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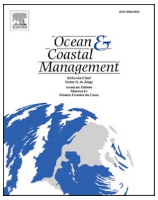

Compartmentalization strategy for coastal flooding mitigation with application to a Northern Adriatic site

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ABSTRACT

A method of compartmentalization has been developed to address the safety concerns of urban areas from coastal flooding, especially in situations where reinforcing the first line of defence (dunes, levees, etc.) is challenging due to, for instance, environmental limitations. Various compartmentalization options can be considered and evaluated in order to govern the flooding. Each option should be modelled with a suited numerical tool to better define the alternatives, determine the minimum height of the elements that bound the compartments and verify their effectiveness for the preliminary design, e.g. for the environmental screening stage. The methodology is demonstrated for a real case study, the flooding of Lido di Volano that occurred on November 22, 2022, using a simplified shallow water equations model designed for GPU computing to simulate large-scale flooding scenarios. Two compartmentalization schemes have been identified, both of which involve raising the existing road level. The maximum water levels in different zones of the study area are assessed as a function of crest height. These schemes have proven to be effective in protecting the urban settlement from flooding. Overall, the proposed method of compartmentalization, supported by a real case study analysis, offers a systematic approach to enhance the safety and the resilience of urban coastal areas. This type of solution capitalises on the experience of the local managers and technicians and may represent a shared solution among the coastal governance actors.

1. Introduction

As a result of the future impacts of climate change, the number of people at risk of coastal flooding is expected to increase significantly. According to the recent IPCC (2023) Sixth Assessment Report (AR6), the number of people exposed to 100-year coastal flooding events is expected to increase by up to 30% globally (57% in Europe) in 2040 compared to 2020 due to sea level rise and population changes. Therefore, there is a growing need for research into policies, interventions and mitigation measures for the management of marine inundation. From an engineering perspective, several measures can be taken to reduce the probability of flooding and/or mitigate its consequences (Ciampa et al., 2021; Zanuttigh, 2011). As pointed out by van Gent (2019) and Marini et al. (2020), it is wise to anticipate potential future upgrades, rather than ignoring potential future threats, through adaptation strategies of coastal defences. Among the spatial adaptation measures, compartmentalization is an established strategy in floodplain areas (Klijn et al., 2010; Kreibich et al., 2015) to limit inundation during river floods and, in large cities, to reduce the flooding induced by backflow from the drainage system. This strategy consists of dividing large areas into smaller ones by building levees that have the same or lower height of the primary and principal defence. Usually, compartmentalization is achieved by raising the level of existing linear elements (for instance roads or railways) that already have high heights and can easily be transformed into secondary defence (Koks et al., 2014). The subdivision can create compartments that need to be protected but also detention areas that temporarily store excess water (Dottori et al., 2023).

Klijn et al. (2010) thoroughly discussed whether compartmentalization would be a functional measure to reduce the consequences of flooding, highlighting also where and under which conditions. In fact, the principal objectives of compartmentalization are: to reduce the surface area that can be flooded after a levee failure; to slow down the flooding development; to reduce the number of people to be evacuated; and to create safe evacuation routes. The main disadvantages are the increased risk of loss and damage in the smaller compartments due to the higher water level, and the complexity of design, implementation and maintenance.

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In view of sea level rise and from a coastal governance perspective, compartmentalization can be an effective local and scalable solution that addresses different technical, environmental and socio-economic needs, increasing the resilience of a coastal area and thus developing the United Nation's Sustainable Development Goals (SDGs) numbers 11 "Make cities and human settlements inclusive, safe, resilient and sustainable" and 13 "Take urgent action to combat climate change and its impacts" (Major et al., 2018).

During extreme marine storms, several failures may occur in the primary coastal defence system eventually formed by dunes, sea dikes, wide beaches, etc. These failures can cause flooding that can be governed by one or more compartments. Ideally, compartments close to the most hazardous areas may be monitored to give early warning, and the opening/closure of some compartments may be regulated. In Emilia-Romagna, it is already active an early-warning system (ER-EWS, geo.regione.emilia-romagna.it/schede/ews/, accessed on May 21, 2024) based on two storm impact indicators that translate the model output into a format useful for decision-makers (Harley et al., 2016). Recently, smart water level gauges have become available that integrate energy charging, recording, and transmission, capable of monitoring flooding in real-time (Chang et al., 2018).

Regardless of the multiple benefits, the assessment of the compartmentalization efficiency is not straightforward since few data are available on specific projects. Addressing this coastal management knowledge gap is important since the interest in this mitigation strategy needs to be accompanied by an evaluation of its performance in order to improve its design.

The compartments may be effectively isolated by streets, railways, dunes, walkways, etc. with a crest elevation which is much lower than the maximum offshore sea water level. The aim of this note is to give some advice to define such elevation for design purposes. A design criterion is proposed taking advantage of the use of numerical modelling, which is an essential tool for coastal flooding prediction (Postacchini et al., 2019). The criterion allows for a preliminary evaluation of the suitability of compartmentalization, determining the minimum height of the elements that bound the compartments.

The specific numerical model used is a linearized shallow water model, suited for parallel computing, that takes advantage of the thousands of cores of a Graphics Processing Unit (GPU). GPU cores are less powerful than Central Processing Unit (CPU) cores but are still suited to the linearized model developed by the authors (Favaretto et al., 2018, 2019a), allowing for small grid resolution even for large areas.

The proposed methodology is independent from the specific numerical model used to simulate the flooding, provided that the geographic resolution is sufficiently accurate to describe the details of the area and the features that affect the flooding propagation.

A peculiar case study with two breaches is presented in order to demonstrate the method. The study area is located along the Northern coast of the Emilia-Romagna region (IT), where, in 2022, extreme flooding occurred due to the failure of the primary defence. In order to reduce the flooding risk in the urban area due to a similar future event, the upgrade of existing linear elements in the landscape (roads) was discussed with the local managers and is here analysed.

In addition to this introduction, the paper consists of four more main sections and a concluding paragraph. The second section describes the methodology based on the compartmentalization design criteria and the numerical model used for the simulation of flooding events. The third section presents the study area, the numerical model set-up and the proposed schemes. The fourth section discusses the results and the feasibility of the compartmentalization. In the fifth section, a discussion on the methodology together with its limitations and some recommendations for similar applications are highlighted. Finally, conclusions are drawn.

2. Methods

Coastal managers are faced with the need for coastal flood strategies to anticipate or manage the expected sea level rise induced by climate change. The most natural preventive flood risk management measure is the rising and/or realignment of the primary line of defence, e.g. coastal dikes or sea walls facing onto the sea. van den Hoven et al. (2022) discuss nature-based flood protection solutions based on dike realignment promoting surface elevation increase seaward of the realigned dike in response to sea level rise. Vousdoukas et al. (2020) show that the expected benefits of raising the primary line of defence outperform costs for the majority of the European coasts. However, the environmental constraints frequently do not allow dike rising or realignment and other spatial adaptation measures must be considered.

