Integrated water basin management and risk assessment through advanced modeling techniques

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Abstract

This paper presents some interesting aspects of a comprehensive study on the Adige River Catchment (Italy) for the hydraulic risk assessment and the evaluation of different alternatives for flood risk reduction. The application of a new software tool meant to model fluvial and floodplain hydraulics is described. This software is a combined one-dimensional two-dimensional model where the 1D channel network and the 2D rectangular grid hydrodynamics are solved simultaneously. The hydraulic model has been applied to simulate the inundation processes on river reaches located in the middle and lower part of the catchment. To take the most of this sophisticate model accurate topographic data where required; the use of an airborne remote sensing technique to collect and process topographic data is described. Finally, the methodology used to generate flood hazard, potential damage and risk maps is illustrated. The results obtained highlight the capability of the methodology to cope with problems related to flood hazard and risk mapping.

1 Introduction

The main goal of the Adige River Catchment study promoted by the Autorità di Bacino dell’Adige (Adige River Authority) to lead to the Piano di Assetto Idrogeologico has been the assessment of hydraulic risk and the evaluation of different alternatives for flood risk reduction.

The River Adige, the second Italian one as for length, rises from a spring near Resia Lake (in the Alps) at 1586 m a.s.l. and after 409 km flows into the Adriatic sea. The total draining area is 11'954 km². Average width of the River Adige range from 40 m in the medium-high part of the catchment (with an average slope of 0.1%).

The study is organised in the following main activities:
- set-up of a database with the characteristics of the hydraulic structures located in the study reaches;
- collection and organisation of river topographic data;
- hydrological study for the definition of the flood hydrographs;
- efficiency assessment of the hydraulic structures;
- flood hazard determination and risk assessment;
- evaluation of different alternatives for flood risk reduction.

This paper is mainly focused on the flood risk assessment task.

The initial step of flood risk assessment is the process of flood hazard determination. Hazards are associated with each extreme river stage or discharge, and are defined as exceedance probability $P_E$ of the extreme flood. In practical applications, the result of hazard determination consists of hazard maps. The hazard map for floods shows the area inundated if a flood of magnitude $U$ corresponding to $P_E(U)$ occurs. Various methods and models can have been used to determine such maps. These can be of different complexity ranging from simply intersecting a plane representing the water surface with a Digital Elevation Model (DEM) of the potential flooded area to full three-dimensional solution of the Navier-Stokes equation with sophisticated turbulence closure (Bates and De Roo, 2000).

Until recently the most popular approaches to retrieve flood inundation maps have been one-dimensional finite difference solutions of the full De Saint Venant equations. In such schemes river and floodplains are described as a series of cross section perpendicular to the flow direction and are modelled together. The water level in the main channel and the floodplain is the same and both river and floodplain store and convey water. In the Adige River study this approach has been used to model the river branches located in the upper part of the catchments where the flow could be reasonably assumed to be one-dimensional.

On the lower part of the catchments however where the floodplain area is large compared to the width of the main river, these simple models are not appropriate to describe the inundation processes. Use of one-dimensional hydraulic models on such areas could lead to large errors in term of water level and discharges both in the floodplain and in the main river. To overcome the limitations of one-dimensional hydraulic model, two-dimensional finite element models have been developed (Bates et al., 1992). These schemes solve the non-steady free surface flows in shallow water conditions. Water depth and depth-averaged velocity is computed at each node for each time step. These models, initially developed to study coastal and estuarial domains, have been adapted to simulate the hydraulics of river and floodplain taking into account processes such as sub and supercritical flows and transition from one of these regimes to the other, dry areas inside the computational domain, sills and submerged dikes. Limitations of such models are due to the difficulties to simulate in an efficient way the behaviour of hydraulic structures (bridges, weirs, etc.). For these reasons, in recent years models that integrate one-dimensional schemes with two-
dimensional schemes have been developed. A one-dimensional model is used to solve the hydraulics equations in the channel network, described by the cross sections geometry and incorporating all the important structures. At each time step of the simulation the results obtained in the one-dimensional scheme are used as internal boundary condition for the two-dimensional scheme used to simulate the inundation processes in the floodplain. This last kind of models has been chosen in this study to retrieve flood inundation maps: the characteristics of the integrated one-dimensional two-dimensional hydraulic model, developed by WL | Delft Hydraulics, is described in the following chapters.

