THE IMPACTS OF CLIMATE CHANGE ON THE MEDITERRANEAN AREA:
REGIONAL SCENARIOS AND VULNERABILITY ASSESSMENT
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THE IMPACT OF CLIMATE CHANGE, SEA-STORM EVENTS AND LAND SUBSIDENCE IN THE ADRIATIC

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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.

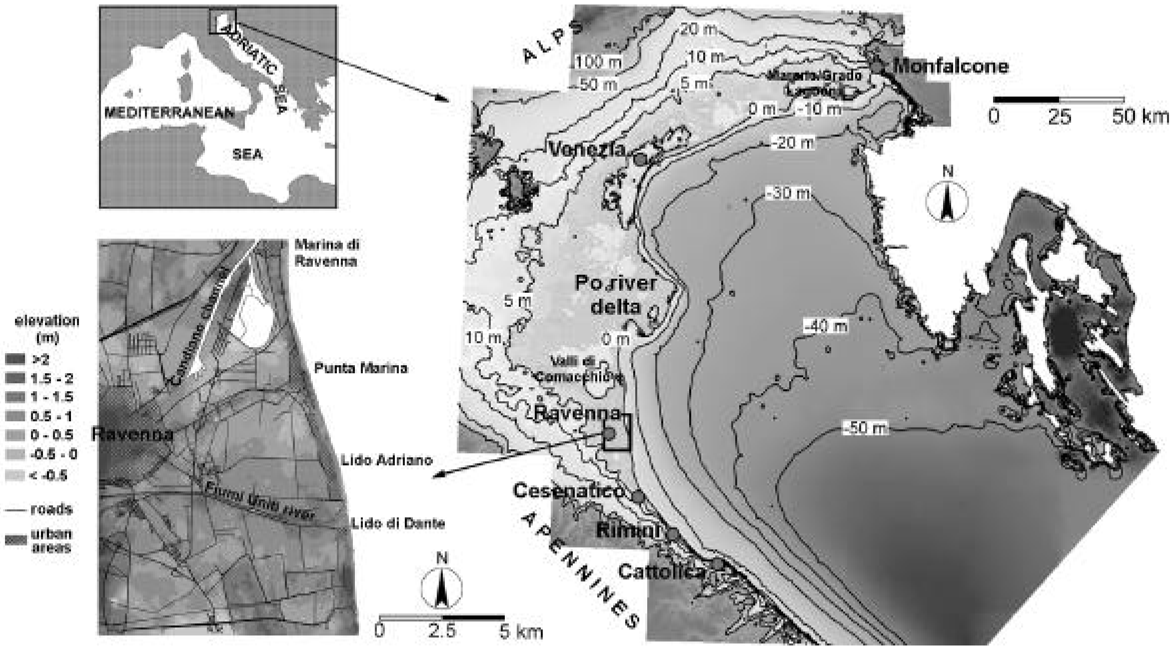

Figure 1. DEM of the Northern Adriatic Sea and the Eastern Po river plain, and the Ravenna coastal area generated on a regular grid of 200x200 m and 10x10 m, respectively.

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.

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 inundation 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 brief description of the integrated modeling system developed to account for the variation of both the ground and the sea level in the next 100 years, the approach followed to define the risk of sea inundation is described, and several maps are provided over the regional area as well as at the local scale of the Ravenna Municipality 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. MODELING ANALYSES

The prediction of each individual event is obtained with appropriate mathematical numerical simulations.

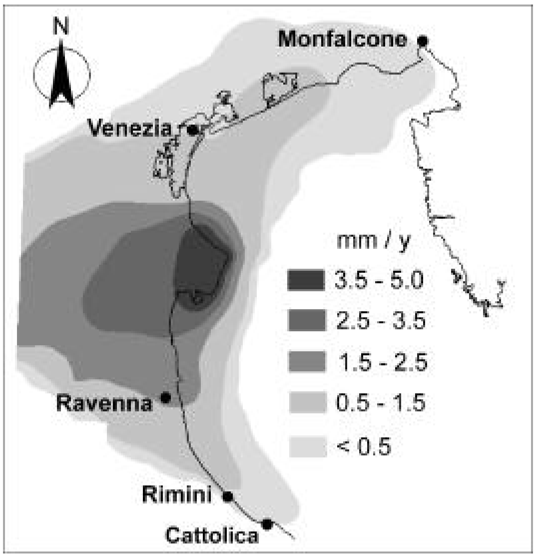

Figure 2. Natural average land subsidence as predicted over the next century in the coastal areas of the Upper Adriatic Sea (after Gambolati and Teatini [1998]).

