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Ship-wake induced sediment remobilization: Effects and proposed management strategies for the Venice Lagoon

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ABSTRACT

More than 3000 commercial vessels navigate through the Malamocco-Marghera Industrial Canal in Venice Lagoon, Italy in a given year, leading to an estimated annual resuspension of 1.2×10^6 metric tons of sediment. Hence, ship wakes contribute to the significant erosion of shoals in the central lagoon which has occurred over the last 30 years. Drawdown associated with the surface depression wave from successive ships induces sediment transport towards the shipping canal, where the cost of dredging amounts to tens of millions of Euro per year. Most ship traffic occurs near an industrial zone, resulting in substantial potential for resuspension of contaminated sediment. Thus, sediment resuspension by ship traffic in the Venice Lagoon has the potential for detrimental economic and environmental impacts.

This paper illustrates the impacts of ship induced depression waves and discusses management options for mitigating those impacts, based on extensive observational data and analysis conducted in Venice Lagoon, Italy. This article helps to further the understanding of the processes that govern sediment transport along the shipping channel and employ this knowledge to develop specific management recommendations.

A reduction in the navigation speed of ships, an increase in the distance between successive ships, and limiting navigation to tidal levels above 0.3 m from the local 1897 reference mean sea level can help to minimize these problems.

1. Introduction

In order to divert the route of cruise ships from the historic center of Venice, the Port of Venice has recently proposed a project for the construction of a new navigation channel from the existing waterway, which connects the Malamocco Inlet with the Porto Marghera Industrial Zone (PMIZ) to the passenger terminal located in the southwestern part of the city. This new navigation channel will considerably increase the already heavy traffic in the commercial shipping pathway in the lagoon of Venice.

Designated as a UNESCO World Heritage Site, the entire lagoon is an environmentally sensitive area (Suman et al., 2005). While much attention has been given to the environmental impact of the MOSE Project (a system of barriers designed to protect the city of Venice from frequent flooding events) (e.g. Strozzi et al., 2009), there has been little discussion about the impact of the navigation of large vessels through the naturally shallow coastal lagoon (Ciavola, 2005; Gelinas et al., 2012; Rapaglia et al., 2011; Parnell et al., 2015).

Navigation of large vessels in semi-enclosed and/or narrow coastal waterways presents several environmental concerns. Some of the more pronounced issues include the introduction of exotic species through ballast water release; the emission of effluents into

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the water and exhaust into the air; and the release of contaminants from anti-fouling paint (Goldberg, 1995; Hayes and Sliwa, 2003; Ricciardi and Rasmussen, 1998). Much attention has been given to these impacts, but relatively little discussion has concerned the entrainment, transport and deposition of sediments both within shipping channels, on nearby shoals, and along the coast from the propagation of wakes (Ciavola, 2005; Erm et al., 2009; Gelinas et al., 2012; Houser, 2010; Parnell et al., 2008; Rapaglia et al., 2011; Schoellhamer, 1996; Soomere, 2006; Soomere et al., 2009). When vessel wakes interact with bottom sediments they create high near-bottom current speeds and shear stress leading to sediment resuspension and eventually shoreline erosion processes. As these waves propagate to the shoreline they are often marked by high wave energy flux and can erode beaches and salt marshes (Houser, 2010; Parnell et al., 2008). The erosion of these environments leads to unusually high suspended sediment concentrations, and this increase in turbidity can be detrimental to the health of the waterway (Kucera-Herzinger et al., 2009). Increased turbidity from sediment resuspension can affect phytoplankton abundance, causing trophic cascades in biological food webs (Eriksson et al., 2004). The degradation of organic matter that adheres to these fine-grained sediments requires oxygen; therefore increased turbidity may also contribute to benthic anoxia. Elevated water speed from the passage of ships can reduce or prevent the development of aquatic vegetation and benthic algal communities (Eriksson et al., 2004; Francoeur and Biggs, 2006) and possibly harm the development of juvenile fish communities (Kucera-Herzinger et al., 2009; Wolter and Arlinghaus, 2003; Wolter et al., 2004). The remobilization of contaminants from sediments impacted by vessel wakes may present an important pathway for contaminants to re-enter the water column (Bloundi et al., 2009; Pettibone et al., 1996).

Much of the central Venice Lagoon has been subject to erosion since the building of the Malamocco-Marghera Industrial Canal (MMIC) in 1970 (Bettinetti et al., 1996; Molinaroli et al., 2009). While the building of this canal most certainly changed the hydrodynamic processes of the lagoon, it is unlikely that the increase of currents through these channels is fully responsible for the large volume of sediments lost, not only in the channels but along the shoals near the channels, since 1970. Over 50 cm of sediment has been lost throughout much of the area (Molinaroli et al., 2009), and hence, it is likely that there is an additional force acting on sediment transport and erosion in the central lagoon.

This aim of this paper is to illustrate the impacts of the depression waves (otherwise known as Bernoulli waves or wakes) generated by ships on sediment transport processes and then utilize this information to discuss management options for the mitigation of the impacts. Pressure sensor data from 28 vessel wakes in 2009 enable the assessment of the propagation of ship wakes outside the shipping channel. These data are utilized to calculate sediment transport, where sediment is transported to, and links the processes to sediment entrainment and shoreline erosion which is known to have occurred in the central lagoon between 1970 and 2000 (Molinaroli et al., 2009). We attempt a first order calculation of the annual volume of sediment resuspended on the shoals by ship wakes and compare this number to dredging estimates from the MMIC. Due to its proximity to the PMIZ, many of the sediments have high concentrations of contaminants (Bellucci et al., 2002; Zonta et al., 2007) that may also be remobilized. As it is possible to modify the parameters of ship wakes by changing the operation of the vessels (Rapaglia et al., 2011), we recommend that the reduction in speed of large ships will reduce dredging costs and improve water quality in the lagoon of Venice. In addition, we believe that these impacts must be considered if the Port of Venice decides to construct a new, larger navigation channel.

1.1. Ship wakes and their effects

Entrainment (including resuspension) of sediment, caused by the propagation of ship wakes over shoals, is dependent upon the characteristics of the waves produced by the passage of the ship, which in turn are determined by vessel draft, width and length, speed and other operational factors such as trim, as well as the size of the navigation channel through which the vessel is traveling (Schoellhamer, 1996; Parnell and Kofoed-Hanson, 2001; Soomere, 2007). These factors determine the properties (types, shape, steepness, height, period, etc.) of the wave or wave groups generated by the passage of the ship.

A ship moving through deep water creates a classical Kelvin wake wave. In shallow water, defined in terms of the ratio of water depth to wavelength of the disturbances, the situation is quite different, with many different wave types (linear and nonlinear) and groups being produced. The key determinant in this context is the dimensionless depth-based Froude number

$$Fr = V\Big/\sqrt{gh}$$

where V is the ship speed (m/s), g is the gravity constant and h (m) is water depth (see Parnell and Kofoed Hansen, 2001; PIANC, 2003; Soomere, 2007; 2009 for reviews). At Fr near or exceeding 1, linear wave theory can only be conditionally applied, and wave groups of many different types are generated including precursor solitons, long crested leading waves, Kelvin waves, and various ‘envelope’ wave packets of often small but very steep waves (Soomere, 2007). In shallow navigation channels (such as the MMIC described in this study), ships tend to move slowly, leading to Depth Froude numbers less than 1 (typically 0.3–0.5 in our case), with the Kelvin wakes being very small, and having limited effect on sediment entrainment and erosion.

