A distributed technique for flood damage assessment using GIS and a 2D hydraulic model

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Abstract

When flood risk mitigation actions are planned, the assessment of what the expected annual damage would be with or without the proposed measures assumes a fundamental role with reference to cost-benefit analysis. The expected annual damage is computed by integrating the damage-probability function which, depending on the size of the problem and on the data available, can be calculated according to different methodologies, varying in their degree of complexity, described in the relevant literature. This paper presents a methodology aimed at predicting and quantifying the damage caused by flood events. Such a methodology combines the 2D hydraulic model's capability to accurately simulate and describe the evolution of flooding with the GIS ability to carry out spatial analysis operations. The results from the 2D hydraulic model (water level, velocity and persistence time in each computation cell) are crossed with the raster maps featuring the characteristics of the elements at risk (land use, economic parameters). By the application of damage functions (or vulnerability curves) to each of the cells within the domain, damage maps are derived and the total value of the economic damage associated with the simulated flood event is finally determined. This distributed methodology has been validated using information data from a flood event (July 1981 at Salorno, Bolzano) which occurred in the study area. Given the good results of the above-mentioned validation, the same methodology was applied to quantify the expected annual damage in the areas affected by flood risk along the Adige river between the city of Bolzano and the confluence with the Noce river and to determine the benefit expected from different scenarios of flood reduction measures.

Keywords: flood damages, 2D hydraulic model, GIS, flood reduction measures.
1 Introduction

The possibility of assessing what the expected damage would be in an area affected by flood risk assumes fundamental importance in planning the structural or non-structural actions in regard. The costs of the different hypotheses of intervention (including the so-called "zero hypothesis") must be compared with the benefits derived by the interventions themselves. The benefits of each hypothesis are calculated by observing the difference between the currently damage value and the residual damage value following the implementation of the mitigation measures. The detailed quantification of damages is equally important for the correct planning of the flood mitigation works (such as retention basins) whenever those structures cause the flooding of a particular portion of the territory: in this case, the ideal sizing based on cost/benefit analysis may differ from the sizing calculated using normal hydraulic engineering criteria (Pingel and Ford [1]).

The damages caused by a flood event can be divided as being either tangible (quantifiable in economic terms) or intangible (difficult to assess in economic terms, such as psychological damage or the inconvenience caused by the interruption of daily social activities, etc.). Damages can also be divided into direct (caused directly by contact with floodwater) or indirect (caused by the subsequent interruption or destruction of economic or social activities) damages (Penning-Roswell and Chatteron [2]).

The model employed considers both direct and indirect damages.

The typical approach suggested in literature for the estimation of direct flooding damages is to assume for each land use class different damage functions that link the hydraulic variables with the subsequent damage as a percentage of the asset's total value lost. In practice, only the water level is usually ever considered in the application of this method (Banovec [3]) and the contribution of other factors such as the water flow velocity and flood duration are ignored. This approach is due to the fact that the damage curves available are usually based only on the water level and to the fact that in the past the numerical simulations of the flooding areas were created using 1D hydraulic models.

Today's availability of 2D hydraulic models permits deeper investigations that also take other factors such as water flow velocity and persistence of inundation into account (Frank et al. [4]).

2 Methodology

The methodology developed for the estimation of flood damages combines the capability of 2D hydraulic models to simulate and accurately describe flooding development with the capability of the GIS to perform spatial analysis operations.

The hydraulic model used to simulate flooding is the SOBEK model developed by WL|Delft Hydraulics. This model integrates a 1D hydrodynamic module that simulates the propagation of the flood in the bed of both the river and its tributaries with a 2D model for the simulation of the flooding over the surrounding land (Frank et al. [5], Fattorelli et al. [6]).
The damage prediction model reads the grids of the results provided by the hydraulic model and calculates the damage in each one of the flood-affected cells. Reading begins with the corresponding value of the land use class required for the application of the function that links the hydraulic variables to the damage percentage. The value of damage in percentage of the asset's total worth is then multiplied by the asset's unit value determined on the basis of economic and geographic data.

