Sea defences design in the vicinity of a river mouth: the case study of Lignano Riviera and Pineta

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Sea defences design in the vicinity of a river mouth: the case study of Lignano Riviera and Pineta

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Abstract. To guarantee the proper functioning of sea defences over a medium-long period, the knowledge of the complex interaction between tidal currents and nearshore wave field is fundamental in order to estimate the longshore sediment transport. In particular, the morphological evolution of coastal environments close to river mouths is deeply affected also by the riverine sediment transport, which can contribute to the overall coastal balance of erosion and deposition processes. Groynes are commonly used to intercept the longshore sediment transport and to stabilize the littorals, as the case of Lignano beach near the Tagliamento river mouth. In particular, the groyne closest to the river has been shortened in the recent years, influencing in this manner the coastline balance. In this study, a numerical model coupling a morphodynamic model and a wave generation spectral model has been used to study the effects of the variation of the groyne length on the beach. Results are presented and discussed, showing that the numerical modelling can be used for the sea defences design to improve the integrated coastal zone planning and management.

1. Introduction

The European Union has a coastline of about 68000 km. More than half of the EU population lives within a distance of 50-km from the coast, and in 2001 the 14% of the EU population lived within 500 m from the coastal line. Hence, the coastal protection is a key point, which involves economic, environmental, engineering and social aspects.

Coastal systems are extremely dynamic, since several natural processes, such as tides, wind waves and sedimentary riverine inputs interact with each other, carrying important consequences on the overall morphodynamic balance [1-4]. This complex interaction can also deeply affect the economic activities linked to the utilization of these environments, requiring continuous interventions with the aim to mitigate erosion processes and correctly manage the resources [5-9].

The local actions can be implemented through the construction of shore protections, which can interfere in different ways with the coastal sediment transport, in order to reduce the impact on the coast of extreme events as storms and high tides and to facilitate deposition mechanisms [10-11]. Nevertheless, it has been seen during the last decades that many sea defences have not reached the expected results despite of high construction and maintenance costs, and in some cases, they have further deteriorated the sediment balance in the surrounding areas [12].

Groynes are hard coastal defences commonly used to directly intercept the longshore sediment transport, and, for this reason, the correct design of these structures becomes fundamental to guarantee both the structural strength and an adequate effectiveness in stabilizing the morphological evolution of littorals.

In literature, many studies have been undertaken on the groynes efficiency to balance erosive phenomena [13-15], but the suggestions on which is the optimal length allowing to intercept the right amount of sediments are still relatively scarce.

Most of Italy's coastlines are in a precarious equilibrium as they are characterized by a widespread erosion trend [16-19]. The present paper focuses the attention on the study of a series of groynes built along Lignano Riviera and Pineta beaches, in the northern Adriatic Sea. Despite their presence, the shoreline continues to undergo an erosive tendency, and repeated storm surges in the recent years have severely damaged the groynes cover, showing that it has been realized with undersized rocks. In particular, the groyne of the Lignano Riviera beach, which is closest to the Tagliamento river mouth, is very long compared to the beach profile. Since it is directly influenced also by the riverine sediment input together with the longshore current contribute, its excessive length could deeply affect the overall balance of the whole Lignano beach.

In order to study the influence of the length variation of the groyne, and to evaluate how this parameter can change the erosion and deposition balance along the beach [20], a morphodynamic-spectral coupled model has been applied. This approach takes into account the combined action of river flow, tides and wind waves, which governs the sediment transport processes and this interaction can be considered as the basis for the proper planning of the interventions in estuarine context, where the presence of all these factors increases the complexity of the phenomena. In this sense, the numerical modelling can represent a useful and versatile tool for the proper management and development of the coastal zone [21].

In section 2 the numerical model is briefly recalled; in section 3 the field site is introduced and in section 4 the wind data are analysed. Finally, in sections 5 and 6 the numerical simulation is described and the results are presented and discussed.

2. Numerical model

For this study, a numerical model able to manage the coupling between a morpho-hydrodynamic model and a wave generation spectral model has been used [22].

The hydrodynamic model is based on the classic 2DH shallow water equations, and the morphodynamic one considers the depth-average advection-diffusion equation to compute the suspended sediment transport while the changes in the bed elevation due to erosion and deposition are described by the sediment continuity equation written on a control volume near the bed [23]. For the numerical integration of these equations a shock-capturing finite volume method is used, which is second order accurate both in time and space, assuring a proper propagation also in wet and dry conditions [24-25].

