USE OF FORECAST WAVES FOR SEDIMENT TRANSPORT SHORT TERM PREDICTION DURING THE OPERATIONAL PHASES OF A BEACH NOURISHMENT: EXAMPLE OF EMILIA ROMAGNA PROJECT 2022

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Beach nourishment from relict sand deposit is considered as the main soft engineering intervention for the coastal defense from extreme events and sea level rise. For the success of the intervention a detailed study of the physiographic units is needed as well as the study on the sand compatibility but even the management of the operation in the execution in phase play an important role. To optimize the dredging and nourishment activities, limit the overall impact of the intervention and obtain a more stable beach profile in the short term after the intervention, forecast waves for sediment transport prediction can be used during the operational phase.

Keywords: Beach nourishment, wave forecast, relict sand deposit.

INTRODUCTION

Due to the increase of extreme severe storms frequency, combined with the sea level rise, the coastal erosion and the consequent vulnerability of the coastal areas, where most of the human activities are placed, is becoming more and more severe (Benetazzo et al., 2012; Vousdoukas et al., 2018; Romagnoli et al., 2021; Vecchio et al., 2024).The importance of the preservation of the coastal areas has a fundamental role for the economy of the population as for the social growth and the safety of the inhabitants.
One of the possible interventions of coastal management to defend the coastal areas characterized by sandy shore, is represented by the beach nourishment (Finkl, et al., 2002; Hughes, & Vassiliev,2005) consisting of the supply of new sand to advance the shoreline helping the resilience of the coastal areas.
As it has a very low impact on the overall environment, since the defense system doesn't need concrete permanent structures, it is also classified as a soft engineering intervention (Jones & Simmonds, 2013; Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2012; European Environment Agency, 2015).
Different kind of beach nourishment projects have been taken all over the world and in Italy itself using different technologies and design approaches (Stive et al., 2013; Escudero et al., 2020; Muñoz-Perez et al., 2020; Moreno, 2021). A beach nourishment intervention has to be accordingly planned taking into account the physiographic unit and the features of the area (MATTM 2019, Pranzini 2020). The sand can be taken from earth quay material or relict sand from relict deposits offshore.
In particular, in general, the beach nourishment made with relict sand it's preferable as it can help to restore the original environment of the area, increasing the natural resilience of the environment without compromise the natural and original feature of the site.
Key aspects for the success of a beach nourishment are the design approach, the choice of the relict sand deposit and the operational methodologies (MATTM 2019) and the implementation of numerical modelling has become an essential tool for coastal planning, decision support and risk assessment (van Duin et al., 2004; Burcharth et al., 2014; Karambas, 2014; Samaras et al., 2016).
Reliable information regarding nearshore wave dynamics, hydrodynamics and sediment transport can support coastal planning and hazard mitigation (Stockdon et al., 2012; Idier et al., 2013; Archetti et al., 2016; Bonaldo et al., 2019), and, if performed in real time, building works and maritime operations, improving performance and ensure cost-effective projects.

EMILIAROMAGNA BEACH NOURISHMENT 2022

The Emilia Romagna shoreline, also called *Riviera Romagnola*, is a very important touristic Italian waterfront with an extension of around 110 km.

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The area is highly urbanized and has a key role for the economy of the Adriatic Sea with an affluence of approx. 60 million of tourists every year. The area is also characterized by the presence of natural reserves thanks of the presence of natural dunes and wetlands.
The shoreline is highly affected by subsidence phenomena, contributing to highlight the sea level rise phenomenon. Also, in the past years extreme natural hazards affected the areas with floodings and sea storms endangering inhabitants, environment he historical heritage (Ravenna) and the economy (AA.VV., 2012; Perini et al., 2017; AA. VV., 2018).
As it is a strategic area both for the economy but also for the environmental heritage, the Emilia Romagna Region defined an Integrated Coastal Zone Management Strategy for which the beach nourishment is one of the key interventions with a planned recurrence of 5/6 years. In spring 2022, the 4° nourishment project for the Romagna beaches was carried out (called "Progettone 4").

