

Decision support system for urban flood management

A. J. Abebe and R. K. Price

ABSTRACT

This paper presents the development of a decision support system (DSS) for flood warning and instantiation of restoration activities in two urban areas, the Liguria Region in Italy and the Greater Athens catchment in Greece, with the potential of extension to other locations with similar flooding problems. The tool is designed to work at the centre of a set of meteorological and hydrologic/hydraulic forecast models together with telemetric data acquisition networks. The study reveals the complexity and uncertainty involved in managing flooding in the study areas. Issues about the validity and extended benefits of the system are also discussed.

Key words | decision support system, flood degree thresholds, urban flood management

A. J. Abebe (corresponding author)
R. K. Price
Hydroinformatics & Knowledge Management,
UNESCO-IHE,
PO Box 3015,
2601DA Delft,
The Netherlands
Tel.: +31 15 215 1839
Fax: +31 15 212 2921
E-mail: abebe@ihe.nl, rkp@ihe.nl

INTRODUCTION

Many regions experience severe flooding from natural causes. The problem is particularly pronounced in areas of steep, complex orography where there can be a rapid buildup of storm conditions. In past decades the severity and rapidity of flooding has increased in mountainous areas of Southern Europe bordering the Mediterranean due to urbanisation, causing higher runoff rates and more rapid catchment responses. Flood forecasting and real time monitoring have been found necessary to take reactive measures such as issuing flood warnings, planning emergency activities and initiating restoration.

A report by the European Environment Agency (2001) indicated that floods are the most common cause of natural disaster in Europe. According to the report, there were 157 major floods during the period 1971–1995, and in 1996 alone there were 9 such events. The cost of damages in the period 1991–1995 was estimated as ECU 99 billion. Due to the severity of the problem the European Commission has sponsored several flood-related projects (see, for example, Catelli *et al.* 1998).

One of these projects was TELEFLEUR (TELEmatics assisted handling of FLOOD emergencies in URban areas), which has been sponsored by DG 13 under its Telematics Applications Program, Environment Sector. The objective of the project was the development of a comprehensive

operational system for handling urban flood emergencies that combines telematics technology with advanced forecasting of meteorology and hydrology encapsulated in a DSS. The purpose of the DSS is to manage the dynamic information acquired by telemetry, feed these data along with relevant static data to an array of modelling tools, forecast flooding conditions and assist public authorities in decisions regarding emergency measures. The target areas are the Liguria Region in Italy and the Greater Athens area in Greece. Severe and devastating flooding has been observed in both areas several times in the past two decades.

This paper covers different aspects of the DSS prototype developed under this project. The most common types of flooding in Europe are those occurring in large basins at the middle and lower courses of rivers and due to flash floods caused by intense local or regional precipitation. This paper mainly focuses on flash floods, as they are more prevalent in the Mediterranean coastal areas where both target areas are located. These floods are often characterised by a short response period and a few hours of inundation. Some aspects of the particular meteorological and hydrologic/hydraulic forecast models used in the study areas are also discussed for the sake of completeness.

REVIEW OF FLOOD DEFENCE ALTERNATIVES

Linsley & Franzini (1992) outline the commonly used measures of flood damage reduction as: (1) reduction of peak flow by reservoirs, (2) confinement of the flow within a predetermined channel by levees, flood walls or a closed conduit, (3) reduction of the peak stage by increasing velocities with channel improvement, (4) diversion of the flood waters through bypasses or floodways, (5) temporary evacuation of the floodplain, (6) floodproofing of specific properties, (7) reduction of flood runoff by land management and (8) flood insurance.

All the above alternatives except temporary evacuation and flood insurance involve some sort of structural intervention. Structural intervention alone cannot provide a complete protection against floods since, among other reasons, the design capacity of structures is limited, operational defects are possible and structures could fail. Some reports indicate that reliance on protection by structural measures may actually increase the risk associated with flooding (De Bruijn & Klijn 2001). Even though economic analyses of repeated flood damage may demand structural intervention, it generally requires significant investment and time to implement compared to a non-structural measure.

After decades, and even centuries of engineering works along rivers, a growing number of engineers are moving toward solutions favourable to the natural environment which increases the importance of non-structural measures such as early warning systems. Another reason to invest in flood warning systems is that, especially in urban areas, flooding does not necessarily occur in natural streams that could be contained with structures such as dikes. At times of flooding, even urban roads turn into floodways. In addition, there are pressures to limit the provision of adequate passages and flood plains due to the low frequency of flood events and the economic value of the space needed in urban areas.

Therefore, whether or not structural intervention is in place, the presence of a system that can assist public protection authorities in making flood forecasts sufficiently in advance to achieve a complete and orderly evacuation, and provide guidance in instantiating restoration activities, is important. The costs for development

and implementation of a DSS for flood warning and restoration are far less than the damages reported for the more severe flood events or the costs for developing adequate flood defence structures.

