FLOOD RISK ASSESSMENT IN URBAN AREAS

M. FERRANTE and L. UBERTINI (*)
University "La Sapienza", Dipartimento n° 37 "Idraulica, Trasporti e Strad"
Via Eudossiana, 18 – 00184 Roma, Italy
(*) and National Research Council

F. GUZZETTI and F.NAPOLITANO
National Research Council

Floods in urban and rural areas have caused extensive damage to the structural and infrastructure systems as well as great social and economic impact. During the November 1994 event in the Piemonte Region (Northern Italy) the propagation of the flood wave produced large damage to private and public buildings, to industrial sites, to the road and railroad networks and particularly to bridges that proved to be highly vulnerable. The inundation caused serious problems to the urban drainage and sewer systems, to water supply and distribution systems, and to the power and telephone lines. Historical data on past inundations suggest that this type of damage is typical of flooding events.
To assess the potential damage due to flooding, to evaluate possible actions prior and during a flooding emergency, and to help allocating limited resources for flood hazard reduction, multidisciplinary studies, based on a variety of expertises, must be completed. Such studies should include: a comprehensive hydrological investigation aimed at the characterization of the probability of occurrence on an event and, where available, the design and operation of a real-time meteorological and hydrological forecasting system; the build up of a numerical model for flood wave propagation on a floodplain; the mapping of vulnerable (hazardous) areas; and the design of a warning and alarm system to assist local authorities and the population.
In the paper we outline the social and economical problems posed by floods; we analyze the availability, role and application of historical data; we discuss basic principles of floodplain management systems, including structural and non structural measures, and techniques for real time flood forecasting. Finally we present the results of the application of Tiber river in Rome.

1 Introduction

Population growth, urbanization and expansion of settlements and life-lines over potentially hazardous areas have largely increased the impact of natural disasters. In Italy the population has grown from 13 millions in 1700, to 34 millions at the beginning of this century, to the actual 56 millions of people. Between 1950 and 1980 the population has grown about 20%; in urban areas the increase exceeded 50%, outlying the tendency toward urbanization. During the same period about 100,000 kilometers of new roads were built; more than the total length of roads available in 1865.
Among natural hazards flooding and landslide occurrence, often referred to as *hydrogeological hazard*, are highly dangerous. Despite that hydrogeological hazard has been recognized dangerous for years, and that large resources have been

allocated to mitigate it, in many countries the economic losses and casualties due to floods and landslides are greater than recognized, and generate a yearly loss of property larger than that from other natural disasters, including earthquakes, volcanic eruptions and windstorms. Flood impact include damage to a variety of structures, utilities and communication networks, as well as family and community disruptions, dislocations, injuries and unemployment. Casualties due to flooding are larger in the developing countries, whereas economic losses are more severe in the industrialized world. Both may be increasing because of the higher value of endangered structures and the larger number of people potentially involved. Recent estimates suggest that, in the last 3 decades, the economic losses and the number of people killed or left homeless by flooding events has steadily increased [1]. For the same period the meteorological and climatic conditions have remained largely unchanged.

In the last few years catastrophic rainfall events have occurred in the Mediterranean area, leading to floods, flash floods and shallow landsliding. These events have outlined the urgent need for the implementation of forecasting systems able to predict meteorological conditions leading to disastrous runoff occurrences, and of policies for issuing warnings or alarms to local authorities and the population. Indeed, early warning systems in urban areas appear to be the only non structural measure suitable for reducing risk, if diffused with enough lead time and adequate reliability.

Flood and flash flood forecasting requires both the evaluation of the predictability of ground effects of large or extreme rainstorms, as well as the evaluation of the social response to an early warning message. Quantitative Precipitation Forecasting (QPF) is the crucial issue in the Mediterranean area where the social organization response time to perform suitable preliminary actions is larger than the watershed response time. The deterministic approach to QPF is suitable for early warning with time scales of few hours and space scale of hundred kilometers still requires major research efforts in the field of mesoscale meteorological models. Multisensor data sources, polar and geosyncronous satellites, meteorological radar and telemetering raingages networks are sources of data that, at different scales, can be used to estimate rainfall intensity and storm areal coverage.