Figure 1 Location of the n.7 project sites (*Lotto 1- Messa in Sicurezza di tratti critici del litorale nelle provincie di Rimini, Forlì-Cesena e Ravenna con sabbie sottomarine da aree off-shore "Progettone 4"*- Executive Design - Agenzia per la Sicurezza Territoriale e Protezione Civile- Regione Emilia-Romagna)

The project of 2022, financed by Emilia Romagna Region with 22 M€, consisted in the nourishment of 7 beaches along the coast between Ravenna-Punta Marina (at North) and Misano Adriatico (at South), along 90 km of coasts (Fig.1).
For each site, a shore advancement (zero-line progress) of an average of 40 m was planned and achieved, with a total volume of 1,1 million m^3 and a net total length of intervention of 11 km.

The execution of the project has been carried out by DEME, through its Italian Branch SIDRA, between March and May 2022.
The sand for the nourishment has been taken from a borrow area (relict sand deposit) situated 30 NM offshore the coast using a Trailing Suction Hopper Dredger.

Project and Design
The Beach Nourishment strategy of the area is based on the availability of relict sand deposit offshore in the Adriatic Sea.

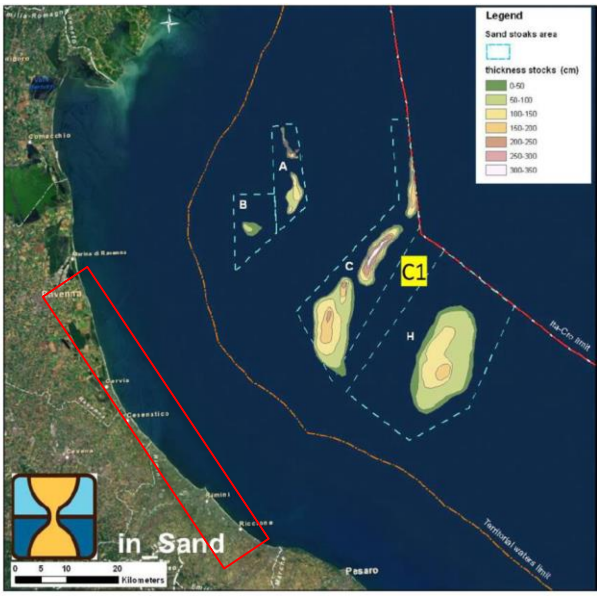

Figure 2 Map of the relict sand deposits suitable for beach nourishment. Highlighted deposit C1, in red square area of intervention. (*Lotto 1- Messa in Sicurezza di tratti critici del litorale nelle provincie di Rimini, Forlì-Cesena e Ravenna con sabbie sottomarine da aree off-shore "Progettone 4"-* Executive Design - Agenzia per la Sicurezza Territoriale e Protezione Civile- Regione Emilia-Romagna)

On the north Adriatic continental offshore, offshore from Emilia-Romagna, six subsea sandy deposits have been identified: A, A1, B, C1, C2, C3 and an extensive silty-sandy body H (Figure 2).
These deposits were formed during the seal level rise during the last ice age, around 18'000- and 6'500-years BC, and were discovered and studied from the 70s through geotechnical and geophysical surveys.
In total, it was estimated that there were approximately 195 million m3 of sand in the first six deposits and another 195 million m3 of silt in the H deposit (*Regione Emilia Romagna* - *Servizio Geologico, sismico e dei suoli*).
For the Project of 2022 part of the deposit **C1** has been used (Figure 2).
As the relict sand deposits are a limited resource, detailed management plans were developed to optimize the use of the areas and, in the design phase, a management plan of the deposit C1 was made, by dividing the deposit in sub areas with different exploitation priority to reach the final project volume.

To test the granulometric compatibility between the relict sand deposit and the location to be nourished, granulometric analysis were performed on the sand from C1 deposits and from all the 7 sites to be nourished.
From the results from the test on C1 the following parameters of the sand were derived:

- Sand Content >91%
- Mudstone content <9%
- D50= 0,18 mm.

The sand, compatible with beach nourishment intervention according to the Italian legislation was then compared with the granulometric analysis from the other sites.
In Figure 3 is shown the comparison between the granulometric curve of one of the samples in C1 and the beach in the site of Riccione.

