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Characteristics of ships' depression waves and associated sediment resuspension in Venice Lagoon, Italy

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ABSTRACT

The character of ships' wakes and the consequent sediment resuspension induced by the passage of commercial vessels in Venice Lagoon, Italy was investigated during July, 2009. Suspended sediment concentration (SSC), water depth, and water velocity were measured on the shoals alongside the shipping channel after the passage of forty vessels. The ships' passage produced large waves of depression with troughs oriented at an average angle of 44° to the channel. High water velocities are recorded opposite the direction of wave propagation and may exceed 2 m s^{-1} at the rear edge of the trough. Ten vessel-induced wakes led to SSC concentrations above 400 mg L^{-1}, ~30 times higher than the average background concentration. When large wakes passed over the shoals, maximum concentrations persisted for several minutes and elevated concentrations persisted for nearly an hour. The height of a ship's wake can be related to the product of the depth-based Froude number, Fr, and a blocking coefficient, S, according to $Fr^{3.5}S^{1.6}$. Because of the sensitivity of the height of the wake to the ship's speed, we suggest a method for calculation of a ship-by-ship velocity threshold below which shear stress does not exceed the critical erosive stress level for sediments.

1. Introduction

As the shipping industry continues its rapid expansion it is important to gain a better understanding about the development and propagation of ships' wakes from channels toward shoals and to understand their role in erosion processes. Ships' wakes have been found to be an important factor in shoreline erosion and transport in rivers (Nanson et al., 1994), bays (Parnell et al., 2008; Soomere et al., 2009), lakes (Hofmann et al., 2008), tidal creeks (Ravens and Thomas, 2008), and on salt marshes in estuaries (Houser, 2010). Several of these studies investigated the relative importance of wind waves compared to ship waves and found that, due to the frequency of wind wave events, wind waves were the most important contributor to erosion. Houser (2010), however found that the energy from ships' wakes was much higher than that from wind waves and, therefore, ships' wakes remain an important factor in salt marsh erosion in the Savannah River estuary. Meanwhile a limited number of studies analyzed benthic sediment resuspension and sediment transport associated with ships' wakes (Erm et al., 2009; Hofmann et al., 2008; Schoellhamer, 1996; Wiberg and Sherwood, 2008). These studies show that increased bottom water velocities from ships' wakes lead to significant sediment resuspension along shoals and transport of the sediment with the water current. Such resuspension can redistribute contaminants, contribute to the shoaling of channels and reduce light levels in the water column.

As ships pass through a narrow channel they produce both Airy or oscillating waves, and a wake, which is marked by a significant drawdown and surge of water (Houser, 2010). The latter has been called the Bernoulli wake (PIANC, 2003), depression wake (Soomere, 2007) drawdown and surge wave (Houser, 2010; Nanson et al., 1994) or ship-induced bore (Ravens and Thomas, 2008). Soomere (2007) in a review of non-linear components of ship wakes describes this type of wake as a depression-area wake or consequently, ship squat (Gourlay, 2006, 2008). (For simplicity we will use the term "Bernoulli wake" in this document). This depression wave is a nonlinear effect strongly connected to the vicinity of the sailing regime to critical velocities, rather than an effect of the local water velocity fields. In coastal waters with narrow fairways, the Bernoulli wake propagates across the neighboring shoals. The exact vessel parameters which determine the characteristics of the Bernoulli wake, the propagation of the wake onto the shoals, and how it interacts with bottom sediments remain poorly understood (PIANC, 2003). While studies have shown that ships' wakes can be an important factor controlling shoreline morphology (Soomere et al., 2009), it is often unclear as to

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the type of wake (Bernoulli or Airy waves) responsible for erosion, sediment remobilization, and transport (Houser, 2010). In large bays or open water areas it may be difficult even to distinguish ships' wakes from wind waves using conventional instruments, thereby making it complicated to isolate the effect of vessel-generated waves (Nanson et al., 1994; PIANC, 2003). However fairways, enclosed lagoons and protected harbors make this separation possible and also provide environments where the different ship wakes can be seen (PIANC, 2003). In shallow coastal waters the proximity of shoals to the shipping channel allows the Bernoulli wake to frequently propagate onto the shoals where it can then be separated by shape and frequency. Venice Lagoon, therefore, is an ideal location for understanding vessel impacts on the environment.

While there has been some discussion of the possible negative impacts shipping has on lagoons, such as pollution from ballast water and emissions and the introduction of invasive species (e.g. Goldberg, 1995; Hayes and Sliwa, 2003; Ricciardi and Rasmussen, 1998) less attention has been paid to the impact of sediment resuspension from commercial vessels in lagoons. Lagoons, such as Venice Lagoon, represent highly dynamic and complex ecosystems. Although lagoons are naturally turbid due to their relatively shallow depths, terrestrial runoff, and anthropogenic development (Neil et al., 2002), an increase in suspended sediment can be detrimental to the health of a lagoon by reducing sunlight penetration and releasing particle-bound contaminants into the water column (Streets and Holden, 2003). In this context, there is an urgent need to understand the effect ships' wakes have on sediment dynamics and morphology.

Sediment resuspension and erosion of shoals from ships' wakes are of concern in Venice Lagoon; there is a long history of ships' wakes which propagate unimpeded across the lagoon shoals. Some of these wakes are generated by very large commercial vessels, cruise ships or ferries navigating a deep, narrow channel dredged across shallow shoals. The vessels may be slow moving but they may also occupy a significant fraction, say more than 10%, of the cross-sectional area of the channel and the wakes they generate propagate immediately into very shallow water. Over the shoals, these wakes produce high, near-bottom current velocities (Bauer et al., 2002), leading to substantial sediment resuspension (Erm et al., 2009; Schoellhamer, 1996; Wiberg and Sherwood, 2008). Some of the sediment resuspended by wakes on the shoals may find its way into the channel, where preferential deposition and shoaling will increase dredging demand (Umgiesser et al., 2004). Indeed, there was a marked increase of water depth (adjusted for local subsidence rates) in the vicinity of the Malamocco–Marghera shipping channel during the period from 1970 to 2000 (Molinaroli et al., 2009) possibly caused by ships' wakes propagating across the shoals. Industrial, sediment-bound contaminants will also be spread by periodic resuspension due to ships' wakes.

We have documented how ships influence suspended sediments in a shallow-water area of Venice Lagoon, Italy. We aim to ascertain which parameters of the vessel most influence the formation of the Bernoulli wake. We describe the characteristics of ships' wakes caused by large, slowly moving vessels which transverse a narrow, deep channel across a shallow lagoon that are especially important in the resuspension of sediment. We will also discuss how changes in the ships' speed and the timing of transit in relation to the tide might minimize adverse impacts due to sediment resuspension.

1.1. Previous work

A substantial amount of literature exists concerning the development and propagation of waves from passing vessels (e.g. Velegrakis et al., 2007), including investigations concerned with the properties of the wake once it leaves the channel (e.g. Didenkulova et al., 2009; Houser, 2010; Parnell and Kofoed-Hansen, 2001; Schoellhamer, 1996) and consequent resuspension (Erm et al., 2009; Hofmann et al., 2008; Nanson et al., 1994; Osborne and Boak, 1999; Schoellhamer, 1996; Soomere and Kask, 2003; Soomere et al., 2007). Of these investigations, most are concerned with the study of a far-field wake from fast ferries and its effect on sediment erosion and resuspension on the shoreline (e.g. Parnell et al., 2008). However, in Venice Lagoon the shoals are immediately adjacent to the shipping channel and are thus affected by the Bernoulli wake which develops on the side of the hull (Soomere, 2007). Gourlay (2008) has shown that it is possible to predict the squat of a ship based on a Fourier transform method for different channel geometries and that this method holds best for slender ships. Gourlay (2001) and Soomere (2006) discuss the development of a supercritical bore or a soliton which advances in front of the ship; however in these cases channel walls limit the propagation of the bore. Ravens and Thomas (2008) however demonstrate that laterally propagating waves can be converted into bores. Therefore, while the bore normally follows the ships motion, solitons and, as pointed out by a reviewer, bore-like events may occur at some distance from the channel. The height of waves is expected to increase greatly as the ship-induced waves move onto the shoals and optionally interact with one another. Moreover, the particular configuration of the cross-section of the channel may lead to effects similar to those occurring at high Froude numbers even for ships sailing at moderate Froude numbers (Torsvik et al., 2009). While theoretically no bore can occur in front of a ship moving at sub-critical Froude velocities, the width-averaged Froude number of some of the ships is high enough to cause a large displacement of water in the channel (Torsvik et al., 2009). Water velocity then must increase around the sides of the ship to replace the water displaced by the large ship (PIANC, 2003). The increase in velocity must be balanced by a decrease in pressure creating a noticeable depression around the sides of the ship (Oebius, 2000). It is important to note that as the velocity of the ships increase, their sailing speed moves closer to the critical regime, which leads to greater height of the depression wake. When recorded on an instrument within the deep channel near the ship, the Bernoulli wake produced by this pressure difference may take the shape of a symmetrical solitary wave (Oebius, 2000) however the shape of the wave will be modified as it propagates over the shoals. It is likely that the shape of the wave at critical speed is determined by the interaction of two undulating bores (El et al., 2007; Grimshaw and Smyth, 1986).