The vulnerability curves used by the program can be selected from any of those available in literature (e.g. USACE [7], Dutta and Herath [8]) generally function of exclusively the water level or experimentally constructed on the basis of the water velocity and persistence time (e.g. Frank et al. [4]) as well.

The expected annual damage (EAD) value in the studied area exposed to flood risk was calculated by considering different flood events characterised by different return time values; a simulation using the 1D-2D hydraulic model was conducted for each flood event in order to obtain its respective characteristics (water level, velocity, and flood duration) in the different computation cells in the area of study. The results provided by the hydraulic model for each event simulated were then used in the damage prediction model to provide the corresponding damage value. The EAD for the area under study (Frank et al. [4]) was then calculated by integrating the damage-frequency curve.

3 Validation of the damage calculation methodology

The methodology proposed was validated by using the data observed after an important flood event that occurred on July 19, 1981, when the Adige River broke its banks near Salorno.

The leak was around 300 meters long and put approximately 500 hectares of land under water including almost the entire municipality of Salorno (Figure 1); the water reached the height of four meters and the area remained flooded for almost a week.

The 1D-2D hydraulic model was used to simulate the flood event with the breaking of the banks and the consequent flooding of the plain. The results provided by the model were compared with the observed data collected by local Authorities. The comparison showed that the hydraulic simulation not only predicted both the extension of the flooded area and the water level with precision, it also offered a good estimation of the wetting and drying times in the various sections of territory involved in the event (BETA Studio [9]).

The damage data computed for each cell in the study's domain have been coupled with those evaluated and entered in the same GIS. A comparison demonstrates excellent correlation between the values calculated and those observed at both the global (Table 1) and distributive levels (Figure 2).

The possibility of validating the values by the comparison with distributed observed data is essential to overcome one of the limitation usually affecting distributed hydraulic models: many different spatial patterns of grid-square effective parameter values can lead to the same aggregate response, but give different spatial predictions (Bates [10]).
Figure 1: The Adige River basin closed at Trento and the location of the study area. The enlarged panel shows the area flooded in July 1981; the arrows indicate the point where the river broke its banks.

Table 1: Damage values predicted by the model and observed after the 1981 flood event in Salorno (BZ).

<table>
<thead>
<tr>
<th>Type of damage</th>
<th>Value of damage [millions of €]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
</tr>
<tr>
<td>Agriculture, harvest loss</td>
<td>6.2</td>
</tr>
<tr>
<td>Agriculture, destruction of crops</td>
<td>7.1</td>
</tr>
<tr>
<td>Agriculture, rural structures</td>
<td>6.8</td>
</tr>
<tr>
<td>Urbanised territory</td>
<td>52.1</td>
</tr>
<tr>
<td>Productive activities (direct)</td>
<td>16.5</td>
</tr>
<tr>
<td>Productive activities (indirect)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

¹ Not available.
² Value reported by the local press for two of the leading industries in the area.
In order to assess the significance that the parameters of water velocity and flood duration assume for the purpose of making an accurate estimate of damage, a comparison was made (Frank et al. [4]) by applying the damage model using vulnerability curves based only on the water level. The comparison shows (Figure 3) that 70% of the cells in the computation domain had an absolute value error inferior to 10% when the complete model was used, while such level fell to 50% when the model based only on water level was used. It must also be noted that when the complete model was used, the error curve was substantially symmetric in regard to the central class, while the model based only on the water level shows a general under-estimation of the damage. An analysis of the damage maps shows that the results of the model based only on water level differ from the results observed precisely in the areas characterised by the highest flood propagation velocities.

