MODELLING THE CATASTROPHIC MAY 2023 FLOODS ALONG THE EMILIA ROMAGNA LITTORAL WITH THE COASTS GIS-BASED TOOL

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Planning eco-compatible, cost-efficient management strategies ensuring the continuity-of-daily-life and promoting adaptation to climate change can be efficiently supported by GIS-based tools, that allow risk assessment for a number of scenarios and for a variety of clusters of solutions. In this paper the recent flood events along the Emilia Romagna littoral are modeled with the COASTS GIS-based decision support system including different hydraulic models, specifically X-Beach and Mike21. The flooding model results are compared with the available inundation limits recorded after the flood. The hydraulic load considered the combination of rainfall, storm surge, waves and river discharges in the specific area of Cesenatico, a seaside town close to Cesena in northern part of Italy. The inundation modelling restitutes cautious inundation area and therefore the economic damage is also overestimated with respect to the registered damage compensation.

Keywords: coastal flood; coastal risk; decision support tools; numerical modelling; Emilia Romagna littoral

INTRODUCTION

In recent years coastal risk assessment and management have been supported by a range of newly developed GIS- based Decision Support Systems (DSS) that allow to perform scenarios analysis, integrating climate, social, economic and environmental data and accounting for a range of mitigation measures. Some of these are commercial solutions while other are research tools and then not available to managers and technicians. Among others:

- The Community Adaptation Viewer (Lieske, 2015) elicits user awareness of the flood exposure level, damage potential and risk reduction by selected adaptation measures.
- The DSS by the FP7 RISC-KIT project (Bogaard et al., 2016) consists of an Early Warning tool and a Bayesian network for impact assessment at regional scale.
- DESYCO (Torresan et al., 2016) provides exposure, susceptibility, risk and damage maps due to coastal erosion and flooding, saltwater intrusion, water quality and ecosystem deterioration.
- COMASO (Coelho et al., 2020) is essentially a guide for decision makers among a group of tools that can be applied in standalone mode or in a sequential order to assess coastal erosion and design management solutions (beach nourishment, coastal structures).
- The Coastal Resilience DSS (https://coastalresilience.org/tools/) is a visualization platform where ecological, social, and economic information can be viewed alongside sea level rise and storm surge scenarios in specific geographies. In addition, a modular, configurable plugin architecture allows specific geographies to have apps designed specifically for geo-processing and display, accordingly to the needs of stakeholders, policies and planning processes.
- Saferplaces DSS (https://saferplaces.co/) integrates Earth Observation satellite data and allows to assess pluvial, fluvial and coastal hazard in combination with mitigation measures.
- The COASTS DSS - that is the topic of this contribution- origins from the FP 7 THESEUS project (Zanuttigh et al., 2014). It allows nearly real time modelling of vulnerability and risk scenarios under river and coastal flood, coastal erosion and rainfalls. It introduces mitigation and adaptation plans, delivering risk maps and quantitative indicators useful for managers and policy makers. The COASTS-DSS can either run a simplified model based on shallow water equations, resulting in a few minutes of computation, or it can now be run by uploading results of more detailed numerical models, such as X-Beach and Mike 21.

This paper presents the application of the COASTS DSS to a case study along the Northern Adriatic coast, in the Med Sea, and compares the surveyed inundation line and the compensation damages with the results of the hydraulic and economic models. First an overview of the tool is given. Then, the case study is describes considering the environmental conditions, the more significant storms and the local littoral management. Finally details about the hydraulic and economic models are given with the main outcomes.

THE COASTS DSS

The primary objective of the COASTS Decision Support System (DSS) is to provide an integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding, which address technical, social, economic and environmental aspects. The DSS supports decision-making in coastal management in order to resolve ambiguity regarding the choice of the

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combination of intervention measures from an available portfolio. It is an "Interactive" tool so that users can compare the results of different combination of scenarios and while testing the scenarios be trained to a fully interdisciplinary risk assessment in the area and to the selection of the sustainable solution for risk mitigation and/or adaptation. End-users should be primarily coastal managers with an intermediate level that need to make sound decisions regarding spatial planning and coastal protection.

The software is based on high spatial resolution information on wave climate, habitats, society and mitigation options that vary depending on the site. The DSS input database for each site has to include the Digital Terrain model – as detailed as possible; hydraulic structures and infrastructures position and geometry; map of land-use including critical facilities; list and/or map of geo-referenced significant social and economic parameters, such as: age, gender, if inhabitant is employed or unemployed, the occupation depending upon whether skilled or unskilled, sick population, etc; geo-referenced maps of habitat types and species including: rare species, rare habitats, commercially important marine habitat, habitat relevant for coastal protection.

The steps of running the DSS are represented in Figure 1. Each step is explained in the following.

