“CHANNELING THE GREEN DEAL FOR VENICE”
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IDENTIFICATION OF SOLUTIONS

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ANNEXES

1 CONTENT

A series of comprehensive modelling activities was conducted to quantify the impact of maritime traffic on the Malamocco – Marghera Channel (abbreviated as MMC in the following) and surrounding areas. Possible solutions are identified aimed at minimizing the erosion processes that are now affecting the tidal flats surrounding the channel, thus achieving sustainable navigation conditions.

To match this ambitious goal, following Public Tender procedures, the Contract was awarded by Port of Venice to a Consortium led by DHI S.r.l. and formed by DHI A/S, Force Technology, HS Marine S.r.l., Cetena S.p.A. and Around Water di Andrea Zamariolo Ph.D. Geol.

The present document describes the design approach addressing the whole study and the design solutions foreseen, based on the comprehensive study developed by the Consortium.

With reference to the "*Capitolato Tecnico*" the present document includes the following deliverables:

17. *Relazione tecnica inerente alla progettazione delle opere di difesa proposte, con relativi elaborati grafici;*
18. *Relazione tecnica inerente alla progettazione delle soluzioni gestionali;*
19. *Relazione tecnica economica inerente alle soluzioni selezionate*

The first part of the report describes the design process and the design solution, developed considering navigational, hydrodynamic and morphological issues. This part of the report includes the contents of both the contents of both §17 and §18 of the tender requirements; these contents, in fact, are both part of the design process and are strictly related one to each other.

The second part of the report provides an estimate of dredging volumes related to the structural design. These volume calculations are not developed according to a preliminary design level and are affected by a series of uncertainties (discussed in the report).

2 BATHYMETRIC DATASETS

The bathymetry of the project area is based on the four datasets listed in Table 2-1. A single dataset covering the entire lagoon has not been available, hence several surveys carried out at different periods and related to different areas of the lagoon had to be used instead.

The design is based on the latest survey provided by the Port Authority, performed by Elmar in 2022 and covering the whole navigation channel and submerged banks. The areas that are not covered by this latest survey have been modelled considering previous available surveys.

Table 2-1. List of bathymetric datasets used in the re-design proposal.

Source	Dataset no.	Time	Resolution [m]	Vertical datum
Autorità di Sistema Portuale del Mare Adriatico Settentrionale	1	2002	1	IGM42
Provveditorato (Ex Magistrato delle Acque) [1]	2	2018	~100	IGM42
Autorità di Sistema Portuale del Mare Adriatico Settentrionale	3	2017 to 2021	1	IGM42
Consiglio Nazionale delle Ricerche	4	2013	1	IGM42
Autorità di Sistema Portuale del Mare Adriatico Settentrionale	5	2022	1	IGM42

3 SYNTHESIS OF BASELINE MODELLING

The base analysis aims at evaluating the contribution of different effects upon the morphological evolution of the channel and the surrounding shallow flats. The purpose of this analysis is to focus design solutions, both structural and operational, on the most critical points and phenomena.

3.1 Navigation

An extensive series of real time manoeuvring simulations has been run considering the present lay-out of the channel, for the purpose of risk analysis and development of design proposal. These simulations highlight the critical points where groundings are likely to occur. The list of tested vessels is reported in Table 3-1, while in the following Table 3-2 the full list of simulation runs is reported, together with specific remarks of grounding conditions.

In the following figures (Figure 3.2 to Figure 3.6) a series of track plots are reported together with yellow arrows where groundings were most likely to occur.

The entrance route, from Bocca di Malamocco to S. Leonardo bend, is not critical because the channel is wide and deep, and the vessel speed is high enough to enable effective manoeuvring.

After S. Leonardo bend, the channel narrows abruptly and frequent groundings occurred, both in inbound and outbound routes.

To the north of S. Leonardo bend, the channel has another (milder) bend; there is no channel enlargement in this bend. Though most critical runs grounded before negotiating the bend, this is indeed a critical issue that must be properly addressed in channel optimisation (see Figure 3.1).

The new terminal ro-ro in Fusina does not have a proper manoeuvring basin, a local channel enlargement should be considered for both ship manoeuvring and tug assistance. Tug assistance is indeed a general issue for the port, because the dredged channel is narrow and the submerged banks are not deep enough for the tug to operate.

The inner channel, between turning basin #3 and #4, is too narrow and does not allow safe manoeuvring at arrival or departure of larger ships, even in mild wind conditions at slow speed.

The ship manoeuvring simulations allowed for the definition of the first draft proposal of channel optimisation; successive simulations have been run considering further optimisation in order to provide safe navigation at slower speed while minimizing the dredging volumes.

The full set of simulations can be found in the real time simulation report.

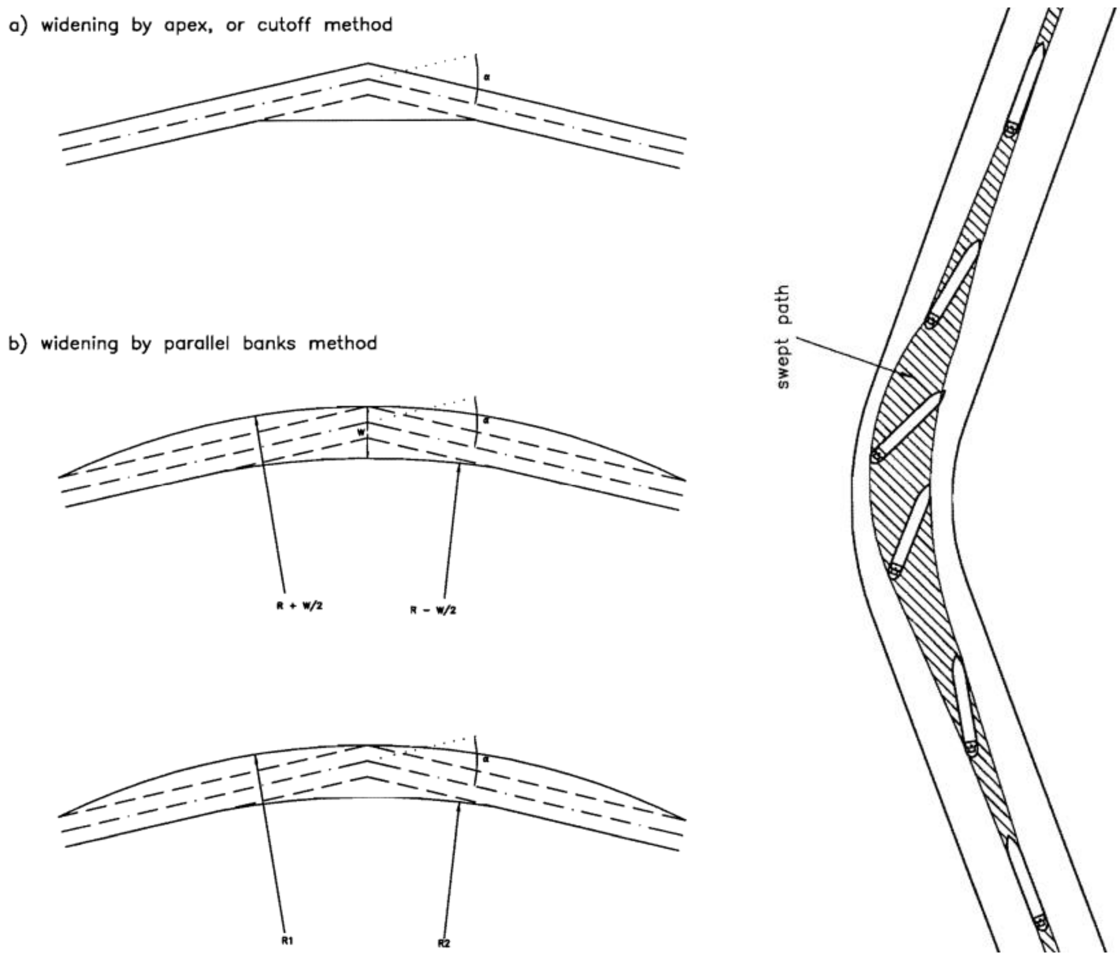


Figure 3.1. Methods of channel widening through bends (left) and swept path of a vessel negotiating a channel bend (right).

Table 3-1. Ships used in the simulations.

Ship No.	Name	Ship Type	Description	Load Con.	LOA m	Lpp m	Bmld m	Tf m	Ta m	Displacem	Prop.	Rudd.	Bow thrst.	Stern thrst.
3644	"Gold Sapphire"	Cruise Ship	294 m	S	294.0	261.0	32.2	8.3	8.3	50453	2F	2	3	3
3481	Roberta	Bulker	51.000 DWT	L	200.0	191.0	32.2	11.0	11.0	55690	1F	1	1	0
3601	"Atlas"	Container Ship	2.680 TEU	L	215.6	206.2	32.2	11.0	11.0	48571	1F	1	1	0
3556	Costa Luminosa	Cruise Ship	294m	S	294.0	265.4	32.25	8.1	8.1	47646	0	0	3	2AZ(fp)
3297	Tor Magnolia	RoRo	199.8m	L	199.8	190.3	26.5	7.7	7.7	21248	1C	1F	2	1
3583	"Melusina"	RoRo	215 m	L	215.0	205.0	26.5	7.7	7.7	25341	1C	1	2	2
3764	Multratug 4	Tug VSP	36m, 72 t BP	S	36.0	34.0	12.5	5.7	5.7	855	2VS	0	0	0
3852	Svitzer Maitland	Tug ASD	30m, 70 t BP	S	30.0	25.6	11.0	4.6	4.8		0	0	1	2AZ(cp)

Table 3-2. List of executed runs.

Run no	Ship	Type	Cond	Wind speed (m/s)	Wind dir (deg)	Current File	Wave file	Wave height	Wave direction	Wave period	Remarks
101	3644	Cruise	294 m	5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	
102	3644	Cruise	294 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
103	3644	Cruise	294 m	10	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
104	3644	Cruise	294 m	10	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	grounded. Lossing control when slowing dov
201	3644	Cruise	294 m	10	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
202	3644	Cruise	294 m	12.5	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
203	3644	Cruise	294 m	10	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
204	3481	Bulker	200 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	grounded in the first turn
205	3481	Bulker	200 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	grounded due to bank effect
206	3481	Bulker	200 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	
207	3481	Bulker	200 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
301	3481	Bulker	200 m	12.5	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	grounded east side of the channel
302	3481	Bulker	200 m	10	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
303	3481	Bulker	200 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	
304	3481	Bulker	200 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
305	3481	Bulker	200 m	12.5	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	grounded. Departure. Wind and bank effect.
306	3481	Bulker	200 m	12.5	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
401	3601	Container	294 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	
402	3601	Container	294 m	10	45	Venice_2021_24-1-2020-2000hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
403	3481	Bulker	200 m	12.5	67	Venice_2021_24-1-2020-2000hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
404	3601	Container	294 m	15	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
405	3297	RoRo	200 m	12.5	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
406	3297	RoRo	200 m	12.5	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
407	3297	RoRo	200 m	12.5	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
408	3556	Cruise	295 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	Stopping and drifting out of channel
409	3556	Cruise	295 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
501	3297	RoRo	200 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
502	3601	Container	294 m	7.5	23	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_5ms_NE_wind.wmp	1	ENE	1	Grounded. Difficult to steer at low speed
503	3601	Container	294 m	10	45	Venice_2021_24-1-2020-2000hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	
504	3297	RoRo	200 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	Ship behavior not realistisc
504	3601	Container	294 m	15	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
505	3556	Cruise	295 m	15	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
601	3297	RoRo	200 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
602	3435	RoRo	220 m	10	45	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_15ms_NE_wind.wmp	1	ENE	1	
603	3601	Container	294 m	12.5	67	Venice_2021_9-1-2020-1520hrs.cur	Venice_2021_wave_10ms_NE_wind.wmp	1	ENE	1	Grounded. Difficult to steer at low speed

Figure 3.2. *Grounding area next to turning basin #3 (run 104).*

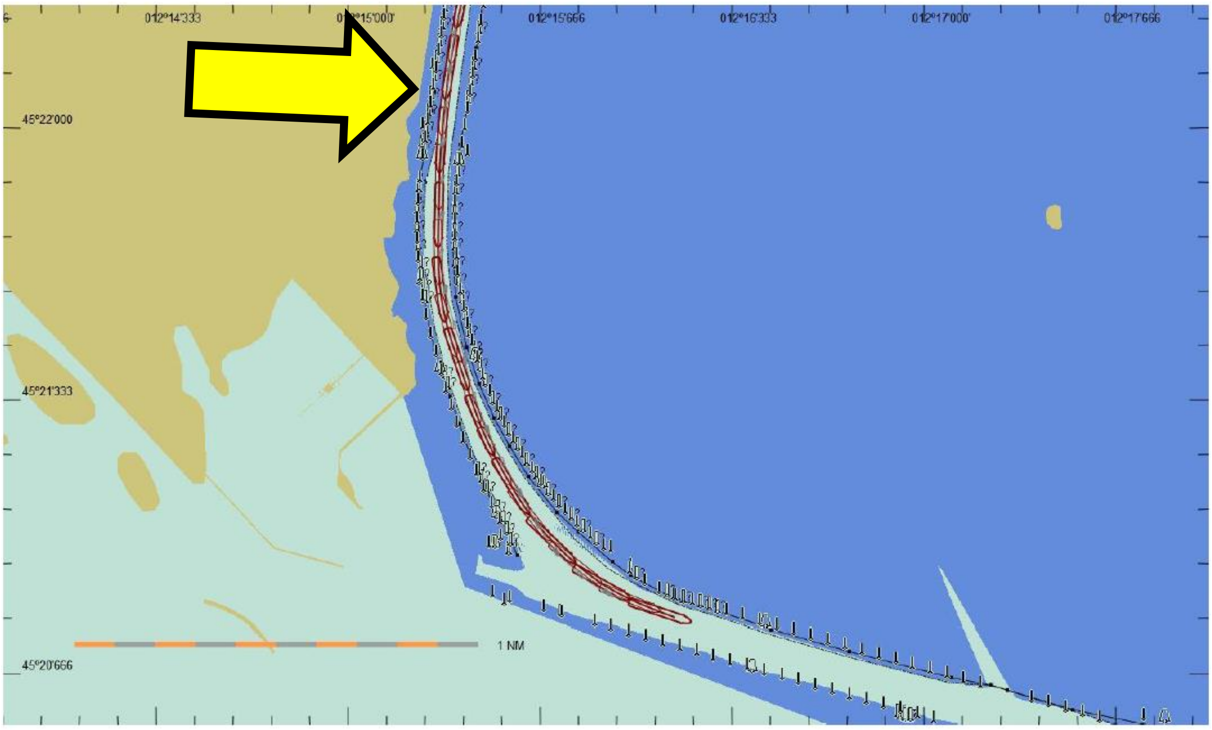


Figure 3.3. *Likely grounding area at S. Leonardo bend (run 201).*

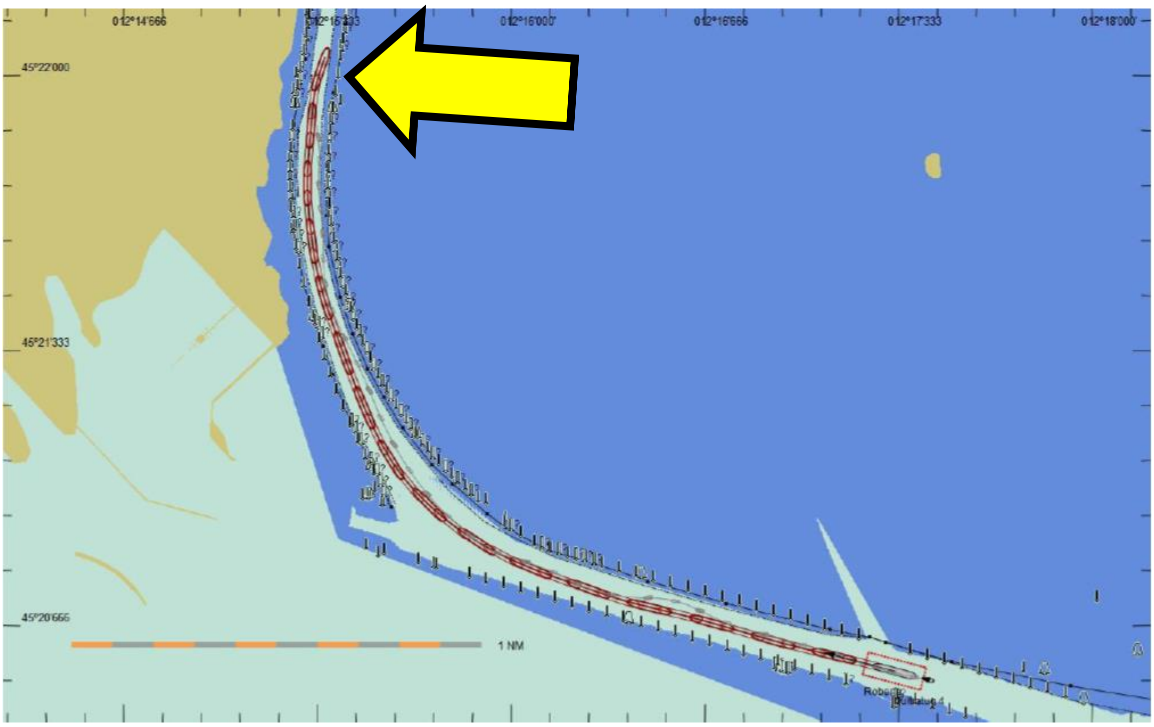


Figure 3.4. *Grounding area at S. Leonardo bend (run 204).*

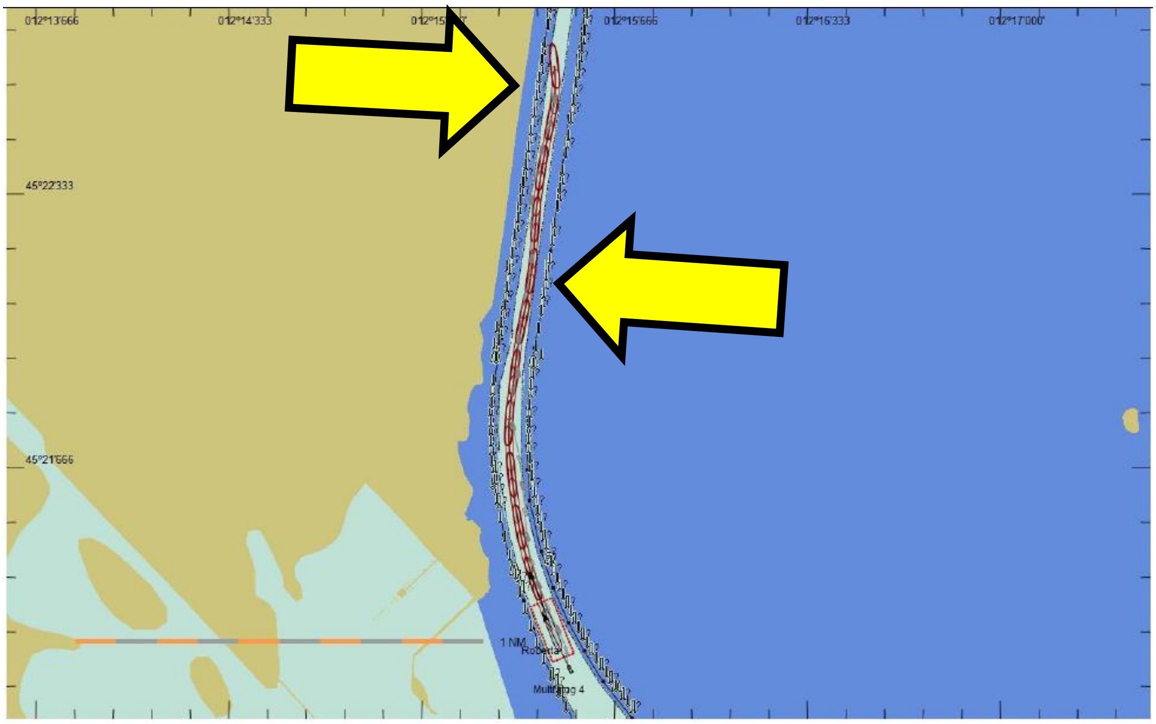


Figure 3.5. *Grounding area north of S. Leonardo bend (run 205).*

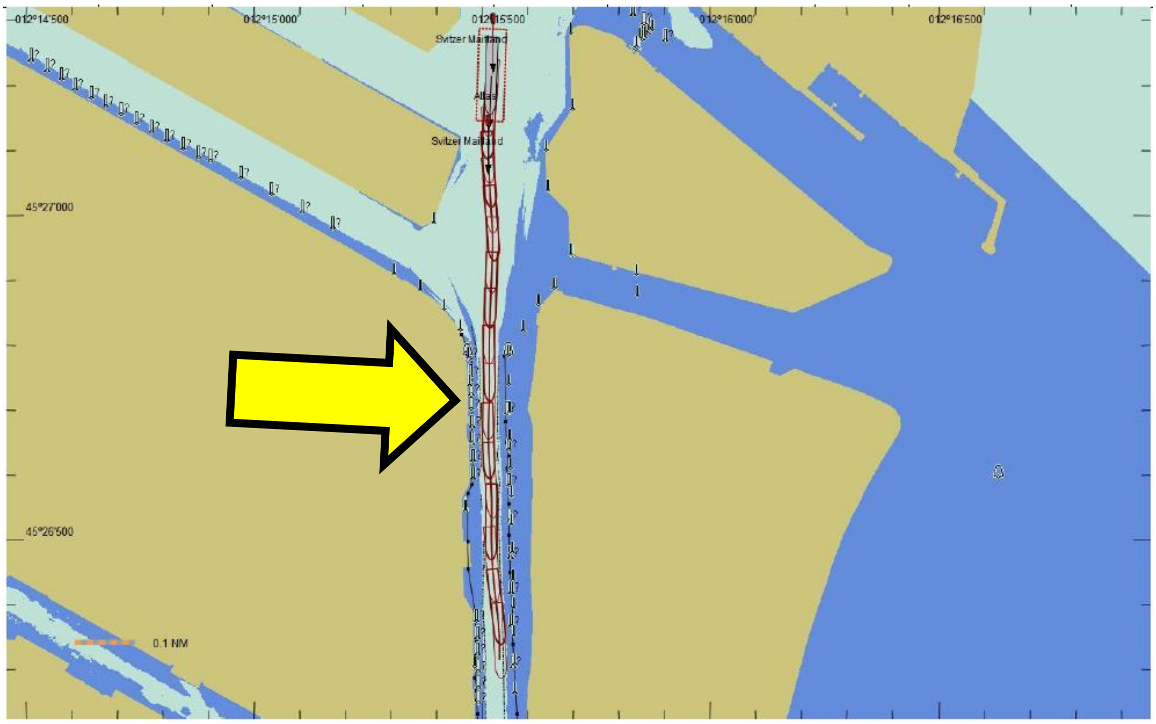


Figure 3.6.   Grounding area south of turning basin #3 (run 502).

3.2 Displacement waves

The primary wave (or displacement wave) is associated with acceleration of the flow under - and around the vessel hull. This flow acceleration generates a drawdown, which to a stationary observer, is seen as a long-period transient wave. This type of wave is especially important in narrow channels (such as the MMC) where the drawdown can become quite significant.

The formation of the primary waves follows the below principals:

- at the bow, a stagnation point is formed due to vessel relative velocity reduction, causing an increase in pressure (i.e. a local increase in water level travelling ahead of the vessel);
- along the sides of the vessel, the flow is re-accelerated causing a decrease in water level, known as the drawdown;
- at the stern, the flow decelerates again causing an increase in water level.

During the baseline modelling, all selected vessels have been simulated inbound and outbound routes, assuming a navigation speed of 10 knots and water level set to zero m MSL. The baseline modelling also investigates whether there is a difference between inbound and outbound traffic with respect to the erosion potential. The erosion from the bed is regulated by the bed shear stress magnitude. When the modelled bed shear stress exceeds a critical value, sediment is eroded from the bed and dispersed into the water column. The critical value of the bed shear stress for erosion varies across the domain and through the bed layers. The suspended material is allowed to settle and deposit onto the bed when the bed shear stress becomes smaller than the critical value.

