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Article

Land Use Scenario Modeling for Flood Risk Mitigation

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Abstract: It is generally accepted that flood risk has been increasing in Europe in the last decades. Accordingly, it becomes a priority to better understand its drivers and mechanisms. Flood risk is evaluated on the basis of three factors: hazard, exposure and vulnerability. If one of these factors increases, then so does the risk. Land use change models used for ex-ante assessment of spatial trends provide planners with powerful tools for territorial decision making. However, until recently this type of model has been largely neglected in strategic planning for flood risk mitigation. Thus, ex-ante assessment of flood risk is an innovative application of land use change models. The aim of this paper is to propose a flood risk mitigation approach using exposure scenarios. The methodology is applied in the Pordenone province in northern Italy. In the past 50 years Pordenone has suffered several heavy floods, the disastrous consequences of which demonstrated the vulnerability of the area. Results of this study confirm that the main driving force of increased flood risk is found in new urban developments in flood-prone areas.

Keywords: land use modeling; flood risk; flood hazard; urban growth

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1. Introduction

This paper presents a methodological approach for the integration of land use scenario modeling and flood risk assessment. It is widely agreed that natural risks are the product of hazard and its consequences [1]. Within this approach flood risk is a function of hazard, exposure and vulnerability [1-3]. If any one of these factors increases, then risk increases. In this framework, hazard is defined as the occurrence of a hydrologic flood event with a given probability. Exposure is among the anthropogenic factors that contribute to flood risk, and it is usually represented by the population and assets located in hazardous zones. Vulnerability is defined as the susceptibility of the exposed structures when in contact with water, *i.e.*, the extent to which the subject matter could be affected by the hazard. It is accepted that flood risk has grown in many areas of Europe [4], and that the temporal evolution of exposure and vulnerability have to be fully assessed especially in urban areas [5]. In the past decades the increase in exposure, due to new urban developments and the associated land use dynamics, is recognized as one of the main causes of increasing flood risk in Europe [4,6]. Conversely good land management and planning practices, including land use regulations, represent suitable non-structural solutions to minimise flood losses [7-9].

European policies are recently tackling the issue of reducing exposure and vulnerability to flooding [10]. Flood risk management has shifted from structural defence against floods to a more comprehensive approach. Within this approach the full disaster cycle of prevention, protection, preparedness, response and recovery, is considered in the management and prevention of flood disasters. The full implementation of integrated flood risk management, will, however, take some time. It will therefore be essential to further reduce exposure and vulnerability to floods in order to reduce flood risk. Actions oriented at avoiding development in flood-prone areas, adapting future development to the risk of flooding, improving protection measures and promoting appropriate land-use, agricultural and forestry practices are all necessary in the short term.

In the proposed methodology, a cellular automata-based (CA-based) model [11-13] is used for exploring different land use development paths. The impacts and effectiveness of various urban and regional planning instruments and policies can be assessed by means of scenario simulation. Thus, the exposure component of flood risk can be estimated and measures and policies aimed at flood mitigation can be developed and duly tested. Until recently this type of approach has been neglected in strategic planning for flood hazard mitigation. Ex-ante assessment of flood risk in urban areas remains in fact an innovative application of land use change models, and, to propose a flood risk mitigation scheme including exposure scenarios is a key rationale of this paper.

In order to demonstrate the feasibility of the methodology, a study case is shown. We present an ex-ante flood risk assessment in the Pordenone province in northern Italy. Historical land-use maps and one scenario produced by the land use model were used for the assessment. In the last 50 years Pordenone has suffered several disastrous floods. The consequences have clearly demonstrated how vulnerable this area is. Nevertheless, the historical and simulated development paths show that awareness seems not to be at the required level, nor is a change in the urban development strategies evident in this area. On the contrary, results of this study confirm an increasing exposure to floods over time, mainly as a consequence of new urban developments in flood prone areas. In the following sections the spatio-temporal approach is illustrated.

2. Methods

2.1. Assessing Flood Risk: Factors of Risk

Several factors contribute to the occurrence of flood disasters. One is the natural event of extreme precipitation and consequently excessive river discharge and flood water levels. The second aspect is represented by human interventions that play a relevant role in the occurrence of flood disasters. The main socio-economic drivers include:

- Socio-economic trends such as land use and population trends, floodplain development *i.e.*, urban decentralization, sprawl, development in flood-prone areas.
- Low level of awareness among the public, stakeholders, policy makers and planners in understanding the causes and impacts of extreme weather events.
- Failure of structural measures for flood defence.
- Lack or loose application of measures to mitigate the impact of extreme weather events as part of the spatial planning framework.
- Lack of information (including flood risk mapping) and studies that can be instrumental for raising awareness and other purposes.

