A Conceptual Model for Sediment Transport in the Inner Plata River

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ABSTRACT: A conceptual model of sediment transport along the IPR is proposed, based on the interpretation of the flow as evolving in three corridors, with very weak mixing among them. The model is built based on analyses of the river bottom river morphology, the predominant bottom sediment textures, and the suspended sediment load. This conceptual model will be used as a reference for future numerical model studies, based on which it will be verified and, eventually, corrected.

1 INTRODUCTION

The Plata River is the end point of the Plata Basin, the second largest fluvial basin in South America (Figure 1). The Inner Plata River (IPR) has freshwater (from which its denomination as a 'river' arises), as a consequence of the large fluvial discharge (with a mean value of about 22,000 m^3/s) from the main tributaries, the Paraná and Uruguay Rivers; but, at the same time, the water currents are tidally dominated (a characteristic of an estuary), as a consequence of its large width (of the order of 50 km). Moreover, due precisely to its large width, wind waves are internally generated, which creates a hydrodynamic climate akin to a coastal zone.

Figure 1. Location of study zone.

In the present paper, a conceptual model for sediment transport through the IPR is formulated, which constitutes a reference to build a detailed numerical model of sediment transport for the whole Plata River, the main task of a study under way within 'Freplata' Project (Argentine-Uruguayan cooperation, with collaboration and financing by the French Government).

2 RIVER MORPHOLOGY

Figure 2 shows the Digital Elevation Model (DEM) of the IPR bottom, where the morphologic units (CARP 1989) are identified. From upstream to downstream, three zones are distinguished: the Upper Plata River (UPR), the Upstream Intermediate Plata River (UIPR), and the Downstream Intermediate Plata River (DIPR). On top of it, the 'flow corridors' are distinguished, which constitute a representation of the mean flow as a set of three corridors, each one associated to each main tributary of the IPR: Paraná de las Palmas, Paraná Guazú, and Uruguay Rivers, with minimum mixing among them (Jaime et al 2001, Menéndez et al 2002). Note that a 'recirculation zone' also exists.

In the UPR, Playa Honda Shoal is the deposition site for sediment transported under suspension through Palmas and Guazú corridors (see below). The deposition is lower on the Northern Fluvial System, within the Uruguay corridor; besides, relatively high depths are maintained along the Martín García Channels; these effects are due to the confinement of the Uruguay corridor between the Guazú corridor and the (stable) Uruguayan coast.

Once in the UIPR, the width expansion of the Uruguay corridor, after the coastal hard point in Colonia, has led to the formation of Ortiz Big Shoal, while the mainstream of the flow proceeds through the Northern Channel, adjacent to the coast. In the case of the Guazú corridor, the flow maintains high depths all along and across (Big Hole of the Intermediate Channel), except for Ortiz Small Shoal. Along the Palmas corridor, coastal sedimentation has occurred.

At the DIPR, the bottom morphology seems to be under ocean influence (which includes storm surge action, linked to 'Sudestadas'): relatively high depths are observed for the three flow corridors, except for elongations from the Ortiz Big Shoal. Sedimentation has taken place in the recirculation zone adjacent to the Argentine coast.

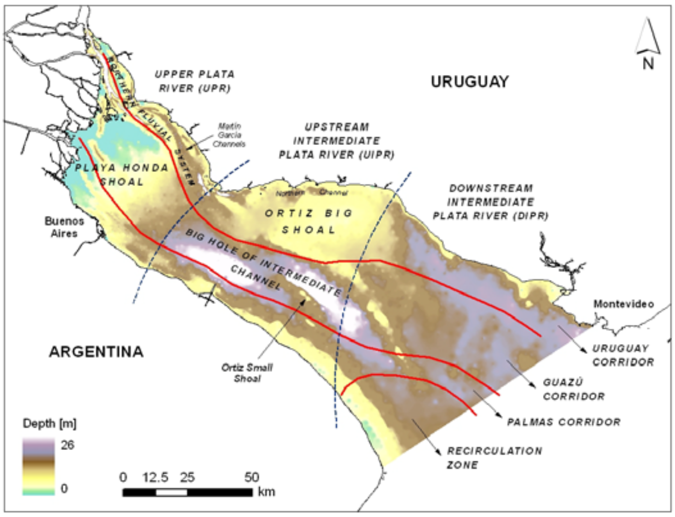


Figure 2. DEM, morphologic units, and flow corridors.