The open source spectral model SWAN is used to generate wind waves. SWAN is a third generation model based on the wave action density balance equation, which considers all source terms from the input generation by wind to the dissipations due to both wave breaking in deep and shallow waters, and the bottom friction; also the energy transfers resulting from the wave-wave non-linear interactions are included [26].

The coupling of the two models is managed by a main program in which the models run separately one after each other for 1200 s before exchanging the results. In fact, at every run the results of the spectral model in term of the main wave parameters and the gradients of radiation stresses become the input data for the morphodynamic model. Similarly, the morphodynamic results such as current velocities, bottom elevation and water level become the input data for SWAN.

3. Field site

Lignano Sabbiadoro beach is located in the Northern Adriatic Sea between the Tagliamento river mouth and the lagoon inlet of Lignano (Figure 1a-b). It is dived into 3 beaches, which are respectively from west to east: Lignano Riviera, Lignano Pineta and Lignano Sabbiadoro.

A series of 10 groynes perpendicular to the coastline has been built along Lignano Riviera and Pineta beaches. The westernmost groyne, that is the closest to the Tagliamento river mouth, is the main object of this study. It was built in 1963 and, originally, its length was larger than the actual, which has been recently reduced to 110 m in order to facilitate the movement of the Tagliamento sand from the river mouth to the North-East. Every year the beach surrounding this groyne is cleaned up from woods and shrubs carried by the Tagliamento river floods and it is subject to nourishment interventions.