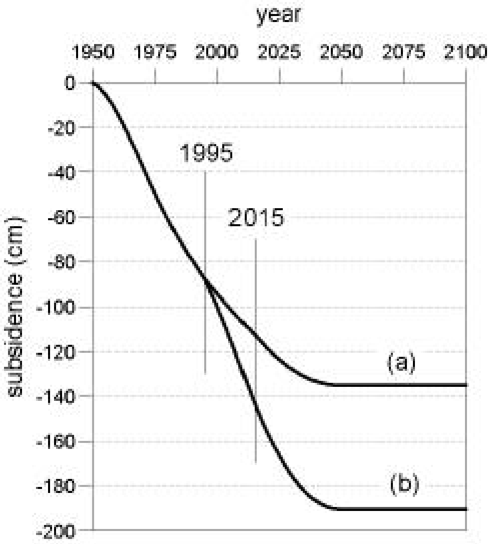

Figure 3. Simulated land subsidence at Ravenna with (a) the optimistic and (b) conservative groundwater pumping scenarios (after Gonella et al. [1998b]).

2.1 LAND SUBSIDENCE MODELS

The prediction of natural land subsidence, assessed in 0.5 mm/year at Venice, 2-2.5 mm/year in the Ravenna area and 4-5 mm/year in the Po river delta (Figure 2), is obtained with 1-D nonlinear finite element models of soil compaction driven by unsteady groundwater flow in the accreting sedimentary basin underlying the Upper Adriatic Sea during the last 10^6 years [Gambolati and Teatini, 1998].

Land settlement due to water withdrawal from the multiaquifer system underlying the Romagna region (extending south of the Po river delta) is predicted by coupling a 3-D finite difference hydrologic-flow model with a 1-D finite element consolidation model. Both models are calibrated using the piezometric decline and subsidence records of the last 50 years (of the order of some tens of meters and centimeters, respectively), and are applied with two realistic scenarios of water pumping, one optimistic and another more conservative. In the most critical areas the prediction indicates an anthropogenic land settlement of the order of 1 m (Figure 3) in the next century [Gonella et al., 1998b].

Land subsidence caused by gas production is estimated by a 3-D nonlinear poro-elastic finite element model. The model is applied to the Angela-Angelina gas field, located offshore in front of Ravenna at a depth between 3000-4000 m, and predicts a final settlement of about 15 cm of the coastal area which lies above the reservoir (Figure 4). Based on the results from the simulation of the similar field of Dosso degli Angeli located north of Ravenna, the coastland subsidence shown in Figure 4 is conservatively doubled to account for the compaction of the deep aquifer hydraulically connected to the depleted gas-bearing formations [Teatini at al., 1998].

