GIS Simulations of the Inundation Risk in the Coastal Lowlands of the Northern Adriatic Sea

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Abstract The Northern Adriatic coastland comprised between the cities of Monfalcone and Cattolica is characterized by locations of great tourist interest, such as the Venice Lagoon and the Romagna Riviera, and areas with a very precarious environmental setting, such as the Valli di Comacchio and the Po river delta. Therefore the coastal management and the design of new defence works of the littoral have to be made with the utmost care, possibly with the aid of numerical predictions of the coastal morphodynamics and the flood risk analysis of the lowland involved. In the study area land may subside due to sediment natural compaction and subsurface fluid (water and gas) withdrawal. At the same time littoral transport of solid material can contribute appreciably to change the shore morphology. Mean sea level may rise permanently due to global climate change and occasionally due to tides and intensive storm events. The predictions of each individual process is obtained using *ad hoc* mathematical models and the outcome of the numerical simulations are managed with a GIS (Geographical Information System). Coastline evolution until the year 2100 is investigated and risk factor maps of the low-lying coastal areas are generated which account for the hazard of the expected event, and the land economic value and vulnerability.

1. INTRODUCTION

The Northern Adriatic basin comprises a very precarious coastal environment subject to continuous morphological changes that can prove appreciable even over short geological time scales such as the historical and the modern eras. This area contains lagoons (*e.g.* the Venice and the Grado-Marano Lagoons north of the Po river delta and the Valli di Comacchio south of the delta), salt and fresh water marshes, and reclaimed land separated by channels and watercourses originating from the Alpine and the Apennine ranges. The coastland, with an elevation in many areas which does not exceed 2 m above mean sea level (Figure 1), has experienced recent pronounced modifications in response to both natural and anthropogenic factors.

The European project CENAS (Study of the Coastline Evolution of the Eastern Po Plain Due to Sea Level Change Caused by Climate Variation and to Natural and Anthropic Subsidence) developed in the framework of the EU Environmental Programme, has addressed the morphodynamical evolution of the Northern Adriatic coastal profile due to sea level rise, storm surge and wave set-up, littoral sediment transport, and land subsidence due to natural sediment compaction, groundwater withdrawal from a well developed multiaquifer system and gas production from a number of reservoirs scattered through the basin. The combined effects of these occurrences can create serious stability problems for the Northern Adriatic shoreline.

Gornitz [1991] identifies three fundamental consequences of relative sea level rise: intensified flooding, increased coastline retreat and increased saltwater intrusion. According to Bird [1996], the study area has experienced a general widespread relative settlement of more than 2 mm/year over the past three decades. This rate has locally been enhanced by anthropogenic factors. Broadus [1996] has developed a kind of "coloring book" approach to assess the economic impact of a projected relative sea level rise. First, a scenario is selected that identifies a possible relative rise due to the combined sea level change and local land settlement at a specified time and with a given return period (related to a local sea level change of meteo-marine origin). The area subject to inun-