In the proposed methodological approach, risk is defined as a potential loss having uncertain occurrence and magnitude. The so-called risk triangle approach developed by Crichton [2] calculates risk as the area of a triangle whose sides are represented by the amplitude of hazard, exposure and vulnerability. If any of the sides increases, the area of the triangle, *i.e.*, the amount of risk, increases also. Hence, risk is the result of the interaction of these three elements. Hazard, exposure and vulnerability change over time [14]. Hazard can increase as a consequence of shifts in the environmental system e.g., climate change or changes in the hydrological cycle. Flood hazard is measured in return periods e.g., 20, 50 or 100-year. This is the average interval of time within which a given flood water level will be equalled or exceeded. It is expressed as a probability within a given period of time. Changes in vulnerability and exposure are the result of human intervention. New urban developments and structural measures for flood defence, such as dykes, can be developed in a matter of years. This timing makes a difference with regard to the “hazard” aspect, which is expected to change at a slower pace as a consequence of climate variations. Structural interventions such as dykes can reduce the hazard in flood-prone areas. Conversely new developments in the floodplain may increase exposure, and consequently the amount of risk in the area concerned. Risk maps are usually produced for current climatic conditions. Thus, the current situation assessed on each of the three components of risk is represented in flood risk maps [1]. In this approach risk management should address the three components of risk. Hence land use regulations become the most important tool for flood risk management from the spatial planner’s perspective.

The three components of risk are usually represented using geo-referenced datasets for the production of flood risk maps. Spatial analysis techniques using Geographical Information Systems (GIS) are currently among the most appropriate means to handle the huge volumes of data required for the assessment of large regions. Availability and quality of data remains a limiting factor in order to achieve a realistic representation of the three components of risk. Based on mathematical calculations, including return period probabilities for each location, risk can be estimated. Also simplified procedures can be applied in which a number of assumptions are made in order to produce flood risk maps [1].

Comprehensive flood risk studies should consider a number of anthropogenic factors that could increase exposure and vulnerability to floods. Extensive building in flood-prone areas may increase the number and magnitude of flood disasters over time. Current land use trends together with the number of urban areas historically located in floodplains make a dangerous cocktail in Europe. A shift in the climatic conditions could produce a further increase in flood disasters with far reaching implications on the economy, sustainable development and human health in the affected areas. Mitchell [15] remarks that the spread of low-density suburbs and sub-urban areas is a particularly significant factor in the conversion of rural lands near European cities, including floodplains. But far more important than any of these are shifts in the location of industries and homes impelled by economic factors and lifestyle choices.

This study is a first step towards a more comprehensive method integrating land use change models and flood risk assessments. The resulting land use scenarios are integrated with a pre-defined flood hazard map. The environmental system is assumed to remain within the observed variability. Hence, the flood hazard map is not updated with the simulated land use changes. This approach is useful for short to medium term studies e.g., 10 to 20 years. It is also an approach which is sufficiently straightforward to be applied by urban or regional planning departments and watershed management authorities. There are still several challenges to be addressed in future work. Land use models could be dynamically linked with hydrological models [16] in order to take into account updates of both systems. This type of linkage would enable to analyse reciprocal effects between land use change and flood hazard. It would enable a dynamic modeling approach for long term studies, including those of the long term impacts of climate variations under several climatic scenarios and the corresponding land use scenarios [17,18]. It goes without saying that the issue of calibration and validation in the latter type of approach, featuring coupled models, is challenging.

2.2. Land-Use Modeling for Flood Risk Assessment

One of the most promising fields for land use change models is the analysis of impacts of natural hazards and anthropogenic climate change. However, land use change models are hampered by a number of challenges preventing them from producing detailed long term scenarios. Reginster and Rounsevell [19] and Rounsevell *et al.* [20] presented a continental-wide scenario study. Unfortunately, results of this study seem not well suited for impact assessments of extreme flood events because of its coarse spatial resolution. Solecki and Olivieri [17] propose an approach for urban land use simulation using narrative scenarios from the IPCC SRES (International Panel on Climate Change Special Report on Emissions Scenarios) [21]. The A2 and B2 scenarios were used to produce future regional land use development patterns and associated land use change for a health impact study in the New York Metropolitan Region. An attempt at integrating land use simulation and flood risk assessment is the GLOWA Elbe II-program. The Land Use Scanner land use model was used in this project [22,23]. The goal of the project was to model future land use in the Elbe river basin in order to make a spatial inventory of opportunities and threats with regards to flood risk and management.

Arthur-Hartranft *et al.* [24] present potential applications based on a coupling of microclimate and surface hydrology models with the SLEUTH urban growth model [25]. The resulting urban land use changes bring about a site-specific climate and hydrology, enabling planners to determine when and to what extent their microclimate and water resources may become impacted by urban growth.