As an example, the drawdown levels considering the inbound and outbound passage of Con-S are listed in Table 3-3 and Table 3-4, eastern and western extraction points respectively. The cells in the tables have been coloured according to the draw down magnitude.

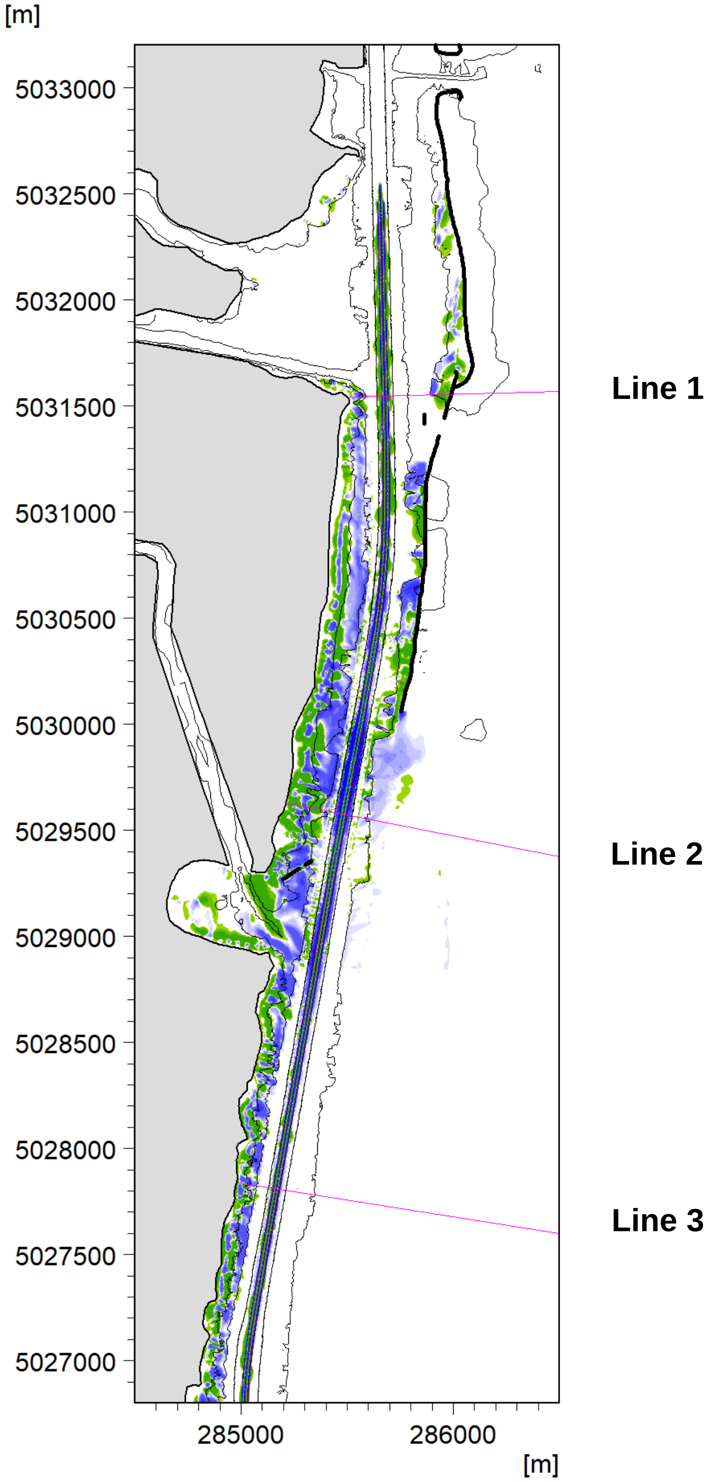


Figure 3.7. Reference lines for model results.

In the previous figure, the three pink lines, numbered 1 to 3 starting from north, are used to evaluate the modelled drawdown levels:

- line-1 is located in an area where the displacement wave has a quite limited area to spread out on since the channel here is framed by the western shoreline and the eastern structures;
- line-2 is located south of the area influenced by the eastern structures;
- line-3 is located north of the San Leonardo bend in a fairly un-restricted part of the channel.

Table 3-3. Overview of modelled minimum water levels at eastern line extraction points during in- and outbound passage of Con-S.

WL (m MSL)	Margin	200 m	400 m	600 m	800 m	1000 m	1200 m	1400 m
Line-1, In	-1.05	-0.97	-	-	-	-	-	-
Line-1, Out	-0.61	-0.48	-	-	-	-	-	-
Line-2, In	-0.67	-0.49	-0.28	-0.22	-0.18	-0.14	-0.12	-0.10
Line-2, Out	-1.06	-0.69	-0.33	-0.22	-0.15	-0.12	-0.10	-0.08
Line-3, In	-0.53	-0.45	-0.34	-0.25	-0.13	-0.08	-0.05	-0.04
Line-3, Out	-0.64	-0.53	-0.36	-0.28	-0.21	-0.16	-0.13	-0.11

Table 3-4. Overview of modelled minimum water levels at western line extraction points during in- and outbound passage of Con-S.

WL (m MSL)	Margin	75 m	100 m	125 m	150 m
Line-1, In	-1.14	-1.26	-	-	-
Line-1, Out	-0.73	-0.76	-	-	-
Line-2, In	-0.82	-0.79	-0.79	-0.79	-1.03
Line-2, Out	-1.11	-1.11	-1.09	-0.99	-1.13
Line-3, In	-0.72	-0.72	-0.77	-0.78	-0.49
Line-3, Out	-0.74	-0.74	-0.86	-0.9	-0.48

Based on the tables, it can be observed that at Line-1 the drawdown levels are larger during the inbound passage, while at line-2 and 3 the drawdown levels are larger during the outbound passage. At Line 2 and 3, the drawdown decreases with increasing distance to the channel. Drawdown at the western side are slightly larger. At the margin of the channel, drawdown in excess of 1 m are observed. Further away into the lagoon the dissipation rate decreases.

In Figure 3.8 a map of the maximum modelled bed shear stress is shown (inbound passage of Con-S). The difference between inbound and outbound passage is plotted as the right panel in the figure. Inbound passages cause larger bed shear stresses in the northern part of the domain, where the east-side structures are located, while outbound passages cause larger bed shear stresses in the southern part of the domain, south of the east-side structures. Bed shear stresses are larger (>7.5 Pa) on the western side of the channel than on the east side.

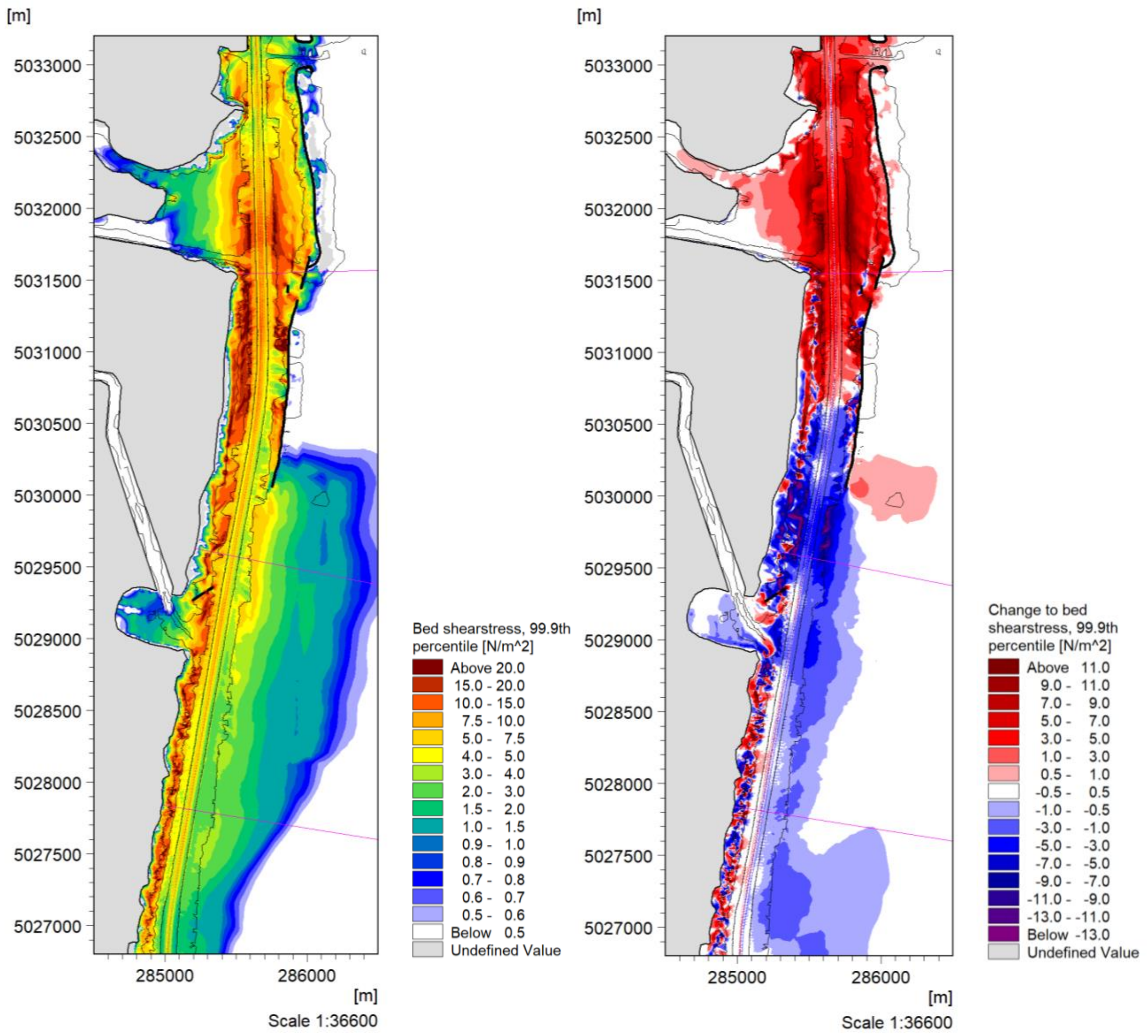


Figure 3.8. *Map of maximum modelled bed shear stresses during inbound passage of Con-S (Left). Map of difference between inbound and outbound maximum bed shear stress (in minus out) during Con-S passage (Right).*

3.3 Kelvin waves

The movement of a ship through water is often characterized by a system of waves originating from the ship's bow and stern (see Figure 3.9 and Figure 3.10). This wave pattern is termed the Kelvin wake or the secondary waves. They arise as the result of pressure differences along the ship's hull.

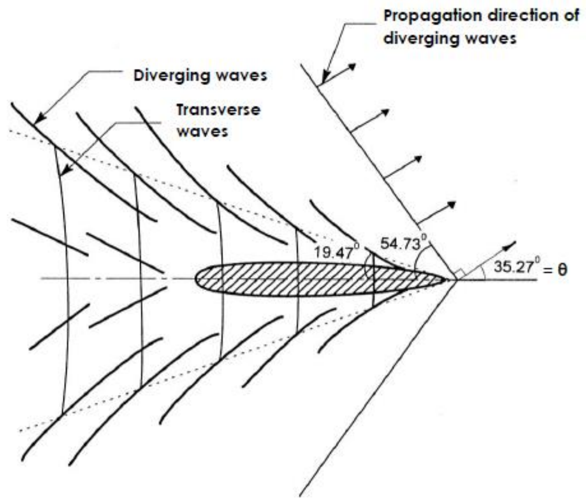


Figure 3.9. Theoretical illustration of Kelvin Wake.

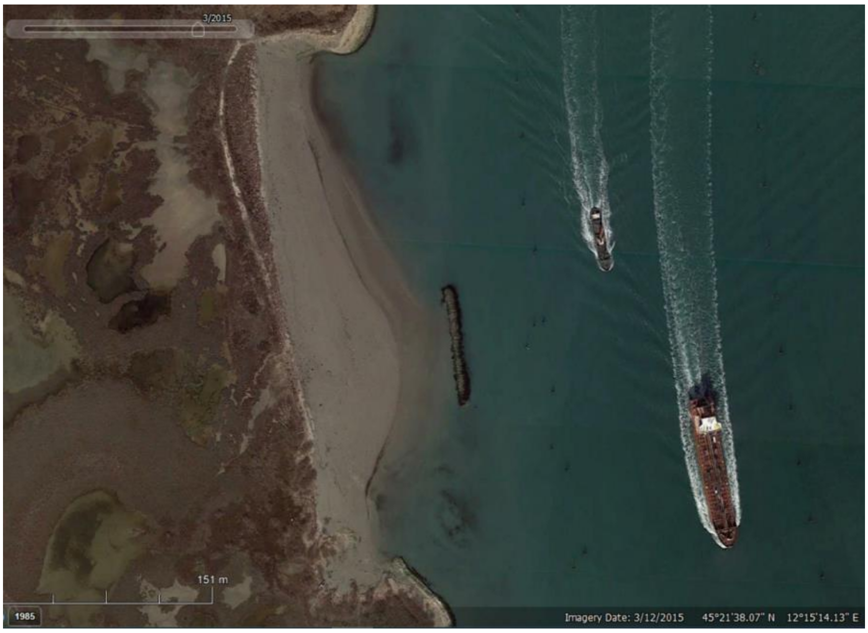


Figure 3.10. Google Earth satellite image from December 3rd, 2015 illustrating Kelvin waves in MMC at northern part of the San Leonardo bend.

Table 3-5. *Overview of maximum Kelvin wave height.*

H_{max} (m)	7 knots	8 knots	9 knots	10 knots	11 knots
Con. S	0.03	0.07	0.15	0.26	0.43
Con. L	0.05	0.11	0.23	0.42	0.71
Tan. S	0.02	0.05	0.13	0.27	0.48
Tan. L	0.02	0.06	0.14	0.28	0.49
Bul. S	0.00	0.02	0.05	0.10	0.18
Bul. L	0.01	0.02	0.06	0.13	0.23
Gen.	0.07	0.16	0.33	0.58	0.97
Ro-Ro	0.00	0.01	0.02	0.04	0.07
Cru. S	0.00	0.02	0.06	0.13	0.24
Cru. L	0.01	0.04	0.09	0.19	0.34

The diverging Kelvin waves propagate away from the vessel, out of the channel and onto the shallow flats. If the wave generated velocities are high enough, they can mobilize sediment at the bed and cause a net transport.

As an example, the resulting bed shear stresses, in front of Fusina land reclamation areas, are shown in Figure 3.11: the top map shows the maximum bed shear stress during an outbound passage of Nervion Valley (used for hydrodynamic model calibration) travelling at 9 knots while the bottom one shows the average Kelvin wave height corresponding to 10 knots outbound.

The critical bed shear stress for erosion on the flats is about 0.7 Pa and as such, the Kelvin waves should only be expected to contribute notably to the vessel generated sediment transport close to shore and not to any large extent on the flats along the MMC.

The height of the Kelvin waves depends strongly on the vessel speed. An increase in vessel speed from 8 to 10 knots leads to an increase of the Kelvin wave height by a factor 3 to 5. For a vessel speed of 8 knots, a maximal wave height of 0.16 m was found (General cargo vessel), for 10 knots, this value increases to 0.58 m.

Model simulations show that Kelvin waves cause a net annual sediment transport of around 0.025 m3/year/m. The related annual bed level change is negligible (less than 0.5 mm/year).

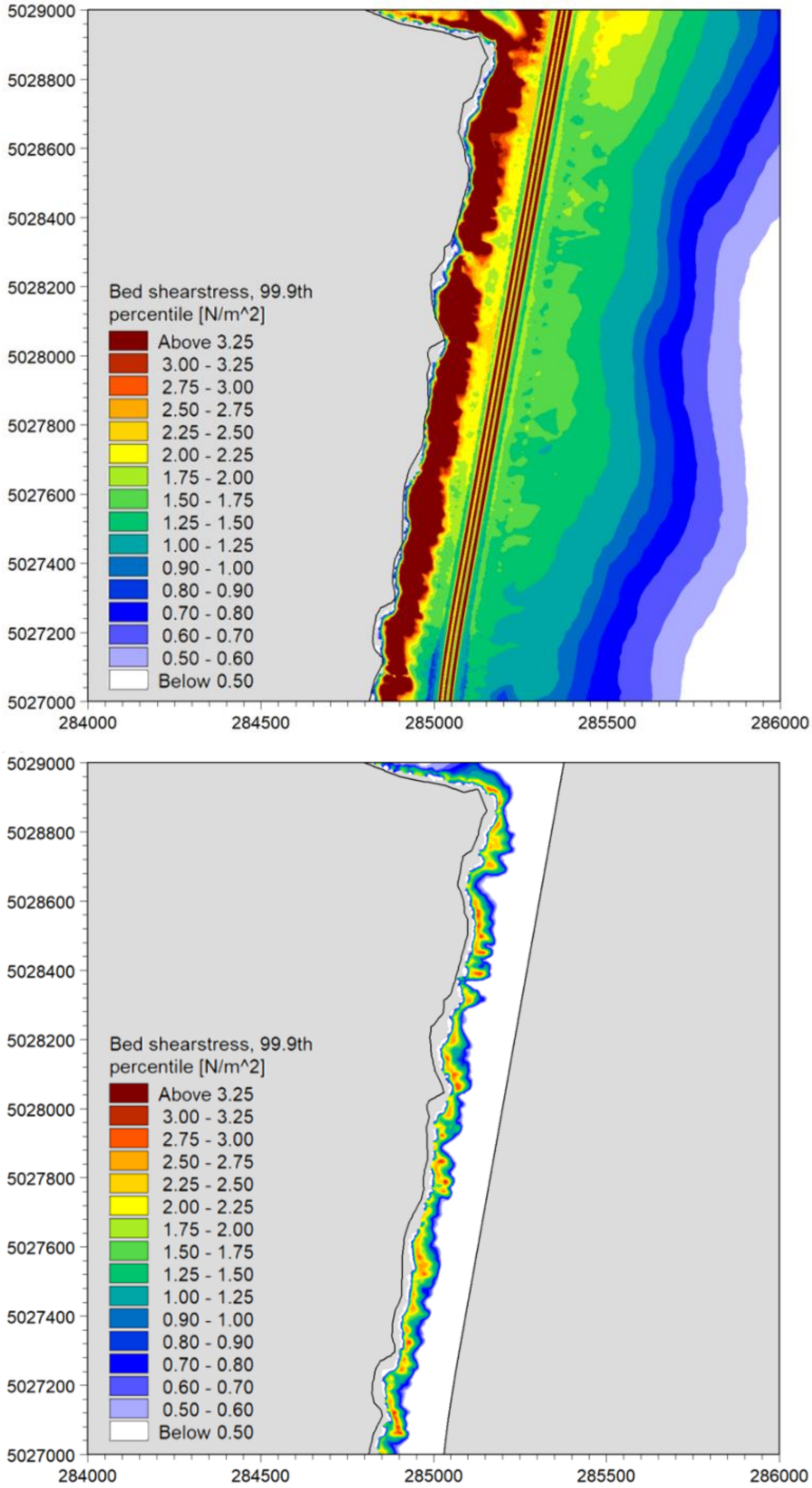


Figure 3.11. Map of bed shear stresses from primary waves (top) and Kelvin waves (bottom).

3.4 Propeller wash

The propellers of the vessels passing the Malamocco channel create jet flows that have an impact on the mobilization and transport of sediments on the channels bed. In this section, the importance of the propeller-generated flow on the sediment balance in the channel is analyzed.

The generation of the propeller generated jet is illustrated in Figure 3.12. As the ship propeller rotates, water is contracted and pushed backwards into a jet. Close to the ship, the width of the jet, indicated in Figure 3.12 as D_0, is slightly smaller than the radius of the ship propeller, D_p. The radius of the jet widens with distance from the ship. The strength of the flow decreases with both horizontal distance from the ship as well as the vertical distance from the centerline.

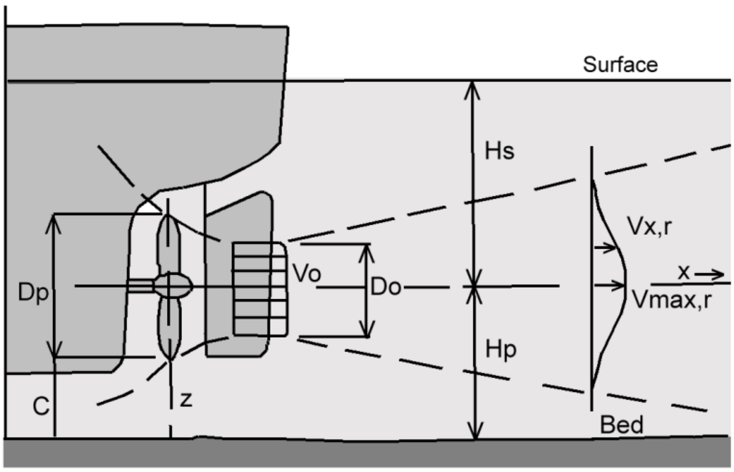


Figure 3.12. Illustration of propeller generated jet flow behind a ship.

The model simulations clearly show that the maximal bed shear stress caused by the propellers is significantly smaller (at least an order of magnitude) than the maximal bed shear stress generated by the displacement waves.

The mean flow and the bed shear stress in the area behind the ship are both directed towards the center of the channel. Further, away from the ship a weak residual current is generated in the propagation direction of the vessel, hence parallel to the channel.

The propellers will cause turbulent eddies in the area behind the vessel. The main effect of this additional turbulence is that suspended sediments will be mixed more intensively across the water column. Therefore, suspended sediment concentrations are high in the area at the rear of the vessels. However, there is no net flow causing significant exchange of sediment between the channel and the neighboring areas. Therefore, it is concluded that the propellers of the vessels will only have a marginal effect on the sediment balance of the channel.

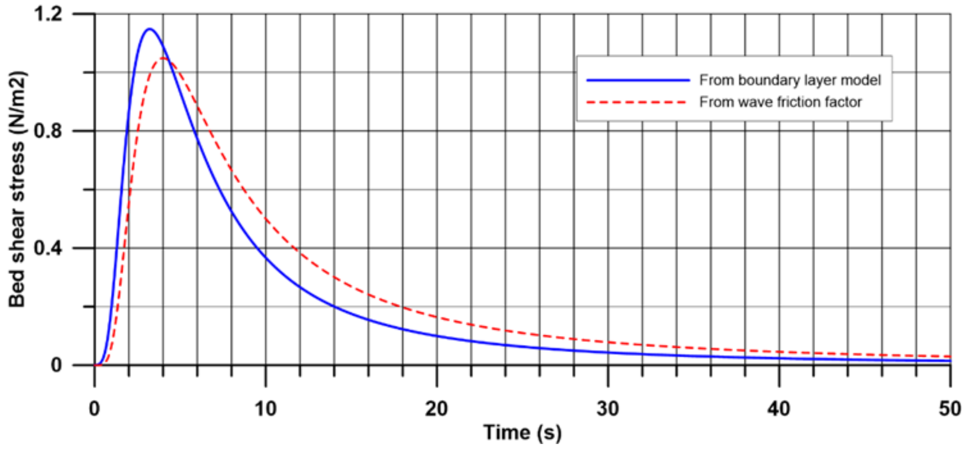


Figure 3.13. *Time development of the propeller generated bed shear stress caused by a container vessel with length of 200 m, navigating with a speed of 10 knots.*

3.5 Natural forcing

The influence of waves on the morphological evolution of the lagoon has been investigated by means of a 3D model. The wave forcing was derived from a comprehensive database of sea states inside the lagoon produced during project phase 1 and derived by wave hindcast modelling.

