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Sand transport measurements in Chioggia inlet, Venice lagoon: Theory versus observations

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ABSTRACT

This paper presents results of recent measurements of sand transport made in Chioggia inlet as part of an extensive monitoring programme in the Venetian inlets. Measurements were made in order: (1) to define a relationship between sand transport magnitude and tidal flow; (2) to derive the thresholds for sand transport; (3) to identify the dominant modes of transport; (4) to evaluate the concentration profiles of sand within the benthic boundary layer; (5) to compare bedload transport observations with model predictions using existent bedload formulae; and (6) to produce yearly estimates of bedload transport across the inlet. The vertical distribution of sand in the water column was sampled using modified Helley–Smith bedload samplers at three sites. Transport was found to vary according to the flow and bed grain size, with considerable temporal and spatial variability. A difference of up to three orders of magnitude in transport was observed through the inlet, with higher transport rates measured on the seaward part. The dominant mode of transport in the central inlet was suspension, while bedload was dominant in the mouths. The measured profiles of sand concentration varied with the tidal stage and seabed grain size according to the Rouse parameter (R). R was high at the inlet mouths ($1<R<2$), indicative of a well-developed bedload layer. The inverse movability number (W_s/U_*) was also higher at these sites and appeared to be grain size dependant. Formulae for bedload transport were tested against field data; stochastic methods such as Einstein–Brown, Engelund–Hansen and Van Rijn produce the best fits. The coupled model SHYFEM-Sedtrans05 appears to simulate well observed transport for most conditions of flow. Long-term bedload predictions indicate a dominant export of sand, with a yearly average of 4500 m^3.

1. Introduction

The magnitude of sand transport on the Adriatic shores of Venice lagoon is evident from the presence of depositional features such as accreting beaches, sand bars and ebb-tidal deltas (Guerzoni and Tagliapietra, 2006; Villatoro, 2007). Volumetric analysis and current modelling show that the main contribution to these features is littoral drift; however, the magnitude of sand transport across the tidal inlets and its impact on the littoral cell is not yet know (Amos et al., 2006, in press; Helsby, 2008). Sand transport estimates have mostly been obtained through numerical simulations (Coraci et al., 2007; Tambroni and Seminara, 2006). The models however, have not been validated due to lack of measurements of the mass transport across the inlets. An annual loss of approximately 1 million m^3 of sediment has been calculated through long-term bathymetry analysis of Venice lagoon (Carbonin and Cecconi, 1997). According to Tambroni and Seminara, (2006) who used a simple hydrodynamic model to estimate sand transport in the inlets of Venice, only 10% of the amount lost is sand.

The activities reported in this paper are part of a greater project to monitor the transport of solid matter between the Adriatic Sea and Venice lagoon. The study aims to combine ADCP measurements made both continuously at a fixed point in each inlet and periodically across inlet sections (Kovačević et al., 2008) with estimates from the coupled model SHYFEM-Sedtrans05 (Ferrarin et al., 2008). The upward looking, fixed ADCPs do not read the bottom 2 m of the water column due to side lobe interference (Heinz-Hermann, 1994). Thus, the crucial near bed sediment transport remains undetected. The measurements presented in this paper were carried out in order to provide information about that bottom layer to supplement the ADCP data. Bedload transport cannot be neglected in the estimation of a sediment budget: Soulsby and Damgaard (2005) suggest that the evolution of bed

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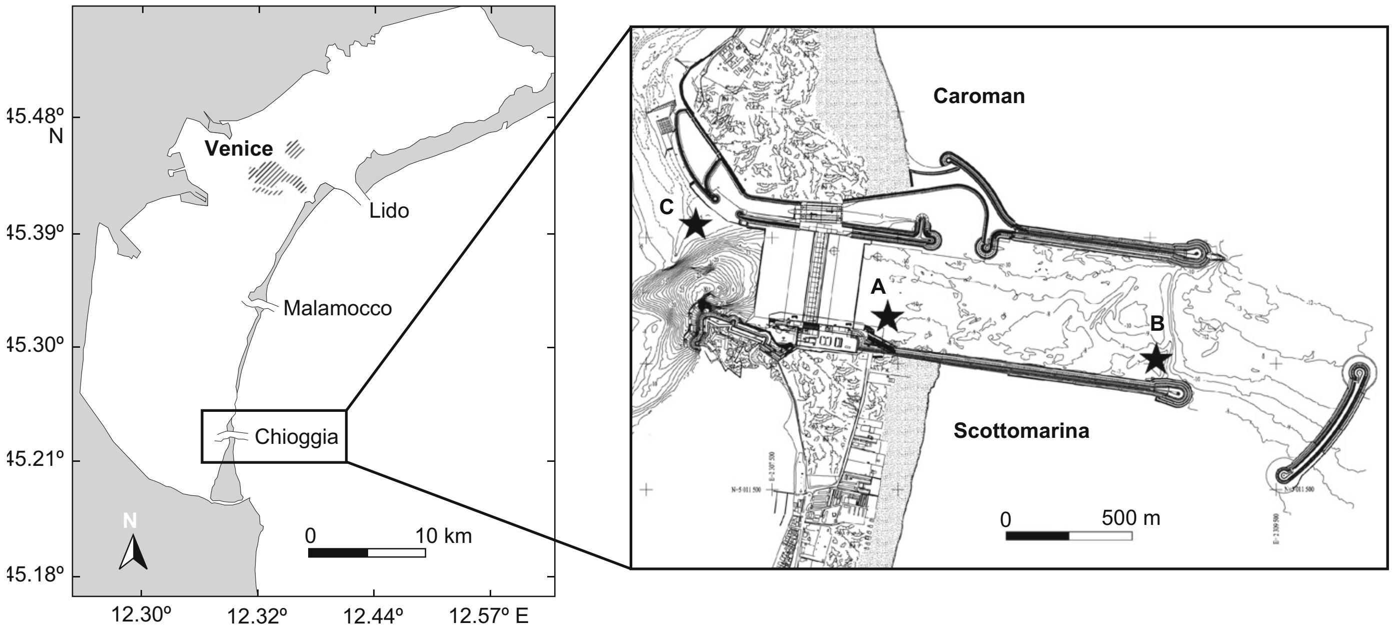

