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A sediment fluxes investigation for the 2-D modelling of large river morphodynamics

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ABSTRACT

A complete understanding of alluvial-bed dynamics is desirable for evaluating a variety of issues related to water resources.

Sediment fluxes were investigated in a bifurcation of the large Parana River near Rosario, Argentina. The backscatter estimations from the Doppler profilers provided the suspended load of the sediment forming the riverbed. An echo-sounder was applied to track the dunes yielding the bed-load estimation.

Aiming to show the usefulness of the recorded data, a 2-D numerical code was applied to the 10-km long and 2-km wide Rosario reach. The morphodynamic module was un-coupled from the hydrodynamics assessment, which enabled the long-term prediction of the river morphology accounting for the hydrological yearly variation with a quasi-steady approach.

Numerical experiments were performed to test the sensitivity of the hydrodynamic model to the computational time-step and mesh size, to test the un-coupling scheme performance regarding the full-dynamic modelling, to test the accuracy of the sediment transport formulae based on the field evidence and, finally, to provide guidance to properly fix the model parameters.

1. Introduction

The transport of the sediment forming the riverbed has been widely studied to understand the alluvial bed dynamics and its reciprocal feedback with the hydrodynamics. The sediment transport is commonly classified based on the following dominant mechanisms: the bed-load is referred to as the transport occurring near the riverbed in which the stream flow sweeps the bed particles over the underlying sand bedforms or the gravel bed and the suspended load in which the particles are transported fully suspended in the water column. The suspended-load, containing the finer particles, often represents the majority of the transported sediments reaching the sea; therefore, the measurement technologies have primarily focused on the flux of the suspended materials [1–7]. However, the morphology of large rivers is also influenced by sand fluxes close to the bottom.

Detailed and frequent measurements of the sediment transport in a river stream-flow are desirable for the evaluation of many issues related to river hydro-morphodynamics, such as the effects of climate change on the river morphology and the riverine habitat, the safety of the civil engineering structures (e.g., bridges and embankments), and the maintenance of the navigation channels and hydropower intakes. River sediment transport and deposition–erosion patterns are primarily responsible for determining the channel morphology of large rivers [8,9]. The sediment that feeds the delta at the river outlet serves to build coastal landforms and maintain the shoreline [10–13].

The Parana River represents an important waterway for the South America region of the La Plata Basin, which joins parts of Argentina, Bolivia, Brazil, Paraguay and Uruguay. Therefore, the dynamics of the water and sediment along this watercourse has been studied by various authors, with the principal aim of clarifying the interrelationships among the climate, hydrology, riverine hydraulics and morphology, which affect the water resources and fluvial structures, such as bridges, ports and levees [14,15].

Over the last years, field techniques and analytical or numerical models have been applied to study these interactions along

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Notation

a	reference level for the sediment concentration assessment over the riverbed	P	sand porosity
C	Chézy parameter ($m^{1/2}/s$)	Q_{ref}	flow discharge (m^3/s)
C'	specific skin friction parameter	R_n	radius of curvature, direction n
C_b	river bars celerity	R_s	radius of curvature, direction s
cr	morphodynamic model compression rate	RHS	Reynolds stresses
d	sediment diameter (m)	s–n	computational grid directions
D	normalised particle diameter	s	relative density of the sediment to the water
f	correction factor for suspended-load concentration	sf	morphodynamic model scale factor
g	gravitational acceleration (m/s^2)	S	total sediment transport rate
$\bar{h}$	average dune height (m)	S_b	bed-load
h	water depth (m)	S_l	suspended-load
H	water level (m)	S_s	sediment transport flux, direction s
hd-ts	hydrodynamic time-step (s)	S_n	sediment transport flux, direction n
hev	horizontal eddy viscosity (m^2/s)	T	oscillation period of local flow velocity
k	total-load calibration coefficient	u	local flow velocity (m/s)
k_b	bed-load calibration coefficient	u'_*	effective friction velocity over the grains
k_l	suspended-load calibration coefficient	v_m	migration velocity (m/day)
L	dune wave length	z	bed level
L_b	river bars wave length	ϑ'	shields parameters
md-ts	morphodynamic time-step (s)	Δu	oscillation amplitude of local flow velocity
md-st	morphodynamics to the sediment transport time scales ratio	ϑ_c	critical shields parameter
		τ	shear stress
		τ''	bedforms drag
$p-q$	mass flux variables in the grid s–n directions	τ'	skin friction

the sandy rivers [2,16,17]. New methodologies [18–20] have overcome the traditional limited measurement devices used in the past; consequently, the data taken by these new methods may assist the numerical models simulation for a better understanding of the riverbed dynamics. Innovative instrumentations employed in river surveys include Acoustic Doppler Current Profilers (ADCPs), which could be used to characterise the secondary flows and the vertically averaged velocity patterns [22,22], to evaluate the shear stress by fitting the logarithmic velocity profiles [16,23] and to study the suspended-load [2,7,24]. Concerning the sand-beds, acoustic technologies have also been applied to track the bedforms, eventually estimating the bed-load. This approach for dune tracking consists of applying a single or multi-beam echo-sounder in repeated surveys to measure the dune geometries and their translation lengths [26–30].

In the present study, acoustic techniques were applied to estimate the sediment fluxes in the Parana River near Rosario, Argentina, discerning among the sediment grain sizes and the dominant transport mechanisms (i.e., suspended and bed-load). The used devices (i.e., the ADCPs and a single-beam echo-sounder) were easily deployed compared with traditional samplers and provided detailed data for the monitoring and forecasting of the sediment fluxes and the resulting morphology. Aiming to show the usefulness and applicability of these data, the river channel morphodynamics was simulated with an existing two dimensional (2-D) numerical model (Mike21C by the Danish Hydraulic Institute-DHI [32]), assuming the shallow water approximation.

In more detail, the single- and multi-frequency backscatter techniques were applied to characterise the suspended-load of the sand forming the riverbed, whereas the bed-load was estimated by tracking the dunes with a single-beam echo-sounder in the same field campaign.

The 2-D hydro-morphodynamic model simulated the water–sediment flow and the bed level interaction by applying an un-coupled and quasi-steady approach. In the computations, the yearly discharge variations in the river were considered, and the morphology of the channels was accurately represented.

A wide sensitivity analysis was performed regarding the effect of the time steps, the computational grid and the adopted transport formulae on the resulting morphology. The acoustic surveys provided the reference data, in previously unrated detail, for the calibration of the sediment transport formulae implemented in the numerical model (i.e., the total-load formula has been given by Engelund and Hansen [33] and the suspended- and bed-load formulae by van Rijn [34,34]).

This accurate modelling will foster an efficient management of the river to meet the objectives, such as the navigation channel maintenance.

The paper is organised as follows. The next section presents the materials and methods, with a particular focus on the study site, the applied measurement techniques and the mathematical model. This section also briefly introduces the performed numerical simulations, focusing on the available historical data, i.e., the stage-discharge relationship, the water level records and the river morphology maps, which were used as the boundary conditions and for the model set up. Section 3 reports the achieved results in terms of the estimated sediment fluxes in the field, the numerical model parameters from the sensitivity analyses and the morphology calibration. Aiming to provide a general guidance for the numerical modelling of large river morphodynamics, the outcomes of these analyses are then discussed in Section 4, highlighting the following: (i) the dependence of the model parameters on the observed morphological features, (ii) the usefulness and limits of the estimation of the sediment fluxes using acoustic backscatter. The concluding remarks are reported in the final sections.

This study extended our investigation regarding the Parana River: the interconnections among the applied methods, and the previous and current results and objectives are outlined in Fig. 1.