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To cite this article: Marco Petti *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1203** 022104

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Relocation of Dredged Material from Marano and Grado Lagoon: An Example of Sustainable Management

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Abstract. The high degree of dynamism of coastal and lagoon morphodynamic processes often implies the need for dredging operations to maintain the navigability of the main waterways towards harbours or sites which have important tourist or economical value. In particular, within sheltered and shallow lagoons this phenomenon is continuous and involves large volumes of material that requires to be properly managed. The dredged materials can provide sediments for environmental enhancement and they can be used, as an example, to create or improve habitats, mudflats and salt marshes. Numerical model can be a valuable tool to investigate the morphological evolution of the disposals, especially in the medium term, with the aim of verifying the sediment stability and the bed level changes. The present paper shows an example of sustainable management of cohesive materials dredged from two channels of the Marano and Grado lagoon. The non-linear interactions between tidal currents and locally generated wind waves are reproduced by means of a coupled spectral-hydrodynamic model associated with a transport equation to compute sediment load concentration. The comparison of the results confirms the validity of the adopted procedure.

1. Introduction

The dynamic balance of coastal environments is the result of the continuous exchange of sediments between currents and wind waves, which trigger the main morphological processes in the surf zone [1–4]. Similarly, confined basins and lagoons are governed by locally generated wave motion, which can lead to sediment resuspension on the shallow depths of tidal and subtidal flats, where the tidal currents alone are not strong enough to produce shear stress exceeding the critical erosion threshold [5–11]. Tidal currents convey the material inside the main channels, where it is deposited during the transition phases between ebb and flow. The trend often deriving from this mechanism is therefore a flattening of the lagoon with a deepening of the shallow areas and the consequent silting up of the channels [12–13].

From an engineering point of view, this poses several problems, in particular the maintenance of the navigability of the waterways and therefore the need for periodic dredging operations. On the other hand, large volumes of dredged material are created, which require to be treated or relocated within the basin depending on whether chemical and ecological compatibility with the environment is guaranteed [14–17]. Furthermore, even in the case of uncontaminated sediments, some issues still remain unresolved such as where and how to carry out the relocations in order to ensure sufficient stability of the material to the erosion processes in the medium-long term, ranging from months to years.

The Marano and Grado lagoon is a coastal basin in the Northern Adriatic Sea (Italy), which has undergone a net loss of sediments from its tidal flats in the last decades with the consequent periodic silting of its main channels [12,18]. A total volume of mud ranging about from 50,000 to 100,000 m^3 is annually dredged from the waterways that connect the main tidal inlets with the harbours and the sites of interest located within the lagoon, and this forced the local authorities to develop a morphological study to plan dredging and manage the disposal of the material. The best solution from an environmental point of view seems to be not to isolate the dredged sediments, but to use them for the requalification of habitats, mudflats and saltmarshes, in compliance with the chemical and sedimentological properties [19,20]. This choice requires the selection of the target areas for the disposal of the dredged material and the study of the bottom shear stresses induced by the non-linear interaction between tidal currents and wave motion which can affect the morphodynamic stability of the site.

The present study describes the application of morphodynamic modelling to achieve sustainable management of materials dredged from the main waterways of the Marano and Grado lagoon. A coupled spectral-morphodynamic model is applied to generate the local wave field and to reproduce the temporal variation of water level, current velocities and the bottom height within the lagoon over a period of an average year. Two different project interventions are proposed, assuming or not a temporary protection lasting one year, such as to allow the sediments to partially consolidate. Section 2 presents a brief overview of the study site and dredging data; the numerical model and the method setup are described in section 3, the simulation results are compared and discussed in section 4.