Two representative sea states generated by northeasterly wind system (i.e. Bora) were simulated; one energetic and rather rarely occurring sea state and a more frequent one. Figure 3.14 to Figure 3.15 show the significant wave height values reached in the lagoon at the peak of the two sea states. Maps of maximum bed shear stress (BSS) reached at each computational domain node at any time for the simulated sea states are illustrated in Figure 3.16 and Figure 3.17. The levels of shear stress associated to the more energetic wave field are of comparable magnitude to the bottom stress produced by Kelvin waves generated by passing vessels and of lower relevance when compared to vessel displacement waves, although potentially covering a much wider area of the lagoon. Expectedly, lower values of bed shear stresses are observed in deeper navigation and natural lagoon channels. More frequent and less energetic sea states show a little impact to sea bottom in terms of total stress leading in turn to reduced seabed erosion and water turbidity.

The maximum values of depth averaged suspended sediment concentration (SSC) reached in the lagoon during at the peak of the more energetic sea state are in the range of 100-500 mg/l on shallow tidal flats with lower levels of concentration below 5-10 mg/l observed in the Malamocco-Marghera, deeper natural channels and area less exposed to waves. For more frequent and less energetic sea states, the turbidity level drops drastically to values below 10mg/l for almost the entirety of the lagoon.

The entirety of the sediment mass provided as initial condition (nearly 100 %) settles to the sea floor within a full tidal cycle. Figure 3.18 and Figure 3.19 show the total amount of sediment deposited at the end of tide cycle (12 hours) for the two wave scenarios simulated. The portion of sediment mass that does not settle on the seabed within a full tidal cycle travels outside the lagoon.

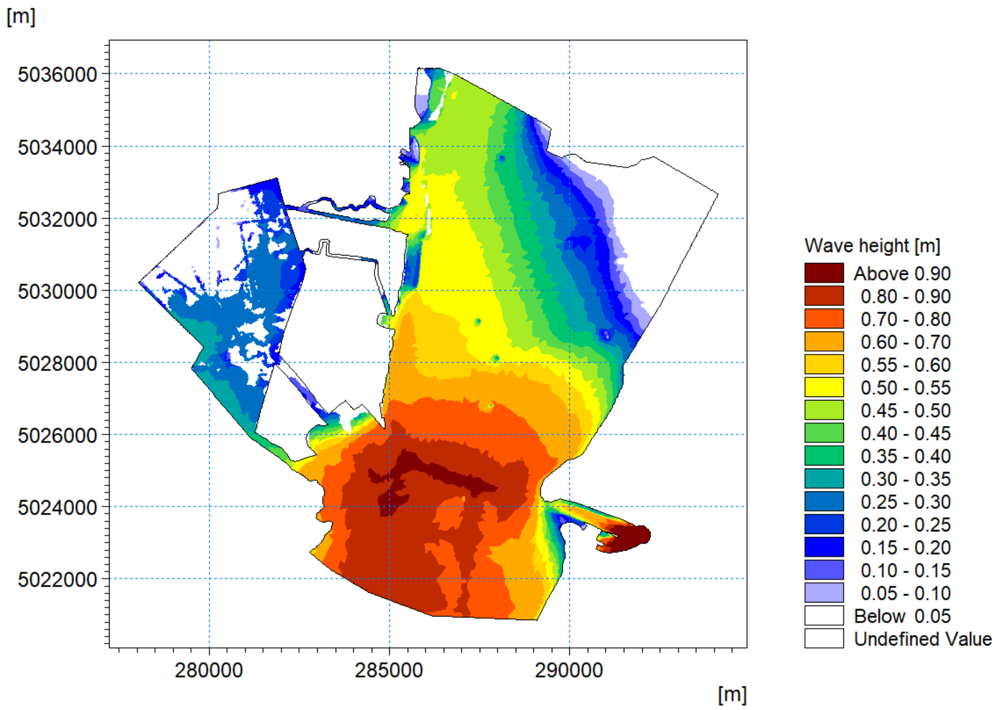


Figure 3.14. Map of significant wave height (H_{m0}) for an infrequent sea state.

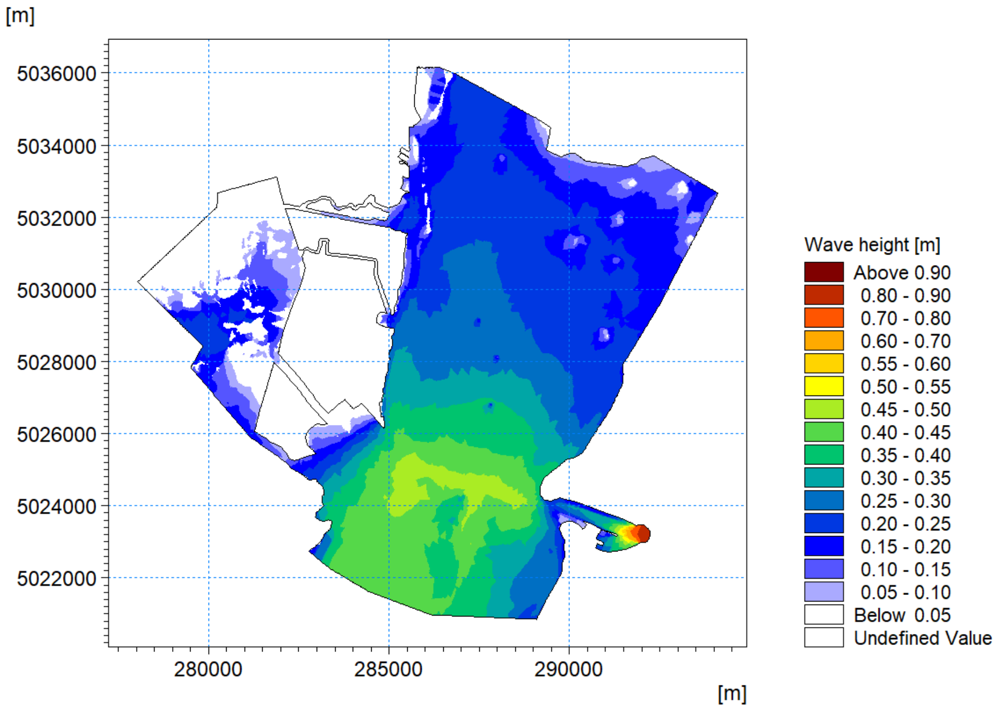


Figure 3.15. Map of significant wave height (H_{m0}) for a frequent sea state.

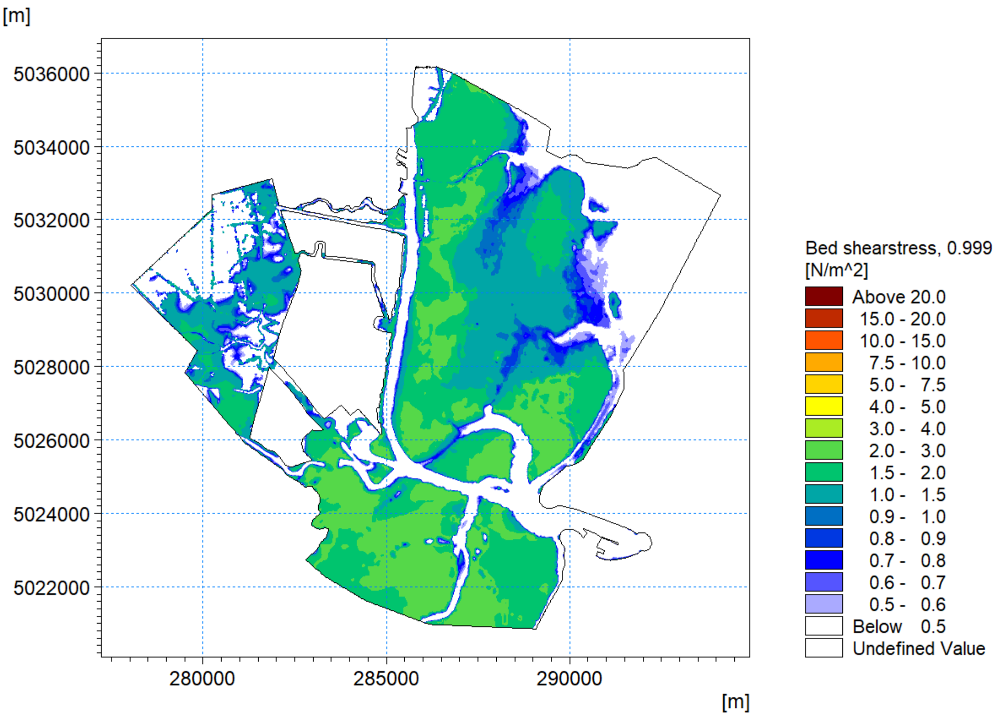


Figure 3.16. Map of BSS associated to an infrequent sea state.

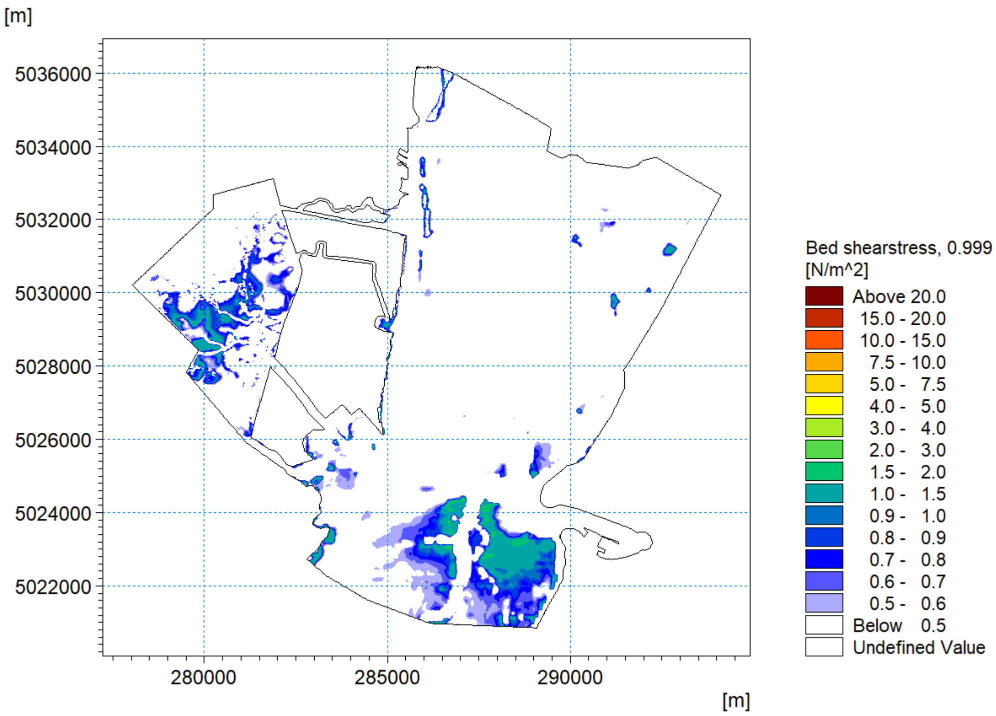


Figure 3.17. Map of BSS associated to a frequent sea state.

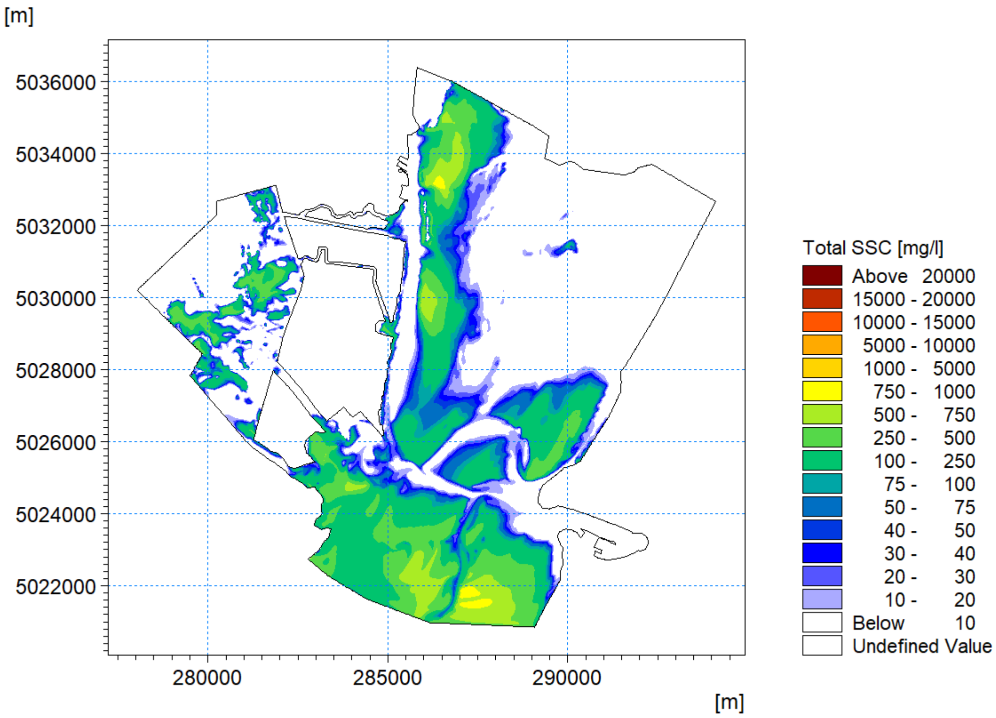


Figure 3.18. Map of SSC at the peak of an infrequent sea state.

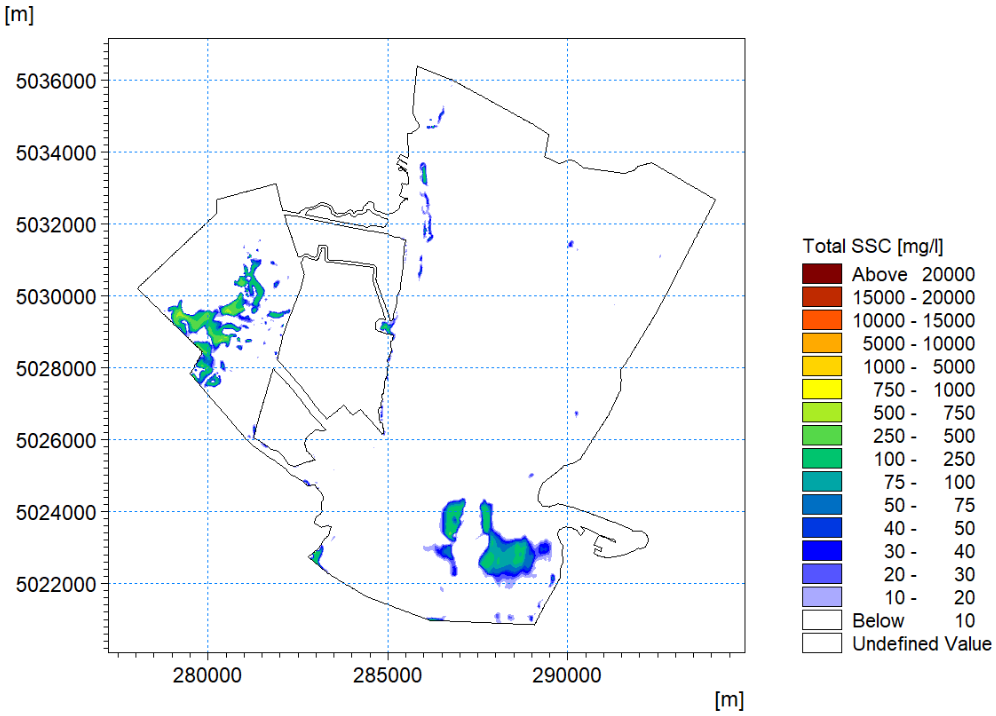


Figure 3.19. Map of SSC at the peak of a frequent sea state.

3.6 Baseline study conclusions

- The drawdown level depends upon the bathymetry of the channel: the larger and more unrestricted the channel (width and depth), the smaller the drawdown wave. The drawdown levels increase moving north from the San Leonardo bend and become especially large in the area where the channel is bordered by structures along the eastern side.
- Whilst the structures prevent the draw down from spreading out and impacting the lagoon, the draw down level becomes locally larger (in the area west of the structures).
- The draw down level of the vessel generated displacement wave depends on the channel geometry but generally increases with the displacement volume of the vessel.
- The draw down level decreases with distance to the channel centre line.
- The width of the zone with active sediment transport from vessel generated displacement waves depends upon the channel geometry but increases relatively linearly with the displacement stencil volume.
- The modelled large vessels represent about 17% of the total modelled events but can cause up to 60% of the total modelled erosion. This indicates that, if the mitigation measures can be targeted at the larger vessels, it will have a significant influence in terms of reducing the vessel generated erosion along the channel.
- Preliminary model tests investigating the reduction of vessel speed from 10 to 8 knots between San Leonardo and Fusina showed that the vessel speed has a significant influence on the drawdown magnitudes, as well as on the bed shear stress magnitudes on the surrounding flats.

4 INFLUENCE OF CANAL DREDGING ON GROUNDWATER TABLE

4.1 Foreword

Fresh groundwater resources are found at quite low depths, i.e., 30÷40 m and even less than 10 m beneath the Venice lagoon bottom (Teatini et al., 2017, see following par.). Like the hydrogeological setting of other lagoons, the silty-clayey layer marking the boundary between the marine Holocene and continental Pleistocene deposits precludes or at least reduce the vertical leakage of the salt waters downward into the underlying fresh-water aquifers. However, the large petrochemical industrial district of Porto Marghera has been in operation since the 1950s at the lagoon-mainland interface representing a main source of soil and water pollution around the area (e.g., Zonta et al., 2007). Despite an almost 50-km long cut-off wall built-up along the Porto Marghera quays to prevent discharge of contaminated waters into the lagoon (Paris et al., 2011), results from chemical analyses provided evidence of heavy metals contamination in sediments and pore water. This contamination has been found not only in front of the industrial site (Gieskes et al., 2015), but also at distance. Although quite gentle in the shallower subsurface, the natural groundwater flow from the mainland seaward has likely transported the contaminants into the lagoon ecosystem over the last decades.

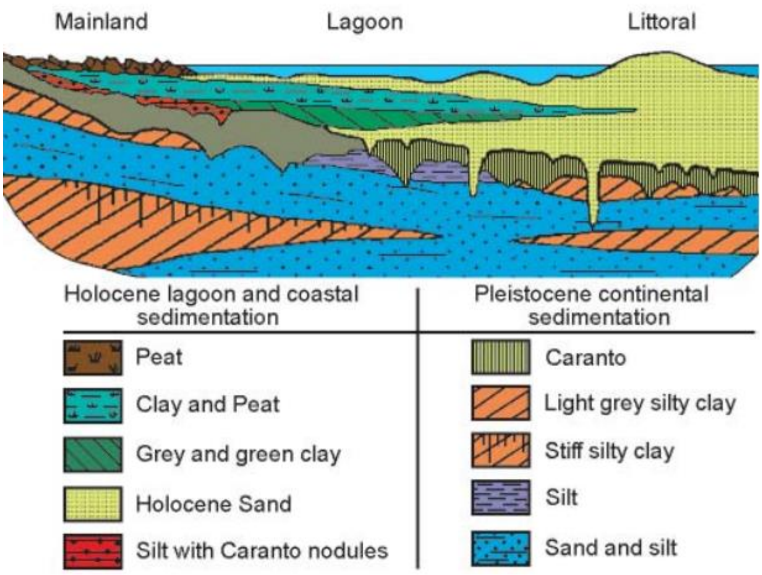


Figure 4.1. Stratigraphic sequence of the Venice Lagoon (Gatto and Previatello, 1974).

Cutting of the clayey Pleistocene and Holocene deposits in coastal zones can significantly increase the exchange between groundwater and surficial water bodies. In such a case, the anthropogenic and/or natural contaminants can be transported via the groundwater flow.

A modelling study presented by Teatini et al. (2017) provides a first evaluation of how the MVC (Marghera to Venice Channel) can affect the lagoon groundwater. The interruption of the Caranto aquitard favours the saltwater flow downward in a medium to long time interval, in the range of a few decades. Electromagnetic surveys and marine electric topographies carried out within the lagoon between Venice and Chioggia clearly pointed out that groundwater with a salt content similar to the marine waters is found beneath 5-15 m below m.s.l. only where the caranto layer have been cut, by natural erosion or channel excavation (Tosi et al., 2009; Zecchin et al., 2014).

The salt contamination remains localized around the incision, with an important role in controlling the depth of percolation played by the actual layering of the sedimentary deposits below the channel.

The more interesting result from the modelling approach by Teatini is that a significant influence on the groundwater–surficial water exchange is expected to occur, because of the excavation and vessel traffic. Each large ship generates a depression wake, pumping out the groundwater from the shallow deposits around the excavation. Although the ship wake lasts a couple of minutes, the large groundwater velocity induced in the surroundings of the excavation, combined with the length of the channel, are responsible for an efflux in the order of 50–100 m^3 per ship, i.e., 25 000–50 000 m^3 per year. The contaminants might be released into the lagoon because of ship wakes, with a considerable amount in the mid-term. Thus, limiting the digging or the reshaping of the canal could also limit the efflux of the contaminants along the canal, due to the release into the lagoon because of ship-wakes, with a considerable amount in the mid-term.

The final recommendations are to plan proper measures to limit the risk of contamination of the lagoon water during the years following dredging. Moreover, considering the importance and the fragility of the Lagoon of Venice, a number of new and more detailed information will be necessarily collected to provide a more accurate quantification of the possible environmental impacts of the canal dredging on the subsurface system of the Venice Lagoon.

The suggestions of Teatini must be considered very carefully, because of the potential impacts involved in the modification of the existing channels. However, it must be stressed that the potential cross contamination (pollution or salinization) between lagoon saltwater and freshwater aquifers is forced by the drawdown and occurs along the channel bottom.

The proposed design solution (see Figure 4.2 and following chapters) has very limited impact on the channel section: the channel cross section has only minor changes, while the dredged depth remains the same. Hence, from geometrical point of view, no significant change will occur. The proposed design solution, indeed, has a strong impact on the gradient governing this cross contamination: the structural and operational solution foreseen by the present study aims at minimizing the drawdown, thus reducing the migration of groundwater during ship passages to an even lower rate than the present one. This effect is presumed to occur also in the present configuration of the canal, although not yet monitored. Thus, we can suppose that only in the case of significant changes in the physiography of the canal, due to excavations along new trajectories in the waterway, intercepting and dredging the aquitard (i.e. the Caranto layers), the impact on the hydrogeological system and water quality will be relevant.

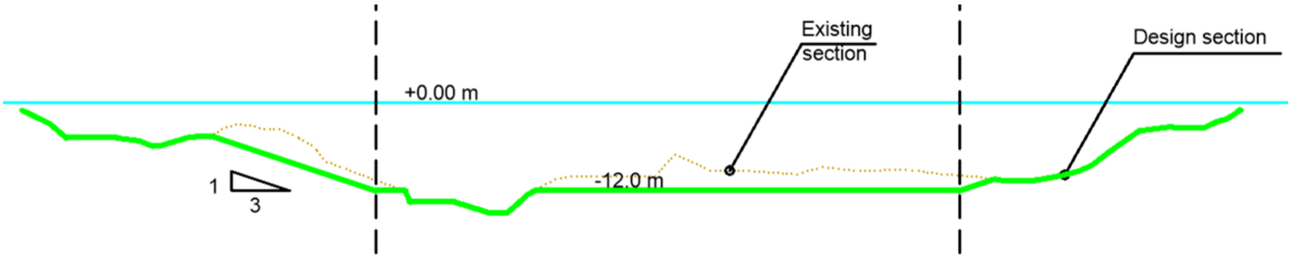


Figure 4.2. Sketch of modified cross section of the channel according to the design proposal.

4.2 MVC study

A first (and, to date, the only) comprehensive investigation aimed at quantifying the effects of dredging on the hydrogeological system underlying the Venice lagoon has been carried out by Teatini et al. (2017). The study analyses the hypothesis of opening a new 10-m-deep and 3 km long canal to connect the city passenger terminal to the central lagoon inlet, here referred as MVC (Figure 4.3, left). Simulations and design refer to two main sections, each with a specific hydrogeological setting (Fig. 1, right). Section 1 has a hypothesized channel bottom close to the Aquitard 2, whereas Section 2 has the bottom at the middle of the Aquifer 1-2 layer, due to the absence of the intermediate aquitard.