2 Historical perspective

In Italy stories on inundations and mass movements go back to the pre-Roman period. Since then thousands of events have been reported. Floods, flash-floods, debris-flows and landslides have repeatedly caused damage and claimed live. All major Italian rivers have caused large inundations in historical time. In this century all Italian Provinces experienced at least once an inundation or a landslide. In many Provinces destructive or damaging events occurred recursively, in places with very high frequency and affecting large areas [2, 3].

The social and economical impact of flooding and landsliding is heavy in Italy. In this century the toll amounts to: 12,000 casualties; more than 350,000 people (temporarily or permanently) homeless; tens of thousand of houses and bridges

destroyed or damaged; and hundreds of kilometers or roads and rails damaged [3, 4, 2]. Only in the nineties' inundations, debris-flows and landslides have killed more than 120 people and affected, locally recursively, about 60% of all Italian Provinces [3].
Major hydrological disasters occurred: in the Polesine area (18 November 1951), where about 100 km^2 of land were inundated, at least 52 bridges were destroyed, 170,000 people were left homeless and 100 were killed; in the Salerno area (25-26 October 1954), where at least 205 casualties and 92 missing were reported; and in Florence (3-4 November 1966), where 35 people died and damage to the cultural heritage was enormous, producing world-wide emotion. Some of the most catastrophic events (Vajont, 9/10/1963, 1917 casualties; Stava, 19/7/1985, 269 casualties; Valtellina, 28/7/1987, 27 casualties and 19,500 people evacuated) occurred as a combination of both landsliding and flooding.
More recently, in the Piemonte Region floods and mass-movements in the Po River basin and in its tributaries, chiefly the Tanaro River, claimed 70 live, injured 86 people, left 2226 people homeless and more than 10,000 people temporarily unemployed. Over 100 bridges were damaged and 10 of them were completely destroyed. Bridge damage was due to erosion of the gravel abutments and, surbordinately, to base erosion that caused subsidence and overflowing. Damage to bridges was also caused by trees and other water-borne materials which locally produced temporarily dams and obstructions. Roads, rails and communication and utilities networks in 496 townships were damaged by erosion and inundation. The total economic damage was provisionally estimated in excess of 16 billion US$.
Despite the long record of meteorologically-induced hydrological catastrophes, until recently a nation-wide inventory of sites affected by inundations and landsliding was not available. In 1989 the Italian Minister of Civil Protection requested the National Group for Prevention of Hydrogeological Hazards (GNDCI) of the National Research Council (CNR) to complete an inventory of historic geo-hydrological events. The Minister's request followed several meetings of a government committee on natural and human-induced risks (Commissione Grandi Rischi) that urged the Ministry of Civil Protection to complete an inventory aimed at defining hydrogeological risk for the entire nation.
The inventory of information on landslides and floods, known as the AVI Project, was completed by seventeen research teams, each collecting information in one or two Italian Regions. Twenty-two journals were systematically searched for the period 1918-1990 and 350,000 newspaper issues were screened. About 150 experts on floods and mass-movements were interviewed and more than 1400 published and unpublished technical and scientific reports were reviewed. More recently the inventory was extended to cover the period 1991-1994. About 50 regional or local journals were systematically searched, and information on hundreds of inundations and mass-movements was stored into digital tables.
In spite of the limitations due to the complexity of the Italian territory, the different awareness of the impact of floods and mass-movements on the territory, the limited time and resources available, and the techniques used to complete the inventory, largely based on the review of newspapers and chronicles, the result of the AVI Project represents the most comprehensive archiving of hydrological events ever