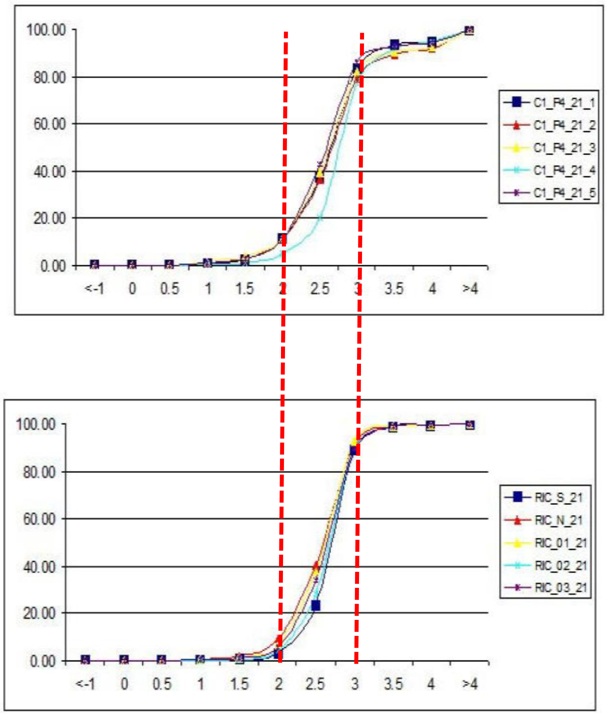

Figure 3 Comparison between granulometric curve from C1 (top), and granulometric curve from Riccione site (bottom) in ϕ scale. (*Lotto 1- Messa in Sicurezza di tratti critici del litorale nelle provincie di Rimini, Forlì-Cesena e Ravenna con sabbie sottomarine da aree off-shore "Progettone 4"*- Executive Design - Agenzia per la Sicurezza Territoriale e Protezione Civile- Regione Emilia-Romagna)

In the design phase of the project were also defined, for each of the location:

- The inshore line advancement between 30 and 60 m depending from the location;
- The connection height with the existing profile (around + 1 m.a.s.l.):
- The slope of the beach profile above and below water.

In total, the project foresees an amount of approximately 1,1, million m^3, with an average incidence of 100 m^3/lm.

Table 1. Design parameters Emilia Romagna Beach Nourishment project.			
Site	*L (m)*	*Volume (m3)*	*(m^3xm)*
Misano sud	1.680	185.000	110
Riccione	1.500	175.000	117
Igea Marina	1.500	115.000	77
Cesenatico	1.000	105.000	105
M. Marittima	1.410	170.000	121
Lido di Dante	1.450	130.000	90
Punta Marina	1.500	200.000	80
TOTAL	**11.040**	**1.080.000**	**100 (av.)**

Execution methodologies

The location of the borrow area C1 was approximately 30 NM distant from every of the n.7 locations, with a depth of -40 m.s.l.

Operationally, one of the main constraints of the beach nourishments is the limited time, as the intervention should be executed after the winter season and before the start of the touristic seasons. In this specific case, the contractual time was of 90 days.

The work has been executed using a Trailing Suction Hopper Dredger (TSHD Bonny River).

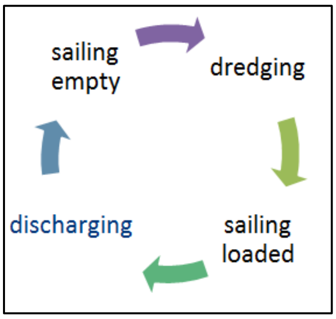

Figure 4 Dredging cycle.

To maximize the load of the dredger and minimize the number of dredging cycles (sailing to the borrow area, load - dredging, sailing to the nourishment site, discharge - pumping ashore Figure 4), for each a duration of 8 hours was needed, the coupling point of the dredger was located to a bathy of -10 m.b.s.l.. In this way an average production of 10.000 m^3 per cycle was reached, with a production of 30.000 m^3 of pumped sand per day. To reach the coupling point, two lines of pipes were used in parallel.
Depending on the bathy of each location, and from the extension of the site to be nourished, the pipelines have the following features:

- Lido Di Dante, Milano Marittima, Cesenatico, Igea Marina:
    - Sinkerlines: DIA 1000 mm; length: 4120 m
    - Floating line: 216 m
    - Land lines: DIA 1000 mm; length: 816 m
- Riccione, Misano Adriatico:
    - Sinkerlines: DIA 900 mm; length: 1500 m
    - Floating line: 156 m
    - Land lines: DIA 900 mm; length: 1128 m

The use of two different pipelines on parallel also allows to avoid idling time of the dredger during the shifting of the pipeline from a location to another.

