Fine Sediment Transport Modes in the Itajaí-Açu Estuary, Southern Brazil.

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ABSTRACT


The present study assesses the fine sediment transport modes observed in the Itajaí-Açu estuary. The data to elaborate a conceptual model that describes the fine sediment dynamics in the system were obtained from three main sources. (1) Daily water and suspended sediment load, monitored since 1998. (2) Weekly surveys along the estuary, when vertical profiles of salinity and particulate suspended matter (PSM) were taken, from November 1998 until November 1999. (3) Hourly data of near bed currents and PSM in the channel tidelag, at 4 km from the inlet, during 70 days. The interpretation of these data set allowed to produce a conceptual model where two predominant modes of fine sediment transport can be distinguished, named as Marine Mode and Fluvial Mode. The former is observed when the river discharge and river borne PSM-load are low (< 200 m³.s⁻¹ and < 10 ton.day⁻¹), respectively. During such periods the estuarine trapping efficiency is high and the tidal currents drive the near bed processes, with erosion periods associated with spring tide currents, and net transport landwards. The Fluvial Mode is fully developed when the river discharge exceeds 1,000 m³.s⁻¹. The river borne PSM-load can be higher than 10,000 ton.day⁻¹, and the trapping efficiency is null. Strong erosion is observed, with unidirectional flow seawards independent of the tidal phase, resulting in net exportation of sediment. The Marine Mode is the dominant in time, and can last for several months. The Fluvial Mode, on the other hand, lasts from hours up to few days.

ADDITIONAL INDEX WORDS: Fine sediment dynamics, sediment trapping, sediment budget.

INTRODUCTION

Despite the importance of the dynamics of fine sediment for the coastal evolution, environmental quality and economic development, e.g. sediment load (MILLIMAN and MILEDE, 1983), pollutant adsorption (FORSTNER and WHITMANN, 1983), and port navigation (Parker, 1989), this issue is rarely assessed in Brazil. Even worldwide, only in few estuaries this topic is well understood, e.g. Chesapeake Bay in The U.S.A. or the Gironde in France. Such lack is greatly because the fine sediments are transported by suspension, and its dynamics controlled by supply, mineralogy, hydrodynamics and biology activity, comprising time scales ranging from seconds to centuries, and space scales ranging from centimeters to hundreds of kilometers (Dyer, 1986; MEHTA et al., 1989).

A reasonable number of studies concerning its hydrodynamics and sedimentology were developed in the Itajaí-Açu estuary. Such studies were developed since 1980 (VARGAS, 1983; DOBEREINER, 1985 and 1986; HOMSI and NOVAES, 1987; and PONC,ANO, 1987), aiming to rise basis for engineering works for harbor improvements. A new impulse of studies began in the 1990’S, covering not only the area of port interest (SCHETTINI and CARVALHO, 1998) but the entire estuarine system, from the upper limit of tidal intrusion until the adjacent inner shelf where the river plume spreads (SCHETTINI et al., 1998). Even though, the estuarine sediment budget is not well understood, and the objective of this paper is to contribute in this issue assessing the main transport modes in this estuary.

STUDY AREA

The Itajaí-Açu estuary is located between the Itajaí and Navegantes cities (26° 55' S & 48° 40' W; Figure 1), about 100 km north from Florianópolis, the State Capital, receiving the contribution of a drainage basin of 15,500 km². Its morphology is very simple, like a meandering river, with mean width of about 200 m. Its inlet is stabilized with jetties, which were built to improve the navigation to the Itajaí port. According to the sectors distinction proposed by DIONNE (1963), the lower estuary with marine dominance comprises the reach between the inlet until the Itajaí-Mirim river mouth, 7 km upstream. From this point until the Luiz Alves river mouth, about 30 km upstream from the mouth, characterizes the middle estuary, with high salt stratification. The higher estuary is from this point until 70 km from the mouth, where only tidal elevations is observed (Figure 1). The lower and middle estuary are classified as highly stratified/salt wedge types according to the HANSEN and RATTRAY (1966), Circulation-stratification diagram (SCHETTINI, 2002).

The tidal regime is mixed with semi-diurnal dominance. The mean tide is of 0.7 m, ranging from 0.4 to 1.2 m during neap and spring tide periods, respectively. During low discharge periods the tides penetrates until 70 km upstream, and behave synchronous (e.g. NICHOLS and BIGOS, 1985) until 55 km upstream. Meteorological tides play an important role as they can reach up to 1 m as response to passage of cold fronts (TRUCCOLO, 1998).

The river discharge is monitored daily since 1934 at the Indaiail gauge station, at 90 km upstream, representing 70 % of all drainage. The mean discharge is 228 282 m³.s⁻¹, presenting poor seasonal patterns. The discharge is predominantly low, with random peaks higher than 1,000 m³.s⁻¹. Although, some years present typical tropical conditions with mean discharge of about 500 m³.s⁻¹ during the whole Summer (SCHETTINI, 2002).

