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Representing future urban and regional scenarios for flood hazard mitigation

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ABSTRACT

In this paper we analyse urban and regional growth trends by using dynamic spatial models. The objective of this approach is twofold: on the one hand to monitor sustainable development trends and on the other hand to assess flood risk in urban areas. We propose the use of future urban scenarios in order to forecast the effects of urban and regional planning policies. This paper is organised in two parts. In the first part we analyse a study case in Friuli-Venezia Giulia (FVG) Region in northern Italy. We analyse several spatial indicators in the form of maps describing population growth, spatial patterns, and the historical growth of built-up areas. Then we show the results of a dynamic spatial model for simulating land use scenarios.

In the second part of the paper we show some preliminary results of a pilot study case. Two future scenarios produced by the model were used for a flood risk assessment in Pordenone (one of the four provinces of FVG). In the last 100 years Pordenone has suffered several heavy floods. The disastrous consequences of those heavy floods have shown how vulnerable this area is. The flood risk analysis is based on a hydrological hazard map for the Livenza River catchment area. Early results of this study show that the main driving force of natural disasters damage is not only increasing flood hazard, but increasing vulnerability, mainly due to urbanisation in flood prone areas.

Keywords: Flood hazard, urban development, urban simulations, urban scenarios.

1. INTRODUCTION

In this paper we analyse urban and regional growth trends by using dynamic spatial models. The objective of this approach is twofold: on the one hand to monitor sustainable development trends and on the other hand to assess flood risk in urban areas. We propose the use of future urban scenarios in order to forecast the effects of urban and regional planning policies. In the last 20 years the extent of built-up areas in Europe has increased by 20%, exceeding clearly the 6% rate of population growth over the same period (EEA, 2002). The situation is still more worrying seeing that in some European regions the population has even decreased in the last 20 years, whilst the built-up areas continue to grow mainly in suburban and exurban areas. This trend contributes to unsustainable development patterns, and moreover, the exposure to natural hazards is increasing in large regions of Europe.

This paper is organised in two parts. In the first part we analyse a study case in Friuli-Venezia Giulia (FVG) Region in northern Italy. We analyse several spatial indicators in the form of maps describing population growth, spatial patterns, and the historical growth of built-up areas. Then we show the results of a dynamic spatial model for simulating land use scenarios. The model is based on a spatial dynamics bottom-up approach, and can be defined as a cellular automata (CA)-based model. Future urban scenarios are produced by taking into account several factors –e.g. land use development, population growth or spatial planning policies–. Urban simulations offer a useful approach to understanding the consequences of current spatial planning policies.

Inappropriate regional and urban planning can exacerbate the negative effects of extreme hydrological processes. Good land management and planning practices, including appropriate land use and development control in flood-prone areas, represent suitable non-structural solutions to minimise flood damages (Barredo et al., 2004). The overall effects of these measures in terms of both sustainable development and flood defence can be quantified with the proposed modelling approach.

In the second part of the paper we show some preliminary results of a pilot study case. Two future simulations produced by the model were used for a flood risk assessment in Pordenone (one of the four provinces of FVG). In the last 100 years Pordenone has suffered several floods. In that period the two major events were the heavy floods of 1966 and 2002. The disastrous consequences of those heavy floods have shown how vulnerable this area is. Early results of this study show that the main driving force of natural disasters damage is not only increasing flood hazard due to climate change, but increasing vulnerability, mainly due to urbanisation in flood prone areas.

2. SPATIAL DYNAMICS IN FVG: A TERRITORIAL APPROACH

In the last fifty years the FVG region underwent dramatic transformations. FVG passed from being a rural area into a dynamic urban region. It is part of the "North-East" of Italy where vast changes have occurred in demographic terms and population movements. It can be seen in the past and current settlement structure and land use pattern. FVG accommodates 1,183,000 inhabitants on a surface of approx. 7,850 km^2. It is divided up into the provinces of Udine, Pordenone, Trieste and Gorizia. The provinces of Udine and Pordenone account for the 91% of the FVG's area. On the other hand, the municipalities of the five biggest cities –Trieste, Udine, Pordenone, Gorizia and Monfalcone– account only for the 35% of the total population of FVG in 2000 (*FVG Region, n.d.*).

In terms of land use, the territory of FVG could be subdivided on large and scarcely populated mountain and footslope areas, with share of natural lands over 75% in the north (Figure 1). In the southern lowlands the predominant landscape is composed by extensive agricultural and urban land uses, with a low share of natural areas –under 25%–. This pattern has remained stable during the study period of fifty years, showing very slow dynamics in mountain areas and large-scale changes in urban land use on the plain area.