A DSS for flood management essentially makes use of one or more models to make forecasts and a telemetry system for data acquisition. The choice of models depends on factors such as the hydro-meteorological characteristics of the area, the desired level of accuracy, the intended forecast time and the cause of flooding. For floods due mainly to excess flow in rivers, a routing model using upstream data may be used, or even more accurate forecasts can be made by tracing the depth contours using a series of stage gauges (see, for example, Laushey and Huang 2001). When the travel time of the flood peak gets shorter and the main cause of flooding is local precipitation, the latest observed precipitation could be used along with a runoff model. However, the use of observed precipitation data might not ensure adequate forecast time. In that case precipitation forecasting may be required. Generally, forecast accuracy decreases as the forecast horizon increases. Even in using forecasted precipitation, different forecasting methods trade-off forecast accuracy with lead time.

STUDY AREAS

The development of the system was targeted at the Liguria Region in Italy and the Athens area in Greece. Parts of both areas have been severely flooded several times in the past 20 years. The Athens area is part of one large catchment of 430 km², whereas the Liguria Region consists of several small catchments, the largest of which, Entella, has an area of 370 km². The two application areas share similar topographical and meteorological characteristics. Both include urban areas situated on the coast and are prone to flash flooding by runoff from mountainous areas. Flooding is a major threat in both areas since: (1) both areas consist of upper catchments with steep slopes, (2) the distances between the mountains and the sea are short and (3) urbanisation and high population density is concentrated in the lower parts of the catchments, which experience the cumulated effects of the runoff.

Table 1 | Recent severe flood events in Athens (Source: Water Corporation of Athens)

Event	Date	Area	Remarks
1	02/11/1977	Podoniftis Basin	Overflow of Podoniftis
2	11/12/1977	Nikaia	
3	05/02/1978	Podoniftis Basin	Overflow of Podoniftis
4	20–21/11/1993	Saronikos Coast	
5	29/01/1994	Menidi, NW Athens basin	
6	31/05/1994	Athens Centre	
7	21/10/1994	Podoniftis Basin	Overflow of Podoniftis & Kifissos
8	27/01/1996	Thriassion Pedion & East Attiki	
9	12/01/1997	Kifissos & Podoniftis Basins	Overflow of Kifissos

Flooding occurs within a few hours of the occurrence of heavy precipitation, which is often too short a time to take preparatory measures. Hence, it is inadequate to issue flood warnings based on hydrological simulations from monitored precipitation. Therefore it is believed that flood forecasts, and thus warnings, should largely depend on forecast precipitation. Warnings that depend largely on forecasted precipitation involve considerable uncertainty and a high likelihood of false alarms. In both cases there was insufficient documented data of past flooding episodes. Table 1 shows the recent severe flood events in the Athens area. As shown in the table, the available data are mainly qualitative, indicating only the presence of a flood or overflow of particular streams.

PRECIPITATION FORECASTING

In both areas, the response times to intense precipitation are limited to a few hours. The use of observed precipitation does not allow sufficient lead-time to make flood forecasts and issue warnings. Thus meteorological forecasting has to be used. Two forecast ranges were considered:

1. Very short-range forecast ('now' casting): This is often done with satellite imagery or radar-based techniques. It gives relatively reliable forecasts, allowing localisation of rainfall in space and time. The forecast can be conducted up to 3–6 hours ahead. However, with short hydrological response times, there must be a highly organised emergency plan to work with such a forecast.
2. Short-range weather forecast: This enables forecasting to be done up to 72 hours in advance, thus giving sufficient lead time to make flood forecasts and issue flood warnings. This is often done using atmospheric models. The drawback is that they do not allow exact timing, localisation and intensity estimation.

For the areas considered in TELEFLEUR, a short-range precipitation forecast is selected. That is done using an array of nested meteorological models. The first of these models is a global circulation model (GCM) maintained by the European Center for Medium-range Weather Forecast (ECMWF) in Reading, UK. It covers the Northern Hemisphere with a ground resolution of 55 km grid. Forecasts are made for the coming 72 hours on a daily

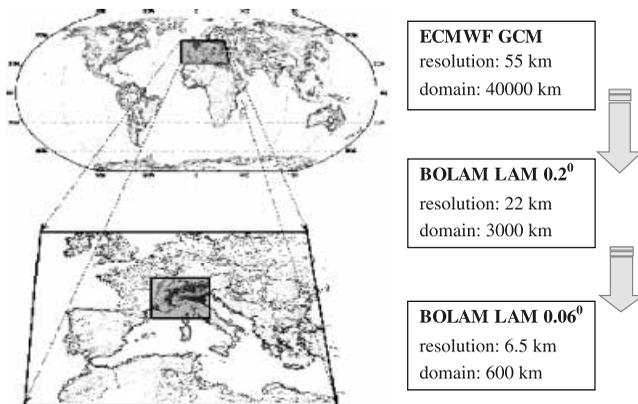


Figure 1 | Nested chain of meteorological models.

basis. The model takes approximately 12 hours to run. Nested within the GCM there are two limited area models (LAM) developed at the University of Bologna, Italy (Buzzi *et al.* 1994): one is nested within the other to achieve a higher resolution (Figure 1). The finer model has a surface resolution of 6.5×6.5 km.