1.2. Study site: Venice Lagoon

The study was completed along the shoals outside the Malamocco–Marghera industrial channel of Venice Lagoon, Italy. With a surface area of more than 500 km^2 Venice Lagoon, located in north-eastern Italy, is the largest Italian lagoon (Fig. 1). It is shallow with an average depth of 0.8 m; however it is crossed by numerous natural and man-made channels, which are all maintained by an active dredging program and reach depths of 10 m or more. The lagoon is connected to the sea by three inlets with a mean total tidal discharge of 6500 $m^3\ s^{-1}$ (Cucco and Umgiesser, 2006; Gačić et al., 2002). The tidal excursion in the lagoon is about 0.3 m to 1.1 m during neap and spring tide respectively.

Concurrent with the development of the Porto Marghera Industrial Zone (PMIZ) between 1920 and 1970, a new channel known as the Malamocco–Marghera channel (or locally known as Canale dei Petroli) was dredged from the Malamocco Inlet to the PMIZ. This channel has a total length of 20 km, mean width of 200 m, and a depth of 12 m to accommodate medium-sized container ships, bulk carriers, and tankers. After entering the lagoon, the channel heads directly west towards the mainland cutting through natural tidal channels. It then makes a sharp right-hand turn north towards the PMIZ, where it stretches alongside the mainland for 14 km (Fig. 1) in an almost straight path.

Grain size at the channel bottom ranges from sandy-silt to silty-sand sediments, the finer fraction more easily resuspended (Saretta et al., 2010; Zonta et al., 2007). Our measurements indicate that the

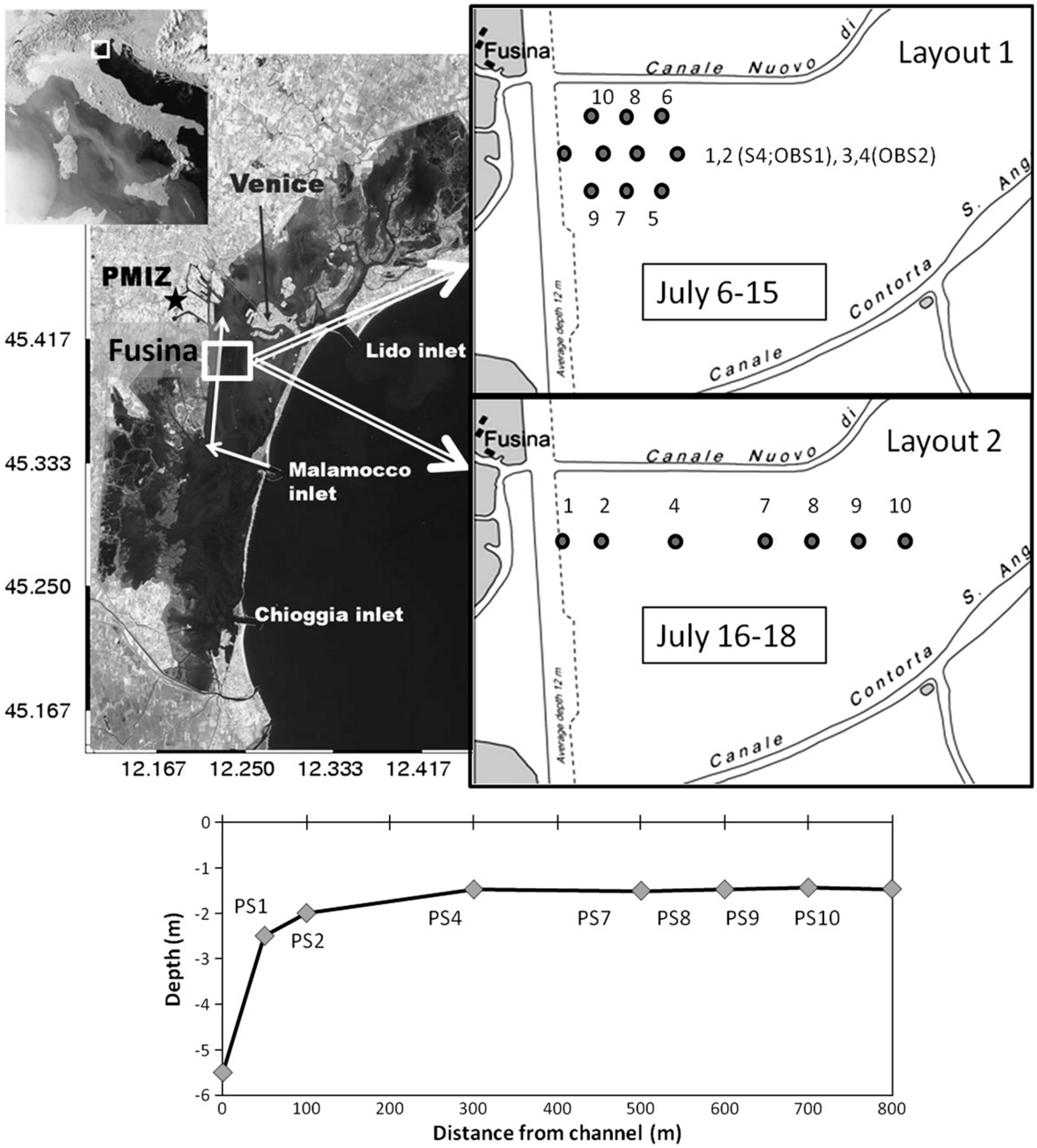

Fig. 1. Map of study location, Venice and Porto Marghera Industrial Zone (PMIZ) labeled for reference. Thin white arrows mark the location of the Malamocco–Marghera industrial channel. Layout 1: close-up view of Porto Marghera Industrial Zone with the location of the instruments used in pressure sensor layout 1. Layout 2: close-up view of Porto Marghera Industrial Zone with the location of the instruments used pressure sensor layout 2. The third inset shows the bathymetric profile of the shoals taken from the pressure sensor depths.

sides of the channel are exceptionally steep rising towards the shoal with a slope of about 25% on the east side and 30% on the west side. The slopes at the edge of the channel are very steep and must be maintained by a dredging program. East of the channel the seafloor quickly shoals to depths ranging between 1 and 2 m (Fig. 1). This shallow-water area extends 5 to 8 km lagoon-ward of the channel for its entire length. In most locations a wave can travel unimpeded along the shoal for several hundred meters to kilometers until it is dissipated naturally *via* bottom friction, white capping, depth-induced breaking and, possibly, deformation of the sea bed (Chan and Liu, 2009).

Our study site is located in these eastern shoals, 2000 m south of the PMIZ and directly seaward of Fusina (Fig. 1). Tidal currents in this part of the lagoon are generally low (<0.05 m s^{-1}) due to its distance from the inlet and relatively open water location, however winds can increase currents to over 0.15 m s^{-1} (Coraci et al., 2007). The lagoon is naturally sheltered from high wind waves, due to limited fetch length. Although we do not have any data of annual wave climate in this area, our measurements show that southeasterly winds caused significant wave heights in the study period of up to 0.2 m (the fetch is 8 km in this direction). An analysis of annual hourly wind data measured at a nearby meteorological station from the year 2009 provided by the Venice municipal authority (*Istituzione Centro Previsione e Segnalazione Maree, Comune di Venezia*) shows that our study period was representative of the annual wind climate with an average wind speed of 3.23 m s^{-1}, which is only slightly higher than the annual mean (3.11 m s^{-1}). Sustained winds above 7.5 m s^{-1} occurred 2.1% of the time during our study period and 1.96% of the time during the year. Six storms were recorded in 2009 in which the sustained wind speed reached 10 m s^{-1}, though none occurred during our study period. Empirical relationships for the forecasting of wind-waves (Goda, 2003) predict that the maximum significant wave height reached in 2009 could be no more than 0.5 m, and that this height was likely only attained during these 6 storms. The fetch length and the presence of Scirocco conditions, however, can lead to waves creating bottom stress values above 0.7 Pa, and may be a cause of the extensive erosion seen in the area (Umgiesser et al., 2004).

