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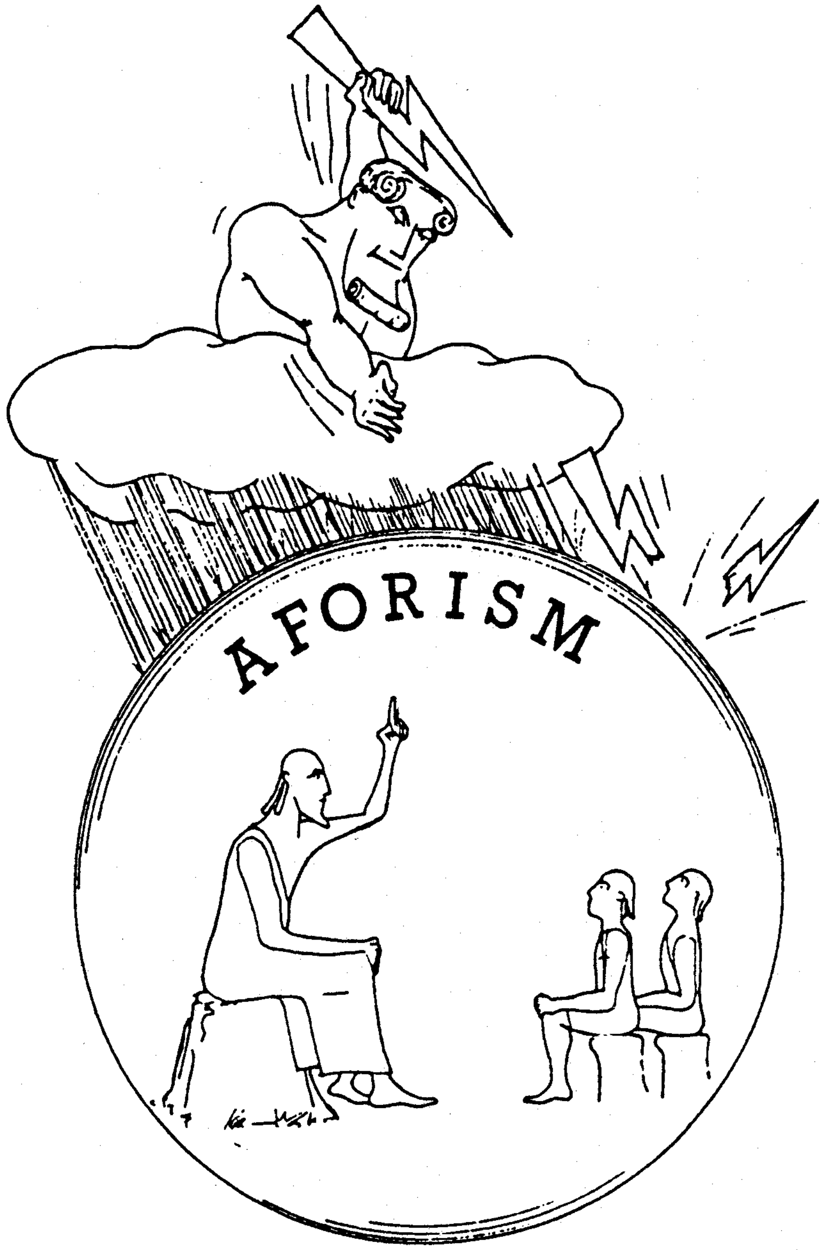

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

Third Annual Report (1993-1994)

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THIRD YEAR REPORT

1. INTRODUCTION

In recent years decision makers, in the field of flood risk management, have become increasingly interested in decision support systems that present in a synthetic and graphical form the alternative choices and the evaluation of the expected damages or benefits arising from their decisions. Therefore, to be of any practical value, the expert systems must allow for simulation of alternative management policies under the uncertain evolution of natural events.

In the field of flood risk mitigation and control the present state of the art allows for the development of reliable rainfall-runoff models, but in general the forecast is strongly affected by the knowledge of the uncertainty associated with future rainfall. In addition, a wide gap exists, at present time, not only between Meteorologists and Atmosphere Physicists on one side and Hydrologists, Soil Physicists and Engineers on the other side, but also between Scientists and Decision Makers.