The results from these models cannot be used directly because they still have to be interpreted by a meteorologist. This is because there is a high level of uncertainty in the results from the models due to the complexity of weather phenomena, making it impossible to localise the events either in space or in time. A meteorological synoptic analyst produces three schemes of forecasts:

1. Maximum 12 hours cumulative precipitation, 2000 km^2 domain.
2. Maximum 6 hours cumulative precipitation, 500 km^2 domain.
3. Maximum 3 hours cumulative precipitation, 100 km^2 domain.

Each of these schemes results in multiple meteorological scenarios. The number of scenarios depends on the number of grid boxes each meteorological model uses to cover the catchment. The scheme that uses a model with larger grids results in fewer scenarios whereas the finer model results in more scenarios. All the scenarios are treated with equal likelihood of occurrence.

HYDROLOGY AND HYDRAULICS

The DSS is designed in such a way that it can work with any flow-modelling system only with the help of a post-processor that can transfer the data in the right format. The operational flow-modelling system used for the current study areas consists of a detailed conceptual rainfall–runoff model and an associated hydraulic model for the calculation of flood stages. The hydrologic model employs well-established building elements such as the Curve Number method of the US Soil Conservation Service for runoff generation from natural areas, runoff coefficients for runoff generation from paved areas and a flow routing procedure based on a cascade of linear reservoirs.

The model was tested with the available historical data in two ways. First, the system response was simulated using as input observed rainfall from past events. The existing system geometry was used and parameter values were estimated. Simulation results were compared with reported qualitative information on local flooding shown in Table 1. Since the qualitative data on past flood episodes are not adequate, the flow model has to be constantly updated with the availability of new data and with physical changes in the catchment. Also, at this stage, the model used along with the DSS is based on modelling the flow in the waterways. A spatial inundation model would certainly be more informative in indicating the actual threats of flood. However, analysis has to be made to decide which component model is worth improving: the meteorological or hydraulic/hydraulic model.

In operational settings the model has to work with forecasted precipitation. The resolution of the precipitation forecasts of the meteorological models discussed above does not satisfy the data needs of the hydrological/hydraulic model used for the purpose of the DSS. The temporal resolution of the precipitation forecast is particularly low. A study by Michaud & Sorooshian (1994) highlights the relative importance of the rainfall sampling time interval compared with the density of sampling locations. As a result, it became necessary to carry out model simulations for all the scenarios generated from the meteorological forecasts and to determine the worst case scenario.

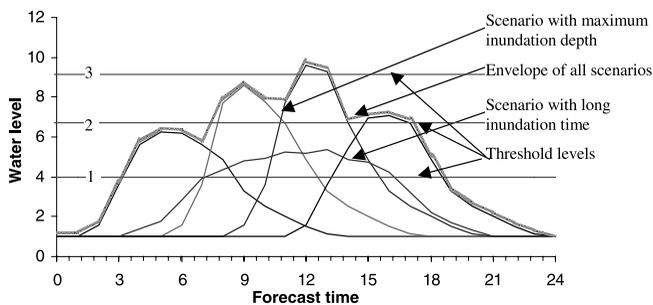


Figure 2 | Identifying worst case scenarios.

WORST CASE SCENARIO

Two criteria are used to define the worst case scenario for each water level forecast location. The first is the scenario resulting in maximum inundation depth at a given location. Since the inundation depth is the primary indicator of flooding, this scenario will be identified out of the set of simulated scenarios. The second indicator is the time of inundation. The longer the time of inundation the greater the damage. Therefore the scenario causing the longest inundation period at a given location is also identified as a worst case. One more scenario was included to assist in the decision-making: the envelope of all the scenarios. The envelope may seem to be an overestimation of the events: however, it can be used as an estimate of the worst damage that can happen as a result of any of the scenarios. Figure 2 shows an illustration of how worst case scenarios are identified. The figure is not the result of an actual simulation. In reality, the meteorological forecasts result in far more scenarios than those shown in the figure.

THE DECISION SUPPORT SYSTEM

There are various definitions of what a DSS is. A broad definition is that a DSS is a system that assists a decision-maker or a relatively small group of decision-makers to make a decision regarding a problem by the use of readily available resources. In recent decades, the advances in computing technology, geographic information systems and the Internet have given multiple dimensions to the

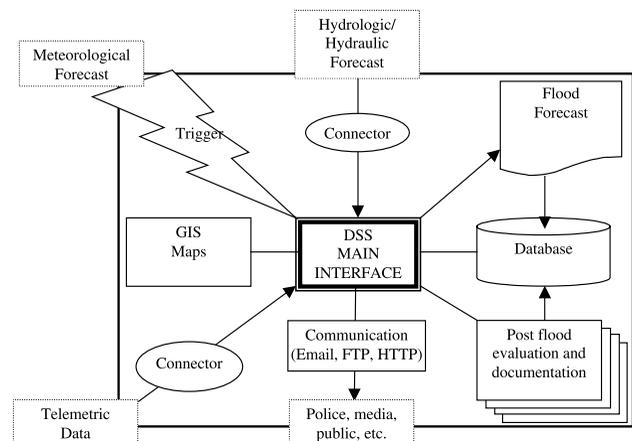


Figure 3 | Operational diagram of the DSS.

development and application of DSSs. Simon (1977) views the functional aspect of a DSS in four phases. Accordingly a DSS provides *intelligence* which refers to the gathering of data and information, *design* of multiple solution options to resolve the problem, a *choice* of the alternative that seems to best resolve the problem and a *review* of whether the selected option is appropriate. These principles have been followed in the design and implementation of the TELFLEUR DSS.