Ships are near maximum allowed speed (5.56 m s^{-1}) when passing our study location. An analysis of shipping statistics from the Port Authority of Venice website implies that between 2000 and 3000 large (length > 100 m) ships pass through this shipping channel every year (Port of Venice website, http://www.port.venice.it/pdv/Home.do?metodo=carica_home).

During a preliminary sampling in March 2009, an acoustic Doppler current profiler (600 kHz Teledyne-RDI Workhorse Rio Grande ADCP) was used to collect current data prior to and directly after a ship passage across the shipping channel. Acoustic backscatter data of the instrument was additionally used to estimate the concentration of suspended particles by calibration with direct measurements of SSC in water samples (Defendi et al., 2010).

An across channel ADCP transect taken after the passage of a vessel shows resuspension directly in the path of boats with drafts greater than 8 m (e.g. Fig. 2). The ADCP data show that significant resuspension (greater than 100 mg L^{-1}) occurs throughout the water column directly below the ship; these sediments remain in suspension within the channel for 5 to 20 min after the passage of the ship. There is a distinct dark cloud near the surface of the water column but this cloud quickly disappears suggesting that it is most likely bubbles created by the propeller motion. The figure shows some resuspension on the shoals outside the channel as well; however no connection between resuspension in the channel and on the shoals is found (Fig. 2).

2. Methods

Measurements were made between 6 and 18 July, 2009. Vessel data were obtained using an Automatic Identification System (AIS) receiver and Ship Plotter software. The AIS data give the user ship dimensions, vessel speed, vessel direction, and vessel heading information (Cairns, 2005).

An InterOcean S4 electromagnetic current meter was deployed at 45° 24.364N 12° 15.739E; 100 m above the seabed in a mean tide water depth of 2.1 m about 50 m perpendicular to the east edge of the shipping channel (Fig. 1). The instrument recorded data with a sampling frequency of 1 Hz. It was also equipped with an optical backscatter (OBS) sensor and a pressure sensor. An auto sampler was mounted on three buoys and set to collect 600 mL of water at 1 m below the surface. A GPRS receiver allowed it to be activated via message from a mobile phone, providing background and instantaneous suspended sediment samples at the passage of waves. Hand samples were also taken using a peristaltic pump to aid in calibrating

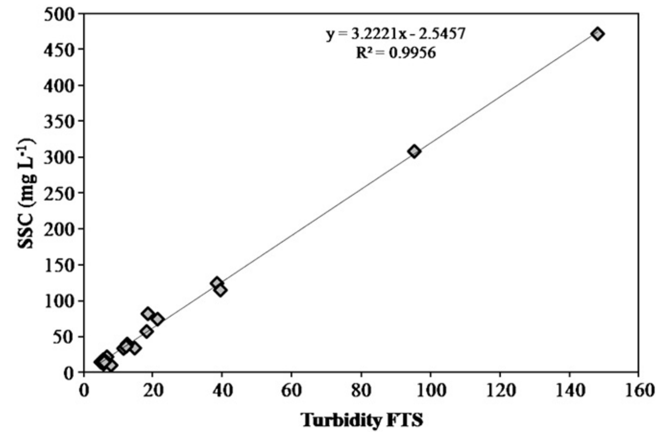

Fig. 3. OBS calibration data. The correlation of turbidity recorded by the OBS sensor within the S4 electromagnetic current meter is plotted against SSC (mg L^{-1}) collected in both hand and automated samples.

the OBS (Fig. 3). Two hundred milliliters of water were filtered through 0.4 μm pre-weighed polycarbonate and suspended sediment concentration was determined by weight loss at 105 °C.

Ten pressure sensors (Cera-Diver data logger, Schlumberger Water Services) were utilized throughout the sampling campaign and the sampling interval was set to 1 Hz. The sensors were deployed at the sea floor using cylindrical steel housings fixed to 0.2 m diameter concrete disks. The sensor locations were taken with a handheld GPS and buoys were left in place while the sensors were removed, for data retrieval, to mark the exact location. The pressure sensors (PS1–PS10) were placed in three parallel linear transects perpendicular to the shipping channel from 6 July to 15 July in an effort to determine angles of wave propagation (Layout 1; Fig. 1). The middle transect contained PS1–PS4, with PS1 and PS2 50 m apart and PS2–PS4 each 100 m apart. (The OBS and S4 were located at PS2.) The mean tide water depth shoaled from 2.5 m at PS1 to 1.8 m at PS4 moving away from the channel. PS9, PS7 and PS5 were located 100 m south of the middle transect, and PS10, PS8 and PS6 100 m north of it. In both the southern and northern transect, pressure sensors were spaced at 100 m intervals. The pressure sensor configuration was modified from 16 July to 18 July. During this period all working sensors were laid out in a single transect perpendicular to the channel. The middle transect of instruments did not change from their original position, but the other pressure sensors were repositioned to extend this line, with each sensor 100 m apart (Fig. 1; Layout 2).

Wave height for all measurements was calculated from normalized pressure sensor data as the difference between the depth of the

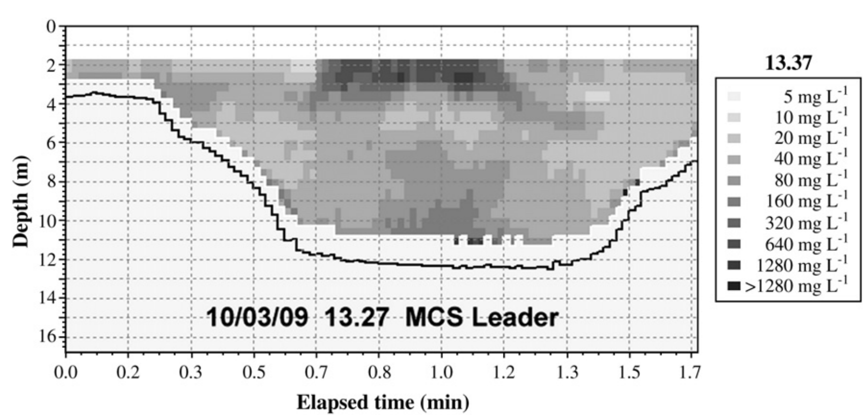

Fig. 2. ADCP data collected across the channel after the passage of *MSC Leader* on 13 March, 2009. Elevated SSC concentration can be seen for at least 18 min after the passage of *MSC Leader* in the channel. Very high concentrations directly after the passage in the center of the channel are not SSC but rather most likely air bubbles created by the movement of the propellers.

Bernoulli wake trough and the height of the crest. Wave height was measured by pressure sensors and the S4 electromagnetic current meter. Oscillatory wake components of the Airy wake could influence our measurements after the Bernoulli wake drawdown and surge. In addition, because the instruments are set to 1 Hz it is possible that we are underestimating the wave height by missing the extreme trough and crest. Given the strength of the pressure signal, the shallowness of the water, and the non-linear nature of the wakes, we did not attempt to correct for attenuation with depth based on linear wave theory (Ellis et al., 2006). We have chosen, for simplicity, to report the absolute values as reported by the S4 pressure sensor. As a result, we may be underestimating the maximum wave height (Ellis et al., 2006).

The program Sedtrans05, which includes an application developed for use with cohesive sediments, was utilized to calculate bottom shear stress from the measured sediment grain size and water column and wave parameters (Neumeier et al., 2008). We compare the results from our bed shear stress calculation with sediment erosion thresholds as reported in the literature for the area.

3. Results

A total number of 40 full events could only be included in our analysis (Table 1). With each of these events, SCC, water elevation, current velocity and direction were recorded by the S4, coincident with ship information received from the AIS system. Fig. 4 shows water depth and associated resuspension data after the passage of three ships representing a range of vessel sizes and resuspension event magnitudes from relatively small to large events. From the large amount of data available, we will provide evidence here of the principal characteristics of the wakes and of the resulting resuspension.

3.1. Wake plane-view

The plane-views of wakes can be reconstructed from the arrival times at each pressure sensor. These seem to be best described as a second order polynomial. For example, the wake of the vessel *M/T Tigullio* is shown in Fig. 5. The angle, α, is the angle that the trough makes relative to the channel orientation, that is, relative to the ship's heading. For the vessel *M/T Tigullio*, the spatially averaged value of α was 41° but the trough left the channel at an angle of about 67°. The average value of α for twenty-two cases recorded was 44°. For some reason, α was slightly larger, 48°, for inbound ships heading north and slightly smaller, 42°, for outbound ships headed south. This difference may be due to the ships' speed: the average speed of the inbound ships was 4.4 m s^{-1}, while the average speed of the outbound ships was greater at 4.7 m s^{-1}.

Table 1
List of ship properties and their corresponding wave and resuspension events.