Compartmentalization is a spatial adaptation measure that involves creating compartments by building or raising the level of existing linear elements (e.g. streets, railways, parks, pedestrian roads, bike lanes, walls) to act as a second line behind the primary and principal defence. Other examples of spatial strategies are land zoning (Koks et al., 2014; Kirby et al., 2021), development planning (Losada et al., 2019), and protection of vital infrastructure (Vamvakeridou-Lyroudia et al., 2020). The aim of compartmentalization in a coastal area is to mitigate the effects of a primary defence breach by limiting the extent of the flood. Compartmentalization is employed also where the source of flooding is fluvial and/or pluvial.

Compartmentalization can be achieved through different subdivision strategies to create sub-areas. These compartments can be areas to be protected or areas to be used as storage (expendable). As described by Oost and Hoekstra (2009), three subdivision strategies can be envisaged: the first, named partition strategy, consists of sectioning the area into compartments of similar dimensions by building orthogonal levees, the second is the double-line strategy, where a secondary defence is located behind the primary one (Marijnissen et al., 2021 point out the importance of the area between the dikes to protect the hinterland), the third consists of building levees around the most valuable areas behind the primary defence. In principle, even open compartments may contribute to slowing down the flood and safeguarding other areas.

In order to choose the best compartmentalization scheme, a preliminary design workflow formed by five steps (schematized in Fig. 1) is envisaged.

1) Identification of points at risk of breaching along the main levee system.
2) Simulation of a real event that causes inundation in the urban settlement with a numerical model able to reproduce the flooding. As highlighted by Seenath et al. (2016), hydrodynamic models are better suited for detailed coastal flood assessment than GIS modelling (or bathtub approach, i.e. based only on topography, the flooded area are the ones with elevation lower than the flooding level) which leads to over-estimation in flood extent and consequently to over-management.
3) Identification of possible linear elements that can be upgraded. This step needs to be performed in agreement with the coastal authorities in order to highlight possible environmental or architectural constraints.
4) Definition of the minimum element crest height on the basis of the maximum water level reached along these elements during the real flood simulation. Simulation of flooding with the identified schemes considering also different crest heights around the minimum one.
5) Assessment of the advantages and disadvantages of the schemes in order to allow a preliminary design.

2.1. GPU-suited numerical model

The numerical model employed was developed by the authors

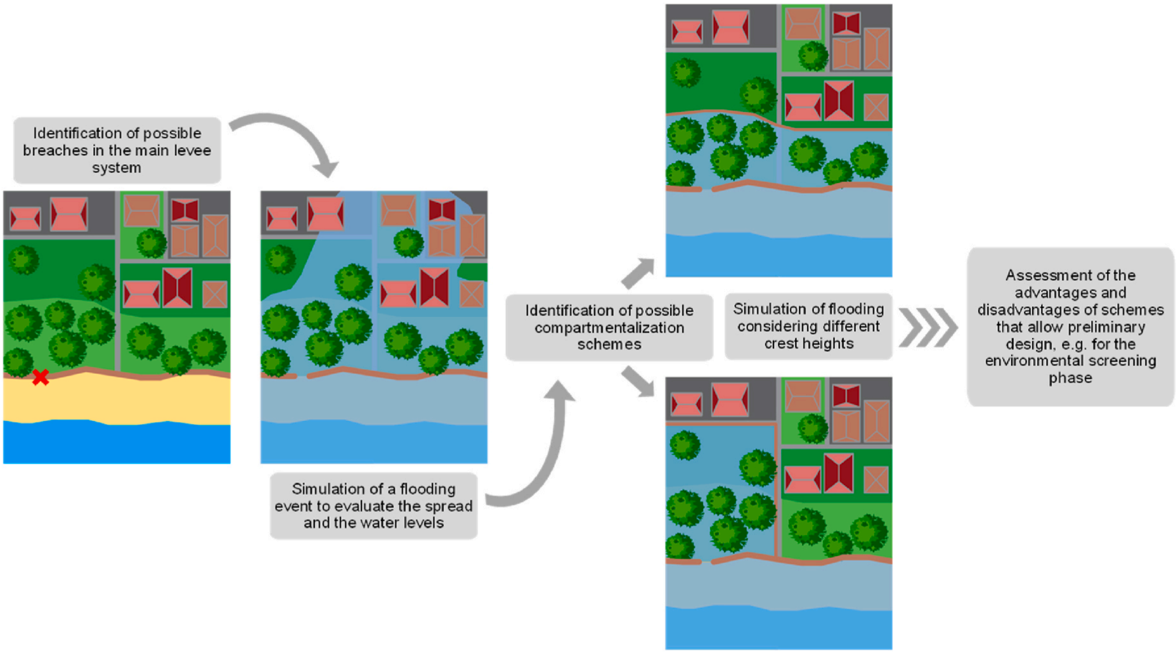

Fig. 1. Workflow for the compartmentalization design.

(Favaretto et al., 2018, 2019a). It is a flood model that uses a raster-based approach to solve a simplified form of the shallow water equations (SWE) for each cell in the domain. This simplification makes the model suitable for graphics processing unit (GPU) acceleration. The model solves the mass conservation equation and momentum conservation equations in the x- and y-directions to simulate flooding on a raster grid, i.e., designed to solve the equations on high-resolution raster Digital Terrain Models (DTM). The model includes the inertial and friction terms while neglecting the advection term. The inclusion of inertial effects is crucial to prevent overestimation of flows between neighbouring cells and to accurately represent the physics of flow in specific areas, accounting for the actual duration of the flood. The incorporation of the friction term is crucial for accurately simulating flow propagation. In the absence of small-scale features, bed friction dominates the advection term, rendering it negligible (Hunter et al., 2007). To enable parallel computing, the friction term is linearized using a K_H coefficient that accounts for the linearized turbulent flow. Details about the linearization are described in Favaretto et al. (2019a). The final formulation of the SWE is as follows.

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0 \tag{1}$$

$$\frac{\partial q_\xi}{\partial t}+gw_F\frac{\partial h}{\partial \xi}+g\frac{q_\xi}{(K_H w_F)}=0 \tag{2}$$

where $\xi = x$ or y, $h = w + z$ (w = water depth, z = bed elevation) is the water surface elevation, q (m^2/s) is the discharge per unit width assuming a rectangular channel. The K_H can be evaluated with the following equation:

$$K_H=\frac{8gQ_{MAX}}{3\pi K_s{}^2 w_F{}^{1/3}} \tag{3}$$

where K_s is the Gauckler-Strickler friction coefficient that depends on the type of land use and typically ranges between 10 and 50 $\mathrm{m}^{1/3}\,\mathrm{s}^{-1}$; w_F is the maximum available depth that can flow through two adjacent cells, defined, following Bates et al. (2010), as the difference between the highest water-free surface in the two cells and the highest bed elevation; Q_{MAX} is the maximum discharge flowing through the cells.

A first-order in space and time discretization scheme is used (i.e. Euler scheme that reduces memory requirements). To improve the model stability, a semi-implicit treatment is implemented for the friction term. The domain is a regular grid, i.e. formed by square cells, and possibly coincides with a DTM. To avoid non-physical discontinuities in the flow, a numerical relaxation technique is implemented which also reduces the dispersion error in the numerical scheme. This technique involves taking a weighted average of the flow rate of neighbouring points. To maintain the positivity of the numerical solution, the maximum flow discharge between adjacent cells is limited. In order to maintain a positive water level in the cells, the proposed model enforces the discharge limitation by a two-step approach. Specifically, if the depth variation Δh evaluated in a cell is negative (i.e. the cell is emptying), its absolute value must be less than or equal to the current available depth. To maintain mass balance, since the cell is emptying too much, the "negative" volume is subtracted from all the spatially connected cells with positive water levels.