One of the main limitations of an effective use of two-dimensional hydraulic models is the inadequate data provision, especially for what concerns the topographic data. Recently new techniques have been developed, particularly in the airborne remote sensing field, to provide data with the required resolution and accuracy. In this paper a system called TopEye, used to collect the topographic data on floodplain area, is described.

Flood hazard maps obtained from the hydraulic study have been used in combination with potential damage maps to retrieve risk maps as illustrated later on.

The results obtained highlight the capability of the methodology to cope with problems related to flood hazard and risk mapping.

2 Hydraulic Study

To perform a comprehensive analysis of flood hazard, the following four steps were included in the assessment. The first step entails a detailed analysis of recorded critical events as well as the collection of hydro-meteorological data to perform a statistical evaluation and generate design flood hydrographs. The second step involves the collection and organisation of geometrical and topographic data. The third step involves the set up and calibration of the hydraulic model for simulating the flood plain flooding processes. The fourth and final step concerns the simulation by the hydraulic model (one dimensional-two dimensional or only one dimensional depending on the characteristics of the site).

The design of flood events for different return times was performed according to different approaches relatet to the availability of discharge data series. For gauged sites the flood hydrographs were defined using a method for statistical analysis of the recorded data (Maione et al. 1999) together with an analysis of the typical shapes of the historical flood hydrographs. For ungauged sites flood hydrographs were obtained using the regionalization procedure adopted in the VAPI Project for the North East Italian Regions (Villi and Bacchi, 2001).

Geometry of the rivers was analysed trough the set up of a database containing river cross sections (3800 cross sections with more than 400 specially measured for the present study) and hydraulic structures such as
bridges, weirs and culverts (all of them measured through special field survey). Floodplain topographic data with the resolution and accuracy required by the 2D-hydraulic model have been specially provided by an airborne laser system as described later.

Two different approaches were followed to perform hydraulic simulations:
- for Adige River (from middle-high part of the course to the outlet) and for other three significant sites a combined 1D-2D hydraulic model was used, whose characteristics are described in the following chapter. These river reaches are characterised by a slope less than 1%, have embankments, and they are surrounded by a large valleys or flat areas.
- upper reaches, with values of slopes comprised in a range of 1÷5%, generally with no embankments, and situated in narrow valley. In those cases the flow can be reasonably assumed to be one-dimensional.

The study concerned the main river and its tributaries for a total river network of 1770 km length; on more than half of entire network were performed hydraulic simulations to evaluate the hydraulic risk.

2.1 The 1D-2D Hydraulic Model

The Sobek Channel Flow - Overland Flow (Sobek CF-OF) system is a package designed by WL | Delft Hydraulics. In normal conditions (in case of no flooding) hydrography can be modelled as a one-dimensional (1D) network, if large areas are inundated then assumptions for 1D flow are normally no longer valid. In that case the system becomes truly 2D. The system is designed to deal with any kind of flows, sub or supercritical including hydraulic jumps or floodwave bores (Frank et al. 2001).

The computational domain is split into a one-dimensional network, with general volumes of arbitrary shapes, and a two-dimensional part with rectangular computational cells. The equations to be solved are based upon the momentum balance and the conservation of mass. For the momentum balance the 1D and the 2D system remain strictly separated. That means that velocities or discharges belong either to the 1D part or to the 2D part. For the conservation of mass, being a scalar quantity, the appropriate 1D and 2D volumes are combined so that they share the same water level. (Figure 1).

Both the 1D and the 2D grids are staggered (Figure 1a). This means that, for the finite volume approach applied, the momentum volumes are different from the mass volumes. There is no interaction between the 1D and the 2D momentum volumes. This means that vertical velocities and shear stress interaction between 1D flow and 2D flow are neglected. For each momentum volume, the momentum balance relationship is applied. The numerical implementation is such that in the vicinity of steep gradients proper shock conditions are being fulfilled, both for 1D and 2D volumes (Stelling et al. 1998).
The interaction between the 1D and the 2D part takes place via mutual volumes, see Figure 1b. For mutual 1D/2D mass volumes the following equation is solved:

\[
\frac{dV_{i,j}(\zeta)}{dt} + \Delta y((uh)_{i,j} - (uh)_{i-1,j}) + \Delta x((vh)_{i,j} - (vh)_{i,j-1}) + \sum_{l=K_{i,j}}^{I-K_{i,j}} Q_n = 0
\]  