Vessel	Avg. speed (m/s)/ Fr. number	Length (m)	Width (m)	Draft (m)	S4 elevation (m)[a]	Wave height (m)[b]	Max. SSC (mg/L)	Event duration (s)	SSC # (mg s/L)	BKG/MAX current vel. (m/s)	Safe speed (m/s)[c]
MV Nurettin AMCA	4.84/0.45	118	18	5.3	1.48	0.12	14	48	128	0.04/0.38	>5.56
Gabion	3.96/0.37	128	28	6.4	1.51	0.38	245	540	68,018	0.12/1.03	4.31
Stolt Pondo	3.4/0.31	170	26	8	1.56	0.14	10	10	160	0.11/0.22	3.56
MSC Antonia	3.4/0.31	188	24	8.1	1.8	0.14	13	300	640	0.04/0.15	3.56
MSC Leader	4.2/0.40	201	23	6.7	1.41	0.41	330	540	90,000	0.08/1.13	**3.71**
Grande Sicilia	4.32/0.40	177	31	8.3	1.48	0.56	400	2200	323,371	0.12/2.12	**3.18**
Melody	3.81/0.35	100	18	5.9	1.64	0.1	70	40	3000	0.12/0.32	>5.56
RBD Borea	3.19/0.29	130	21	6.2	1.67	0.06	30	90	1600	0.13/0.30	5
Tucana	5.66/0.51	88	12	3.9	1.96	0.14	170	120	12,704	0.17/0.64	>5.56
Coral Leaf	5.06/0.45	108	17	6	2.23	0.23	300	180	29,068	0.15/0.87	>5.56
MV Nurettin Amca	4.58/0.41	118	18	4.6	2.24	0.11	323	240	13,734	0.15/0.34	>5.56
Lia Ievoli	4.63/0.41	131	20	7.6	2.39	0.19	75	240	15,424	0.19/0.59	4.92
East Coast	4.94/0.44	64	9	4.5	2.38	0.04	70	60	3840	0.23/0.24	>5.56
Jia Xing	3.65/0.33	169	27	7.4	2	0.15	72	300	7200	0.22/0.25	3.75
Ain Zeft	5.14/0.46	109	15	5	2.13	0.32	107	120	30,768	0.23/0.66	>5.56
Clipper Karina	4.63/0.41	116	20	6.1	2.41	0.23	30	65	1344	0.11/0.41	>5.56
St. Constantine	4.89/0.44	104	16	4.5	2.3	0.18	10	50	576	0.12/0.26	>5.56
MSC Mirella	3.45/0.31	177	32	9.1	2.18	0.2	88	180	7200	0.21/0.57	**3.15**
Novorossiysk Star	4.37/0.39	180	26	7.7	2.09	0.47	400	1140	121,536	0.18/1.29	**3.67**
Calajunco M	4.17/0.38	162	23	7.1	1.86	0.31	260	780	91,072	0.12/0.85	**4.14**
Adrianople	3.65/0.33	188	28	7.6	1.86	0.25	180	720	70,608	0.14/0.59	**3.43**
Salerno Express	4.99/0.45	140	19	5.5	1.87	0.3	160	180	22,944	0.15/0.59	5.43
Carlos	3.7/0.34	176	31	7.7	1.88	0.36	400	840	98,280	0.12/0.90	**3.36**
Adria Blu	5.6/0.50	94	15	5	2.06	0.11	50	100	2304	0.08/0.27	>5.56
Oasis West	4.84/0.43	145	21	6.3	2.15	0.22	10	200	480	0.22/0.58	4.92
MV Kemal G	3.86/0.34	129	18	8.2	2.3	0.2	70	100	2400	0.09/0.40	4.99
Elefsina	4.63/0.41	138	21	6.1	2.31	0.14	50	60	800	0.10/0.25	5.17
Sari Zeybek	4.32/0.39	106	16	8	2.3	0.11	10	10	30	0.08/0.20	>5.56
Mar Adriana	3.04/0.27	144	23	7.9	2.3	0.12	10	150	1920	0.09/0.24	4.31
Leopold Staff	3.4/0.30	199	26	8.9	2.35	0.1	5	10	20	0.13/0.44	**3.35**
TK Istanbul	5.4/0.48	114	18	4.6	2.35	0.14	35	50	1600	0.08/0.33	>5.56
Marja	4.8/0.43	100	18	5.5	2.35	0.12	5	5	10	0.11/0.12	>5.56
Uni Assent	4.22/0.38	165	27	7.3	2.36	0.26	100	360	12,552	0.09/0.62	**3.93**
Salerno Express	4.84/0.44	144	19	5.5	1.85	0.21	137	180	11,200	0.17/0.69	5.31
Hellenic Voyager	4.84/0.44	193	27	6.5	2.03	0.57	400	1200	153,600	0.07/1.42	**3.75**
Wehr Elbe	3.91/0.35	208	30	9.3	2.03	0.37	400	1800	181,920	0.12/1.07	**2.94**
Carlos G	3.6/0.33	176	31	7.5	1.87	0.4	400	720	85,840	0.16/1.02	**3.4**
Calajunco M	4.22/0.38	162	23	7.1	1.9	0.3	200	360	17,608	0.17/0.84	**4.17**
Hokuetsu Ace II	3.65/0.33	210	32	8	1.89	0.31	400	300	82,224	0.21/0.97	**3.01**

[a] Elevation as recorded by the S4 electromagnetic current meter.
[b] Wave height given as the maximum trough elevation to the following peak.
[c] Theoretical maximum navigation velocity for each ship at an S4 water elevation of 2.1 m (lagoon tidal level of ~0.4 m) assuming an MSP resuspension threshold of 0.7. When the maximum velocity is greater than 5.56 m s^{-1} it is essentially a null point as this is the maximum navigation velocity allowed by law in Venice Lagoon. Emboldened speeds were from ships that require a slower speed than actual travel velocity.

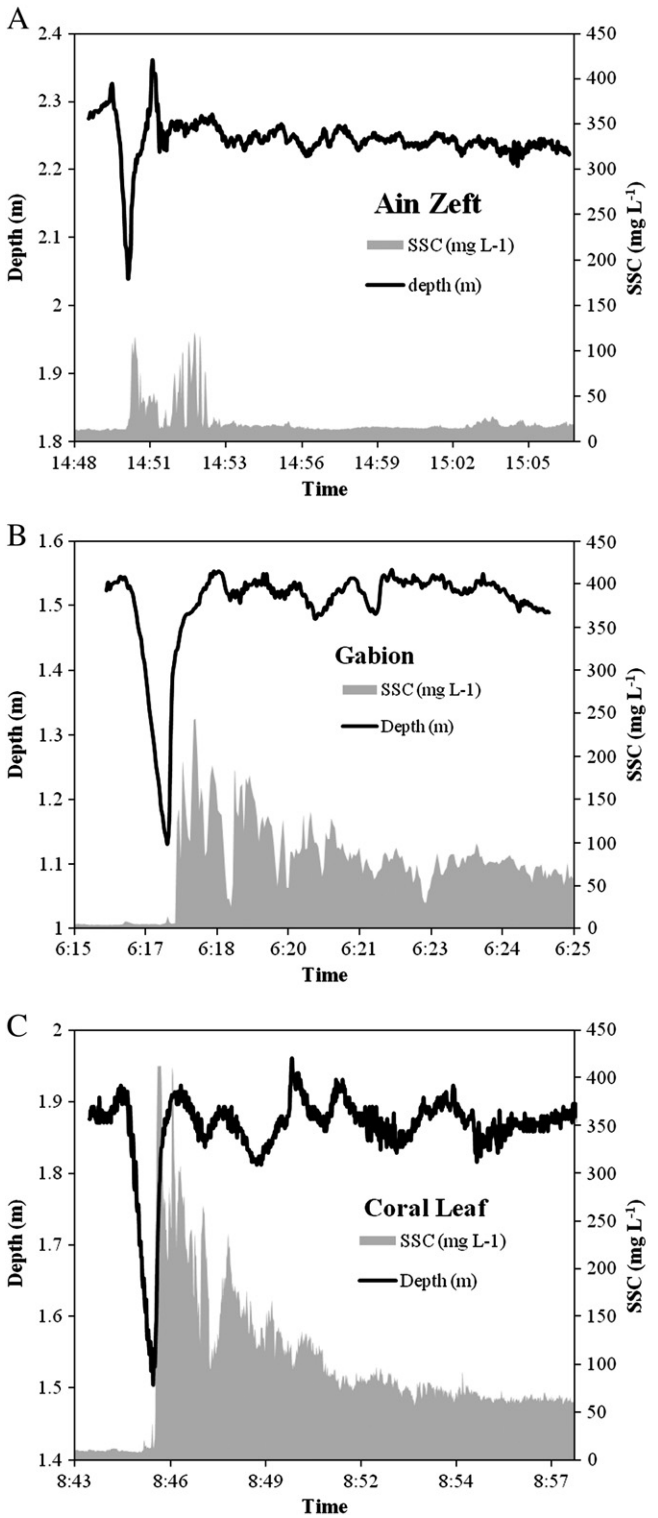

Fig. 4. Three graphs of water depth and SSC time series as recorded by the S4 sensor after the passage of four ships. The resuspension events run the spectrum of magnitude from small event (A) to large (C). Please note that the SSC scale is the same in all 4 graphs, while the depth scale and time scale change depending on the event.