The code is written in MATLAB and uses the Parallel Computing Toolbox.

The data required for the simulations are: i) a raster of the ground elevations, for instance, a DTM; ii) the position of the shoreline where the initial condition is applied; iii) a time series of sea levels and waves (significant wave height, peak period and wave direction); iv) if available, a raster of land-use. The initial condition is the sum of sea level and significant wave height near the shoreline. If the time series of the waves is available offshore, nearshore propagation is required that can be performed through spectral wave models (e.g. SWAN, WW3) or a one-line model (e.g. Dally et al., 1985).

The model was validated through a combination of analytical and experimental benchmarks and the analysis of real cases of coastal flooding. Favaretto et al. (2018) tested the model's performance in large domains, using the model to simulate oscillatory flow in a parabolic bowl with friction and successfully comparing the results with the corresponding analytical solution of the shallow water equations. In the same paper, the authors employed a comparison with the experimental study of solitary wave interaction around a circular island by Briggs et al. (1995) to validate the model's capacity to reproduce flow propagation in a three-dimensional domain. Through the comparisons with Synolakis' (1987) experimental investigation of a solitary wave run-up on a simple beach, Favaretto et al. (2019b) tested the numerical ability to reproduce wet/dry transitions and to assess the relevance of the advection terms. Furthermore, the model was employed to replicate actual flooding events, including the one that occurred in Caorle (VE) in December 2008 (Favaretto et al., 2018) and the inundation that took place in Jesolo (VE) in November 2019.

3. Case study

The investigated area is an 8 km long stretch of coast located in the Emilia-Romagna region (Fig. 2), between Lido delle Nazioni and the inlet of the Goro lagoon (part of the Po Delta area). This littoral area is characterized by low elevations and a high trend of land subsidence, up to −10 mm/y (Da Lio and Tosi, 2019), making it particularly vulnerable to coastal erosion and flooding (Perini et al., 2016). Along the investigated stretch, the beach and the inland areas are Special Areas of Conservation and Special Protection Areas (ZSC-ZPS in Italian), namely Bosco di Volano (code IT4060007), Valle Bertuzzi, Valle Porticino-Canneviè (code IT4060004) and Sacca di Goro (IT4060005).

In the southern part (~2.7 km, between points 1 and 2 in Fig. 2), the coast is protected by a revetment formed by a rubble mound sea dike with a crest freeboard at about 3.5 m m.s.l., damaged in several parts due to overtopping during the last extreme events. The central part (~1 km, between points 2 and 3) is protected by 16 wooden groins and a wooden sea defence filled with sandbags. The beach width is about 20–25 m. The Northern part (between points 3 and 4) is a low sandy spit where the sand accumulates since the longshore sediment transport is directed from South to North. This part is not protected by structures and the beach width is about 80 m. The protection against flooding is guaranteed by a fragmented system of dunes. In the inland area, an urban settlement is present (Lido di Volano).

On the inland side, the area is bounded by a long levee named "Acciaioli", used as a scenic road, characterized by a crest freeboard at + 4 m m.s.l., and built in 1966, after the extreme marine storm event that caused extensive flooding.

The fragmentary defence of this stretch of coast does not guarantee protection against coastal flooding during marine storms that characterise this area (Pranavam Ayyappan Pillai et al., 2022). In fact, on November 22, 2022, an extreme event occurred in the Northern Adriatic Sea (Mel et al., 2023). The meteorological conditions formed by two blocking anticyclones triggered a pressure drop (down to 985 hPa) and

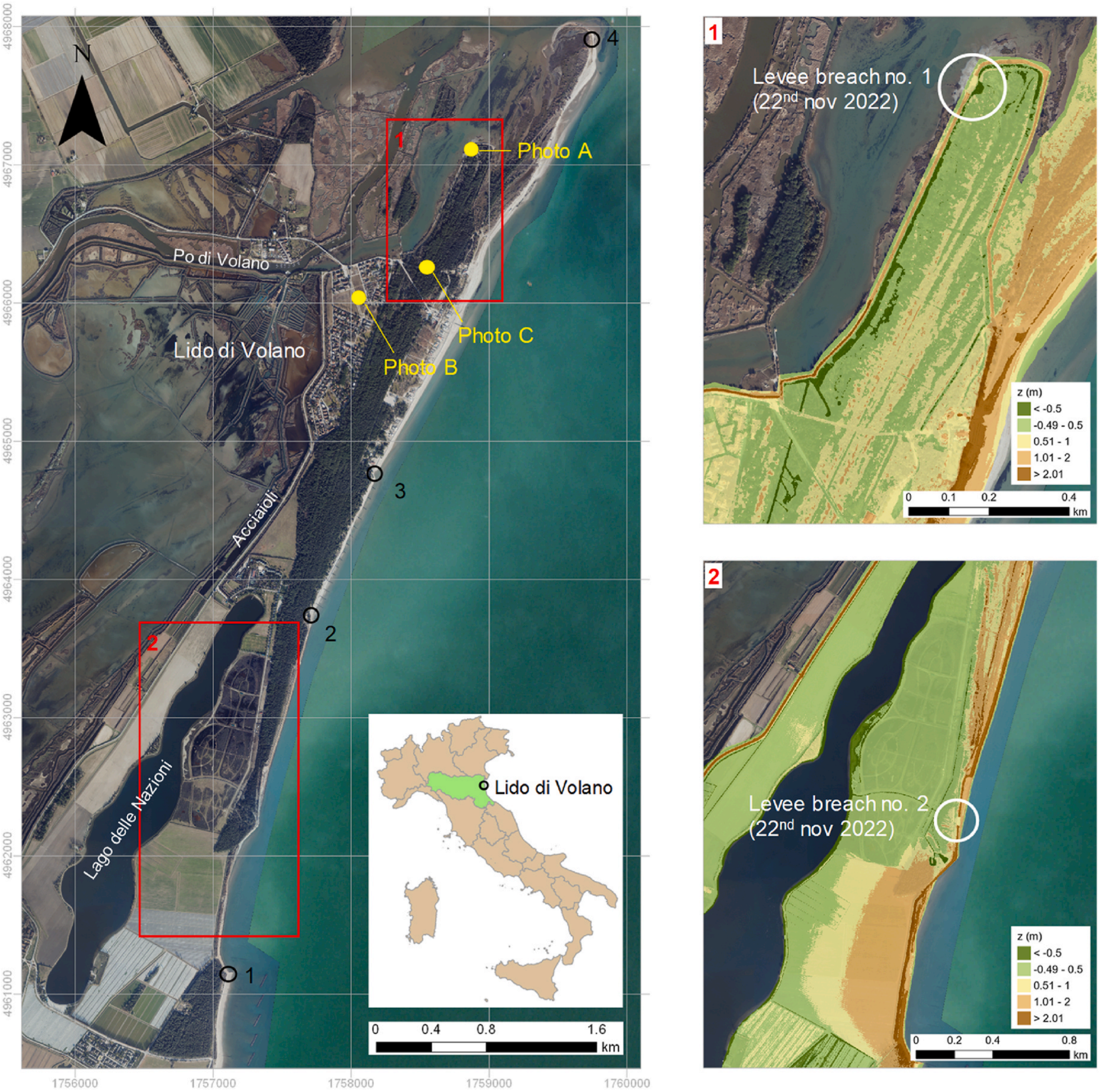

Fig. 2. Study area: Lido di Volano. The left map shows the area under investigation and the locations of the photos. The right maps show the inland elevation for the red areas highlighted in the map and the location of the Levee breach that occurred on November 22, 2022.