prepared in Italy and, to our knowledge, one of the most extensive in the world. More than 5000 flooding events and more than 10,000 landslides were identified; information on the location, type and date of occurrence (if known) were stored into a computer data-base; and a synoptic map showing the distribution of sites affected by inundations and landslides was prepared [2, 4]. More recently, through the systematic review of all sources of information (chiefly the over 30,000 newspaper articles), sites affected by inundations and landslides were provisionally mapped at 1:1,000,000 scale. The result represents the most detailed, nation-wide map of geo-hydrological catastrophes ever prepared for Italy.
Under the assumption that catastrophic events will occur in the future under the same (or similar) circumstances that lead to past events, a consequence of "uniformitarianism", a widely accepted principle in geological hazard assessment, historical data on past destructive events represent a valuable aid to hydrological hazard evaluation and mitigation at various scales. Historical data can be used to validate statistically or physically based models. Indeed, the only way a geological prediction (i.e., a flood forecast or a landslide hazard assessment) can be validated (proved correct or faulty) is through time. Practical, social, economical and ethical considerations largely limit the time available for model testing and calibration. Historical data, albeit with large uncertainties, allow for a "backward" validation, or falsification, of predictive ("forecasting") models.
Various attempts have been made to test applications of the historical data collected by the AVI Project for hazard evaluations at different scales. Historical information on the damage caused by inundations and landslides allows a preliminary evaluation of the most common types of damage and the identification of the most vulnerable infrastructures. Not surprisingly, the transportation network (roads, rails, bridges, etc.) was found to be the most vulnerable, followed by the utilities networks and by private buildings. Industrial sites were damaged more by flooding than landsliding. Insurance companies have used the historical information collected by the AVI project, combined with proprietary data on the damage caused by inundations, to rank the over 9000 Italian municipalities according to their expected degree of flood susceptibility. We are currently attempting a similar classification for mass-movements. The spatial and temporal frequency of inundations was provisionally ascertained at the regional scale. Graphs showing the number of times each site was inundated were prepared for each Region. In most Regions the number of inundated sites was found large (>100), confirming that flooding is widespread, but sites more frequently ("recursively") inundated were relatively few, suggesting that highly vulnerable (most critical) sites are limited in number. To study their spatial distribution maps showing the location and frequency of flooding events were prepared (Fig. 1, modified from [4]). Lastly, historical information on floods and landslides were used at the basin scale to ascertain hydrological thresholds for the occurrence of catastrophic hydrological events [5].

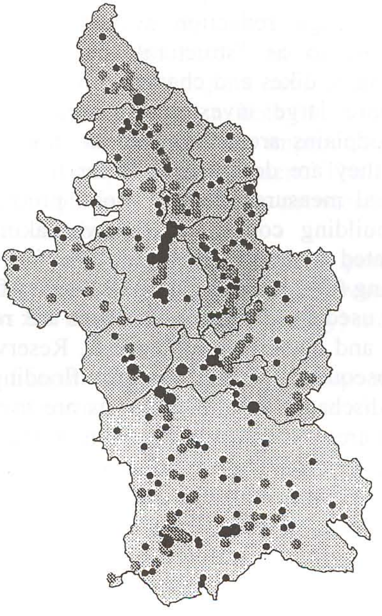

Figure 1. Distribution of flooding events in the Tiber River Basin from 1918 to 1990. Increasing dot size represents higher frequency

These examples show that careful analysis of historical data on floods and landslides may constitute a valuable aid to hydrological hazard assessment and mitigation. The analysis of damage caused by past events may provide useful information on the type of the most vulnerable structures. Maps showing the distribution of damaged sites, ranked according to their frequency of occurrence, may help in the location of areas to be investigated in detailed with site specific flood wave propagation simulations; may aid the decision making process of resources allocation at the national and regional scale; and may guide the planning of remedial measures and defence systems at different scales. Lastly, providing the base for the identification of thresholds for the occurrence of catastrophic events, historical data may represent an important part of any real-time hydrological hazard alarm and defence system.

3 Floodplain management systems

Inundation of a floodplain occurs where water overtops the main channel banks, resulting in an overbank flow that extends on the floodplain. The main river channel is, most commonly, a well defined channel carrying low flow, that can locally meander through the floodplain. The overbank flow is shallower than the channel flow and flows at a much slower velocity. For large floods, floodplain may acts as a reservoir, temporarily storing flood flow. The goal of flood control is to reduce or avoid the negative effects of flooding. Measures modifying the flood runoff are referred to as "flood control" measures and consist of engineering structures, river