2. Study site

The Marano and Grado lagoon, depicted in figure 1, is a coastal shallow basin confined between the Friuli Venezia Giulia plain and the Adriatic Sea, in the North East of Italy. It has extensive tidal flats characterized by a quite uniform bathymetry located between the internal channels that branch off from the six tidal inlets which connect the lagoon to the open sea. The sedimentological composition is mainly characterized by fine and cohesive materials, even if sand content progressively increases towards the inlets [12,13].
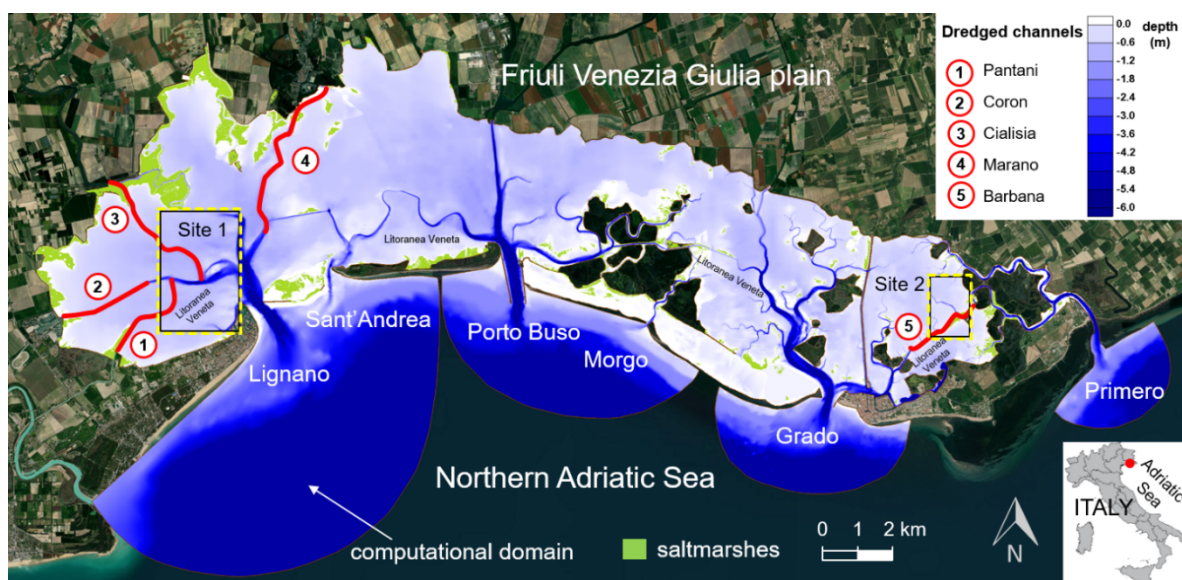

Figure 1. The Marano and Grado lagoon and its geographical location in the Italian context. In evidence: the six tidal inlets, the computational domain with the water depth contour, the saltmarshes distribution in green and in red the channels specified in the legend which often require dredging interventions. The sites framed by the two yellow-black rectangles were considered as dumping areas of the dredged material.

Many of the inner lagoon channels require periodic dredging operations due to the deposit of sediments from the surrounding tidal flats. These deposits can compromise the navigation toward the internal harbours of the lagoon and the main sites of interest, as the lagoon has an important tourist, economic as well as environmental value. Dredging operations are generally planned according to the economic resources of the local authorities and the navigability conditions of the channels themselves. Table 1 summarizes the volumes dredged in the overall period from 2008 to 2016 in the critical branches highlighted in red in figure 1. The volumes dredged during 2017 are also reported. These interventions involved two channels: the Pantani channel, belonging to the Litoranea Veneta, an important transversal waterway of the lagoon and the Barbana channel, which connects the Grado inlet to the homonymous island, which is an important pilgrimage destination.

Table 1. Volumes dredged in the overall period 2008 - 2016 and volumes dredged during 2017.