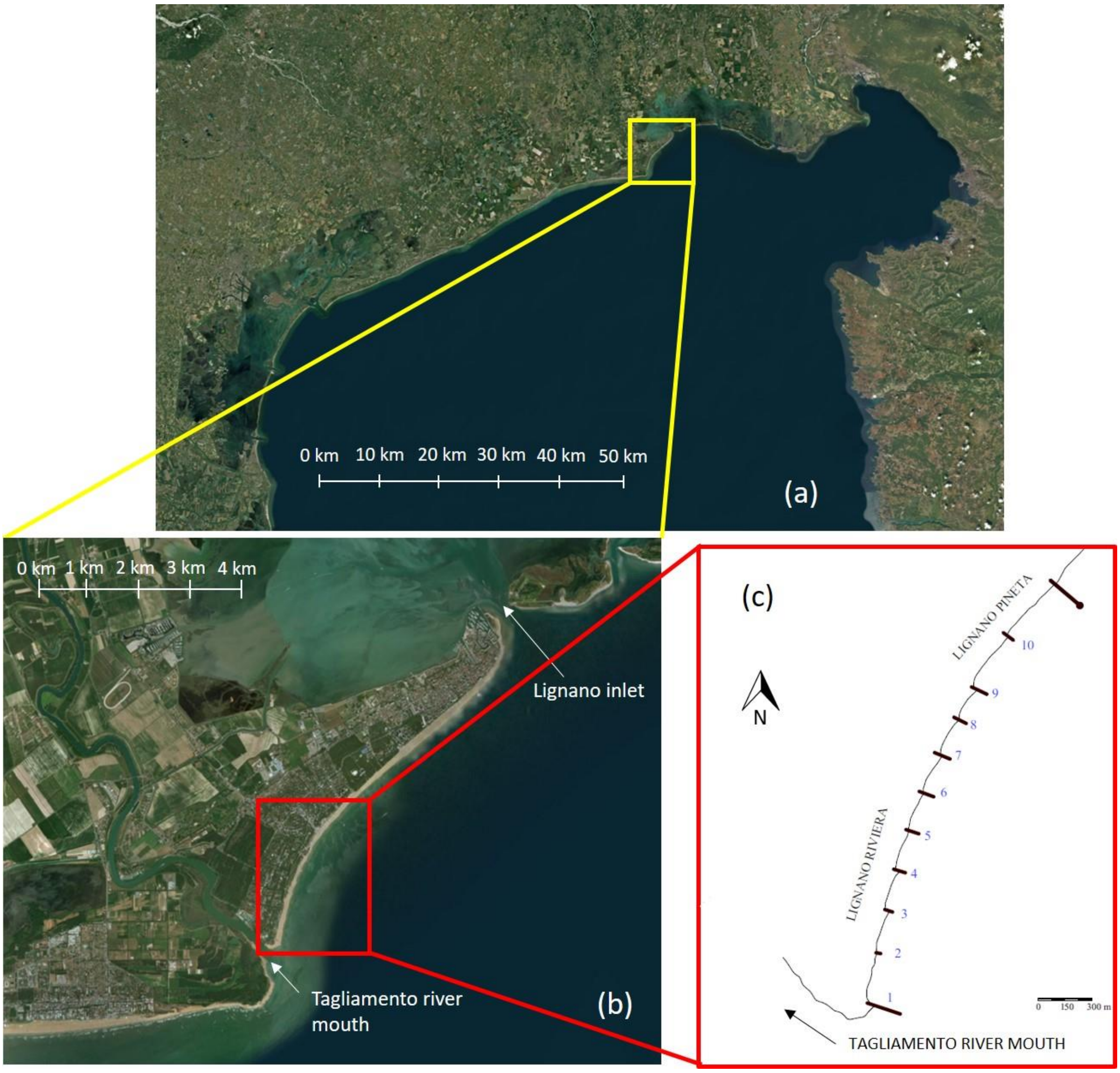

Figure 1. (a) Northern Adriatic Sea, (b) Lignano peninsula and (c) Lignano Riviera and Pineta beaches.

4. Wind data analysis

A proper local wind regime analysis is the basis for the wind waves generation and hence for the sea defences design. In this section, the procedure adopted to derive the average annual wind climate is briefly summarized.

Three anemometric stations have been considered, being one located in Lido Diga Sud (VE), one in Lignano (UD) and one in Grado (GO), as depicted in Figure 2.

Figure 2. Location of the anemometric stations.

The wind data collected from these stations have been analysed in terms of both direction and intensity, for a total of more than one million of data covering the years between 1998 and 2017. These have been acquired as different time series and the sampling intervals have been uniformed through a simple moving average to obtain only hourly data for all the anemometric stations. Any different sampling intervals have been corrected through linear interpolation.

Wind speeds have been divided into intervals of 2 m/s each; the interval between 0 and 2 m/s represents calm events. Also wind directions have been grouped in classes as reported in Table 1.

Table 1. Wind direction data partition.

Wind	Tramontana	Grecale	Bora/Levante	Scirocco	Ostro	Libeccio	Ponente	Maestrale
Angular range (°N)	[330-15]	[15-60]	[60-105]	[105-150]	[150-195]	[195-240]	[240-285]	[285-330]

The validated data of the considered anemometers have been drawn up to obtain the relative directionally frequency diagrams, as depicted in Figure 3. Due to the possible interference that the surrounding inhabited area could determine on the wind data, for each anemometric station the polar charts sectors representing the off-shore wind conditions have been identified as:

- Lido Diga Sud (VE): from 0°N to 120°N;
- Grado (GO): from 120°N to 270°N;
- Lignano (UD): from 270°N to 360°N.

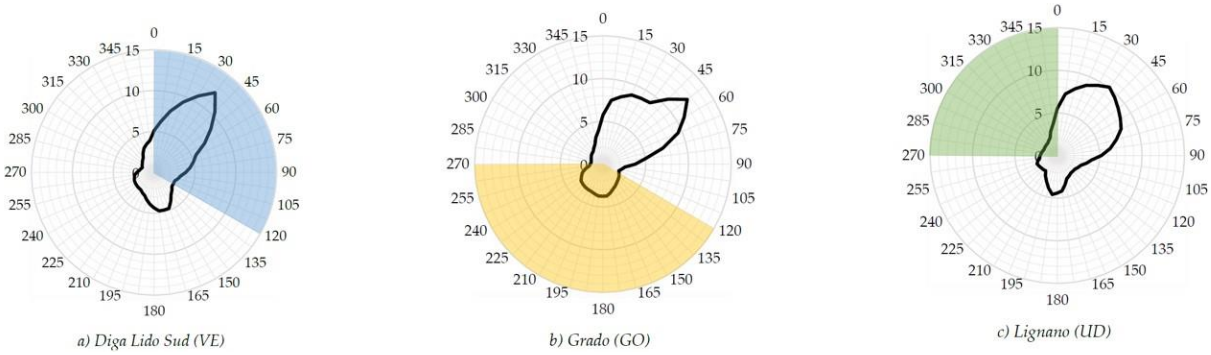

Figure 33 Representative sectors of the considered anemometers.

These sectors have been rearranged to create a single directionally frequency distribution representing the offshore annual average wind regime. From this polar chart, the velocity duration curve reported in Figure 4 has been deduced.

Preliminary simulations have shown that less frequent but more intense winds deeply affect sediment transport rather than more frequent but less strong ones. In particular, only wind speeds higher than 10 m/s can significantly influence sand movement.

Following these considerations, it has been decided to sum up the wind velocities higher than 10 m/s into two classes: 10 to 14 m/s and 14 to 22 m/s; in particular, an average velocity of 12 m/s has been chosen as representative for the former interval and of 17 m/s for the latter.