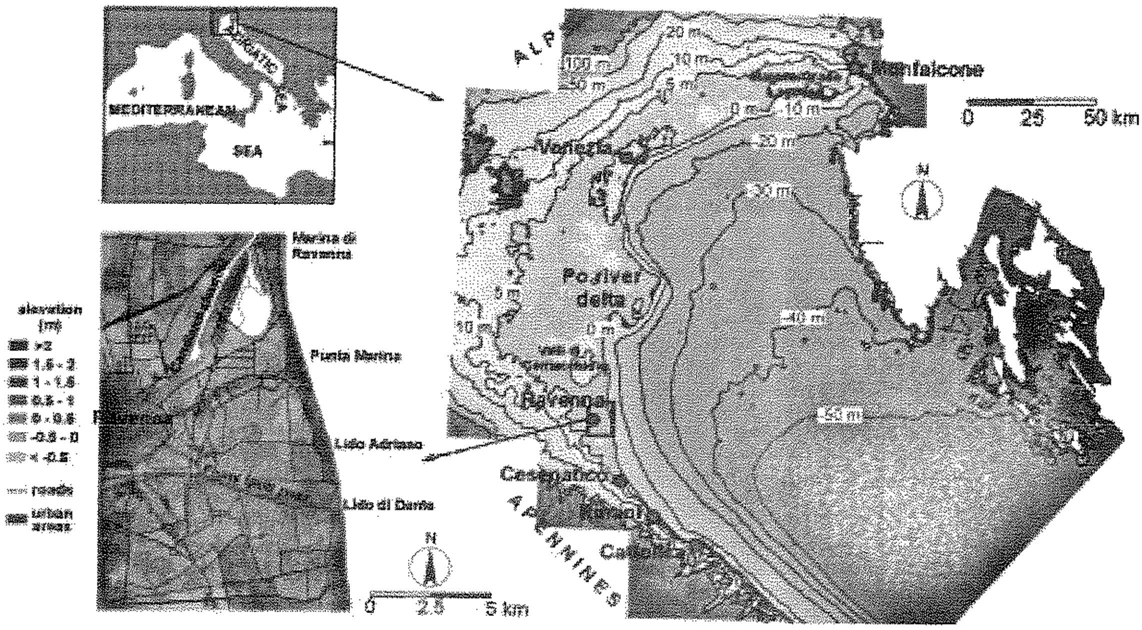

Figure 1: DEM of the Northern Adriatic Sea and the Eastern Po river plain, and the Ravenna coastal area generated on a regular grid of 200×200 m and 10×10 m, respectively.

dation is then identified using topographic information and "colored in" on a map. Finally, if economic indices of the flooded areas are known (*e.g.* demographic information, land use pattern), the economic impact evaluation and risk analysis can be performed with the production of very useful risk "colored" maps.

The present note describes the application of the procedure mentioned above to the Northern Adriatic coastal area with the prediction projected to the end of the next century. The investigation is carried out by the use of the public domain GIS known as GRASS (Geographic Resources Analysis Support System) originally developed by the USA-CERL and presently enhanced and supported by the Baylor University in Texas [Clamons and Byars, 1997]. By GRASS the outcome from the numerical analyses addressing the numerous processes studied by the CENAS project is combined with a DEM (Digital Elevation Model) of the area in order to find out those lowlands which are most likely to be flooded both permanently and occasionally, and to asses the expected coastline regression during the decades to come.

After a short description of the approach followed to define the risk of sea inundation, several maps are provided over the regional area as well as at the local scale of the Ravenna Municipality (one of the most renown historical Italian cities located in the coastland) to show the potential coastline regression in 2100 for a pessimistic land subsidence scenario, the areas that are expected to be flooded during a storm with 1 and 100 year return period and the risk factor maps.

2. GIS OF THE NORTHERN ADRIATIC COASTLAND

GIS is employed in the CENAS project with two primary objectives, *i.e.* georeferencing and processing geographic field data, and integrating the simulation results from each numerical model used to study the littoral dynamics and perform the risk analysis over the coastal lowlands.

Adriatic Sea data derived from the Hydrographic Office's Chart 1440 of the Adriatic Sea (scale 1:1000000), the Nautical Charts of the Hydrographic Marine Institute (scale 1:250000) and several bathymetric profiles measured along the coast, together with the DEM of the National Geologic Survey (derived from maps at the 1:25000 scale) and the CTR (Technical Regional Maps, scale 1:10000) of the coastal region are homogenized and georeferenced with GRASS and then interpolated to produce the DEM of the entire Adriatic Sea over a 6000×6000 m grid, primar-