	1 Pantani	2 Coron	3 Cialisia	4 Marano	5 Barbana
Volumes dredged from 2008 to 2016 (m³)	143,000	206,200	63,000	89,500	30,600
Volumes dredged during 2017 (m³)	65,000	-	-	-	5,000

Two areas were identified to relocate the sediments of the Pantani and Barbana channels respectively, as indicated in figure 1. The choice of the two sites was made in order to place the material close to the dredged channels, thus reducing the costs of the interventions. Furthermore, both the chemical and the sedimentological compatibility of the sediments was verified. The disposal project was defined with the aim of maintaining and increasing the intertidal surfaces, i.e. saltmarshes and mudflats, both for their role in the morphological and hydrodynamic balance of the entire lagoon and because they constitute the substrate for ecological habitats. It was proposed to arrange the material dredged from the Pantani channel at the intersection between the Cialisia and Coron channels (Site 1 in figure 1), to form a surface having a uniform depth of -0.55 m from the still water level (SWL), as shown in figure 2. The mean tidal amplitude for the Marano and Grado lagoon is about 0.40 m [21] and this implies that the sediment disposal remains submerged.
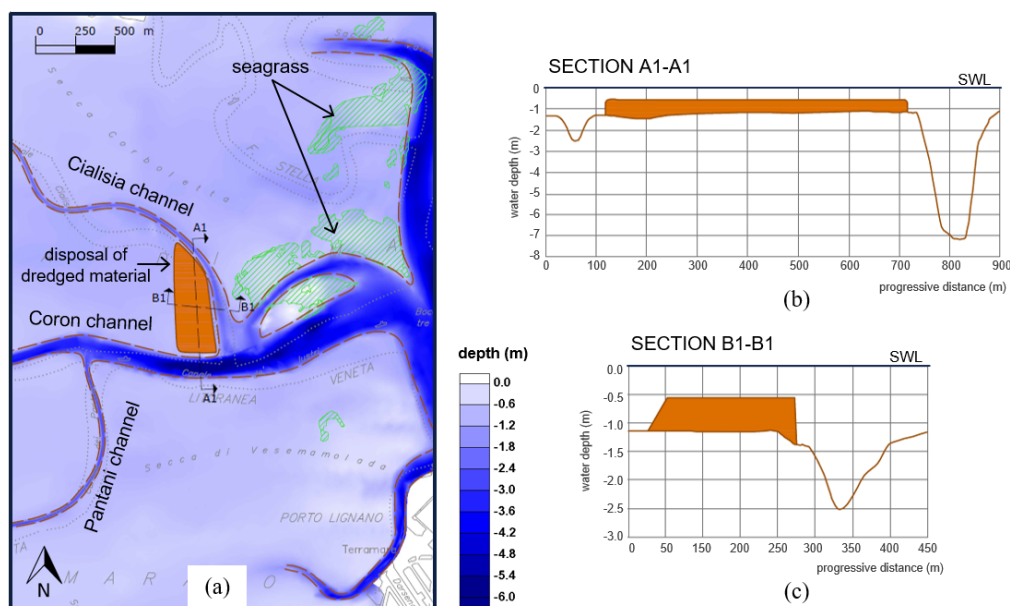

Figure 2. Site 1: project for the disposal of the material dredged from the Pantani channel; (a) plan view, (b) longitudinal section and (c) cross section.