Because the celerity vector is perpendicular to the wakes' trough, the celerity vector can be combined with the arrival times between pressure sensors, which were oriented perpendicular to the channel, to find the angle of the wake relative to the channel (α). The celerity (c) of the wake trough in shallow water is approximately $c=[g(h-H)]^{-1/2}$ where g is the acceleration due to gravity, h is the still water depth and H, in this case

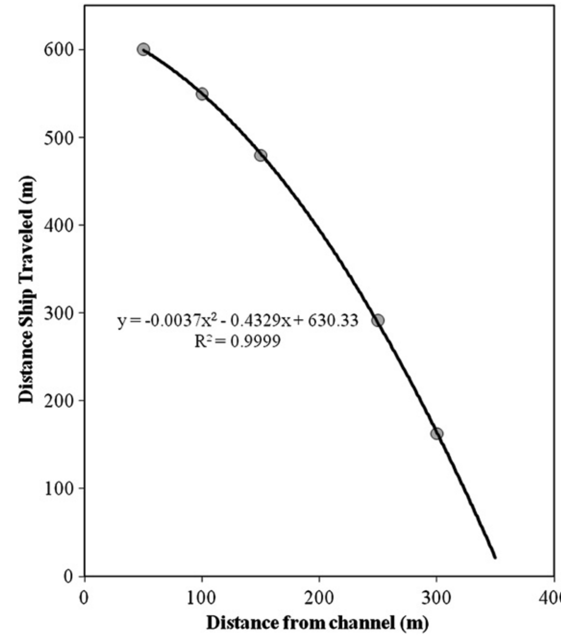

Fig. 5. Plane (aerial) view of the measured wake. Obtained by multiplying ship speed by differences in pressure sensor arrival times to determine the distance ship had traveled. Distance = 0 is when trough reaches first pressure sensor. The wake is well-described by the second order polynomial $y=-0.00037x^2-0.4339x+630.33$. At the channel (x = 0), the angle the wake makes with the channel is about 67°. The figure was intentionally plotted inversely in order to emphasize the shape of the wake that occurs (in an aerial view) of a ship traveling north.

is the depth of the trough. If the transit time of the signal is T between two pressure sensor a distance, D, apart, then $\alpha=\arccos(c*T/D)$.

3.2. Wake characteristics

Fig. 6 shows the propagation of the wake produced by the ship *Wehr Elbe* (length: 208 m, width: 30 m, draft: 9.3 m) through the field of pressure sensors. The *Wehr Elbe* was traveling north at a speed of 3.9 m s^{-1}. The initial wake profile (at PS1) showed a slight crest followed by a deep, asymmetric trough and a slightly larger, subsequent crest. The trough, however, is the principal characteristic with a trough depth, H, equal to about 17% of the water depth. It took 51.3 s for the trough to move the 250 m from PS1 to PS4. This corresponded to a wave speed of 3.13 m s^{-1} at an angle of 50° to the channel.

As the wake travels over the shoals, the depth of the trough decreased from 0.52 m at PS 1 to 0.25 m at PS4. This corresponded to a rate of change of 0.0018 m per meter of travel (perpendicular to the trough or 44° from the channel). The rear edge of the trough steepens with distance traveled (Fig. 6). The crest preceding the trough, being in deeper water, travels at a higher celerity, and outruns the trough. As a result, it becomes less pronounced as the wake travels over the shoal. Meanwhile, the crest of the wake following the trough, also being in deeper water, travels at a higher celerity and steepens the trough's rear edge as it tries to overtake the trough itself. The horizontal speed in shallow water waves is proportional to the water level elevation. The height of oscillatory waves behind the trough also increases with the distance traveled.

The records from *MSC Poesia* (293, 7, 8, 36; Fig. 7A) show the same features. The wake profile is initially a small crest followed by a deep, asymmetric trough and a trailing crest. The trough depth decreased with travel over the shoal. The leading crest moves forward away from the trough while the trailing crest steepens the rear edge of the trough. In general, frictional losses over shoaling water would tend to decrease the trough depth. Although we have only a few examples in

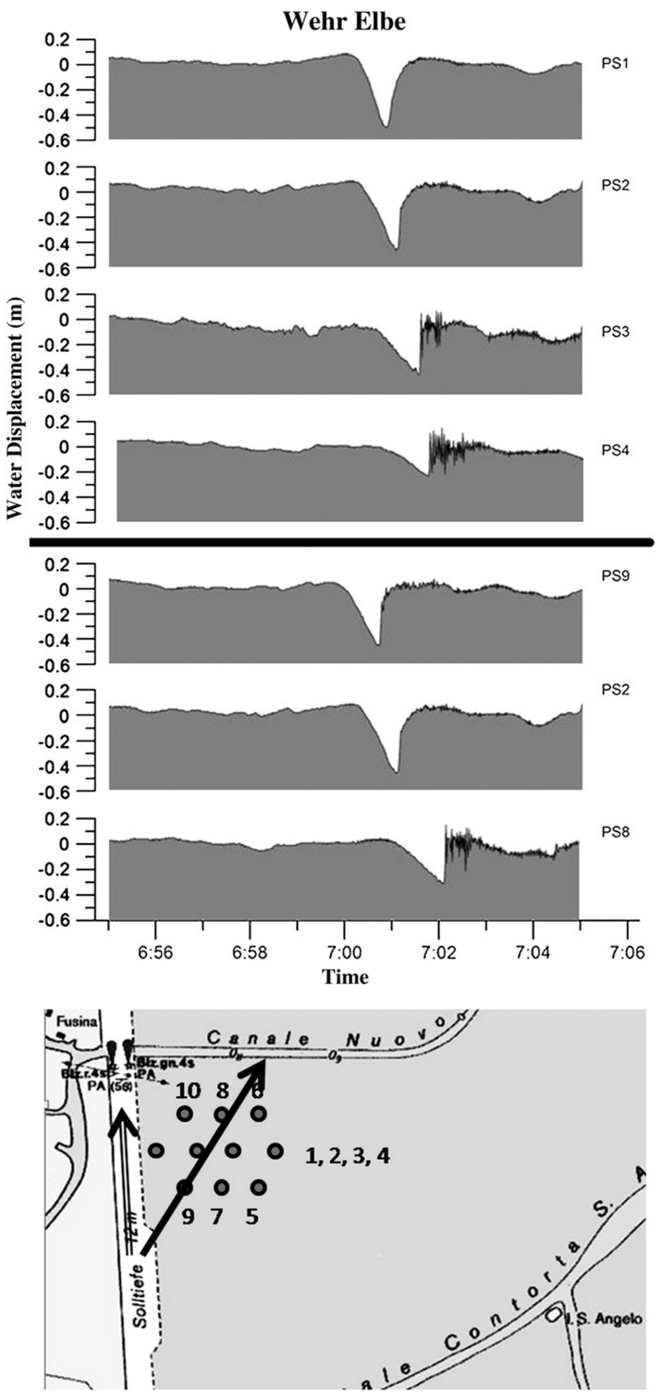

Fig. 6. Depth recorded by pressure sensors while in Layout 1, after the passage of *Wehr Elbe*. Layout 1 allows for the replication of the direction of the waves as seen in the inset. The first four graphs show the timing of the wave and the change in wave shape as it moves perpendicularly away from the channel. The second three graphs show the timing and wave dynamics in the direction of the wave as shown in the inset. Therefore pressure sensor 2 is repeated. The angle between the trough of the wave and the channel is approximated by the two arrows. This angle starts at 67° and averages 44° after the propagation over the shoals.

our data, when the trough depth starts out being greater than 0.5 m in this setting, the trough depth decreased as it traveled into shallower water in such a way as to keep $g = H/h$ equal to about 0.5 as the water depth decreased. There seemed to be some tendency for initially deeper troughs to be attenuated more rapidly as they propagated over the shoals, perhaps an expected result. Troughs of smaller initial depths propagated nearly unchanged over the shoals.