Figure 5 Dredger Bonny River during execution of Emilia Romagna beach nourishment.

In order to optimize the work, minimize the sand losses was one of the key factors in a beach nourishment management. This aspect is so important not only to limit the time of the intervention, but also because of the non- renewal of the relict sand deposits, and therefore to reduce the overall project impact in the environment.
Generally, the design phase is very important to define the stability of the beach profiles, based on the granulometry and the general sea state of the area.
However, the short-term conditions occurring during the operations can have large impact on the stability of the beach profile and its morphological evolution.

Therefore, during the Emilia Romagna beach nourishment project in 2022, a short-term prediction model was implemented to optimize dredging activities and nourishment, aiming to provide, basing on the wave forecasts close to the intervention areas, the prediction of the morphological evolution of the beach profile after the nourishment.

MATERIALS AND METHODS

The Mediterranean Sea Waves Analysis and Forecast system (Korres, et al., 2021) by CMEMS was used to provide wave forecasts offshore the intervention area. The dataset, coming from WAM Cycle 4.6.2 wave model, is composed by hourly wave parameters at 1/24º horizontal resolution covering the Mediterranean Sea and provides up to 10 days of wave forecasts.

Figure 7 shows the location of 2 grid nodes, chosen to extract wave forecast during the nourishment operations; one northern N1, offshore Ravenna, and the other one southern N2, offshore Rimini.

The extracted offshore sea conditions were propagated towards shore through spectral model and the wave conditions extracted at – 4 m of depth forced the cross-shore model at each location of the nourishment in order to predict the modification of the beach profile. This modeling chain was implemented by means of the well-known MIKE21 suite (developed by ©DHI Group).

In order to implement numerical models, it was necessary to collect:

- bathymetric data before the nourishment intervention, from survey made by Emilia Romagna Region in 2018 (*ante operam*);
- the design profile of the transect due to the nourishment activities, provided by SIDRA;
- final profile after the nourishment (*post operam*).

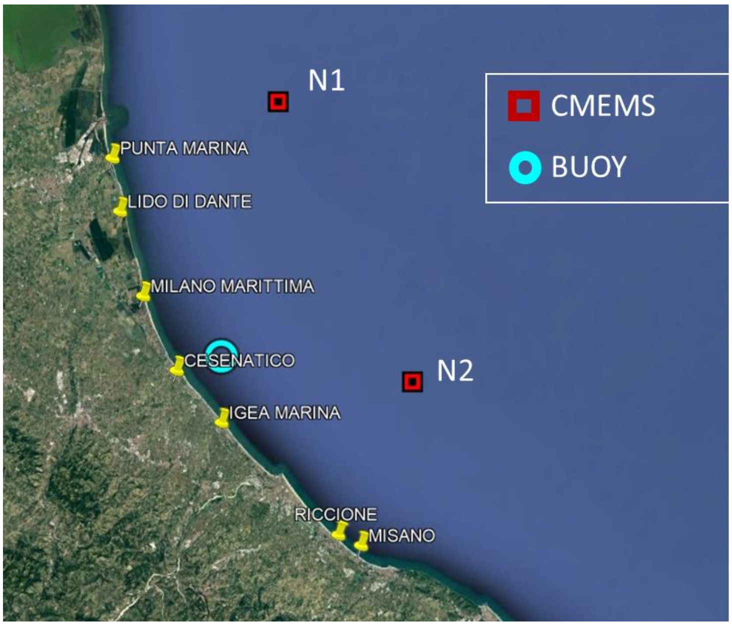

Figure 6 Location of the two CMEMS nodes where forecast wave data were extracted during the nourishment project (sites are also reported on the map, together with the position of the Nausicaa buoy).

OPERATIVE BULLETIN DURING THE PROJECT - EXAMPLE OF LIDO DI DANTE BEACH

During the execution of the project, before the starting of the beach nourishment in a specific location, the results of the model were available to the site. The wave condition forecast extrapolated form the CMEMS were than propagated until the -4 m.a.s.l. and specifics operative bulletins were made for each location before the start of the operations, considering the forecast in the 5 days after the operations start.