The first step consists of the selection of the scenario:

- Climate scenarios, including wave height, storm surge, sea level rise, river discharge, rainfall rate, event duration.
- Erosion scenario, that can be roughly calculated through a 1-line model for unprotected wide beaches or it can be represented by uploading a specific shoreline.
- Economic and social scenarios, essentially based on expected changes or trends of the population and on the gross domestic product.
- Environmental scenarios, limitedly for now to subsidence.
- Erosion scenario. Based on the selected significant wave height and sea level the shoreline position is estimated in time, according to a modified and adapted method from Miller and Dean (2004). A limitation is that the presence of long-shore interruptions of sediment transport, such as jetties, marinas and groynes, is not accounted for. However, the user has also the possibility to upload or draw a new shoreline position based on long-term time series and/or his/her expert judgment.

The second step consists of the selection of the mitigation options, including:

- Engineering mitigations, such as barriers, floating breakwaters, sea walls, etc… that can be drawn by the user or uploaded through a shapefile.
- Ecologically based mitigations, such as management or construction of dunes, reinforcement of salt-marshes, creation of biogenic reefs; these mitigations can be represented as a change of the habitat map and where applicable also a change of the bottom elevation.
- Economic and social mitigations such as evacuation plans, land use change (for instance managed realignment), insurance premium; the user can interact by modifying the insurance premium value, the percentage of evacuated people or the destination of a given area.

The third step consists of the hydraulic modelling. The user can decide to run the simplified model included in the DSS by default, which is based on shallow water equations, or to upload the results of a more accurate model, such as Mike 21 by DHI or X-Beach among the more popular ones. The results can be uploaded as shapefiles of flood depth and velocity.

The fourth step consists in the selection of the impacts to be estimated. Economic, social and ecological data are combined with the results of the hydraulic model (flood depth, duration, velocity) to produce vulnerability maps through appropriate "damage" functions (Zanuttigh et al., 2014).

The fifth and final step is the Risk Assessment, which integrates the engineering, social, economic and environmental impacts into the spatial distribution of a quali-quantitative risk indicator. The user can adopt relative weights for each impact, based on Kodikara et al. (2010), or can decide for equal weights.

As well as other more accurate modelling chains, this DSS cannot provide the user with an indication of uncertainty of the results of each scenario. This because of the uncertainty related to the geographic, social, economic, environmental, hydraulic input data; to the numerical model and the calibration parameter; to the combination of strategies; and to the non-linear interactions associated to these uncertainties. However, the relatively fast running time allows the user to examine many different scenarios and to perform a sensitivity analysis of the results, i.e. a comparison of the results of different scenarios considering that all the results are affected by the same simplifying assumptions and uncertainties.

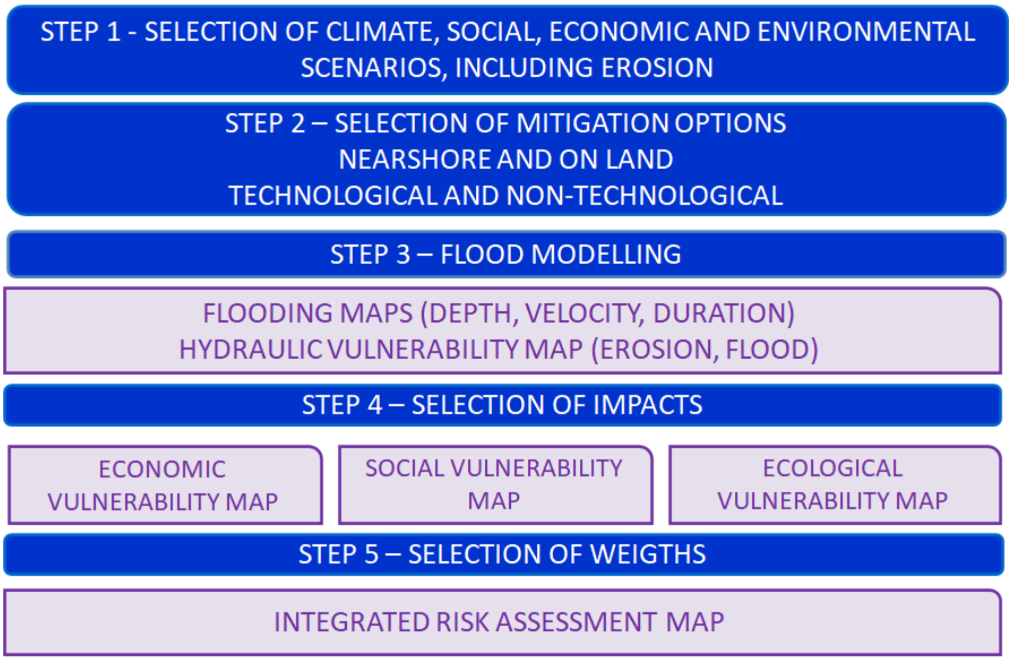


Figure 1 The steps of COASTS DSS.