4 Calculation of the estimated flood damages

The methodology described was applied to the bottom of the Adige River valley, as shown in Figure 4, with the objective of calculating the value of the potential flood damage currently affecting the territory on the basis of objective criteria. The calculation of the EAD permitted a comparison of the different hypotheses of intervention for the mitigation of the hydraulic risk by means of an accurate economic cost/benefit analysis.
Hydrograms for flood events with different return times were obtained for the Adige River both upstream from the confluence with the Isarco River (basin equal to 2,642 km²) and downstream from the point of confluence (6,926 km²) on the basis of a detailed hydrological study carried out by BETA Studio [9]. The implementation of the Adige River hydraulic simulation model also featured the insertion of the network of smaller irrigation canals and other elements present in the territory such as hydraulic works and road and railway underpasses, while a grid of 20mx20m square cells was used to schematise the geometry of the bottom of the valley (countryside, roads, etc.). This grid was constructed by processing the topographic data obtained through altimetric laser measurements (LiDAR). The economic values of the damage caused by each one of the events were obtained by applying the damage prediction model together with the results of the hydraulic simulations.

Figure 3: Percentage of computation of various classes of error in the estimation of harvest loss obtained using the full model and the model based exclusively on water level (Frank et al. [4]).

Various hypotheses of intervention were formulated and analysed for the mitigation of the hydraulic risk, and the construction of two outline retention basins were selected from among these: the first on the right shore of the Adige River upstream from the point of confluence with the Isarco River (the Ponte Adige basin); the second on the river's left shore in the municipality of Ora (Figure 4). The first basin occupies an area of around 282 ha and permits a fill-up of 6.0 \(10^6\) m³, while the second occupies 166 ha and can receive 4.5 \(10^6\) m³. Given the elevated economic value of the orchards in the area under analysis, all the design measures deemed capable of minimising damages to these crops were studied and adopted, particularly those that involved limiting flood propagation
velocity and the water persistence times within the areas. Appropriate constructions for the adjustment of the flow entering the retention basins permit to maximise hydraulic efficiency and adopt rules of management such to flood the basins only when strictly necessary.

Figure 4: The Adige River basin closed at Trento. The figure shows the current flood-prone area in the part of the basin under investigation and the location of the proposed measures for flood damage reduction.

The solutions proposed allow the elimination of the risk of flood damage in all events with return times of less than 150 years. The calculation of the damages considered both the residual damage risk value caused by the flooding of the Adige River and the value of the damages caused to the areas inside the retention basins whenever these latter are flooded (Figure 5).

Figure 6 shows the damage probability function for the current condition and the flood mitigation scenario. The area in between the two curves indicates the benefit expected from the interventions proposed in the studied part of the basin.

5 Conclusions

This paper presents a methodology for the assessment of flood damage in GIS environment. Such methodology integrates raster-based maps obtained by a 1D-2D hydraulic model (water level, velocity, and flood duration in the different
computation cells) with geographic and economic data (land use maps, assets’ values) and produces damage maps based on vulnerability curves.

Figure 5: Estimated residual damage following the implementation of the flood reduction plan: damages are indicated according to different return periods for both residual flooding and the use of retention basins.

Figure 6: Damage-probability function for the current condition and the flood mitigation scenario. The area in between the two curves indicates the benefit expected from the actions proposed.
The existing information on the damage produced by a real flood event (Salorno, July 1981) allowed the validation of the applied methodology. The comparison between the observed data and the calculated ones revealed the ability of the model not only to precisely assess the overall damage for the different classes of land use considered, but also to indicate the correct spatial variability of the damage in the different portions of the flooded territory. Besides, it become evident that an accurate estimation of the damage needs to take into account not only the water level but other factors as well (usually disregarded in traditional applications) such as water velocity and flood duration.

The same methodology was successfully applied to determine the benefit expected from different scenarios of flood damage reduction measures.

The ability to predict with a good degree of precision the damage resulting from a flood event on the basis of hydraulic simulations make it therefore possible to apply this methodology effectively in land planning and risk mitigation actions.

References