For each bulletin this information was then available:

- Prevision of wave height at -4 m.a.s.l. in the 5 days after the start of the operations (Figure 7);
- Wave height along the transept (considering the morphology of the transept before the nourishment) in the 5 days after the start of the operations (Figure 7);

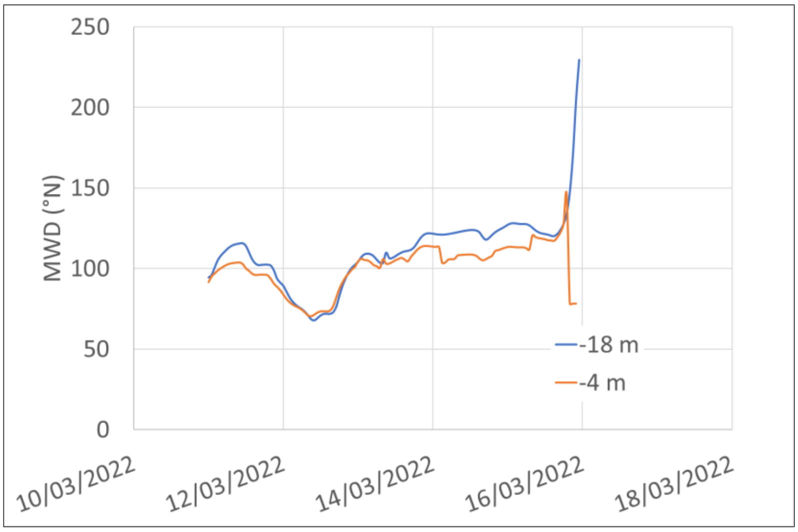

Figure 7 Wave height propagation at -4 m asl. (Site of Lido di Dante).

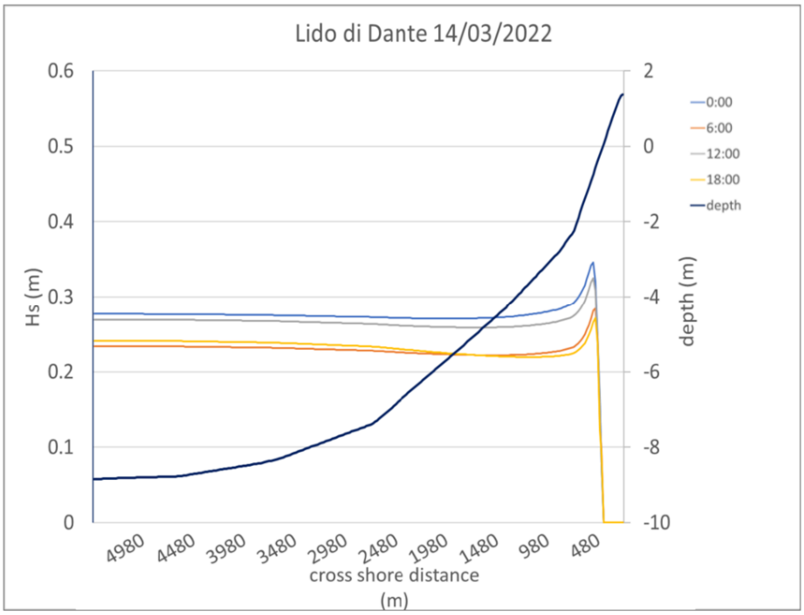

Figure 8 Wave propagation along the transept (Site of Lido di Dante).

The propagated wave forecast has been than used to implement a cross-shore morphodynamical transport model and simulate the shape of the shore in the short term so to verify the respondence with the design criteria within 5 days after the nourishment intervention (Figure 9).

The bathymetric data of the transept before the nourishment intervention has been obtained by the survey made by Emilia Romagna Region in 2018, the profile of the transept due to the nourishment activities has been set using the technical specifications defined by the design (beach amplitude increase, elevation of the connection point with the existent beach, below water design slope).