DSS outline

The TELFLEUR DSS is designed to work at the centre of other essential components such as the hydro-meteorological forecast models, the telematic network and relational databases. Figure 3 shows the operational link between the DSS and these components. The DSS is loosely coupled to the other components. Since the response time of both study areas is limited to few hours, the main trigger for initiating the activities involved in flood warning is the severity of the meteorological forecast. If the DSS is to be applied in catchments with a slow response, precipitation and upstream water level data obtained from telemetry and the outputs of hydrologic/hydraulic forecasts may serve as triggers to further activities. As discussed in Abebe & Price (2001), these consist of a warning system, a restoration system and GIS, database

and communication modules. A description of their functionality is given in the following subsections.

The intelligence aspect of the DSS is achieved by the help of the telemetry network that helps to acquire real time data and a link to databases. The results of the hydrologic/hydraulic model are water level and flow time series at representative cross sections along the watercourses of the catchment under consideration. This information is not sufficient to build an inundation map or other damage description, particularly taking into consideration the degree of uncertainty under which the forecasts are produced. Therefore the TELEFLEUR DSS is set to work on a point time series basis. At first the catchment is divided into basins according to natural watersheds and/or municipal boundaries. These locations are associated with a representative cross section of a watercourse that, when overflowed, affects that particular basin. The water level forecasts at this cross section are used as representative to determine whether the area has a flood threat. If two or more watercourses pass through an area, then the time series at more than one cross section may be associated with that area.

The representative cross sections are assigned water level thresholds, which are to be used as means of classifying the water levels into verbal flood degrees. The number of thresholds to be used depends on the number of flood degrees the decision-maker wants to classify. TELEFLEUR uses three threshold levels, which help to classify the flood into three degrees with simple classification rules such as:

If threshold 1 is exceeded then flood degree is MILD.

If threshold 2 is exceeded then flood degree is SIGNIFICANT.

If threshold 3 is exceeded then flood degree is SEVERE.

Obviously, if *threshold 1* is not exceeded then the flood degree is *NO FLOOD*.

The DSS simulates a number of scenarios and provides four outcomes for each basin. These outcomes are flood degrees *severe*, *significant*, *mild* and *no flood*. It also provides the associated probabilities of occurrence of these degrees for each basin. The probabilities help as

means of making a choice among the possible degrees of flooding. Associated with each degree of flooding there will be a list of actions to be taken by authorities or the public. For instance, expecting a mild flood might be associated with actions such as advising the public to store clean water sufficient for a day or two, closing some public areas, etc. In response to expecting a severe event, authorities can advise people in the affected area to go to a predefined safe location, to make an evacuation, advising hospitals to increase emergency handling facilities, etc. The DSS has an interface that enables adding, removing or editing the courses of action followed in response to expecting a flood of a particular degree. These lists of action are also automatically included in the flood pages generated by the communication module of the DSS prototype. The list of actions is not hard coded; this enables the DSS to be a platform that can be upgraded with the gain of more experience. In addition to archiving day-to-day decisions made by the DSS regarding the expected degree of flooding at each location, the database module of the prototype has an interface to enter the actual observed degree. Obviously, the extent of the flood has to be evaluated by an expert. After sufficient such records are made, experts can review where and when the flood degrees are wrongly forecasted and why. Consequently, the component models and decision parameters of the DSS can be evaluated. This comprises the review phase of the functionality of the DSS.

The warning system

The warning system (Figure 4) is used for issuing flood-warnings after analysing the model forecasts. It is based on the results of the hydrological/hydraulic simulations resulting from the array of meteorological models, or can also include other forecast systems such as radar technology. It allows visualisation of flood warnings as a GIS map layer with descriptive marks.

The restoration system

The restoration system (Figure 5) is used during the instantiation of restoration activities after a flood event

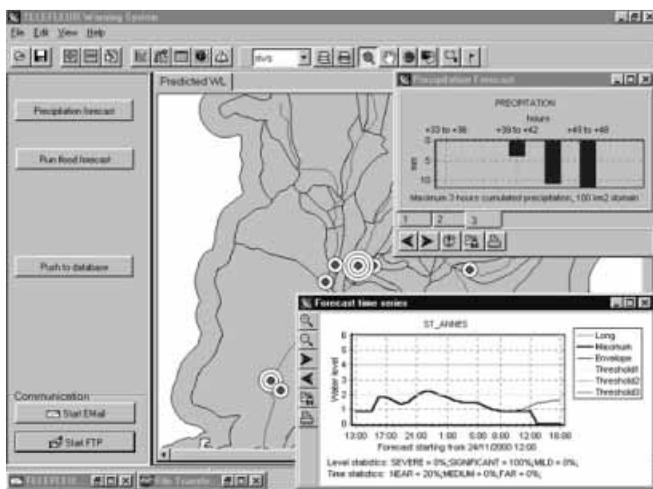


Figure 4 | The warning system.