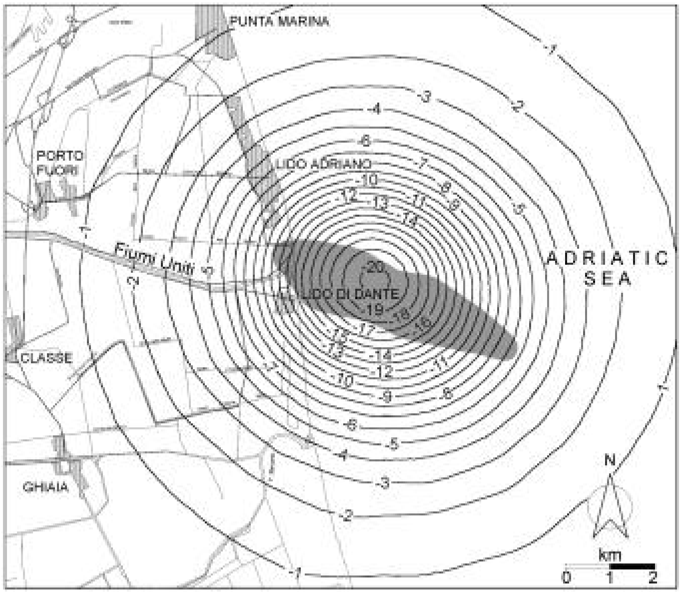

Figure 4. Land subsidence (cm) over Angela-Angelina gas field due to reservoir compaction in 2014 (after Teatini et al. [1998]).

2.2 HYDRODYNAMIC AND WAVE MODELS

The forecast of the mean sea level rise due to storm effects is made by taking into account tides, storm surges and wave set-up.

The Adriatic Sea model to simulate tides and storm surges is built from a 2-D depth averaged model, with a resolution of 6x6 km [Yu et al., 1998]. The model is mainly driven by the boundary forcing at the southern opening made from seven tidal components and by the atmospheric forcing over the whole basin. Storm surges are simulated by taking into account the effects of both the atmospheric pressure gradients and the winds blowing over the sea surface.

The wave climate during an extreme event is calculated from wind data in the Adriatic Sea using the WAM model on a 12x12 km grid [Decouttere et al., 1998a]. The WAM model is a third generation wave model established by the WAM group in 1988, and is based on the principle that a sea state is a superposition of a large number of sinusoidal components each having a different frequency and running in a different direction. The wave set-up has been determined by using the significant wave height, the wave period and the directional spreading factor of the radiation stress.

The hydrodynamic and wave models are calibrated over seven selected historical storms occurred in the period 1986-1992. As an example, Figure 5 gives the results from the WAM model for the storm of January 31, 1986. The forcing factors of the most severe event, i.e. the one that has produced the highest surge level along the Ravenna coast, and is characterized as a “scirocco” type storm with the wind blowing from the south - south-east direction at a moderate speed, a long fetch and a duration of several days, have been increased so as to obtain expected extreme levels with 1, 10 and 100 year return periods. These levels turn out to be equal to 1.5, 2.0 and 2.5 m, respectively, along the Ravenna shoreline. The extreme surge level in the Upper Adriatic Sea predicted in 2100 for a storm with a 100 year return period is shown in Figure 6.

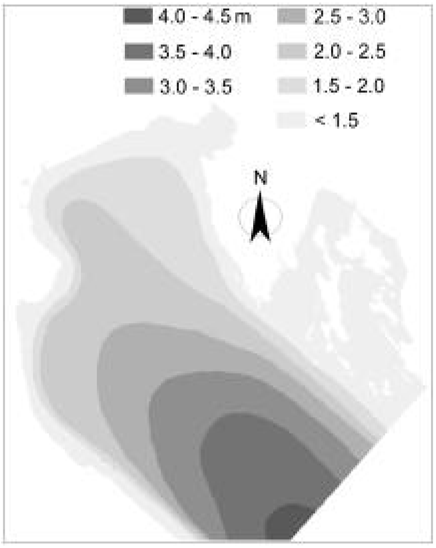

Figure 5. Output (significant wave height) of the WAM model applied to the Upper Adriatic Sea for the storm of January 31, 1986 (after Decouttere et al. [1998a]).

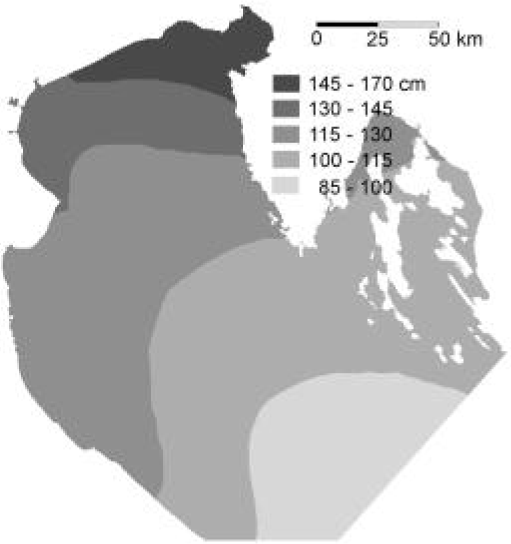

Figure 6. Map of the storm surge in the Upper Adriatic Sea for a meteo-marine event with 100 year return period (after Yu at al. [1998]).