strong south-easterly combined with intense north-eastern winds. This scenario resulted in a sea level maximum of 1.45 m at the Porto Garibaldi tidal gauge, 1.38 m at the Ravenna tidal gauge and 1.49 m at the CNR platform (in front of the Venetian lagoon). The maximum significant wave height was Hs = 4.4 m at the CNR tower and Hs = 4.1 m at the Ancona buoy (Fig. 3).

During this extreme event, two breaches occurred along the defence system in the study area. The first breaching was localized in the Northern part, along a levee called "Argine della Madonnina" (upper right panel in Fig. 2), and extensively flooded the Lido di Volano urban settlement, as can be seen in the photographs shown in Fig. 4. The authorities, arriving on-site during the night, needed several hours to close the breach, and several weeks to restore the levee. The second breaching occurred in the Southern part (lower right panel in Fig. 2) and the sea flooded only some fields.

3.1. Compartmentalization schemes

A mitigation strategy is deemed necessary in the study area especially to reduce the risk of flooding in the urban area of Lido di Volano. The most logical solution is to upgrade the existing principal defence line formed by levees and dunes that bound the entire zone (yellow line in Fig. 5). However, this option is not possible in this area due to environmental constraints that limit the maximum levee dimensions. In these circumstances, the compartmentalization option is particularly appropriate: where raising the level of existing linear elements is environmentally feasible, this option can effectively reduce costs, and global impacts on natural habitats, and merge with urban development requirements.

Two different roads have been identified as possible linear elements that can be raised in level in order to create compartments. The two possible layouts are shown in Fig. 5. In the first one, named "Scheme 1", a levee 550 m long is built along a beaten path that connects the urban settlements (Lido di Volano) with the beach, crossing the maritime pine woodland. This scheme could be associated with the double-line strategy and allows the creation of a detention area in the pine woodland. In the second configuration ("Scheme 2"), a levee 1500 m long is built along a street that encloses the urban settlement. This scheme is associated with the third type of subdivision strategy, mentioned in section 2, protecting the most valuable area.

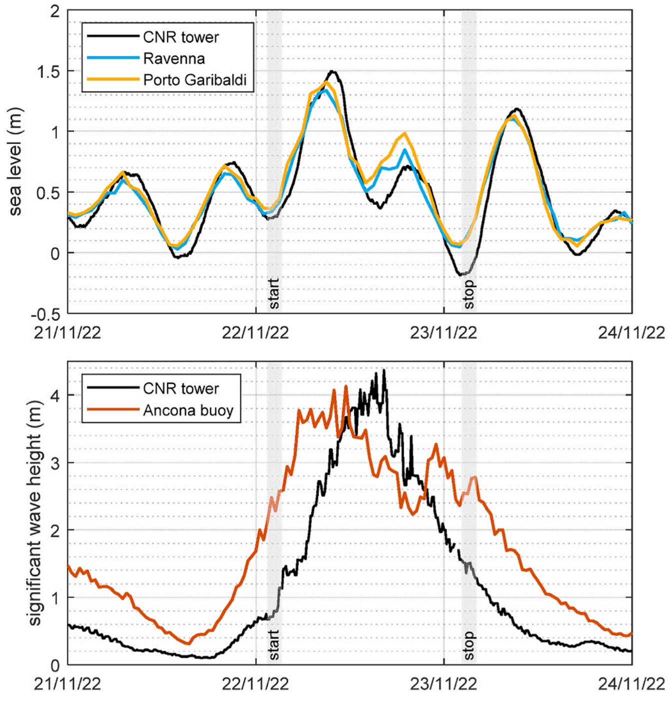

Fig. 3. Time series of sea levels and waves during the storm occurred on November 22, 2022

The real flooding event simulated and used to define the element crest height is the one that occurred in November 2022. The same event was recently used by Cabrita et al. (2024) as a reference case in order to analyse specifically the dune overtopping and create a database of Total Water Level scenarios for flood modelling.

3.2. Numerical model setup

A set of simulations is conducted to replicate the actual flood event and assess the impact of possible compartmentalization designs.

The computational grid is based on a DTM collected by the Emilia-Romagna region in January 2023. The DTM has a resolution of 0.5 m × 0.5 m and the model is derived from the altimetric information obtained from 2023 LiDAR (airborne) surveys. The image acquisition was carried out under conditions with limited foliation, minimal snow residue and sun inclination of not less than 25°. Further information on the quality of the DTM can be derived at https://geoportale.regione.emilia-romagna.it/approfondimenti/prodotti-lidar-e-ortofoto (accessed on May 21, 2024). Since DTM is not able to capture underwater elevations, the data were initially cleaned to remove the area in correspondence to the submerged beach and the rear artificial lake (named Lago delle Nazioni). For simplicity, a uniform depth, equal to −1.5 m is set in this latter area.

The grid has been modified to account for the two breaches that occurred during the event. The location of the breaches was determined using orthophotos taken in the following months, which show the reinforced sections and the reconstruction work carried out to ensure the continuity of the levees. Since flooding begins immediately after the breach occurs, the simulations could be divided into two phases. The first phase involves the grid with undamaged levees, while the second phase includes the breaches, that were both 35 m long (according to the gathered information). However, as the exact timing of the breaches during the night is unknown, for simplicity the simulation begins directly with the two gaps and from the moment when the sea level reached approximately 1 m, which is roughly 50% of the height of the levee where breach number 1 occurred. The height of the breaches was chosen to match the elevation of the land behind the levee. The breach extension is critical for the simulations as it governs the flooded volume.

The final regular grid covers an area of 2 km × 8.2 km, with square cells of only 2 m, i.e. the total number of cells is $4.075*10^6$. To reproduce the compartmentalization schemes, the model grid is artificially manipulated by changing the elevation values where appropriate.

The shoreline position is obtained from the aerial photograph taken in 2022 and the land use is based on a regional database (geoportale.regione.emilia-romagna.it/approfondimenti/database-uso-del-suolo, accessed: January 19, 2024). The land use is grouped into 3 classes, each one corresponding to a roughness coefficient. The Manning coefficients assigned to the categories are: cultivated areas or covered with grass 20 $m^{1/3}\ s^{-1}$, areas covered with trees 15 $m^{1/3}\ s^{-1}$ and urban or low industrial areas and paved or unpaved roads 30 $m^{1/3}\ s^{-1}$. The values are consistent with those used by Le Gal et al. (2023), except for the urban land use, which is rougher in the present choice. Le Gal et al. (2023) suggested a coefficient in the range of 12.5–33 $m^{1/3}\ s^{-1}$ for cultivated areas or covered with grass, 10–40 $m^{1/3}\ s^{-1}$ for areas covered with trees and 77 $m^{1/3}\ s^{-1}$ for urban areas. In a subsequent paper, Le Gal et al. (2024) verified through extensive sensitivity analyses for 17 test cases, including two in the Emilia-Romagna region, that model results are relatively not sensitive to the friction configuration.