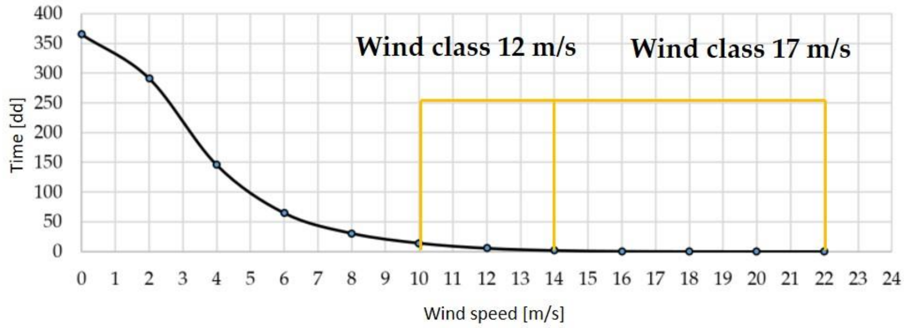

Figure 4. Wind speed duration curve.

A seasonal analysis on wind data that exceeds 10 m/s attests that the main blowing directions are that of Bora/Levante (75° N) and Scirocco (165°N) (Figure 5). In particular, Scirocco winds prevail in spring, Bora/Levante winds in autumn and winter, and both Scirocco and Bora/Levante winds in summer. The obtained velocities have been associated to Scirocco and Bora/Levante directions.

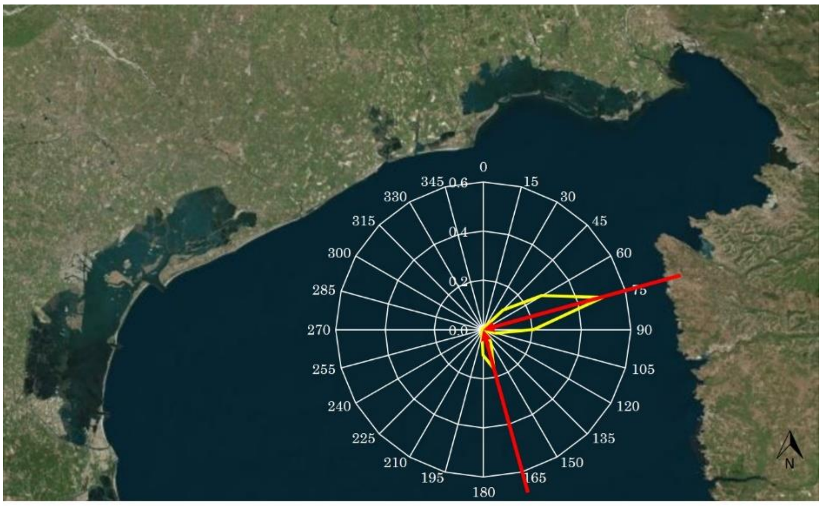

Figure 5. Offshore directionally frequency distribution of higher wind speeds.

At this point, it is necessary to establish a suitable time sequence of the wind events both in terms of direction and intensity, which have been calculated from the relative frequencies:

- 4 days of 12 m/s Scirocco wind;
- 8 days of 12 m/s Bora/Levante wind;
- 8 hours of 17 m/s Scirocco wind;
- 40 hours of 17 m/s Bora/Levante wind.

These different wind classes have been alternated with calm periods to allow the suspended material to deposit and the sequence is represented in Figure 6a. To reduce computational times a morphological factor FM has been used, as a parameter which amplifies the erosion and deposition volumes [27]. This allows the simulation to last 1 day instead of 4 (Figure 6b).

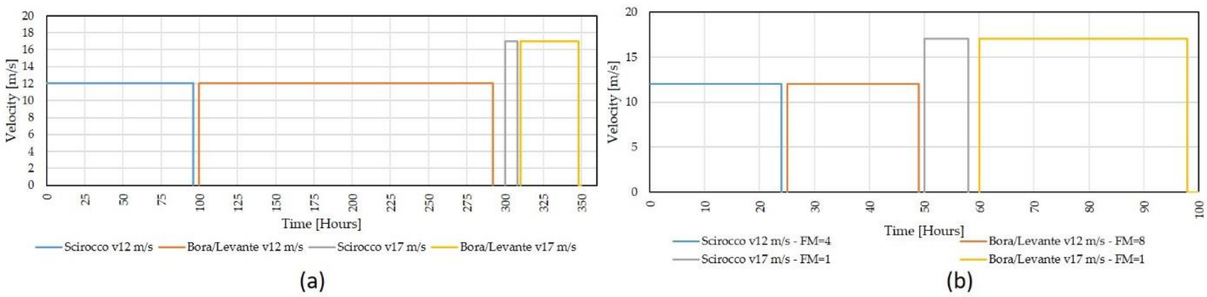

Figure 6. (a) Real wind time sequence; (b) simulated wind time sequence.