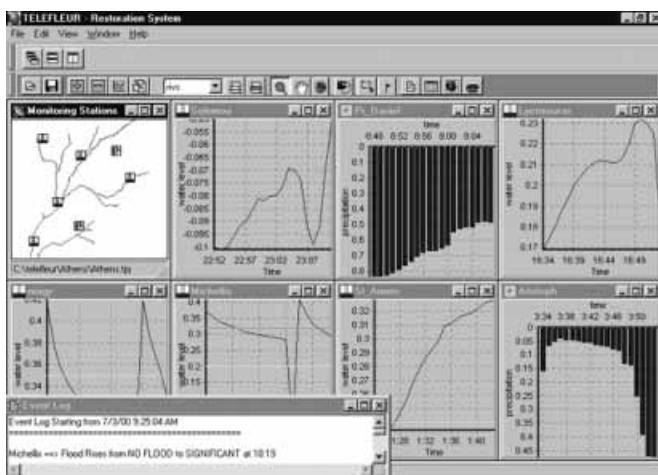


Figure 5 | The restoration system.

has subsided. It uses real time data obtained from the remote water level and precipitation monitoring stations via the telemetric system. Data acquisitions can be made either on request or at regular time intervals. The restoration system allows the visualisation of real time data graphically, and subsequently generates an event log when the water level at the remote monitoring stations rises above or falls below defined threshold water levels. Individual windows can be activated for each location on alert. When operated in unattended mode, the event log can be reviewed for any new developments. For instance,

if the water level subsides at a location for some time, decision-makers can initiate restoration activities in that area.

Supplementary modules

The GIS module is used to visualise the relative location of the watercourses, roads, emergency aid locations, escape routes, etc., depending on the availability of digital maps containing this relevant information.

The communication module facilitates the issuing of flood alarms, flood statements and other information using three means of communication. Electronic mail is implemented to send flood statements from the Command Centre. File transfer protocol (FTP) is used to upload and download data and other information between the Command Centre and other FTP servers. It is also equipped with hypertext transfer protocol (HTTP) to automatically generate day-to-day flood warning pages that can be dumped to a web server and can be accessed by the public across the Internet. The use of conventional communication techniques such as telephone and fax remains important in the Command Centre.

The database module is used internally by the warning system for archiving day-to-day decisions of the DSS into a standard database. Date-indexed records on past DSS activities can be easily accessed and interrogated using the calendar and standard query language (SQL) interfaces of the module. Also it has a provision to store observed flood events as judged by experts into the database. This is important for a later analysis of the past records for evaluation of the performance leading to the possible upgrade of models and decision parameters. This helps to store post-event expert evaluations of flood degrees into a database.

Flood degree thresholds

Krzysztofowicz (1993) defines a flood as the portion of a hydrograph above the flood stage. This definition is suited for the case of river based floods. In case of urban flash floods it is often difficult to have clearly definable banks since the flow does not follow a specified course. It is thus

difficult to have a threshold that marks the line between flooding and no flooding.

Once catchment models are set up, thresholds are perhaps the most important decision parameters of the DSS. Making a sensible selection of flood degree thresholds is an important part of setting up the DSS. This is because no matter how good the forecasts are, as long as the thresholds are wrongly set to figures that do not represent the perceivable degree of the flood, the resulting flood degrees will be misleading. This will entail all the range of possible consequences, from false alarms to failing to detect an imminent flood.

Setting flood degree thresholds

Flood thresholds can be set using flow or velocity as well as water level. Weighted combinations of inundation depth and velocity may also be used. A recent report from US Geological Survey has shown that most lives are lost when people are swept away by flood currents whereas most property damage results from inundation by sediment-laden water (Perry 2000). Since the damage associated with inundation depth is dependent on the cross section of the flow and the property in the area, a sensible way of fixing the flood thresholds would be the use of damage versus inundation curve.

The conversion from water levels (and currents) to flood degrees, which is basically a conversion from numbers to words, is not just a technical problem. In fact, care has to be taken to ensure that flood degrees generated by the DSS take into consideration the meaning the words bear in the particular language where it is to be applied. This is important not only for decision-makers but also for other interested parties such as the media and public in case warnings are issued.

Multiple thresholds

TELEFLEUR uses three threshold levels and classifies the flood degree into *mild*, *significant* and *severe* (see Figure 1). The benefit of using more than one threshold in urban flash flooding relates to the fact that different water levels can be used to mark different ranges of coverage of the flood and associated damage. This can be considered

as one way of managing the uncertainty associated with the forecasts.

Dynamic thresholds

Haines *et al.* (1990) proposed a threshold that depends on the fraction of people in the community who responded to the previous warning. It is dynamic since, for instance, the fraction decreases after issuing a false alarm. The idea of updating the thresholds is reasonable, especially for the first stages of the implementation of a warning system. But care has to be taken to maintain public trust in the warning system. If a flood event is not detected it does not necessarily mean that the thresholds are wrongly set; it could also result from errors in model forecasts.