Fig. 1. Venice lagoon and Chioggia inlet. Study sites A (2006), B (2007) and C (2008) are marked with stars (adapted from Consorzio Venezia Nuova, 2006).

morphology at a local scale may depend more on bedload than suspension, since bedload reacts quickly to local flow conditions, whereas suspended sediment does not.

Amos et al. (2006, 2008) reported good results on initial attempts to measure bedload and suspended sand transport using modified Helley–Smith samplers in Lido and Chioggia inlets. This paper builds upon those results by including two field campaigns at two other study sites within Chioggia inlet. The primary objective of this study is to understand the mechanisms and patterns of sand transport in Chioggia inlet, and to provide a comparative data set against Lido inlet in order to understand sand transport and exchanges with the Adriatic Sea. In particular, we aim to identify the magnitudes and dominant modes of sand transport in the inlet. To achieve this, one needs to:

(i) derive the thresholds for transport and suspension. The critical condition at which sand starts to move, and whether it is transported as bedload or in suspension has been subject to wide debate in the literature (Amos et al., in press). According to Bagnold (1966), sediment finer than 125 μm moves directly into suspension, however this has been contested by McCave (1984). The suspension criterion of Lane and Kalinske (1941), also termed the movability number by Collins and Rigler (1982) is defined by the ratio of the frictional velocity (U_*) to the particle settling velocity (W_s). The inverse movability number has been evaluated as 2.5 by Van Rijn (1984) and Niño et al. (2003), and as 2 by Samaga et al. (1986). Komar and Clemens (1985) suggested a value closer to unity, whereas Lee et al. (2004) shows it to vary from 0.3 to 5. The ratio W_s/U_* can be related to the dimensionless grain diameter (D_*) though the Shields parameter (θ), which can be used to identify both the motion and suspension threshold through experimentally derived curves. The accurate evaluation of the inverse movability number is therefore key to the identification of threshold conditions and the subsequent prediction of sand transport;
(ii) obtain a relationship between sand transport magnitude and tidal flow magnitude;
(iii) define the distribution of sand sizes and grain settling velocity with height above the bed;
(iv) identify the sand transport pathway through the relation of transport to bed grain size;
(v) test the validity of the Rouse profile of concentration against the measured vertical distribution of sand by identifying the patterns of the distribution of sand in suspension under different tidal flow conditions, and thus allowing for the future computation of the distribution of sand in suspension through the Rouse parameter ($W_s/\beta\kappa U_*$);
(vi) compare measured transport rates with model predictions; and
(vii) produce yearly estimates of bedload transport.

1.1. Study site

Chioggia inlet is the southern most of three openings connecting Venice lagoon to the North Adriatic Sea (Fig. 1). The inlet has an average depth of 8 m, with a 12 m deep artificially maintained navigation channel and a maximum tidal range of 1 m. The tidal wave in Chioggia inlet precedes those at Malamocco and Lido by up to 1 h (Gačić et al., 2004). The inlet cross-sectional area has recently been reduced from 500 to 400 m as a result of the MOSE locks and refuge port construction (Fig. 1).

The inlet has been the access to the port of Chioggia since Roman times, and has suffered human-induced changes ever since: The most important of these being the construction of stabilising jetties, which took place from approximately 1912 to 1930; smaller modifications continued until the 1950s (Bon et al., 2001; Rinaldo, 2001). The more recent work on the MOSE project began in 2004 and is still under way (Consorzio Venezia Nuova (CVN), 2006). Fig. 1 shows a plan of the proposed MOSE facilities at Chioggia. The detached breakwater, refuge port and locks had been completed at the time of this study; the barrier and its operation equipment are still to be put in place. The southern jetty has resulted in progradation of up to 9 m/annum of the adjacent Sottomarina and Caroman beaches (see Fig. 1) (CORILA, unpublished data, 2006). Also an ebb-tidal delta has resulted, which has an accretion rate of 50,000 m^3/annum (Amos et al., 2006;