3.3. Wake-generated water velocities

As the Bernoulli wake travels across the shoal, the small crest preceding the trough produces water velocities of about 0.3 m s^{-1} (recorded at 0.5 m above the sediment surface by the S4 sensor) in the direction of travel of the wake (Fig. 8A,B). Water velocities then slowly increase to 1.4 m s^{-1} in the opposite direction of wave travel as water is drawn towards the shipping channel. Maximum velocities of 2.1 m s^{-1} are briefly produced as the steep, trailing edge of the trough passes. The trailing crest and any secondary waves following the trough generate water velocity less than 0.4 m s^{-1}. The maximum velocity recorded by the S4 sensor during the passage of each ship is listed in Table 1.

The weather conditions during this measurement campaign were variable with periods of wind (max. sustained wind 9 m s^{-1}) and precipitation (data from the municipality of Venice). The winds increased the baseline SSC concentration level, to 12 mg L^{-1} on average but occasionally reached above 20 mg L^{-1}. No correlation was observed between background current velocity and the magnitude of the resuspension event (Table 1). Of the 40 waves listed in Table 1, twenty produced a SSC change of greater than 100 mg L^{-1}. The maximum suspended sediment concentrations from each resuspension event were well correlated with both maximum water velocity recorded at 0.5 m above the sediment surface and maximum shear stress calculated with the Sedtrans05 (Fig. 9). Vessel velocity, length, width, and draft; wave height, SSC event data and water velocity data associated with each resuspension event are reported in Table 1. In some cases SSC exceeded the maximum detection limit of the sensor, we report only the calculated values rather than attempting to determine the actual maximum value through the reproduction of the curve based on settling velocities, due to complications associated with current and sediment transport away from the sensor.

When consecutive ships pass the sensor within minutes of each other, the increase in water velocity towards the shipping channel can occur while SSC is still high from the previous Bernoulli wake. In Fig. 10 we show the data relative to vessels *MSC Leader* (201, 23, 6.7) and *Grande Sicilia* (177, 31, 8.3) which passed our instruments within 10 min of each other on July 8th. The waves from both ships lead to high SSC concentrations with *Grande Sicilia* causing an event beyond the maximum detection limit of the S4 OBS sensor. The resuspension event caused by *MSC Leader* is recorded after the wake had already passed the sensor and the water velocity had returned to the low background speed. It appeared that the majority of the sediment, which is resuspended, will re-settle very close to the spot from which it was removed. However as *Grande Sicilia* passes, the water velocity increases up to 2.1 m s^{-1}, more than an order of magnitude higher than the typical tide and wind driven current speeds (Coraci et al., 2007). Water is, therefore, drawn with entrained sediment towards the channel very quickly and for up to 100 s before the wake of *Grande Sicilia* passes the S4 sensor, effectively returning the current velocity to background levels.

4. Discussions

4.1. The effect of vessel navigation on sediment resuspension in Venice Lagoon

As the vessel velocity increases and as the size of the vessel in relation to the channel cross-section increases, the height of the Bernoulli wake usually increases. Schoellhamer (1996) concluded that wave height is determined by a combination of the depth-based Froude number (Fr), which is based on the velocity of the ship (v) gravity (g) and the depth of the channel (h) (where $Fr = v(gh)^{-0.5}$) and the blocking coefficient (S) of the ship, which is the ratio of product of the ship's width (B) and draft (D) to the product of the width (b) and depth (d) of the channel, that is $S = (B*D)/(b*d)$.

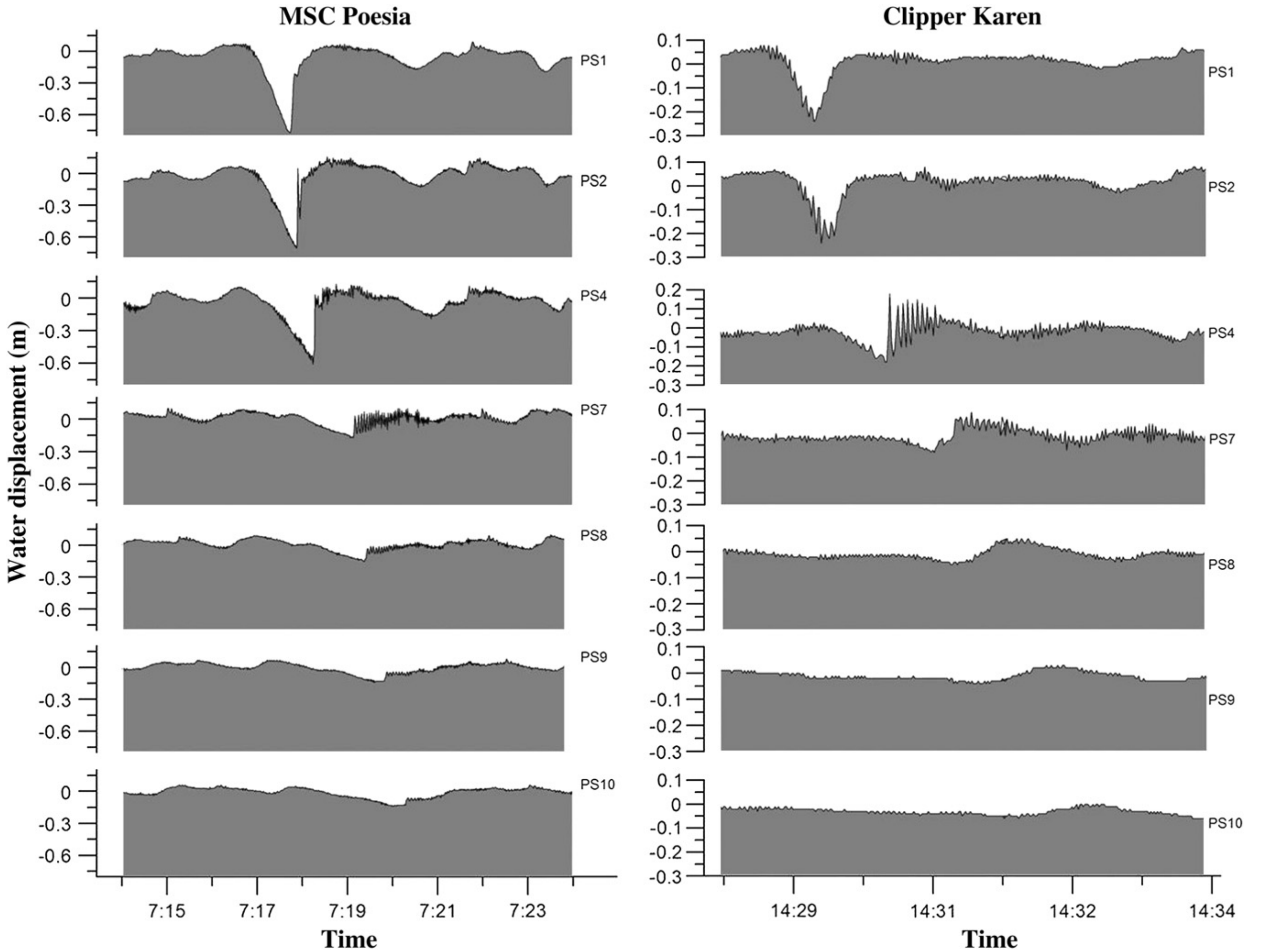

Fig. 7. Depth recorded by pressure sensors while in Layout 2, which allows for the measurement of the propagation length of the wave. A: after the passage of *MSC Poesia*. B: after the passage of *Clipper Karen*.

Schoellhamer (1996) found when using the relationship $Fr^{2.4}S^{1.6}$ there was a linear correlation with non-dimensional wave height ($\gamma = H/h$). A relationship determined on the basis of our measurements was slightly different than Schoellhamer; in Venice Lagoon the best-fit relationship ($r^2 = 0.57$, $p < 0.001$) was found empirically to be $Fr^{3.5}S^{1.6}$, suggesting an enhanced importance of the ship's speed in Venice Lagoon (Fig. 11A). The difference in the relationship presented in this study and the study of Schoellhamer (1996) is likely due to the different wake components measured to determine wave height.

Neither the total resuspension nor the duration alone can fully account for the magnitude of the resuspension event, but rather an integration of the two parameters is needed (Erm and Soomere, 2006). The duration of the event depends on both the settling speed of the resuspended sediment and the rate of advection of the resuspended sediment past the sensor. We would expect the settling speed of resuspended particles to be constant. At a nearby site, Amos et al. (2004) measured a settling speed of 0.00073 m s^{-1} in the summer of 1998. In principle, it would require about 35 min for the water column to clear of SSC due to settling alone. This is consistent with the observed duration of elevated suspended sediment concentration; the advection due to tidal currents is weak.