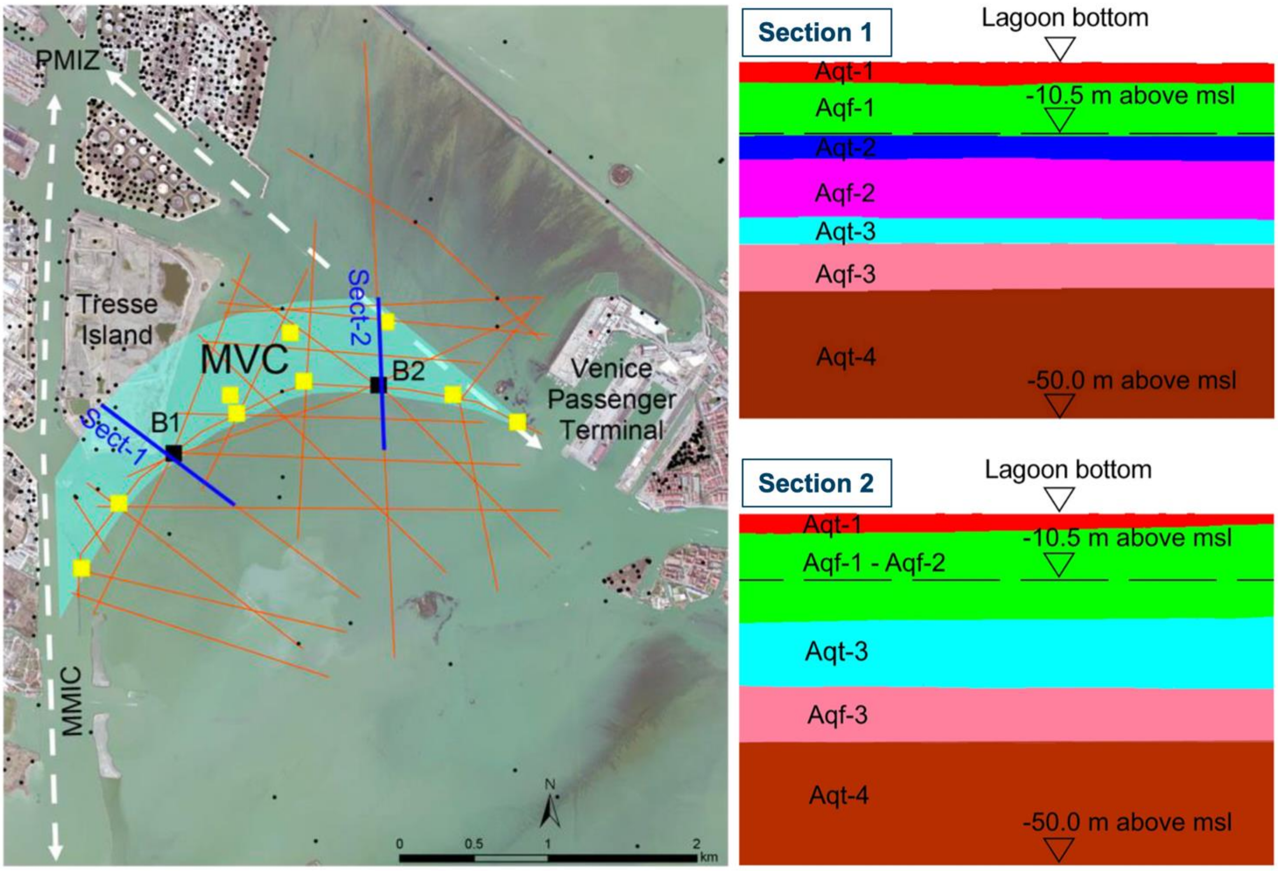


Figure 4.3. Location of the reference sections for the analysis on the possible effect of MVC canal dredging on the hydrogeological system. The simplified hydrogeological setting is reported as alternance of aquitards (Aqt) and aquifers (Aqf) in the two sections, on the right (after Teatini et al., 2017).

A modeling study has been developed to evaluate the short (minutes), medium (months), and long (decades) term processes of water exchange, as well as the pollutant exchange between the shallow aquifer system and the lagoon, possibly enhanced by the canal excavation, and ship wakes. The numerical results allowed for the quantification of groundwater volume and the mass estimation of anthropogenic contaminants that were probably released into the lagoon from the canal bed by the action of depression waves produced by ships over the previous decades from the nearby industrial area. The model's results also make it easier to comprehend how hydrogeological layering affects how salt concentration and tidal fluctuation are transmitted into shallow brackish aquifers that lie beneath the lagoon's bottom.

It must be noted that all the statements expressed in the paper by Teatini refer to the dredging of the new MVC channel and cannot be properly referred to minor modifications of an existing one.

4.2.1 Tidal effects

The dredging of a new relatively deep channel in a tidal environment can perturb the natural pressure and flow fields in the shallow subsurface. The effect of the different stratigraphic sequence is obvious, with an approximately 85% reduction of the pressure fluctuation within the clayey layer (Aquitard) with respect to the oscillation of the lagoon level (Figure 4.4a). The MVC dig reduces the time lag and the attenuation of the perturbation at depth. These effects only manifest in the channel's surroundings and are quantitatively negligible (Figure 4.5).

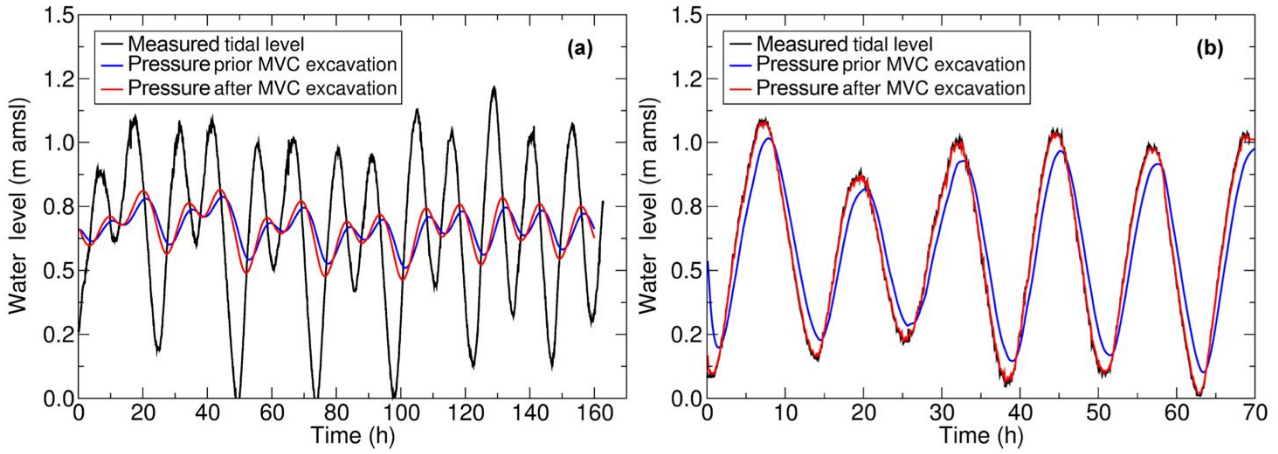


Figure 4.4. Behaviour of the pressure at a depth of -13 m in Section-1 (a) and Section-2 (b), respectively, prior to and after the MVC excavation. The tide fluctuation is provided for comparison (after Teatini et al., 2017).

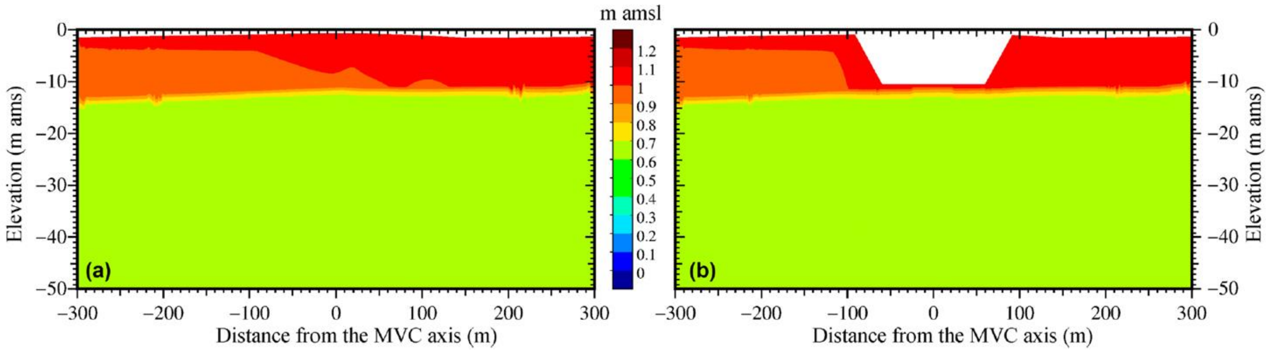


Figure 4.5. Computed pressure distribution (a) prior to and (b) after the MVC excavation at the maximum tidal level highlighted in Figure 4.4 for section 1 (after Teatini et al., 2017).

4.2.2 Ship-wake effects

Although a depression wave caused by a ship transit develops over a period of a couple of minutes, which usually is a very short time for hydrogeological processes, its height is sufficient to affect the groundwater pressure and flow fields in the proximity of the channel bottom.

Figure 4.6 provides the pressure distribution in the surroundings of the MVC, Section-2 (idealized as a newly dig section), computed by FLOW3D model, at the significant time steps, during the transit of the large commercial vessel Cargo-Hazard A. The pressure gently rises before the ship passage, significantly decreases soon after the transit, and then recovers with a gradient that changes its sign during each phase, mainly during T4 and T5, as reported in Figure 4.6c. The pressure change affects the portion of the subsoil down to the top of the first clay layer (aquitard) below the channel bottom, and extends laterally up to about 30 m from the channel slope, as reported in Figure 4.7.

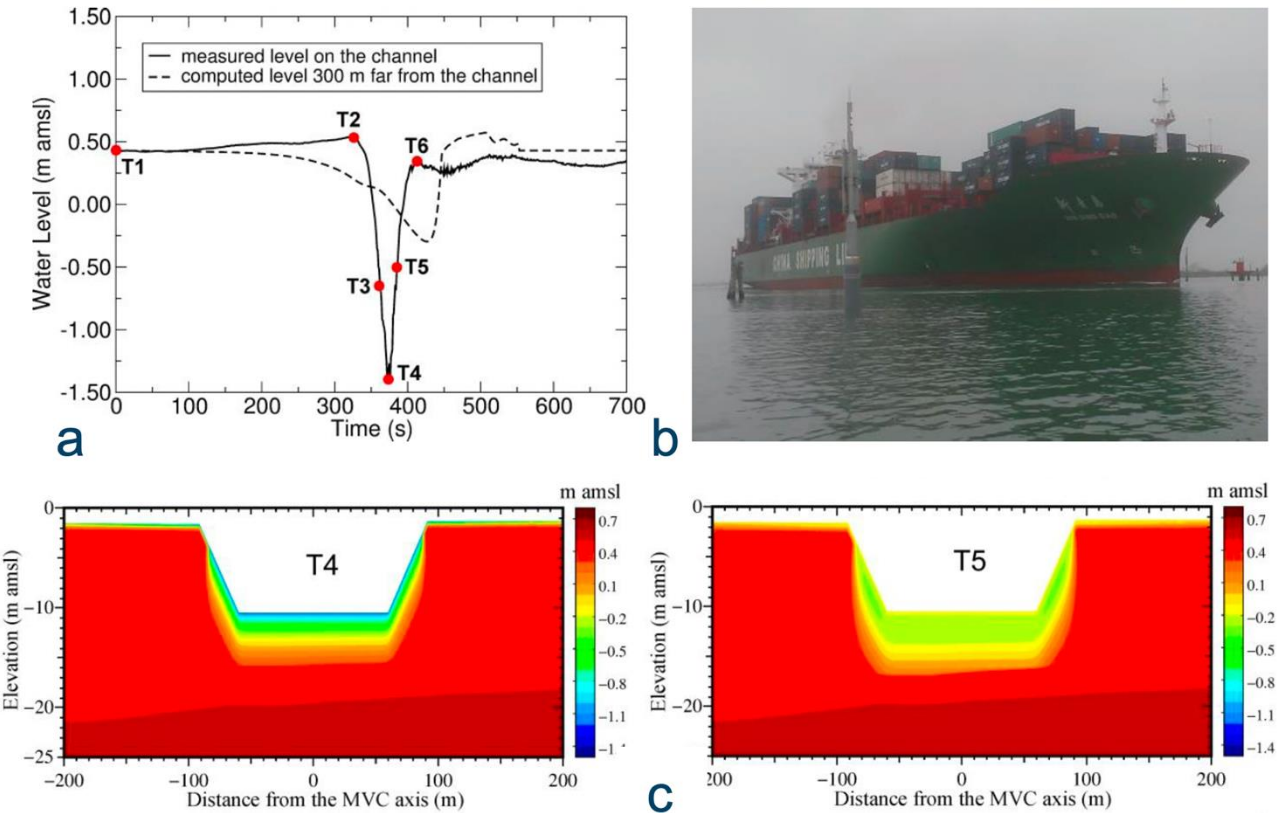


Figure 4.6. Computed pressure distribution at the times T4–T5 (a) during the transit of the Cargo-Hazard A (b), through the Section 2 (after Teatini et al., 2017).

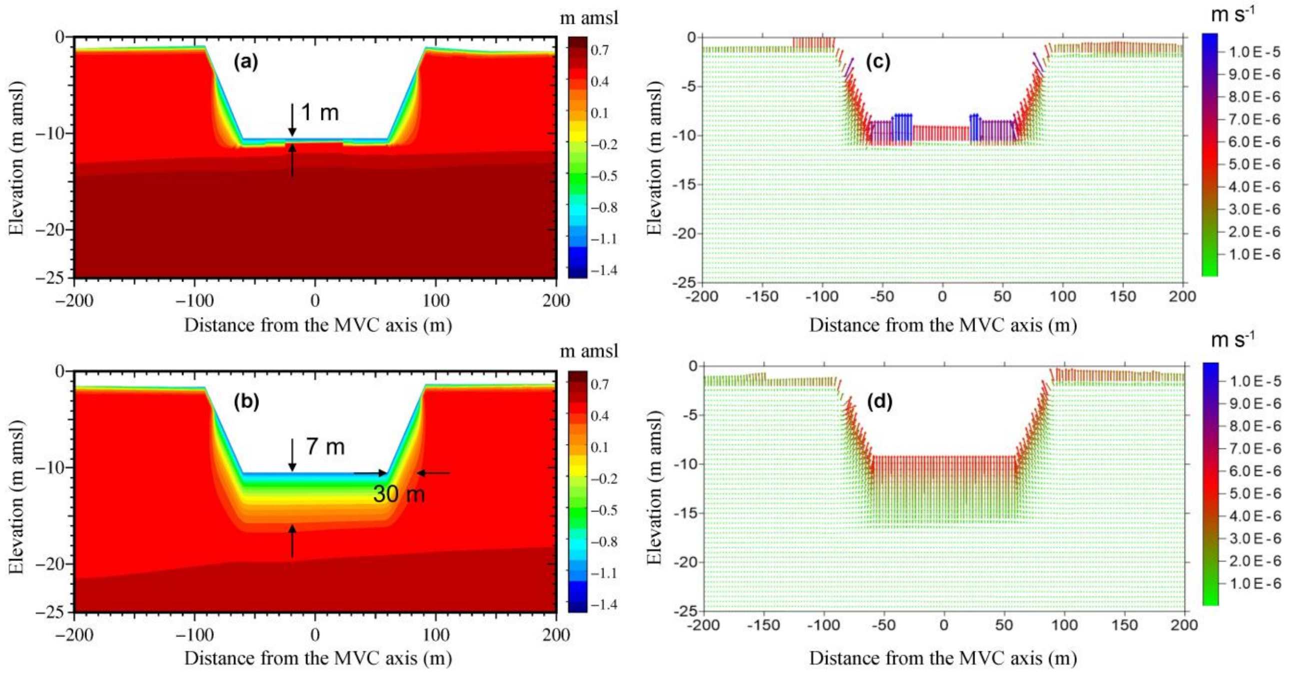


Figure 4.7. Computed pressure distribution (a, b) and velocity field (c, d) at the maximum wake induced by the Cargo-Hazard A transit in Section 1 (a, c) and Section 2(b, d). The dimensions of the subsurface portion feeling the ship transit are highlighted in panels (a) and (b) and are strongly affected by the presence of the aquitard layer (lowest dark red) (after Teatini et al., 2017).

The typically short duration of such events precludes the propagation of the pressure change far from the channel edges. The velocity field in correspondence to the maximum depression is provided in Figure 4.7c and Figure 4.7d. The ship generates a sort of "piston effect" with an efflux distributed along the whole channel bottom and slope. The maximum values of the velocity amount to 1.1×10^{-5} m s^{-1} and 0.6×10^{-5} m s^{-1} for Section 1 and Section 2, respectively. The highest velocities are computed in Section 1 due to the vicinity of the Aqt-2 top to the MVC bottom, and the consequent pressure gradient is much larger than in Section 2.

The seepage from the MVC bottom and slope (between times T2 and T4 in Fig. 4) amounts to 3.25×10^{-2} m^3 and 2.63×10^{-2} m^3 per meter length of the channel for Section 1 and Section 2, respectively. If we consider a total length of approximately 3 km, as designed in Figure 4.3, each commercial vessel produces a cumulative groundwater volume flowing into the MVC totaling ca. 100 or 80 m^3 assuming Section 1 or Section 2, respectively, as representative of the lagoon subsurface. Therefore, a value of about 90 m^3 can be estimated on average.

The same computation was carried out for the ship wake caused by a cruise ship moving at 7.7 knots. The results provided by the hydrodynamic model were used to force FLOW3D. The computed subsurface pressure and velocity fields are qualitatively similar to those previously described (Figure 4.6 and Figure 4.7), with smaller values determined by the lower wave height used as a forcing factor. The average efflux along the whole MVC is reduced by 50%, i.e. 45 m^3 per ship transit.

Teatini et al. (2017) provided additional consideration on the potential contaminant release from the subsurface into the lagoon due to the maritime traffic, which could enhance the transport of chemicals through the efflux caused by the pressure gradient. The interconnection of the groundwater flowing from the industrial area of Marghera was considered, too. Data are reported in terms of concentration and can be easily extrapolated considering different scenario of maritime traffic.

4.2.3 Aquifer salinization

Figure 6 shows the outcome of the model in terms of relative concentration (c) at the end of the simulation period, i.e., 10 years after the inception. The results are presented for both the sections addressed by the study. The effect of the MVC excavation is pointed out by comparing the two settings, i.e., the present condition and that where the MVC is dredged. Cutting the top clayey layer, the excavation favors the propagation at depth of the seawater, with an increase in c from the initial 0.7 value to more than 0.9 in the surroundings of the canal. The salt propagation downward is more pronounced in Section-2 than in Section-1 because of the Aqt-2 presence directly below the MVC bottom in the latter. Note that the increased contamination remains located in the surroundings of the channel excavation, with Aqt-3 completely precluding the salt transport at larger depth.

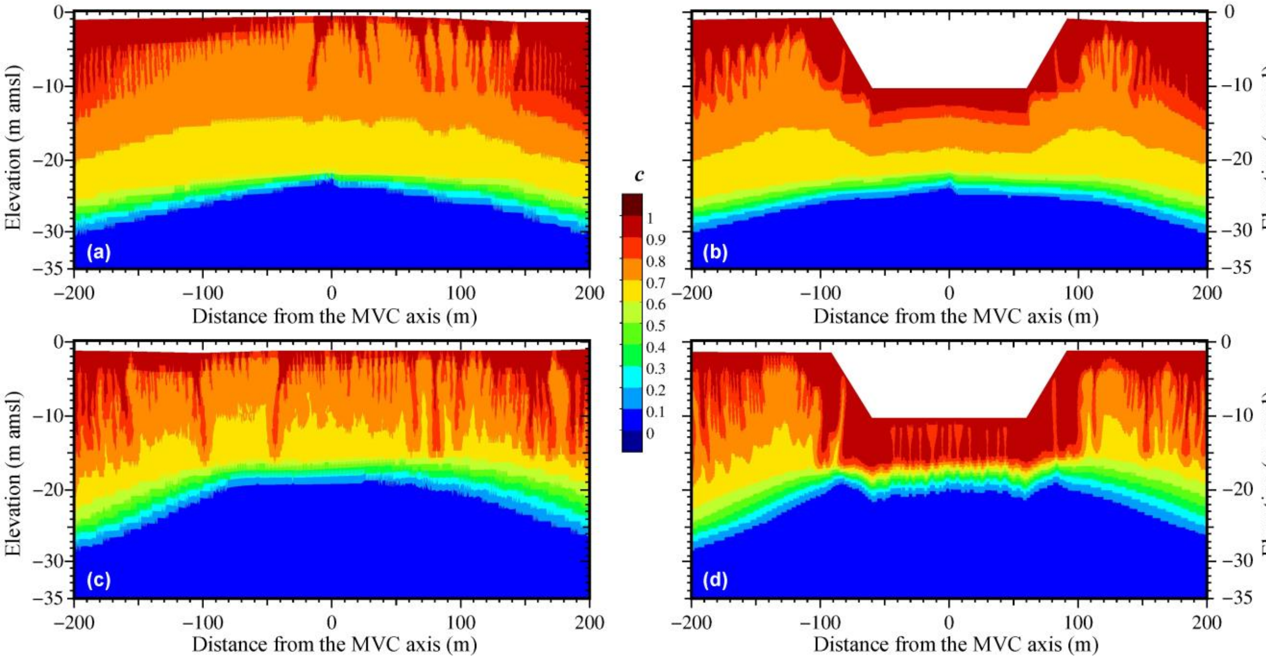


Figure 4.8. Relative salt concentration in (a, c) initial conditions and (b, d) after 10 years as computed in (a, b) Section-1 and (c, d) Section-2 in the present (a, c) and channelized (b, d) conditions, respectively (after Teatini et al., 2017).

5 DESIGN PROCESS

The “optimal design solution” shall be found as the best compromise between different aspects:

- functionality;
- safety;
- environmental impact.

There is indeed a strategic relationship between the project requirements and dimensions:

- design ship characteristics (type, displacement, length, width, draft);
- channel layout, width and depth;
- navigation safety and functionality.

Here below channel data (Table 5-1) and design ships (Table 5-2) are reported.

Table 5-1. Overview of channel dimensions.

Design depth according to Port Masterplan (PRP)	**-12.0**	m s.m.m.
Channel base width (present)	60.0	m
Channel base width (according to Port Masterplan)	140.0	m
Water depth at MOSE (Malamocco locks)	**-14.0**	m s.m.m.
Max draft allowed for navigation (present, see Ord. 39/16)	**11.5**	m

Table 5-2. Design ships.

Design ship	Type	LOA	Beam	Draft (max)
CMA CGM Rigoletto	Container	349	42.8	14.50
CMA CGM Cendrillon	Container	334	42.8	14.50
RDO Concord	Container	304	40.0	14.50
Andrea Palladio	Dry bulk	235	43.0	13.50
MSC Magnifica	Cruise	294	32.0	8.00
Quantum of the Sea	Cruise	348	42.0	8.80
Cruise Olimpia	Ferry	225	30.0	7.15
Phoenix Hope	Liquid bulk	244	42.0	15.00
Malamocco locks dimensions	-	371	51.0	13.50
Malamocco locks ship limits	-	280	39.0	12.00

The design process aims at providing navigation functionality and safety while reducing environmental impacts and dredging volumes.

The assessment of the possible design solutions has been developed through data collection and successive analysis steps, always supported by numerical modelling. The detail of models increased throughout the design progress. Step 1 to 3 have been supported by baseline studies.