In this study a CA-based land use change model is used in an ex-ante flood risk assessment on the basis of land use scenarios for the medium term of 20-years. The information on hazard is incorporated from a flood hazard map produced by the regional water authority [26]. Different methods for flood hazard mapping are available in the literature [27]. Flood hazard areas are delineated through floodplain analyses, requiring detailed hydrological computer-based modeling, and using observations on historical flood occurrence. Premiums for flood insurance are based on results of this type of study [28]. Sophisticated methods, based on hydrological modeling and climate scenarios, were also developed by Dankers and Feyen [29]. Flood defence measures are included for the production of the flood hazard maps. Structural measures such as dykes, dams, and reservoirs are taken into account for the delineation of the areas exposed to floods at different return intervals. Also non structural measures are included in flood hazard assessments.

The role of the land use change model alongside historic land use maps in this study is intended to produce scenarios of future urban land use enabling the analysis of exposed areas from a multi-temporal perspective. Typically, flood exposure and risk are investigated with current land use maps. This study uses historical land use datasets for assessing the evolution of risk over the past 50 years as well as scenarios for the assessment of risk as a consequence of different urban development paths and future land uses. Land use was mapped using remote sensing imagery and digital orthophotos. The resulting datasets were implemented at 100 m grid size. Four dates are available: 1950, 1970, 1980, and 2000 (Figure 1). The land use datasets from the government of the Friuli-Venezia Giulia Region have been implemented using a similar methodology and coding scheme to that adopted by the CORINE project [30]. By means of the historic land use datasets and the urban land use scenarios, this approach enables a realistic evaluation of several non-structural measures—mainly zoning regulations and land use control measures—for flood mitigation as well as the estimation of past, current and potential future damage based on flood water levels [31].

2.3. The Cellular Automata-Based Model

The CA-based model used in this study supports the exploration of spatial developments in cities or regions caused by autonomous developments, external factors, and policy measures using structured "what-if analysis". The model application was first developed by White *et al.* [11] and later implemented by Barredo *et al.* [12,13] in several study cases. The consequences of trends, shocks and policy interventions are visualized by means of dynamic "year-by-year" land use maps as well as spatially explicit socio-economic and environmental indicators represented at high spatial resolution. It is not the objective of this paper to give a detailed description of the CA-based model. However, we include a short overview of its characteristics. A more detailed technical description of the model can be seen in Barredo *et al.* [12,13].

The model features a layered structure representing processes operating at three embedded geographical levels: the global level (1 administrative or physical entity), the regional (n administrative or physical entities within the global level) and the local (N cellular units within each regional entity). However, in this study the regional level is not implemented, as it consists of one region only which is identical to the entity at the global level.

At the global level, growth figures, based on the scenarios defined for the residential land use classes (Residential continuous dense, Residential continuous medium dense, Residential discontinuous, Residential discontinuous sparse), the economic land uses (Industrial, Commercial, Services), the expansion of agricultural (Arable land, Permanent crops, Pastures, Heterogeneous agriculture) and natural land uses (Forests, Scrublands, Sand plains and bare soils) are entered in the model as global trend lines. Subsequently, at the local level, the global demands are allocated by means of a constrained CA-based land use model of the type developed by White, Engelen [32], and White, Engelen and Uljee [11] evolving on a 100 by 100 m grid. Land use transition within a cell is determined by four factors:

1. The physical suitability, represented by one map per land use function modelled, describes the degree to which the cell is fit to support the particular land use function and the associated economic or residential activity.

2. The zoning or institutional suitability, represented by one map per land use function modelled, specifies, for different planning periods, whether the cell can or cannot be adopted by the particular land use function and the associated economic or residential activity.

3. The accessibility, represented by one map per land use function modelled, determines the ease with which the particular land use function and the associated economic or residential activity can fulfil the cell's needs for transportation and mobility given the underlying transportation system.

4. The dynamic impact of land uses in the area immediately surrounding the cell. For each land use function, a set of spatial interaction rules determines the degree to which it is attracted to, or repelled by, the other functions present in the cell and its immediate surroundings: a 196 cell neighborhood. A high attractiveness increases the probability that the function will occupy the cell, otherwise, the location will remain available for other land uses. In the dynamic application of this principle, new land uses invading a neighborhood will thus change its attractiveness for activities already present and others searching for space. This process constitutes the highly non-linear character of this model.

2.4. Model Calibration

The model calibration follows the approach proposed in White *et al.* [11] and further developed in Barredo *et al.* [13] and in White and Engelen [33]. The key parameters to be adjusted are the weights of the spatial interaction rules and the stochastic perturbation parameter. The spatial interaction rules represent distance dependent attraction or repulsion relations between each possible pair of land use classes [11], a weight for each discrete distance value in the neighborhood. When applied to the particular configuration displayed on the land use map, their combined effects result in transition potentials, one per land use modelled, for each cell. The transition potential determines whether the cell will or will not change into another land use class. A stochastic perturbation parameter is included to simulate the inherent stochasticity of the simulated system. It is a component of the transition potential and reproduces a realistic degree of scatterness and sprawl of the urban system.

