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Suspended Sediment Circulation in Semi-enclosed Docks, Puerto Galván, Argentina

Abstract

The circulation pattern of two docks at Puerto Galván (Bahía Blanca Estuary, Argentina) have been studied in relation to dredging operations. Even though both docks have different designs, the study shows that they are prone to import material. During the measurements, a fluid mud layer at the docks and in the Canal Principal was first detected in the estuary.

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Introduction

Puerto Galván (Figure 1) is one of the five harbours that form the Bahía Blanca Harbour System, the largest and deepest of Argentina. The harbours are all located along the Canal Principal of the Bahía Blanca Estuary, a mesotidal, coastal plain environment (Perillo, 1995) formed by a series of major NW-SE trending major channels separating extensive tidal flats, low salt marshes and islands. The geomorphology and physical characteristics of the estuary are described in detail elsewhere (Perillo and Piccolo, 1999) including a recent review of its major environmental features (Perillo *et al.*, 2000).

Although the main economic activity of the harbour system is related to the export of agriculture products, especially grains, in recent years there has been a marked increase in the export of oil, gas and especially petrochemical derivatives. In 1989-90 a major dredging operation moved the nominal depth for the navigation channel and harbour sites to 13.8 m (45 ft), which

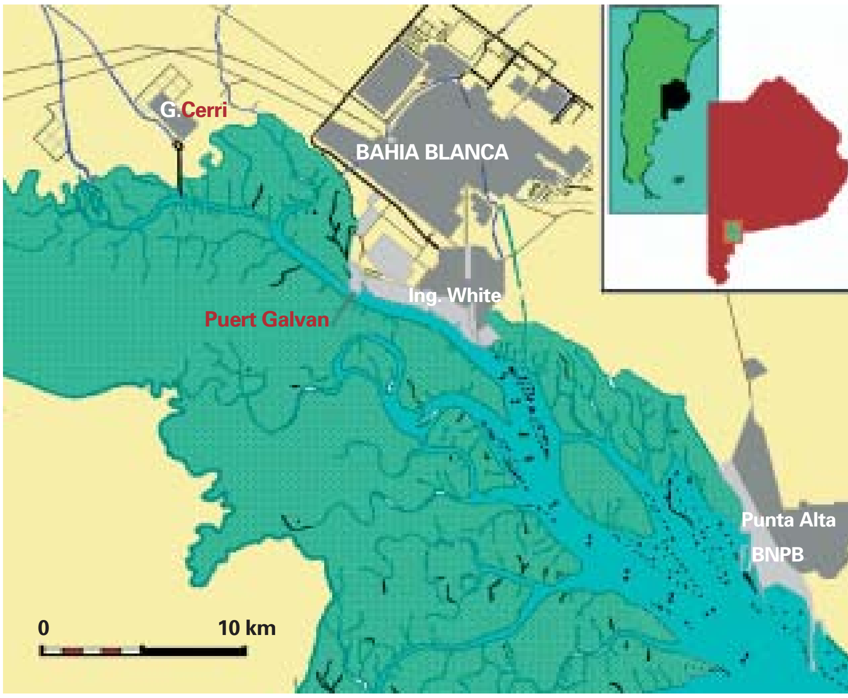

Figure 1. Location map of the study area in the Bahía Blanca Estuary, Argentina.

stimulated an immediate increase in the economic activity of the harbours as larger vessels were allowed to enter into the system.

However, there are a series of sites both along the channel and at the harbours that require periodic maintenance. In particular, both Ingeniero White and Puerto Galván harbours have sites that are semi-enclosed and act as sediment traps. There is an estimate of 500,000 m^3 of fine silt and clay that must removed annually from these sites by harbour authorities. Traditionally this operation is being done by hopper dredgers that then carry the material to different sites in the estuary for disposal.

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During the year 2000, the company having the contract for the system maintenance suggested to the harbour authorities, Consorcio de Gestión del Puerto de Bahía Blanca (CGPBB), the use of a new dredging procedure for the semi-enclosed sites. This procedure is based on water injection into the bed sediments. As the sediments become fluidised, they move along a slope towards the deeper portions of the Canal Principal where, hopefully, the strong tidal currents may disperse them within a relatively short period of time.

Before any agreement could be reached for the change in operational procedure, the CGPBB decided to evaluate the operation of the dredger as well to assess a preliminary environmental impact that the dredger may produce into the estuarine environment. The tests were performed at two sites of Puerto Galván where 50,000 m^3 of sediments were dredged in May 2000.