On the contrary, the project for dumping the material dredged from the Barbana channel was to create artificial marshes on the Fra' Simon channel side, as depicted in figure 3 (Site 2 in figure 1). The Barbana channel requires annually dredging operations to maintain the navigability toward the island, and for this reason the proposal provides for subsequent addition of sediments. In this case the saltmarsh is 0.12 m above the still water level and therefore emerges at low tide and remains submerged at high tide.
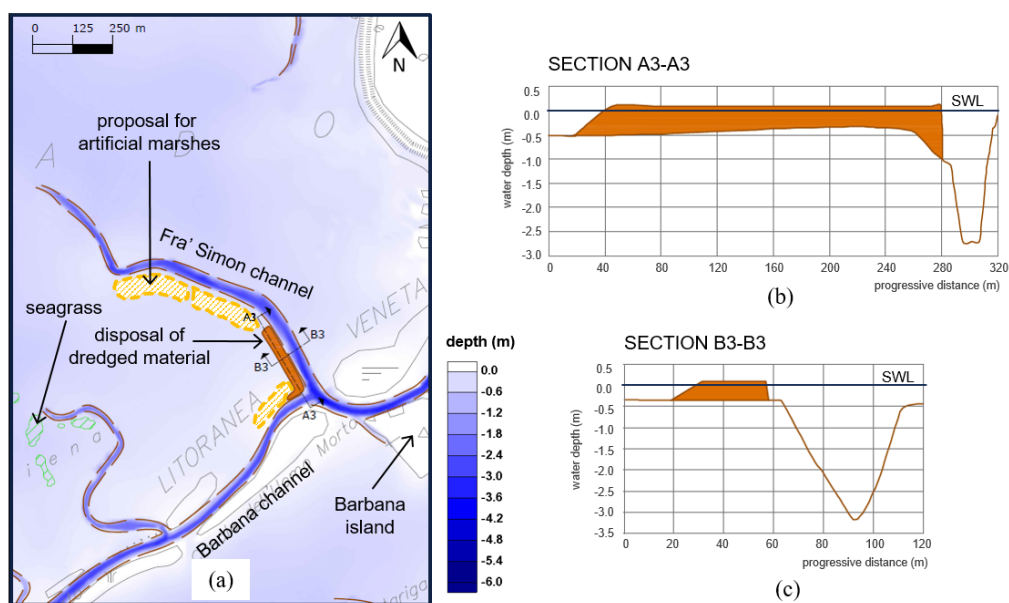

Figure 3. Site 2: project for the disposal of the material dredged from the Barbana channel; (a) plan view with the proposal for artificial marshes, (b) longitudinal section and (c) cross section.

A morphodynamic model has been applied to verify the morphological evolution of the two proposed sediment placements, over a period of one or two years.

3. Numerical modelling and method setup

The numerical model used to simulate sediment dynamics induced by the non-linear interaction between tidal currents and wind waves, couples a morphological-hydrodynamic model and a fully spectral wind-wave model. The former in-house model [22,23] is based on classic bi-dimensional shallow water equations associated with a transport equation that solves the advection-diffusion equation in order to study the concentration distribution of the suspended load. These equations provide the hydrodynamic field in terms of depth-averaged variables, while the sediment continuity equations at the bottom, respectively for sand and mud, compute the temporal bed evolution [12]. The momentum equations take into account the forcings due to radiation stress tensor and the bottom shear stresses calculated by Soulsby [24] as a combination of the amount due to both the current and the wave motion. The latter is generated by means of SWAN [25], an open source third generation model which solves the wave action balance equation including all energy terms, such as wind input, dissipations and non-linear transfers. The morphological-hydrodynamic model is integrated with a finite volume method, while SWAN applies a finite difference approach. They interact through water depth, bottom height, currents, wave field and radiation stresses. A main program runs separately one after each other and manages the mutual exchange of data on a regular grid. The resulting coupled model has been successfully applied in many coastal contexts, to investigate the morphodynamic processes acting in the Northern Adriatic surf zone [26], in an area close to the Lignano tidal inlet

[27,28] and to study the average annual morphological evolution of the entire Marano and Grado lagoon, with particular attention to the silting of its channels [12].

The present study has been developed on the basis of the procedure followed by Petti et al. [12] to obtain the overall bathymetry changes in the medium period. In this case, particular attention has been paid to the morphological evolution of the two sites described above. The procedure was mainly focused on the reconstruction of the sequence of winds and tides acting over an average year, and the assignment of the critical erosion threshold for cohesive sediments. Figure 4 shows the wind speeds and directions derived from the anemometric measurements, and the annual average tide obtained by a spectral analysis. The critical shear stress is assumed spatially variable ranging from 0.5 Pa to 1.8 Pa depending on the different morphological structures that characterize the lagoon environment.
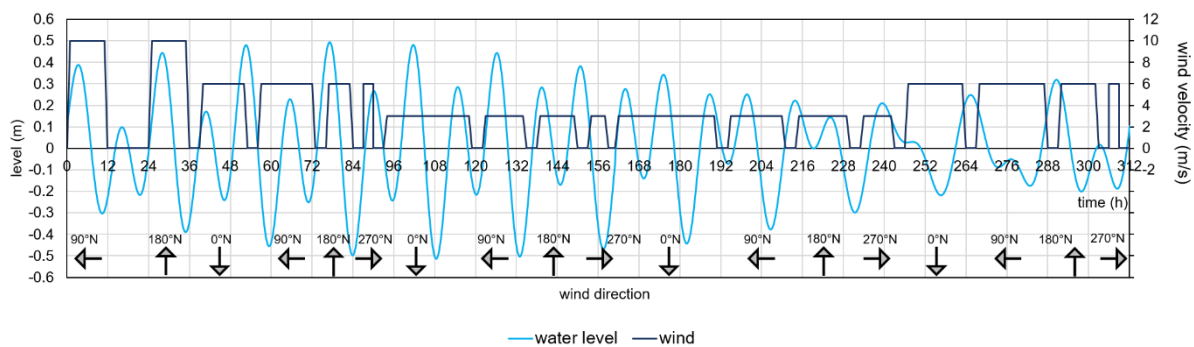