A clear limitation of the COASTS DSS is that risk perception is not represented and therefore social resilience and its effects in terms of preparedness and changes of cohesion, livelihoods and opportunities is also not represented. This may affect the effectiveness of social adaptation measures such as evacuation plans and the social impact of different clusters of solutions.

Since the users get the results for each computed scenario, they may achieve misleading decision if based on a single DSS run only. It is therefore important to warn the user that the best methodological compromise is running multiple storm scenarios and by post-processing the results of these scenarios to get the sources-consequences function. An alternative solution is to define few relevant parameters/indicators and compare their values for different scenarios. In the COASTS DSS, according to Zanuttigh et al., (2014b), these parameters include for instance: the percentage of the flooded area with respect to the total area under investigation; the percentage of the flooded area characterized by flood depth greater than 0.5 m with respect to the total area; the percentage of beach retreat; the percentage of the flooded area characterized by land value losses greater than or equal to 30% of the total value loss.

THE CASE STUDY

Overview of the Regional territory

The Emilia Romagna littoral is located in the North East of Italy and comprises 130 km of low and sandy coast, most of which are strongly urbanized. The impact of this site for the Italian economy can be summarised with a few figures relative to tourism activities: 41 Mperson/day in the period May-September, 3’384 hotels, 154’000 employees, and a gross income per year of 9.8 billion €. A decennial coastal plan was recently published addressing the problem of integrated coastal zone management (Preti, 2009). The Emilia Romagna beaches face the Northern Adriatic Sea, a relatively shallow epi-continental shelf with low tidal amplitude. A general erosive tendency is mainly caused by the reduced sediment transport rates of the rivers and by the increased anthropogenic subsidence. Subsidence, eustatism and erosion of dunes pose a serious threat for coastal flooding.

The two recent major storms

In 2023 the Emilia Romagna region was hit by two events, the first between May 2 and 3, and the second between May 15 and 17 on a still saturated land. Therefore, the second one was the most severe, with an average of 200 mm of rain falling across the region in a 36-hour period, and some areas recording over 500 mm. There were 15 fatalities, over 36,000 people evacuated, at least 376 landslides, and 714 closed roads (ERCC, 2023). The regional government has provided a provisional estimate of €5 billion in economic damage, but this figure is expected to change as the full extent of the disaster materializes.

Although Italy is a flood-prone country and regions like Emilia-Romagna have high exposed value, the insurance penetration is lower than that of other developed European countries (ANIA, 2022). Specifically, non-life insurance penetration in Italy was 1.9% of GDP in 2021 (the closer rate being 2.3% in Germany and the highest rate being in The Netherlands, i.e. nearly three times higher than in Italy).

Academic research indicates that flood risk in the Po Valley is changing due to two main factors. First, climate change is resulting in the intensification of extreme hydrological events due to a change in the atmospheric dynamics in the Mediterranean area (Rousi et al., 2021). Second, there has been an increase in the number of people exposed to flooding due to land-use and land-cover modifications (Persiano et al, 2020). During flood events, the man-made drainage network is increasingly overloaded due to the significant soil sealing from agricultural to urban and due to heavily modified water body with insufficient levee in respect to the flow rates generated by runoff. At the same time, flooding has caused more significant damages due to the increase in exposure values (Pistocchi et al., 2015).

Along the coast, the storm of May 2023 (Figure 2) was characterized by a peak significant wave height H_s=3.23 m and two peak sea water levels z_s=0.89 m, the first one being in phase with the peak H_s. Both peak values of H_s and z_s correspond to a return period Tr=1 year and the overall impact on the coastal area was thus limited especially if compared with the tremendous impact in the inland areas close to rivers. Details about threshold values and morphological impacts on the Emilia Romagna littoral can be found in Perini et al. (2011) and Armaroli et al. (2012).

The storm of May 2023 along the coast was therefore also not comparable with the storm of February 2015, which can be considered the most severe storm recorded in the Northern Adriatic Sea in the recent history. This storm (in Figure 3) was characterized by extremely high values of both peak sea level (z_s up to 1.20 m) and of peak wave height (H_s up to 4.66 m), corresponding to a return period Tr=100 and 10 years respectively. The two higher sea levels were contemporary with the two higher peak wave heights. Moreover, the duration of the high values of both z_s (>1 m) and H_s (>3.5 m) was also exceptional (around 14 hours).