The estuarine bed along the lower estuary is dominated by clayey deposits with some sand and silt content. In the middle and higher estuary an increase of coarse sand of fluvial origin is observed. The river sand load never was assessed, although it must be considerable as dozens of small dredges continually operates along the higher estuary. The sand in the lower estuary is of marine origin, according to PONC,ANO (1987).
METHODS

Suspended Sediment Load

The daily suspended sediment load (SSL) monitoring begun in November 1998, at the Indaiá gauge station. This station is maintained by the National Water Agency (ANA), which performs periodic calibrations of the water discharge rating-curve. Water samples are collected near to the water level pole at the time of measurements. Once per week the samples are transported to Itajaí where they are analyzed by gravimetric analysis: filtration through a pre-weighed membrane. Despite the samples being punctual through the cross section, this strategy allows an accurate visualization of time variations of SSL.

Time and Space Distribution of Particulate Suspended Matter

Forty seven surveys were carried out from November 1998 until November 1999, nearly at a weekly basis, to record the longitudinal and vertical distribution of salinity and particulate suspended matter (PSM) along the lower and middle estuary. These surveys were performed using an inflatable boat, starting at the estuarine mouth and moving upstream until some distance upstream from the tip of the salt wedge. The distance between sampling stations varied between 1-1.5 km. Salinity and temperature profiles were recorded with a conductivity-temperature-depth (CTD) probe (SensorData SD-2002®), and turbidity with an optical backscatter probe (Seapoint®). The CTD data were reduced to provide vertical resolution of 0.5 m, at the same levels of the turbidity readings. The turbidity signal was converted to concentration of PSM using a calibration curve obtained in laboratory using local PSM concentrated bulk solution. The majority of the surveys were during low tide, being completed in less than one hour, thus allowing to obtain a synoptic view of the estuarine structure at a given tidal phase.

The estuarine trapping efficiency to retain river borne PSM was assessed using a conservative coefficient given by TE = 1 - PSM\textsubscript{H}/PSM\textsubscript{L}, where PSM\textsubscript{H} is the averaged concentration of the upper 2 m of water column at the higher estuary, with complete absence of salinity in the water column, and PSM\textsubscript{L} is the concentration at the estuarine mouth. The choice of defining the upper 2 m of water column was arbitrary, based on three aspects: (1) it is of about ¼ Of the mean estuarine depth; (2) it is less influenced by bed resuspension, and (3) because of the dominance of fluvial advection transport in the upper layer.

Near Bed Processes

The near bed processes were assessed with a moored tripod...
of sensors in the channel talweg, about 4 km upstream from the mouth, during a 75-days period, from September to November 1999. The tripod contained an acoustic current meter Falmouth™ Wave3D-ACM®, recording current speed and direction, hydrostatic pressure, conductivity (although this sensor failed), temperature and turbidity, leveled about 1 m above the bed. The data were acquired from 5 minutes bursts at 5.5 Hz, every 20 minutes. The yield shear stress, ?? was estimated from the long channel velocity component, U, using the quadratic stress law, τ = C_D ρ_u U^2, with the drag coefficient for muddy beds of C_D = 0.0022 (e.g. DYER, 1986), and constant water density of ρ_w = 1,025 kg.m^-3.

RESULTS

The concentration of PSM at the Indaiála gauge station was strongly ruled by river discharge variations, being the former directly and the latter inversely related to the discharge. Both responded quickly to changes in the discharge. This was closely followed during one hydrologic event. A peak of 800 m³.s⁻¹, the salt intrusion length was of about 10 km and the fresh water PSM concentration was of up to 150 mg.l⁻¹. The PSM distribution agreed very well with the salt distribution, with high PSM values in the upper layer, low values in the saline bottom layer, and a gradual decrease along the upper layer from the head to the estuary mouth. At March 2, the discharge decrease to 400 m³.s⁻¹, the salt wedge length was 14 km and the fresh water PSM concentration increased to 250 mg.l⁻¹. The discharge continued decreasing during the following days, stabilizing at around 200 m³.s⁻¹, with the same occurring with the PSM concentration, that stabilized at around 30 mg.l⁻¹. Although, the salt intrusion length continues advancing landwards, reaching about 28 km at March 10. The PSM distribution agreed very well with the salt distribution in all surveys, being less evident for the surveys at low discharge.

The mean trapping efficiency (TE) was 0.53 0.25, ranging from zero to 0.93. The relationship between the TE and discharge presented a complex pattern, which was arbitrarily split in two modes of variation. There is one mode of variation, which is associated with low river discharge, varying from almost zero to almost one, and another, which presents inverse and linear relationship to the discharge. In order to establish an empirical model that relates river discharge and trapping efficiency, the samples that appear to have better relationship with the discharge were separated visually (the black circles in the Figure 4). The resulting model was TE = 0.84 7.6 Q, with r² = 0.70 (Schettini and Truccolo, 1999; Figure 3). After prolonged dry periods the salt intrusion exceeds 30 km. On the other hand, when the discharge is higher than 1,000 m³.s⁻¹ all seawater is flushed out from the estuarine basin. Similar results have been reported by DÖBERENNER (1985).

Two events of high discharge occurred in a 10-day period during the monitoring with the tripod moored in the channel talweg. During the rest of the period the discharge was low. The comparison between a fortnight period which preceded the events, when the estuarine hydrodynamics was primarily driven by tidal currents, and a second fortnight period when the two events took place, allowed us to produce an excellent picture of what happens near the bed under different conditions.