The calibration method requires running the model over a calibration period for which actual initial and final land use maps are available. These are typically a historical and the current land use map, 1980 and 2000 respectively in this study. The simulated land use map is compared with the actual land use by means of a set of goodness-of-fit measures. Model parameters are consequently re-adjusted and the model is run over and over until the desired level of similarity is achieved. The last set of parameters thus obtained is used for the generation of future land use maps unless scenarios are simulated including processes that affect the interactions between land-use classes directly. In the latter case, the parameters are modified to incorporate such processes.

The calibration procedure operates in two steps. Firstly, overall dynamics, system wide features and land use patterns are verified. Next, fine-tuning is carried out to get as much spatial details and pattern similarity as possible at the cellular level.

For the exercise described, the model was calibrated using historical and reference land use datasets which were compiled for Pordenone [34]. Thus, the increase or decrease in the number of cells for each land-use class represents the historical trend observed over the 20-year period. The stochastic perturbation was set at 2.9. After some initial runs applying visual comparison between the simulated and actual land-use maps, the first phase of calibration used the classical coincidence matrix and derived Kappa statistics as goodness-of-fit measures. Table 1 shows Kappa statistics obtained from the comparison between the simulated and actual map for 2000. The table shows the statistics for each land-use class and for the whole area. Most land-use classes show a reasonably good concurrence. Industrial and commercial classes show the poorest fit. The latter land use class appears in a number of scattered, small to medium sized clusters.

It has been shown that procedures using coincidence matrices are poorly suited for testing the morphogenetic capacity of land use change models [11,35]. This is so because they are based on independent comparisons between pairs of cells. However, the existence of land-use patterns might be better understood, holistically, at the level of the whole region. Scenario modeling of land use should account for the overall appearance of the region with regard to the precise distribution and development of land-use patterns. Thus, to fine-tune the calibration, a second method based on spatial metrics was applied, which accounts better for the similarities in locational patterns.

Spatial metrics have been largely applied in ecological landscape studies. More recently they are used in sustainable landscape planning [36] and analysis of urban land use change [37]. Spatial metrics typically measure spatial configuration of landscapes, and can be used to enhance the understanding of relationships between spatial patterns and spatial processes [38].

Table 1. Kappa statistics for Pordenone province calibration 1980–2000. The values have been obtained by comparing the actual and simulated land-use maps of 2000.

Land-use classes	Kappa statistic
Residential continuous dense	0.769
Residential continuous medium dense	0.908
Residential discontinuous	0.860
Residential discontinuous sparse	0.809
Industrial	0.665
Commercial	0.510
Services	0.751
Arable land	0.949
Permanent crops	0.762
Pastures	0.979
Heterogeneous agricultural	0.935
Forests	0.982
Shrublands	0.930
Sand plains and bare soils	0.861
Overall	0.949

Spatial metrics are powerful instruments for the comparison of categorical maps because of their ability to measure similarity between spatial patterns. Their most instructive use is in comparing alternative landscape configurations, either the same landscape at different periods, or the same landscape under alternative scenarios, as in this case [39]. The metrics used for map comparison must be complementary. They should account for different aspects of pattern structure and avoid redundancy. The set of spatial metrics used here addresses the main landscape aspects defined by McGarigal *et al.* [40] (Table 2). Mean-based metrics, such as mean patch area, shape index and proximity index, can convey more useful information if evaluated in light of their variation using second order statistics, such as the coefficient of variation (CV). In the CV, greater variability indicates less uniformity in pattern. Thus CVs for these metrics have been included in order to verify the goodness of the corresponding mean-based metric. The proposed set of mean-based metrics must be understood as an attempt to measure similarities between categorical maps in aspects such as scatterness, spatial configuration, pattern morphology, subdivision and dispersion/isolation of patches. Additionally, Simpson's diversity index can be interpreted as an overall landscape heterogeneity index [39,40]. This metric is measured at landscape level analysing the whole region *i.e.*, all land-use classes simultaneously.

The metrics used for comparison have been calculated for the simulated and the actual land-use maps using Fragstats [40]. Next, Pearson's correlation coefficient has been calculated for each metric by using the values obtained from each map on each land-use class. The correlation coefficients shown in Table 2 were significant at the 99% level.

Table 2. Pearson's correlation coefficient of the spatial metrics calculated from the actual and simulated land-use maps of 2000. Note that Simpson's diversity index is a probability, thus it is not compared through the correlation coefficient.