The distribution of settlements in the FVG region has a structure based on the following main elements:

- core cities –Pordenone, Udine, Gorizia, Monfalcone and Trieste– maintaining the industrial, commercial and transport activities along the west-east axis in the lowland;
- a structure composed by urban and rural settlements of medium, small and very small size, on the plain and on parts of the footslope areas;
- relatively isolated and low populated mountainous areas –i.e. northern areas- (Figure 1B).

Driven by different factors, demography in FVG shows a drop in population of 37,529 inhabitants (3.1%) in the last fifty years (*ISTAT data*). The population dynamics can be differentiated in terms of territory. In mountains and footslope areas there has been a systematic depopulation process. On the other hand, the lowland areas have showed a population increase in province centres in the 50's and the 60's related to the Italian economic boom. The late shift of economic activities to the outskirts of the main centres led to population growth for those more peripheral municipalities from the 90's (Figure 1A).

2.1 Settlement dynamics

In line with the rest of Northern Italy, in the last fifty years the settlements structure in FVG has shown several changes. The traditional historical heritage polarised pattern **–**i.e. centre-periphery**–** could be still observed in the 50's and the 60's. Then it changed to node-linear development of first-ring conurbation around major cities and transport links. Such a consequence of that development style in the 70's and the 80's is the widespread area development (*MOLAND, 2000*). The latter corresponds to the growth of urbanised areas in small and medium size municipalities in the 90's (*Regione Autonoma Friuli-Venezia Giulia, 1997*). By analysing statistical data, it could be concluded that after a period of centralisation in the 50's and 60's, the main cities of FVG entered in the de-centralisation stage at the beginning of the 80's (see Table 1 and Figure 1A).

Cities	**1951-1971**	**1971-1981**	**1981-1991**	**1991-2000**
Trieste	-0,2	-7,2	-7,8	-6,9
Udine	38,2	1,2	-2,8	-3,9
Gorizia	5,3	-2,9	-7,1	-3,7
Pordenone	74,3	10,0	-4,0	-2,8
Monfalcone	20,6	2,0	-10,0	-0,6
Tolmezzo	21,0	3,8	1,5	-0,3

Table 1. FVG: Variation of resident population in the main urban centres in percentage

Municipality size (inhabitants)	**1950's**	**1970's**	**1980's**	**2000**
0-2000	2.65	5.65	6.59	7.39
2000-5000	3.78	6.87	8.25	9.01
5000-10000	6.77	12.23	15.65	17.24
10000-20000	8.53	15.84	18.34	19.89
> 20000	29.6	41.4	45.4	48.9

Table 2. FVG: Average ratio of urbanised/non-urbanised land by municipality size in percentage

In FVG both the rising standards of living, on the one hand, and the increased mobility on the other, led to a de-centralisation process, i.e. the formation of the so-called 'diffused city'. It can be defined as a multi-centered and networked urban structure with 'softened' functional hierarchies (*Bessusi et al., 1998*). In the period under consideration the ratio of urbanised land in FVG doubled in the 50-80's period and continues to grow (Table 2 and Figure 2). In some medium size municipalities a triplication of urbanized land could be observed.

The aforementioned trends are accompanied by a dramatic decrease of population density in residential areas. This process can be seen in Figure 1A in the four capital cities of FVG. Furthermore, in most of cases the new residential areas show a discontinuous/scattered spatial pattern as can be seen in Figure 1B and 2.