During the evaluation studies a series of interesting features of the circulation of suspended sediments and the presence of fluid mud, never before described for the estuary, were discovered. Therefore, the aim of the present article is to describe these processes and how they may induce an increased sedimentation within the sites independently of the dredging mechanism employed. No attempt will made here to analyse the characteristics of the quality of the dredger used or the dredging operation.

Characteristics of the Study Area

Puerto Galván is located on the northern margin of the Canal Principal of the estuary (Figure 1). It comprises two docks (5 and 2/3) located to the east and west, respectively, of a wharf. All harbour operations are made along the wharf and the docks have maximum operational depths along it.

Dock 5 (to the east of the wharf) is closed for three sides and open only to the Canal Principal. It is approximately 600 m in length and 120 m wide at the mouth with maximum dredged depths of the order of 9 m. The operative maximum width, however, is about 80 m. The eastern shore of the dock was originally a tidal flat that was reclaimed during the 1989-90 dredging. Two major petrochemical plants are being built there but they have no access to the dock facility. Although no detailed study of the siltation rate of this dock was made, the values are quite large and require at least one or two maintenance dredgings per year. Bed sediments are silty clays with no traces of sand.

Even though Dock 2/3 is also about 600 m in length and 120 m wide at the mouth, it continues further inland in the Galván tidal channel. Maximum dredged depths at this site are 12 m. The western border is formed by a low tidal flat that is fully covered by at least 0.5 m of

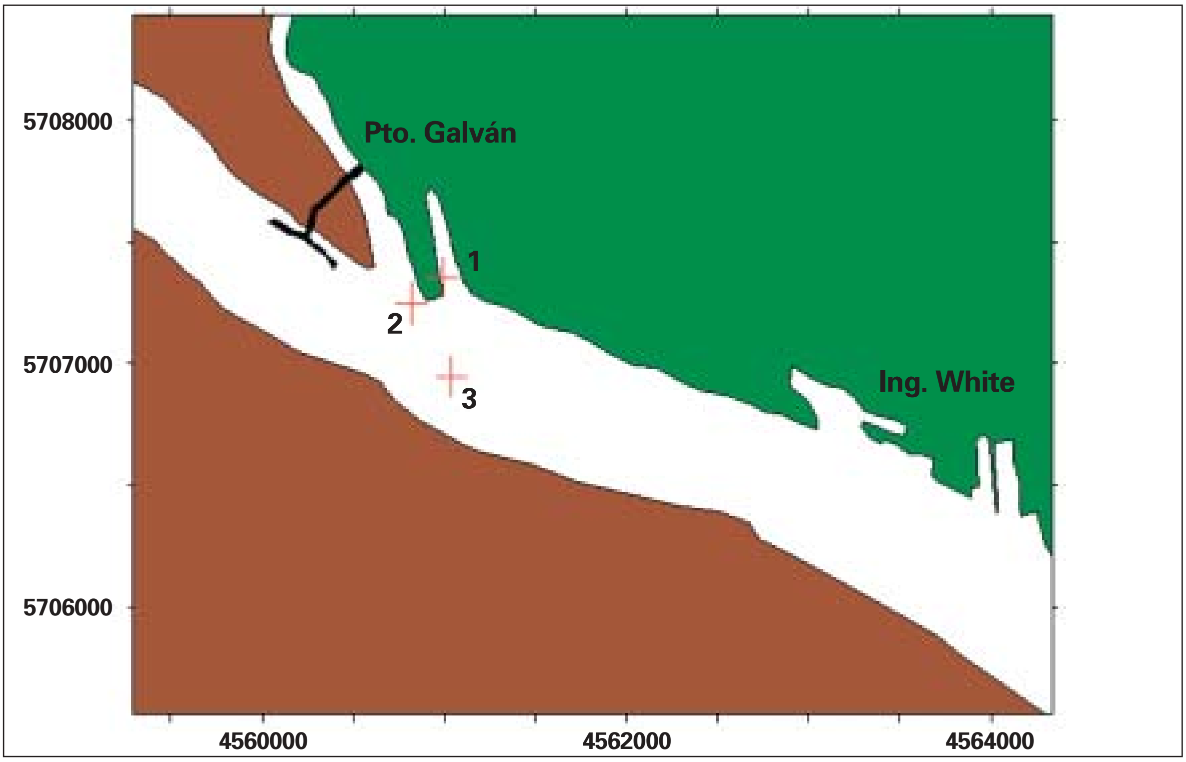

Figure 2. Location of the three stations during the measurements made in May 18, 2000. The brown colored area represents flood-prone tidal flats. Map is in Gauss-Krüger coordinates.

water even during neap tide. The only "barrier" is an open bridge (Figure 1) towards the natural gas transfer dock located on the Canal Principal. Bed sediments are mostly silty clays with less than 5% of sand.