AFORISM has been conceived, first of all, in order to fill these existing gaps, by creating a double common experiment:

- An inter-comparison of different approaches in rainfall-runoff modelling and their use both for planning and real time flood forecasting and management, aimed to the mitigation of natural hazards.
- A feasibility study, based upon the Reno river, aiming at integrating all the innovative technologies in an operational decision support tool for flood forecasting and flood impact analysis.

The main objectives of AFORISM have been:

(i) To study the level of aggregation and the required interfaces to set up a comprehensive flood forecasting scheme which will use radar data, telemetering rain-gauge network data as well as the ECWMF model results, to perform a dynamic stochastic forecast of future rainfall traces, by means of a Limited Area Model. The Quantitative Precipitation forecasts will then be fed into a rainfall runoff model, and a flood routing model to perform real time flood forecasting in flood prone areas. On the basis of an Expert System the impact of alternative management scenarios will be analysed and presented to the decision makers on the basis of a Geographical Information System (GIS).

(ii) To compare a number of different rainfall-runoff models ranging from the extremely simplified event models, through the continuous lumped semi-distributed models to the complex distributed differential models, in view of their inclusion in the forecasting and management system of objective (i) and the possibility of improving the representation of catchment behaviour.

(iii) To disseminate the results to all EU agencies mainly involved in flood risk mitigation and control.

AFORISM was carried out by the following research groups:

1) University of Bologna:
   - 1.a Institute for Hydraulic Construction (UNIBO-ICI)
   - 1.b Department of Physics (UNIBO-ADG)
   - 1.c Centro IDEA (UNIBO-IDEA)
2) Regional Meteorological Service of Emilia Romagna (ERSA-SMR)
3) University College Cork, Department of Civil Engineering (UCC-CORK)
4) University of Newcastle Upon Tyne, Department of Civil Engineering (UNUT-DCE)
5) National Technical University of Athens, Department of Water Resources Hydraulic and Maritime Engineering (NTUA-DWR)
6) Instituto Superior de Agronomia, Departimento de Engenharia Rural (ISA-DER)
7) Institut National Polytechnique de Grenoble (IMG-LTHE)
8) Ecole Polytechnique Federale de Lausanne, Institut d'Aménagement des Terres et des Eaux (EPFL-IATE)

A number data sets from several catchments of different sizes (ranging from 70 km^2 to 4,000 km^2) was used for the inter comparison of the rainfall-runoff models and most of the data were made available to all participants. Hydrological data were thus obtained for the Evinos (Greece), the Gardon d'Anduze (France), the Menthue (Switzerland), the Réal Collobrier (France), the Reno (Italy), the Rio Alenquer (Portugal), and the Sieve (Italy). The Reno river was also used as the basis for assessing the integrability of all the components analysed within the frame of AFORISM, furthermore a common experiment was launched with the meteorologists in order to evaluate the possibility of using in real time the quantitative precipitation forecasts issued by the atmospheric Limited Area Model (LAM) as input to the rainfall-runoff. The choice of the Reno river as the basis for the integration of the different procedures was made taking into account the interest in the project expressed by the Authorities responsible for the forecasting and control of floods. In particular strong links were created with the Reno River Authority, the Hydrographic and Mareographic Service, the Emilia-Romagna Regional Authorities responsible for Civil Protection.

The project, which was carried out in a period of three years was concluded by an International Seminar with the participation of National and International Authorities: this interaction with the Authorities in charge has in fact been the peculiarity of AFORISM, where the scientific approach on one side was confronted and compromised with the needs and the requirements set forth by the Authorities in order to jointly define a successful operational tool.