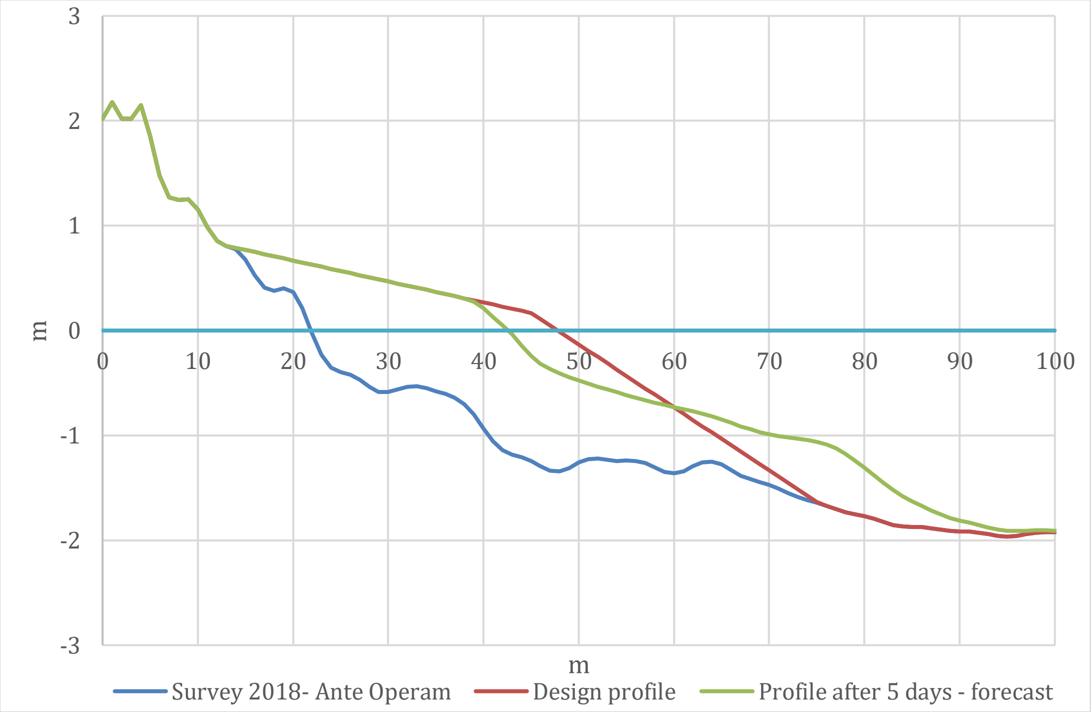

Figure 9 Modelling of the beach profile 5 days after the nourishment (site of Lido di Dante).

RESULTS

Operational Applications

The information received at the site from the operational bulletin were used to redefine some of the operational boundary conditions.

At first, the cross-shore model was used to verify the correct setup of the reclamation, in terms of location and height of the reclamation bund.

One of the main causes of losses in a beach nourishment in in fact the failure of the reclamation bunds with consequent loss of the material outside form the design profile.

The example of Lido di Dante site cross shore model prevision shows a quite unstable profile in the days after the intervention. From the results analysis was then proposed to revise the design above water and under water so to have a more stable profile in the short and midterm maintaining the volume balance per each cross sections already defined in the design.

The revised design obtained from the model results analysis, was then used as *operational design* during the beach nourishment executions.

The results of the cross-shore modelling were then used in all the locations, prior to the start of the works in each location, to verify the stability of the original design.

Out-surveys performed the days after the nourishments helped to evaluate the truthfulness and consistency of the modelling results, as well as the stability of the profile in the short term.