Warning phase vs restoration phase

Threshold water levels are as important for the restoration system as they are for the warning system. However, the magnitude of the thresholds for the warning and restoration systems may not necessarily be the same due to at least the following four reasons:

1. The forecast locations at which warnings are based might be different from those with measuring equipment. The equipment is usually installed on structures such as bridges whereas model forecasts can be made at other locations as well.
2. The urgency of alerting people for possible floods is not the same as that for starting restoration activities. It is reasonable if authorities want to be confident that further flooding is not anticipated within a few hours of commencing restoration activities.
3. The level of uncertainty involved in both systems is different since the warning system uses forecasts most of the time whereas the restoration system uses observed data.
4. The physics of flood events is such that rising and falling floods behave differently because of the loop rating effect. Falling floods involve lower discharges and consequently slower velocities than rising floods for the same water level.

Taking all these factors into consideration TELEFLEUR has a provision to use different threshold levels for the warning and restoration systems.

Uncertainty measures

Any forecast involves uncertainty. Therefore it is important to give a measure of the uncertainty along with the forecasts. A study by Georgakakos (1986) suggests the incorporation of uncertainty in hydro-meteorological observations and forecast models. It is, however, not an easy task to provide uncertainty estimates along with flood forecasts. The main reason is that the forecast involves a series of models each contributing to the forecast uncertainty. The process of converting forecast time series to verbal flood degrees adds to the uncertainty. Since several likely scenarios forecasted by the synoptic analyst are simulated, the TELEFLEUR DSS uses the probabilities of exceeding the thresholds to estimate the uncertainty of the forecasts. For instance, if a total number of 100 likely scenarios is simulated, and at a location A, the hydrographs of 20 of these scenarios exceed *threshold 3*, then the probability of a *SEVERE* flood at location A is 20%. This is repeated for all flood degrees and all locations at which forecasted water level time series are used as a basis for warning. This, however, can be easily contested since the scenarios generated by the synoptic analyst may not include all the possibilities. That is why the envelope of all scenarios is also considered.

OPERATIONAL SEQUENCE OF MODELS AND THE DSS

The available effective forecast time mainly depends on the lead-time of the meteorological forecast. If a 72-hour in advance forecast is made by the GCM, as shown in Figure 6, the effective flood forecast time depends on the time elapsed by all meteorological models, the time needed to make hydrologic/hydraulic forecasts and the time needed to make a decision.

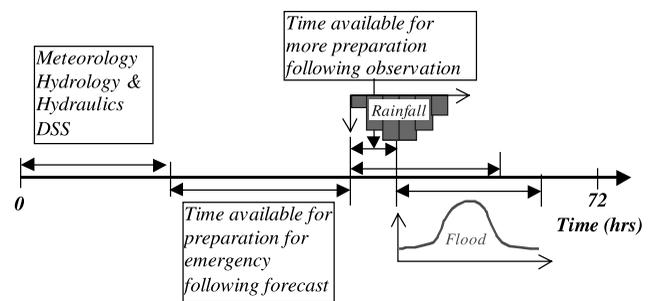


Figure 6 | Operational procedure of the flood management system.

The following is a proposed operational procedure for a typical operation of the DSS:

1. Generate precipitation forecasts using meteorological models, namely GCM through LAM or other forecast techniques such as radar imagery.
2. Visualise graphically the precipitation forecasts for possible extreme events (intense precipitation forecast initiates further processes).
3. Simulate using hydrologic and hydraulic models to forecast the water level hydrograph at various points.
4. Compare all the water levels within the time series with the relevant water level thresholds to analyse the evolution of the flood through time within the forecast period.
5. Determine peak water levels within the forecast period and their respective arrival time.
6. Prepare graphical output display through the GUI of the DSS as layers of a GIS map.
7. Generate (compose) flood statements using a built-in flood statement format and generate HTML code for possible access by the public via the Internet.
8. Analyse the results for the need of possible issuance of warnings to the concerned authorities (police, fire, hospital), media and/or general public.
9. Dump the forecasts into the standard database system for documentation.
10. Issue warnings by available means of communication such as: telephone for immediate actions, faxing the generated flood statement,

posting an HTML page on an Internet server, sending warning statements to authorities via e-mail or posting flood statements to an FTP site.

11. Watch the monitoring system to confirm the situation and to prepare for restoration activities.

VALIDITY ASSESSMENT

The validity of the forecast models in a DSS can be assessed with respect to, say, observed measurements. However, there are several problems. First, since flooding is caused by extreme hydro-meteorological events occurring infrequently, 'sufficient' data may never be available for the validation of such models. Second, the comparatively long time between flood events means that the physical domain undergoes minor or possibly major changes before a flood occurs again. Third, if or when the flood occurs again it may not affect the same part of the catchment due to the spatial variability of the rainfall. Ensuring the validity of a DSS for flood management is even more complicated in that close numerical reproduction of observed events is not the only criterion.