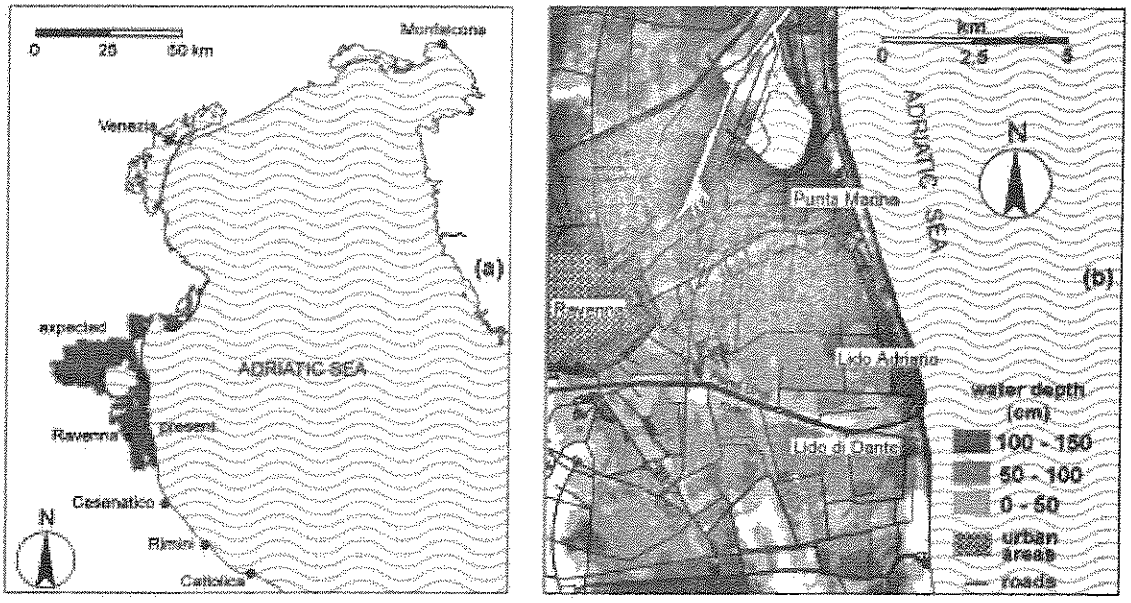

Figure 2: (a) Potential regression of the Northern Adriatic coastline in 2100 with the pessimistic anthropogenic land subsidence scenario; (b) projected flooded areas of the Ravenna coastland in 2100 with the same land subsidence scenario.

ily used by the storm surge [Yu *et al.*, 1998] and storm wave [Decouttere *et al.*, 1998a] models, and the more refined DEM of the Northern Adriatic Sea and neighbouring coastland on a 200×200 m grid (Figure 1) used in the wave refraction [Decouttere *et al.*, 1998b] and the littoral morphodynamic [Gambolati *et al.*, 1999] models. To provide a more accurate representation of the coastal area, a DEM with a resolution of 10×10 m has been generated for few local sites located along the coast, *e.g.* the Municipality of Ravenna (Figure 1).

The outcome from the various modeling simulations developed to predict the phenomena affecting the coastal stability are georeferenced and visualized by GRASS and maps are produced by interpolation of the model output on a 200×200 regular grid. Land subsidence of natural and anthropogenic origin is predicted with the aid of finite element models [Gambolati and Teatini, 1998; Teatini *et al.*, 1998; Gonella *et al.*, 1998b; Gambolati *et al.*, 1999], sea level rise due to global climate change is taken from the evaluation by IPCC 92 (Intergovernmental Panel on Climate Change) reconfirmed four years later by Raper *et al.* [1996], and the sea storm effects, *i.e.* wave set-up, tide and storm surge, are provided by Decouttere *et al.* [1998a] and Yu *et al.* [1998].

3. RISK ANALYSIS OF THE POTENTIALLY FLOODED LOWLANDS

In accordance with the methodology developed by UNDRO (United Nation Disaster Relief Office, 1995), the inundation risk factor R is defined as:

$$R = H_t \cdot E \cdot V \qquad (1)$$

with:

$$H_t = 1 - \left(1 - \frac{1}{rp}\right)^t$$

H_t is the flooding hazard equal to the probability that a selected storm event with a return period rp occurs at least once during the time interval t (set to 100 years in the analysis that follows), E is the economic value of the flooded area and V the relative damage suffered by the area subject to flooding. The unit of rp and t is year.

Through land use maps obtained from the Minister of Environment, A.R.S. Service, and then georeferenced with the projection system selected for the CENAS study, a normalized economic values is associated to each land use class with $E = 100$ for dense and sparse urban areas, 63 for industrial areas and infrastructures, 19 for agricultural zones and areas with few houses, 9 for uncultivated zones permanently covered by natural vegetation, and 0 for internal water (river with a significant dimension, lakes, internal lagoons).

V is also called "vulnerability" of the area and, on a first approximation, may be taken equal to the water elevation over the flooded area. For each cell into which the study area is divided (200×200 m and 10×10 m at the regional and local scale, respectively), the vulnerability is assessed by GIS by combining the results from the simulations of land subsidence and mean sea level rise with the available DEMs. By the DEM of the study area, the ground elevation map in 2100 is generated by decreasing the present height by the amount of expected natural and anthropogenic land subsidence. The maps of the mean sea level rise for the selected return period are built by adding the simulated sea storm effects to the eustatic rise caused by climate variation. Estimate of the potentially flooded lowlands and related water elevation at a given time is performed with GRASS by intersecting the ground level with the expected mean sea level at the same time and with the selected return period.