modifications and damage reduction systems. Construction of flood control structures are referred to as "structural measures". They include: reservoirs, diversions, levees, banks, dikes and channel modifications. Structural measures are expensive and require large investments. Measures that modify the damage susceptibility of floodplains are referred to as "non structural". Requiring minor engineering works, they are designed to lower the potential damage of flooding events. Non structural measures include: flood proofing, early warning systems, land use control, building codes and policy making. Floodplain management considers an integrated approach of all engineering, non structural and policy measures for managing (i.e., minimizing) losses due to flooding at the basin scale.
The most commonly used flood control structures are: reservoirs, diversions, levees, embankments, dikes and channel modifications. Reservoirs act temporarily storing flood water for subsequent release after the flooding event, thus reducing the magnitude of peak discharge flow. Diversions are used to partially reroute flood flow from vulnerable areas. They are designed to lower the magnitude of an event at any specific site. Levees, dikes and embankments keep flood water away from vulnerable areas, where damage may be high.
Lastly, channel modifications and redesign are made to improve channel efficiency, i.e., its ability to carry water downstream. Channel modifications are mostly used as local protection measures, but can be integrated with other flood control measures into an efficient flood-control system.
Non structural measures aim at decreasing flood susceptibility and at reducing potential damage. They include: flood proofing, early warning systems, and land-use control policies. Flood proofing consists of a range of actions designed to modify the damage potential of individual structures susceptible to flooding. Actions, most desirable on new facilities, include: putting structures and building at higher elevation; water proofing of exterior walls; rearrangement of structural working space. The goal of warning systems is to provide notice, with adequate lead time, to inhabitants that, if properly advised, may act to reduce or avoid damage. Proper lead time may allows for moving things to safer places within buildings, perform minor proofing and remove properties susceptible to flooding. The greatest value of a warning system is to avoid or reduce the loss of life. Flood warning requires real time flood forecasting systems and efficient communications to inform and advice the population. Lastly, land-use control refer to the set of administrative policies and actions that can regulate land-use in a floodplain areas, so that its use is compatible with flooding hazard. Policies, actions and controls consist of land zoning, and building codes, acquisition of land and property, flood insurance, as well as information programs by local, regional and national agencies.

4 Real time flood forecasting

In order to design and operate a flood control system flood forecasting is necessary. Hydrological *forecasting* refers to the ability to estimate, in real time, future states of hydrological parameters, such as the assessment of the discharge and water levels, at various sites in a river network as a result of observed or predicted hydrographs. Forecasting means the estimation of rivers conditions at a given future time or within a specific time interval, and differs from a *prediction*, which is the estimation of future conditions without any temporal reference. There is an ongoing effort in real time hydrological forecasting in both developed and developing countries. The former are mostly concerned with the improvement and expansion of existing forecasting systems for floodplain management. The latter concentrate on the design and implementation of data acquisition networks as well as on the acquisition of basic forecasting capabilities.

The forecasting period may vary from a short to a long period. In small urban watersheds time may be in the order of just a few hours; whereas the forecasting period for large basin (such as the Po basin in northern Italy) may be in the order of several days.

An important concept in flood forecasting is that of *lead time*: the time between the issuing of a forecast and the expected occurrence of the event. Lead time may, or may not, correspond to the *warning time*, the time between the issuing of a warning and the occurrence of the event. Short term forecasts, with a lead time greater then 6 hours and less than few days, are most useful for flood warning purposes and real time water resources management. As the lead time increases, forecast accuracy usually decreases.

Flood forecasting includes three steps: getting real-time rainfall and stream flow data collected by appropriate networks of instruments, through microwave, radio, or satellite communication systems; using these data into rainfall-runoff and stream flow routing simulation computers programs; and forecasting rates of flow and water levels for periods ranging between few hours and few days, depending on the size and shape of the watershed.

There are two types of a short term hydological forecast models: channel routing and rainfall-runoff modeling. A forecast can be based on channel routing models, on rainfall-runoff models, or on a combination of both. The choice depends on the forecast lead time T_f, the concentration time T_C, and the ratio between scale of the meteorological event triggering the flood and scale of the catchment upstream to the site for which the forecast is prepared.

The routing of water down a river channel is described by hydrodynamic equations of unsteady flow known as the de Saint Venant equations. Forecasts based on the solution of these equations are referred to as *dynamic wave models* and can be solved using finite difference or finite elements numerical schemes.