However, a vessel traveling in shallow water (such as a navigation channel) forms a depression in the water surface around the vessel (frequently called ‘squat’, Gourlay, 2008), caused by the displacement of water by the vessel and the increase in water velocity around the sides of the boat. An increase in velocity must lead to a decrease in pressure thereby causing a depression in the water surface below and on the sides of the boat. This feature causes the depression wave (Soomere, 2007) (alternatively called Bernoulli wave) which can propagate as a highly non-linear, asymmetric wave onto adjacent shallow-water areas (Parnell et al., 2015).

As depression waves propagate onto the shoals they result in high current speeds for tens to hundreds of seconds. This extended period of high current speeds, as well as the amplitude of the wave, increases the potential to produce high bottom shear stress for a long period of time, significant sediment entrainment, resuspension and transport (Houser, 2010; Rapaglia et al., 2011) potentially exposing deeper layers of sediment to entrainment and allowing for the remobilization of contaminants within sediments (Ciavola, 2005; Rapaglia et al., 2011).

1.2. Study site: Venice Lagoon

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 generally very shallow with an average depth of 0.8 m; however, a network of natural and dredged channels (depth > 5 m) cut through the shoals and are in some cases maintained by an active dredging program (Fig. 1). The lagoon is connected to the sea by three inlets with a mean total tidal discharge of 6500 $m^3\ s^{-1}$ (Gačić et al., 2002).

One of the major modifications to Venice Lagoon was the

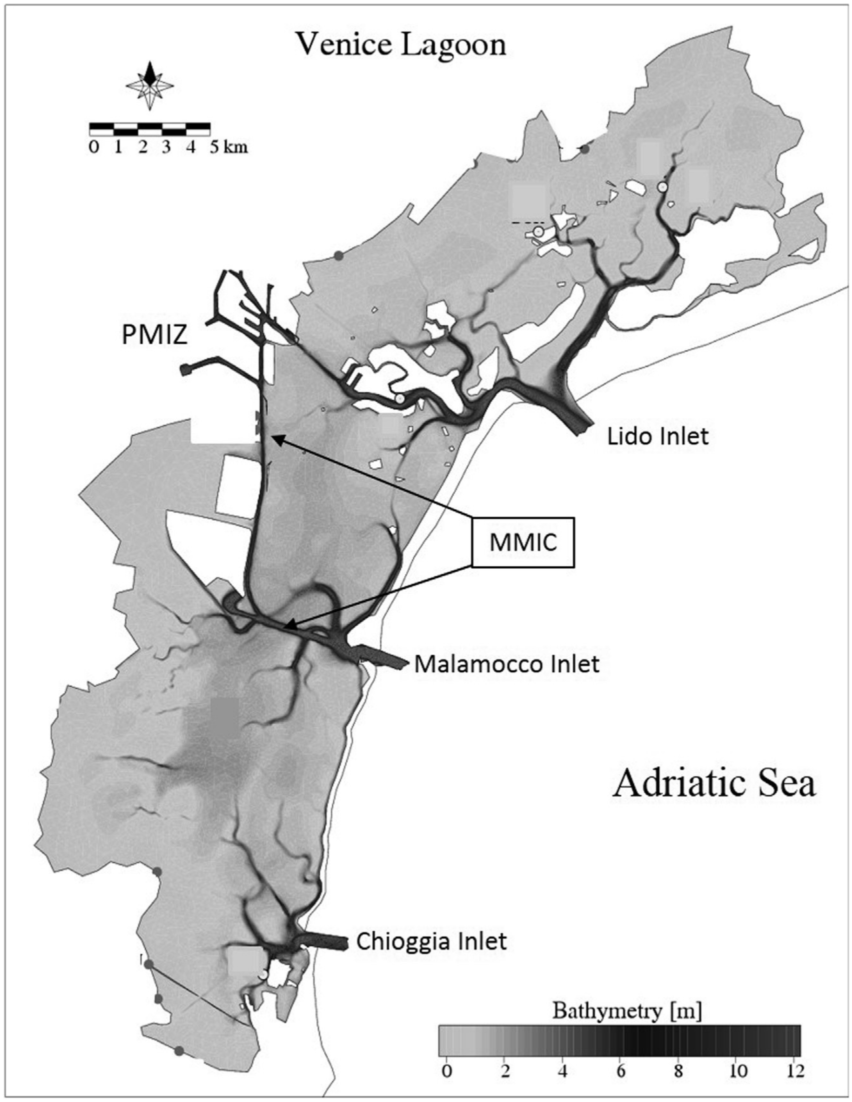

Fig. 1. Bathymetry of the Venice Lagoon (50 m resolution). Darker colors show deeper water. Depth is in meters, below mean sea level. Background image courtesy of C. Ferrarin.

development of the Porto Marghera Industrial Zone; built between 1920 and 1970 (PMIZ; Belluci et al., 2002; Suman et al., 2005). It contains several important industrial sectors (petroleum refineries, chemical industries and power plants). Byproducts of some industrial processes were previously discharged directly into the lagoon or deposited on the marshland surrounding the industrial district (Suman et al., 2005). Many of the associated contaminants spread into the sediments of the adjacent lagoon (Bettinetti et al., 1996; Belluci et al., 2002). The quality of the sediment near the industrial zone was considered to be so poor that the entire area was designated a “contaminated area of national interest” in 1999 (Zonta et al., 2007). More recent evidence, however, suggests the quality of the uppermost lagoon sediment in the vicinity of the PMIZ is slightly improving (Secco et al., 2005; Zonta et al., 2007).

Concurrent with the development of the PMIZ, a new channel known as the MMIC (or locally known as Canale dei Petroli) was dredged from the Malamocco Inlet to the PMIZ. This channel, completed in the early ‘70s, 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 (Fig. 1). The shallow-water area extends 5–8 km east of the channel for its entire length. The bathymetry of the shoal has depths between 1 and 2 m below mean tidal water level (Fig. 1). In many locations a wave can travel unimpeded over the shoal for several hundred to thousands of meters until it is dissipated naturally through bottom friction, whitecapping, and depth-induced breaking. Our study site is located on this eastern shoal, 2000 m south of the PMIZ and directly seaward of the area known as Fusina (Fig. 2).

Molinaroli et al. (2007, 2009) describe the sediment 500 m from our study site as class 2 sediment; “very silty slightly sandy mud”, and correlate the grain size to average background current velocity and wave regime in the area. Zonta et al. (2007) reported several cores in the area and found the sediment to be characterized by a silt–fine sand fraction with 20–40% mud (Fig. 3). Interestingly, Zonta et al. (2007) found a decrease in the mud fraction in the upper sediments closest to the industrial channel corresponding to those sediments resuspended by currents and waves (2007). This will be discussed later in the paper.