3 BOTTOM SEDIMENT TEXTURE

Figure 3 presents the distribution of bottom sediment texture (Lopez Laborde & Nagy 1999), following Shepard Soil Texture Triangle (Shepard 1954), together with the flow corridors. A more detailed map of the bottom sediment texture for the UPR was developed by Urien (1966), as shown in Figure 4, where the flow corridors are also represented. In Figure 5, zoning of the bottom sediment is shown, according to its genetic association (Parker et al 1985), together with flow corridors; note that no distinction is performed between the Uruguay and Guazú Rivers contributions.


Figure 3. Bottom sediment texture (adapted from Lopez Laborde & Nagy 1999) and flow corridors for the IPR.


Figure 4. Bottom sediment texture (adapted from Urien 1966) and flow corridors for the UPR.


Figure 5. Genetic association of bottom sediments (adapted from Parker et al 1985) and flow corridors for the IPR.

Original point data on sediment texture from 11 different sources were provided by SOHMA (Navy Hydrograph Service of Uruguay), and used to categorize them according to the USDA Soil Texture Triangle. By crossing these categorization map with the morphologic units maps and with the flow corridors (Figure 6), and taking into account the above presented antecedents, the conceptual distribution shown in Figure 7 was produced, which indicates zones with dominant textures. It is observed that:

(i) Sand and Loamy Sand dominate at the head of both the Guazú and Uruguay corridors heads; (ii) Silt and Silt Loam follows as the dominant texture downstream throughout the UPR; this zone extends beyond the UPR for the Palmas and Uruguay corridors; (iii) Silt Loam and Silty Clay Loam predominate next for the Guazú and Palmas corridors, covering the rest of them; (iv) Silty Clay Loam is the predominant texture over practically the remaining part of the Uruguay corridor; (v) Clay predominates in the recirculation zone, and as a patch on the Uruguayan coast, when approaching Montevideo.

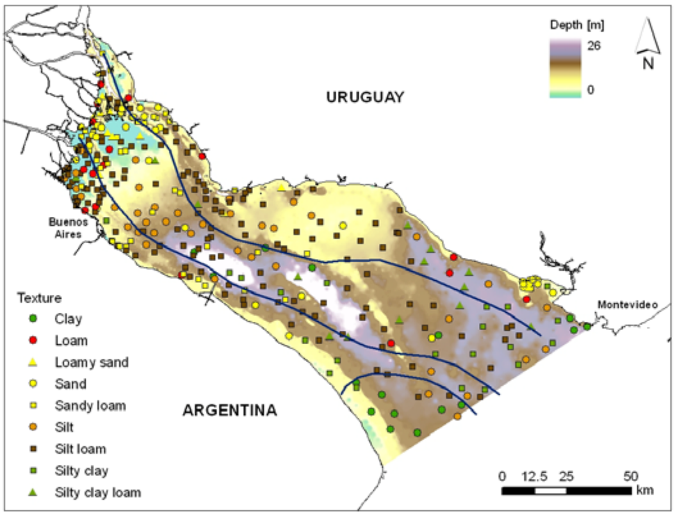


Figure 6. Categorization of point data samples, morphologic units, and flow corridors for the IPR.

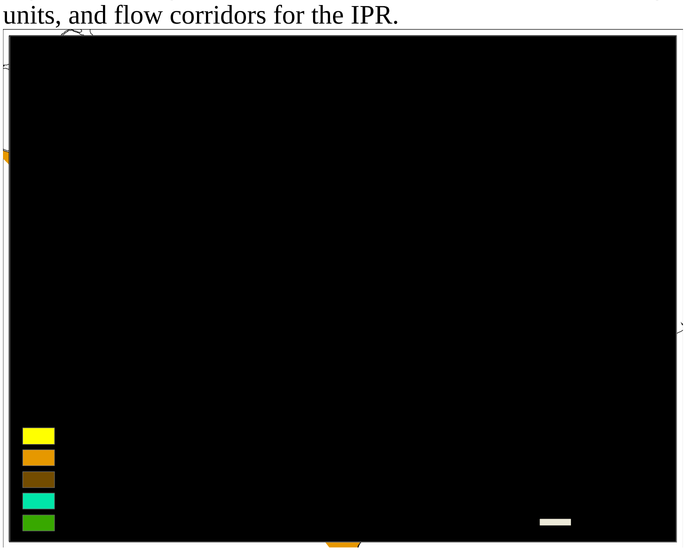


Figure 7. Zoning of dominant bottom sediment textures for the UPR.