Several forecasting models for river discharge based on rainfall data have been proposed. Complex rainfall-runoff models use a variety of water storages (i.e., rainfall interception, soil moisture and surface storage) and water fluxes (i.e., infiltration, evapotranspiration, snowmelt, interflow, groundwater baseflow and surface runoff from rainfall and snowmellt), producing results of different complexity. More simple models have been successfully used for forecasting purposes. If the catchment response is assumed to be linear with respect to the effective rainfall, methods based on the convolution of the impulse response with the effective rainfall can be used to forecast river discharge. Effective rainfall is the total (cumulative) rainfall minus the losses due to infiltration, interception, and surface pounding; and the impulse response function is the hydrograph response of the catchment to a unit amount of effective rainfall over the whole basin. The instantaneous unit hydrograph model is an example of such approaches.

5 The Tiber River in Rome

The governing equations for simulating gradually varied, unsteady flow in open channels are known as the *de Saint Venant's* equations and, in a gravity-oriented cartesian coordinate system, are given as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

and

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta \frac{Q^2}{A}\right) + gA\left(\frac{\partial h}{\partial x} + S_f\right) = 0 \tag{2}$$

where: x is the distance along the channel measured horizontally; A is the cross-sectional area measured normal to x; Q is the discharge; h is the water depth; S_0 is the channel bed slope; S_f is the friction slope; β is the momentum correction coefficient; t is the time; and g is the gravitational acceleration.
The Manning's formula can be used to evaluate the friction slope:

$$S_f = \frac{n^2 Q|Q|}{A^2 R^{4/3}} \tag{3}$$

where: n is the Manning roughness coefficient and R is the hydraulic radius.
Many 1-D models based on *de Saint Venant's equations* have been proposed in the literature and used for flood routing in hydrologic models [6]. These models require a friction factor to be specified to take into account the effect of surface roughness (e.g. Manning's n). The roughness may vary largely perpendicularly to the flow direction, from channel to floodplains, due to the presence of vegetation and other (isolated or small) obstacles; nevertheless the 1-D models may still be used, provided that, basing on the velocity distribution on the cross-section area, the total cross section is treated as a composite section and floodplains geometry and roughness are specified separately.
When a flood propagates in an urban area, the flow is divided in a network of channels, linked to the main river channel; the evaluation of a global friction factor to take in account in a 1-D model of the head losses due to the presence of streets and buildings in floodplains is a rather unexplored, challenging problem.
Assuming that flow spatial variability on the horizontal plain cannot be neglected the *de Saint Venant's* equations expanded to 2-D can be used; but in this case the computational burden due to the combined effect of the extension to a 2-D case and the geometry complexity may be too large, even for a small area. As a first attempt, a 2-D, depth averaged, finite element hydrodynamic model [7] was used to analyze the flood propagation in urban areas based on a simple geometry. A part from small areas where 2-D effects prevailed, mainly at crossroads and in squares, in each

street/channel the flow was mostly 1-D. This result suggests that it is possible to use a model based on an open-channel network, provided that some hydraulic conditions are specified concerning the physical conditions of the junctions, based on mass and water surface or total head continuity equations [8]. The mass continuity equation at each of the N nodes can be written as:

$$A_i \frac{\partial h_i}{\partial t} = \sum_{j=1}^{k} Q_{ij} + Q_{ie} \tag{4}$$

where: A_i is the area contributing to the storage capacity at node i; Q_{ij} is flow rate for the j-th channel converging in i; Q_{ie} is the flow rate exchanged at node i with the outside elements; h_i is the water depth at node i; and t is time. Assuming that the free surface elevation at endpoints of each channel j converging to node i, z_{ji}, is the same as that of the node i , z_i, reduces the number of the unknowns to N:

$$z_i = z_{ij} \qquad (i = 1,...,N) \tag{5}$$

As pointed out by Natale *et al.* [9], this condition produces errors during the falling limb of the hydrograph but "the error is not significant for applications purposes, as it occurs after the passage of the peak discharge".