Krzysztofowicz (1993) and Krzysztofowicz *et al.* (1994) suggest the use of two parameters based on a Bayesian framework. The first is a relative operating characteristic (ROC), which shows the feasible trade-offs that the system offers between the probability of detection and the probability of false warnings. The second is a performance trade-off characteristic (PTC), which shows the feasible trade-offs between the expected number of detections and the expected number of false warnings per year. Unfortunately such assessments can only be done once the system is implemented and events occur or adequate past records are available. Models for a utilitarian measure of performance are also indicated by Krzysztofowicz (1993) based on the expected annual reduction of monetary losses and expected number of lives saved annually. Such analyses can be performed on the basis of damage from past flood events in the application area.

The validity assessment considered at this stage is based on the impacts that the system would bring. This assessment is intended to justify the need for using a DSS

for flood management. The criteria are subjective, mainly qualitative and some of them long-term:

1. Having a well-established system for assessing the effect of a forecast based on acquired meteorological data on possible flooding of urban areas.
2. Possibility of getting forecasted flood levels that are critical for possible evacuation and preparation in case of emergencies (duration as well as magnitude) with directions to safe escape routes.
3. Availability of sufficient time for early preparation of manpower and resources to deal with possible flood catastrophes once it is established that the occurrence of flood is imminent.
4. Possibility of identifying locations highly vulnerable to flooding for planning businesses, construction as well as flood mitigation projects such as detention basins, dikes, etc.
5. Presence of a tool for research, demonstration and training on decision-making with uncertainty in urban flood management.
6. Consolidation of knowledge and experience about warning systems to be developed in other flood prone areas.
7. Effect on the general public, both in terms of providing security and issuing warnings for events that eventually may not occur.

Validation in this context is used to see whether the system serves the intended purpose. It tests the system for the stated operational requirements as well as the integrity of the whole system, and any associated extended values.

It is obvious that it is not possible to validate such a system right away since flood events are extreme events and happen infrequently. However, such a system can be validated qualitatively. Records of past flood episodes, if available, can be used in the validation in the form of a drill, for example.

The following are outlined as possible validity requirements:

1. Acceptable physical functioning of every component individually and the whole system as a unit, testing access to the central functions such as online data,

testing users' acceptance of the clarity of DSS interface and functionality.

2. Application of the system in identifying flood prone areas for infrastructure, environmental and physical planning, and educational and research purposes. Does the type and amount of information obtained from the system help in this?
3. Evaluating the possibility of extending the applicability of the system to other areas having similar problems. These are areas having similar topography, meteorological and hydrological responses and facing the threat of flooding. It is important to know how much additional work is necessary to apply the system to these areas.

Social aspects

Urban flood management is important because it involves peoples' lives and property. Urban areas have the advantage of more communication facilities and disaster management resources including manpower compared to rural areas. On the other hand the social and economic consequences associated with false alarms are also more significant. The issuing of false alarms may result in the 'shepherd crying "wolf"' too many times, making its application less trustworthy. The decision to issue flood warnings to the public has to be preceded with adequate awareness to avoid both indifference or panic. Georgakakos (1986) suggests the need for such systems having an educational component as a design requirement.

The validation process of a DSS should not stop at the technical level. A new set of challenges will be faced in operational settings in which the social aspect of the flood management system is one and perhaps the most important of them. Flash floods result from extreme hydro-meteorological situations and it is not always possible to have sufficient data to address adequately the social aspects of the validation process at the development stage. However, the technical aspect of the design of a flood management system has to support the long-term social validation process. It has to be technically enabling to incorporate social aspects whenever data of such a sort is

available. In TELEFLEUR, one of the reasons for the incorporation of a database module that archives day-to-day activities of the DSS (including the type of warnings issued) and the assessment of experts after a flood event is intended to lay a technical basis for storing data needed for validation. However, more can be done in this respect such as including a socio-economic risk assessment module. Such a module would typically incorporate the views of emergency response agencies and community groups. In the long term, the view towards the type of protection against floods and the standard of safety against floods could change. Therefore, once a technically sound DSS is established, ensuring the validity of its performance has to be taken as an adaptive learning process.

CONCLUSIONS AND REMARKS

The study has shown that the problem of flood warning based on forecasts is one of great complexity and uncertainty. In urban areas, it is even more complicated for two basic reasons. The first is that urban areas present a complicated physical domain, which is often not possible to incorporate adequately in a model. The second reason is that human activity, such as the construction of sewer lines, paved areas and waterways, change the physical domain from time to time, increasing the discrepancy between model and observations.

However, if flooding is present as a threat, forecasts have to be made in order to save lives and property which, to make matters worse, are concentrated in urban areas. The consequences of possibly wrong forecasts are also more pronounced in urban areas, in which case false alarms could result in a loss of public trust. Results can, however, be improved with better forecasting techniques, improved catchment models, more experience in using the DSS and increased appreciation by the population of the meaning and implications of flood warnings.

Once model forecasts are performed, the principal parameters to determine the presence of a flood are the thresholds used to classify the magnitude of the flood into verbal degrees. The use of multiple thresholds and thus

multiple flood degrees is important to mark the varying levels of damage associated with urban flash flooding. At its present stage, the DSS does not provide a means to fix the threshold levels and this process has to be done separately. But its database module can be interrogated to evaluate if flood degrees are consistently being under- or overestimated in comparison to actual observed flood degrees. This can be used a means to adjust the thresholds accordingly.