On the other hand, the Canal Principal at the study site has been dredged to a nominal depth of 15 m and includes the turning area for the vessel, therefore providing over 500 m width at low tide. Dredging of the Canal Principal was done up to 200 m inland of the gas transfer dock. Since then, there has been no need for maintenance as the dynamics of this reach of the estuary is very strong and prevents siltation over a hard bed formed by a Pliocene semi-consolidated silty sand formation (Perillo and Piccolo, 1999)

Methodology

Three field cruises were made respectively before, during and after the dredging operation. These studies included surveys of the bed of the Canal Principal with a side scan sonar and bed sampling and measurements of physical and suspended sediment parameters. During each cruise four stations were located at the sites and the Canal Principal (Figure 2) (only three stations were used during the first survey).

Along a complete tidal cycle (over 13 h), at each station vertical profiles of magnitude and direction of the tidal currents (as well as depth of the instrument) were determined using an FSY 2D acoustic currentmeter with data gathered at 1 s interval while the equipment was slowly lowered and hoisted from the surface to the bottom and back. Simultaneously vertical profiles of conductivity, temperature and NTU were obtained in a similar way using an InterOcean MiniCTD fitted with and D&A optical backscatter sensor (OBS). The latter was calibrated in the laboratory using water samples collected during the cruises to obtain the suspended sediment concentration *(C)*. The conversion was linear and the correlation coefficient was 0.99. In all cases a complete profile took less than 5 minutes to complete even to the maximum depths of 17 m; therefore, all values were considered as they were taken simultaneously at time *t*.

Each station was occupied sequentially following the general methodology designed by Perillo and Piccolo (1993, 1998) to study residual circulation in estuarine cross-sections having only one set of instruments.

An average of 16 profiles per station was determined on each study period. Data was post processed and calibrated in the office by standard procedures to obtain vertical profiles of the different variables interpolated to non dimensional depths *z* referred to the total depth of the station at the moment the profile was measured. For the present case, the discussion is only about the distributions of suspended sediment concentration