2. Methods

A suite of instruments was utilized to simultaneously record water depth, current speed and direction, and turbidity. A transect consisting of a calibrated optical backscatter sensor (OBS), an S4

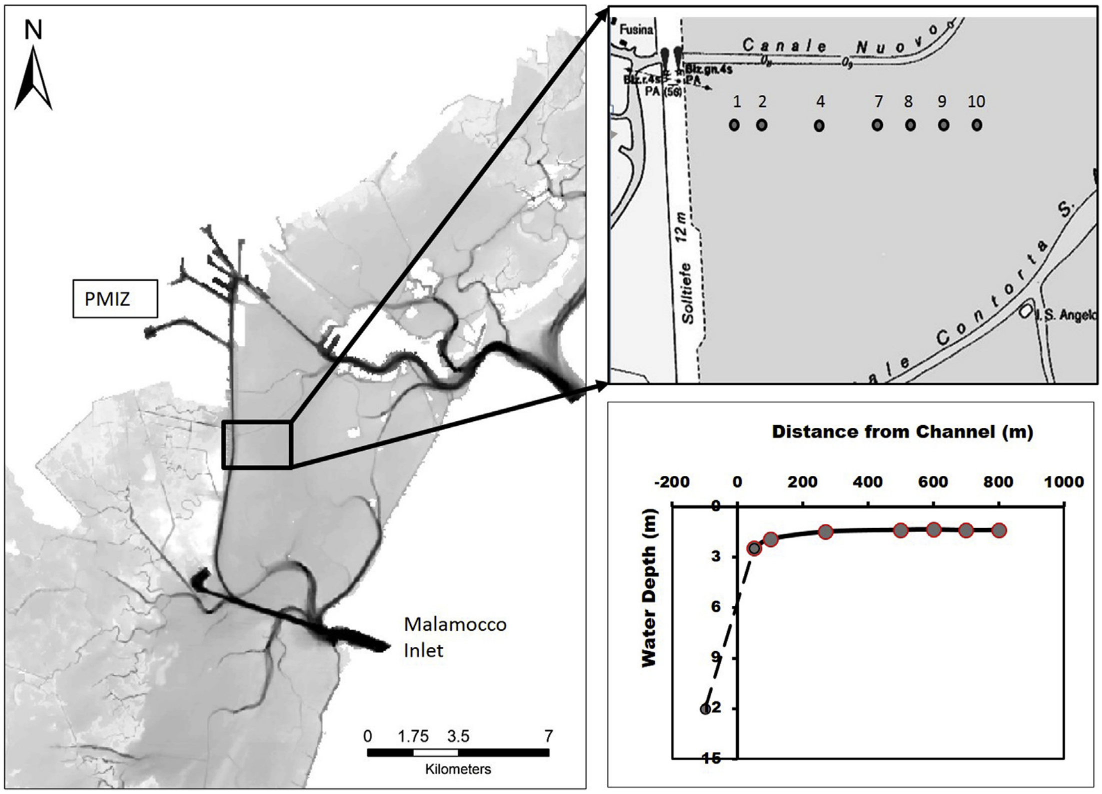

Fig. 2. The study area and location of instruments within the Venice Lagoon. The upper inset shows the pressure sensor layout. The bottom inset shows a depth profile of the pressure sensor transect.

electromagnetic current meter, and pressure sensors was emplaced between July 6–18, 2009 two km south of the PMIZ on a shoal east of the channel (Rapaglia et al., 2011; Fig. 2). Due to the relatively homogenous sediment found in the area (Fig. 3) and the short deployment times, the calibration of the particular OBS instrument was made with a large series of manual samples collected with siphon bottles or with an autosampler (Rapaglia et al., 2011). All instruments were set to measure at a rate of 1 Hz which is

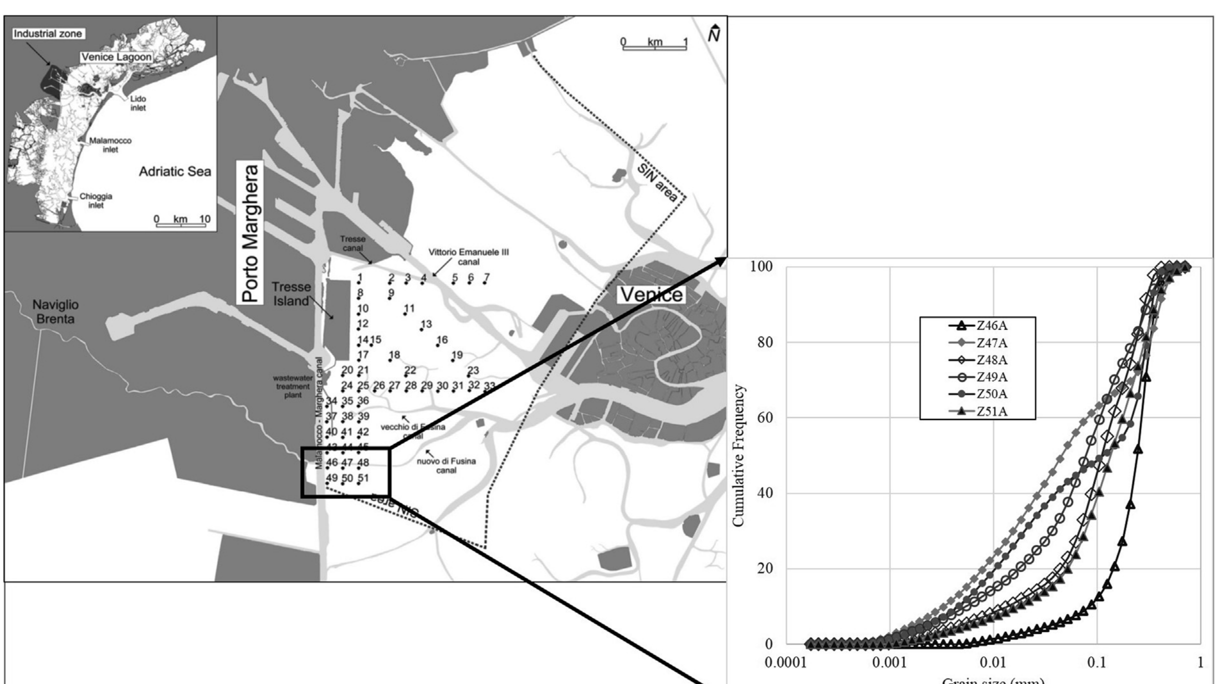

Fig. 3. Grain size distribution curves from 6 cores in the area of the Fusina study site. These cores were collected for a previous study on heavy metal pollution in the Porto Marghera Industrial Zone. All cores (including the six relevant cores) for that study are found in the larger image (which is modified from Zonta et al., 2007).

appropriate to measure long-period perturbations like the depression wave.

Pressure sensors were deployed in a channel-perpendicular transect in an attempt to quantify the propagation distance of the wave onto the shoals. Seven pressure sensors were set in order from PS1-PS10 (PS3, 5, and 6 malfunctioned) at a distance of 50 m, 100 m, 300 m, 500 m, 600 m, 700 m, and 800 m east of the channel in depths ranging from 2.5 m (PS1) to 1.5 m (PS10) below mean sea level. There was little change in depth from PS4 to PS10 (Fig. 1). As the sensors were in shallow water, pressure attenuation correction was not applied. Wave height is calculated as the difference between the elevations of the maximum trough and the following peak.

Water velocity data and sediment concentrations were used to determine total transport of sediments in each wave.