The boundary condition for the raster-based inundation model is set in correspondence with the limit of the raster DTM, i.e. the shoreline (elevation equal to 0 m msl). The initial and boundary conditions were created using Porto Garibaldi sea level and Ancona wave data shown in Fig. 3, transferred with a geographic transposition methodology to a

Fig. 4. Photos taken the day after the flooding (November 23, 2022): a) the Levee breach; b) the Lido di Volano flooded; c) the pine woodland flooded (Screenshots from YouTube, www.youtube.com/watch?v=EFx0pc9sjhM, accessed on September 9, 2023).

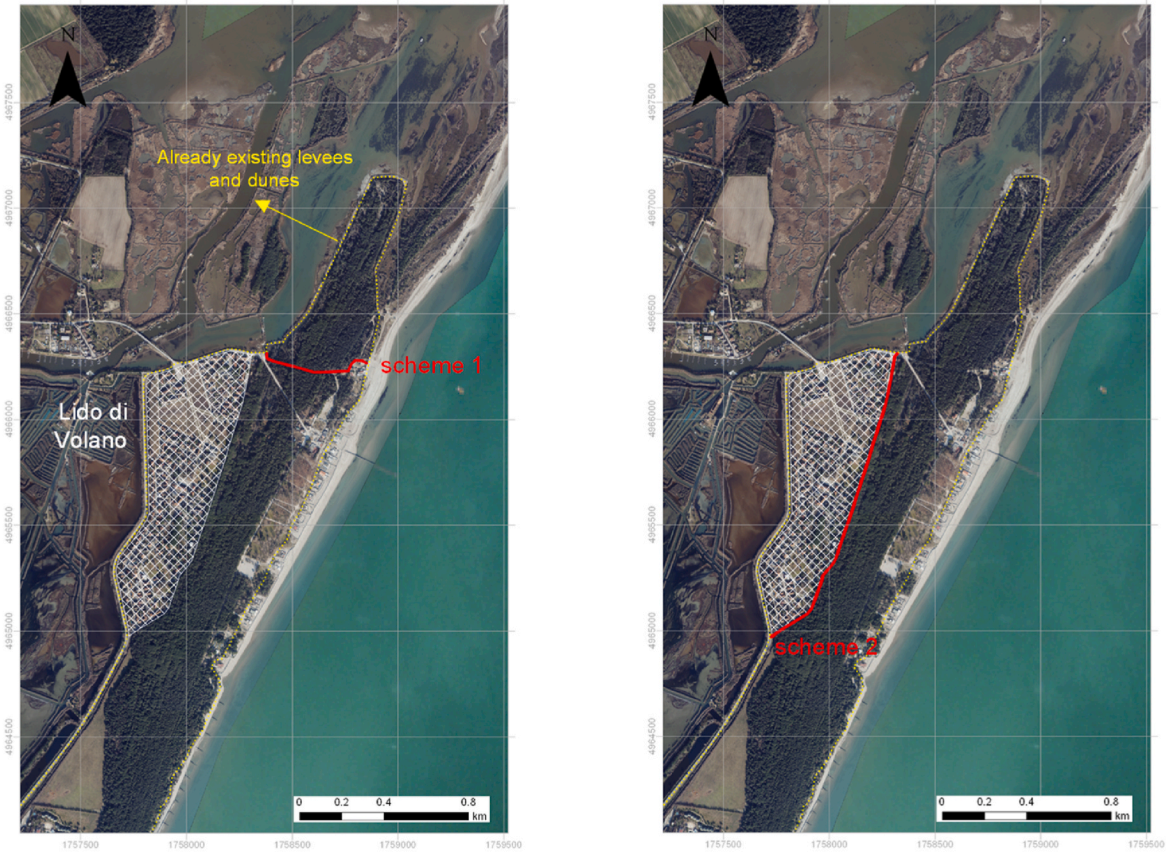

Fig. 5. Designed schemes for the two compartmentalization: for Scheme 1 (on the left) a small levee, 1.5 m high, is foreseen along a beaten path; for Scheme 2 (on the right) a small levee is foreseen along a street that encloses the urban settlement (Lido di Volano, i.e. the gridded area).

virtual station located offshore the area of interest (by comparing the effective fetches). The validity of the geographic transposition was recently discussed by Savasta et al. (2022). Then, the Dally et al. (1985) 1D wave transformation model is used, based on a bathymetric survey collected in 2018, to propagate the wave and hence assess the boundary conditions at the raster DTM limit. The simulations cover 24 h between November 22, 2022, 2 a.m. and November 23, 2022, 2 a.m., with a time step of 0.2 s.

The final flooding maps display the maximum flood level reached at each point. For the sake of understanding, the lake area, relevant to the truthfulness of the simulations, is removed from the final maps.

For the present study, a 64 GB RAM workstation with a GPU NVIDIA TESLA K80 (4992 core NVIDIA CUDA, 24 GB memory) is used. The simulation for the real flooding in the actual scenario is repeated also changing the grid resolution (dx = 2, 4, 6, 8 and 10 m) and using a 32 GB RAM computer to highlight the potentiality of the parallel computing.

4. Results

4.1. Compartmentalization design

The definition of the linear element crest height is based on the simulation of a real flooding event that occurred on November 22, 2022. The result in terms of maximum water levels reached at each point of the grid during the extreme event is shown in Fig. 6. The flooded areas correspond to the ones recognizable in the photographs (Fig. 4) and reported by the local authorities. Two inundations occurred due to the two breaching phenomena highlighted with two yellow stars. The total flooded area is 2,78 km^2 and the mean water level in Lido di Volano is 1 m.

The simulated flooding map shown in Fig. 6 is critical to define the crest height in correspondence to the two compartmentalization schemes shown in Fig. 5. In fact, the maximum level reached in

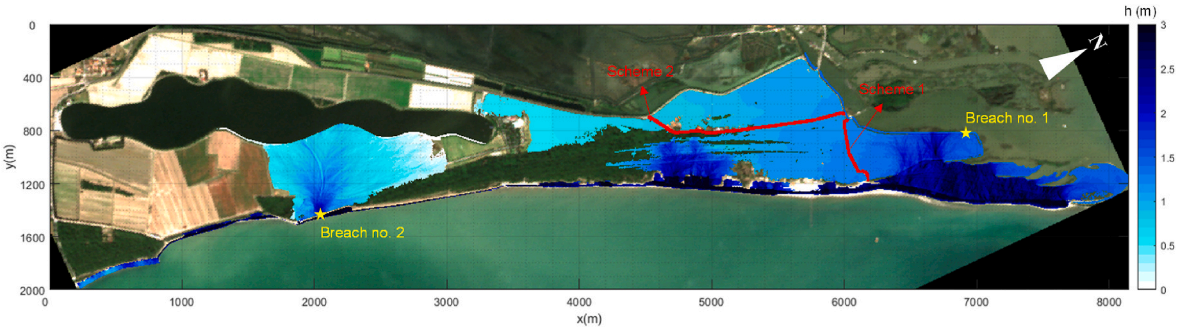

Fig. 6. Simulated flooding map (water level) after the two breaching phenomena occurred during the November 22, 2022 storm event. The red lines highlight the position of the two possible levees.

correspondence to Scheme 1 is 1.5 m, whereas the maximum level reached in correspondence to Scheme 2 is 1.15 m. Two solutions are envisaged, after examining the maps.