At the regional scale it is not possible to account for the improved safety of an area because of the protection exerted over this area by natural as well as man made obstacles to water ingress inland such as dams, embankments, and dunes. In fact the DEM resolution at this scale is such that the typical size of the previous structures easily escapes the representation. However, an analysis is performed at the local scale (*e.g.* at the site of Ravenna) where high resolution maps are available. To account for the actual possibility for an area to be flooded, a position/shape index I is defined and eq. (1) becomes:

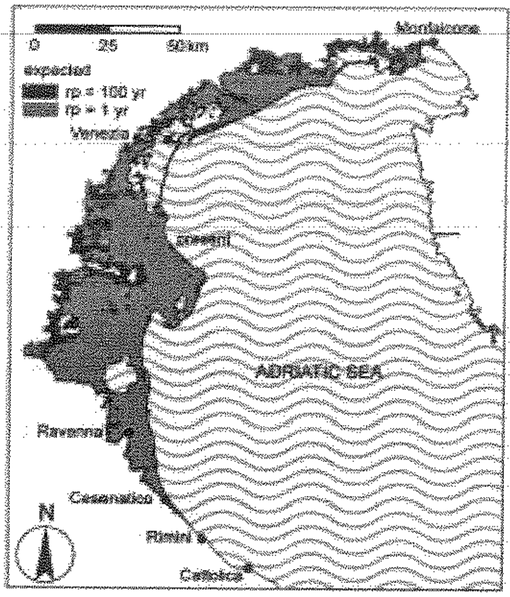

Figure 3: Potentially flooded lowlands in 2100 with a sea storm of 1 and 100 year return period and the pessimistic anthropogenic land subsidence scenario.

$$R = I \cdot H_t \cdot E \cdot V \tag{2}$$

The simulated area is subdivided into a number of cells based on the major obstacles to water flooding. An I value is assigned to each cell taking into account the the cell position with respect to the inundation sources, the average elevation of the cell and its boundary, and the percentage of the cell boundary across which the water enters the cell. The distribution of I for the local study sites is given in Gonella *et al.* [1998a].

4. FLOODED LOWLANDS AND RISK FACTOR MAPS

Shoreline regression with an indication of the projected permanently flooded areas is obtained by combining the projected DEM of the coastland with the mean sea level rise caused by global climate change. Figure 2a shows the permanent coastline regression in 2100 as predicted by the simulations under a pessimistic groundwater pumping scenario [Gonella *et al.*, 1998b] with the projected sea level rise of Raper *et al.* [1996]. The lowland which turns out to be potentially flooded amounts to 910 km^2. For the same conditions, the flooded areas of the Ravenna coastland obtained with the more reliable local analysis is presented in Figure 2b, which also gives the water depth. Occasionally flooded lowlands in 2100 with the pessimistic land subsidence scenario are shown in Figure 3 for storm events with 1 and 100 year return period rp. Notice the extensive ingress of sea water even for relatively small rp (1 year) at the end of the next century.

The maps at the regional scale of the normalized risk factor at present and in 2100 for the subsidence scenario mentioned above are shown in Figure 4. Similar maps are shown in Figure 5 at the local scale for the site of Ravenna where eq. (2) is used instead of eq. (1). Inspection of Figure 4 and 5 indicates the areas which are most at risk of flooding and receiving a measurable damage, and where protection action is to be most likely planned in the years to come. Note the significant reduction of the flooded coastland obtained in the present situation with the more detailed and accurate local analysis (Figure 5a) compared to the regional result (Figure 4a).