3. Results

Results from a different experimental setup at a nearby location, which showed that depression waves are indeed controlled by the speed and size of vessels, and that these depression waves lead to major resuspension events, are reported in Rapaglia et al. (2011) and Gelinas et al. (2012).

Suspended sediment concentration (SSC) measured using calibrated OBS sensors shows that elevated SSC events are directly linked to the propagation of depression waves across the shoals (Fig. 4). High SSC (>100 mg L^{-1}, turbidity >30 FTU) are measured after the passage of large amplitude wakes (>0.3 m), and, in general, SSC increase is inversely correlated with tidal elevation. Fig. 5 shows the relationship between current velocity during the passage of a ship depression wave. As the depression wave propagates onto the shoals, the related drawdown (the modified pressure field) increases water speed up to two orders of magnitude beyond background speed in the direction of the canal (Fig. 5). This increase in speed leads to the entrainment of sediment. Current direction shows a slow reversal in current towards the ship (220°) as the depression wave draws water off the shoals. Current speed increases towards the channel for tens of seconds before the depression wave peak (surge) reaches the sensor. Maximum SSC at 0.5 m above the sediment–water interface is achieved as the peak speeds are recorded on the S4 sensor (Fig. 4), and immediately after the passage of the wake, current speed returns to or close to background levels. Successive depression waves can be formed while SSC concentrations are still high, increasing the water speed in the direction of the canal (Fig. 6). It is important to note that

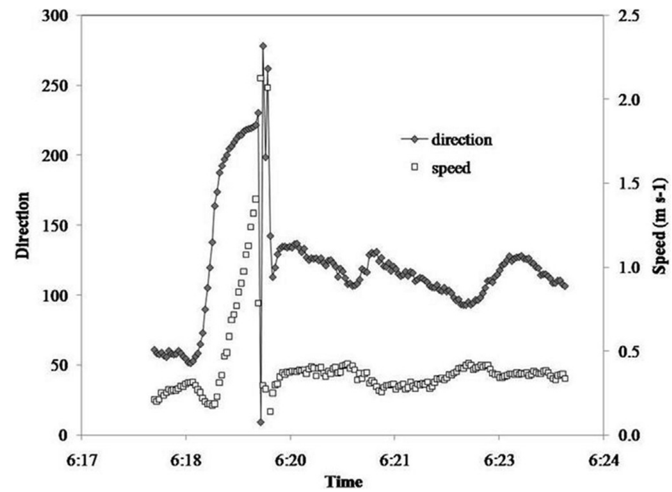

Fig. 5. Current speed and direction during the passage of a ship's depression wave measured by the S4 sensor.

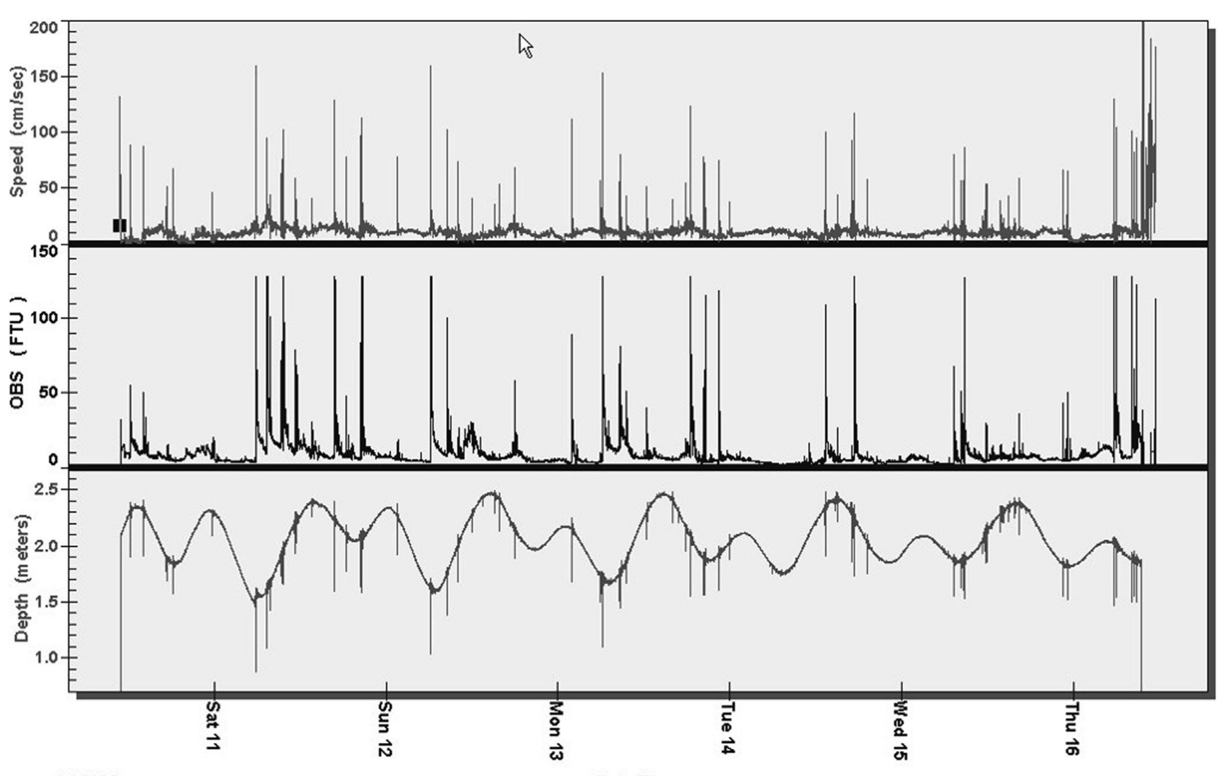

Fig. 4. Time series recorded by the S4 electromagnetic current meter with built/in OBS sensor and pressure sensor.

some of the sediment in suspension measured by the sensors is due to lateral advection associated with the wave, and therefore may not be necessarily associated with the sediment entrained directly below the sensor. We assume, however, that our sensor is a proxy for processes occurring over the shoals and that there is a balance between settling and resuspension as the wave moves over the shelf.

Twenty-eight ship wakes passed the pressure sensors, 22 of which were recorded by all of the pressure sensors to a distance of 800 m onto the shoals. When a large depression wave is formed all instruments recorded a slow drawdown (up to 90 s) of the water level before the passing of a wave (Fig. 6). The presence of a drawdown is irrespective of the wave height at the sensor, however generally higher waves are associated with longer drawdown periods and higher current speeds (Rapaglia et al., 2011).

From the large amount of data recorded by the pressure sensors, we show and describe in detail two cases in order to estimate the propagation length of the wake (Fig. 7). Fig. 7A shows the propagation of the wake from the vessel *Magnos* (149 m length, 20 m width, 8.6 m draft) as it passed northward through the shipping channel. The wave recorded at PS1 is marked by an initial drawdown followed by an instantaneous increase in wave height of ~1.8 m, followed by a further drawdown as seen in each of the other pressure sensors. We do not know the cause of the sharp increase of 1.8 m in water elevation as recorded in PS1 during the initial drawdown phase of the wave from *Magnos*. After a 50-s drawdown, in which this level decreases by 0.8 m, the return to normal water elevation, after the passage of the face of the wake, takes only 6 s. The wave form is very similar at PS2 (100 m from the canal) and PS4 (300 m from the canal) and includes a drawdown of about 0.7 m at these sensors before the steep face returns. While the size of the wave decreases to about 0.2 m at a distance of 500 m from the canal, the duration of the drawdown increases to 90 s. This shape is also seen in the pressure sensors located 600 and 700 m from the canal. Fig. 7B shows the depression wave after the passage of *MSC Annamaria* (188, 29, 7.5). The pattern among the pressure sensors is very similar to the wake produced by *Magnos*, however the wave is smaller (0.5 m at PS1, PS2 and PS4). The drawdown of this wave can be detected at PS10, 800 m onto the shoal, whereas it was not after the passage of *Magnos*. Both figures show the passage of small wake generated waves after the passage of the depression wave and this development is most pronounced 300–500 m onto the shoal. The characteristics of propagating depression waves over shallow shoals have been described and modeled in terms of Riemann wave theory (Parnell et al., 2015).