Figure 4. Sequence of winds and water levels used to simulate the morphological changes of the Marano and Grado lagoon over an annual period.

The hydrodynamic computational domain is depicted in figure 1 and it covers the entire lagoon basin and a portion of the sea in front of the lagoon inlets to assign water level boundary conditions. The elements are quadrangular and irregular and they have been adequately strengthened compared to the previous mesh of Petti et al. [12] to represent the material dumping sites with greater precision. Three different simulations have been performed on the basis of specific conditions for the two sites depending on the presence of a temporary protection or not and the consolidation state of the material. In fact, it has been proposed to protect for a period of one year the newly relocated material in the site 1 as it is close to an area reserved for shellfish farming. This solution can prevent sediments not yet consolidated from being eroded and then deposited in the reserved area or inside the Cialisia and Coron channels. On the contrary, it was established that the artificial marsh along the side of the Fra' Simon channel did not require to be protect. The list of the simulations is reported in Table 2 and each of them covers a period of one year.

Table 2. Performed simulations with different setup conditions for the two sites according to the presence of a temporary protection or not and the consolidation state of the material.

	Site 1		Site 2	
	protection	τ_{crit} (Pa)	protection	τ_{crit} (Pa)
Sim1	no	0.5	no	0.5
Sim2_1	yes	not erodible	no	0.5
Sim2_2	no	0.7	no	0.7

Sim1 considers both disposals unprotected and not yet consolidated and the critical erosion threshold for cohesive sediments has been assigned equal to 0.5 Pa. This low value was used in the previous simulations performed by Petti et al. [12] to characterize mudflats that, due to some causes, some of which can be external, are subject to greater mobility of the cohesive sediment. In the simulation Sim2_1 the relocated material, dredged from the Pantani channel, is protected and not

erodible, while Sim2_2 represents the second year of simulation having as initial condition the status reached at the end of Sim2_1. The difference compared to Sim1 concerns the critical shear stress equal to 0.7 for both the disposals, which is the value assumed for the consolidated tidal flats. As a comparison, in the following the abbreviation sim0 refers to the morphodynamic simulation of the lagoon without any disposal over the average year.