5. The simulation set-up

Two computational grids have been defined: one for the morphodynamic model and one for the spectral model. The morphodynamic mesh (Figure 7a) covers the entire area of the Lignano littoral and it develops until almost the Istrian coasts. Moreover, also the last 10 km of the Tagliamento river have been added as a prismatic canal, with the aim to reproduce the river sediment input. The computational grid has about 177000 quadrangular irregular elements, with dimensions that vary from offshore 200 m x 200 m, passing through near-shore 20 m x 20 m, until to reach a minimum size of 0.4 m to represent the groynes. The spectral domain is the same as in Petti et al [28] and the spectral parameters are set according to previous applications in similar contexts [4, 22, 29, 30].

Available surveys [31] have been used for the bottom elevation of both morphodynamic and spectral domains.

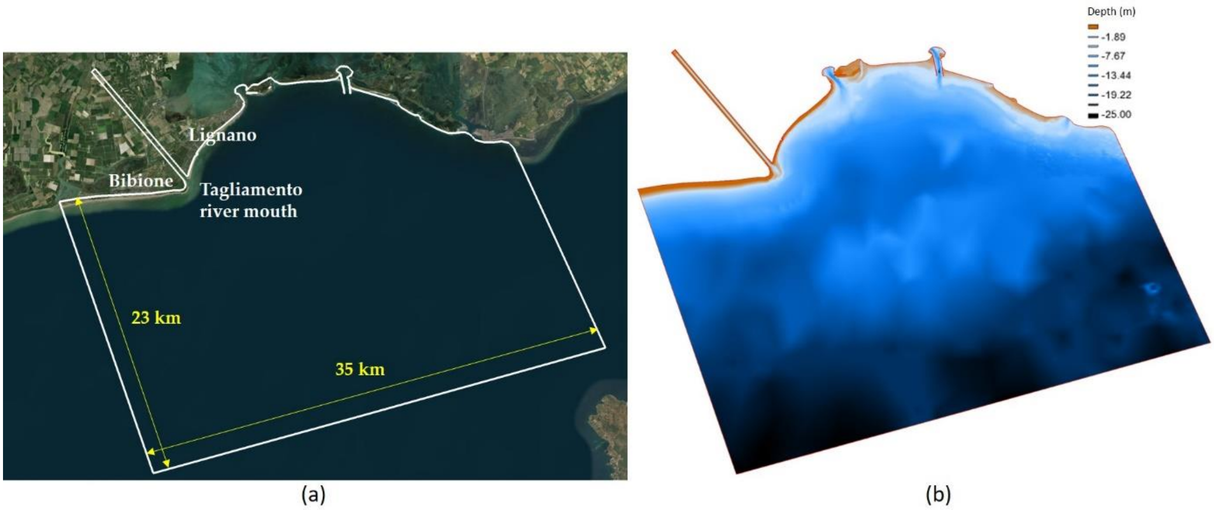

Figure 7. Morphodynamic computational grid: (a) boundaries, (b) bottom elevation.

In order to simulate the morphological effects of an average year, the same tidal oscillation presented in Petti et al. [28] has been used, according to the previously described wind events. Also all other parameters of both the morphodynamic and spectral models have been set as in Petti et al. [28].

5.1. Sediment transport from Tagliamento river

Rivers have a key role in the morphological evolution of estuarine environments. In the present case study, the floods of the Tagliamento river yearly transport great amounts of sand towards the river mouth, with important implications on the overall sedimentary balance of both the Lignano and Bibione beaches. From experimental evidences, the estimate of this sand volume carried by the river to the sea reaches approximately 300000 m^3/year, which are deposited to form a mouth bar that inevitably affects the longshore sediment fluxes. Some preliminary morphodynamic simulations have been performed to recreate the estuary bar, considering three significant flood events per year [21], an average tidal oscillation with an amplitude of 40 cm, a suspended sediment load of 300000 m^3, and no wind waves. The bottom elevations obtained from this preliminary simulation has been used as the initial condition for subsequent simulations.

6. Simulation results

The previously described conditions have been set to simulate the morphological effects of an average year. In order to quantify the longshore sediment transport, 5 coastal cross-sections have been defined (Figure 8a); each of them is 800 m long and it is subdivided into 4 subsections. In Figure 8b the net average annual sediment flux is shown on each subsections.