4. Discussion

4.1. Effects of ship traffic on erosional processes in Venice Lagoon

> *"Ciaci, moor your boat, otherwise it will be destroyed!' Surprised I asked why and he responded 'A large ship just passed in the Petrol Canal!'… immediately after, I saw a wave coming; this wave struck fear in me at first sight… 'If the wave arrived here intact from the Industrial Zone (Fusina) all the way to the lock of Moranzani, how many kilometers could it travel unimpeded through the open lagoon?'…"And so I asked myself 'If every waves takes away, let's say, a millimeter of sediment, then with time this becomes centimeters, and after the passing of years will it be meters?!"*

This is an excerpt from an autobiography by a Venetian gondolier, Sergio Tagliapietra "Una vita per il remo" recounting an event that occurred around 1990.

What this experienced rower describes and deduces in his tale corresponds to what is known from morphological studies. A recent study by Molinaroli et al. (2009) revealed evidence that significant erosion along the shoals near the MMIC has occurred over the last four decades, effectively deepening the shoals by more than 0.5 m (after local subsidence and dredging practices have been accounted for). Zonta et al. (2007), found an anomalous lack of fine-grained sediments in the vicinity of the channel (Fig. 3), and suggested that the fine-grained sediments might have been removed by some erosional processes. Amos et al. (2004) report that the bottom shear stress threshold for entrainment of cohesive sediments in this section of the Venice Lagoon to occur is around 0.7 Pa. Umgiesser

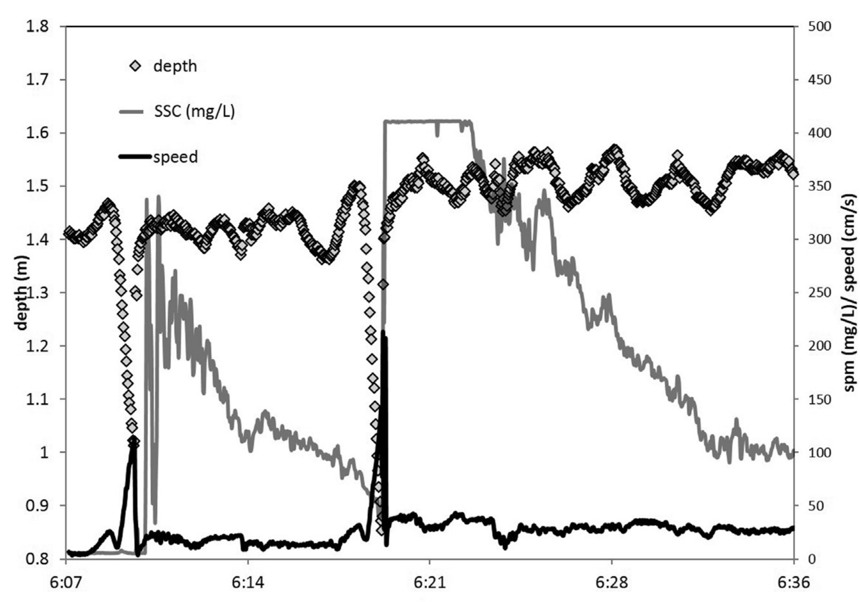

Fig. 6. Depth, SSC and water speed during the passage of two large ships (MSC Leader and Grande Sicilia) in succession on 8 July 2009. Water velocity increases due to the drawdown of the depression wave before SSC has settled to pre-disturbance levels. The flattened SSC line around 6:21 AM for a period of several minutes is due to complete saturation of the OBS sensors.