Spatial metric	Pearson's correlation coefficient
Weighted mean patch area	0.91
Mean patch area CV	0.95
Total edge	0.99
Weighted shape index	0.97
Shape index CV	0.96
Weighted proximity index	0.95
Proximity index CV	0.96
Splitting index	0.99
Simpson's diversity index	Actual: 0.78; Simulated: 0.74

Table 2 shows overall high correlation coefficients obtained for most of the metrics and the relatively similar Simpson's diversity index for both maps. An almost perfect correlation is obtained for the splitting index and total edge. The lowest correlation is that of the weighted mean patch area. The similarity between both maps displayed in the values of Simpson's diversity index refers to the comparable degree of clustering. In addition the correlation coefficients obtained for the coefficients of variation (CV) of mean patch area, shape index and proximity index indicate a relatively good fit between the variability of these metrics in both maps.

A final remark refers to the limitations of the calibration procedure implemented. The result of the calibration is largely influenced by the quality of the datasets in both the initial and the final map of the calibration interval. Inconsistencies in either of both maps can easily lead to a calibrated but wrong model behavior. This is also why land use maps for intermediate dates are necessary if the model output is used for other than purely academic purposes.

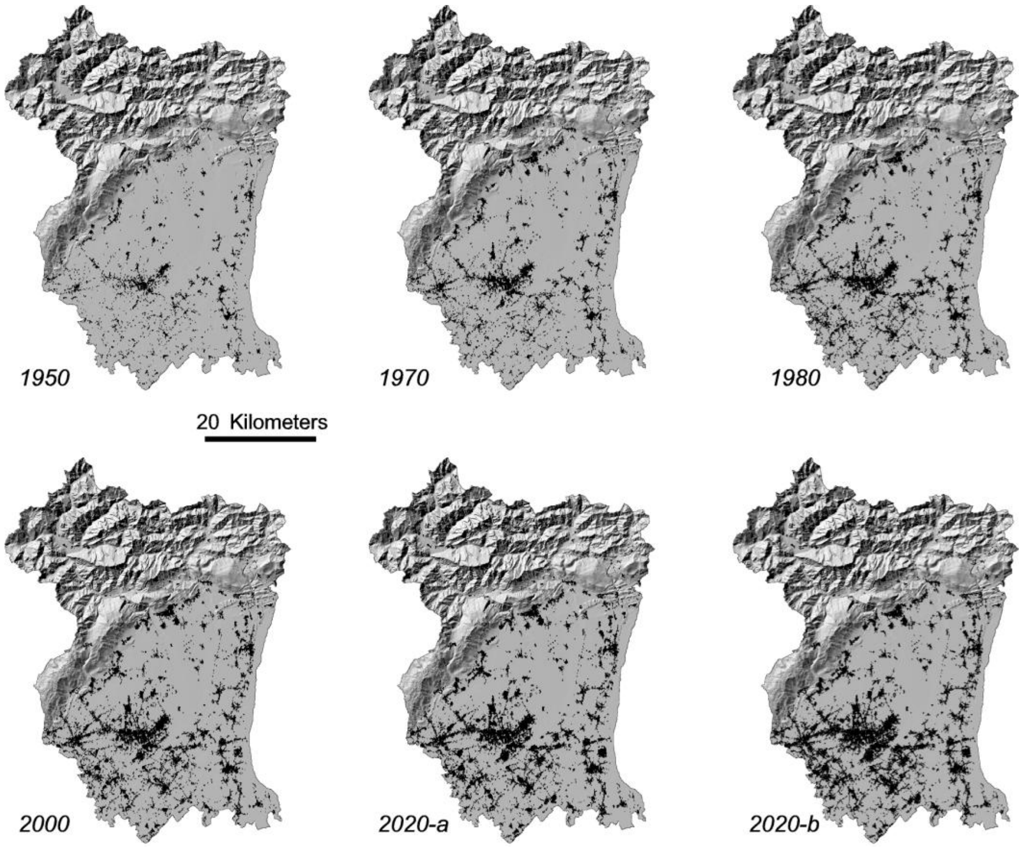
3. Results

3.1. Land Use Scenarios

Urban areas in Pordenone have been growing during the past decades in a rather sparse manner (1950 to 2000 in Figure 1). Two scenarios for the period between 2000 and 2020 were implemented. In both scenarios urban land-use classes are expected to grow following the trends observed in the period 1980–2000. Land demands for individual land-use classes are defined accordingly.

Different urban growth styles can be simulated using CA-based models: spontaneous, diffusive, organic and road-influenced [25], or combinations thereof. The latter is probably what happens in real situations. The first scenario (2020-a in Figure 1) is an example of organic growth influenced by roads. New built-up areas spread outwards from existing ones. The larger the built-up cluster, the larger will be its influence in the organic growth. The second scenario (2020-b in Figure 1) is an example of spontaneous growth influenced by roads. New built-up areas are not necessarily adjacent to existing urbanized cells. Rather they grow in their vicinity. Spontaneous growth is more strongly influenced by the stochastic parameter than organic growth. In consequence, new urban cells are located less deterministically. In both scenarios the influence of roads is important for the growth of new built-up areas.