4. Results and discussions

Figure 5 and figure 6 show, for each site respectively, the spatial distribution of erosion and deposits of sediment that derive from the performed simulations, computed as differences between final and initial bed levels. The latter are the same for all the depicted panels and they correspond to the initial bathymetry of the computational domain without any material disposal.
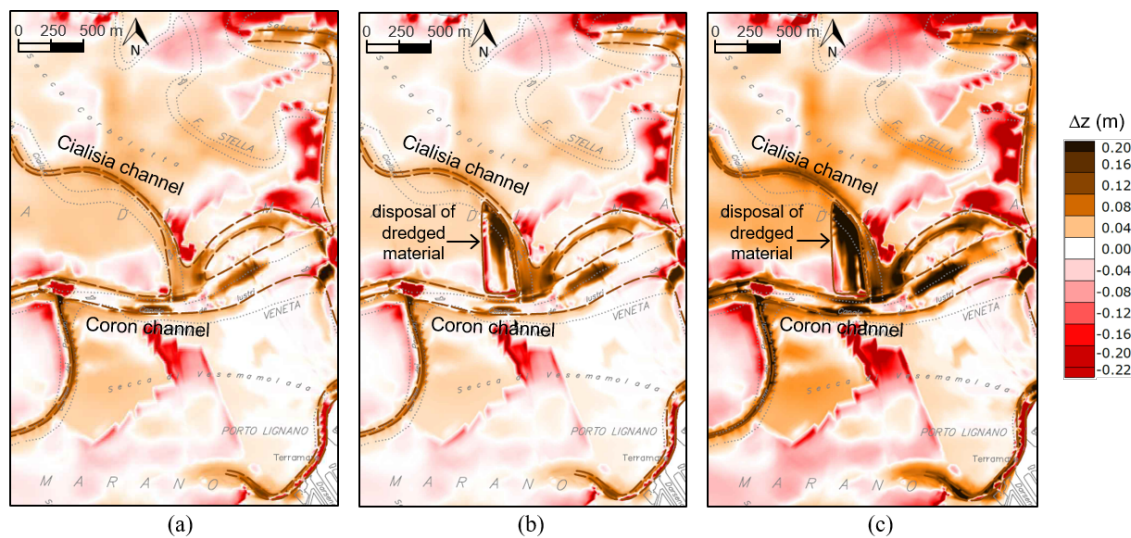

Figure 5. Morphological changes in the site 1 at the end of: (a) Sim0, without the disposal; (b) Sim1_1; (c) Sim2_2. The contour legend shows the difference between final and initial bed levels; the latter are the same for each panel.

Figure 6. Morphological changes in the site 2 at the end of: (a) Sim0, without the disposal; (b) Sim1_1; (c) Sim2_2. The contour legend shows the difference between final and initial bed levels; the latter are the same for each panel.
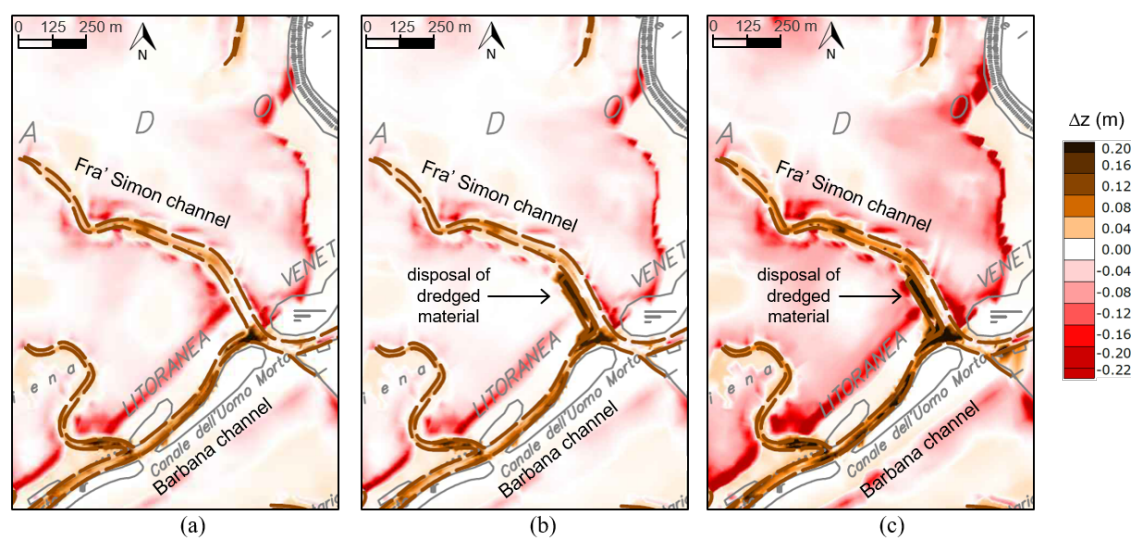
The results depicted in figures 5a and 6a represent the morphological changes of bed elevation over an average year for the two sites, which have been obtained from Sim0 without any material dumping. In particular, it can be observed that site 1 presents, in normal conditions, both deposits and erosions of sediments, the latter concentrated in the southern part close to the Coron channel. On average, the water depth within the area at the intersection between the Coron and Cialisia channels is about 1.2 m. Sediment deposits are concentrated both in the northern portion of the subtidal flat and inside the channels, and in particular along the Pantani channel. This result is consistent with the need for dredging a large amount of material as indicated in table 1. On the contrary, site 2 mainly shows a loss of sediments, although it seems more sheltered from the action of wind and wave motion. In this case, the average water depth is much shallower and about 0.58 m, and therefore the wave bottom shear stresses, even if small, are still sufficient to resuspend sediments. Figures 5b and 6b refer to Sim1 and they show the losses of material from the two disposals at the end of one year, considering unconsolidated sediments and in absence of any temporary protection. This condition involves a great erosion of the first area with a considerable loss of material, which has been calculated equal to about 85% compared to 30% of site 2, as shown in table 3. This difference is probably linked to the fact that site 1 covers a larger area, equal to about 13.7 ha, than the 0.8 ha of site 2. Furthermore, the latter is close to the edge of the Fra' Simon channel and it acts as a barrier protecting the neighbouring subtidal flat, which effectively has less erosion than in the previous case Sim0.