1) a levee with elevation +1.5 m in correspondence of Scheme 1,
2) a levee with elevation +1.2 m in correspondence of Scheme 2.

To check the GPU performance, the real flood event simulation is re-run changing the grid resolution and using a different computer without the GPU. The computational times are displayed in Table 1. The times are comparable for coarse resolution (dx larger than 8 m), whereas for finer resolution the computational time using a GPU decreases exponentially and for a resolution of 2 m, the GPU time is one-ninth the CPU time.

4.2. Effect of compartmentalization design

The results in terms of maximum water level in the flooded areas are shown in Fig. 7. The water level is given in colour scale and the flooded regions are immediately visible. Water depth maps can be obtained by subtraction with the topo-bathymetric maps.

The first scheme aims at confining the flooding in the pine woodland area at North, creating a detention area that stores the water. The second scheme confines the flooding outside the urban settlement, inundating a larger area of the pine woodland with a shallower water depth, eventually a better scenario to reduce the environmental damages.

To further investigate the suitability of the two mitigation options, additional simulations are performed changing the crest height and evaluating from the maps the mean water level in Lido di Volano. The crest height is varied from 0.5 m to 1.5 m for both schemes. The area surrounding the Lido di Volano settlement flooded due to breaching no. 1 is subdivided into 4 subzones, highlighted in Fig. 8.

Figs. 9–11 and 12 show the extent (in m^2) of the flooded areas in the four subzones for the different schemes and crest height, highlighting also the flooded areas during the real event. A small map included in the figures highlights the zones. The colour of the dots and the stars represents the spatially averaged maximum water depth.

Fig. 9 is relative to zone no. 1 (red in Fig. 8), which is Lido di Volano. It is worth noticing that for Scheme 2 with a crest height of 1 m (or less), the flooded area exceeds that which occurred during the real event. In fact, with this configuration, the urban settlement becomes a compartment bounded by the levee. If the water overflows the secondary defence, the flooding cannot spread to other areas (such as the field in the south, like during the real flood) and remains enclosed inside the urban settlement, acting as a detention area.

Table 1
Computational time for a 24-h simulation using five different grid resolutions and two different computers (with and without the GPU).

Resolution	dx = 10 m	dx = 8 m	dx = 6 m	dx = 4 m	dx = 2 m
number of cells	163′000	254′500	452′214	1′018′500	4′075′000
CPU time (hours)	0.7	1.3	2.6	8.2	56.2
GPU time (hours)	0.5	0.6	1.0	1.8	6.6

Fig. 10 is relative to zone no. 2 (blue in Fig. 8). The flooded extent in these areas is very similar for the different compartmentalization schemes and crest heights, and is essentially equal to that observed during the real flooding. Therefore, this area does not suffer any measurable disadvantages due to the project (while all other areas benefit from it).

Fig. 11 shows the results for the third zone (green in Fig. 8) that, during the real event, is flooded due to breaching no. 1 and due to some beach run-up and dune overtopping, modelled and only generically confirmed by locals. Considering Scheme 1, the flooded area decreases with the increase of the crest levee. The minimum flooded area cannot be further reduced by raising the levee level, as it is caused by dune overtopping contribution. Considering Scheme 2, the flooded areas are the same for all the crest heights.

Finally, Fig. 12 shows the flooded areas in the fields south of the urban settlement (zone 4, yellow in Fig. 8). This area is well-protected by both schemes as long as the levee crest is above 1 m.

The analysis indicates that both schemes are suitable for protecting the urban settlement from flooding. However, Scheme 1 is effective only if the breach occurs along the levee called “Argine della Madonnina”, while Scheme 2 may be effective even if the flooding originates elsewhere.

Regarding Scheme 2, and considering the potential future sea level rise due to climate change, it is possible that in the event of higher sea levels than those simulated in this study, flooding could overflow the secondary levee and cause the urban area to become a closed basin.

From an environmental perspective, Scheme 1 poses some advantages as it confines the flooding to a small area of the pine woodland, preserving a larger natural area. However, the compartmentalization levee increases habitat fragmentation and such anthropogenic modification can be a critical feature of coastal dune ecosystems (Chadwick et al., 2022).

Smart water level sensors are suggested to promptly restore possible flooding of natural areas.

5. Discussion

Due to climate change and rising sea levels, it is mandatory to assess potential flooding scenarios. This can create a resilient area able to cope with the increased risk and raise political awareness (Morelli et al., 2024). Rasmussen et al. (2021) find that multiple floods are often the causes that elicit earnest planning and participation during the design stage, favouring consensus-supported mitigation strategies. The proposed methodology for compartmentalization could be useful to facilitate participation in the choices of which elements to upgrade or which

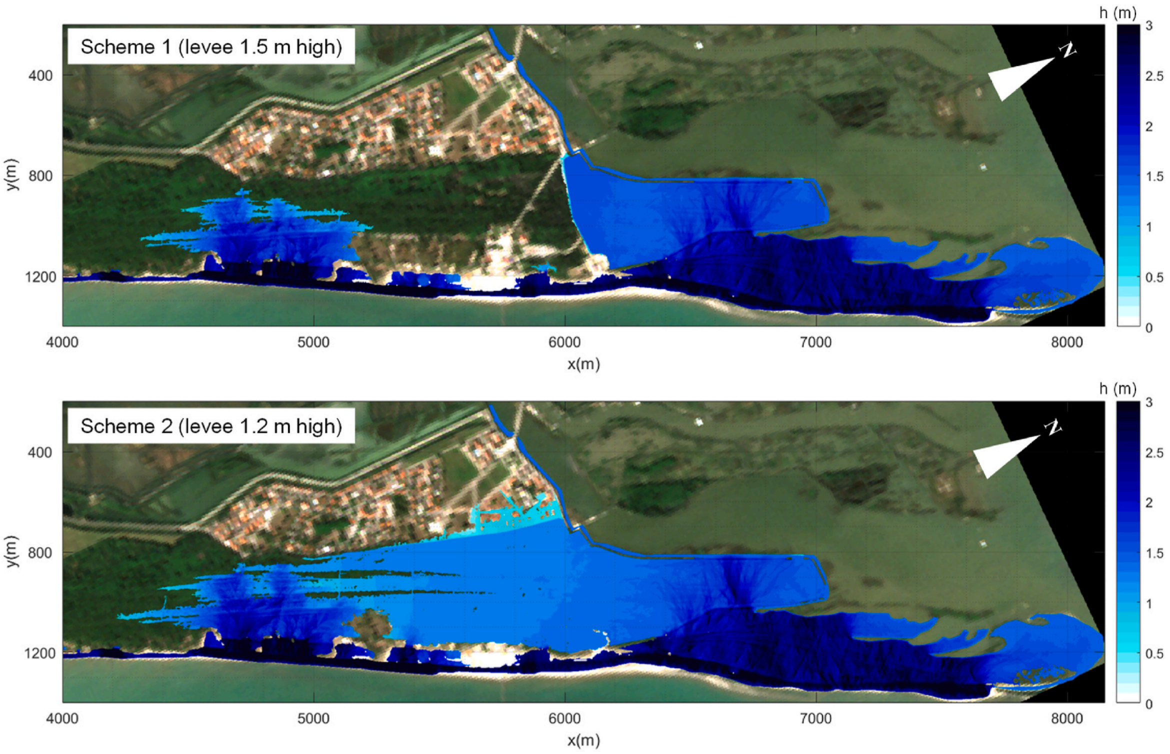

Fig. 7. Simulated flooding map (water level) for the two compartmentalization schemes.