Figure 1. Built-up areas (in black) in Pordenone Province between 1950 and 2000. (2020-a): 2020 year simulation for organic growth; (2020-b): 2020 year simulation for spontaneous growth.

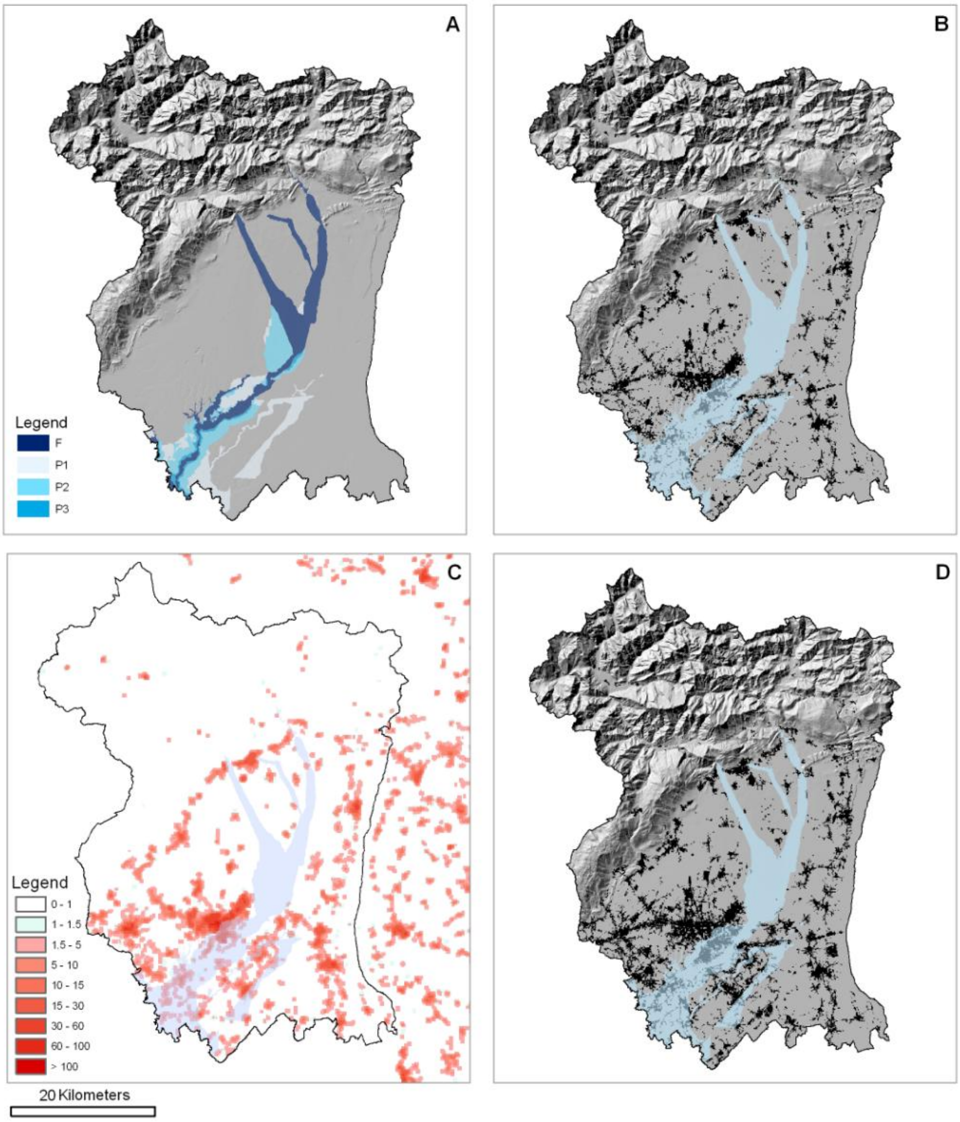


For better readability of the maps in Figure 1, the original 24 land-use classes have been aggregated in two classes, built-up and non built-up. Based on a visual inspection, the predicted urban pattern in both simulations seems realistic and the general form of the built-up area of 2000 is largely maintained. This is mostly due to the configuration of the transportation network, the suitability layers, the zoning regulations, and effect of the original land-use configuration of 2000. Existing urban nuclei have expanded and more and larger nuclei have appeared in the peripheral areas. However, taking into account the urban growth trends of the last decades the more realistic simulation seems to be that of spontaneous growth (2020-b in Figure 1). This simulation will be used in the ex-ante flood risk assessment of the following section.