4 SUSPENDED SEDIMENT

The bed load of the Paraná and Uruguay Rivers practically do not reach the Plata River, which is then fed by the suspended load of those tributaries, including both fine sand and wash load. The wash load of the Paraná River is composed by about C_s = 300 mg/l of silt, and C_c = 100 mg/l of clay, as indicated by measurements at 'Paso Alvear' in Figure 8 (Menéndez 2001). The wash load of the Uruguay River is much lower, of the order of 100 mg/l.

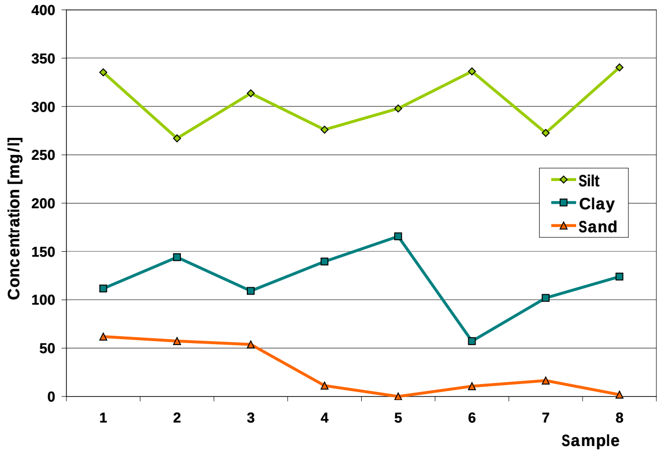


Figure 8. Suspended load composition at 'Paso Alvear', on the Paraná River.

The major portions of fine sand and coarse silt transported by the Paraná and Guazú Rivers deposit right after injection into the Plata River, giving rise to the continuous advancement of the Paraná Delta Front (see next section).

A portion of silt, from the remaining suspended load flowing through Palmas and Guazú corridors, deposits along Playa Honda Shoal; this shoal then continuously grows in height. The siltation process is clearly indicated by the decrease in suspended sediment concentration when moving downstream from the Delta Front, as shown in Figure 9 (Menéndez 2001). The fitting curve has the expression

$$C(x) = C_c + C_s e^{-x/L} \tag{1}$$

where x is the spatial coordinate along the navigation channel, which lies practically within the Palmas corridor (x = 0 is the Delta Front; Buenos Aires is located around km 30), and L = 25 km. Eq. (1) is the solution to the advection equation with deposition

$$U \frac{dC}{dx} = -\frac{w_s}{H} PC \tag{2}$$

where U is the drift current intensity, w_s the mean sediment fall velocity, H the water depth and P the probability of deposition factor due to Krone (van Rijn 1993):

$$P = \begin{cases} 1 - \dfrac{u_*}{u_{*d}} & if \;\; u_* < u_{*d} \\ 0 & if \;\; u_* \geq u_{*d} \end{cases} \tag{3}$$

with u_* being the tidal mean shear velocity, and u_{*d} its critical value for deposition.

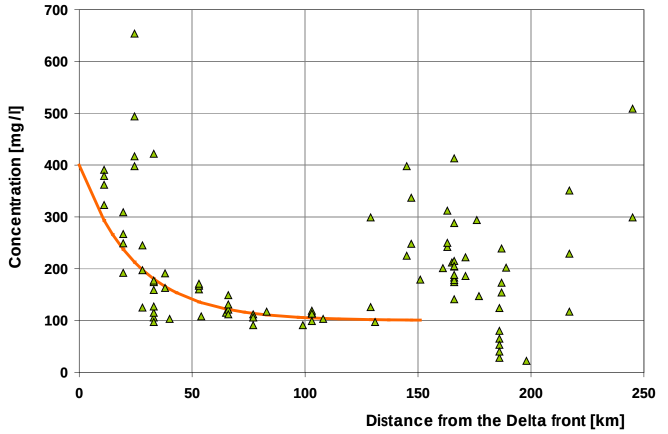


Figure 9. Distribution of suspended sediment concentration along the IPR.