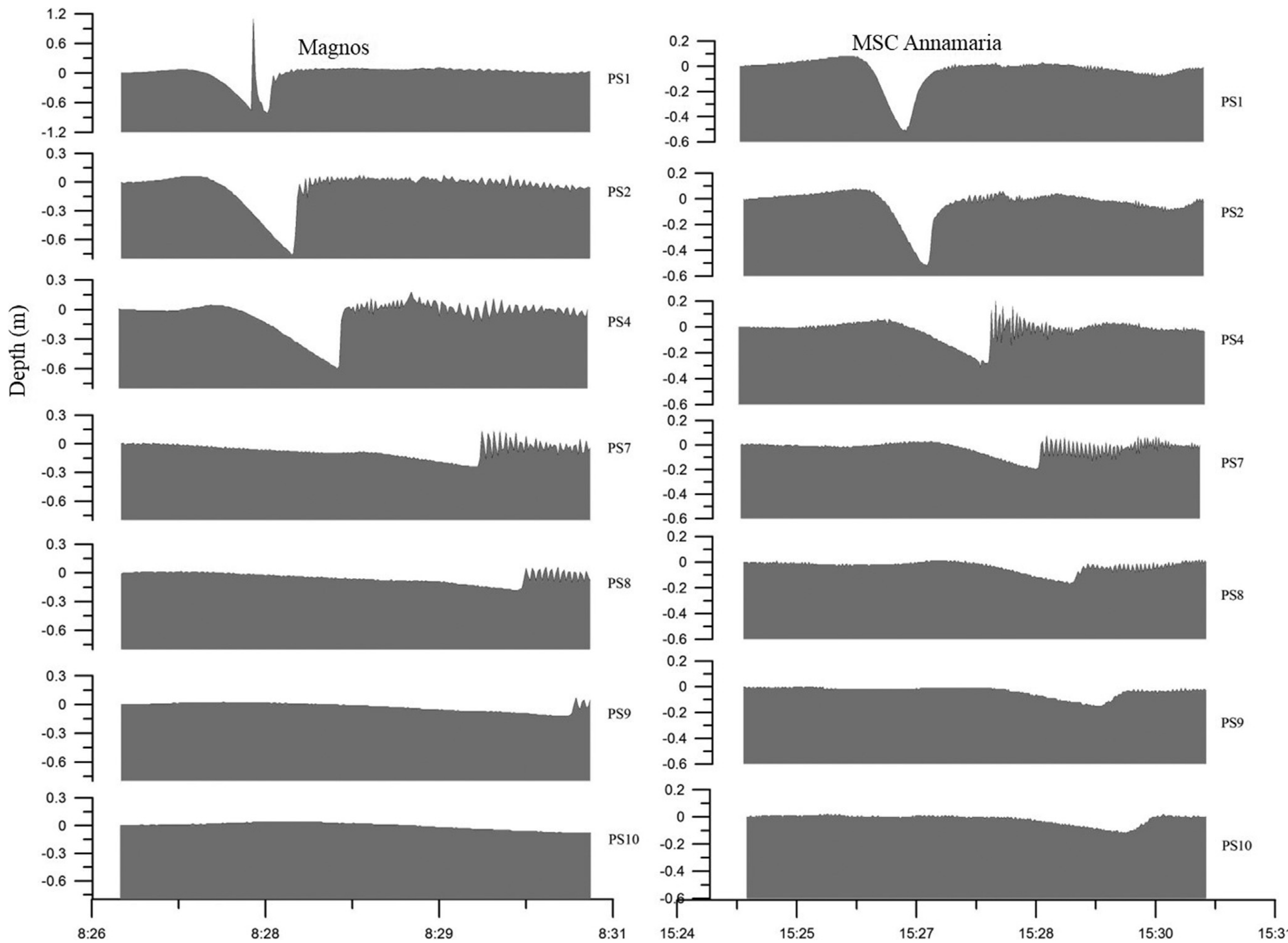

Fig. 7. Propagation of the depression wave as recorded on the pressure sensor transect. A. After the passage of Magnos on 18 July 2009. B. After the passage of MSC Annamaria on 18 July 2009.

et al. (2004) report that this value can be exceeded during strong Scirocco conditions, and therefore, undoubtedly, storms play a role in the transport of sediment. Rapaglia et al. (2011) and Gelinas et al. (2012) have found that bottom shear stress from large ship wakes greatly exceed these entrainment thresholds as well and, therefore, suggested that one of the likely causes of entrainment on the shoal is from the passage of ship wakes.

The entrainment of sediments does not necessarily imply erosion or removal since some mechanism is required to transport the sediment. Our data show that when multiple ships pass the shoals within close temporal proximity (i.e. <20 min) to one another depression waves from successive ships transport the suspended sediment both towards and away from the channel in a stepwise pattern (Figs. 6, 8 and 9). In other words the depression wave begins to resuspend sediment as the bottom current speed increases (Fig. 6). This increase is in the direction of the shipping canal (Fig. 8—in red). Between 71 and 121 s the drawdown associated with the depression wave is seen. During this period the water column is moving towards the navigation channel. Here, speeds reach up to 0.8 m/s in the direction of the channel. Between seconds 121–141, we have a reversal of the wave direction and a strong decrease in water speed. After second 141, the event has passed the sensor location and current speed has returned to background levels (Fig. 9). Suspended sediment concentrations are highest during the drawdown, but remain elevated for many seconds after the event. Therefore if the background current direction is away from the channel, net overall transport will be away from the channel and the background velocity is towards the channel, and net overall transport will be towards the channel. Hence, change in net sediment deposition and transport if only one ship passes through the channel, will mainly be due to background currents after the resuspension event. The velocity may oscillate for many seconds after the passage of the wave, but overall speed remains low until another ship increases the speed of the water again in the direction of the channel and therefore draws the water and suspended sediments towards the channel (Figs. 6 and 8). In this case, initial net transport of sediment will be towards the channel at high speeds, likely transporting larger (sand-sized) particles towards the channel, which given the fact that a dredged channel creates acts as sink for sediment, much of the resuspended material will then be deposited in the bottom of the channel. Sediment that remains in suspension, however, is likely to be fine-grained, and this sediment will be transported in the direction of background current. As metals have a higher affinity for fine-grained sediments they may be preferably transported onto the shoals, but further discussion of this possibility is beyond the scope of this manuscript.

Rapaglia et al. (2011) suggest that some of the sediment, which is resuspended from the shoals, is transported towards and is eventually deposited in the shipping channel, requiring frequent dredging interventions. A very similar process is occurring in the

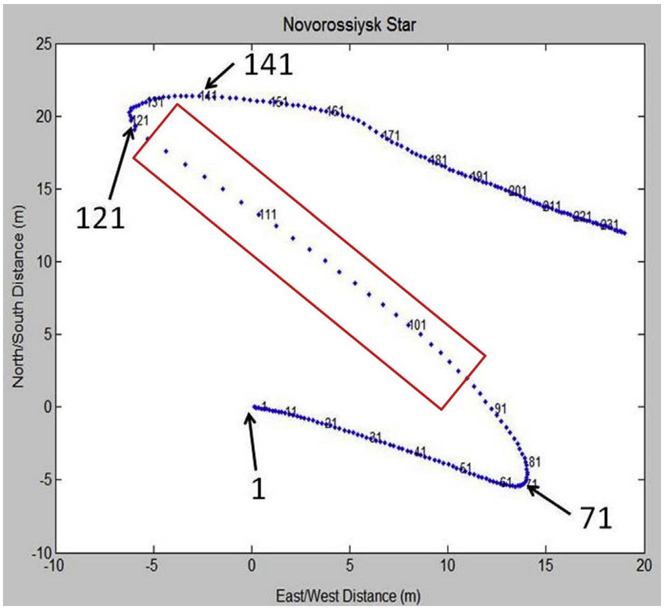

Fig. 8. Net transport of a theoretical water particle during the passage of Novorossiysk Star. Numbers denote time in seconds during the passage of the ship. The time starts recording when the bow of the ship passes the S4. The first 71 s of the figure show the background current velocity. The box marked in red shows the period of maximum shear stress. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Gulf Intracoastal Waterway, specifically along the Galveston–Baytown shipping channel. Bank erosion and channel filling is occurring along much of that shipping channel (Townsend et al., 2014). It is likely, therefore, that this process is occurring along many narrow shipping channels located adjacent to shoals. In the case described herein, the Port Authority of Venice is required to spend millions of Euro on dredging each year, yet there is very little sediment input from river discharge in this area, which was the former mouth of the since relocated Brenta River (Zuliani et al., 2005). Therefore, it is likely that the main source of sediments, which need to be dredged, is the shoal itself rather than being of terrestrial origin. Rapaglia et al. (2011) suggest that by using an empirical relationship, which they call the modified Schoellhamer relation (MSR), it is possible to determine the maximum navigation speed at which the wake-produced current will maintain bottom shear stresses below the entrainment threshold and, therefore, no or minimal sediment resuspension. This will reduce one of the possible sources of erosion in this section of the Venice Lagoon.