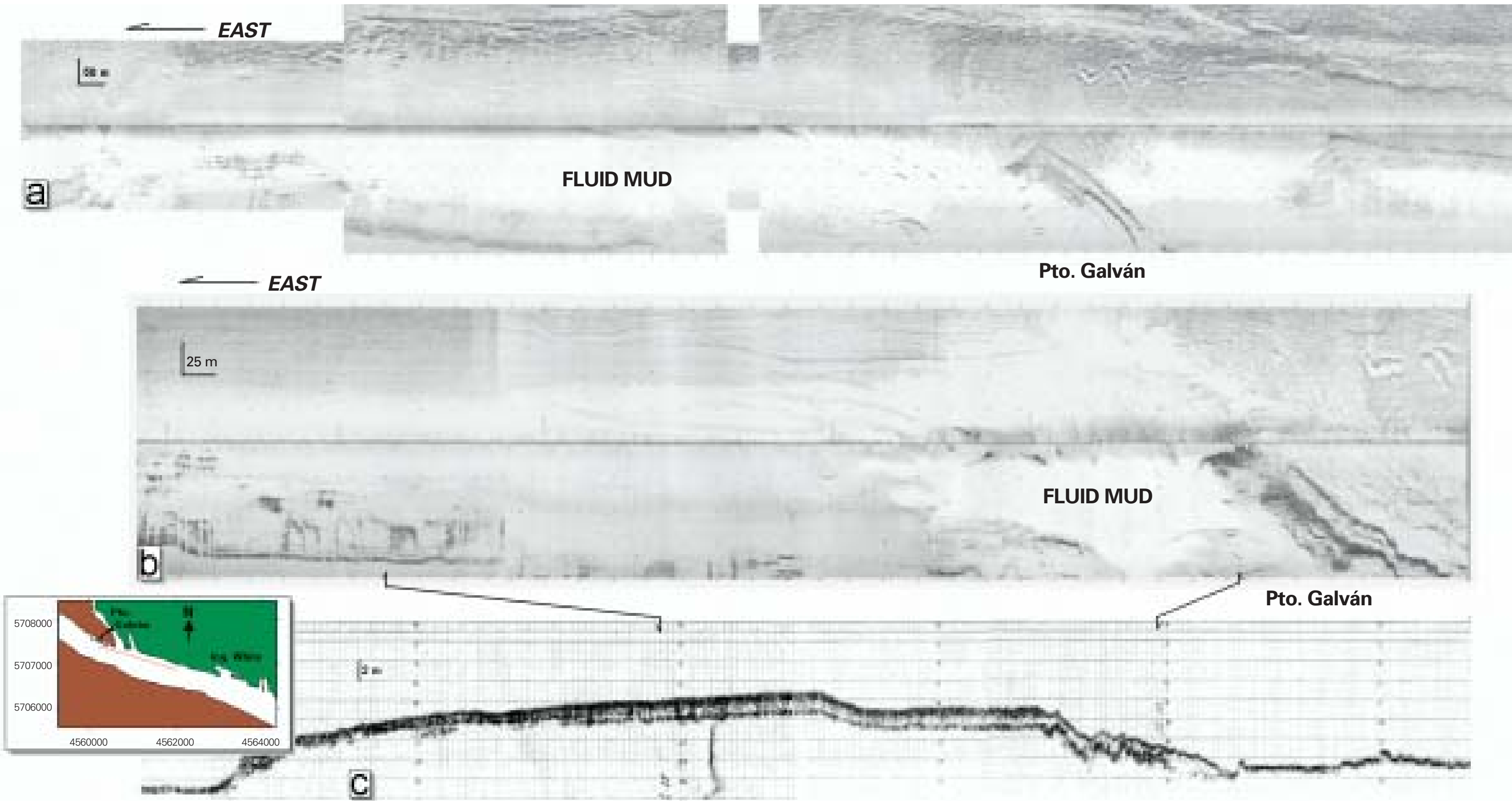

Figure 3. Side scan sonar records from the Canal Principal before and after the dredging showing the presence of mud fluid layers at the bottom of the channel.

C and fluxes *(F)* calculated by

$$F(z,t) = u(z,t)\ C(z,t)$$

where ***u*** is the longitudinal component of the velocity estimated normal to the cross-section of the site. In most cases the transversal component *(v)* was relatively small and it will not be considered further.

Results and Discussion

Predredging conditions were evaluated by sampling three stations (Figure 2) on May 18, 2000. Tidal range during the study period was 3.68 m at the Ing. White tidal station which is about the mean tidal range for this part of the estuary. Current velocities at station 3 reached peak velocities of 0.66 m/s. Also, two side scan sonar profiles were made along the Canal Principal close to the entrance to the docks. A ribbon parallel to the channel 50-75 m wide of fluid mud (Figure 3a) is observed superimposed to the typical hard bottom of the channel. During this survey, there was no dual frequency echosounder to estimate the thickness of the layer. Although from the vertical profiles, done soon afterwards, the thickness was always less than 50 cm.

Suspended sediment concentration at Station 1 (Dock 5) during the tidal cycle and in almost all the water column was below 50 mg/l (Figure 4a) except for a resuspension event that occurred at the end of the ebb and beginning of the flood that increased the concentration to 400 mg/l. Some resuspension also occurred at max flood, but maximum concentrations were below 90 mg/l. Current velocities in this dock were always quite small (less than 0.25 m/s) which resulted in fluxes of suspended sediment in the same proportion. Although there are large periods of outward fluxes (Figure 4b), even during flood conditions, the net flux indicates that the dock is importing sediment and acts as a trap (Table I).

At Station 2 (Dock 2/3) concentrations were much smaller than the previous case (Figure 4c). Maximum SSC was 140 mg/l at high water slack at the beginning of the measurements and from then on, it was always below 50 mg/l. However, when the fluxes are analysed, they show a behaviour completely different to the one expected. As will be presented further on, the same circulation was observed in all three cruises, clearly indicating that this is the common behaviour at this dock. During the ebbing tide, the circulation and the resulting SS flux pattern was directed towards the inner dock, whereas during the flood stage, the circulation was reversed. The net flux is practically balanced (Table I).

During the first cruise (18/05/00) samples from only one station in the main channel (Figure 2) were taken. The concentration of SS for the area was typical for the estuary. In most of the tidal cycle and the water column, the SS was less than 30 mg/l with maximum of 65 mg/l (Figure 4e). Some resuspension events were observed, especially during flood. The net flux is also typical for the estuary which has a strong ebb-dominance (Perillo and Piccolo, 1999), especially on the northern part of the Canal Principal.