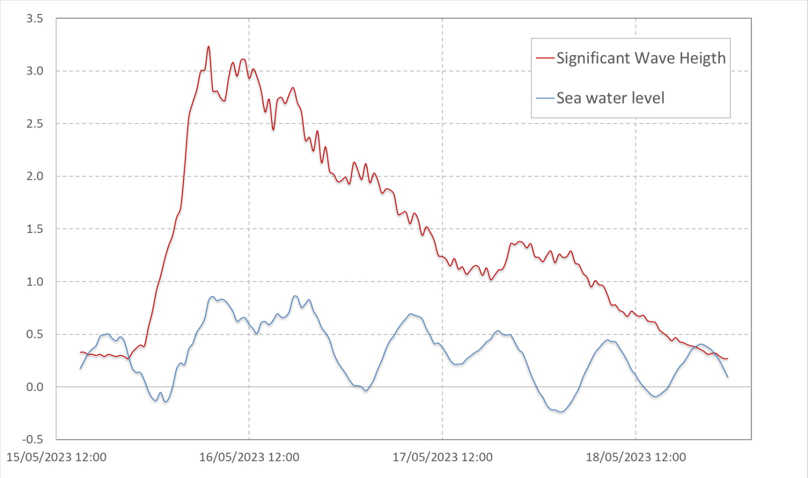


Figure 2. May 2023 storm: sea water level and significant wave height.

The town of Cesenatico

Cesenatico municipality is included in the province of Forlì-Cesena. It is famous for its marina and is a well-known touristic resort with a sandy beach rich in bathing facilities. The coastline is approximately 7 km long and is divided by the harbour jetties into a Northern and a Southern area. Details about the littoral and the defences in this area can be found in Preti et al. (2009) and Martinelli et al. (2013).

Cesenatico harbour jetties are placed at end of a continuous line of defence structures that starts several km Southward. The building of emerged barriers started in the 60's, after the construction of the long breakwater protecting the Port of Rimini, that interfered with the North-directed sediment transport.

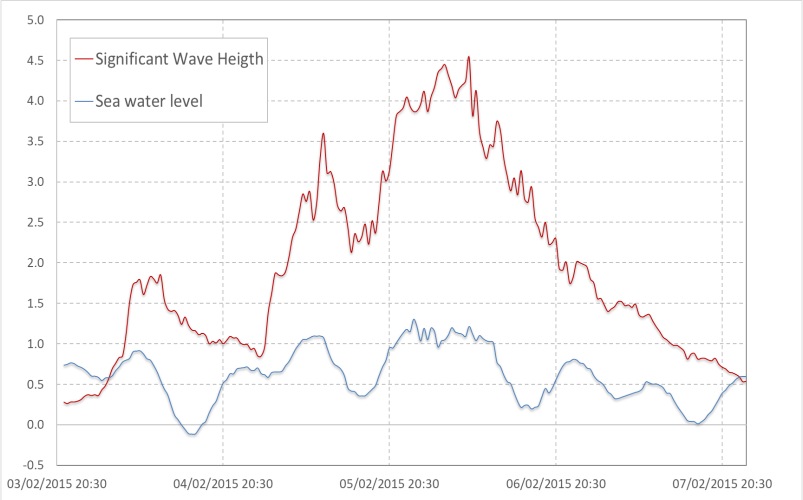


Figure 3. February 2015 storm: sea water level and significant wave height.

As the erosion progressed toward North, the beaches were protected with hard structures, that in turn shifted the erosive trend downdrift. Such vicious circle interested the Southern beach of Cesenatico in 1974 but did not bypass the port. To face the beach erosive tendency, the following structures were first built:

- Cesenatico South: emerged barriers in 1974.
- Cesenatico North: three small groynes in the 70's; in 1978 Longard tubes were placed along the shoreline but were damaged by the sea and removed after a few years; in 1983 a nourishment (150'000 m3) protected by a geo-synthetic submerged barrier was carried out.

The area suffered also for anthropogenic subsidence since the 70's due to extraction of water for industrial and agricultural use. In 1982, extractions were forbidden and the lowering trend slowly returned similar to the natural subsidence. Subsidence rate however reached dramatic values, up to 1.2 m in the period 1950-2005, with consequent flooding and erosive problems.

Due to the increased frequency of the flood events through the beach and the canal harbour intake, these defence works were carried out:

- Center of Cesenatico: defence of the area immediately to the South of the Jetty with emerged barriers, crest level 1.5 m a.s.l. (1997).
- Cesenatico North: Construction of a submerged barrier 0.8 km long, 12 m wide, 250 m distant from the shoreline virtually replaced the geosynthetic barrier. Nourishment with 160'000 m3 of sand. Removal of a 70 m long groyne placed 400 m Northward of the jetty (2003-2005).

The following specific defence to high water events was also constructed (2005):

- Construction of a sea gate, "Porte Vinciane", 2.0 m high a.s.l., closing the canal harbour for water level exceeding 0.9 m a.s.l.; to face sedimentation at the entrance of the canal harbour, dredging operations have to be performed usually twice per year or exceptionally after intense storms.
- Set-up of a pumping system in connection with "Porte Vinciane", whose operating capacity of 18 m^3/s is much greater than what is necessary to drain an extreme rain event; in case of combined flood and sea storm with closure of the sea gate, it is assumed that the plant can still drain into the sea up to 8 m^3/s, whereas the rest has to be discharged by Canale Tagliata.
- Widening of Canale Tagliata (new section 20 m wide, slopes 1:2, height of river walls 3 m a.s.l) to assure the outflow up to the reference discharge of 90 m^3/s, based on the indication of the "Bacini Romagnoli" Authority.
- Set-up of a sewer-drain by-pass system of the railway and streets crossing Canale Tagliata;
- Increasing the potential (from 10 to 17 m^3/s) of the pumping system of the Canale Tagliata; the plant collects the water drained from the low-lying areas of Cervia and Cesenatico;
- Construction of a series (4) expansion basins.
- Control and upgrade (in terms of section and height) of channel banks and streets crossing the channels.