The total impact of the wakes can be described by an "SSC number" in mg s L^{-1} (given as "M" by Erm and Soomere, 2006). The quantification of the SSC number is accomplished by integrating the area below the resuspension peak as recorded by the OBS ($SSCnumber = \int_{t1}^{t2} SSC$). Successive events, which interrupted the volume of the peak, were estimated by the exponential decrease in the resuspension curve. The SSC number correlates fairly well with the non-dimensional wave height (Fig. 11B; $r^2 = 0.68$, $p < 0.001$). Extremely large resuspension events were recorded after the passage of the ships *Grande Sicilia* (177, 31, and 8.2), *Novorossiysk Star* (180, 26, and 7.7), *Hellenic Voyager* (193, 27, and 7.3), and *Wehr Elbe* (208, 30, and 9.3) (Table 1). In these cases, the SSC went beyond the maximum detection limit of the OBS sensors and therefore the obtained SSC number is certainly an underestimate.

Resuspension events occur when bottom shear stress exceeds the threshold for sediment erosion to occur. Amos et al. (2004) reported bottom shear stress thresholds of 0.7–0.8 Pa for this section of Venice Lagoon. Although bottom shear stress could not be directly measured, theoretical values of shear stress from each Bernoulli wake, for the measured grain size ($d_{50} = 0.03$ mm), were calculated using the program 'Sedtrans05' (Neumeier et al., 2008). Of the 40 events recorded by our instruments, 32 exceeded the threshold stress reported by Amos et al. (2004), and corresponding SSC events are very small below this value. Fig. 9B shows the correlation ($r^2 = 0.88$, $p < 0.001$) between calculated maximum bottom shear stress of each event and the corresponding SSC number. The x intercept of the regression line is at 0.69 Pa, which is in very good agreement with the reported shear stress threshold of Amos et al. (2004). Results from 'Sedtrans05' also show that the bed shear stress generated by the wave and the background current is much higher than by the current alone.

As an empirical expedient, we established a new parameter by multiplying the Schoellhamer relationship, with the exponents

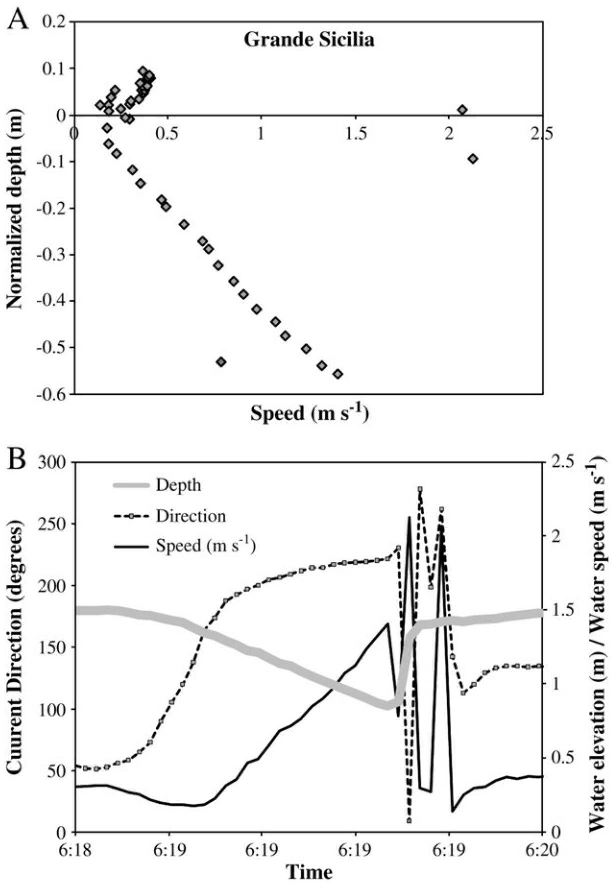

Fig. 8. A. Water velocity vs. depth normalized to the pre-disturbance water level after the passage of *Grande Sicilia*. Water velocity increases in the direction of the channel (opposite the direction of wave propagation) as the drawdown occurs. When the rear edge of the trough reaches the sensors, velocity increases immediately to around 2 m s^{-1} as water level increases to pre-disturbance depth. B. Water velocity, water current direction, and actual water depth is shown for the same wake as above. The sensor was pointing to the northeast, therefore 200° from the sensor heading reveals water current direction towards the channel opposite to wave propagation.

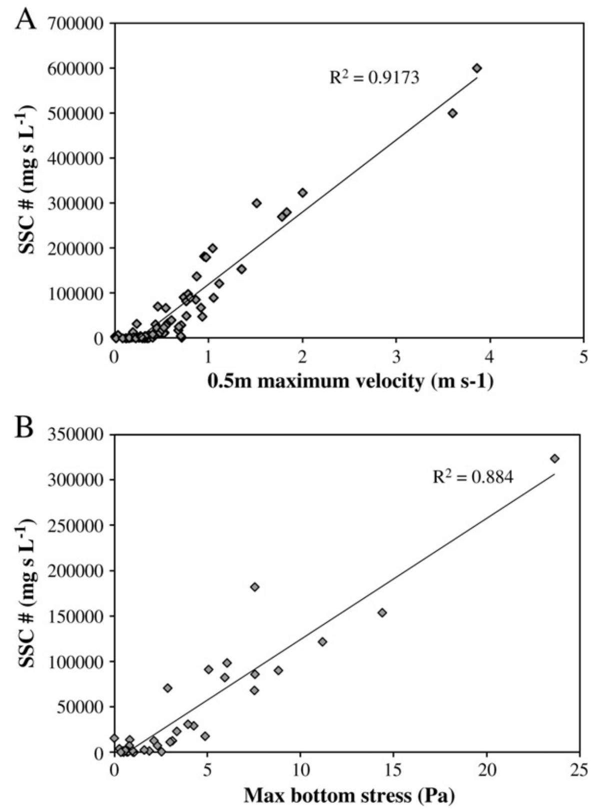

Fig. 9. A. SSC # as a function of maximum water velocity as recorded by the S4 sensor at 0.5 m above the sediment surface. B. Maximum bottom shear stress (Pa) calculated using the program Sedtrans 05 vs. the SSC #.

previously determined in Venice Lagoon, by the ratio of the ship's length (l) and the shoal's water depth (h). This modified Schoellhamer relationship (MSR) is then $Fr^{3.5}S^{1.6}\, l\, h^{-1}$. The MSR was correlated to the SCC number (Fig. 12; $r^2 = 0.84$, $p < 0.001$). Using the results of this correlation a threshold was set for all resuspension events marked by a SSC number greater than 35,000 mg s L^{-1}, which occurs at an MSR value of 0.7 (Fig. 12). If an MSR equal to 0.7 is considered to be the threshold for major resuspension events to occur, we can calculate maximum vessel operating velocities with respect to water level. This maximum safe velocity can be simply and quickly calculated on a ship-by-ship basis (Table 1). If the threshold value is not exceeded, large waves with high current velocities will not be generated. This will greatly reduce the magnitude of resuspension events in the lagoon. According to this threshold we can recommend a maximum navigation velocity coincident with minimum resuspension (Table 1). For example, the vessel *Novorossiyk Star* traveled past our sensors at a speed of 4.37 m s^{-1} at a tidal level of 2.09 and leading to an MSR value of 1.29. In order to reduce this value to 0.7 at the same tidal level, the ship would have to reduce its navigation velocity to 3.67 m s^{-1}.

4.2. Bernoulli wake as a source of erosion

A recent study by Molinaroli et al. (2009) has revealed evidence that significant erosion along the investigated shoals occurred over the last three decades, effectively deepening the shoals by more than 0.5 m near the Malamocco–Marghera channel. Bottom shear stress near the threshold value for erosion to occur (0.7 Pa) should be expected under Scirocco wind conditions in the vicinity of the Malamocco–Marghera channel (Umgiesser et al., 2004). While this would cause much lower concentrations than those due to ships' wakes (Fig. 9), they would impact a larger area and may persist for longer time periods. However, annual hourly wind data show that the occurrence of large Scirocco wind events are rare and that wind-generated waves rarely are greater than 0.5 m (Goda, 2003). Meanwhile, navigation is almost constant year round (as stated earlier, statistical analyses of the Port of Venice show that more than 4000 ships enter the port annually at least two-thirds of which pass through the Malamocco–Marghera channel), often producing large wakes, which lead to the inference that shipping-induced waves are a factor leading to erosion in this area of Venice Lagoon (http://www.port.venice.it/pdv/Home.do?metodo=carica_home).