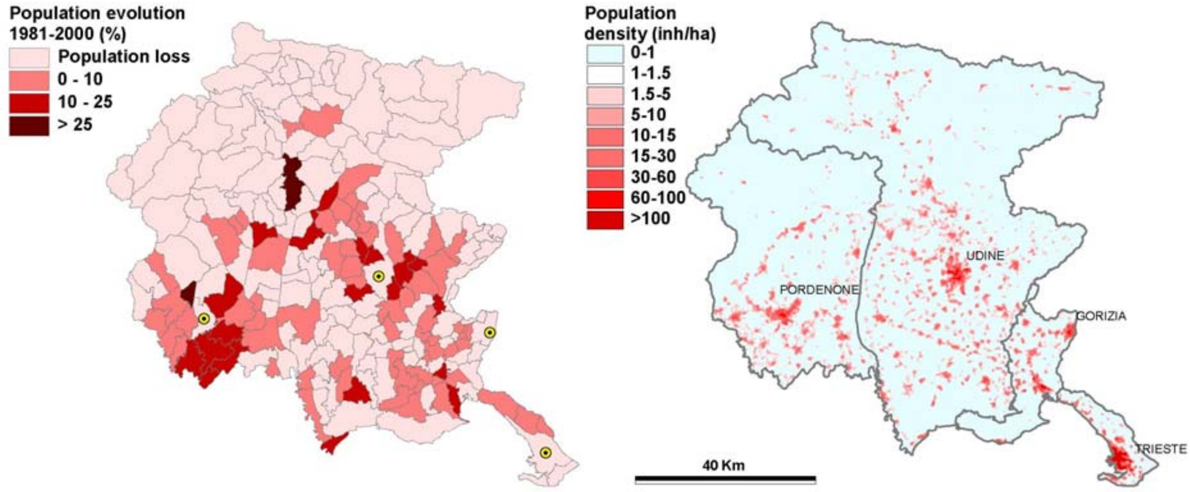

Figure1. FVG: Left A) Population evolution 1980-200 by municipalities.
Right B) Population density in 2000.

3. THE DYNAMIC SPATIAL MODEL FOR URBAN SIMULATIONS

The theoretical formalism of CA was introduced in the late 1940's by the mathematicians John Von Neumann and Stanislaw Ulam. However, it was in the late 1960's when John Conway developed the first CA: Game of Life. CA are a joint product of the science of complexity and the computational revolution (*Couclelis, 1986*). CA can be defined as discrete dynamical systems, and are often described as the spatial counterpart of non-linear differential equations (*Barredo et al., 2003*). Such equations, although being fully deterministic, are able to produce very complicated behaviours (*May, 1976; Glass, 2001*) e.g. bifurcations, stable limit-cycle oscillations and chaos. Thus it is not surprising that CA may simulate complex processes in 2-dimensions. In CA complexity emerges from iterations of very simple rules applied at local level in simple individuals i.e. cells. Hence the state of each cell in an array depends on the previous states of the cells within a neighbourhood, according to a set of transition rules.

CA have a remarkable potential for modelling complex spatio-temporal processes. Very simple CA can produce surprisingly complex forms through a set of basic rules. An understanding of CA leads to the conclusion that the description of complex systems need not be themselves complex, let alone "complicated" (*May, 1976; Couclelis, 1988*). Despite it, a main concern is how to get in use all the modelling potential of CA for urban processes. To this end several approaches have been so far proposed. The first one was the work of Prof. Tobler (*1970*). However, it was in the last years when CA have gained popularity as modelling tool for the simulation of spatially distributed processes. To this end several approaches have been proposed (*Batty and Longley, 1986; 1987; Clarke and Gaydos, 1998; White and Engelen, 1993; 2000; White et al, 1997; 1999*).

The model used in this study is the MOLAND model (see *Barredo et al., 2003, 2004, Lavalle et al., 2004*). The model, specifically developed for urban and regional development assessment, is based on a spatial dynamics bottom-up approach, and can be defined as a cellular automata (CA)-based model (*Barredo et al., 2004*). The model includes as input several georeferenced datasets for the future simulation of urban areas. Thus, future urban scenarios can be produced by taking into account the trends in land use pattern, population growth and spatial planning policies. Urban simulations offer a useful approach to understanding the consequences of current spatial planning policies.