For the UPR the water depth H is about 4 m, and the drift current velocity U is around 0.10 m/s (Menéndez 2001). Taking into account that the Manning roughness coefficient is about 0.015 (Jaime & Menéndez 1999), the shear velocity (based on the drift current) is u_* = 7.1 mm/s. The critical shear velocity for deposition has been estimated from previous studies as u_{*d} = 8 mm/s for silt (Harrison & Owen 1971); it is certainly much lower in the case of clay, then indicating no deposition. As $L = UH/(Pw_s)$, it turns out that w_s = 0.075 mm/s for silt, which corresponds to a mean diameter d_{50} = 9 µm, consistent with observations, as shown in Figure 10 (Menéndez 2001). Note that, at about 120 km from the Delta Front, there is an increase in suspended sediment concentration (Figure 9), an indication that a source of sediment (erosion) is present.

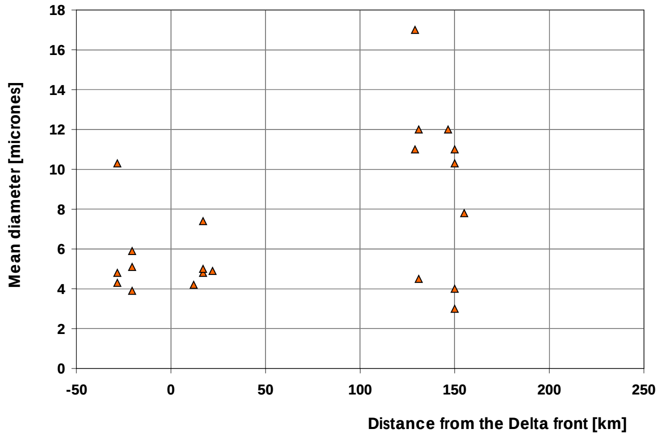


Figure 10. Distribution of suspended sediment mean diameter along the IPR.

The siltation rate along Playa Honda Shoal can now be obtained from

$$S(x) = \frac{w_s}{(1-p)} PC(x) \tag{4}$$

where p is the porosity of the silt deposits, which is about 0.5 (Menéndez 2001). The result is shown in Figure 11. Note that the predicted siltation rate is of the order of 10 cm/year close to the Delta Front (no direct measurements have been reported).

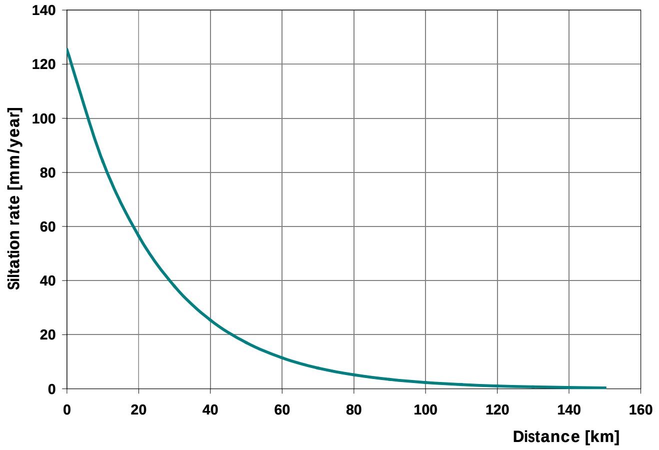
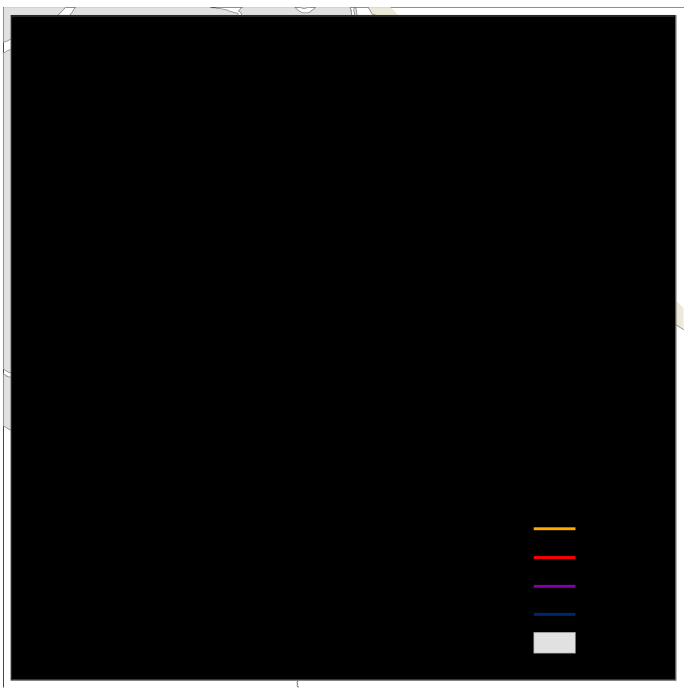