Our data (Fig. 10) suggests that the impact of ship induced resuspension events is magnified when several ships pass by the shoals in close temporal proximity to one another. This is often the case as groups of ships are allowed to enter and exit the lagoon in succession. Series ship's wakes will draw the suspended sediment from the previous wave towards the channel because of the Bernoulli pressure phenomenon. The overall process can be represented by a stepwise movement of sediments, which is triggered by the successive passage of ships and is always directed toward the channel independent of the ship direction (northward or southward). Because dredged channels are already out of equilibrium with the ambient, depositional environment, accumulation rates tend to be much higher in channels than on the neighboring shoals. It would seem that sediment resuspended on the adjacent shoals would likely be deposited in the channel. As a result, the process of ships' wake resuspension may lead to the need for more frequent dredging. In addition, multiple ships may increase the impact of sediment

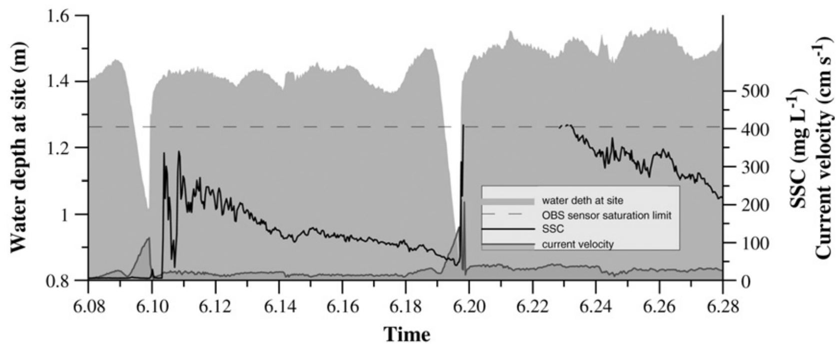

Fig. 10. Measured water depth (gray background), current velocity (black line with shadow), and suspended sediment concentration (black line) during the passage of the *MSC Leader* and *Grande Sicilia* within 10 min of each other on 8 July. The passage of the depression wake from both ships is clearly recorded by the instruments with the first wake passing between 6:09 and 6:10 am and the second between 6:19 and 6:20.

resuspension due to increasing instability of the benthic layer and susceptibility to erosion with the passage of each successive ship.

4.3. Theoretical wake profile

The observed wake profiles appear to take the form of an N-wave (Fig. 13; Tadepalli and Synolakis, 1996) with the trailing edge of the trough being steeper than its leading edge and followed by a small crest. The dominant features of these wakes include an inverted soliton contributing to the leading trough. Although the similarity of the wave form to an N-wave may be coincidental, it seems possible that an N-wave form repeatedly witnessed within this study could be generated by the sudden, Bernoulli depression along the side of the ship.

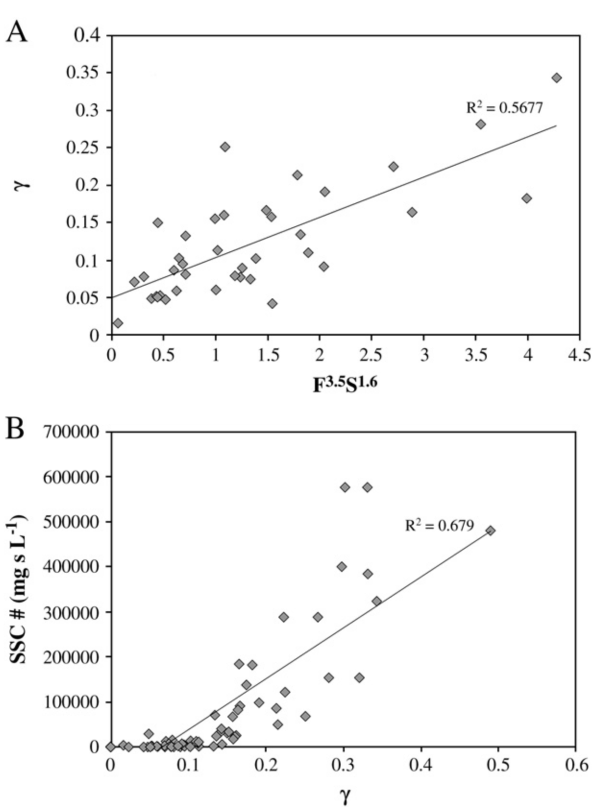

Fig. 11. A. Non-dimensionalized wave height as a function of the empirical Schoellhamer relationship B: SSC# as a function of non-dimensionalized wave height.

5. Conclusion

The particular situation in Venice, as in many industrial ports, has large, slow moving vessels traveling in deep channels cut through shallow water areas. Often, the ships occupy a significant fraction of the channel cross-section. In this study we have shown that ship wakes progress at an average angle of 44° to the channel. We have found that the principal feature of the wakes is a depression wave of substantial height. The trough of the wake is preceded by a much smaller crest and followed by a slightly larger crest. The depth of the trough decreased (due to friction) and the rear edge of the trough steepened as the wake progressed over the shoals. Meanwhile, the greatest water velocities (up to 2.1. m s^{-1}) are produced under the rear edge of the trough; resuspension principally occurred with the passage of the rear edge of the trough; concentrations increased with increasing size of the trough and decreasing water depth. The magnitude of the SSC event was correlated with the non-dimensional wave height. Not all ships created large effects. In fact, only about 40% of the shipping-induced waves were associated with changes in SSC of more than an order of magnitude above background SSC. Sediment resuspension thresholds were determined for the measured median grain size based on wave height and water current velocity, which determines bottom shear stress. These thresholds matched very closely with experimental sediment resuspension data calculated from wave heights and both are higher than numbers previously reported for Venice Lagoon.

Water was drawn at velocities ≤ 1.4 m s^{-1} in the opposite direction of wave propagation and was observed to occur for tens of seconds before the rear edge of the trough passed the sensor. This phenomenon of opposite directions for wave propagation and water flow, though very important for sediment transport and dredging issues, is rarely reported in the literature.

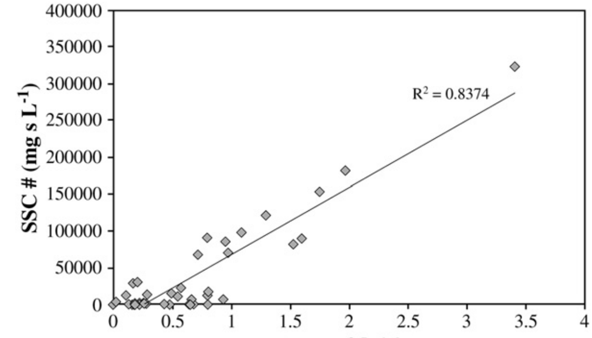

Fig. 12. SSC number as a function of the modified Schoellhamer relation (MSR).

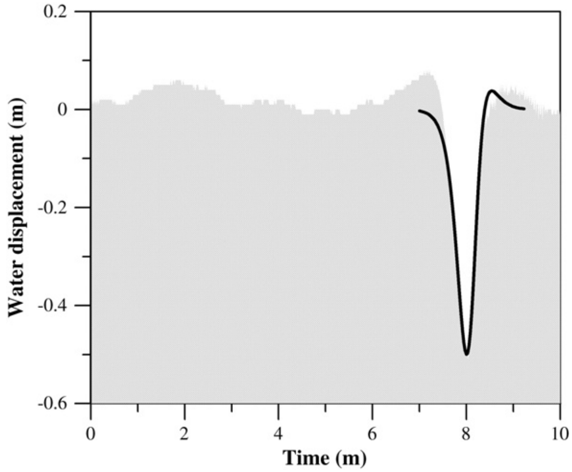

Fig. 13. Comparison of the measured water elevation as the wake from the vessel *Wehr Elbe* passes PS1, which is represented by the gray background, to a calculated N-wave profile, which is represented by the solid black line.

With the wave and vessel data, we modified the Schoellhamer relation (MSR) to satisfactorily describe the impact of ship waves. Our results suggest that if the ships can be regulated to travel below the critical threshold level of the MSR which causes the formation of these strong waves, the amount of sediment resuspension in the central Venice Lagoon and related harmful effects can be controlled.

Further research needs to be done to better understand the propagation of waves along the shoals, the depth to which resuspension occurs, the ecological impact of resuspension events, and how multiple ship passages affect the process. Erosion occurred along the shipping channel over the last 30 years and the impact of commercial vessels is likely to be one of the important factors in this erosion. The ramifications of this issue may increase in the case of an expansion of the port traffic and a deepening of the existing navigation channels, as was recently suggested in international media e.g. (Associated Press, 2009). This problem is not isolated to Venice Lagoon; it is an issue affecting many ports around the world. A better understanding of the coupling of vessel parameters and sediment resuspension is crucial as this large industry continues to grow within the global economy.

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