By considering resuspension we attempt a simple first order calculation of total sediment movement. More than 4000 ships (>80 m length) enter Venice Lagoon each year (Port of Venice website, http://www.port.venice.it/pdv/Home.do?metodo=carica_home). About 1000 of these ships are cruise ships or private yachts, which enter through the Lido Inlet and navigate into a large natural channel to the passenger terminal of the city's port (Tronchetto), therefore not affecting the study site. Approximately one third of the remaining 3000 ships can produce large depression waves which propagate onto the shoal area causing resuspension events in the study area (14 of 40 ships examined by Rapaglia et al. (2011) caused major effects). Fig. 7 shows the propagation length of two depression waves onto the shoals as recorded by pressure sensors. The depression waves are recorded 700–800 m onto the shoal, however the size of the waves significantly decreases between 300 and 500 m from the channel. When the depression wave is large (i.e. >0.3 m) high bottom stress values lead to SSC values well in excess of 400 mg L^{-1} (measured at 0.5 m above the sediment bottom; Rapaglia et al., 2011). With this information, we propose that it is reasonable to assume that each of the 1000 depression waves that propagate onto the shoals each year cause significant sediment resuspension for a distance of 300 m and for the entire length of the channel (20 km). Therefore, an area of 6 km^2 of the lagoon sediment will be impacted by these waves. We can calculate the total annual resuspension with the equation: $R_{annual} = ((A^*D)^*SSC_{avg})^*n$. Where: R_{annual} is the total annual resuspension (kg), A is the area (m^2), D is the average depth (m), SSC_{avg} is the integrated average water column SSC (kg m^{-3}), and n is the annual number of resuspension events. Assuming a water column average of 0.1 kg m^{-3} (100 mg L^{-1}) of sediment is resuspended (a conservative estimate) across 6 km^2 of shoals whose average water depth is 2 m, a total of 1.2×10^6 kg or 1200 metric tons of sediment mobilized by each wave event. An annual estimate of 1000 large events leads to 1.2×10^6 metric tons of sediment mobilized per year. According to the Port of Venice 1.0×10^7 m^3 of sediment have been dredged from the industrial canal in the last 13 years (Knuth, 2010). If we assume an average bulk density of these cohesive sediments to be 1500 kg m^3 (Amos et al., 2004), we are left with an average amount of 1.15×10^6 metric tons of sediment dredged each year from the channel, which agrees very well with our estimate of total resuspended material. However it is important to note that our value for the amount of material mobilized annually could be an overestimate due to the presence of breakwaters designed to reduce the propagation of the ship wake onto the shoals for several km alongside the channel, although some video evidence suggests that the wave energy may pass the breakwater and move over the shoals. In addition, as the ships pass the turn in the shipping channel (Fig. 1), they reduce their speed and the likely size of the depression wave which propagates onto the shoal. Finally, it is probable that much of the sediment is redeposited on the shoals near the original location. With these limitations addressed, it remains likely that a very large amount of sediment is being transported in the direction of or into the shipping channel each year.

4.2. Management recommendations

In Table 1 the difference between actual speed and the theoretical optimal navigation speed based on the modified Schoellhamer relation and its correlation to sediment resuspension thresholds from bottom shear stress produced by waves is shown (Rapaglia et al., 2011). Of the 40 ships analyzed in this investigation, 14 require reduction in speed in order to prevent the formation of large waves, leading to bottom shear stress values that greatly exceed the local entrainment threshold values (Amos et al., 2004; Umgiesser et al., 2004; Rapaglia et al., 2011). Given the length of the channel (20 km), an extrapolation of the ships' speed reduction increases the navigation time of these ships from their dock to the Malamocco Inlet from between 1 and 28 min, with an average increase of 11 min. This increase in transit time, wherever feasible, will certainly increase shipping costs, however this increase could be offset by a decrease in dredging costs to the Port Authority.

If we assume that ship wakes do lead to increased dredging requirements in the lagoon, in order to decrease dredging costs, a reduction in sediment resuspension and transport into the channel is necessary. There are three possibilities for an efficient reduction in sediment resuspension caused by depression waves. As larger amplitude depression waves lead to higher current speed a reduction in speed of the ship will reduce sediment resuspension along the shoals near the shipping canal. The second possibility is to restrict the navigation of large ships to periods when the water level is above the mean water level, approximately 25 cm above the local 1897 reference mean of Punta della Salute. At higher tide

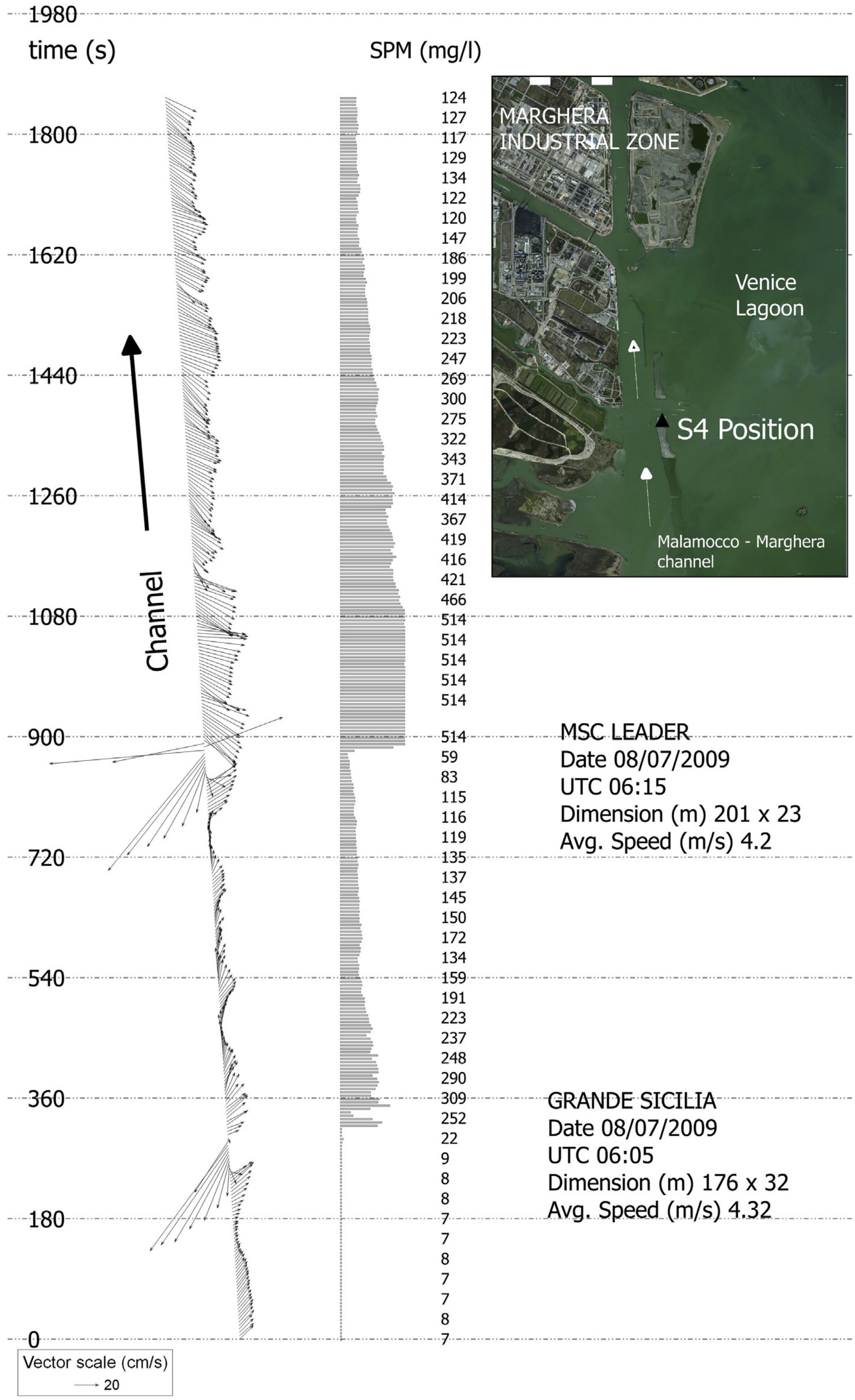

Fig. 9. Net transport of water and its associated suspended sediment concentration during the passage of MSC Leader (dimensions, 201 × 23 × 6.7 m; traveling 4.2 m/s) and Grande Sicilia (177, 31, 8.3; 4.32).