STEP 1 (layout):

- definition of design vessels characteristics;
- definition of environmental conditions (wind, wave, current);
- definition of vessel operational parameters (load, draft, UKC supported by NCOS);
- preliminary definition of channel and turning basins;
- analysis of ship induced waves (Kelvin wake, displacement wave).

STEP 2 (impact analysis):

- analysis of ship manoeuvring, risk analysis and definition of the most critical grounding points;
- definition of ship impacts (present layout, ships, depths, operational practice) in terms of extents, surge/drawdown, waves, currents, sediment transport, erosion, propeller scour.

STEP 3 (analysis of operational solutions):

- analysis of ship manoeuvring, aiming at the definition of minimum safe vessel speed;
- definition of minor layout modifications allowing for safe navigation at lower speed;
- definition of potential reduction of ship impacts related to vessel speed reduction.

STEP 4 (large scale solutions):

- implementation of channel optimization at critical grounding points;
- implementation of channel optimization, considering also nearby wave dissipation areas;
- implementation of new morphological structures (and modification of existing ones).

STEP 5 (design solution and details):

- definition of optimal design solution (structural, operational);
- testing of optimal design solution through numerical modelling;
- volumes

6 CONCEPT

Baseline studies allowed for the assessment of the following basic concepts:

1) Currents and bed shear stress (and related phenomena such as sediment transport and erosion) are mainly related to the displacement wave.
2) Kelvin waves have no significant effect on the erosion of the channel banks and surrounding shallow flats.
3) Bed shear stresses from the propeller are an order of magnitude smaller than those generated by the displacement wave.
4) The propellers have no significant influence on sediment transport and erosion.
5) The submerged channel banks surrounding the navigation channel do have a role in the overall channel hydrodynamics and cannot be simply dismissed (i.e. bordering the navigation channel with emerged structures).
6) Vessel speed is a primary factor in the displacement wave generation, as well as in sediment resuspension and transport.

Based on the concepts listed above, the following design guidelines have been defined:

a) Dredged channel changes are likely to play a minor role in sediment resuspension and transport: the change in effective channel section (including submerged banks), in fact, is negligible.
b) Vessel speed reduction is a primary goal, to be obtained through channel layout optimization (local modifications at critical grounding points).
c) Position and dimensions of the structures (new or existing) bordering the navigation channel must be considered very carefully; they may have negative impact on the displacement wave generation if reducing the effective channel section.
d) Protection structures bordering the navigation channel shall be placed far enough from the dredged channel to avoid a reduction of the effective channel section.

7 MODELLING OF BASIC ALTERNATIVES

7.1 Operational: vessel speed

Baseline studies showed that vessel speed is a primary factor in displacement wave generation and navigation impact on the lagoon morphology (as well as on all the infrastructures bordering the MMC channel).

In the following Figure 7.1 and Figure 7.2 the bed shear stress generated by the most frequent vessel (small container ship, refer to as Con-S) are shown for vessel speeds of 8 and 10 knots, respectively. Reducing the speed to 8 knots makes the difference between erosion (Tau>0.5-0.7 Pa) and no erosion on the flats east of the channel.

Though larger vessels (Con-L or Tan-L) are likely to generate erosion even at 8 knots, there is indeed a huge reduction of navigation impact if the ships sail at lower speed. 8 knots have been assumed as the lowest speed for safe steering and manoeuvring within MMC between S. Leonardo and Fusina.

Lower speed can be considered for the inner part of the channel (north of Fusina), but they were not tested. The new navigation rules issued by the Coast Guard, indeed, state that north of the Cunetta channel (i.e. north of Fusina) the ships must slow down to 6 knots, in fair weather conditions. This limit will provide further improvements in reducing the displacement wave, even though such a slow speed is likely to be reasonably safe only in case of channel section optimisation.

Furthermore, it is important to underline that the navigation in more severe weather conditions is not forbidden, and the new navigation rules allow for speed increase in such conditions for safety reasons. It is therefore required that these high speed events will not occur frequently, because of their residual impact on the lagoon morphology as well as on the infrastructures bordering the canal and on the protection structures, both requiring higher robustness in case of huge wave attack.

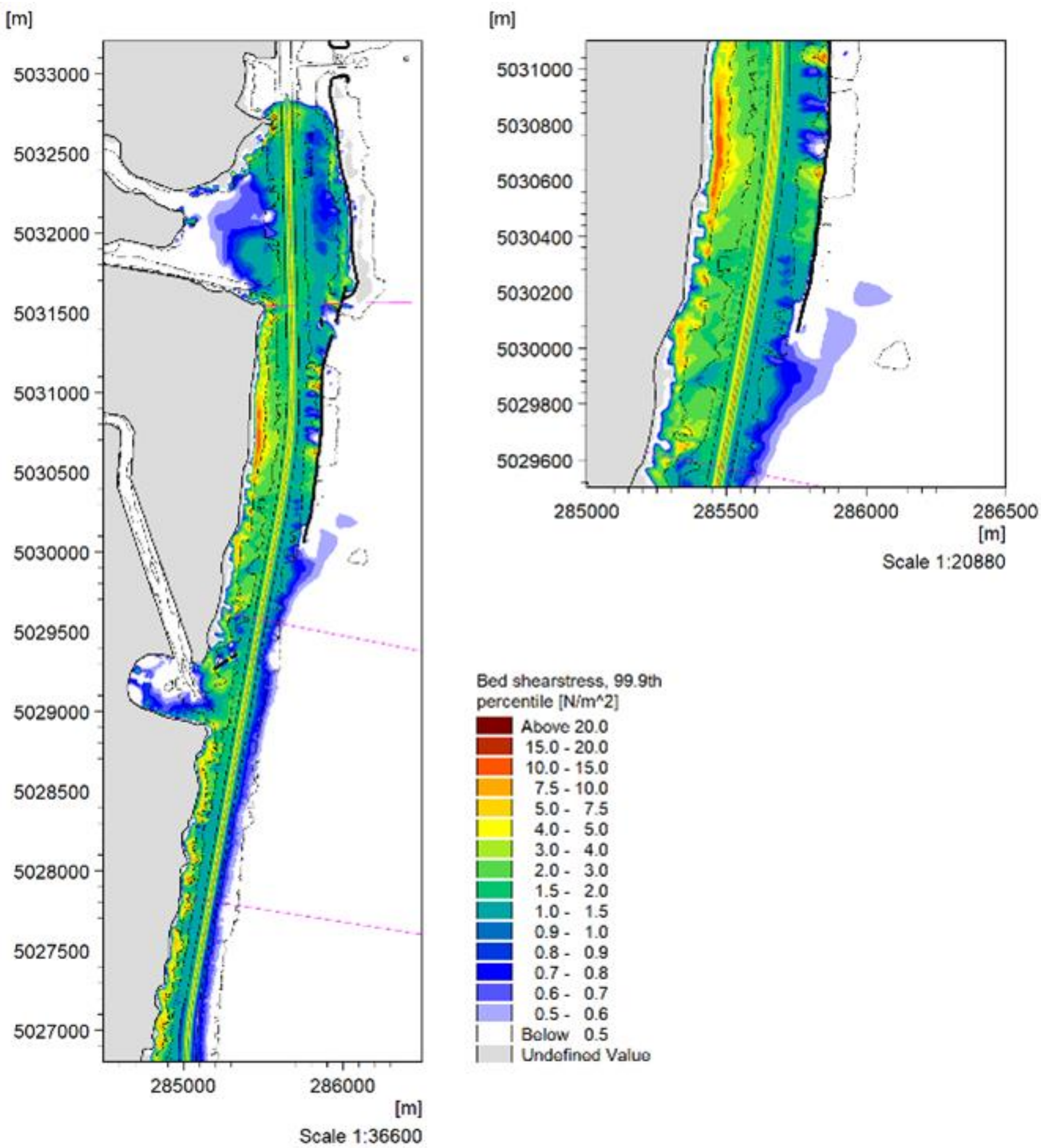


Figure 7.1. Bed shear stress generated by a container ship (Con-S) sailing at 8 knots.

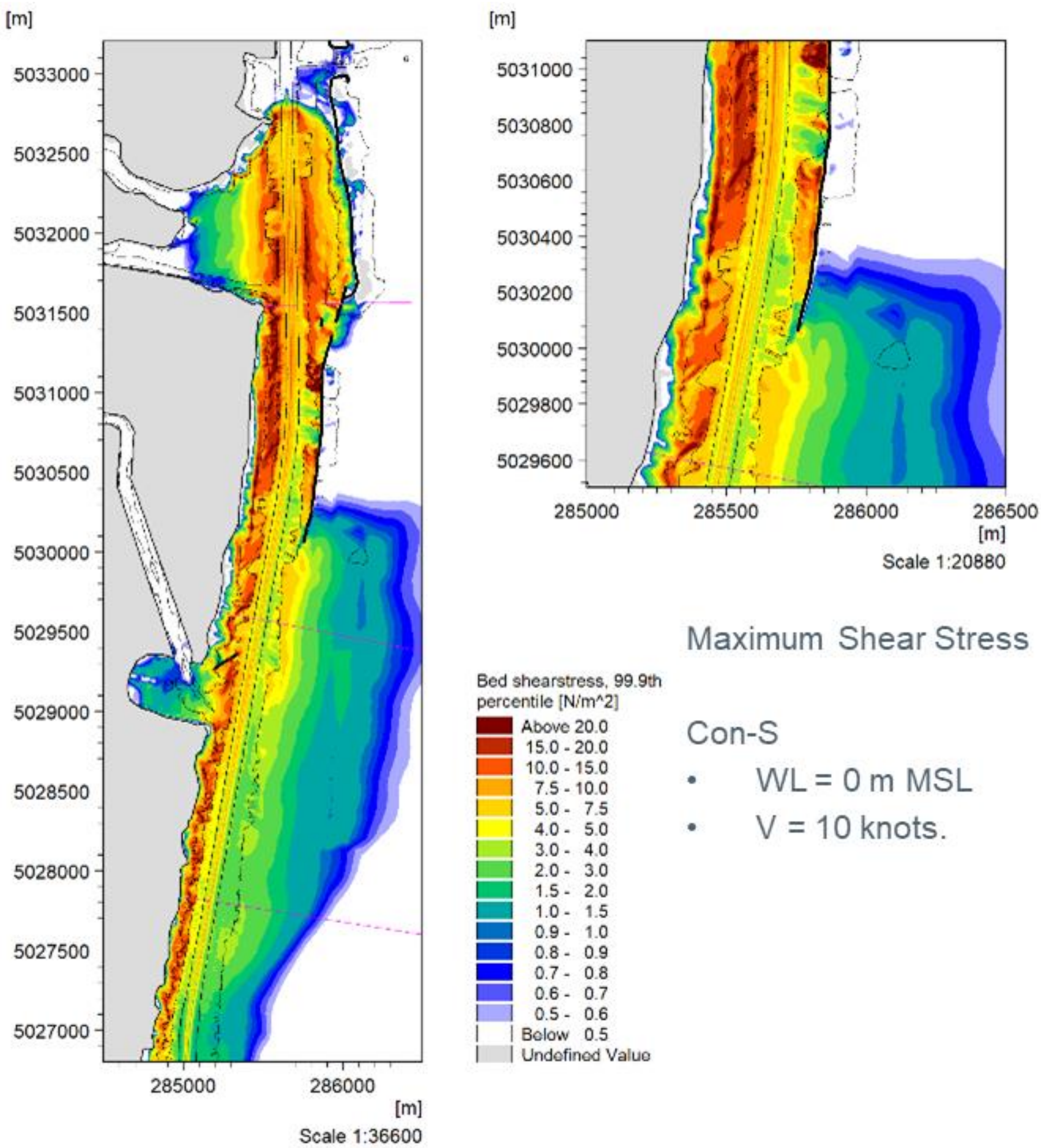


Figure 7.2. Bed shear stress generated by a container ship (Con-S) sailing at 10 knots.

7.2 Structural: channel width

The enlargement of channel width effects has been thoroughly investigated at the very beginning of the design proposal. It was, in fact, one of the most debated issues because of its impact on the dredging volumes. The existing width of the dredged channel is indeed less wide than stated by the Port Masterplan in force, hence the first task was to assess whether a general enlargement of the channel would be useful or required.

The navigation studies proved that, considering the design ships, critical grounding points are not evenly distributed along the channel, but occur at specific locations along the channel. On the other end, the baseline studies and the local measurements proved that the hydrodynamic behaviour of the channel (with reference to the displacement wave generation, especially) depends upon the whole effective channel section and not only upon the dredged one. Hence, it was likely that a limited enlargement of the dredged section would provide no significant benefit in terms of displacement wave reduction.

In order to assess the potential benefits of a general channel enlargement (from 60 to 80 m), a series of hydrodynamic model tests have been performed. In the following Figure 7.3 and Figure 7.4 the bed shear stress generated by a Con-S ship sailing along the existing channel at 10 knots are shown, for a dredged channel width of 60 and 80 m, respectively. The comparison of the results of the simulations confirms that there is almost no difference between the two different channel widths.

In the following Table 7-1 a comparison is provided in terms of drawdown at different distances from the dredged channel axis. The results are extracted along 3 lines perpendicular to the channel axis and refer to the east side of the channel. The 3 lines are located in the most critical part of the MMC channel, with reference to the navigation impact. It can be observed that minor differences can be found right at the margin of the dredged channel but become negligible as the distance increases.

Hence, there is no significant benefit involved in a general channel enlargement and the design proposal has been focused on the local optimisations aiming at lowering the safe navigation speed and increasing the effective channel section.

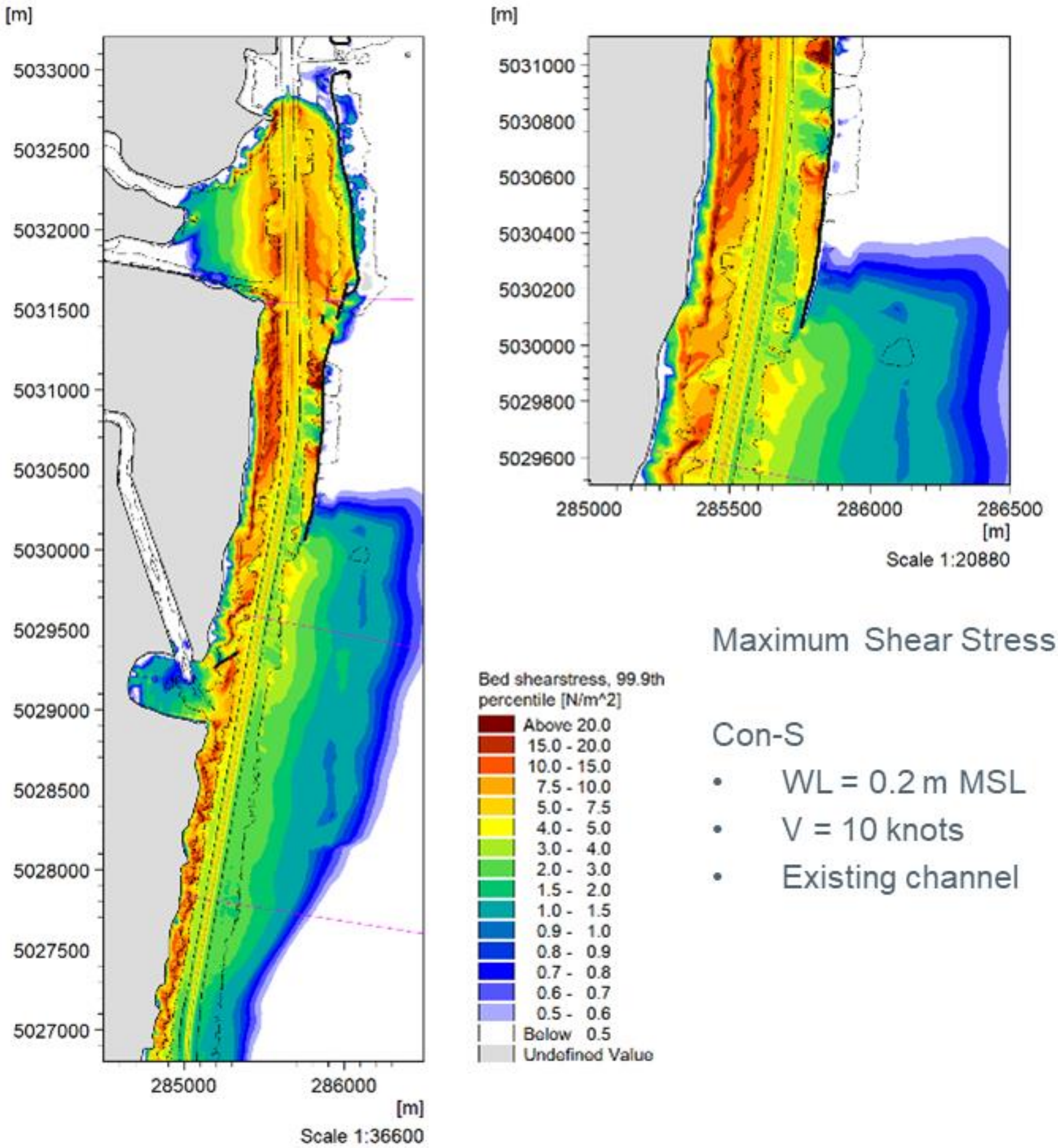


Figure 7.3. Bed shear stress generated by a container ship (Con-S) sailing at 10 knots, channel width 60 m (existing).

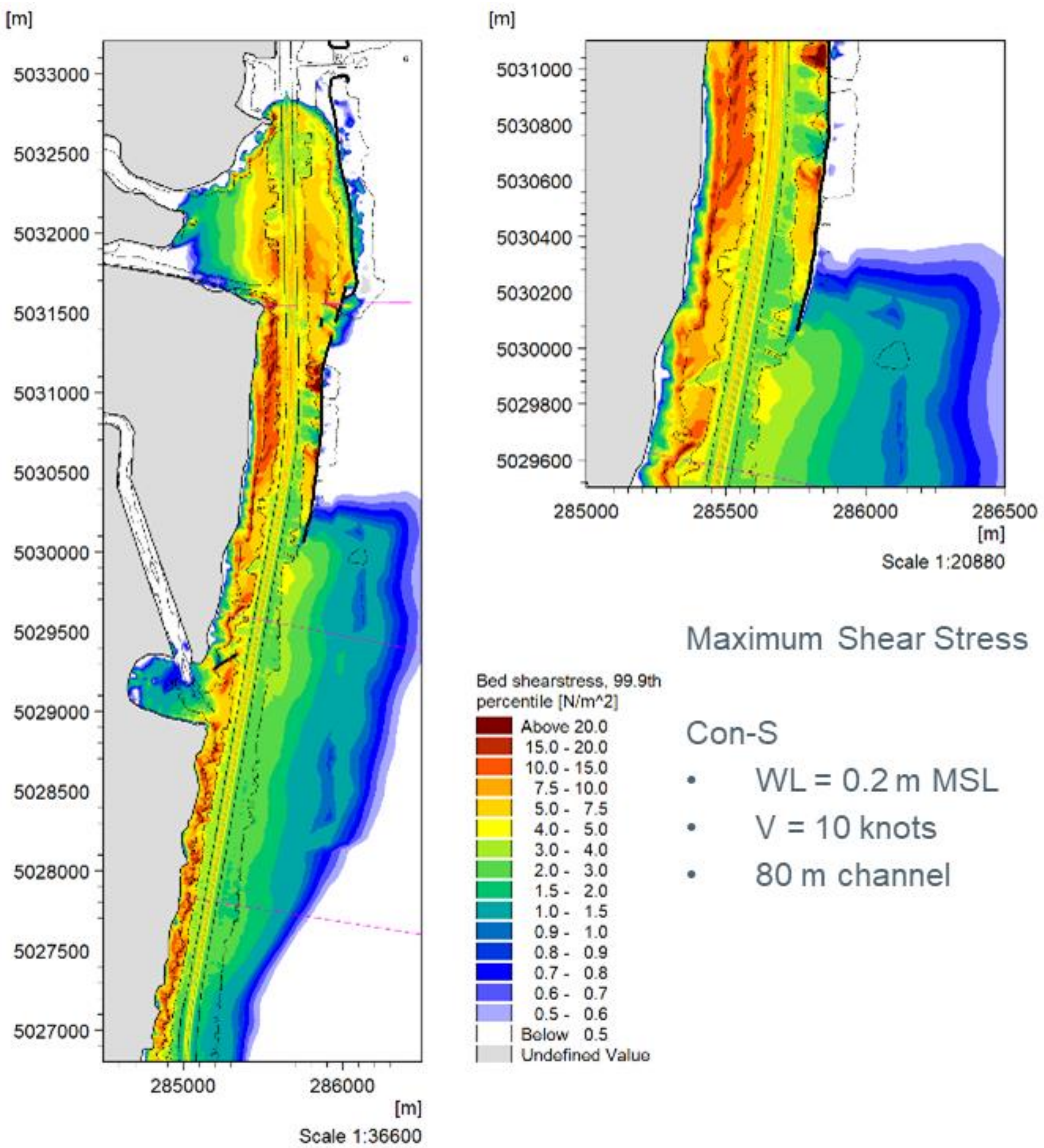
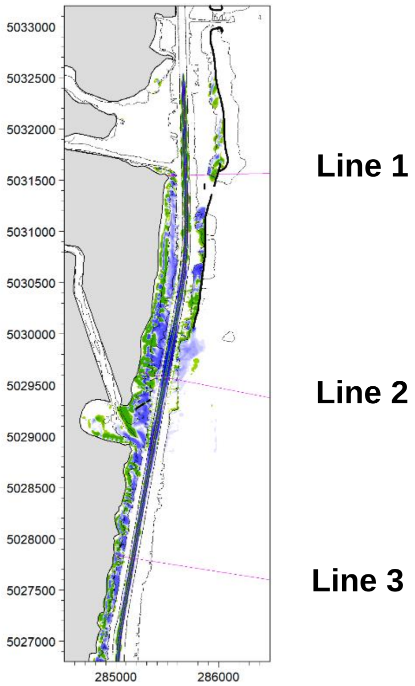


Figure 7.4. Bed shear stress generated by a container ship (Con-S) sailing at 10 knots, channel width 80 m.



Line no. 1	Draw down level (m MSL)							
	Margin	200 m	400 m	600 m	800 m	1000 m	1200 m	1400 m
Existing Channel	-0.89	-0.78	-0.14	-0.06	-0.06	-0.07	-0.08	-0.08
80 m Channel	-0.84	-0.74	-0.14	-0.06	-0.06	-0.07	-0.08	-0.08
Change	-0.05	-0.04	0.00	0.00	0.00	0.00	0.00	0.00

Line no. 2	Draw down level (m MSL)							
	Margin	200 m	400 m	600 m	800 m	1000 m	1200 m	1400 m
Existing Channel	-0.67	-0.49	-0.28	-0.22	-0.18	-0.14	-0.12	-0.1
80 m Channel	-0.57	-0.41	-0.28	-0.23	-0.19	-0.14	-0.11	-0.09
Change	-0.10	-0.08	0.00	+0.01	+0.01	0.00	-0.01	-0.01

Line no. 3	Draw down level (m MSL)							
	Margin	200 m	400 m	600 m	800 m	1000 m	1200 m	1400 m
Existing Channel	-0.49	-0.41	-0.31	-0.19	-0.1	-0.06	-0.05	-0.04
80 m Channel	-0.48	-0.4	-0.31	-0.19	-0.1	-0.07	-0.05	-0.04
Change	-0.01	-0.01	0.00	0.00	0.00	+0.01	0.00	0.00

Table 7-1. Effects of channel enlargement on drawdown.

8 DESIGN SOLUTION

8.1 General description

The re-design proposal has been developed considering the results of the comprehensive study developed by the Consortium and the upcoming works to be developed in the areas bordering the MMC.

An extensive repairing of the land reclamation areas has been recently awarded, which will result in a significant narrowing of the west bank of the MMC between Fusina and S. Leonardo; the aim of this work is to restore the initial shape of these islands after years of erosion (mainly due to the effect of displacement waves).