(a) (b)

Figure 8. (a) Sections position; (b) net average annual sediment flux. The red and blue arrows represent fluxes directed respectively towards the North-East direction and in the opposite one.

It can be easily observed that the overall sediment transport moves from South-West to North-East, suggesting that, in this part of the Lignano coast, the annual average sediment transport is mainly influenced by Scirocco winds.

Moving from the Tagliamento river mouth towards the North, this sand transport constantly decreases, as, close to Lignano Pineta beach, the sediment transport is mainly affected by Bora/Levante winds and it develops from North-East to South-West.

This suggests that during springtime, when Scirocco winds prevail, the sediment transport moves from South-West to North-East creating a sand deposit on to the western side of the groynes. During summer, when Scirocco and Bora/Levante winds are equally frequent, the coastline is in balance. Finally, during autumn and winter, when Bora/Levante winds predominate, the sediment transport mainly moves from North-East to South-West reshaping the coastline profile.

6.1. Groyne length variation

The groynes length is one of the most sensitive parameter for the correct design of these structures, since their role is to intercept the longshore sediment transport. In order to verify the effects of different patterns of the groyne closest to the Tagliamento river mouth, 2 further simulations have been performed, modifying its actual length of about 110 m. In the former simulation, named “groyne shortening”, its length is reduced by 30 m becoming 80 m (figure 9a), and in the latter defined as “groyne lengthening”, it has been extended up to a 140 m-length (figure 9b). The results of these 2 simulations have been compared with those of the previous one, called “current configuration”, in terms of the sediment fluxes which cross sections 1 to 5 of Figure 8a, in an average year.

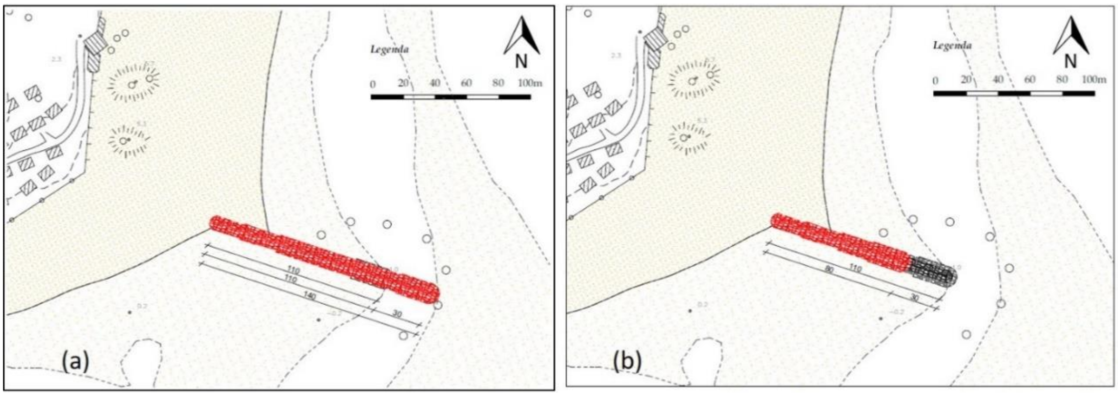

Figure 9. Analysed groyne both in the cases of (a) lengthening and (b) shortening.

In table 2 the results of “groyne lengthening” and “current configuration” simulations are compared. Overall, it can be noticed that a greater length of the groyne reduces the total average annual longshore sediment transport which decreases approximately from 32000 m^3/year to 22000 m^3/year across the section 1. This confirms that the groyne lengthening contributes to deduct part of the sand coming from South-West and from the mouth river, blocking its natural movement towards the Lignano coast. In the remaining coastline, no significant variations can be observed.

Table 2. Total average annual longshore sediment transport.

Section	***1***	***2***	***3***	***4***	***5***
Total average annual sediment flux (m^3/year) *“Groyne lengthening”*	21876	23000	16636	2616	1901
Total average annual sediment flux (m^3/year) *“Current configuration”*	31971	26565	19019	3827	2985
Sediment transport variation (m^3/year)	-10095	-3565	-2383	-1211	-1084

The mass balance applied to two consecutive sections reveals that the groyne lengthening causes some localised erosion phenomena and a consequent disequilibrium in the surrounding areas.

In table 3 the results of “groyne shortening” and “current configuration” simulations are compared. Even in this case, the total average annual longshore sediment transport reduces, decreasing across section 1 approximately from 32000 m^3/year to 25000 m^3/year.

Table 3. Total average annual longshore sediment transport.