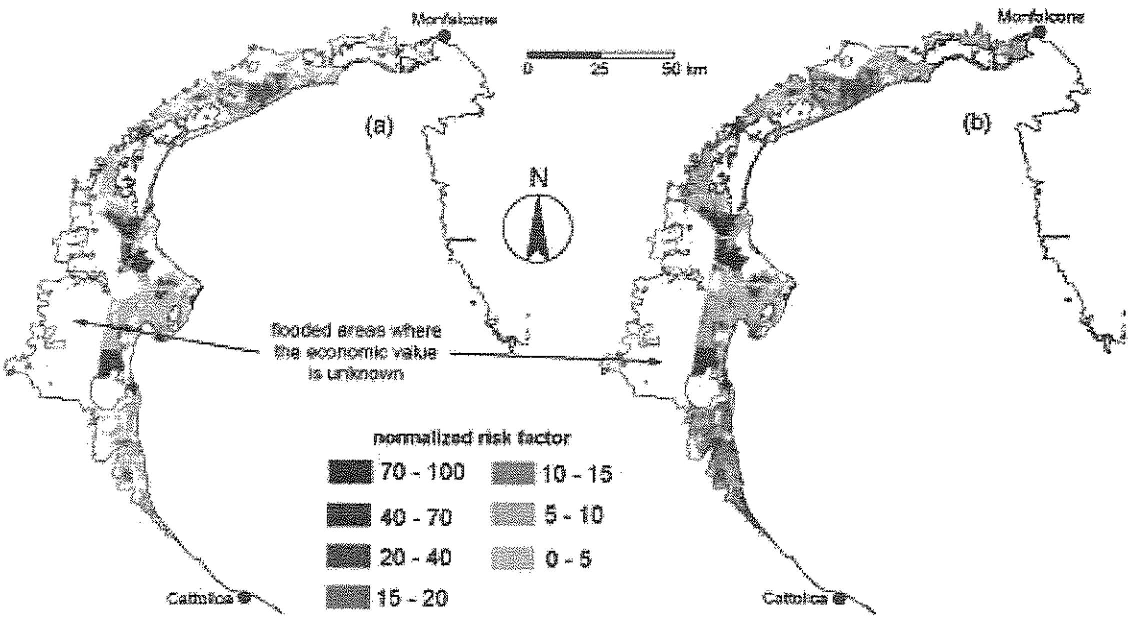

Figure 4: Potential normalized risk factor maps (a) with the present ground elevation and a 1 year return period storm and (b) in 2100 with the pessimistic land subsidence scenario and a 100 year return period storm.

5. CONCLUSIONS

The following conclusive remarks can be drawn:

1. the potential shoreline regression in 100 years from now appears to be quite pronounced in the lowland between the Po river delta and Ravenna;
2. a large portion of the present low-lying areas are potentially flooded in 2100 also with relatively frequent sea storms characterized by 1 year return period;
3. at Ravenna there is a high inundation risk to be taken care of in the future;
4. the reliability of the results decreases as the prediction time and the storm return period increase, and particularly so because of the relative coarse DEM used at the regional scale. Consequently, the projected coastal profile in 2100 under both static and dynamic conditions is to be viewed as a qualitative estimate that can be substantially improved with new data and a more accurate DEM;
5. the integrated modeling approach (consisting of groundwater flow model, natural and anthropogenic land subsidence models, tidal-storm surge and wave models) coupled through a GIS with a DEM of the area addressed by the study proves a very promising tool for the analysis, control and effective management of low-lying coastal areas.

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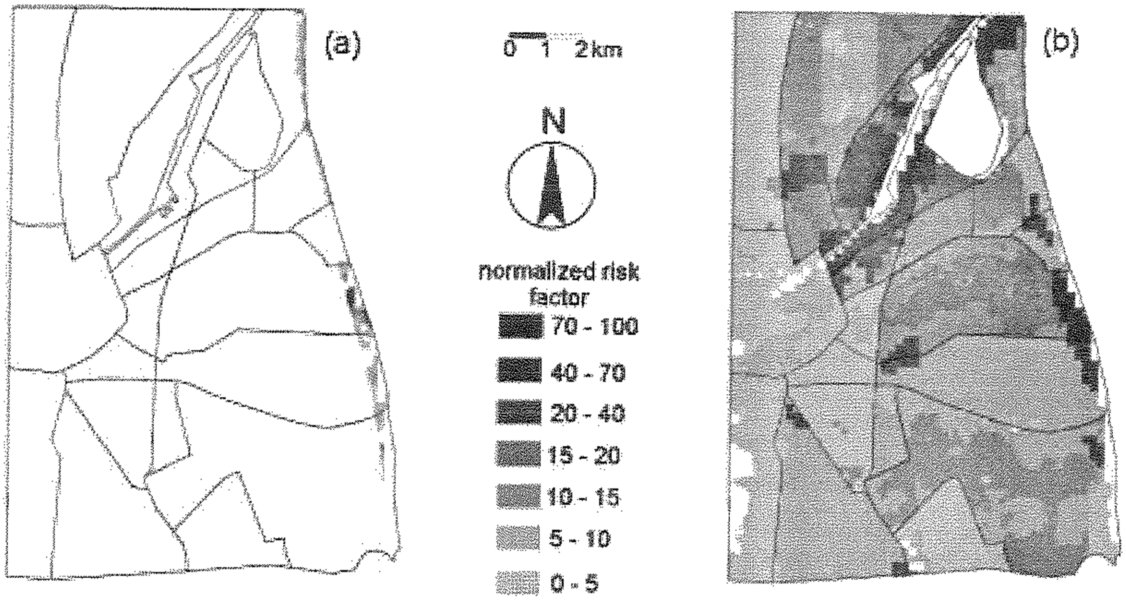

Figure 5: Normalized risk factor maps at Ravenna (a) with the present ground elevation and a 1 year return period storm and (b) in 2100 with the pessimistic land subsidence scenario and a 100 year return period storm.

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