(1)

where: \( V \) = combined 1D/2D volume; \( u \) = velocity in \( x \) direction; \( v \) = velocity in \( y \) direction; \( h \) = total water height above 2D bottom; \( \zeta \) = water level above plane of reference (the same for 1D and 2D); \( \Delta x \) = 2D grid size in \( x \) (or \( i \)) direction; \( \Delta y \) = 2D grid size in \( y \) (or \( j \)) direction; \( Q_n \) = discharge in the direction normal to the mass volume faces; \( i, j, l, K, L \) = integer numbers for nodal point numbering.

For Figure 2b, Equation 1 becomes:

\[
\frac{dV_{i,j}(\zeta)}{dt} + \Delta y((uh)_{i,j} - (uh)_{i-1,j}) + \Delta x((vh)_{i,j} - (vh)_{i,j-1}) + Q_{k+1} - Q_k = 0
\]  

(2)

After discretisation in time by the "\( \Theta \) method" the velocities are eliminated by substitution of the momentum equations into the continuity equation. The resulting system is linear for purely 2D volumes, but if a 1D part is involved the equation might be non-linear with respect to the volume \( V(\zeta) \). This is solved by Newton iteration. The resulting linearised equations, per Newton iteration step, are positive definite and symmetric (Casulli, 1990). The method used for the solution is a combination of the so-called "minimum degree algorithm" (Duff et al. 1986) and of the pre-conditioned CG (conjugate gradient) (Golub and Van Loan, 1983).

The continuity equation is discretised in a way that excludes the possibility of negative volumes. This allows for very efficient and also
realistic flooding of dry beds when the 1D rivers are flooding their 2D surroundings. In normal conditions, i.e. if there is no flooding, the 2D part is not activated. This means that in Equation 1 the \( u_h \) and \( v_h \) values are supposed to be zero.

### 2.2 Digital elevation model of river floodplains

Floodplain topographic data with the resolution and accuracy required by the hydraulic model have been provided by an airborne laser system. The system used in the study is named TopEye (Ackermann 1996).

The primary sensor of the TopEye system is the laser rangefinder. The sensor is able to measure distances between the helicopter and the ground 7000 times per second. Up to five distances can be recorded by each individual laser sounding, and it is capable of detecting object as small as 10 cm in diameter. The sampling density is 0.25 - 2 m. The pulsed laser beam is scanned across the track of the helicopter and as a result of the forward motion of the helicopter, the shape of the scan across the ground is Z-shaped.

The position of the helicopter is determined by GPS. To get as high accuracy as possible Differential GPS (DGPS) is used. The Inertial Navigation System (INS) measures the various attitudes (roll, pitch and yaw) of the helicopter to calculate the three coordinates, with an accuracy of 10 cm. Data from all sensors are recorded on tape during the flight and later calculated in a Unix based post processing system. The points are represented as 3D coordinates in the WGS84 coordinate system together with time registration. Data are then suitable for further processing.

On the Adige River study the methodology has been applied to create height resolution elevation maps on five different zones along the main river and one zone along a tributary, for a total area of 197 km². The average density of the survey has been of 1 point per 2 m².

The 3D collected data have been post-processed to produce the TIN of the study areas. To be used on the hydraulic model the TIN-based Digital Elevation Model was converted into raster grids from 20 to 100 m resolution. A key role on the behaviour of the inundation processes is played by the topographic discontinuities in the floodplain caused by roads, railways, channels etc. In the conversion from TIN to grid DEM resolution problems could lead to loss of accuracy on the description of the above important features. For this reason 3D polylines of the relief were created based on the data collected by the laser system; these polylines have been used to verify and correct the elevations of the grid DEM used in the hydraulic model.

### 2.3 Applications

An example of results obtained with the 1D-2D hydraulic model is shown in Figure 4. The figure shows the water depths in the inundated area adjacent
the Adige River at Trento. The simulation corresponds to a 200 years return time event characterized by a discharge peak of 2900 m³/s.