Figure 11. Distribution of siltation rate along the IPR.

5 PARANÁ DELTA FRONT

Figure 12 shows the Paraná Delta Front advancement during the last two centuries. The mean advancement rate is in the range 50-75 m/year at the south, under the influence of Palmas corridor, and 25 m/year at the north, within the Guazú corridor (Menéndez & Sarubbi 2007). The Delta growth is fed by the coarser fraction of the respective suspended sediment load, constituted by fine sand and coarse silt. This fraction is about 5% of the suspended sediment load (Sarubbi 2007).



6 INTEGRATED VIEW

As a synthesis of the above considerations, the following picture emerges regarding sediment transport in the UPR:

- Along the Palmas corridor: (i) the coarser fraction of the suspended load (fine sand and coarse silt), provided by Paraná de las Palmas River, deposits right after the river outlet, giving rise to the advancement of the southern part of the Paraná Delta Front, at a mean rate in the range 50-75 m/year; (ii) a relatively high rate of siltation occurs just after the Delta Front, leading to the growth of Playa Honda Shoal; (iii) the predominant texture of the bottom sediment in this zone is then Silt and Silt Loam; (iv) siltation diminishes exponentially with distance due to the decrease of silt concentration; from about 100 km from the Delta Front, the suspended load composition is dominated by clay; (v) at this last zone, where the oceanic influence is felt, Silt Loam and Silty Clay are the predominant bottom sediment textures.
- Along the Guazú corridor: (i) the coarser fraction of the suspended load, provided by Paraná Guazú River, feeds the advancement of the northern part of the Paraná Delta Front, at a mean rate of about 25 m/year; (ii) the major part of the remaining suspended fine sand deposits after the Front, leading to a zone where Sand and Loamy Sand are the predominant bottom sediment textures; (iii) as for the Palmas corridor, a high rate of siltation follows, leading to the growth of Playa Honda Shoal, where the predominant texture of the bottom sediment is Silt and Silt Loam; (iv) once in the UIPR, Silt Loam and Silty Clay are the predominant bottom sediment textures, and relatively high depths are naturally maintained, indicating low rates of siltation.
- Along the Uruguay corridor: (i) the major part of the suspended fine sand deposits after the Uruguay River outlet, leading to a predominance of Sand and Silty Sand as bottom sediment textures; (ii) the higher flow velocities arising from the confinement of this corridor between the Guazú corridor and the stable Uruguayan coast, lead to lower siltation rates along the Northern Fluvial System, where relatively high depths are maintained along the Martín García Channels; (iii) the width expansion of the Uruguay corridor, after the coastal hard point in Colonia, has led to the formation of Ortiz Big Shoal; (iv) the zone with Sandy Silt and Silt as predominant bottom textures extends down to the end of Ortiz Big Shoal; (iv) beyond that section, where the oceanic influence is felt, Silty Clay Lome predominates as bottom sediment texture.
- Clay texture dominates in the recirculation zone, and in a patch on the Uruguayan coast, when approaching Montevideo.

7 CONCLUSIONS

The conceptual model of sediment transport along the IPR is based on the interpretation of the flow as evolving in three corridors, with very weak mixing among them. The bottom river morphology provides evidences on the sedimentation patterns. The predominant bottom sediment textures are consistent with the hydrodynamics of the flow corridors, and the suspended sediment concentration.

This conceptual model will be critically used as a reference for numerical model studies under way, but at the same time it will be verified and, eventually, corrected.

8 ACKNOWLEDGEMENTS

This work is part of the activities performed within ‘Freplata’ Project, whose support is acknowledged.

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