3.2. Ex-ante Flood Risk Assessment

Pordenone is an area exposed to frequent flooding. Two flood disasters hit Pordenone recently. In 2002, 580 mm of rain fell in 36 hours. The city of Pordenone was affected by the rupture of dykes, which led to water depths up to four meters in several quarters. Even worse was the flood of 1966, which can be described as the 100-year flood event. Dyke breaches caused 14 casualties. More than 5,000 properties were affected and severe damage was reported in about 24,000 buildings. Flood water covered several tens of thousands of hectares and water depth levels in urban areas reached more than four meters [41].

Figure 2. Pordenone Province (a) Flood hazard areas: F (river bed), P1 (moderate hazard), P2 (high hazard) and P3 (very high hazard). (b) Built-up areas in 2000 (black) and flood hazard areas (light grey). (c) Population density (inhabitants/ha) in 2000 and overall flood hazard areas. (d) Simulated built-up areas in 2020 (black) and overall flood hazard areas (light grey).



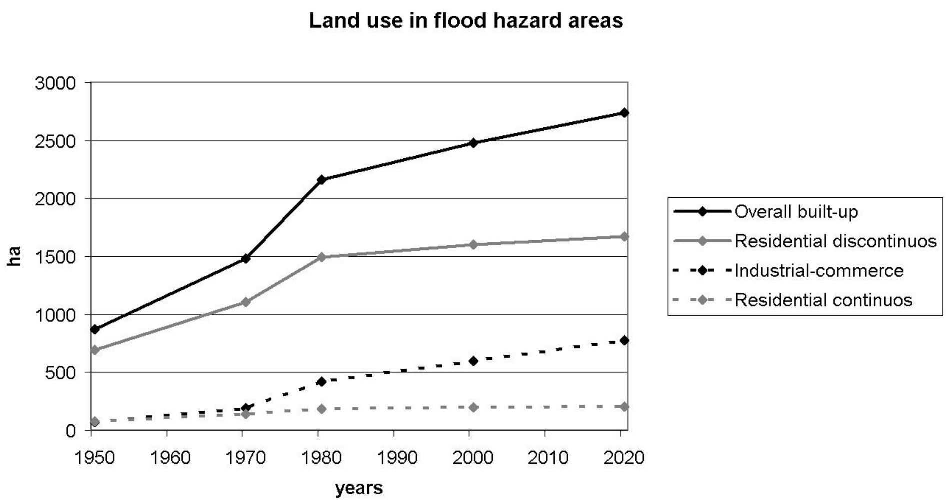
The hazard areas defined in the flood hazard map are the result of a two-step approach. First, the areas prone to a 100-year flood event are mapped. Second, the extent of the areas is verified by using a bi-dimensional flood model and historical flood records. In the flood hazard areas water depth could reach at least 1 meter in the case of the 100-years event. The map is classified in four classes of hazard (Figure 2-a):

- F: Is the riverbed and the floodplain areas inside the dykes. This area is subject to frequent (annual) flooding.
- Very high hazard (P3): Areas close to the dykes, historically flooded by dyke failure.
- High hazard (P2): Areas along dykes and surrounding P3 areas. Critical areas in the case of a 100-years event.
- Moderate hazard (P1): Areas flooded by major historical events and other flood-prone areas.

The vulnerability factor is assumed to be constant over time. We assume that the susceptibility of the exposed structures remains invariant. This facilitates the identification of changes in exposure, which is the aim of this study. Thus, the next step is to identify the assets located in the flood hazard areas. A simple map overlay identifies the built-up areas at risk of flooding (Figure 2-b). Additionally, in Figure 2-c it is evident that a considerable number of dwellers are located in flood prone areas. Even if structural measures for flood protection have been built in recent years, it is likely that a number of dwellers and properties would be affected in the case of a heavy flood event as it occurred in 1966 and 2002. Figure 3 shows the historical evolution of urban land-use classes located in the four flood hazard areas. The figure shows that the residential discontinuous land-use classes were the main contributors to the increase of exposure between 1950 and 2000.

Figure 2-d shows the simulated land use 2020-b overlaid on the flood hazard areas. Figure 3 shows the consequences of the predicted urban expansion in terms of increasing exposure per land use class. Increasing future exposure is in line with the historical trend observed. Thus, flood risk will increase in the coming years in the absence of serious zoning regulation and land use planning measures. The flood hazard areas identified in the map of Figure 2-a represent the hazard under current climatic conditions and are expected to remain stable in the short term. However flood risk increases as demonstrated in Figure 3 by the effect of urban growth in hazardous areas.

Figure 3. Pordenone Province: Land-use classes in flood-prone areas in the period 1950–2000, and forecast until 2020.