Figure 2: Examples of inundation maps (flow depth) for the Adige River at Trento at two different time steps (200 years return time simulation, peak discharge equal to 2900 m³/s).

A DEM grid of 33×11 km² was used to described the floodplain; the resolution of the grid used was 50×50 m². Particular care was dedicated in the description of topographic discontinuities in the floodplain created by channels, roads, railways and open passages under them. River roughness was set through calibration of the model by use of observed rating curves at different locations. Due to lack of hydrodynamic data formal calibration of the floodplains roughness couldn’t be carried out. Floodplain roughness values were set according to a large number of references.

3 Flood risk assessment

To enable flood risk assessment, flood hazard, flood vulnerability and assessment of damages of elements exposed to the risks have to be quantified together. The procedure enables the comparison of the hydraulic danger map to a vulnerability/damage map. Hydraulic danger is defined through the
probability that a defined heavy hydraulic condition occurs (inundation). The vulnerability or susceptibility of a land plot is directly related to its land use. It is a way to describe the sensitivity of a specific land use to the potential flooding hazard, whatever its probability. That is to say that the same land use should have the same vulnerability whether its location is in a flood prone area or not. Analysis of the vulnerability map allows assessing the potential damage.

In agreement with the Adige River Authority a criterion to identify four different levels of hydraulic risk (R4 to R1, with R4 identifying high risk and R1 low risk) was defined overlapping different classes of flood hazard with different classes of potential damage (Figure 3).

![Figure 3: Identification of flood risk classes (R4 to R1) in relation to flood hazard and potential damage.](image)

Results provided by the hydraulic model were analysed in terms of water depth and velocity to draw maps with four different hazard classes; starting from the highest level of hazard to the lowest level the different classes have been identified as follow:

- areas inundated with a water depth greater than 1 m or a water velocity greater than 1 m/s for the 30 years return time flood event;
- areas inundated with a water depth less than 1 m and a velocity less than 1 m/s for the 30 years return time flood event or areas inundated with a water depth greater than 1 m or a water velocity greater than 1 m/s for the 100 years return time flood event;
- areas inundated with a water depth less than 1 m and a velocity less than 1 m/s for the 100 years return time flood event;
- areas inundated only for the 200 years return time flood event.

On a similar way, maps identifying four different classes of potential damage were drown according to land use regulation plans. Starting from the highest level of potential damage to the lowest level the different classes can be summarized as follow:
residential areas, dense factories areas, important communication lines;
- not dense factories areas, unimportant communication lines, areas for sport activities, camping;
- precious cultivations such as vineyards or fruit productions;
- all other types of land use.

Through a GIS system flood hazard maps where overlapped to potential damage maps identifying areas with different levels of hydraulic risk according to the table shown in Figure 3. An example of maps of flood hazard, potential damage and hydraulic risk is shown in Figure 4.

4 Conclusions

This paper has presented some aspects of the flood hazard and risk mapping task carried out as part of the activities of a comprehensive study on the Adige River Catchment. The paper has highlighted a number of advantages from using the methodology applied.

The integrated 1D-2D hydraulic modelling system has proved to represent an accurate and affordable solution to perform hydraulic simulations especially in situations were the traditional one-dimensional models could not adequately represent the hydraulic behaviour. Moreover the model proved to represent an useful tool to produce flood hazard maps as it determines not only flood inundation extent but also water levels and velocity fields, time of flooding and drying in a format that can be easily post-processed by common GIS.

The airborne laser system used in the study supplied accurate and reliable topographic data with the resolution and the accuracy required by the hydraulic model.

As legislation requirements becomes more stringent, the importance of being able to show how answers have been generated (sources of data, modelling assumptions) and the reasons for adopting certain solutions becomes more critical. Using an accurate and systematic framework helps on providing this and provides a mechanism for the work to be critically reviewed independently to verify that the best option is being selected. The system also provides detailed visualisation of results that would help planners convey both what solutions have been considered and also why certain options are being recommended or discarded.

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Figure 4: Example of maps of hazard, potential damage and the resulting flood risk (River Adige at Trento).
sistemazione idraulico forestale, alla delimitazione delle fasce fluviali, alla definizione degli interventi strutturali e non strutturali” in 2000. The authors gratefully acknowledge Arch. A. Goio (General Secretary of the Adige River Authority) and the staff involved in the study.

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