To protect the low-lying urban areas, the Municipality built a soil dike in 2005, integrated into the urban use of the back beach, 20 m wide, 1 m high, 1.4 km long, starting from the southern jetty (extending Southward).

Figure 4. View of Cesenatico i) at the bottom: satellite view with indication of the Northern Area, Southern area and Valverde; ii) top left: view of the Tagliata Channel and of the Northern area; iii) top center: view of the Central area, with the jetties, the marina and the low crested barrier; iv) view of the Southern beach protected by emerged barriers.

The impact of the February 2015 storm in Cesenatico

The inspections carried out on the entire coast, following the storm, highlighted a very serious beach retreat, which caused the destruction of 90% of the "winter dunes" erected to protect the bathing facilities and the built-up area behind the beach, with consequent flooding of significantly anthropized areas. On a large part of the coastal strip, the wind caused flooding and (with the clogging of the sewers) the increase of the water level in the long-shore street behind the beach, with consequent flooding of the basements and ground floors of the affected areas. Significant quantities of sandy material were transported inland.

Strong winds and ground liquefaction led to the collapse of a number of trees in all the areas affected by the phenomena. The violent storms devastated the coastline, causing the disappearance of the beach (both emerged and submerged) for an extension of about 1km. The ingression of water and the movement of sandy material, in addition to strong gusts of wind, caused damage to the public power line. Numerous road sections were closed to traffic. During the emergency phase it was advised not to go out and it was necessary to evacuate 3 schools.

In the inland areas, the considerable and prolonged rains (together with winds that reached 90 km/h) caused the swollen waterways, with consequent damage to productive activities and civil homes.

After the event, the following damage estimates were made in 2015 for a total of around 32 M€:

- Around 100 beach establishments for around 5 M€.
- Around 350 production structures for around 17.5 M€.
- Around 600 private buildings for around 3 M€.
- As regards the public part, a damage of approximately 7 M€ for dune reconstruction interventions, street cleaning, maintenance of roads and public green areas, cleaning and restoration of sewers, public lighting, beach nourishment, maintenance and operation of the sea gates, emergency management.

Overall, 138 damages were reported in 2016 for a total of 5.2 M€. Specifically, 78 reports came from private people for a total of 0.9 M€.

The ascertained damages in Cesenatico (5 km coastal stretch) in 2018 summed up to 1.2 M€. 25 economic activities were awarded a compensation for a total of 0.8 M€.

Figure 5. View of the flood of February 2015 in Cesenatico. From Perini et al. (2015).

MODELLING COASTAL VULNERABILITY

Modelling the flood process

The COASTS DSS includes both chances to use a simplified model, based on bath-tub inundation of the DTM pixels, and to upload the results of an accurate hydraulic 2DH model. The simplified model is currently work in progress, since it is going to be substituted by a simplified model based on shallow water equations. This analysis was therefore carried out using the maps of flood depths and velocities derived by 2DH numerical models, and specifically Mike21 or X-Beach.

The XBeach numerical model was applied in two-dimensional mode (2DH) to simulate the flood from offshore to inland to effectively capture wave-structure interactions and beach run-up dynamics. The following parameters were adopted in the model: a wave friction coefficient set at 0.2 to accurately represent wave energy dissipation; a bed friction factor (Chezy coefficient) calibrated at 30 $m^{1/2}/s$, which, despite being atypical for sandy seabeds, aligned with observations, reducing simulated erosion and improving the energy balance at the wave-seabed interface (Unguendoli et al., 2017); and a breaker parameter in the Roelvink formulation set to 0.42, calibrated for local sandy beaches (Harley et al., 2016).

Boundary conditions were carefully defined to represent the local coastal environment. Offshore wave forcing was described using the JONSWAP spectrum, ensuring an accurate representation of wave energy at the offshore boundary (Almeida et al., 2012). The bathymetry extended to a depth of -8 m to guarantee appropriate wave propagation in the numerical model (Roelvink et al., 2009). The lateral and inland boundaries were set as closed, avoiding full reflection through an extension of the bathymetry by approximately 800–1000 m along these boundaries. The river discharge during the event was included and accounted for at sections corresponding to the Tagliata channel and the harbour canal, located along the inland boundary of the computational domain.