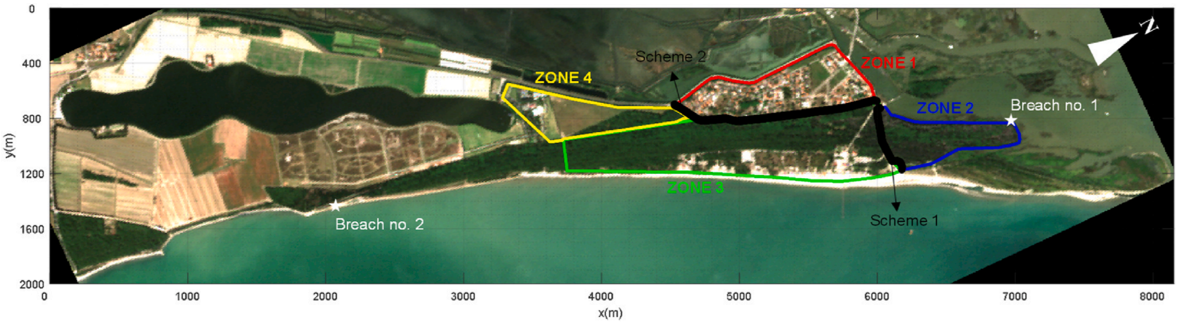

Fig. 8. Subzones in the area surrounding Lido di Volano and plan of the two compartmentalization options.

other functionality could be integrated into the second line of the flood defence system. In fact, compartmentalization and other spatial mitigation measures for coastal flooding can have positive impacts on the population's sense of protection (Quinn et al., 2023).

Creating safe compartments and building or upgrading linear elements are part of a wider urban planning strategy. For instance, critical infrastructures, such as hospitals or schools, could be located in the safest areas. Furthermore, there are several innovative ways to include dikes and levees within the urban context giving the site an additional value. Multifunctional secondary defence can potentially contribute to urban and natural landscape value (van Loon-Steensma et al., 2014).

The transformation of existing elements, by increasing their height while at the same time integrating other uses within the flood protection system, could make this type of mitigation more feasible than the strengthening of the primary defences (Marijnissen et al., 2021), which in some cases may have larger consequences for the habitats. On the negative side, new levees and barriers, even low ones, restrict habitat development, a concept known as the 'coastal squeeze' (Pontee, 2013). The planning of compartmentalization options poses severe problems for highly urbanised coastal areas, and many options may result unfeasible due to environmental constraints and social acceptance. However, they may be a cost-effective solution and a public discussion over these strategies will raise awareness that in the coastal zones there is a strong intrinsic link between urban planning and flooding mitigation planning.

5.1. *Limitations of the analysis*

The proposed methodology is limited in case of lack of topographic details, such as hydraulically important features (Néelz et al., 2006), that cannot be derived from Lidar data (DTM or DSM) and can be usually only supplied by local technical managers. For instance, if the urban stormwater drainage system and the presence of culverts are not included in the flooding simulation, they could lead to an over- or underestimation of the extent of inundation (Gallien et al., 2014). Note that special elements in the numerical grid, such as sink cells to represent manholes, could be used to implement such hydraulic features.

The numerical model requires a specific calibration for the local friction (type of land use) that varies the inundation time and could be critical for flood event management.

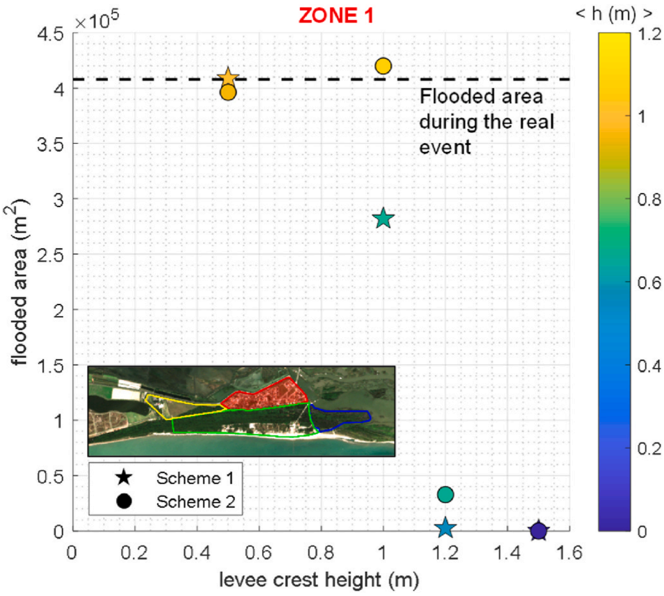

Fig. 9. Flooded area in zone 1 (Lido di Volano urban settlement) implementing different mitigation schemes and different levee crest heights. In this and in the following figures, the stars are relative to Scheme 1, whereas the dots are relative to Scheme 2. Colours indicate the average water level in the flooded areas. The black dashed line indicates the flooded area during the real event.

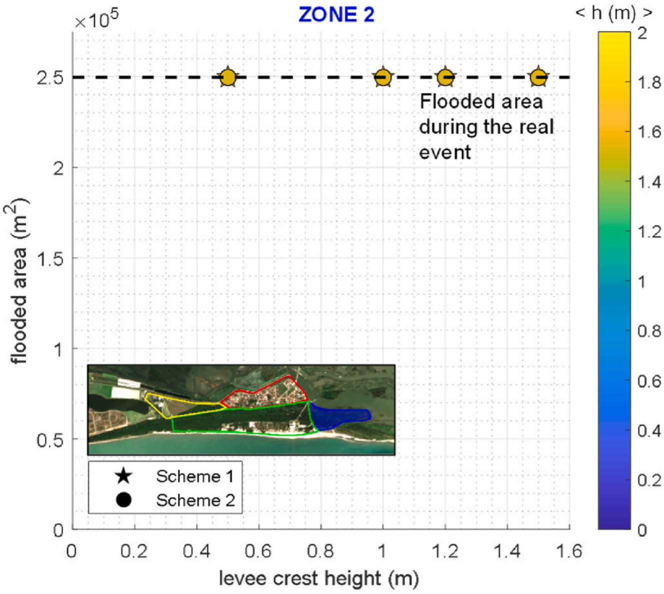

Fig. 10. Flooded area in zone 2 (area bounded by Scheme 1) implementing different mitigation schemes and different levee crest heights.