Moreover, a new island has been foreseen to the south of Isola delle Tresse, keeping more or less the same (small) distance from the navigation channel. The new rules in force, imposing a 6 knot speed in front of this new island, will most likely reduce its impact on displacement wave generation.

In the following paragraphs a general description of the dredging and building of new morphological structures, as well as the suggested modification of the existing ones, is provided; in the attached drawings a more detailed description can be found.

8.1.1 Structural (dredging)

The re-design proposal starts with basin #3 (Figure 8.1), where a local dredging is foreseen in order to smooth the sharp angle between the navigation channel and the turning basin.

The eastern bank of the channel, from basin #3 to basin #4, has been widened by 10 m in order to reduce the risk of grounding for large ships manoeuvring at slow speed. The navigation channel cross section (Figure 8.5) has a base width of 60 m with local enlargements up to 100 m. Submerged bank slope is 1:3 (horizontal to vertical). The layout limits dredging in front of the existing structures; modifications of water depth in front of the existing quays and channel bank protections (including cutoff walls) shall be very carefully considered based on assessment of geotechnical conditions as well as structural integrity/performance.

Turning basin #4 has been widened, according to the Port Masterplan in force in order to provide safe access to Canale Industriale Sud (CIS, southernmost port channel); an additional dredging has been also considered in order to smooth sharp angles at CIS entrance.

A general widening of the MMC channel is foreseen in front of Fusina terminal (Figure 8.2) for allowing safe manoeuvring for chips and tugs at the terminal as well as to regain space for passing ships in case of strong NE wind.

MMC channel show a gentle bend south of Fusina; the existing layout does not consider any widening of the channel section along the berm; hence, a general widening/straightening of the bend is foreseen in the framework of the re-design proposal (Figure 8.2 and Figure 8.3). This widening was initially foreseen at the western side of the bend, but it was later dismissed because of the interference with the upcoming restoration of the land reclamation areas. The final proposal considers widening at both sides of the bend, as well as to the north of it, in order to allow for a more straight route.

Figure 8.3 shows the southernmost part of the bend, together with the northernmost morphological structures, defined as islands/saltmarshes and mudflats. These structures must be located away from the navigation channel banks, in order to allow for an effective channel section wide enough as not to increase the displacement wave.

Island/saltmarshes are emerged structures (almost permanently emerged according to the current MOSE gate management).

Mudflats are artificially built shallow tidal flats (below m.s.l.) to be partially reshaped by natural sediment dynamics. In order to preserve tidal flats and lagoon morphology, it is strongly suggested to reduce wave fetch within the lagoon, according to the general concepts already foreseen in the framework of morphological masterplan proposals.

Figure 8.3 shows also the breakwater lowering aiming at increasing the effective channel section; this channel narrowing is indeed an area of significant local bank erosion in the existing configuration.

Figure 8.4 shows the re- designed S. Leonardo bend, together with the southernmost morphological structures. In order to reduce the risk of grounding when negotiating the bend, a local smoothing of the MMC channel bend has been designed. Smoothing distance extends 1 km north of the existing bend.

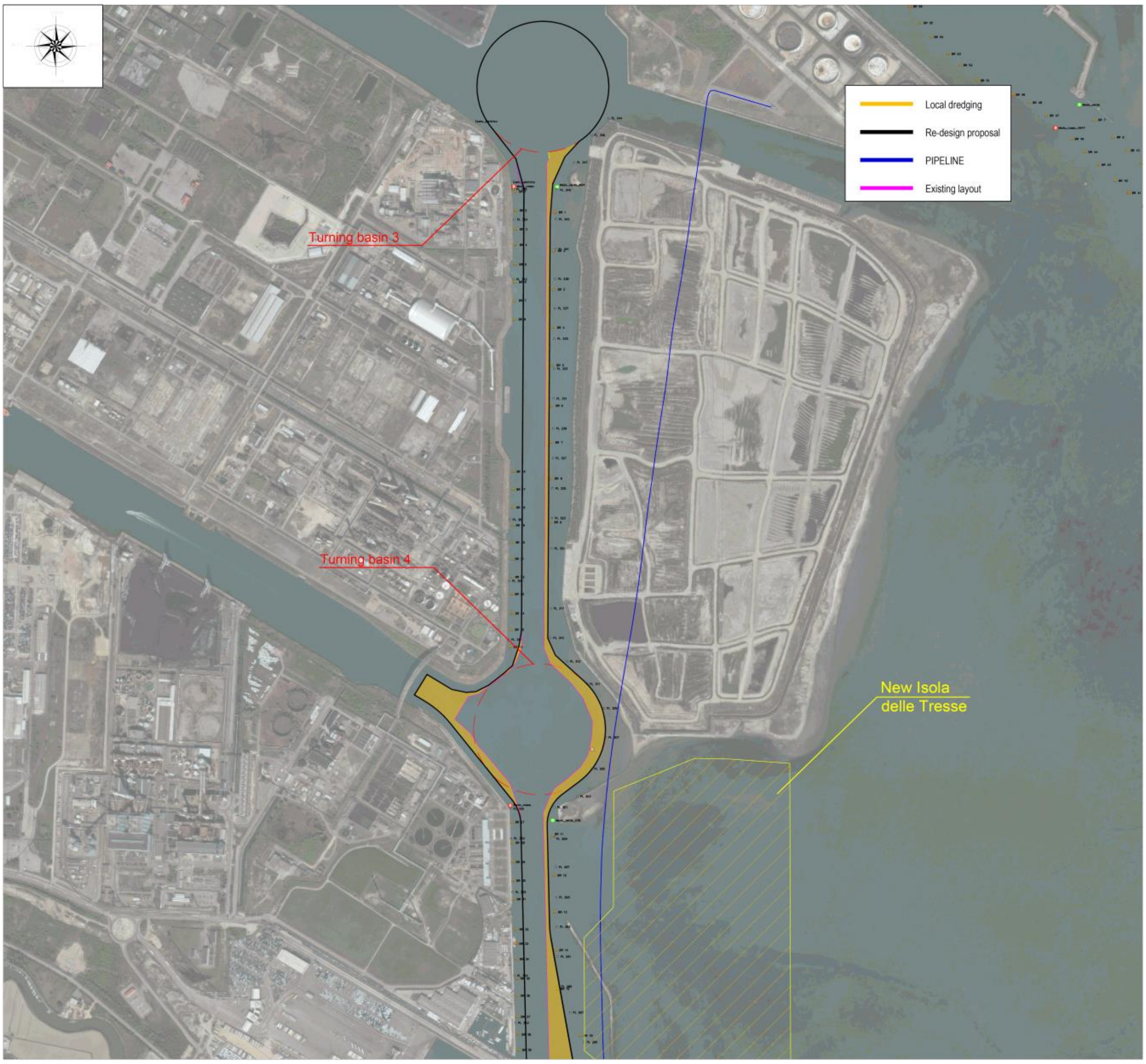


Figure 8.1. Re-design proposal: basin 3 to basin 4.

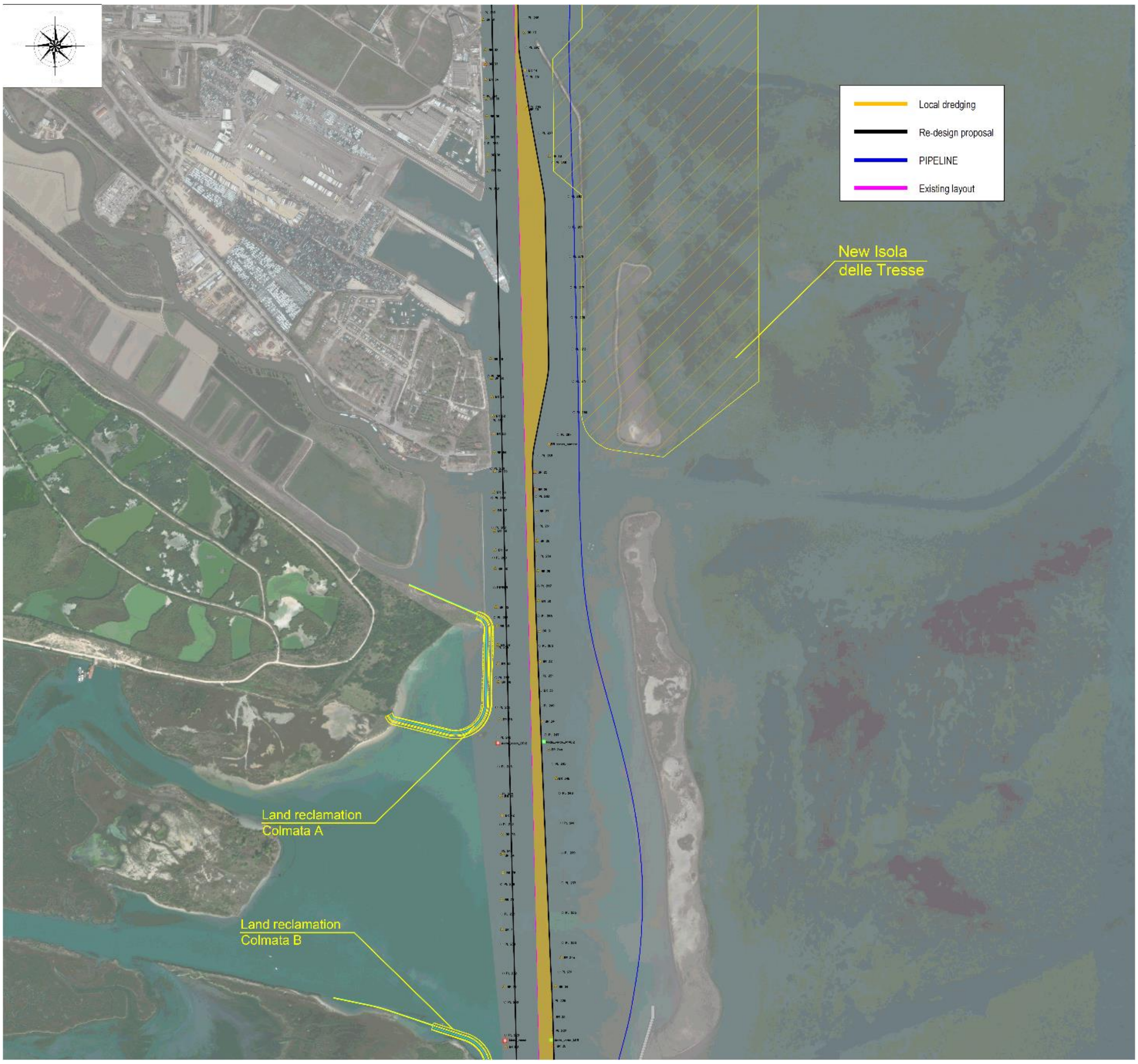


Figure 8.2. Re-design proposal: Terminal Fusina to Canale Cunetta.

Figure 8.3. *Re-design proposal: Canale Cunetta to Colmata D.*

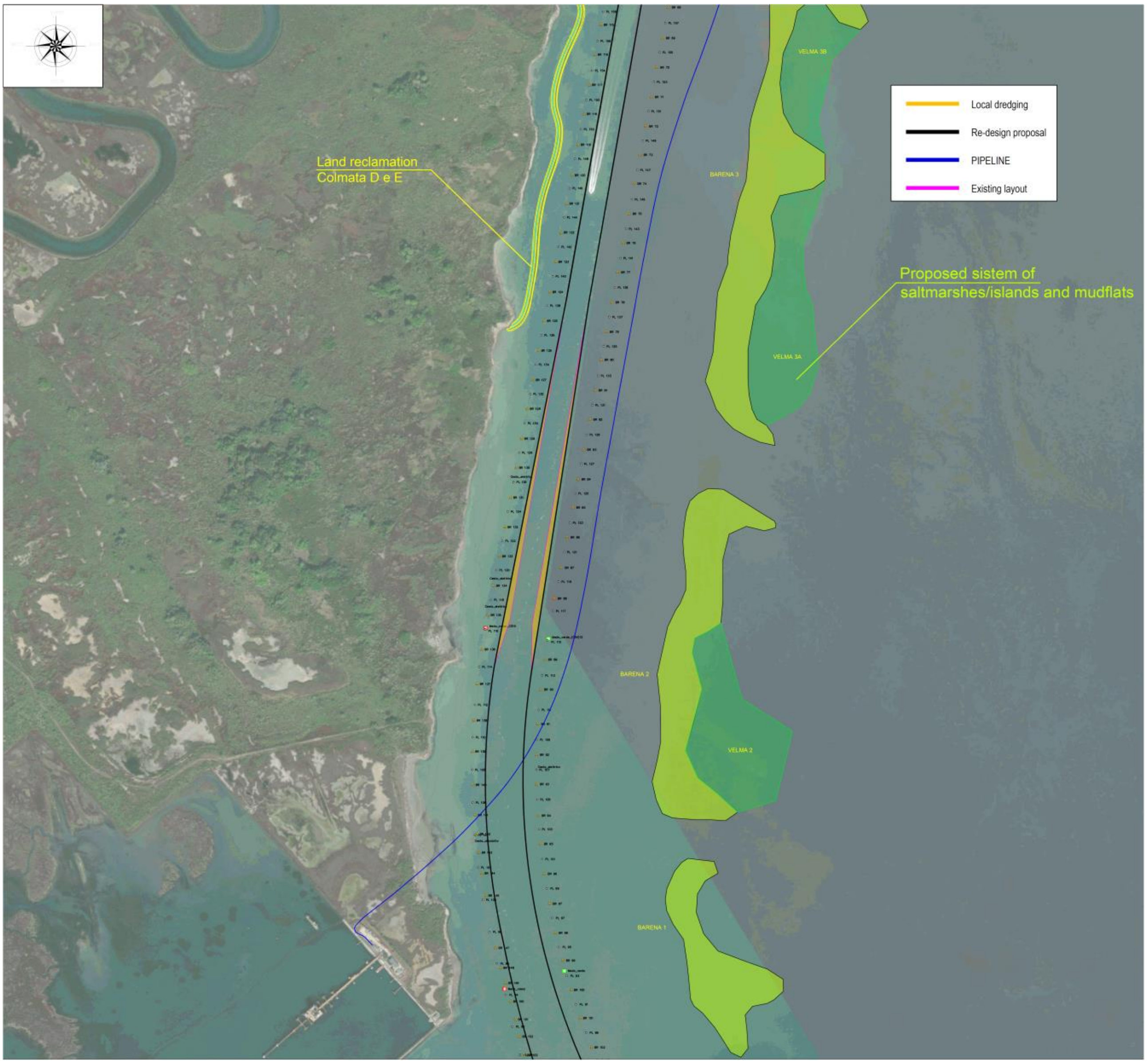


Figure 8.4. Re-design proposal: Colmata D to S. Leonardo.

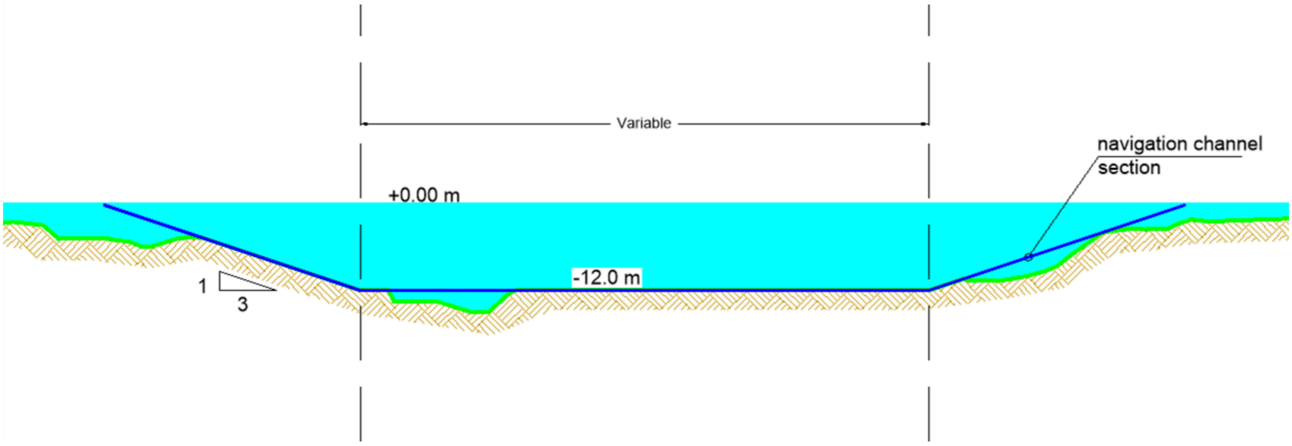


Figure 8.5. Re-design proposal: dredged section of navigation channel.

8.1.2 Operational

Displacement wave is the main responsible for navigation impact on lagoon morphology, and vessel speed has been identified as the dominant parameter governing displacement wave generation.

Widening of the navigation channel has minor influence, while protection structures bordering the channel will result in narrowing of the effective channel section, thus increasing the displacement wave. Deepening of the channel is not an option (not foreseen by the present Port Masterplan). Hence, design effort has been focused on structural optimization (local widening of the navigation channel) aiming at allowing safe navigation at lower speed and maneuvering simulations aiming at testing safe speed limits.

In the framework of the ship maneuvering tests, also the existing channel configuration has been tested for slower speed; the results showed that, in ordinary weather conditions, the speed limit could be reduced. Based on these results, the Venice Coast Guard issued a new regulation (Regolamento per la sicurezza della navigazione, la sosta, gli accosti e le precedenze delle navi e dei galleggianti nel porto e nella rada di Venezia, Ord. 010/2023 dated March 9th, 2023).

The speed limits according to the latest regulation for MMC are reported in Figure 8.6. Lowering by 2 knots the vessel speed will have a significant influence on the navigation impact, but the regulation itself states that in unfair weather conditions ships can accelerate in order to gain safe maneuvering speed. This means that in unfair weather conditions the navigation impact will not be negligible.

Therefore, it is still required to maximize the channel safety in order to reduce the number of events when the speed limits could be exceeded for safety reasons. Moreover, structural optimization are still required at critical points where the existing channel is too narrow or additional structure narrowing the effective channel section are going to be restored (land reclamation south of Fusina) or built (new Isola delle Tresse).

In order to obtain a preliminary assessment of the impact of these high speed events, a comparison has been made of the yearly seabed changes in the existing channel configuration and in the design proposal one, considering vessel speed always blow 8 knots and a 5% high speed events (10 knots). The results are reported in Figure 8.7: though the general speed reduction and the channel optimisation provide a huge benefit in the morphological stability, there is indeed a significant increase of erosion due to the high speed events.

Figure 8.6. Speed limits according to the latest regulation (Ord. 010/2023, March 2023).

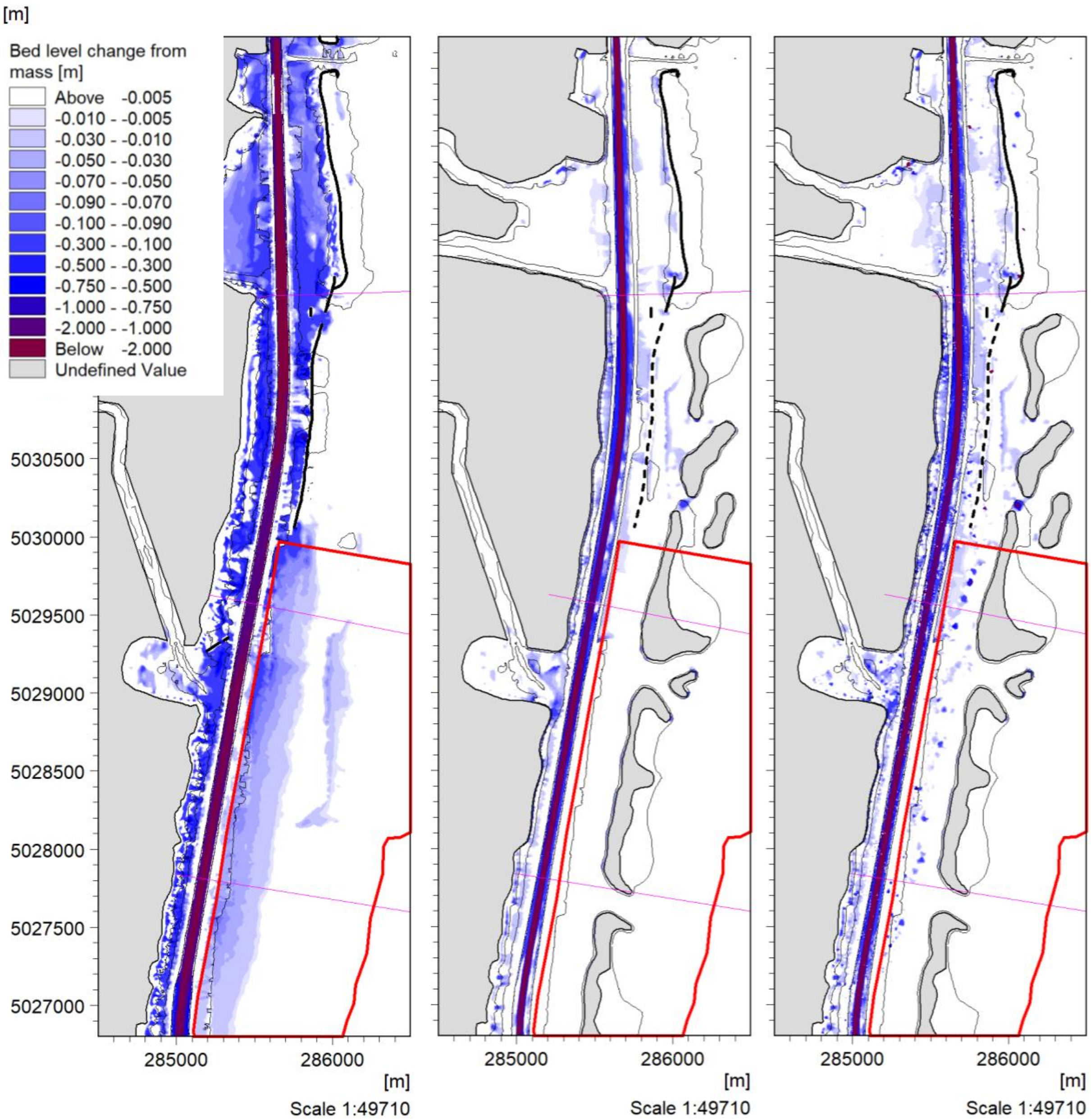


Figure 8.7 *Yearly seabed erosion from vessel traffic for existing channel and 8 kn speed (left), re-designed channel and 8 kn (centre), re-designed channel and 8 kn for 95% of the time and 10 kn for 5% (right).*

8.2 Modelling and validation

In Figure 8.8 an overview of the structural changes is shown. The new design includes:

- 8 new saltmarsh islands along the east side of the channel.
- A southward extension of Isola delle Tresse.
- Restoration of the existing land reclamation between Fusina and S. Leonardo.
- Lowering of some existing structures to a level of -1.2 m MSL.

Though included in the new design, extension of Tresse Island (foreseen) and restoration of existing land reclamation areas (tender awarded) are not part of the mitigation measures studied. The Port Authority has made third parties design drawings of these upcoming structures available.

Figure 8.8 Overview of new structural features (reddish color) in the channel layout.

The changes to the channel layout have enabled a reduction of the vessel safe navigation speed from 10 to 8 knots between the San Leonardo bend and Fusina. Under infrequent very intense wind conditions, the 8 knots limit will not apply.

Comparison between the original (constant navigation at 10 knots) and updated (navigation at 10 to 8 knots) speed profile for an in- and outbound vessel passage is given in Figure 8.9 and Figure 8.10 respectively. The updated speed profile contains a linear change in navigational speed through the San Leonardo bend.