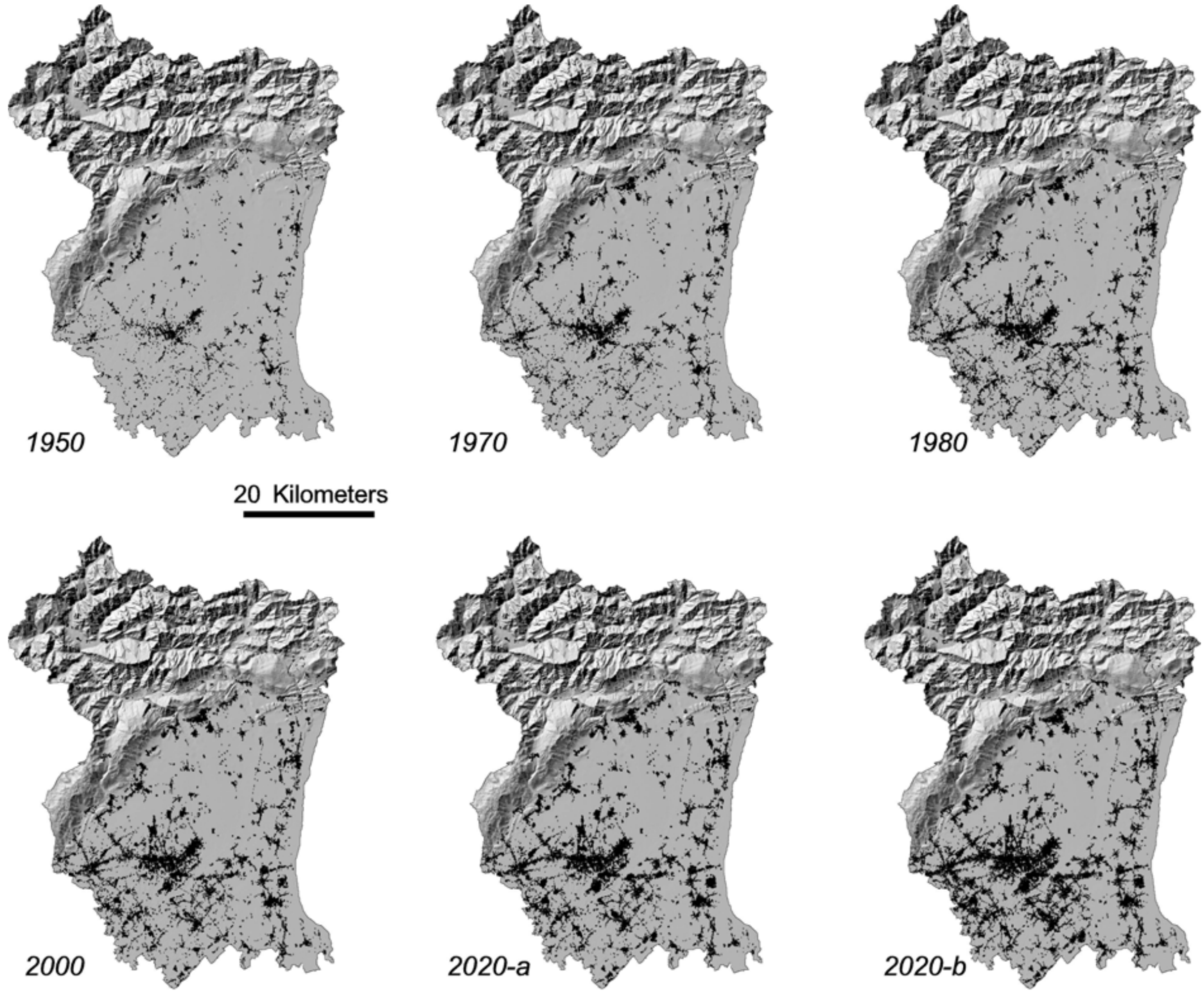

Figure 2. 1950-2000 built-up areas in Pordenone Province. 2020-a and 2020-b are two simulations for 2020 year. 2020-a) Simulation showing Organic growth 2020-b) Simulation showing Spontaneous growth (built-up areas in black).

In this model the probability that an area changes its land use is a function of several factors acting together at a defined time step. The factors that participate in the dynamics are: land use neighbourhood effect, land use zoning regulations, land use suitability and accessibility. The model includes as well a stochastic parameter. It has the function of simulating the degree of stochasticity that is characteristic in most social and economic processes such as cities. Still the factor that makes the system work like a nonlinear system is the iterative neighbourhood effect, whose dynamism and interactivity can be understood as the basis of the land-use dynamics. The iterative neighbourhood effect is founded in the “philosophy” of standard CA, where the current state of the cells and the transition rules define the configuration of the cells in the next time step. An in deep description of the MOLAND model can be found in *Barredo et al. (2003; 2004)*.

The spatial and demographic trends identified in the previous section were represented in the simulation model for Pordenone. Within this approach it is feasible a realistic representation of the future land use in Pordenone based in such trends. The model for Pordenone was calibrated and tested by using time-series data on land use (see *Barredo et al. 2003; 2004*) and through a set of spatial metrics. Two future simulations have been produced until 2020. The first one (2020-a in Figure 2) represents a fairly compact development style for the urban nuclei in the Province of Pordenone. A second simulation more in line with the past trends shows a more scattered development style for the new built-up areas (2020-b in Figure 2). The results of the simulations are realistic and achieve a high level of detail, showing in the second case the effects of current trends on the future urban land use in Pordenone. Note that in Figure 2 the original land use legend of 24 classes have been grouped into two classes: built-up and non built-up areas. Nevertheless, it is noticeable the capability of the model for simulating several types of urban land-use classes simultaneously.