Measurements to control the dredger were made two days after the operations were initiated. By the start of these observations, the dredger had just finished the dredging the Dock 2/3 and started on Dock 5. Therefore, these data correspond to the two extremes of the operation as well as during the dredging. However, the study here covers only the circulation of SS and does not provide any analysis on the way it performed or the quality of the dredging. Due to the continuous operation of the dredger, no bathymetry nor side scan sonar surveys were made during this part of the study.

Figure 5 shows the location of the four stations employed in the study made on 26/05/00 as well as in the third cruise on 21/06/00. The same stations sampled at the Docks 5, 2/3 and the Canal Principal were repeated in the three occasions. For the last two cruises Station 4 on southern part of the Canal Principal was added to cover the conditions for the whole channel.

In Station 1 SS concentration increased at least tenfold in the water column and close to the bottom, maximum values reached 5200 mg/l during max flood (Figure 6a). Although it was expected owing to the dredging procedure, a fluid mud layer developed at the station after the dredger started its operation in the dock between 1 and 2 m thick. The data consider the maximum depth to normalise the information based on the depth at which SS concentration was greater than 7 gm/l. Current velocities were smaller than 0.37 m/s during this cruise at Station 1.

When analysing the SS fluxes for this station (Figure 6b) positive (exportation) values occur over 60% of the time, however, the import values are larger in magnitude. Thus the resulting condition for the dock, even though it was being dredged, shows a net flux inward even larger than in the first cruise.

At Station 2 max SS concentrations are observed just at the end of the dredging with values of 1400 mg/l (Figure 6c), about 10 times those from the previous

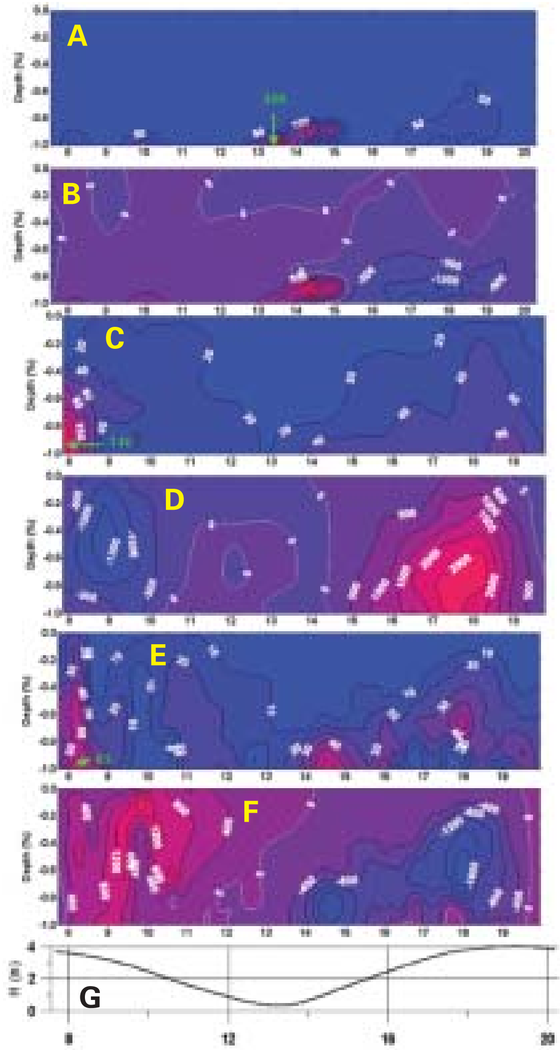

Figure 4. Depth vs time plots of SS concentration (a,c,e) and fluxes (b,d,f) of Draga I. G tidal curve during the measurements.

Table I. Tidal-integrated net suspended sediment flux (mg/cm^2 s) for each station and cruise. Positive values indicate a mouthward flux and vice versa.

Station	Draga I 18/05/00	Draga II 26/05/00	Draga III 21/06/00
1 Dock 5	–662.01	–1232.03	7177.65
2 Dock 2/3	–30.44	9874.92	2484.74
3 C. Ppal. Norte	1872.30	–13051.30	257.36
4 C. Ppal. Sur	—	–13213.20	–2979.50