Section	***1***	***2***	***3***	***4***	***5***
Total average annual sediment flux (m^3/year) *“Groyne shortening”*	24739	24894	17489	2706	1780
Total average annual sediment flux (m^3/year) *“Current configuration”*	31971	26565	19019	3827	2985
Sediment transport variation (m^3/year)	-7232	-1671	-1530	-1121	-1205

This could be ascribed to the arising of currents, which counteract the movement of the sediments along the coastline. Furthermore, in this configuration, the sediment transport variation is generally lower, compared to those obtained with the groyne lengthening. The mass balance between two consecutive sections suggests that in the Tagliamento river mouth area the deposition decreases and the beach is substantially in balance. On the other hand, the groyne shortening leads to an increase of the deposits in the remaining littoral portion.

7. Conclusions

In this paper the study of the morphological evolution of the coastline of Lignano Riviera and Pineta in the northern Adriatic Sea has been conducted through a bidimensional morphological model, coupled to a spectral model. Along this beach 10 groynes have been built, which alter the erosion and deposition processes by means of the interaction with the longshore sediment transport. Furthermore, the sediment balance of the nearshore zone is also affected by the sediments from the Tagliamento river mouth.

In order to reproduce the average annual morphological evolution of the coast, an accurate analysis has been conducted to evaluate the proper offshore wind climate, which is a fundamental input for spectral modelling.

The simulation outcomes suggest that Scirocco wind generates strongest longshore currents, so the sediment transport results mainly directed towards the North-East, and it leads to a sand deposit on the western side of the groynes. On the other side, the Bora/Levante winds, induce currents that drive a sediment transport mainly directed towards the South-West reshaping the coastline profile.

The simulation with an increased length of the groyne closest to the Tagliamento river mouth shows a larger sand deposit to the western side and a consequent wider erosion on the beach towards Lignano Riviera. On the other hand, the shortening of the groyne leads to an increase of the deposits in the remaining littoral portion and at the same time the accumulation on the western side is still guaranteed.

In conclusion, the present paper has shown the applicability of a morphodynamic-spectral coupled model as a useful tool for sea defence design, and to the correct planning and management of the overall coastal balance.

References

[1] J. E. Hansen, E. Elias, J. H. List, L. H. Erikson, P. L. Barnard, "Tidally influenced alongshore circulation at an inlet-adjacent shoreline," *Cont. Shelf Res.*, vol. 56, pp. 26-38, 2013.

[2] Y. Ding, S. S. Y. Wang, "Modeling of wave-current interaction using a multidirectional wave-action balance equation," *Proceedings of the International Conference on Coast. Eng.*, vol. 32, 2010.

[3] A. D. Ashton, L. Giosan, "Wave-angle control of delta evolution," *Geophys. Res. Lett.*, vol. 38(13), 2011.

[4] S. Pascolo, M. Petti, S. Bosa, "Wave-Current Interaction: A 2DH Model for Turbulent Jet and Bottom-Friction Dissipation," *Water*, vol. 10 pp. 392, 2018.

[5] A. M. Vaidya, S. K. Kori, M. D. Kudale, "Shoreline Response to Coastal Structures," *Aquat. Procedia*, vol 4, pp. 333-340, 2015.

[6] S. Poulos, G. Chronis G., "Coastline changes in relation to longshore sediment transport and human impact, along the shoreline of Kato Achaia (NW Peloponnese, Greece)," *Mediterr. Mar. Sci.*, vol. 2, pp.5-13, 2001.

[7] H. M. El-Asmar, K. White, "Changes in coastal sediment transport processes due to construction of New Damietta Harbour, Nile Delta, Egypt," *Coast. Eng.*, vol. 46, pp. 127-138, 2002.

[8] M. Szmytkiewicz, J. Biegowski, L. M. Kaczmarek, T. Okrój, R. Ostrowski, Z. Pruszak, G. Różyńsky, M. Skaja, "Coastline changes nearby harbour structures: comparative analysis of one-line models versus field data," *Coast. Eng.*, vol. 40, pp. 119-139, 2000.

[9] W. Hendriyono, M. Wibowo, B. Al Hakim, D. C. Istiyanto, "Modeling of Sediment Transport Affecting the Coastline Changes due to Infrastructures in Batang – Central Java," *Procedia Earth Planet. Sci.*, vol. 14, pp. 166-178, 2015.