3.1. Future urban scenarios in Pordenone Province

The CA-based model was calibrated by using historical (1980) and reference (2000) datasets which were compiled for FVG. The simulation for the period 1980–2000 initiates using the historical datasets for the year 1980 in order to test the simulation results using the reference datasets for 2000. With this approach we tested the simulation by comparing the results with the actual land-use datasets.

An empirical and practical way for calibrate the model is to use historical datasets. Once the results of the calibration are satisfactory, the future simulation of land-use can be done using the parameters of the calibrated model. Assuming, however, that the interactions between land-use classes will remain stable during the simulated period. The increase or decrease in the number of cells for each land-use class in the modelled period of 20 years has been calculated from the historical and reference datasets.

Accuracy analyses based on spatial metrics and other procedures such Kappa coefficients were used in order to produce a fine-tuned version of the simulation. Another calibrated factor is the random perturbation. In general it is set to reproduce the degree of scatter in the urbanised area of the actual land-use map for 2000. In this case it is also fine–tuned to generate a sufficient number of new seed cells of various land-use classes in new locations such as rural areas, which will subsequently grow into, for example, new industrial, commercial or residential areas. The preliminary results are a useful demonstration of the extent to which the urban CA model can produce realistic simulations.

The two future scenario simulations produced for Pordenone cover a twenty-year period between 2000 and 2020, and were undertaken using the calibrated model. In this case the demands for each land use class were calculated on the basis of land-use growth trends from recent years. Built-up areas in Pordenone are expected to grow showing a similar pattern as in the last decades. During the past four decades it has grown continuously in a rather sparse way (see Figure 2, from 1950 to 2000). Yet, as expected, the initial land-use configuration drives to a great extent the actual urban form. The future land-use growth trends can be obviously altered by a number of factors such as changes in the economic climate or in the land use planning policies.

By using CA-based models it is possible to simulate different urban growth styles: Spontaneous, Diffusive, Organic, and Road-influenced (see *Clarke et al., 1997*), or a combination of them, which is likely what happens in real situations. The simulation 2020-a in Figure 2 is an example of Organic urban growth influenced by roads. It means that the new built-up areas spread outwards from existing built-up areas. Bigger is the existing built-up area, bigger will be the influence in the organic growth. The second simulation, 2020-b in

Figure 2, is an example of Spontaneous growth influenced by roads. In this case new built-up areas not necessarily lie adjacent to existing urbanised cells, however new urbanised cells fall close enough to existing urbanised cells. Spontaneous growth is more influenced by the stochastic parameter than the Organic ones, thus the allocation of new urban cells is less deterministic that in the previous case. In both cases the influence of roads is taking into account for the growth of new built-up areas.

The definition of land-use classes' demands is a key aspect considering that these demands will define in an important degree the spatial evolution in the simulations. All land-use classes are generally foreseen to grow in Pordenone. New residential, industrial and commercial areas are foreseen to grow mainly in peripheral neighbourhoods of the main urban clusters. From a visual point of view, the simulated maps maintain the general form of the existing built-up areas due to the initial conditions of transport network and land-use. The foreseen urban pattern appears to be realistic in both simulations. However, by taking into account the past trends showed in Figure 1 and commented in section 2, the more realistic simulation is that of Figure 2 2020-b –i.e. Spontaneous growth–. Despite it, in both simulations the form of the urban clusters has clearly developed and shows increased built-up nuclei in peripheral areas.

4. Flood risk assesment in Pordenone Province

We show in this section some preliminary results of a flood risk assessment carried out in Pordenone Province. Historical land use datasets and two future simulations were used for the risk assessment. Pordenone is a highly flood-prone area. Two heavy floods hit Pordenone in the last years, the floods of 2002 with 580 mm of rain in 36 hours, and the still worse flood of 1966, which can be described as the 100-year flood event.