The discharge during the first fortnight period was low (150-200 m³.s⁻¹, Period 1, hereafter), and occurred two peaks of
discharge higher than 1,000 m$^3$.s$^{-1}$. During the next fortnight (Period 2, hereafter). During Period 1 the estuarine hydrodynamics was ruled by astronomical tides, with minor role of meteorological tides, observed by the low frequency oscillations of the sea level. The maximum bottom currents reached 0.5 m.s$^{-1}$ either during flood and ebb, with landward residual component of about 0.1 m.s$^{-1}$. The PSM concentration varied according to the tidal regime, reaching the maximum of about 500 mg.l$^{-1}$ during the spring tide current peaks. During Period 2 the river discharge distorted the tidal patterns, rising the water level in 0.5 m and maintaining the currents seaward all the time, independent of the tidal phase, with peaks higher than 1 m.s$^{-1}$. The PSM concentration followed the discharge regime, reaching maximum values similar to those observed during Period 1. During Period 1 the maximum yield shear stress reached 0.9 and 0.7 Pa at flood and ebb, respectively, while during Period 2 the maximum shear reached 0.5 and 2.3 Pa at flood and ebb, respectively.

DISCUSSIONS

The Itajai-Açu estuary is classified as a salt wedge or highly stratified estuary. Conceptually, this means a domination of fluvial advective processes over the tidal and geomorphological ones (DYER, 1990). Even though, considering the time scales of variation of all driving agents, we have that the river discharge is often highly variable, with prolonged dry periods as long as 60 days or even more, periods of moderate to high discharge that can last several weeks, and periods of low discharge with peaks of high discharge randomly distributed. The effects of tides will increase relatively at the prolonged low discharge periods, giving a deterministic nature to the sediment dynamics as a function of the predictability of the astronomical tides.

Previous studies already pointed out that after prolonged low discharge periods the PSM balance is positive (landward), meaning sediment importation from the inner shelf (PONÇ ANO, 1987; SCHETTINI and CARVALHO, 1998). Such results, coupled with the need of regular maintenance of the channel depth with dredging and the high estuarine trapping efficiency during low discharge periods, pointed out that the estuary acts as an settling basin for the major part of river borne PSM load when its hydrodynamics is ruled by tides. Extending this condition for longer periods would cause basin infilling and cross section reduction. However, this process is not observed indicating that there is a mechanism to keep the estuarine basin volume as it actually is, with exception of the artificially dredged regions. The flash floods play this role. Even being brief events, they are energetic enough to erode consolidated beds and exporting both trapped and imported sediments during the tide-ruled period.

A conceptual model for the fine sediment dynamics in the Itajai-Açu estuary can be elaborated from the different sources of data described above. It is considered that the estuarine morphology is close to the hydraulic balance between erosion and deposition, maintained by the opposing actions of infilling during tide dominant periods, named Marine Mode, and erosion and transport during the episodic flash floods, Fluvial Mode. The main characteristics of these hydrodynamic conditions are:

- **Marine Mode**: (1) The river discharge is below the mean discharge (< 200 m$^3$.s$^{-1}$); (2) The PSM load is directly related to the water discharge, being as low as 2 kg.s$^{-1}$. (3) Most of the PSM load is retained in the estuary, as it presents higher trapping efficiency; (4) The near bed currents at the lower estuary induce periodic erosion and deposition, with net landward transport at a rate of 10 kg.m$^{-1}$.s$^{-1}$. This transport is maximum during spring tide periods, while it is null during neap tides. Still it is not possible to assess the time necessary for this regime to enter in steady state after a hydrologic event, but it may be of the order of ten days.

- **Fluvial Mode**: This situation is antagonist to the previous one. (1) The river discharge exceeds 1,000 m$^3$.s$^{-1}$ and all salt water is flushed out of the estuarine basin; (2) The PSM load increases to up to 200 kg.s$^{-1}$; (3) Bed erosion takes place, increasing the estuarine basin volume. The near bed net sediment transport is seaward, being as high as 100 kg.m$^2$.s$^{-1}$; (4) The main transport mechanism is the fluvial advection, implying in null trapping efficiency and full delivery of all PSM load. The fluvial discharge overcomes completely the tidal flood currents, turning the flow unidirectional seaward; (5) High discharge periods usually last only a few hours. One exception was during the El Niño of 1983, when occurred the highest discharge ever measured, of about 5,000 m$^3$.s$^{-1}$, and the period with discharge above 1,000 m$^3$.s$^{-1}$ lasted for weeks. Boreholes of 20 m deep were reported after this event.

Based on the magnitudes of the PSM transport for both situations, it can be suggested that the main source of estuarine infilling is the import of sediment from the inner shelf, and not the effect of river borne sediment trapping. The estuary is the primary source of this material, which is exported during periods of higher discharge. Because the higher concentrations of PSM in the estuary related to the elevation of river discharge, the estuarine infilling was formerly attributed to the direct settling from the river borne PSM.

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LITERATURE CITED