A significant simplification may be introduced when the flow equations for channels are approximated by a steady state similar assumption and including the storage capacity of channels in the continuity equation at the node. For the purpose it is possible to add to area A_i the sum of half of the area of each channel converging to the node [10]. Equations (1) become:

$$A_i \frac{\partial z_i}{\partial t} - \sum_{j=1}^{k} Q_{ij}\left(z_i, z_j\right) - Q_{ie} = 0 \tag{6}$$

where the dependence of the discharge Q_{ij}, on z_i and z_j may be expressed by:

$$Q_{ij} = \frac{AR^{2/3}}{n} \frac{(z_i - z_j)}{\sqrt{|z_i - z_j|}} \tag{7}$$

where A is the cross-sectional area of the ij element; n is the Manning roughness coefficient and R is the hydraulic radius. Equations (4) my be discretized in time, yielding the non linear system of algebraic equations:

$$A_i \frac{z_i^n - z_i^{n-1}}{\Delta t} - \sum_{j=1}^{k}\left[\Theta Q_{ij}\left(z_i^n, z_j^n\right) + (1-\Theta) Q_{ij}\left(z_i^{n-1}, z_j^{n-1}\right)\right] - Q_{ie} = 0 \tag{8}$$

where: Θ is a temporal weighting coefficient, $1 \geq \Theta \geq 0$; Δt is the time step; and the n index denotes the time $n\,\Delta t$. A Gauss Seidel numerical scheme can be used to solve the system.

For a case study, the existing maps at 1:1000 and 1:2000 scale for the northern part of Rome, along the Tiber River from Ponte Milvio to Ponte Sant'Angelo, were digitized. Two kinds of information were gathered: ground elevations and the street geometry.