The flood risk assessment is based on a flood hazard map for the Livenza River catchment area. The map has been produced by the regional Water Authority (Water Authority for the North Adriatic Rivers, 2003). This is a hydrological hazard map for the Livenza river catchment area. The map covers most of the flood prone areas of the Province. Four river flood hazard areas have been defined in that map (see: Water Authority for the North Adriatic Rivers, 2003; Brezger, 2004). The hazard areas have been mapped by using a two-steps approach. In the first phase all the areas prone to be flooded by a 100-year flood event were mapped (100-years rain event of 24-hours duration). In the second phase, the areas have been verified by using a bi-dimensional flood model and historical flood records. In the mapped hazard areas the height of the flood may reach not less than 1 meter in the case of a 100-years event. Next we show briefly the characteristics of the four flood hazard areas defined in the map (Figure 3A):

- **F**: Is the riverbed plus the immediately adjacent floodplain areas inside the dykes. This area is subject to frequently flooding;
- **Very high hazard** (P3): Areas close to the dykes, historically flooded by dikes failure;
- **High hazard** (P2): Areas along dykes and surrounding P3 areas. Critical areas in the case of a 100-years event;
- **Medium hazard** (P1): Areas flooded by past events and other flood prone areas.

By simple map overlapping it is worth noting the current built-up areas at risk of flood in the Livenza catchment area (Figure 3B). Moreover, in Figure 3C it can be seen that a number of dwellers are placed as well in flood hazard areas. Even if structural measures for flood protection have been undertaken in the last years in the Pordenone Province's floodplain, it is foreseeable a number dwellers and properties affected in the case of a new heavy flood in the area as such of 1966. It is also valuable to understand the problem from a historical perspective. Figure 4 shows the evolution in the last fifty years of the main urban land use classes located in the four flood hazard areas. The trends are clearly in line with the settlement dynamics studied in section 2.1. Residential discontinuous land use classes with low population density were the main contributors to the increase in exposure to floods in Pordenone. On the other hand, the areas developed in flood–prone areas were in most of cases placed in hazard classes medium (P1) and High (P2), as can be seen in Figure 5.