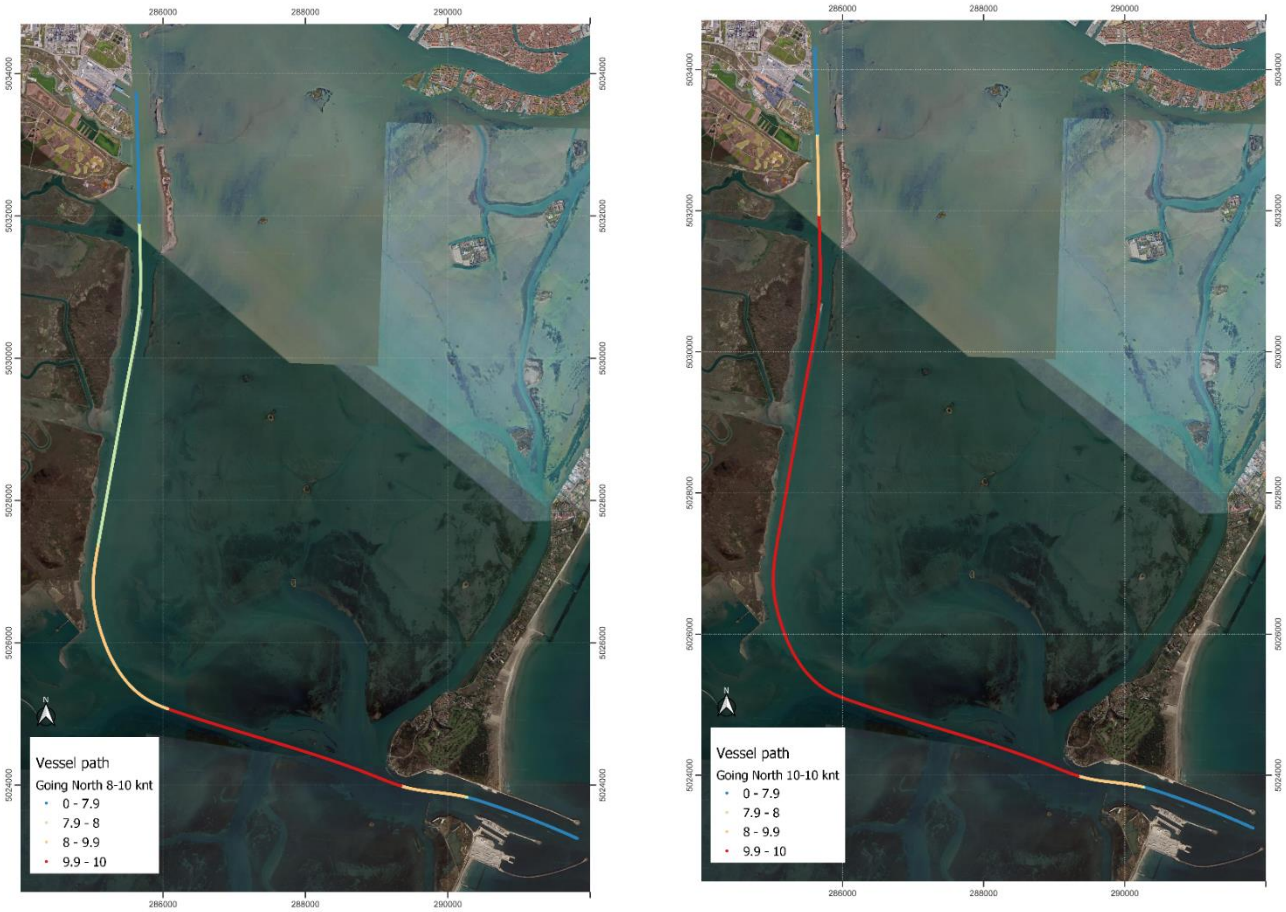


Figure 8.9. Vessel track and speed for inbound passages.

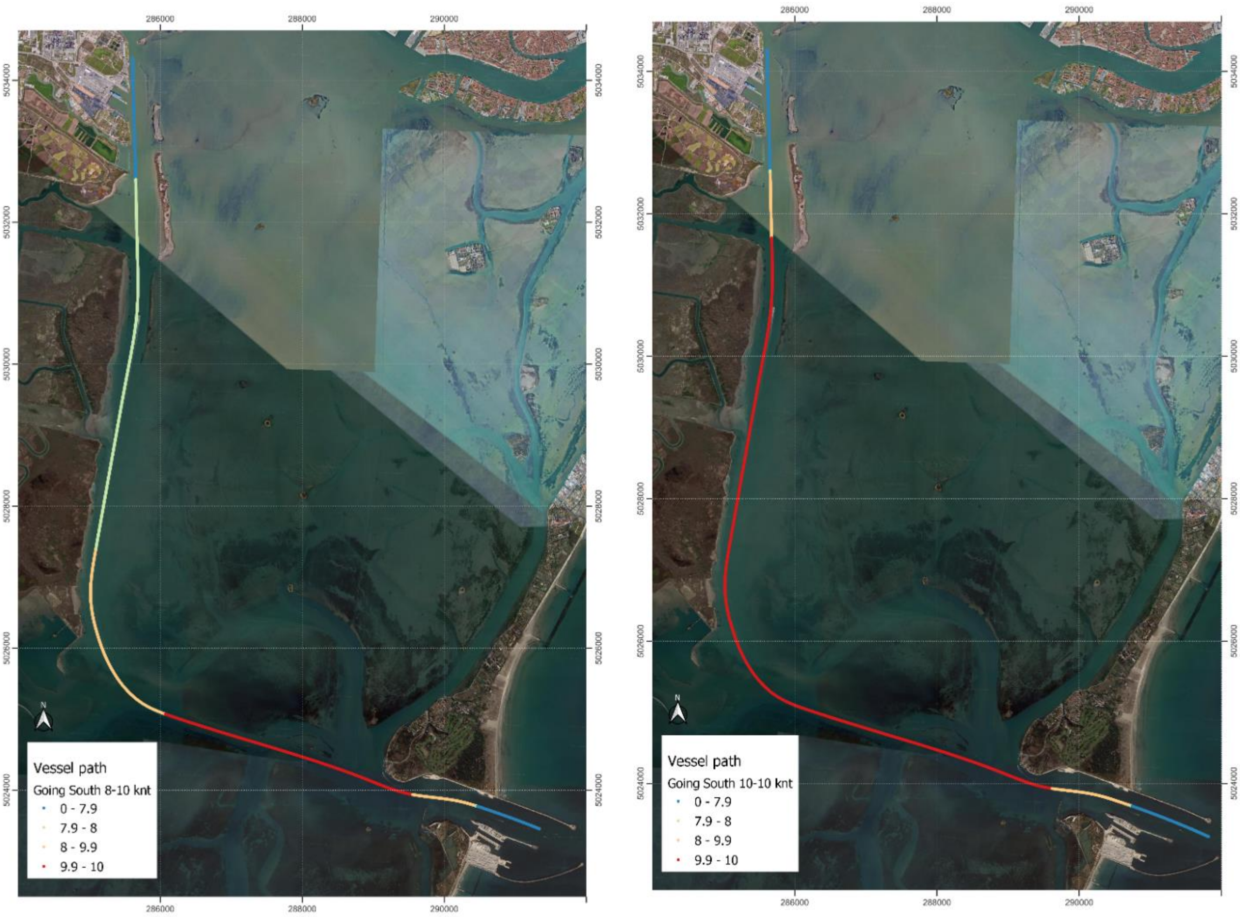


Figure 8.10. Production vessel track and speed for outbound passages.

A series of additional model simulations has been run to investigate Mitigation Scenarios (MS):

a) (MS-a) Effect of speed reduction.
   - Existing channel layout, 8 knots speed between Fusina and S. Leonardo bend.
   - Con-S (most frequent) and Tan-L (most impacting on tidal flats) vessels.
b) (MS-b) Effect of layout optimization and speed reduction.
   - New channel layout, 8 knots speed between Fusina and S. Leonardo bend.
   - All design vessels.

The results, to be compared with the existing scenario, have been extracted along 3 lines (Figure 8.11); the 3 channel sections, including channel banks, nearby flats, restore reclamation areas and new saltmarshes/islands (structures above m.s.l. are not displayed in the graphs) are shown in Figure 8.12. It can be observed that the land reclamation restoration is very close (superimposed) to the channel bank, while the new saltmarshes/islands are more than 250 m apart from the navigation channel bank in order to avoid narrowing of the “active” channel section (with respect to displacement wave generation). The drawdown level depends highly on the bathymetry of the channel: the larger and more unrestricted the channel, the smaller the draw down wave. The draw down levels increase moving north from the San Leonardo bend and become larger where the channel is framed by structures. Structures prevent the drawdown from spreading but makes it locally larger.

Figure 8.11 Location of the three output comparison lines.

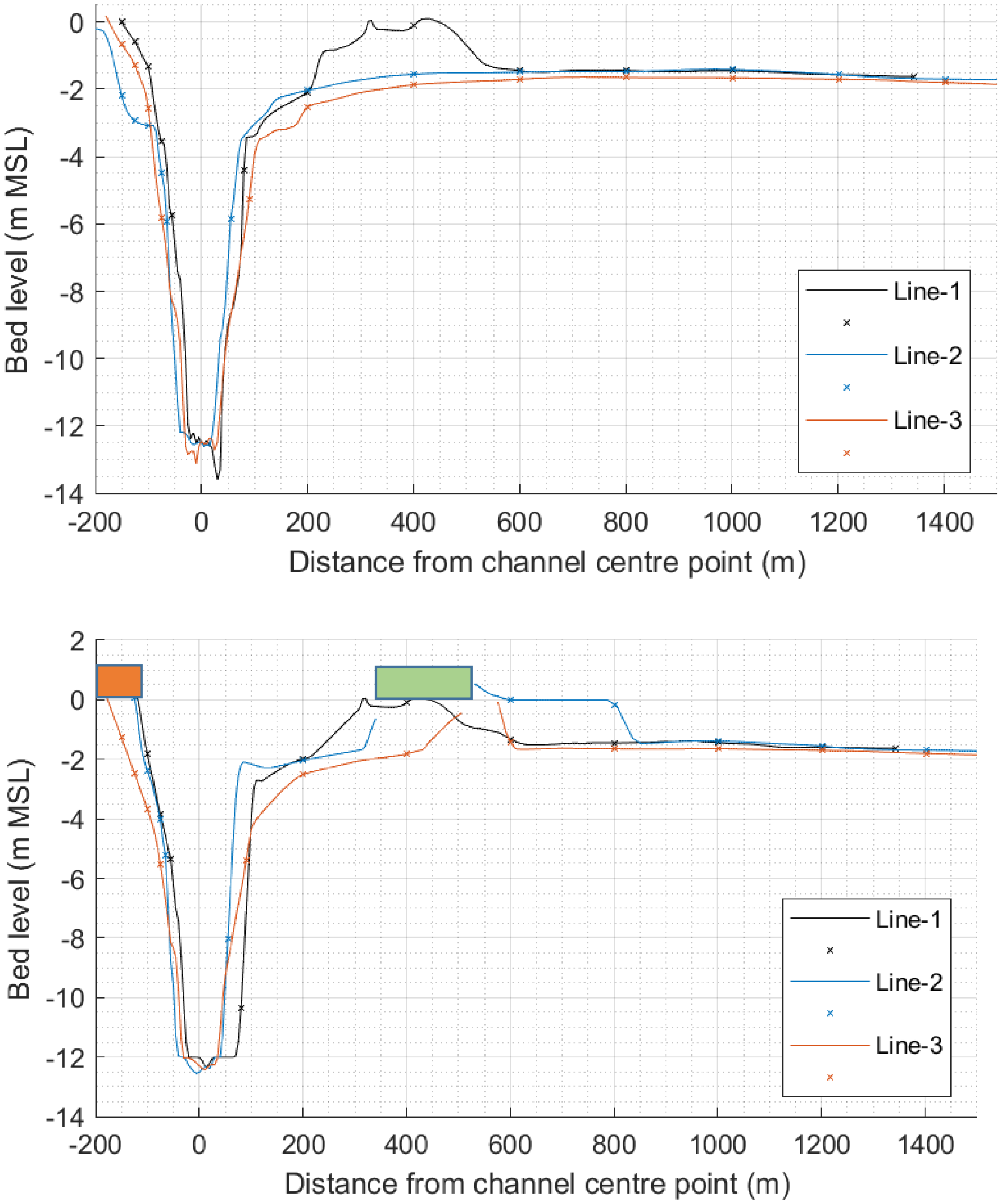


Figure 8.12. Channel cross section considering existing (top) and new (bottom) layout.

In the following Figure 8.13 and Figure 8.14 the maximum bed shear stress (BSS) generated by the inbound passage of the two most representative ships (Con-S, most frequent, and Tan-L, most impacting) are reported. Being the morphological impact related to these stresses, the figures provide a clear overview of the navigation impact and a comparison of the different scenarios.

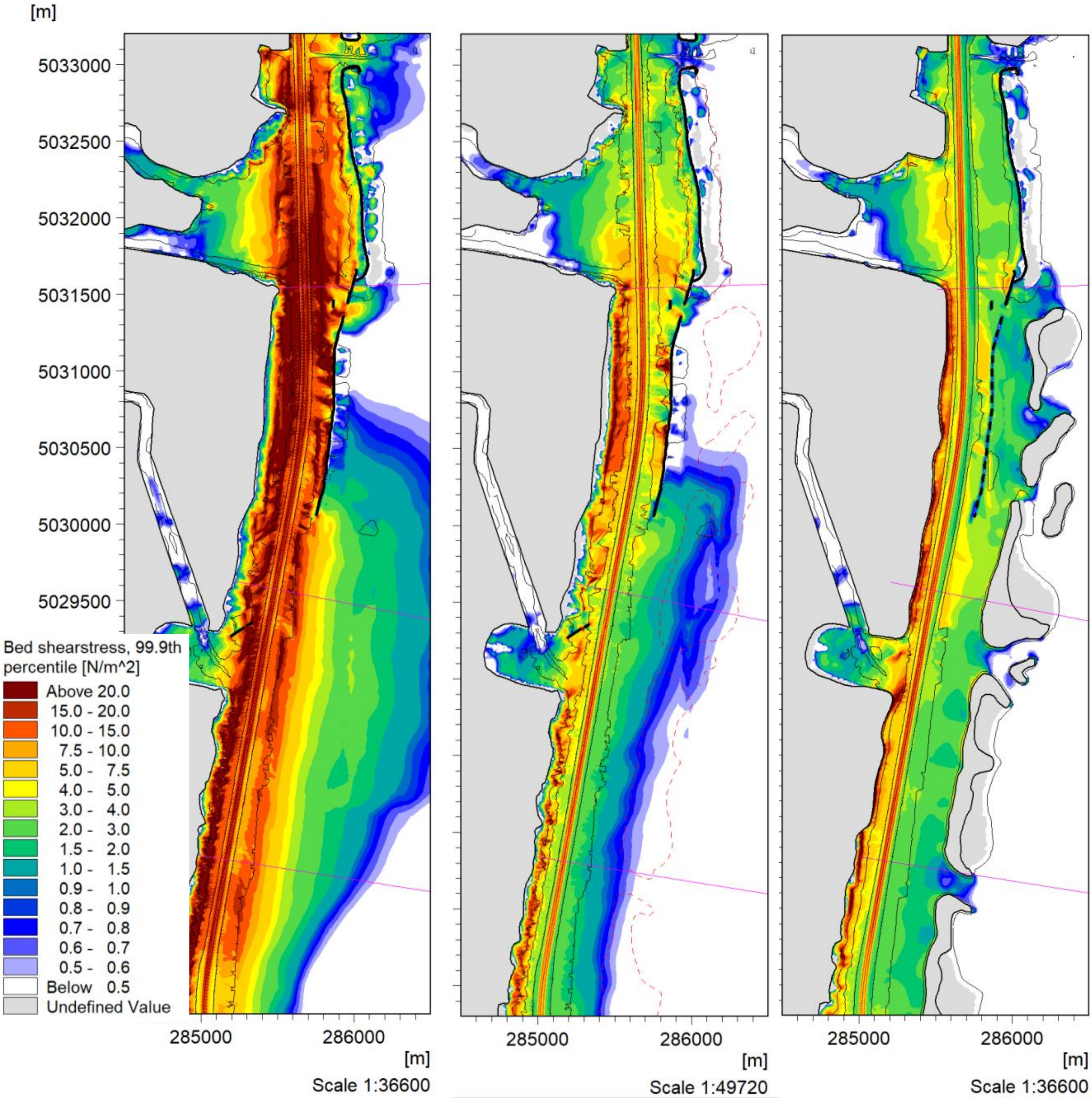


Figure 8.13 Max BSS for inbound passage of Tan-L, for existing, MS-a and MS-b (left to right).

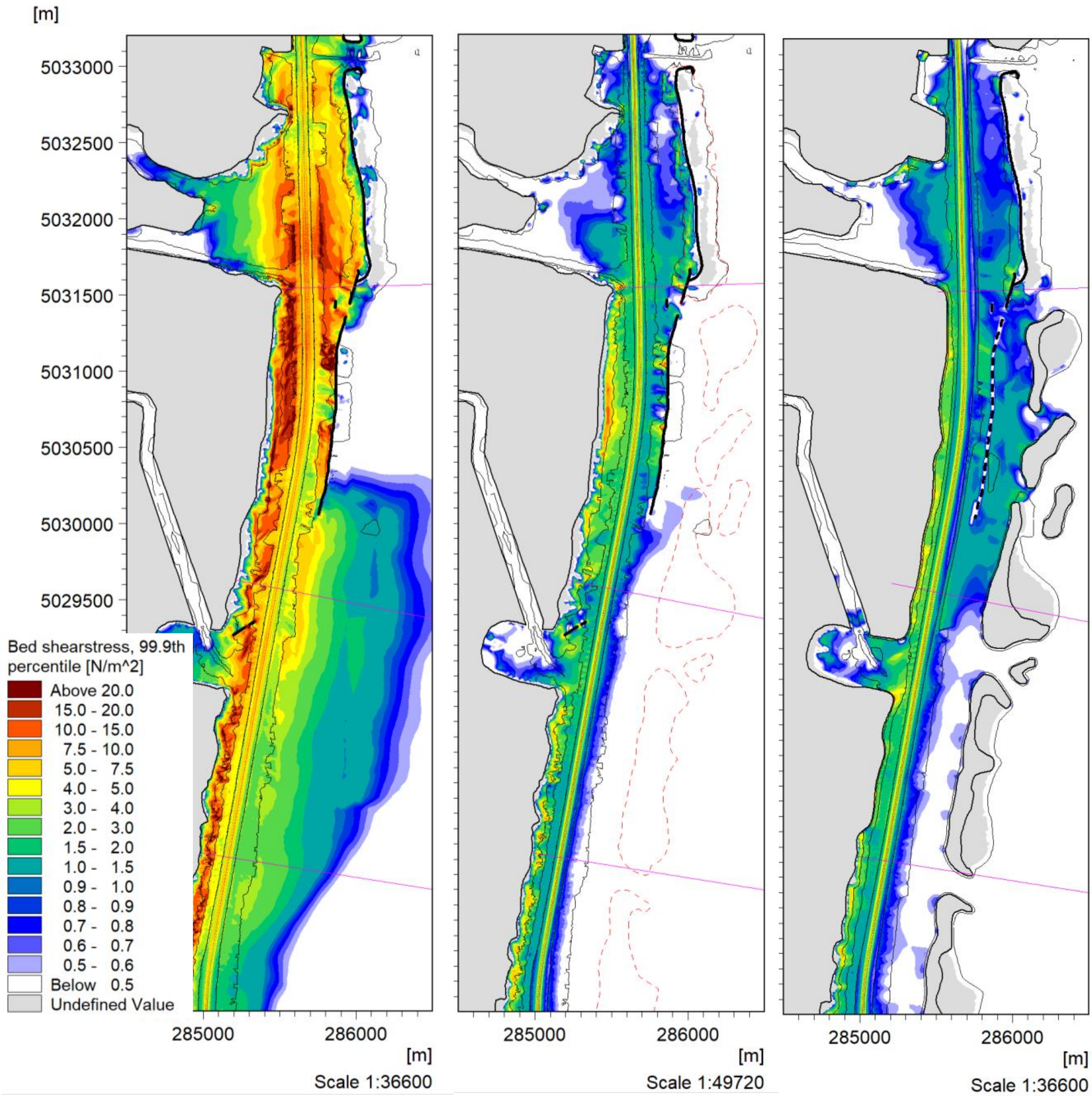


Figure 8.14 Max BSS for inbound passage of Con-S, for existing, MS-a and MS-b (left to right).

The overall effect of the mitigation measures can be observed with respect to MS-b scenario, while MS-a scenario highlights the effect of the operational optimization (already obtained through issuing of the new navigation regulations). But it not just a matter of vessel speed. There is still a significant potential for erosion in front of the land reclamation areas (west bank) and close to Fusina, where the channel width reduces (see Tan-L impact).

The impact north of Fusina will be reduced by lowering the vessel speed; the latest regulation issued by the Coast Guard, indeed, already states that the vessel approaching Fusina shall slow down to 6 knots after crossing Canale Cunetta (see Figure 8.6).

The navigation impact at the restored land reclamation areas is effectively reduced by widening the navigation channel (optimization required for navigation safety) and widening the effective channel cross section. This widening can be obtained by lowering the existing breakwater crest to -1.2 m m.s.l., thus obtaining a general reduction of BSS in the nearby seabed.

8.3 Volumes

The present paragraph reports a synthesis of volume calculations performed by means of DTM comparison (existing bathymetry Vs re-design proposal).

The design depth of the MMC channel is -12.0 m m.s.l.; re-design proposal is described at §8.1.

The design depth accounts for safety clearance and uncertainties, while the overdredging accounts for dredging tolerance.

The dredging area has been divided into 3 lots (see Table 8-1); for each lot the theoretical dredging volume is provided, together with the related overdredging required to obtain the design depth (0.5 m on average, on the whole dredged area).

The fill volumes (Table 8-2) are calculated based on an average depth of -2.0 m m.s.l.; though the dredging volumes have been calculated according to a survey performed in late 2022, tidal flat survey is relatively old.

Fill area has been divided into 8 main lots (Figure 8.15); some of these lots are split between the emerged part (saltmarsh/island) and the submerged one (mudflat).

Table 8-1. Dredging volumes.