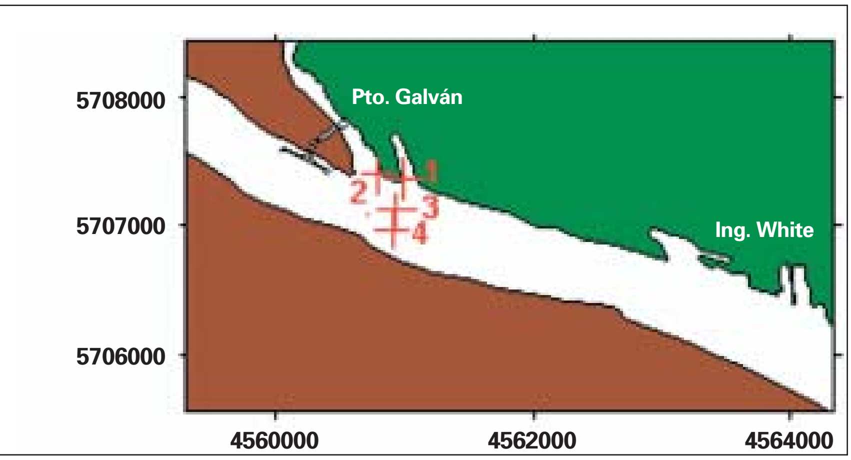

Figure 5. Location of the four stations occupied during the cruises Draga II and Draga III made on May 26 and June 21, 2000, respectively. The brown colored area represents flood-prone tidal flats. Map is in Gauss-Krüger coordinates.

measurement. Although during ebb and at low water slack concentrations are minimal, during the flood concentrations reach above 1000 mg/l close to the surface.

It is evident that the dynamic processes in this dock are quite complex. Again the circulation pattern is reversed from the expected directions (Figure 6d). During ebb fluxes are negative (importing material) which may indicate that the sediment in the Canal Principal is forced into the dock at a larger velocities than the outflow. This may be owing to the effect of barrier produced by the wharf. From mid-ebb the SS flux becomes positive reaching maximum values in mid-flood. Although data gathered at one station alone do not allow a definite confirmation, the flow divergence at the tip of the wharf may induce flow separation and the formation of an eddy. If this is true, the eddy could produce an inverse flow that may explain the differences in the fluxes. Anyway, the net flux at this station is positive (Table I).

The stations at the Canal Principal show maximum concentrations of 500 to 900 mg/l during the dredging (Figures 6e and 6g). These values are between 10 and 15 times those observed in the first cruise. It is interesting to observe that the concentration stays approximately stable along the whole tidal cycle within the lower third of the water column which may be associated to the determinations of fluid mud detected during the measurements. During this stage, a fluid mud layer was expected as this material was produced by the dredger at the docks and driven into the deeper parts of the Canal by gravitational flow and helped by the currents.

When the fluxes at both stations are analysed (Figures 6f and 6h) the exportation (positive) and importation (negative) fluxes are clearly related to the ebb and flood parts of the tide, respectively. However, the magnitudes in both stations are also clearly different. Nevertheless, they both result in a net import flux of the order of –13.000 mg/cm^2 s (Table I).

Figure 7 corresponds to the measurements made on June 21, 2000 at the same four stations described in the previous cruise. The hypothesis was that after about one month, the material deposited by the dredging operation at the Canal Principal should have been distributed along the estuary. One month was considered an adequate time separation based on preliminary unpublished calculations of the residence time for this part of the estuary that may be around 28 days. Because of the effects of the tidal flats that prevents the use of continuity, it is impossible to calculate precisely the residence times for most of the Bahía Blanca Estuary.

SS concentration at Station 1 (Figure 7a) appeared much higher than those observed during the first cruise and even during the dredging. Largest concentrations occur near the bottom and specially during high and low-water slack, although certain resuspension is detected, also close to the bottom, during flood. Combining the data gathered with a dual frequency echosounder while on station and the turbidity sensor, a fluid mud layer developed at the dock. Even though most thickness values were on the order of 1 m, in certain occasions up to 3 m of this layer was detected.

Flow velocities measured along the tidal cycle at Dock 5 were very low, rarely were they over 0.10 m/s, and occasionally reached 0.30 m/s. Therefore, the SS fluxes (Figure 7b) mostly reflect the distribution of SS with peak values coincident with the concentration peaks. The net flux appears, contrary to the previous cruises, exporting material (Table I). However, it is clear from Figure 7b that the largest exportation occurs very close to the bottom at the end of ebb which may indicate the flowing of the mud layer along the deeper portion of the dock towards the Canal Principal.