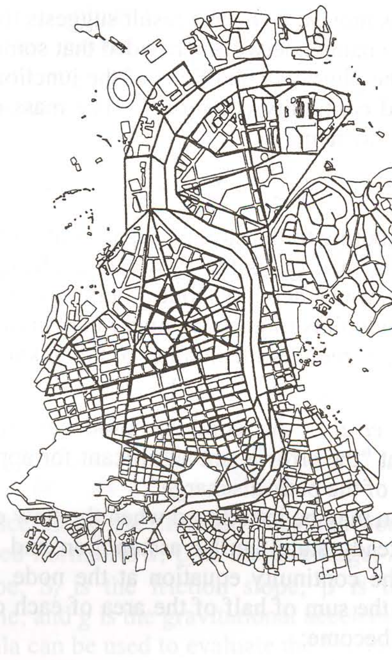

Figure 2: The simulation network

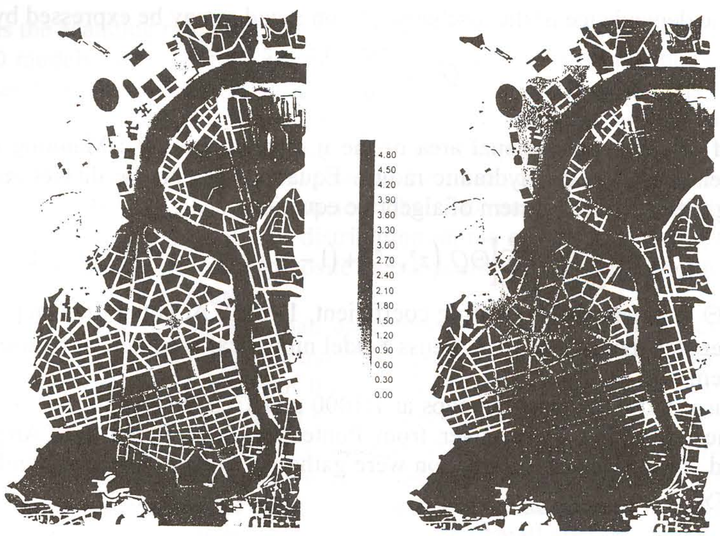

Figure 3: Water depths at t = 12 h

Figure 4: Water depths at t = 24 h

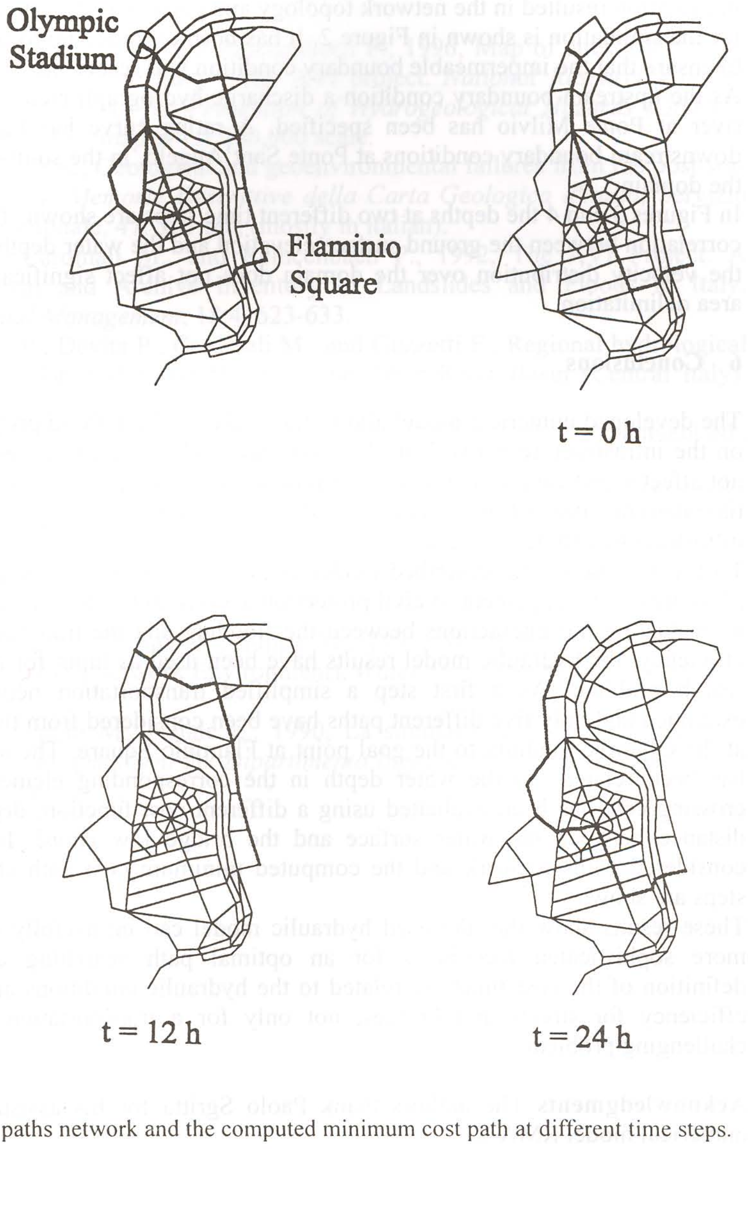

Figure 5. The paths network and the computed minimum cost path at different time steps.

An irregular network was built using ground surface points at the crossroads, representing the street network. Outlines of buildings were converted in vector format and the street/channel geometry was extracted. Combination of this information resulted in the network topology and geometry. The street network used for the simulation is shown in Figure 2. It has been extended up to the hills bottoms to ensure that the impermeable boundary condition was respected.
As the upstream boundary condition a discharge hydrograph incoming in the Tiber river at Ponte Milvio has been specified. A rating curve has been used as the downstream boundary conditions at Ponte Sant'Angelo, in the south-western part of the domain.
In Figures 3 and 4 the depths at two different time steps are shown. There is a strong correlation between the ground surface elevation and the water depths, meaning that the velocity distribution over the domain does not affect significantly the wetted area delimitation.

6 Conclusions

The developed numerical model allows the analysis of the flood propagation effects on the infrastructure network in the urban area. The introduced simplifications do not affect significantly the results approximation and, on the other hand, allow a real time determination of the hydraulic conditions in the network and of the consequent infrastructure efficiency reduction.
To test the use of the described model as a part of the more complex system for planning and management of civil protection actions and to investigate its capability in evaluating the interactions between the flooding and the transportation network efficiency, the hydraulic model results have been used as input for an optimal path search problem. As a first step a simplified transportation network has been examined and only five different paths have been considered from the starting point at the Olympic Stadium to the goal point at Flaminio Square. The single edge cost has been related to the water depth in the corresponding element. The bridge crossing cost has been evaluated using a different cost function, depending on the distance between the water surface and the bridge low chord. In Figure 5 the considered paths network and the computed minimum cost path at different time steps are shown.
These results show that the used hydraulic model can be usefully coupled with a more sophisticated techniques for an optimal path searching algorithm. The definition of the cost function, related to the hydraulic conditions and the network efficiency for streets and bridges, not only for a transportation network, is a challenging problem.

Acknowledgments The authors thank Paolo Sgritta for his assistance using the numerical model RMA-2.

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