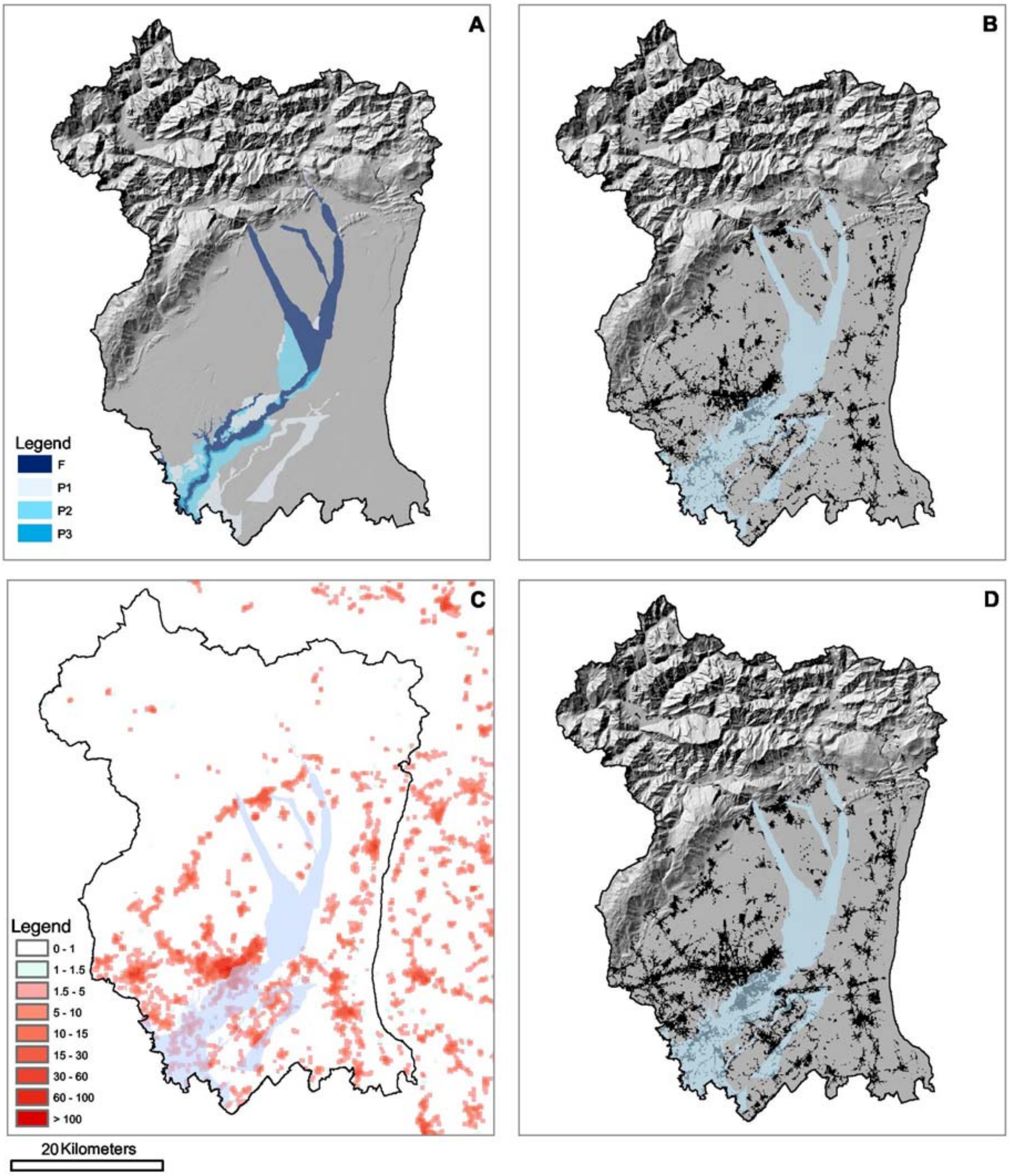

Figure3. Pordenone Province. A) Flood hazard areas: F (rived bed), P1 (medium hazard), P2 (high hazard) and P3 (very high)). B) Built-up areas in 2000 (in black) and overall flood hazard areas. C) Population density (inh/ha) in 2000 and overall flood hazard areas. D) Simulated built-up areas in 2020 (in black) and overall flood hazard areas.

The trends show in Figures 4 and 5 confirms the initial statement about the increasing exposure to floods due to new urban development. In this study the flood hazard areas remained stable over time –which may change under CC conditions-, however the flood risk is increasing over time. Thus, the most worrying situation could be the result of increased vulnerability due to urbanisation in flood-prone areas and the increasing frequency and magnitude of extreme weather events due to climate change (Christensen and Christensen, 2003). This work confirms some ideas about that in Europe the main driving force of natural disasters damage is not only increased hazard due to climate change, but increasing vulnerability, mainly due to extensive building in flood prone areas (CEC, 2004; UN, 2004).

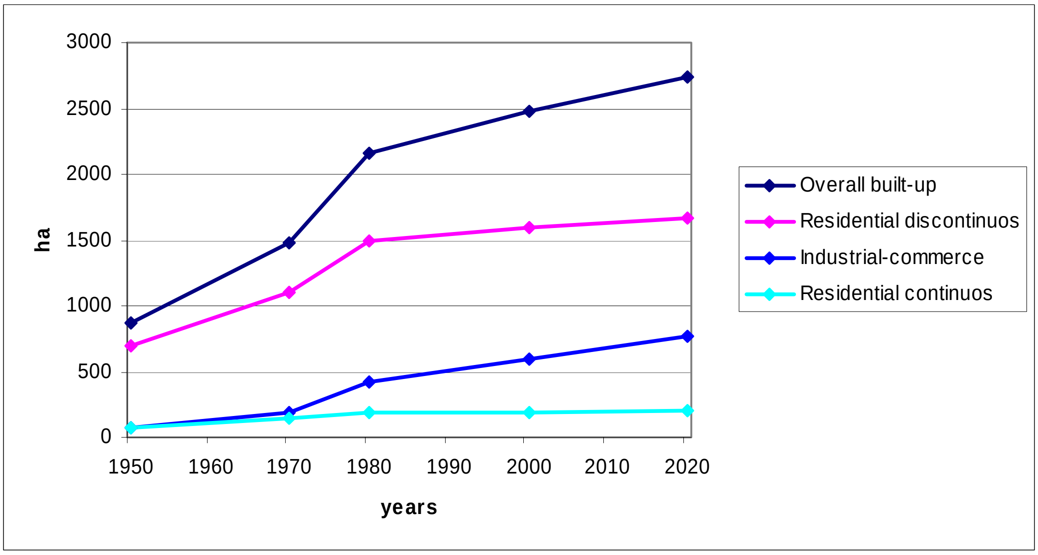

Figure4. Pordenone Province: Land use classes in flood-prone areas over time and forecast until 2020.