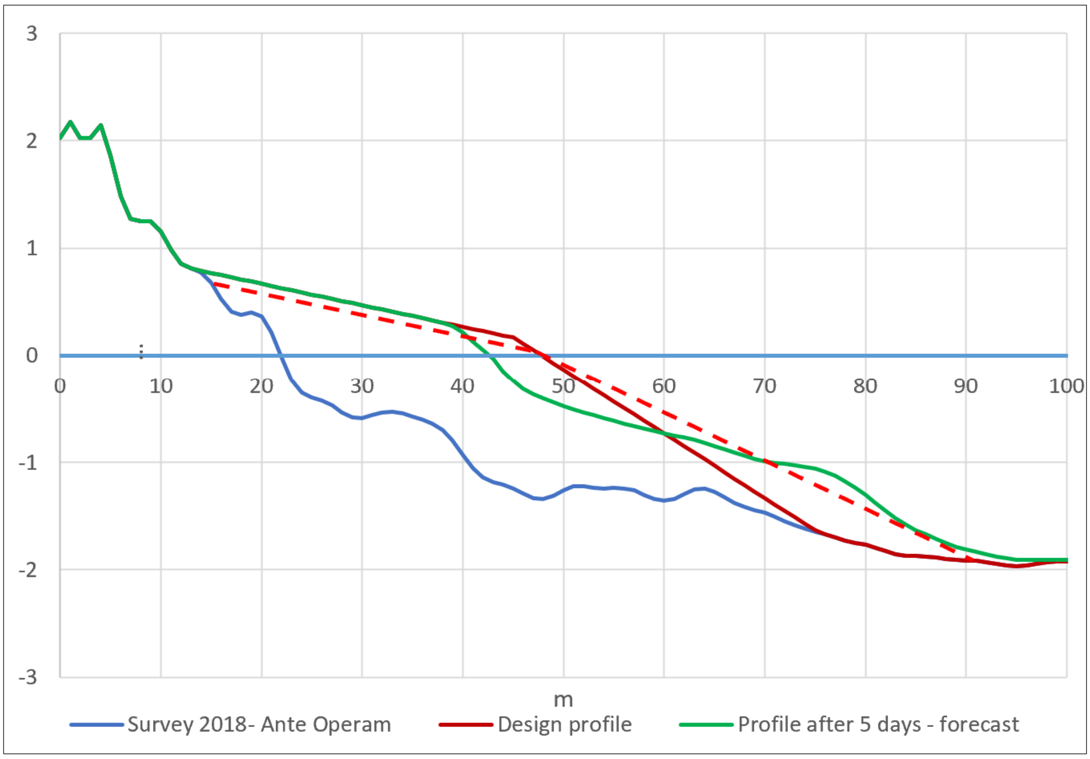

Figure 10 New design overlapped on the model results (dashed line)

Sea State during the project and mid term cross-shore modeling

In the reference period, the historical series between March and July 2022 of the wave data obtained from CMEMS was analyzed to identify the most significant tidal waves responsible for the movement of sand in the transverse direction to the beach.

At each site, the dredging and pumping ashore activities were carried out during low or rough sea conditions, but the rough sea conditions listed above could immediately move the sand from the shore as the works progressed according to the timeline as shown in Figure 11.

Also the data registered from the buoy Nausicaa (offshore Cesenatco site) were used as reference for the midterm modelling.

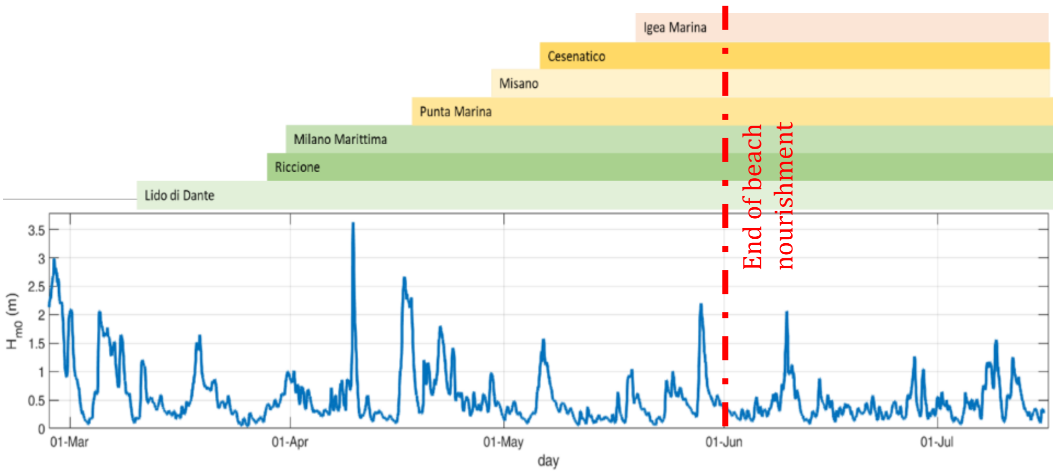

Figure 11 Wave heights during execution period.