Dock 2/3 data shows homogeneous conditions (Figure 7c) with values below 50 mg/l in almost all the tidal cycle. There is only one exception of a resuspension event that occurred about 2 hours before high tide when the concentration reached over 3500 mg/l near the bottom associated to the only moment in which a 0.50 m thick layer of fluid mud was detected. Evidently, for this site, the presence of fluid mud may be restricted to small pools since it was detected only twice. Also with such low concentrations of SS, fluxes were also very low although the directions maintained the inversion described previously (Figure 7d). As in all previous measurements, the net flux was positive (Table I).

SS concentrations for Station 3 (Figure 7e) returned practically to the ones observed during the first cruise, with a peak value of 94 mg/l owing to a resuspension event related to the max ebb velocities. With respect to the fluxes of SS (Figure 7f), even though the peak values were registered near both high-water slack, this was owing to the higher SS concentrations in the water column. During the highest velocities, the larger fluxes occurred near the bottom. The net flux was very small and positive (Table I).

As a result of vessel traffic during the measurements period, Station 4 was located further south than the same station in the previous cruise. That may have implied that an indentation of the tidal flats may have induced a reduction on the velocities obtained at the station in comparison with those occurring on the middle of the channel. Nevertheless, this allowed the observation that this sector acts as a trap for the sediment. During this survey a much higher frequency in fluid mud data was detected (in 8 out of 12 profiles) with a thickness of the order of 1 m or less. Previous data from the same area (i.e., Piccolo and Perillo, 1990; Pérez and Perillo, 1998, Gómez *et al.*, 1997) did not report fluid mud occurrences.

During the sampling, and considering only the water column above the fluid mud layer, maximum concentration occurred at high water slack (Figure 7g) with over 550 mg/l. The rest of the time up to the second high water slack, concentrations were lower than 50 mg/l. SS fluxes have peculiar characteristics owing to the fact that the station was located closer to the southern border of the channel and the effect of the indentation (Figure 7h). This is evident because the positive fluxes are limited to only one part of the ebb and particularly to the upper water column. Even a negative peak flux near the bottom at the beginning of ebb may indicate the possible development of a vortex due to flow separation. The net flux resulted in this case negative with almost –3,000 mg/cm^2 s.

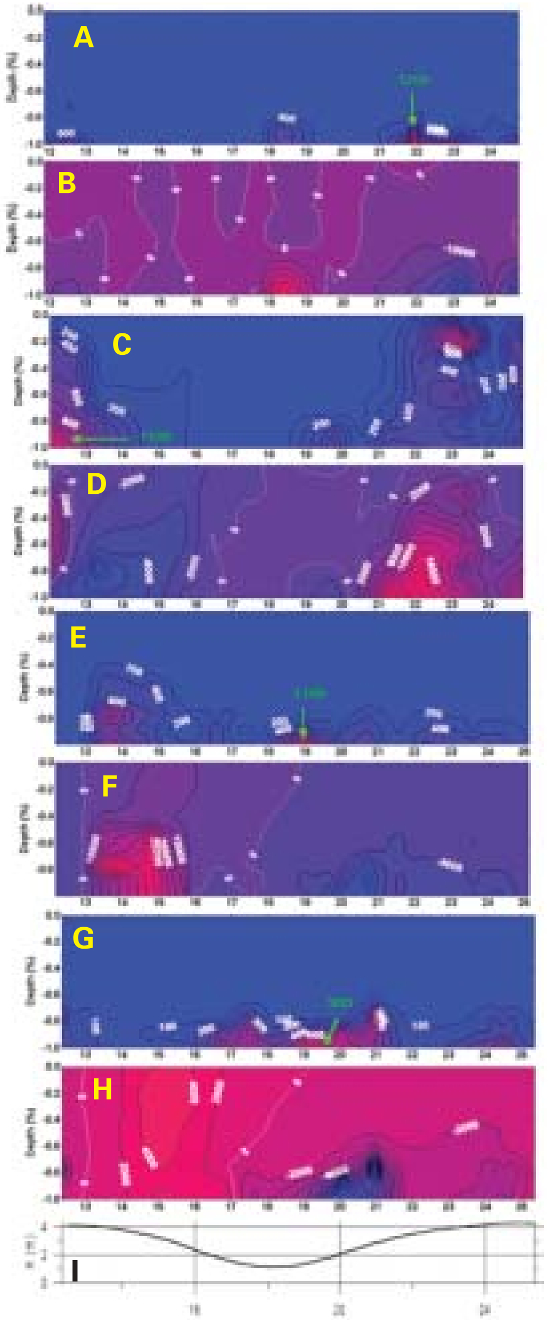

Figure 6. Depth vs time plots of SS concentration (a,c,e) and fluxes (b,d,f) of Draga II. G tidal curve during the measurements.