2.3 SEA LEVEL RISE DUE TO GLOBAL CLIMATE CHANGE

Sea level rise due to global climate change is taken from the evaluation by IPCC 92 (Intergovernmental Panel on Climate Change) [Wigley and Raper, 1992] and reconfirmed four years later by Raper et al. [1996]. Wigley and Raper [1992] provide an estimate of sea level rise ranging from 15 to 90 cm, with a best guess of 48 cm in 2100 (Figure 7). The middle profile of Figure 7 is used in the present study.

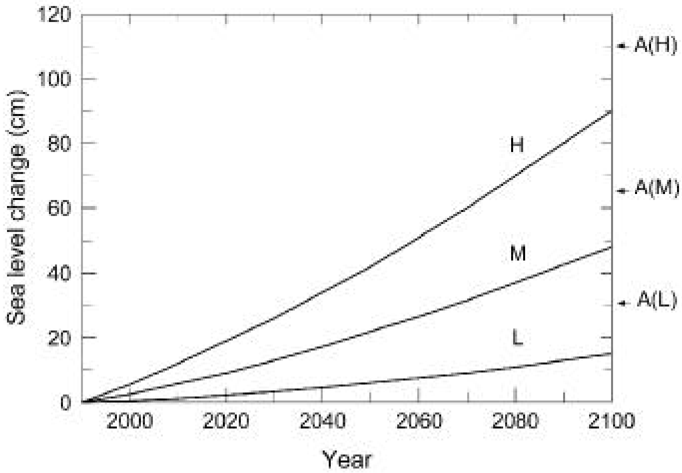

Figure 7. Predicted sea level rise from IPCC 92's "scenario a" by Wigley and Raper [1992]. Corresponding results in 2100 for IPCC 90 "business as usual scenario" are included on the right.

3. 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 6x6 km grid, primarily 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 neighboring coastland on a 200x200 m grid (Figure 1) used in the wave refraction [Decouttere et al., 1998b] and the littoral morphodynamic [Gambolati at al., 1999] models. To provide a more accurate representation of the coastal area, a DEM with a resolution of 10x10 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 200x200 m regular grid.

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:

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

with:

$$H_t = 1-(1-1/rp)^t$$

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 (200x200 m and 10x10 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:

$$R = I \; H_t \; E \; V \qquad (2)$$

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 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].