The hindcast wave data, propagated to the inshore were than used to evaluate the beach profile in the mid term after the nourishment.
As shown in the Figure 11, for the Lido di Dante site, the hindcast covered a period of 3 months after the nourishment.
The reference profile used for the sediment transport model was the beach profile proceeds by the out-survey carried the days immediately after the operations.

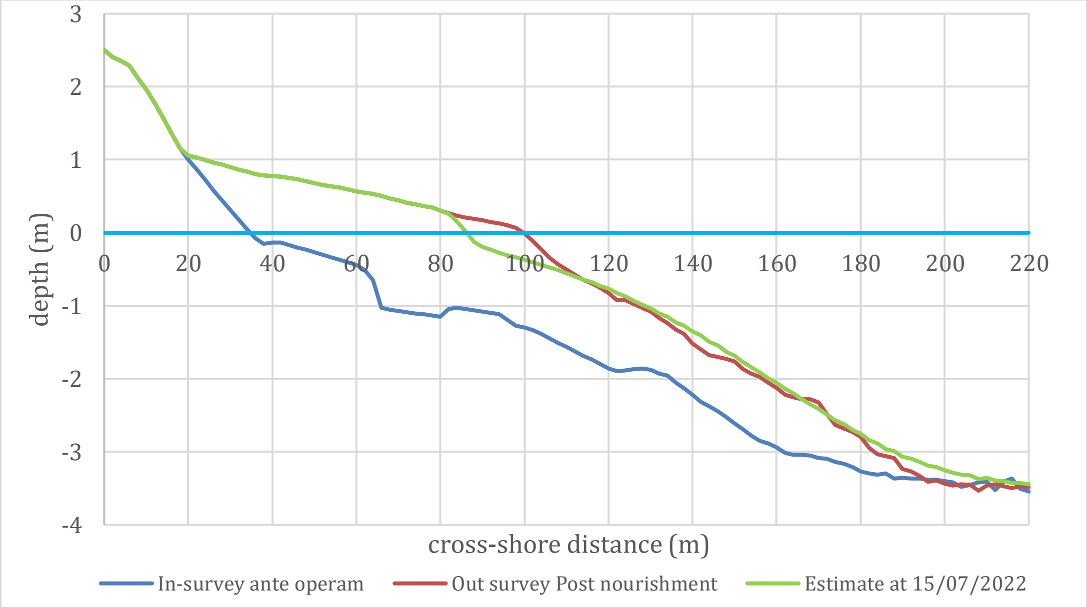

Figure 12 Modelling of the beach profile 3 months after the nourishment (Site of Lido di Dante)

Comparing the results shown in Figure 9 with the once in Figure 12 is possible to see how the profile in the mid term is much more stable compared with the original design profile in the short term.

CONCLUSIONS

The present paper describes the operational use of forecast waves for sediment transport prediction during a beach nourishment project carried in Emilia Romagna (IT) in 2022.
To optimize dredging activities and nourishment, a short-term prediction model was used to provide, basing on the wave forecasts in the vicinity of the intervention area and by means of modelling, the prediction of the morphological evolution of the beach profile in the short term after the nourishment.
Before of the start of the operation, it was provided the simulation of the sea state at the nourishment location and the evolution of the beach profile in the days after the interventions.
The analysis of the results allowed to change operational parameters as the location and level of the reclamation bunds and to optimize the design, leading to a more stable beach profile in the short term.
The obtained results from using this combined methodology during the operations allowed to optimize In this way, the sand losses outside the design cross sections and the failure of the reclamation bunds were limited in the nourishment process.
The stability of the profile in the short term also allowed to limit the sediment dispersion into sea, with a positive impact on environment and on the time needed to finish the works.
In general, this proposed approach was useful to limit the overall impact of the project on the surrounding environment comparing with a beach nourishment with losses issues.
On the base of the achieved results, this combination of numerical modelling during the operational phase is considered a very useful tool to optimize dredging activities in a beach nourishment and the described methods and strategy can be implemented in engineering operations in coastal areas.

ACKNOWLEDGMENTS

Agenzia per la Sicurezza Territoriale e Protezione Civile- Regione Emilia-Romagna who financed the project and made available for this study design data and results.
Project team of DEME involved in the beach nourishment project with particular regards to the Survey department for the data processing that allowed the verify of the model results for each site.

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