. Furthermore, the way the harbour was dredged is the very precise motive why sedimentation has been enhanced and why the harbour authorities must expend large amounts of money to maintain operational navigability. Even though we have not yet proved the reason for the formation of the high frequency fluctuations on the tidal records, there are data and modelling evidences of the presence of internal waves which may be closely related to the fluctuations.

The step acts as a reflection wall that induces a secondary standing wave. At the wall itself, velocities are extremely small producing very poor circulation. Thus any sediment particle or contaminant that drops below the interface becomes trapped and settle at the foot of the step. Based on our sampling, this sector of the harbour is clearly very reductive and even anoxic at times, further demonstrating the lack of circulation and, obviously, oxygenation of the deeper water. In a way, the step may be the counterpart of a high sill in a fjord, inducing a low or even null circulation in the deep lower layer and the estuarine circulation is only restricted to the depth of the crest of the step.

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