4. Discussion

It is worth noting that the two recent flood disasters in the area have not raised land planners' awareness of the importance of settlement. It is likely that the flood mitigation measures implemented, such as dykes, have created an unjustified belief in absolute safety that has led to considerable human encroachment into flood hazard areas [4]. This assessment corroborates the idea that in Europe the main driving force behind flood disaster damages and increasing exposure, is extensive building in flood prone areas [42-44]. Looking into the future, the most dangerous scenario is one of increased flood frequency and magnitude because of changes in the environmental system together with the effect of increased exposure due to urbanization. One worrying environmental element not considered in this study is the potential effect of changing climate conditions that may produce more intense and frequent extreme rainfall events in many European major rivers [29].

Rather than working with the simulated land use 2020-b, which is the outcome of a single model run based on one (calibrated) parameter set, one could have opted to run the CA-based model in its Monte Carlo mode and generate one or more maps displaying the probability of urbanization in 2020. Next is to overlay the latter map(s) with the flood hazard areas. Such an approach enables to take into consideration much better the uncertainty in one or more parameters of the model [45]. It is certainly the preferred approach for applications with a practical policy purpose, as it enables to assess the impacts and effectiveness of policy measures in the context of the broader range of histories that the system could evolve into. An application of this type is that of De Nijs *et al.* [46] aimed at designing spatial planning measures to prevent urban development in restricted (natural) areas and protected culturescapes in the Netherlands.

A number of scenarios can be implemented following the presented approach. Different flood mitigation measures could be designed, assessed and fine-tuned as part of more elaborate scenario exercises for policy making support. This is specifically the case for non-structural measures such as zoning and land use regulations. To conclude, land use change models are useful planning tools for flood risk mitigation.

The need of protecting existing built-up stock in flood-prone areas against flood disasters is recognized. However, the development of new assets in flood hazard zones is far from being a sustainable and coherent approach. Rather, in some cases the option to retreat from flood-prone areas should be seriously considered [43]. A rigorous flood disaster reduction approach would consider measures such as restricting new development or activities in the flood plain, removal of certain physical structures from the floodway and controlling land use practices within the basin [7,8].

There are many drivers of flood disasters. The main natural driver is extreme precipitation and consequently extreme river discharge. However, some "non-natural" drivers are just as much responsible for increased flood risk in Europe. This can be evidenced from the analysis of historical and forecasted urban development. Technical measures such as dykes provide a false perception of safety to dwellers. These types of measures could encourage new developments in flood-prone areas instead of minimizing or ending building definitively. It seems that the interplay and coordinated implementation of technical and spatial measures and instruments is the best, and likely only way, to address flood threats [9]. Moreover, a holistic catchment planning approach for adaptation to floods is required. Reducing flood losses must be considered using the basin as the basic planning unit [7,10].

However, the financial framework of municipalities is often in contrast with the implementation of basin-wide strategies to fight against floods and adapting to climate change. To this end, an active cooperation between local/regional authorities and water authorities is a priority. This cooperation has to be made effective through a legal framework that embeds natural hazards in the spatial planning process. However, this is only the first step. Once the legal measures enter into force, their strict implementation and enforcement becomes a priority. Their loose implementation is as much a danger as the lack thereof. The complex issue of reducing exposure to natural hazards without posing obstacles to the economic development of the concerned region is high on the agenda of policy makers. At EU level this concern is addressed in several policy frameworks such as the directive on the assessment and management of flood risks [10].

5. Conclusions

This paper proposes an approach for spatial planning and flood risk mitigation. Typically, a land use model is used as the core element for the development of an integrated spatial planning strategy. It enables considering different strategies aimed at mitigating the effects of flooding through the definition of spatial and technical measures and legal instruments. Ex-ante assessments of urban development and policy interventions provide a powerful tool for spatial planning and decision-making, including aspects such as zoning regulation, urbanization trends, land-use scenarios and exposure to floods. Nevertheless our study is subject to a number of limitations. First, the Monte Carlo mode for displaying probabilities of urbanization provides a more comprehensive view of the implicit uncertainties of the land use modeling approach. Second, in this study a static hazard map has been used. Dynamic feedbacks between urbanization and flood hazard can be implemented in a coupled hydrologic-land use approach by accounting for the effects of changes in land use in flood water propagation and velocity. Finally, another aspect that can be improved is assessing flood risk changes over time holistically at catchment level. This will produce a more efficient scenario approach in which land use changes in the catchment can be assessed in flood-prone areas.

The main outcomes of the approach presented can be summarized in two aspects. First, it facilitates ex-ante flood risk mapping as a consequence of urban development. Other factors, such as changes in the frequency and magnitude of extreme floods could also be incorporated. Second, it can assist realistic assessment of spatial planning practices synergized with spatial and technical measures for flood mitigation.

Dynamic feedbacks between land use and flood modeling would even be a more advanced step towards an integrated approach. The effects of the expanding built-up area on the frequency and extent of floods and further on the damages to the building stock could thus be assessed. The latter, however, requires advanced models and considerable calibration and validation efforts. In contrast, the approach presented in this paper represents a cost-effective method for the ex-ante evaluation of flood risk.

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