[10] E. Pranzini, "Shore protection in Italy: from hard to soft engineering…and back," *Ocean and Coast. Manage.*, vol. 156, pp. 43-57, 2018.
[11] E. Pranzini, L. Wetzel, A. T. Williams, "Aspects of coastal erosion and protection in Europe," *J. Coast. Conserv.*, vol. 19(4), pp. 445-459, 2015.
[12] D. Jin, P. Hoagland, D. K. Au, J. Qiu, "Shoreline changes, seawalls, and coastal property values," *Ocean Coast. Manage.*, vol. 114, pp. 185-193, 2015.
[13] B. A. Zaid, P. Nardone, M. Nones, C. Gerstgraser, K. Koll, "Morphodynamic Effects of Stone and Wooden Groynes in a Restored River Reach," *E3S Web of Conferences*, vol. 40, 2018.
[14] S. K. Prasad, K. P. Indulekha, K. Balan, "Analysis of groyne placement on minimising river bank erosion," *Procedia Technol.*, vol. 24, pp. 47-53, 2016.
[15] D. E. Reeve, A. Pedrozo-Acuña, M. Spivack, "Beach memory and ensemble prediction of shoreline evolution," *Coast. Eng.*, vol. 86, pp. 77-87, 2014.
[16] G. Barbaro, "Master Plan of solutions to mitigate the risk of coastal erosion in Calabria (Italy), a case study," *Ocean Coast. Manage.*, vol. 132, pp. 24-35, 2016.
[17] S. Ginesu, D. Carboni, M. Marin, "Erosion and use of the coast in the northern Sardinia (Italy)," *Procedia Environ. Sci.*, vol. 32, pp. 230-243, 2016.
[18] G. Anfuso, E. Pranzini, G. Vitale, "An integrated approach to coastal erosion problems in northern Tuscany (Italy): Littoral morphological evolution and cell distribution," *Geomorphology*, vol. 129, pp. 204-214, 2011.
[19] L. C. van Rijn, "Coastal erosion and control," *Ocean Coast. Manage.*, vol. 54, pp. 867-887, 2011.
[20] L. Choufu, S. Abbasi, H. Pourshahbaz, P. Taghvaei, S. Tfwala, "Investigation of Flow, Erosion, and Sediment Pattern around Varied Groynes under Different Hydraulic and Geometric Conditions: A Numerical Study," *Water*, vol. 11, pp. 235-253,2019
[21] A. Valsamidis, D. E. Reeve, "Modelling shoreline evolution in the vicinity of a groyne and a river," *Cont. Shelf Res.*, vol. 132, pp. 49-57, 2017.
[22] M. Petti, S. Bosa, S. Pascolo, "Lagoon Sediment Dynamics: A Coupled Model to Study a Medium-Term Silting of Tidal Channels," *Water*, vol. 10(5), pp. 569, 2018.
[23] S. Bosa, M. Petti, S. Pascolo, "Numerical modelling of cohesive bank migration", *Water*, vol. 10(7), pp. 961, 2018.
[24] S. Bosa, M. Petti, "Shallow water numerical model of the wave generated by the Vajont landslide," *Environ. Modell. Softw.*, vol. 26, pp. 406-418, 2011.
[25] S. Bosa, M. Petti, "A numerical model of the wave that overtopped the Vajont Dam in 1963", *Water Resour. Manag.*, vol. 27(6), pp. 1763-1779, 2013.
[26] N. Booij, R. C. Ris, L. H. Holthuijsen, "A third-generation wave model for coastal regions, Part I, Model description and validation". *J. Geophys. Res*., vol. 104, pp. 7649–7666, 1999.
[27] J. A. Roelvink, "Coastal morphodynamic evolution techniques", *Coast. Eng.*, 53, 277–287, 2006.
[28] M. Petti, S. Pascolo, S. Bosa, E. Uliana, "Marano and Grado Lagoon: narrowing of the Lignano inlet", submitted WMCAUS2019, 2019.
[29] S. Pascolo, M. Petti, S. Bosa, "On the wave bottom shear stress in shallow depths: the role of wave period and bed roughness", *Water*, vol. 10(10), pp. 1348, 2018.
[30] M. Petti, S. Pascolo, S. Bosa, G. Fontolan, A. Bezzi. "Tidal flats morphodynamics: a new conceptual model to predict the evolution over medium-long period". *Water* **2019**, *11*(6), 1176; https://doi.org/10.3390/w11061176..
[31] A. Triches, S. Pillon, A. Bezzi, M. Lipizer, E. Gordini, R. Villalta, G. Fontolan, G. Menchini, "Carta Batimetrica Della Laguna di Marano e Grado"; Arti Grafiche Friulane, Imoco spa: Udine, Italy, 2011, 39p, 5 Maps; ISBN 978-88-95980-02-7.