levels, the depression wave has less of an effect on the shoals as the drawdown is not as great. In addition a higher water level reduces the amplitude of the wave and thereby lowers current speeds. The third possibility is to stagger the times at which ships enter the lagoon. Given the effect shown in Figs. 6 and 9, it follows that successive ship passages may cause a transport of coarser-grained sediment towards the shipping canal, thereby increasing the frequency of dredging interventions. If vessel passages are staggered, with greater distance between each ship it may give more time for particles to settle and reduce the net sediment movement towards the canal. Each of these restrictions may somehow limit the business, because of the excessive reduction of the time slots for the access to the port. Therefore, to minimize the implications of this restriction to port accessibility, a combination of these

Table 1
An analysis of the change in speed necessary for each vessel to achieve maximum navigation efficiency below the Schoellhamer parameter threshold for ship wake induced bottom shear stress defined in Rapaglia et al. (2011) assuming a tidal elevation of 0.3 m above the 1897 reference mean sea level. The safe navigation speed is the maximum speed before crossing the threshold and the increased travel time assumes the decrease in speed is necessary for the entire 20 km long canal.

Vessel	Length (m)	Width (m)	Draft (m)	Avg. Speed ($m\ s^{-1}$)	Safe navigation speed ($m\ s^{-1}$)	Increase in travel time (min)
MV Nurettin AMCA	118	18	5.3	4.84	>5.56	NA
Gabion	128	28	6.4	3.96	4.31	NA
Stolt Pondo	170	26	8	3.4	3.56	NA
MSC Antonia	188	24	8.1	3.4	3.56	NA
MSC Leader	201	23	6.7	4.2	3.71	10.8
Grande Sicilia	177	31	8.3	4.32	3.18	27.6
Melody	100	18	5.9	3.81	>5.56	NA
RBD Borea	130	21	6.2	3.19	5	NA
Tucana	88	12	3.9	5.04	>5.56	NA
Coral Leaf	108	17	6	5.66	>5.56	NA
MV Nurettin Amca	118	18	4.6	4.58	>5.56	NA
Lia Ievoli	131	20	7.6	4.63	4.92	NA
East Coast	64	9	4.5	4.94	>5.56	NA
Jia Xing	169	27	7.4	3.65	3.75	NA
Ain Zeft	109	15	5	5.14	>5.56	NA
Clipper Karina	116	20	6.1	4.63	>5.56	NA
St. Constantine	104	16	4.5	4.89	>5.56	NA
MSC Mirella	177	32	9.1	3.45	3.15	9.3
Novorossiysk Star	180	26	7.7	4.37	3.67	14.5
Calajunco M	162	23	7.1	4.17	4.14	0.6
Adrianople	188	28	7.6	3.65	3.43	5.8
Salerno Express	140	19	5.5	4.99	5.43	NA
Carlos	176	31	7.7	3.7	3.36	9.0
Adria Blu	94	15	5	5.6	>5.56	NA
Oasis West	145	21	6.3	4.84	4.92	NA
MV Kemal G	129	18	8.2	3.86	4.99	NA
Elefsina	138	21	6.1	4.63	5.17	NA
Sari Zeybek	106	16	8	4.32	>5.56	NA
Mar Adriana	144	23	7.9	3.04	4.31	NA
Leopold Staff	199	26	8.9	3.4	3.35	1.6
TK Istanbul	114	18	4.6	5.4	>5.56	NA
Marja	100	18	5.5	4.8	>5.56	NA
Uni Assent	165	27	7.3	4.22	3.93	5.9
Salerno Express	144	19	5.5	4.84	5.31	NA
Hellenic Voyager	193	27	6.5	4.84	3.75	20.1
Wehr Elbe	208	30	9.3	3.91	2.94	28.3
Carlos G	176	31	7.5	3.6	3.4	5.4
Calajunco M	162	23	7.1	4.22	4.17	1.0
Hokuetsu Ace II	210	32	8	3.65	3.01	19.6

measures must be taken on a case-by-case basis by adopting a model where all physical factors, including tide, environmental risks and navigation safety, are considered together with management costs (i.e. port business, dredging of the channels and maintenance of the shores). The model should allow for the combination of the restrictions with other solutions such as alternating the navigation of large and small ships (small ships being less likely to create resuspension events).

In order to alleviate these problems we recommend the following guidelines, which can be added to a model (not described herein) determining maximum navigation efficiency:

1. Allow large ships to navigate through the canal from half tide to high tide; though the canal is deep enough to accommodate ships, the effect of the wave on the shoal is increased at low water levels.
2. Utilize the ship-wake induced bottom shear stress threshold (Rapaglia et al., 2011) to calculate the maximum navigation speed that does not cause large resuspension events.
3. Increase the separation distance between consecutive ship transits, as a combined disturbance causes larger SSC events and more sediment transport in the direction of the canal.

Each of these points should be considered in a management model, which if developed, would help to control the navigation of vessels throughout the Malamocco-Marghera channel. The Venice Port Authority is aware of issues caused by the navigation of ships through the MMIC, particularly with the predicted increase in ship traffic as more ferries and cruise ships pass by the industrial zone and are considering how best to mitigate these issues. Incorporating sediment resuspension and coincident contaminant release into such a model would render it even more effective in the long term.

5. Conclusions

The depression wave from commercial vessels moving through the Malamocco-Marghera navigation channel leads to large-scale sediment resuspension events in the shoals of Venice Lagoon, Italy. Large ships traveling at high speed and during periods of low tide have the largest effects. These events, if extrapolated across the shoals can lead to an estimated resuspension of approximately 1.2×10^6 metric tons of sediment per year. Depression waves from successive ship passages draw water towards the shipping canal while SSC remains high, leading to a stepwise movement of coarse-grained sediments towards the shipping canal. This may significantly contribute to the deepening and erosion of central lagoon sediments which, according to the literature, underwent a significant acceleration in the period from 1970 to 2000, after the opening of the navigation canal. Much of this sediment was possibly re-deposited in the shipping canal forcing the development of a multi-million euro dredging program.

Due to the high concentration of contaminants in sediments on these shoals, it is likely that this process also leads to the remobilization of contaminants from sediments into the water column. This increases the spatial distribution of contaminants within central lagoon and may lead to increased biotic susceptibility to toxic chemical species. Future work is needed to better understand contaminant release from sediments during vessel-induced mobilization, and potential impact on the local ecosystem. Given the uncertainty that remains surrounding hull design, bathymetric effects, and sediment properties, further investigation of this phenomenon is necessary to better quantify the direct effects of these waves.

These issues can be alleviated by reducing ship navigation speed, increasing the separation distance between ships, and restricting navigation of the largest vessels to periods of half to high tide. While, these restrictions will certainly increase shipping costs, the decrease in speed should not be prohibitive. For every one km/h reduction in speed, the travel time of the ship will increase from inlet to port by about 3 min, or a 5% increase in travel time through the Venice Lagoon.

Considering the proposed expansion of the Port of Venice to allow for more ferries, cruise ships and larger container vessels and cargo ships, the process described herein must receive even greater consideration (some of this expansion is already underway). This process is not isolated to the Venice Lagoon; it is likely occurring in other ports around the world where narrow fairways are surrounded by shoals.

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