Dredging lot	Description		Volume
A	From turning basin #3 to #4 (included)	Net dredging	566 751
		Overdredging	121 985
B	From turning basin #4 to Canale Cunetta	Net dredging	659 060
		Overdredging	178 469
C	From Canale Cunetta to S. Leonardo	Net dredging	256 495
		Overdredging	125 674
		Total theoretical dredging	1 482 306
		Overdredging	426 128
		TOTAL	1 908 434

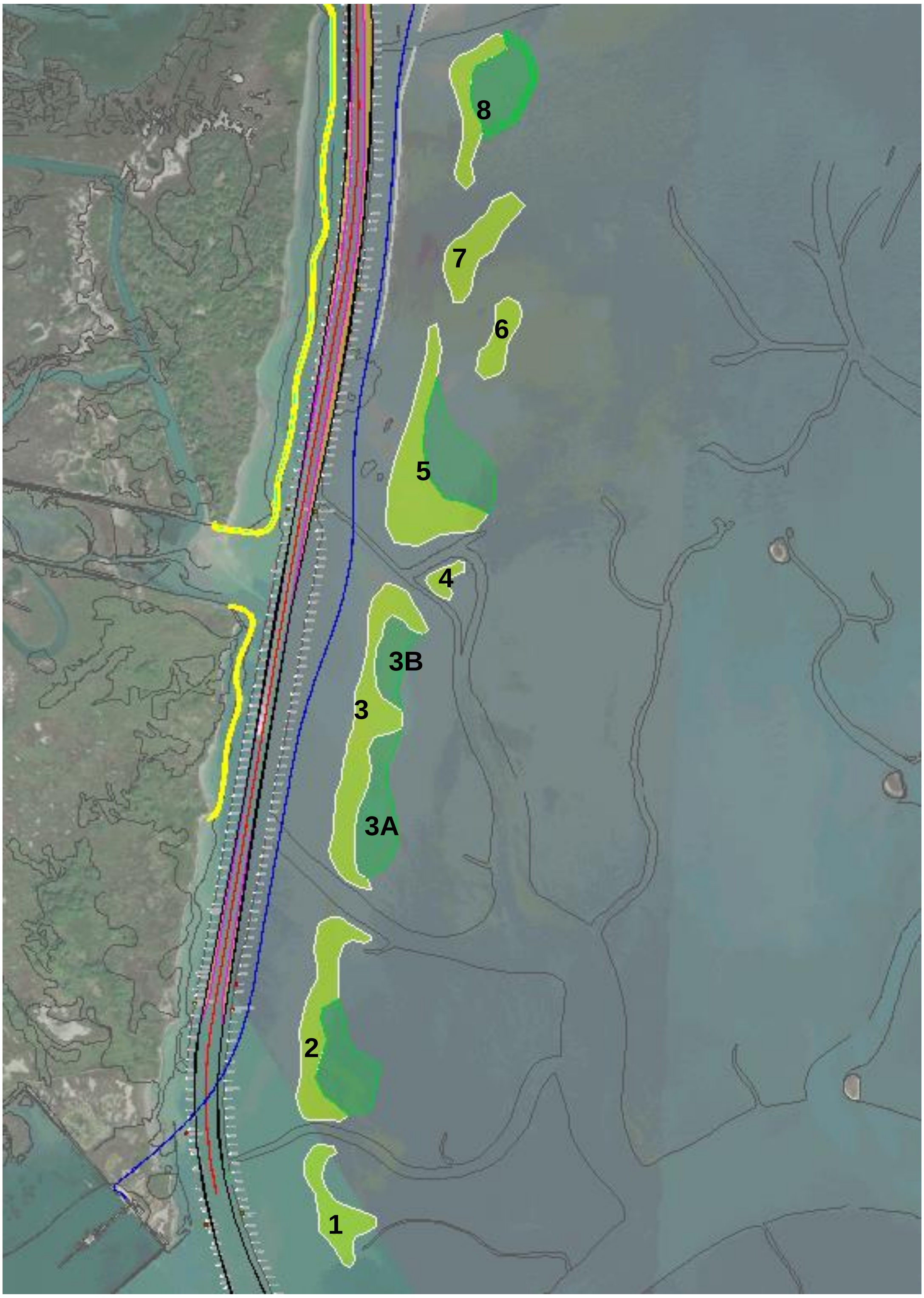


Figure 8.15 Saltmarshes/Islands and mudflats: key plan.

Table 8-2. Fill volumes.

Fill lot	Description	Volume
1	Saltmarsh/island	171 500
2	Saltmarsh/island	291 200
2	Mudflat	156 860
3	Saltmarsh/island	422 156
3A	Mudflat	158 740
3B	Mudflat	86 520
4	Saltmarsh/island	38 276
5	Saltmarsh/island	39 924
5	Mudflat	184 220
6	Saltmarsh/island	96 404
7	Saltmarsh/island	177 408
8	Saltmarsh/island	158 228
8	Mudflat	131 900
	Total saltmarsh/islands	1 755 096
	Total mudflats	718 240
	TOTAL	2 473 336

8.4 Alternative solutions for morphological structures

Conceptual design of morphological structures aims at protecting the tidal flats form major effects of passing ships, without enhancing the displacement wave generation. In other words, placing the new morphological structures at a reasonable distance from the navigation channel (and removing structures too close to the navigation channel) helps reducing the bed shear stress in the channels submerged banks and in the nearby seabed (within the new bordering structures alignment).

Morphological structures produce a primary effect in preventing wave and flow propagating from the channel to the tidal flats, and vice versa. These morphological structures, indeed, were given a three elements configuration: the key element is the breakwater bordering the almost permanently emerged part (saltmarsh/island). The purpose of the breakwater is to withstand wave and flow effect, as well as to provide a confinement facility to be primarily filled with poor quality sediments coming from the dredging activities.

The sediment fills of the saltmarsh/islands have a secondary role in the hydraulic behaviour of the morphological structure, but it is of primary interest in sediment management issues.

The mudflats too, have minor effect in the hydraulic behaviour of the morphological structure, but still they are a valuable resource in terms of sediment management (good quality sediments re-entering the lagoon sediment dynamics). Shallows within the deepening lagoon seabed help also preserving habitats, reducing wind wave generation and wave attack against the eastern borders of the morphological structures.

In the framework of reducing the impact of navigation in the MMC channel, it is therefore important to provide channel side breakwaters first (Figure 3.1), while completing the confinement of salt-marsh/islands and building the new mudflats may come as an environmental restoration and a best practice in sediment management.

According to the upcoming evolution of the environmental legal framework, the design of the morphological structures will evolve into one of the proposed configurations. Other sediment management options may be considered, depending on the environmental quality of sediments that will be assessed following the new regulations. As far as the norm now in force is considered, available data show that most of the sediments should be placed into a confined disposal facility (island) and only a minor part could return into the lagoon sediment dynamics to make new mudflats.

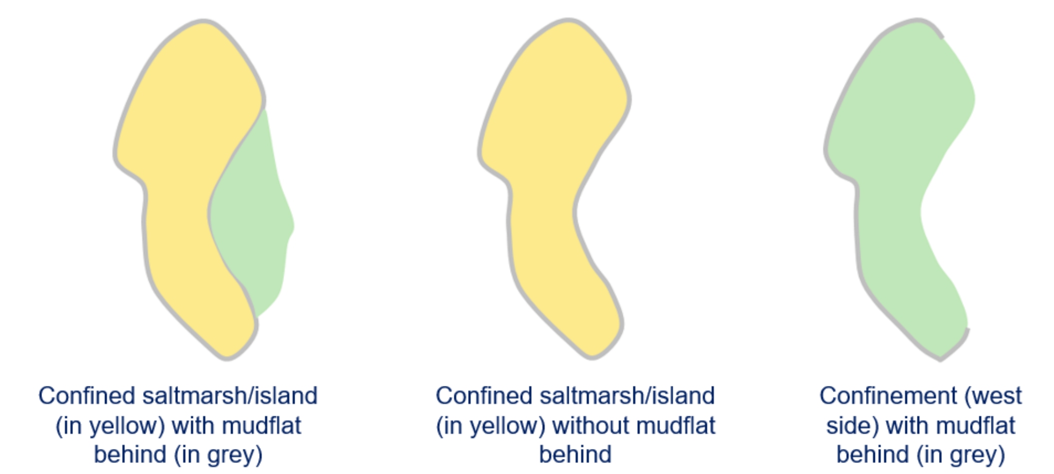


Figure 8.16 – Progressive implementation of morphological structures along MMC channel (placed on the left of the structures).

In the framework of the study, also the new Isola delle Tresse has been considered: this is a CDF placed on the navigation channel eastern border in front of Porto Marghera, to the South of the existing Isola delle Tresse. This structure, to be developed in parallel with the channel optimisation dredging, will be built in successive phases to be filled with sediments not compliant with the morphological rehabilitation of the lagoon. It is likely that a significant part of the sediments to be dredged within the MMC channel will be disposed of in this CDF. According to this possibility, one or more of the proposed morphological structures will be limited to the channel side breakwater.

A specific configuration has not been developed yet for the breakwater; there are indeed a lot of options in terms of shape, materials, dimensions.

Its main requirements can be summarised as follows:

- capability of withstanding the wave action and protecting the fill behind;
- building technology must be in agreement with the local conditions (shallow water, soft soils);
- resilience and easy repairing/upgrading, considering also long term settlements and SLR;
- acceptability in terms of environmental and landscape impact;
- suitable for phased construction.

The main, traditional, technology is the rubble mound structure. Such structures have been used by the Republic of Venice since the early Middle Ages, when volcanic rocks started to be supplied from the nearby Euganei hills and white limestone from the Istrian peninsula (Pietra d'Istria). Nowadays there are not enough active quarries in the Euganei hills and rock supply from the Alps or from the eastern Adriatic sea coasts has become more and more expensive.

Lagoon management performed by the Ministry of Public Works (former Magistrato alle Acque and Consorzio Venezia Nuova, now Provveditorato alle Opere Pubbliche) developed a series of effective solutions for the morphological rehabilitations of the lagoon, most of them indeed not suitable for the high-energy environment bordering the MMC channel.

Latest design of bank protections along the MMC channel (Figure 8.19) consider much more “rigid” and robust solutions, including multiple technologies (rock, sheet piles, rock filled geogrids, etc.).

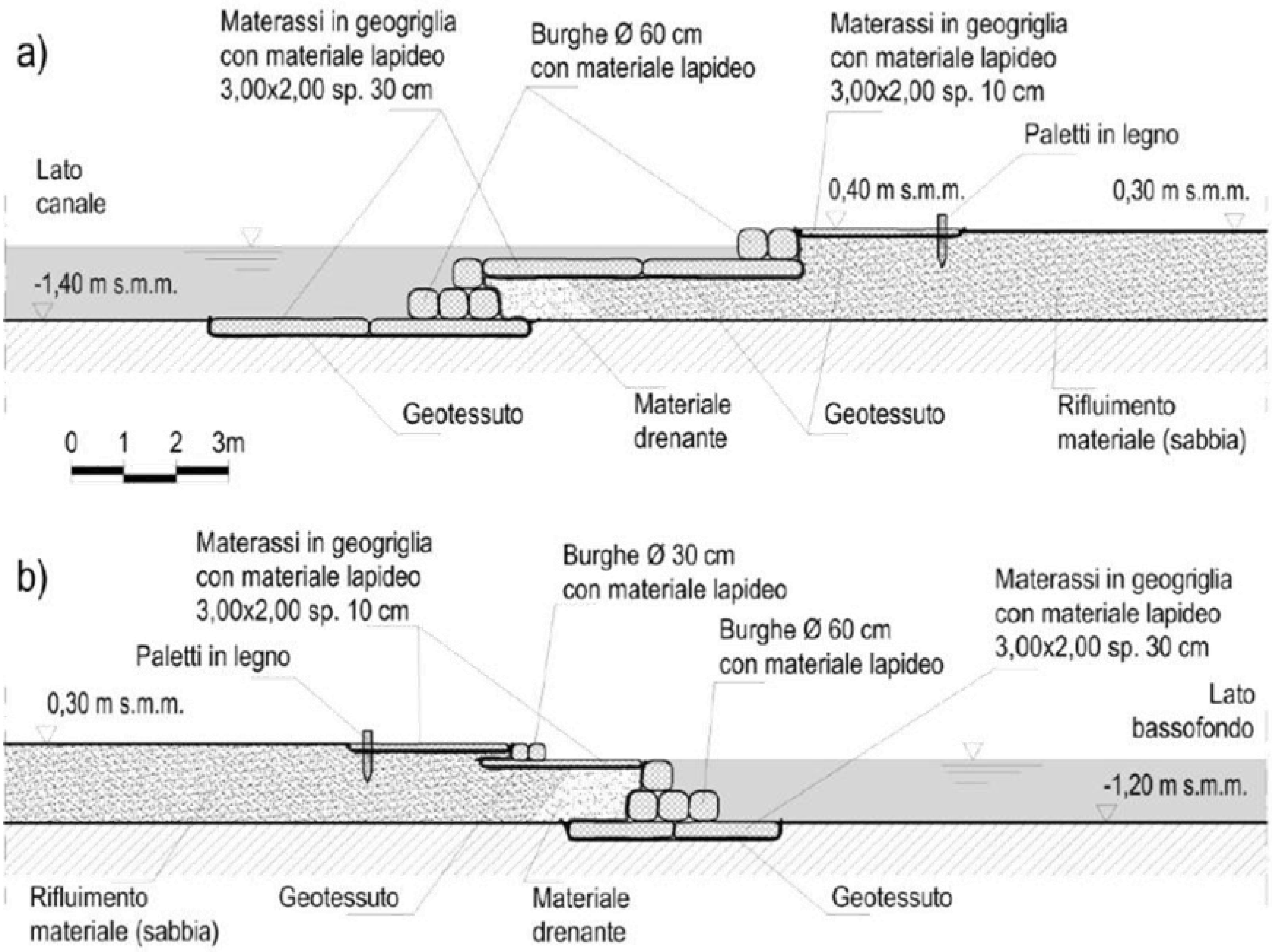


Figure 8.17 – Solutions for morphological structures protection within the Venice Lagoon (Piano per il recupero morfologico e ambientale della Laguna di Venezia; Consorzio Venezia Nuova, aggiornamento 2016).

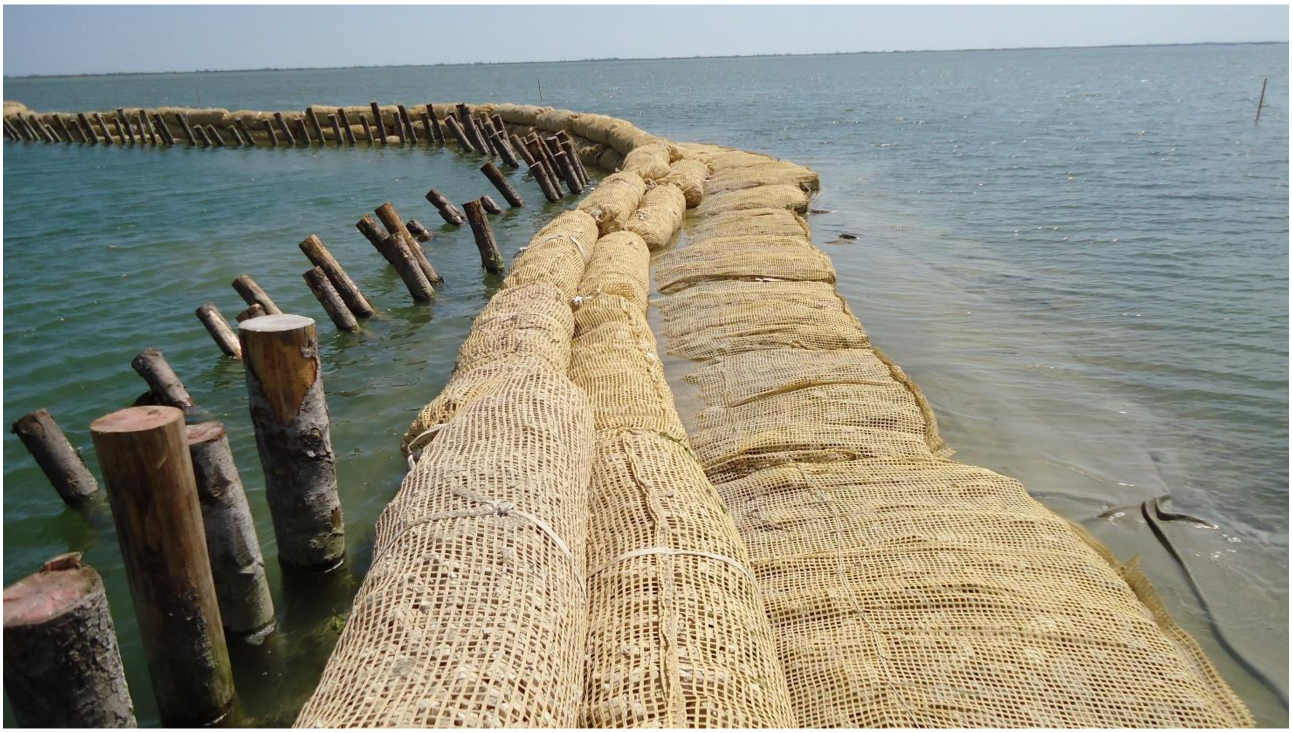


Figure 8.18 – Examples of implemented structures (https://coedmar.it/portfolio-item/barena-ripristino-morfologico-area-canali-cenesa-boer-siletto/).

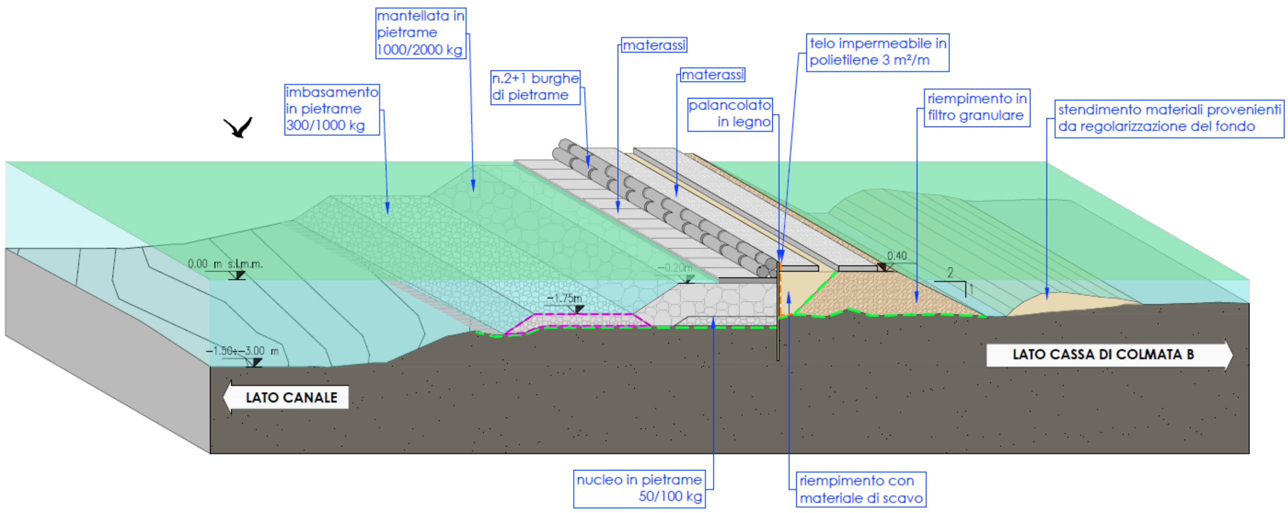


Figure 8.19 – New design of bank protection at the land reclamations bordering the western side ot the MMC channel South of Fusina (Opere di manutenzione e ripristino per la protezione e la conservazione nelle aree di bordo del canale Malamocco Marghera tratto curva San Leonardo e Fusina - Interventi di protezione dall'erosione marina delle Casse di colmata A, B, D-E, lato laguna viva, Venezia; Studio Rinaldo, 2022).

From a very general point of view, the use of geosynthetics may provide effective and cheap solutions for short term implementation of the breakwaters, even though these simple structures alone have a huge landscape impact. Moreover, they may not remain effective in case of differential settlements (it is almost impossible to compensate local settlements of a geotube adding a new one on top). If exposed to UV rays, lifespan of plastic materials reduces and microplastics are likely to be released in the environment.

Most recent geosynthetics solutions include scour proof geotubes and multi-layer textiles, allowing for geotube filling with sand and/or mud. This option extends the range of fill materials, including a larger amount of dredged sediments, thus reducing the need of quarry materials.

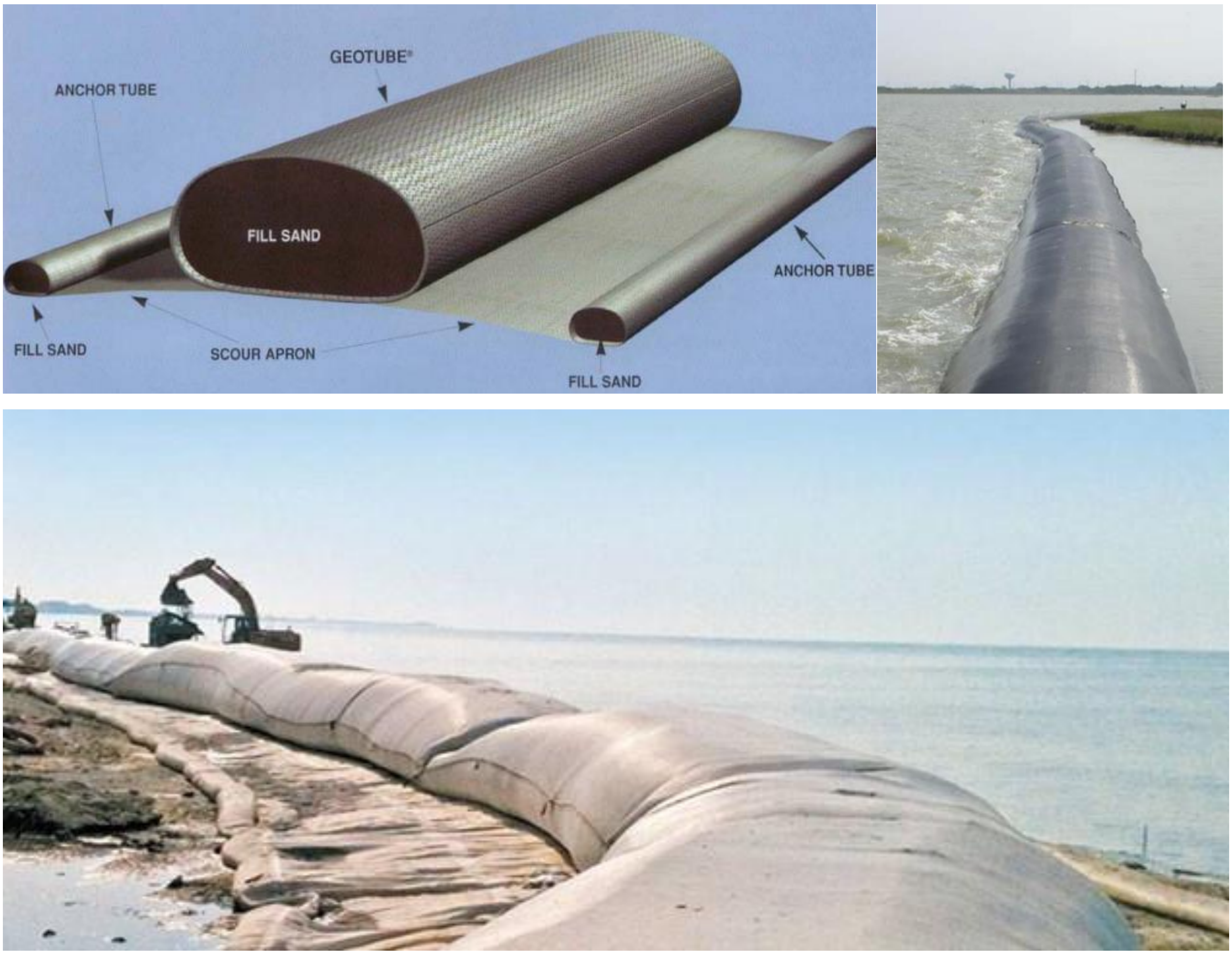


Figure 8.20 – Geosynthetics solutions for bank protection.

An interesting development of geosynthetics solutions for rubble mound structures consists in mixed rock/geotube structures, where the geotube (or geocontainer, geobag, etc.) makes the core of the breakwater. The geotextiles is therefore protected from direct exposure to sunlight and levelling/repair may be done using additional rock only. The solution is very suitable for the lagoon environment, where rock size is relatively small and may hardly affect geotextile integrity during construction.

Figure 8.21 – Geosynthetics solutions for bank protection.

8.5 Uncertainties

The study has been developed at a conceptual level, without going into the details of design.

The study demonstrated that effective solutions, both structural and operational, can be considered for reducing the impact of navigation along the MMC channel. These solutions are relatively simple and, from the operational point of view, have been already implemented by the Coast Guard.

The full development of the proposed solutions, indeed, must undergo a full design process and environmental assessment in order to define the optimal design solution.

A series of uncertainties are still impacting the upcoming design process. These uncertainties will affect the design, but, most likely, they will not affect the conceptual solutions developed within this study. The main uncertainties are:

1) Sediment management rules.
2) Environmental quality of sediments.
3) Tidal flats updated bathymetry.
4) Geotechnical properties of the subsoil.
5) Morphological structures to be (most likely) developed in parallel in the framework of the Venice Lagoon Morphological Plan.

The long-awaited approval of the Venice Lagoon Morphological Plan may positively affect the design of the mitigation structures foreseen by the present study and vice versa. Most of all, any structure limiting the fetches within the lagoon will reduce the wave action against the proposed breakwaters and limit sediment resuspension, preventing sediment loss through the MMC channel (and furthermore reducing its impact).

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