The computational domain was designed to encompass critical coastal areas and offshore zones. The curvilinear grid, generated using Delft3D, featured variable resolution to optimize spatial detail and computational efficiency: approximately 1 m for the polygons representing levees and structures, 2 m for channels and marina sections, 5 m for urban areas, 10 m for the emerged beach, 20 m for rural areas, and 40 m for offshore areas.

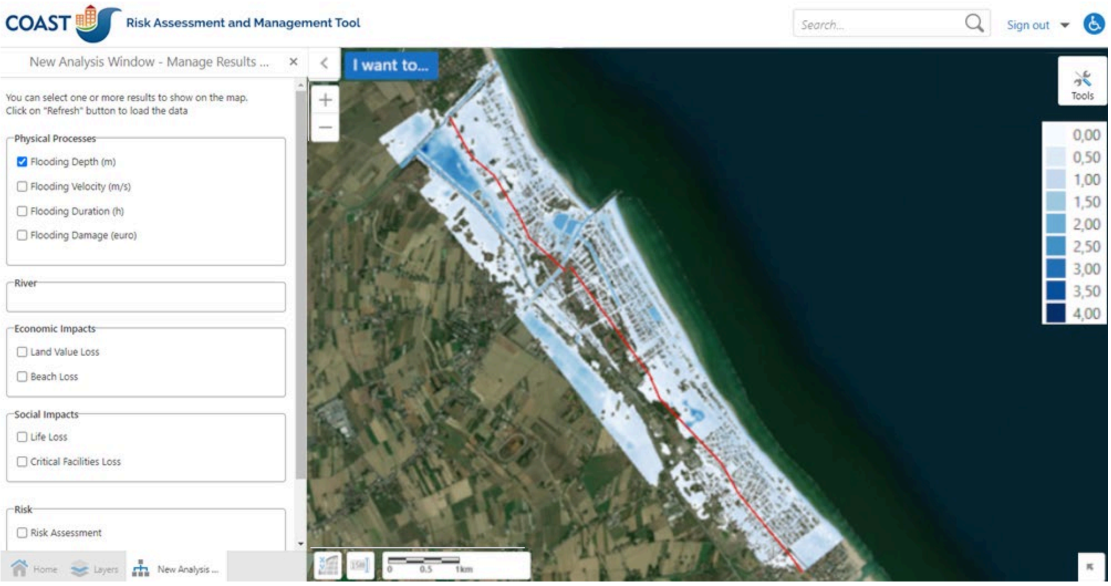
As for Mike 21, an appropriate approach was needed to overcome the model limitations in the representation of structure and beach run-up (Martinelli, et al., 2010). Waves were transferred from offshore till the shore, including wave reduction due to structures (Van der Meer et al., 2005), by means of an analytical ad hoc Matlab procedure. The "off-shore" boundary of the modelling domain was moved to the shoreline and the "shoreline" boundary condition considers a varying level in time given by the sum of storm surge, wave set-up and wave run-up on the beach. Wave run-up was evaluated according to Stockdon et al. (2006). Flooding propagation was then simulated as a dam-break: the potential wave energy represented by wave run-up provides a reasonable velocity for the running-up wave.

Coastal flooding simulation was carried out with MIKE 21 Hydrodynamic module (HD), Release 2024, Flexible Mesh (FM). In the HD module, the following choices were made: low-order time and space integration scheme; constant Manning coefficient roughness, equal to 50 $m^{1/3}/s$; Smagorinsky formulation for eddy viscosity. Boundary conditions were:

- At the shoreline, as discussed above, variable water level in time coupling tide, storm surge and wave run-up.
- Closed boundaries elsewhere (inland and lateral boundaries). To avoid full reflection at closed boundaries, the bathymetry for simulations was appropriately extended of about 800 m along these boundaries.
- The river discharge was imposed at the inlet of the Tagliata channel and of the harbour canal, along the inland boundary of the numerical domain.

Different resolution was adopted for constructing the mesh: from about 1 m for the triangle side representing levees and structures, to 2 m for channel sections and the marina, 4 m for the urban areas, 10 m for the emerged beach, 20 m for the rural areas.

The results are shown in terms of flood depths for Mike21 only in Fig. 6, since the results obtained with X-Beach were pretty similar, proving that the simplified shoreline boundary condition imposed in Mike21 simulations was sufficiently accurate. The comparison with the inundation line obtained by surveys the day after the flood shows that the flooded area is overestimated by the numerical models. It should be noticed however that the surveyed inundation line may not coincide with the maximum inundation line derived from the model first of all because the survey took place the day after the flood, then because of water run-off over the land and inaccurate representation of land roughness.



You can select one or more results to show on the map.
Click on "Refresh" button to load the data

Physical Processes
☑ Flooding Depth (m)
☐ Flooding Velocity (m/s)
☐ Flooding Duration (h)
☐ Flooding Damage (euro)

River

Economic Impacts
☐ Land Value Loss
☐ Beach Loss

Social Impacts
☐ Life Loss
☐ Critical Facilities Loss

Risk
☐ Risk Assessment

Figure 6. Map of flood depths obtained by Mike21 modelling of the May 2023 storm in blue color scale and comparison with the surveyed flood extension the day after the storm.