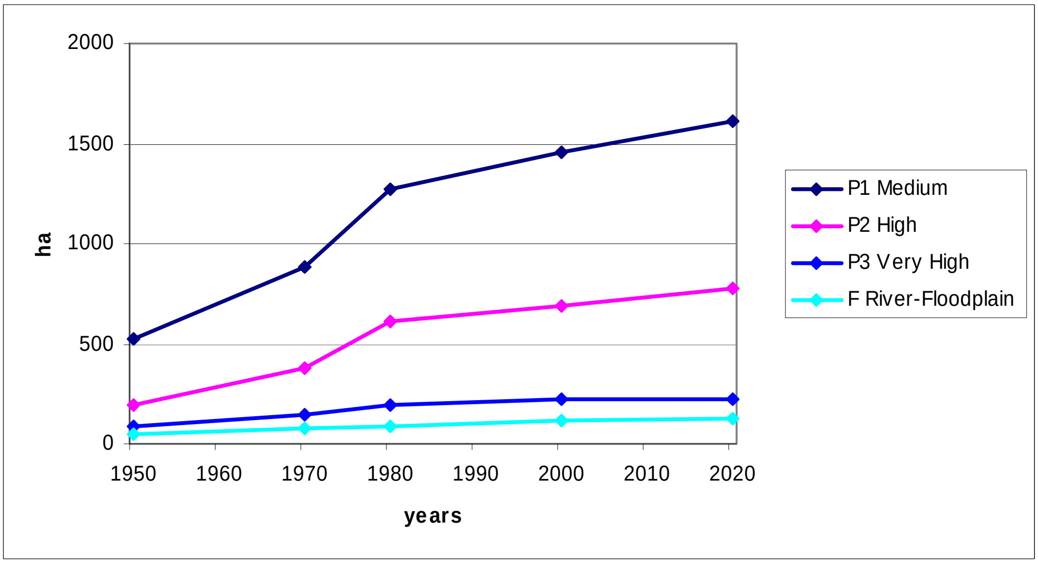

Figure5. Pordenone Province: Built-up by flood hazard areas over time and forecast until 2020.

4.1 Future flood risk assessment

Figure 3D shows the results of the simulation 2020-b (see section 3) overlapped with the flood hazard areas for the Livenza river catchment area. In addition Figures 4 and 5 show the assessment towards the future of that simulation –which is in line with the land use trends of the last 20 years-. It is not surprising that the flood risk is increasing due to of urbanisation in flood-prone areas. It has been happened as well in the last fifty years. Obviously this is one of the keys of the problem. Thus, can we imagine for a moment the scenario of a increased flood hazard –in frequency and magnitude- due to CC and a increased exposure due to urbanisation in this area?

5. DISCUSSION

Within this approach several development scenarios that consider the effects measures and instruments for flood mitigation can be produced. Thus it is feasible to include the effects of land-use change including regional development –e.g. urban expansion- and the effects of CC on flood hazard and risk. The methodology can produce several alternative scenarios by simulating several combinations of technical and spatial measures synergised in order to minimise the flood risk in urban areas.

The main outcomes of this approach can be summarised in:

- Flood hazard and risk mapping
- Forecasted risk maps (based on future climate, extreme events and development scenarios)
- Realistic assessment of spatial planning, spatial and technical measures for flood mitigation

The proposed approach is a very useful planning tool capable of taking into account flood risk trends and possible hazard mitigation measures. The inclusion of realistic future scenarios of urban areas and regions is an interesting option for urban planners and decision-makers. By using such simulations it is possible to better identify the technical and spatial measures and instruments to be implemented or reinforced in order to cope with the increasing risk of floods in Europe.

On the other hand, we can summarise the findings of this article in that there are several elements which take part in flood related disasters. Among the drivers one is the triggering factor i.e. extreme precipitation and consequently extreme river discharge. However, some other "non-natural" issues are as well part of the process:

- Socio-economic trends such as land use and population patterns (i.e. urban decentralisation, sprawl)
- Increased wealth who may produce low density housing in exurban vulnerable areas (i.e. floodplains)
- Low level of awareness among the public in understanding the impacts of CC
- Low level of awareness among policy makers, decision makers and other stakeholders on the impacts of CC
- Lack or loose application of adaptation measures to the impacts of CC in the spatial planning framework (mainly non-structural measures)
- Lack of information and studies/mapping of flood risk areas
- The financial framework of municipalities is sometimes in contrast with the implementation of adaptation strategies to CC
- One key danger in the use of technical measures is the false perception of security they give to dwellers. Moreover, those measures may encourage new developments is flood prone areas instead of minimise it or end to building definitively

The interplay and coordination of measures –technical and spatial- and instruments is the best and likely only way to address the new flood threats poses by CC. Moreover, it is necessary to have a holistic catchment planning approach for adaptation to floods. Reducing of flood losses must be considered using the basin as the basic planning unit (UN, 2004).

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