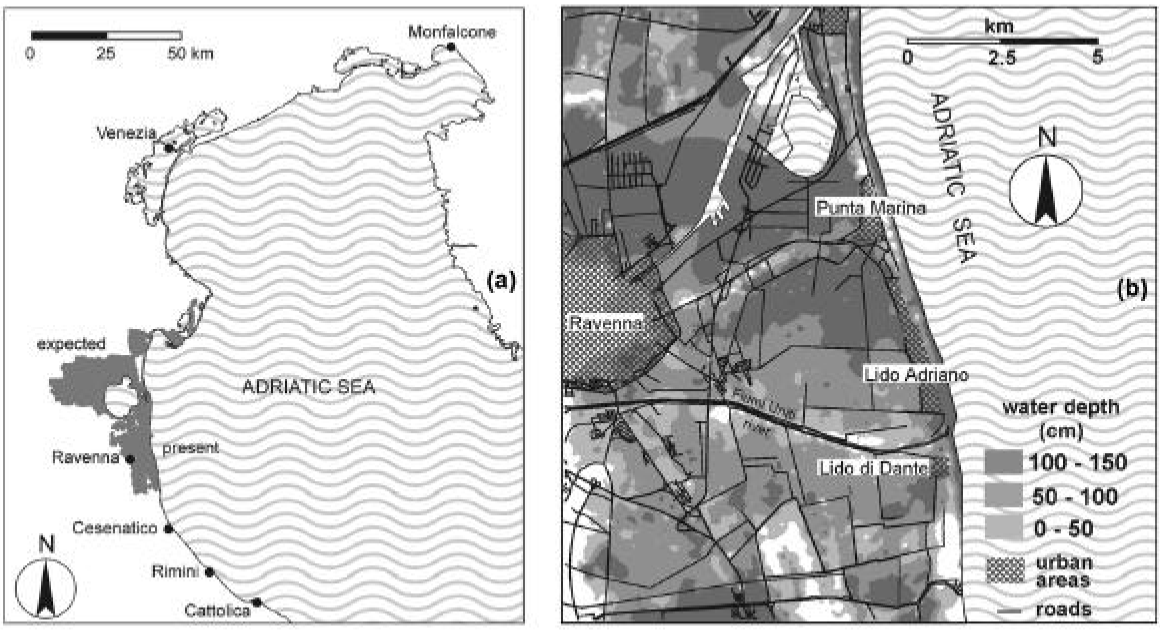

Figure 8. (a) Potential regression of the Northern Adriatic coastline in 2100 with the pessimistic anthropogenic land subsidence scenario (after Gonella et al. [1998a]); (b) projected flooded areas of the Ravenna coastland in 2100 with the same land subsidence scenario (after Gambolati et al. [1999]).

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 8a 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 at 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 8b, which also gives the water depth.

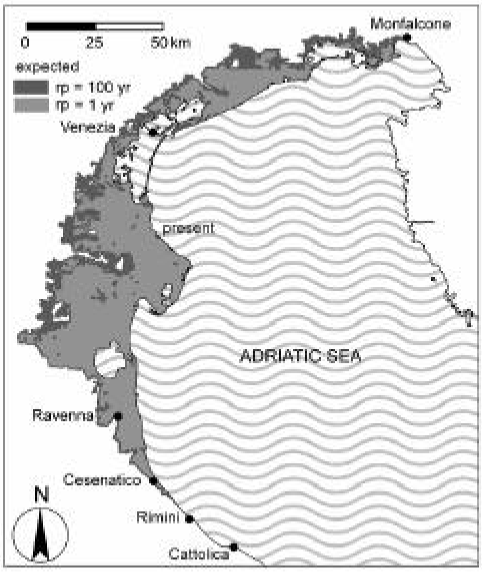

Figure 9. Potentially flooded lowlands in 2100 with a sea storm of 1 and 100 year return period and the pessimistic anthropogenic land subsidence scenario (after Gonella et al. [1998a]).

Occasionally flooded lowlands in 2100 with the pessimistic land subsidence scenario are shown in Figure 9 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 10. Similar maps are shown in Figure 11 at the local scale for the site of Ravenna where eq. (2) is used instead of eq. (1). Inspection of Figures 10 and 11 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 11a) compared to the regional result (Figure 10a).