Modelling the economic impact

The overall economic consequences (EC) of flood in terms of flood depth and flood duration are estimated by applying the following formula:

$$EC = v_{ij} \cdot b_j \cdot F_d + v_{ij} \cdot a_j \cdot \sqrt{F_y} \quad (1)$$

where v_{ij} are the values of land uses in euro/m^2/year from census statistic data; F_d is flood duration and F_y is flood depth; a_j are proportionality constants as functions of F_y that are normalised for each land use j at the maximum value of F_y in 2050 for a storm return period Tr=100 years, assuming different reference percentage of damage depending on the use (for instance, 50% damage for buildings/homes/hotels, 25%

damage for harbors); bj are proportionality constants as functions of F_d that express the expected period to restore economic activities as a factor of duration, depend on the land use (for instance, a value of 30 is set for hotels and of 20 for private services) and are normalized to annual incomes with the days/year. Note that flood velocity is assumed to be irrelevant.

In this case, as both the hydraulic models were run over a fixed bed and as the objective of the assessment is the comparison with the ascertained damages, the economic losses due to beach retreat are not considered.

The total damage obtained by Mike 21 and X-Beach is very close (being respectively 3.0 and 2.9 M€), as it could be expected due to the similar maps derived from the two models for flood depths and velocities. The computed damage overestimates the total ascertained damages of about 50%. The computed damage is due for 2/3 to the water lever and for 1/3 due to the flood duration. The flood duration component may be overestimated not only because of the overestimated flood depth but also for the inaccurate representation of soil permeability.

CONCLUSIONS

The COASTS GIS-based tool allows coastal stakeholders to rapidly assess local risk level, to identify mitigation and adaptation measures, to assess the related reduced impacts and ultimately to select the sustainable risk management strategy.

Still open challenges in risk assessment and specifically with such a tool are:

- The assessment of uncertainty related to different scenarios.
- The representation of resilience.
- The representation of the social risk component.
- The synthesis of hazard, vulnerability and risk maps by relevant indicators agreed among stakeholders.

In Cesenatico -as in most places along the Emilia Romagna region- the dominant flooding parameter is the storm surge level (when z_s>0.8 m), that becomes crucial when coupled with peak exceptional wave heights (in May 2023, Tr=100 years). The maintenance of the urban drainage system (sea gates opening/closure, by-pass and channel banks) and of beach width are essential for the safety of the urban areas. Challenges in ER coastal management include:

- Improvement of adaptation strategies.
- Modification of land use.
- Construction of new lamination basins.
- Improvement of maintenance.
- Integrated sediment stock management.
- Adequate maintenance of (irrigation & drainage) channels.
- Improvement of real time event management (through early warning, risk communication, use of temporary defence barriers).

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REFERENCES

Almeida, L.P., M.V. Vousdoukas, O. Ferreira, B.A. Rodrigues. 2012. Thresholds for storm impacts on an exposed sandy coastal area in southern Portugal, *Geomorphology*, 143-144, 3-12.

ANIA. 2022. Italian Insurance 2021-2022. https://www.ania.it/

Armaroli, C., P. Ciavola, L. Perini, L. Calabrese, S. Lorito, A. Valentini, M. Masina. 2012. Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy, *Geomorphology*, 143-144, 34-51. doi:10.1016/j.geomorph.2011.09.006.

Bogaard, T., S. De Kleermaeker1, W. Jäger, A. van Dongeren. 2016. Development of Generic Tools for Coastal Early Warning and Decision Support, *Proceedings FLOODrisk 2016–3rd European Conference on Flood Risk Management*. https:// doi.org/10.1051/e3sconf/20160718017.

Coelho, C., P. Narra, B. Marinho, M. Lima. 2020. Coastal Management Software to Support the Decision-Makers to Mitigate Coastal Erosion, *Journal of Marine Science and Engineering*, 8(1), 37. https://doi.org/10.3390/jmse8010037

ERCC. 2023. Emergency Response Coordination Centre – Maps. https://erccportal.jrc.ec.europa.eu/ECHO- Products/Maps#/maps/4501

Goda, Y. 2000. Random Seas and Design of Maritime Structures, *World Scientific*.

Harley, M.D., A. Valentini, C. Armaroli, L. Perini, L. Calabrese, P. Ciavola. 2016. Can an early-warning system help minimize the impacts of coastal storm? A case study of the 2012 Halloween storm northern Italy, *Natural Hazards and Earth System Sciences*, pp. 209-222.

Kodikara, P.N., B.J.C. Perera, M.D.U.P. Kularathna. 2010. Stakeholder preference elicitation and modeling in multi-criteria decision analysis – a case study on urban water supply, *European Journal of Operational Research* 206: 209-220.