Conclusions

The study included three cruises covering the conditions prior to, during and post-dredging of the harbour facilities. The results indicate, as was expected by the characteristics of the dredger, an increase from ten- to twenty-fold of the SS concentration from the initial values. However, after one month, the concentration returned to values approximately similar to normal for the area, although somewhat higher. The analysis of the SS fluxes show that both docks have circulation conditions that favour sediment deposition. In both cases, most of the net fluxes indicate sediment importation.

During the dredging and post-dredging stages, a fluid mud layer was detected in both docks and in the Canal Principal. This layer is much more developed in Dock 5 where it reached up to 3 m thick, although in most cases it was below 1 m. The presence of the fluid mud layer further favours sedimentation as turbulence is reduced as well as the capacity for the currents to resuspend the material available. Lack of or strongly reduced turbulence helps deposition of particles suspended near the bottom increasing the sedimentation rate in comparison with a bottom free of a fluid mud layer.

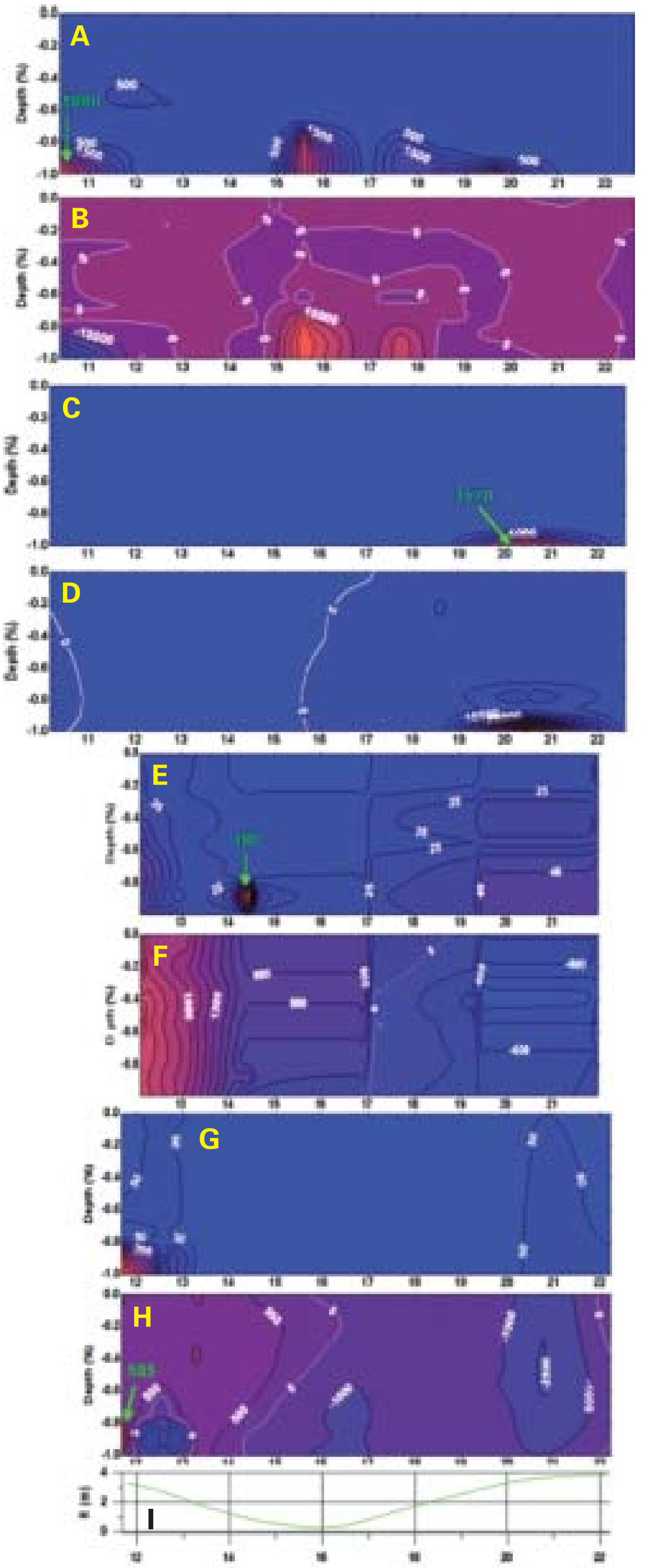

Figure 7. Depth vs time plots of SS concentration (a,c,e,g) and fluxes (b,d,f,h) of Draga III. I tidal curve during the measurements.

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