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The measurement of sand transport in two inlets of Venice lagoon, Italy

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ABSTRACT

Sand transport in Lido and Chioggia inlets was measured using modified Helley–Smith sand traps equipped with 60-micron nets. The traps had an efficiency of about 4% only but provided enough material for analysis. Very fine sand ($0.07 < d < 0.11$ mm) only was collected in the traps. Transport of sand was greatest in the bottom 10% of the water column and followed a Rouse profile. Sand extended to a height of about 4 m above the bed during peak flows corresponding to the estimated thickness of the boundary layer; and observed in synoptic ADCP profiles. The sand in the benthic boundary layer was largely inorganic (>95%); above this layer, organic content varied widely and was greatest near the surface. The movability number W_s/U_* showed a linear relationship to dimensionless grain diameter (D_*): $(W_s/U_*) = (D_*/10)$; $D_* < 10$. Sand concentration in suspension was simulated by a mean Rouse parameter of -2.01 ± 0.66 (Lido inlet) and -0.82 ± 0.27 (Chioggia inlet). The β parameter (Hill et al., 1988) was correlated with D_* and movability number in the form: $\beta = 2.07 - 2.03D_* + 59(W_s/U_*)^2$ ($r^2 = 0.42$). Von Karman's constant was back-calculated from a *Law of the Wall* relationship as a test on the accuracy of U_* estimates; a mean value of 0.37 ± 0.1 (compared to the accepted value of 0.41) suggest U_* was accurate to within 10%. The constant of proportionality ($\gamma = 3.54 \times 10^{-4}$) between reference concentration (C_a) and normalized excess bed shear stress was in line with the published literature.

1. Introduction and background

Carbognin and Cecconi (1997) have defined the annual sediment loss from Venice lagoon to be 1,000,000 m^3, largely based upon bathymetric changes to 1990. Subsequent surveys (2002 and 2006) suggest that losses may be greater than this value (Sfriso et al., 2005; Dawson, 2007), whereas Sarretta et al. (in press) and Defendi et al. (in press) estimated present-day losses of 400,000 m^3. Measurements of the mass transport through the three inlets of the lagoon are limited, and reliance has been placed upon numerical simulations. Such simulations of the fines and sand transport are usually conducted independently (see Garcia and Parker, 1991 for review). Whilst considerable effort and progress on the transport of fines has been made (Neumeier et al., 2008), the transport of sand within the inlets is less well known due to a lack of measurements. The majority of sand in transport is in the very fine to fine sand range ($63 < d < 130$ microns). The movement of such sediment is contentious in the literature. Bagnold (1966) has proposed that sand finer than 125 microns in diameter moves directly into suspension once the threshold for motion is exceeded. However the threshold for suspension has been contested by McCave (1984). In deriving his threshold criterion, Bagnold (1956, 1966) assumed suspension takes place when the still water settling velocity of the sand (W_s) is 0.8 times the friction velocity ($w'_{rms} = W_s = 0.8U_*$). Using this reasoning, the suspension criterion of Lane and Kalinske (1941) was defined by the dimensionless ratio $(W_s/U_*) = 1.25$ (also termed the movability number by Collins and Rigler, 1982 and the inverse Rouse number by Lee et al., 2004). Van Rijn (1984) and Niño et al. (2003) suggested a ratio of 2.5 under high Reynolds numbers. Komar and Clemens (1985) suggested that the suspension criterion should be close to unity, whereas Samaga et al. (1986) proposed a value of 2. Also, according to Van Rijn (1993), the ratio of W_s/U_* depends on the magnitude of the dimensionless grain diameter, D_* (Van Rijn, 1981), and hence is not always a constant:

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Notation

a	reference height of Rouse concentration (L)
B	benthic sand trap sample
C_a	concentration of sand at reference height (ML^{-3})
C_b	volumetric concentration of bed (0.65)
C_d	drag coefficient
$C_{d,z}$	drag coefficient evaluated for flow at height z
C_z	sand concentration of height z (ML^{-3})
C_{mass}	mass of sand in calibration trap (M)
D_*	dimensionless grain diameter
d	mean grain diameter (L)
h	water depth (L)
K_{mo}	eddy diffusion coefficient for momentum
K_s	eddy diffusion coefficient for sand
m	slope of sand concentration gradient
E	epi-benthic sand trap sample
M	water column sand trap sample (0.3 h)
Q_s	sand discharge (ML^{-1})
R	Rouse parameter
R_e	Reynolds number
S	surface sand trap sample
S_{mass}	mass of sand in surface trap (M)
U	horizontal flow velocity (LT^{-1})
$\overline{U}$	mean horizontal flow velocity (LT^{-1})
U_z	horizontal flow velocity at height z (LT^{-1})
U_{crit}	critical horizontal flow velocity (LT^{-1})
$U_{crit,bed}$	critical horizontal flow velocity for bedload transport (LT^{-1})
$U_{crit,susp}$	critical horizontal flow velocity for suspension (LT^{-1})
U_*	friction velocity (LT^{-1})
V	water volume sampled by sediment traps (L^3)
W_s	still water particle settling velocity (LT^{-1})
w'_{up}	mean amplitude of upward-directed component of turbulent flow (LT^{-1})
w'_{rms}	root-mean-square amplitude of vertical component of turbulent flow (LT^{-1})
z	height above bed (L)
z_o	roughness length (L)
Z_r	relative height above bed
α	coefficient of proportionality from Gadd et al. (1978)
β	ratio of eddy viscosity of momentum to sediment
γ	coefficient of proportionality from Owen (1964)
θ	Shields parameter
$\theta_{crit,susp}$	critical Shields parameter for suspension
κ	von Karman's constant
ν	kinematic viscosity of seawater (L^2T^{-1})
ρ	density of seawater (ML^{-3})
ρ_s	density of sediment (ML^{-3})
τ_o	bed shear stress (MLT^{-2})
$\tau_{crit,susp}$	critical bed shear stress for suspension (MLT^{-2})
χ	coefficient of proportionality of the movability number for $D_* < 10$

$$D_* = \left[\frac{g(\rho_s-\rho)}{\rho \upsilon^2}\right]^{0.333} d \tag{1}$$

where υ is the kinematic viscosity of seawater (0.8×10^{-6} m^2/; CRC, 1976). W_s/U_* is constant, when $D_* > 10$, and

$$\frac{W_s}{U_*} = \frac{D_*}{\chi} \tag{2}$$

where χ is a constant, and $D_* < 10$. Our initial evaluation shows that Venetian sand typically falls in the range $1.5 < D_* < 3.5$. What then is the appropriate value of χ? Van Rijn (1993) suggests a value of 4, but this means $W_s/U_* = 2.5$ for $D^* \geq 10$, which is twice that proposed by Bagnold (1966). While Lee et al. (2004, their Fig. 5) shows this ratio to vary between 0.3 and 5 which is close to the range proposed by Komar and Clemens (1985) and Paphitis et al. (2001).

The ratio W_s/U_* is central to the computation of the distribution of sand in suspension through the Rouse parameter ($W_s/\beta\kappa U_*$) as well as to the computation of the appropriate threshold Shields parameter for suspension. Robust predictions of sand transport are not possible unless this ratio is accurately defined. Fortunately, we can define it for the case of two inlets of Venice lagoon. The purpose of this paper is to evaluate the suspension criterion and the Rouse parameter based upon measurements of sand transport in Lido and Chioggia inlets made during September 2006.

Seabed mounted, upward-looking, fixed ADCPs have been installed in each of the three tidal inlets of Venice lagoon and continue to operate (Gačic et al., 2004). These installations monitor the net residual sediment transport through the inlets. An objective of the work was to provide information on sand transport within the lower 2 m of the water column; the region not detected by the sensors.

2. The study region and study context

Venice lagoon is a microtidal estuary situated in the northern Adriatic Sea. It has a spring tidal range of 1 m and is ventilated through three tidal inlets: Lido, Malamocco, and Chioggia (Umgiesser, 2000; Umgiesser et al., 2004). The results reported herein came from the inlets of Lido and Chioggia, shown in Fig. 1. The physical and biological attributes of the lagoon have been compiled by Guerzoni and Tagliapietra (2006). Notably, ebb tidal deltas have been found in bathymetric surveys off the Lido and Chioggia inlets. The volumetric change based on surveys of Lido delta carried out in 1990 and 2006 is order 3×10^6 m^3/a. Samples of the ebb delta show it to be composed of fine and very fine sand; similar to material in the adjacent lagoon (Umgiesser et al., 2005, 2006). A comparison of aerial photographs of the beach at Cavallino (north of the inlet) indicates progradation of 120 m in the last 10 years, and by-passing of sand around the northern breakwater and into Lido inlet. As well, modelling by Umgiesser et al. (2006) and Tambroni and Seminara (2006) suggests an export of sand from the lagoon through the inlets by erosion of the major tidal channels. This notwithstanding, recent work on the sand budget of this inlet (Helsby, 2008) suggest that the sources of sand to the delta are ambiguous.

The estimated accretion off Chioggia inlet is 50,000 m^3/a (Villatoro et al., in press); bottom samples show that most of this material is also fine and very fine sand. A comparison of aerial photographs reveals that the beach adjacent to the southern breakwater has prograded seawards approximately 90 m in the last 10 years (CORILA, Unpublished Data, 2006). Brambati and Venzo (1967) and Brambati et al. (1978) show a northward transport of sand towards Chioggia inlet which could explain in part the origin of the sand. However, there appears to be considerable accumulation north of Chioggia inlet diagnostic of a southerly sand transport,