Table 3. Percentage losses in each simulation of the volume of the material placed in the respective sites. The last column refers to the total losses as the sum of the Sim2_1 and Sim2_2.

	Sim1	Sim2_1	Sim2_2	Tot Sim2
Site 1	-85%	-	-65%	-65%
Site 2	-30%	-30%	-8%	-38%

The results of Sim2_2 are presented in figures 5c and 6c and they represent the morphological changes at the end of the second simulation year which assumed the bed levels obtained from Sim2_1 as initial conditions. In this case, the disposals of dredged material can be assumed consolidated and for this reason they have lost a smaller volume of sediments than the previous case Sim1 at both sites. At the end of two years of simulation, the volumes variation is overall about 65% for site 1 and 38% for site 2.

Both solutions can be considered acceptable even if they involve the loss of material in the medium period. In fact, the sedimentary balance of the entire lagoon can be improved if the material dredged from the channels is not isolated, especially when physical-chemical compatibility is guaranteed. A sustainable relocation allows the sediments to be available again and to be used to maintain or supplement natural processes. Dredged volumes can provide many of the materials required for environmental enhancement, as for example to create mudflats and saltmarshes, the extent of which has been considerably reduced during recent years. Dynamic processes inevitably lead to bottom erosion in shallower waters, but sediments can still remain in circulation. To avoid excessive dispersion of material in the short term, it is possible to adopt temporary protections such as wooden sheet piles or floating containment booms for the time necessary for consolidation. In this regard, the comparison between the morphodynamic simulations for site 1 showed the possible benefits induced by this particular technique.

5. Conclusions

In the present paper, numerical modelling has been applied to study the morphological evolution of the disposals of cohesive sediments dredged from the Pantani and Barbana channels during the 2017 in the Marano and Grado lagoon. The effects of both tidal currents and locally generated wind waves have been adequately reproduce, since their non-linear interaction plays a fundamental role in lagoon and coastal morphodynamic processes. Different solutions have been proposed for the relocation of the material: in the case of the Pantani channel, the improvement of the mudflat at the intersection

between Coron and Cialisia channels have been considered, since the volume to be dredged was large; the material dredged from the Barbana channel was used to create an artificial marsh along the edge of the Fra' Simon channel. The temporal bed level variations have been obtained with the aim to establish the behaviour of the sediments in the medium period. Three different simulations have been performed depending on the presence of temporary protection of the material and different consolidation states. The results showed that both solutions involve the loss of a part of the relocated volumes, but this is acceptable in view of a sustainable use of the dredged material for the improvement of environmental processes. The adoption of temporary protections until obtaining a greater consolidation of the material can limit the losses of sediments in the short term.

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