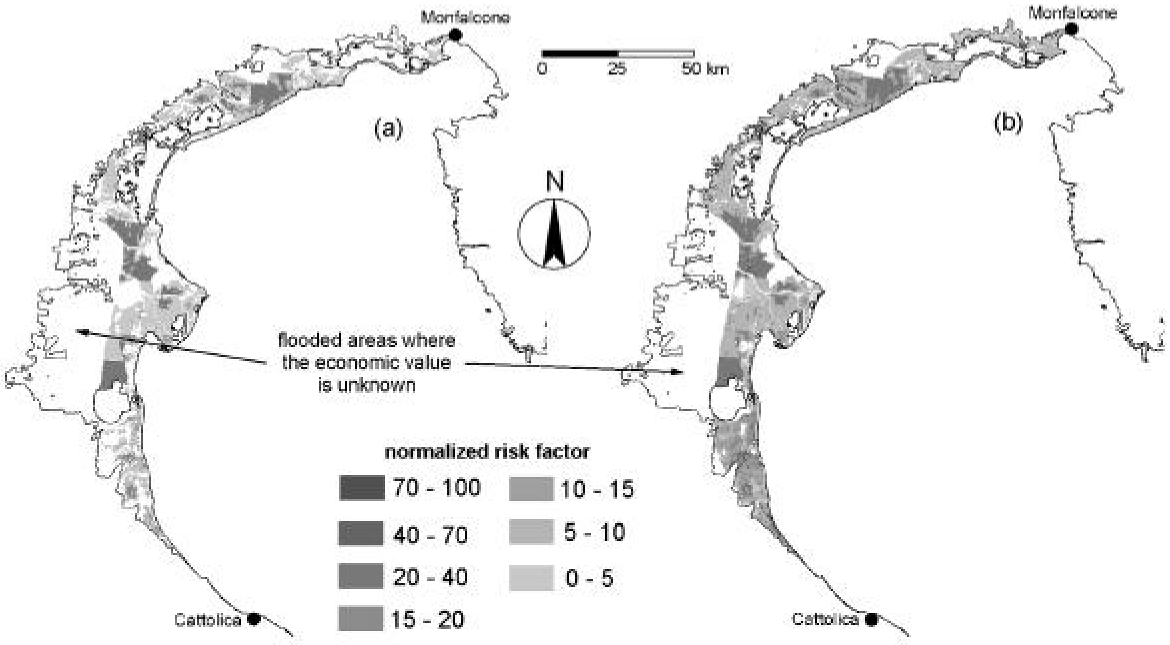

Figure 10. Potential normalized risk factor maps (a) with the present ground elevation and a 1 year return period storm and (b) in 2100 with the pessimistic land subsidence scenario and a 100 year return period storm (after Gonella et al. [1998a]).

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;

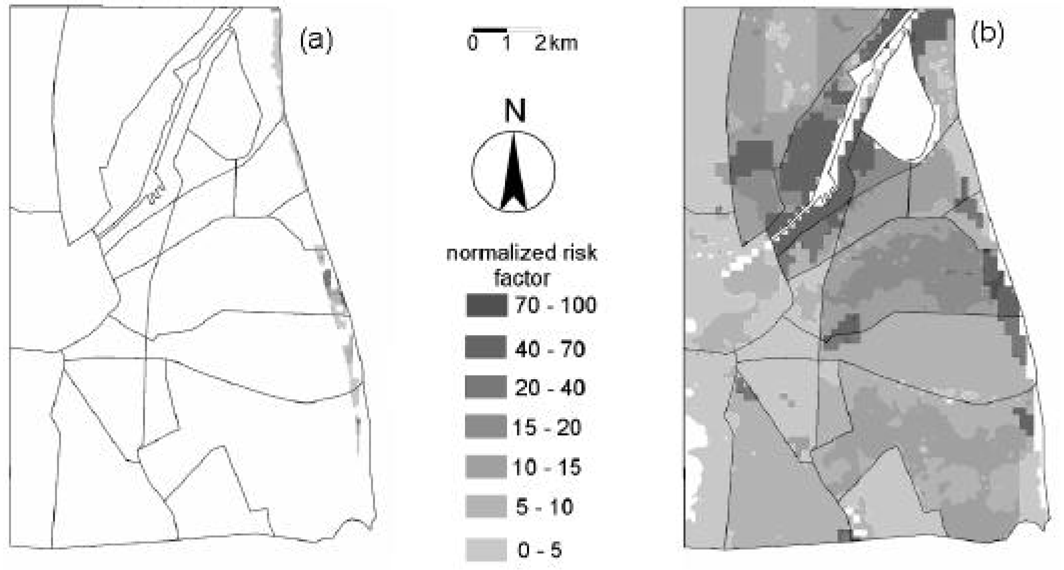

Figure 11. Normalized risk factor maps at Ravenna (a) with the present ground elevation and a 1 year return period storm and (b) in 2100 with the pessimistic land subsidence scenario and a 100 year return period storm (after Gonella et al. [1998a]).

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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