Lieske, D. J. 2015. Coping with climate change: The role of spatial decision support tools in facilitating community adaptation, *Environmental Modelling and Software*, volume 68, pages 98-109.

Martinelli, L., B. Zanuttigh, S. Bagli. 2013. Modelling coastal risk at Cesenatico, Northern Adriatic Sea, Italy*, Proc. Coastal Structures 2011*, JPN, 5-9 Settembre 2011, vol. 1, 59-70, Takahashi S., Isobe M, Kobayashi N. and K. Shimosako eds, ISBN: 978-981-4412-20-9.

Martinelli, L., B. Zanuttigh, C. Corbau. 2010. Assessment of coastal flooding risk along the Emilia Romagna littoral, Italy, *Coastal Engineering*, doi:10.1016/j.coastaleng.2010.06.007.

Miller, J.K., R.G. Dean. 2004. A simple new shoreline change model, *Coastal Engineering*, 51, 531-556.

Perini, L., L. Calabrese, S. Lorito, P. Luciani. 2015. Il Rischio da mareggiata in Emilia-Romagna: l'evento del 5-6 Febbraio 2015. In italian. *Il Geologo*, 53, 8-17.

Perini, L., L. Calabrese, M. Deserti, A. Valentini, P. Ciavola, C. Armaroli. 2011. Le mareggiate e gli impatti sulla costa in Emilia-Romagna, 1946-2010, *I quaderni di Arpa*, pp. 141, Arpa Emilia-Romagna, Bologna, Isbn 88-87854-27-5.

Persiano, S., E. Ferri, G. Antolini, A. Domeneghetti, V. Pavan, A. Castallarin. 2020. Changes in seasonality and magnitude of sub-daily rainfall extremes in Emilia-Romagna (Italy) and potential influence on regional rainfall frequency estimation. *Journal of Hydrology*: *Regional Studies* 32, 100751.

Pistocchi, A., C. Calzolari, F. Malucelli, F. Ungaro. 2015. Soil sealing and flood risks in the plains of Emilia-Romagna, Italy. *Journal of Hydrology: Regional Studies 4*, 398–409

Prahl, B.F., M. Boettle, L. Costa, J.P. Kropp, D. Rybski. 2018. Damage and protection cost curves for coastal floods within the 600 largest European cities*, Scientific Data*, 5(1):180034.

Preti, M., N. De Nigris, M. Morelli, M. Monti, F. Bonsignore, M. Aguzzi. 2009. State of the Emilia-Romagna littoral at 2007 and ten-years management plan, *I quaderni dell'ARPA*. Bologna. In Italian, abstract in English.

Roelvink, D., A. Ad Reniers, A. van Dongeren, J. van Thiel de Vries, R. McCall, J. Lescinski. 2009. Modelling storm impacts on beaches, dunes and barrier islands, *Coastal Engineering* – 56, pp. 1133-1152.

Rousi, E., F. Selten, S. Rahmstorg, D. Coumou. 2021. Changes in North Atlantic Atmospheric Circulation in a Warmer Climate Favor Winter Flooding and Summer Drought over Europe, *Journal of Climate* 34 Issue 6.

Stockdon, H.F., R.A. Holman, P.A. Howd, A.H. Sallenger. 2006. Empirical parameterization of setup, swash, and runup, *Coastal Engineering*, 53(7), 573-588.

Torresan, S., A. Critto, J. Rizzi, A. Zabeo, E. Furlan, A. Marcomini. 2016. DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones, *Ocean & Coastal Management*, vol. 120, pp. 49-63 (ISSN 0964-5691).

Unguendoli, S., M. Aguzzi, N. De Nigris, M. Morelli, T. Paccagnella. 2017. Utilizzo del modello XBeach come strumento di analisi dell'erosione costiera in seguito a eventi di mareggiata, In italian, *Studi Costieri* 2017 – 26, pp. 91-106.

Van der Meer, J.W., R. Briganti, B. Zanuttigh, B. Wang. 2005. Wave transmission and reflection at low crested structures: design formulae, oblique wave attack and spectral change, *Coastal Engineering*, 52 (10-11), 915-929, Elsevier.

Zanuttigh, B., L. Martinelli, F. Bozzeda, M.A. Colangelo, L. Pietrantoni, F. Zagonari, G. Prati. 2014b. Chapter 7. Case studies worldwide. Section 7.6 Risk Assessment and Mitigation in a Low-lying Coastal Area: Cesenatico, Northern Italy. in *Coastal risk management in a changing climate*, Zanuttigh B., Nicholls R., Vanderlinden J. P. editori, 472-505. DOI: 10.1016/B978-0-12-397310-8.00007-5.

Zanuttigh, B., D. Simcic, S. Bagli, F. Bozzeda, L. Pietrantoni, F. Zagonari, S. Hoggart, R.J. Nicholls. 2014a. THESEUS decision support system for coastal risk management, *Coastal Engineering*, 87, 218-239, Elsevier.