The methodology also relies on the location and - more importantly - the dimension of the breach from which the flooding originates. The location could be assessed through expert judgement, historical information or using satellite imagery (providing the location and dimension of old breaches). All these assessments can suffer from spatial and temporal inaccuracies. Furthermore, the temporal evolution of the breach is not included in the flood simulation but could be implemented in the model grid, similar to the hydraulic features, as a special cell with a time-varying height.

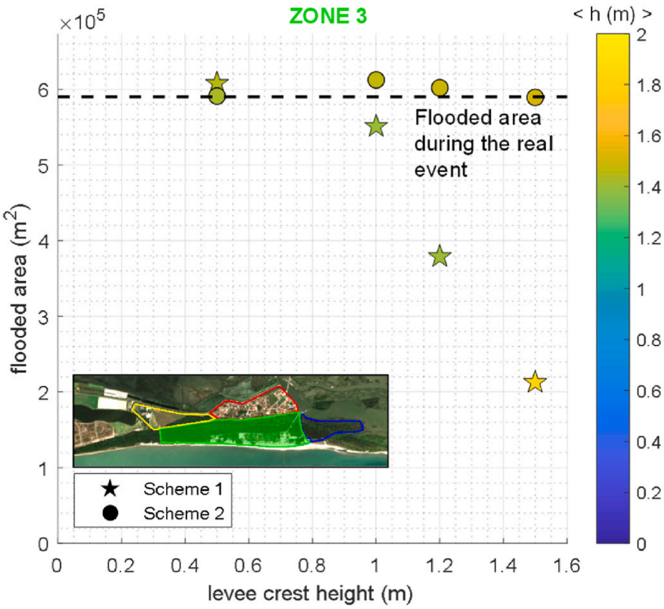

Fig. 11. Flooded area in zone 3 (behind the beach) implementing different mitigation schemes and different levee crest heights.

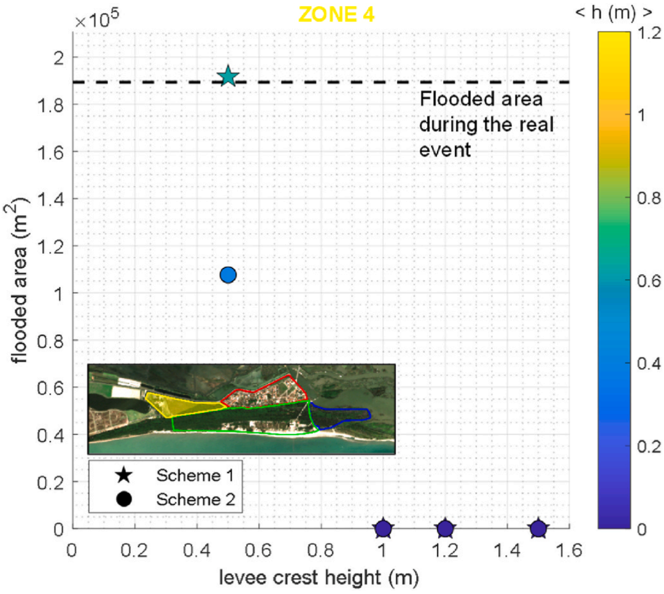

Fig. 12. Flooded area in zone 4 (fields south of the urban settlement) implementing different mitigation schemes and different levee crest heights.

5.2. Recommendation for similar applications

During preliminary design for Coastal flood prevention (required e.g. for the EU regulation by the Water Flooding Directive, 2011/92/EU, December 13, 2011) it is mandatory to investigate a series of alternatives (see also Directive, 2014/52/EU of December 16, 2014 on Environmental Impact Assessment), beside the upgrade of the first line of defence. Among the possible alternatives, the upgrading of a second line of defence with a compartmentalization approach is an option that should reasonably be considered in many circumstances, as it has the potential to reduce both capital and operational costs while minimising visual and environmental impacts. The method described in this note may be considered a useful tool for a quick pre-design and a check of its feasibility.

Actually, in a changing and highly evolving shoreline context, a series of compartments could be considered more feasible in the long term, where changing boundary conditions (e.g. erosion, coastal subsidence, sea level rise) may significantly alter the efficiency of upgrading the first line of defence.

In short, the methods described in this note can represent an efficient decision-support tool for sustainable coastal planning and management (Barzehkar et al., 2021): in order to fully appreciate the efficiency of a compartmentalization scheme, the different risk scenarios should be compared, overlapping the flooding maps produced with the described method. Then, the value at risk and the expected damage, for the different alternatives, can be compared. The methodology can also take advantage of scenarios consisting of combinations of marine forcings, such as those presented by Cabrita et al. (2024) and publicly available (Duo et al., 2024), fluvial forcings and the strength of the first defence system. Such scenarios could be used to demonstrate the effectiveness of the solution adopted.

6. Conclusions

In the present study, a compartmentalization design strategy was proposed (schematized in Fig. 1). The methodology and the effects of compartmentalization have been applied to a case study located in the Northern coastal area of the Emilia-Romagna region. The study area, that was flooded in November 2022, was analysed with two options, and the effects on four zones were examined for various crest heights of the levee used for subdivision. These results are considered very useful for a preliminary design at the environmental screening stage.

Flooding reduction through compartmentalization can be effective in protecting specific valuable areas, such as urban settlements, but some compartments may experience higher flooding (in terms of volume and water depth) than without the subdivision, hence the analysis is quite relevant. In particular, since the rising of the crest levels of the linear elements bounding the compartments may have negative environmental consequences, the "cost-benefit" analysis must be sufficiently accurate to effectively support the decision process.

In order to carry out the study effectively, it is crucial to simulate the entire flood-prone area. This task can be quite challenging, as it may involve modelling large regions, which can be computationally demanding. However, this obstacle can be overcome by employing an appropriate model that is capable of handling such complex simulations. To expedite the computation process, the proposed numerical model utilizes linearized equations, designed to be compatible with acceleration computation using GPUs.

The integration of GPU acceleration is nowadays easily accessible at low cost, through cloud computing, such as Amazon Web Services AWS (Morsy et al., 2018), and hence available to coastal managers. The model and the method proposed allow them to make informed decisions regarding flood prevention, mitigation, and response strategy, ultimately enhancing the overall area resilience.

In conclusion, the present study offers insights that could guide effective coastal management. In order to mitigate the risk of coastal flooding, compartmentalization can be employed to align technical-environmental requirements with the needs of socio-economic systems (e.g. a compartmentalization realized by means of a bike lane to reach the beaches). Therefore, in the context of coastal governance, which involves a multiplicity of actors (including decision-makers, managers and communities), compartmentalization may represent a multidisciplinary option that encourages discussion to find a shared solution and to improve awareness of the resilience of the coastal zone.

Strategically, in order to mitigate coastal flooding, local scale technical solutions may play an important role. Compartmentalization is an example of such a solution since it represents a scalable solution that can have a significant impact, and it capitalises on the know-how, expertise and experience of local technicians.

CRediT authorship contribution statement

Chiara Favaretto: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Piero Ruol:** Writing – review & editing, Visualization. **Luca Martinelli:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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