The study indicates that most of the uncertainty in the system developed for the application areas discussed in this report seems to come from the precipitation forecast. It is known that now-casting techniques, such as the Doppler weather radar technique, provide more localised forecasts (Chen & Kavvas 1992) but the forecast lead-time is limited. Thus, it is recommended to use both short-range forecasting and radar now-casting techniques together, in which case the latter technique could be used to localise the forecasts made by the former as the event approaches. Some reports recommend local calibration of the rainfall forecasting model with the use of rain fields obtained from rain gauges and radar to correct the state variables of the models (Todini 1997).

The use of an integrated information system is needed to assist authorities in planning activities, archive day-to-day situations, monitor real-time events, automate routine activities and eventually provide a better understanding and control over flooding problems. A number of urban areas in the world have similar flooding problems and share similar hydro-meteorological properties as the study areas. The fact that the DSS is loosely coupled with the associated forecast models makes it easily applicable to other river systems with similar response time to meteorological events. That would need meteorological and water level forecast models of that catchment. It can as well be applied to catchments with slow response. In that case, the hydrologic models could use observed precipitation and upstream flow data. The use of observed precipitation will certainly improve the accuracy of water level forecasts. However, the required effective lead time is a key factor here. Analysis has to be made prior to its application. Additional improvements can be made to the DSS in order to make more use of Internet technology. For instance, the use of wireless application technology

(WAP) in remote operation of the DSS and even in the issue of warnings is a potential that needs to be investigated. The modular design approach of the DSS makes upgrading of component parts easier and cheaper.

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REFERENCES

- Abebe, A. J. & Price, R. K. 2001 Decision support system for flood warning in urban areas. *Proceedings of 29th IAHR Congress, Beijing, China, 16–21 September 2001*, vol. C, Tsinghua University Press, Beijing, pp. 78–84.
- Buzzi, A., Fantini, M., Malguzzi, P. & Nerozzi, F. 1994 Validation of limited area model in cases of Mediterranean cyclogenesis: surface fields and precipitation scores. *Meteor. Atmos. Phys.* **53**, 1994.
- Catelli, C., Pani, G. & Todini, E. 1998 FLOODSS: FLOod Operational Decision Support System. *Proceedings of Hydroinformatics '98*. Balkema, Rotterdam, vol. 1, pp. 255–262.
- Chen, Z. Q. & Kavvas, M. L. 1992 An automated method for representing, tracking and forecasting rain fields of severe storms by Doppler weather radar. *J. Hydrol.* **132**, 179–200.
- De Bruijn, K. M. & Klijn, F. 2001 Resilient flood risk management strategies. *Proceedings of 29th IAHR Congress, Beijing, China, 16–21 September 2001*, vol. C, Tsinghua University Press, Beijing, pp. 450–457.
- European Environment Agency. 2001 Sustainable water use in Europe. Part 3 – Extreme hydrological events: floods and droughts. *Environmental Issue Report No. 21*. Copenhagen, Denmark.
- Georgakakos, K. P. 1986 On the design of national, real-time warning systems with capability for site-specific, flash-flood forecasts. *Bull. Am. Meteor. Soc.* **67**(10), 1233–1239.
- Haimes, Y. Y., Li, D. & Stakhiv, E. Z. 1990 Selection of optimal flood warning threshold. In *Risk-Based Decision Making in*

- Water Resources* (ed. Y. Y. Haimes & E. Z. Stakhiv), pp. 74–90. ASCE, New York.
- Krzysztofowicz, R. 1993 A theory of flood warning systems. *Wat. Res. Res.* **29**(12), 3981–3994.
- Krzysztofowicz, R., Kelly, K. S. & Long, D. 1994 Reliability of flood warning systems. *J. Wat. Res. Planning Mngmnt, ASCE* **120** (6), 906–926.
- Laushey, L. M. & Huang, B. 2001 Real-time flood forecasting by tracing depth contours. *Proceedings of 29th IAHR Congress, Beijing, China, 16–21 September 2001*, vol. C, Tsinghua University Press, Beijing, pp. 120–129.
- Linsley, R. K. & Franzini, J. B. 1992 *Water-Resources Engineering*. McGraw-Hill Series, London.
- Michaud, J. D. & Sorooshian, S. 1994 Effect of rainfall sampling errors on simulations of desert flash floods. *Wat. Res. Res.* **30**(10), 2765–2775.
- Perry, C. A. 2000 Significant floods in the United States during the 20th century – USGS measures a century of floods. *USGS Fact Sheet* 024-00, March.
- Simon, H. A. 1977 *The New Science of Management Decision*. Englewood Cliffs, NJ, Prentice Hall.
- Todini, E. 1997 The role of rainfall measurements and forecasts in real-time flood forecasting and management. In *Weather Radar Technology for Water Resources Management* (eds B. Braga & O. Massambani). IRTCUD/University of Sao Paulo, Brazil and IHP-UNESCO, UNESCO Press, Montevideo, Uruguay.