2. MATERIALS AND METHODS

The complexity of the project and the variety of investigations required did not allow, in this phase, mainly dedicated to the analysis of requirements and the assessment of interfaces between the different components, the use of a unified computer platform upon which to develop the entire system. At the beginning of the project, while most of the stochastic rainfall models and the rainfall-runoff models were operational on PCs, the deterministic rainfall models were only available on large processing units such as for instance the CRAY or Parallel Processor Main Frames; moreover Expert System shells, such as for instance G2 or Nexpert were more usefully available on Unix workstations. Therefore, the definition of the most appropriate tools has been one of the scopes of the

project. Also in view of the operational implementation of AFORISM, a general consensus among participant was reached, and the Unix based Risk Workstations were indicated as the most appropriate for the integration and the development of the system, given their expected increase in speed in the nearby future combined to the flexibility and interactive graphical capabilities offered by X-Windows.
From the point of view of hydro-meteorological data acquisition systems, data were mainly provided by conventional ground based gauges, in that this is the most usual situation in practice. Precipitation estimated data in the Reno river were also made available from the ERSA-SMR radar of S. Pietro Capofiume (44° 39' N, 11° 37' E, 11m msl) and were used in combination with the LAM for providing Quantitative Precipitation Forecasts.
With respect to the methods used, most of the project was dedicated to the analysis of the different meteorological, hydrological, hydraulic components in view of their inclusion in the system and their interaction with the end user. Additional work was done for the identification of the most appropriate tools for data bank, geographical information system, decision supporting tools, and graphical means of representation.
A brief presentation of all the components analysed is reported in the sequel, while special attention will be devoted to the choice of the rainfall-runoff component which was one of the main objectives in AFORISM.

Hydro-Meteorological Data Acquisition Systems
Most hydro-meteorological data used in the project were provided by conventional data acquisition systems which are widely spread in the world and which are based upon ground based gauges. In AFORISM, for the Reno river case study these data were also complemented by radar measurements and used for the updating of radar calibration. At ERSA-SMR, where the radar data over the Po valley are available a study was conducted which main task was the improvement of the rainfall estimations using the data from a rain gauge network in the frame of an objective analysis scheme. The radar rainfall is estimated by the reflectivity Z by using the couple of coefficients A=500 and B=1.5 (1) in the Marshall-Palmer relationship tuned during some thunderstorm situations. In order to compute the hourly radar rainfall (comparable to the sampling interval used for the rain gauges) the average speed of storms was assumed about 5 m/sec which required a spatial resolution of 5*5 Km^2. A static clutter mask was applied in order to reject the ground clutter points from the adjustment procedure. The comparison of radar rainfall estimates and the rain gauges data was performed using the scheme proposed by Koistinen and Puhakka (2). Because of such technique combines in a weighted scheme the uniform spatial adjustment and the objective analysis of the adjustment factor (that is the ratio between the rain gauge observation and the radar estimation in the same point), it produces satisfactory results in situations of small and non uniform rain gauge density, like the situation of the Regional Meteorological Service network. The scheme was applied to the data set MATREP (an Italian acronym for the monitoring of thunderstorm in the Po Valley region of Northern Italy) that is a field experiment performed in June 1990 (3). The results were presented at the 2nd International Symposium on Hydrological Application of Weather Radar showing a good performance of the scheme. In fact, the scheme provides a reduction both of the total bias from -0.5 mm to -0.03 mm (i.e. a little radar underestimation) and the root mean square error (rms) from 4.4 mm to 3.5 mm. The differences between the raw radar rainfall estimations and the gauge observations for six hours rainfall amount were initially very large: the values exceed 10 mm for half of the stations, with a maximum of 20 mm of negative difference. The application of the correction scheme to the six hour rainfall produced the better results in terms of decrease

of the errors, which dropped from -7.6 mm to 0.5 mm in terms of bias and from 11.1 mm to 7.1 mm with respect to the rms.

Rainfall Modelling and Forecasting

A primitive equations limited area model, LAMBO (Limited Area Model BOlogna), has been employed to produce high resolution forecasts of precipitation within the AFORISM Project (LAMBO is now running operationally at ERSA-SMR since September 1993). In general a primitive equations model is a model in which, assuming that the atmosphere is in hydrostatic equilibrium, motion is predicted by applying the principles of conservation of momentum, energy and mass and using the law of ideal gases. LAMBO is based on a model originally developed in its older adiabatic version in Belgrade (during the early seventies) as a co-operative effort between the University of Belgrade and the Hydro-meteorological Institute of the former Yugoslavia (HIBU model).

During the last decade, several improvements in the formulation of the adiabatic part of the code have been implemented. Furthermore a complete physical package has been included in the model, in the framework of a co-operation between the University of Belgrade and the National Meteorological Centre of Washington (NOAA-NMC) (4, 5, 6). This version of the model, referred to as the UB-NMC /ETA model, is at the time of writing the operational limited area model of the NOAA-NMC. The version dated 1989, recently upgraded is some parts of the physical parameterization schemes and completely reformulated in its pre- and post-processing sections, is the above mentioned operational model LAMBO.

UNIBO-ADG and ERSA-SMR have implemented the model on the VAX 6310 and CRAY YMP. They have also acquired data sets from the European Centre for Medium Range Weather Forecast (ECMWF) archive and they are in the process of running the model under test conditions. As regards QPF using LAM, most of the work has been done trying to identify the optimal configuration of the model, particularly as concerns the precipitation forecast quality. This has been achieved by means of statistical verification of the LAM over 2 months period, June 1990 and January 1991. The Reno flood event occurred on 25-26 November 1990 has been chosen as the case study for AFORISM in order also to test the operational capability of a forecasting system for flood risk mitigation and control. The UB-NMC model has been run for this case study using both sigma and eta vertical co-ordinates and at various horizontal and vertical resolution (Hor. Res: 10-20-30 Km; Vert. Res: 20-32 vertical levels).

The forecast precipitation fields are very realistic and have been integrated over the Reno Basin to furnish the meteorological precipitation input necessary to run successive flood models of the other project partners (UNIBO-ICI).

At UNIBO-ADGB, most of the work has been concentrated on the assessment of the best method to generate the set of equiprobable initial conditions for LAM integration. The LAGGED AVERAGE FORECASTING (LAF) technique produces results generally very satisfactory for mass and wind fields but, for this application (i.e. QPF), it was found not to be the most suitable approach. In fact for the application in this project, where short range forecasts of quantitative precipitation are required the time lag between two subsequent forecasts of the ensemble, i.e. 6 hours, is too similar to the forecast range itself. The criterion at the base of the generation of perturbations of the initial state is related to the growth rate of the atmospheric unstable modes of interest. These modes have to be dynamically unstable with growth rates similar to the growth rate of the forecast error due to the initial analysis errors. on the basis of such considerations, the most promising method, also considering its ease of implementation, was found to be the Breeding of Growing Modes method, BGM, recently proposed by Kalnay and Toth, of the National Meteorological Centre of the USA (7, 8). The BGM method is based on the "natural" breeding of an initial random perturbation by means of subsequent very short range forecasts (e.g. 6 hours). The description of the method is reported by Kalnay and Toth in the above mentioned references together with their initial application of the method to the NMC data assimilation cycle. Their stated purpose is to breed the high energy modes associated to baroclinic disturbances. In our case, where intense precipitation forecasting is of particular importance, we are interested in breeding also the very fast growing modes (of comparatively smaller spatial scales) associated with unstable convection. These modes saturate typically at lower energy level and much of the work is now devoted in tuning the breeding cycle to this purpose. The method is now operational both on Vax and on Cray YMP 8/432 versions of the numerical model and at present the application of BGM is being extensively tested. The analysis of precipitation estimates, provided by the GPM 500 C radar, collected during the period September-December 1993, is compared to the precipitation data recorded by the SMR (Regional Meteorological Service) automatic network. A case study of a supercell storm occurring during the MATREP experiment has been analysed in detail, looking both the environmental conditions and the morphology of the cell evolution; with reference to the radar rainfall estimates the application of an objective analysis scheme drastically reduced the error in the direct radar estimates.

Stochastic Rainfall Models

As opposed to deterministic QPF, stochastic rainfall models may provide reasonable ensembles of precipitation scenarios at low computer time expenditure. Within the frame of AFORISM it was considered essential to implement and to use the stochastic precipitation ensembles in order to perform a sensitivity analysis of the rainfall runoff process to rain as well as to evaluate the forecasting capabilities of the stochastic univariate and multivariate generators.

UNUT-DCE has developed a multivariate rainfall model based upon the Modified Turning Band (MTB) concept and is in the process of calibrating the model on data provided by EPFL-IATE. Monte-Carlo experiments have been performed with the MTB Model to produce many synthetic rainfall events. The effect of sampling these rainfall fields with networks of tipping bucket rain gauges has been simulated to produce data sets reminiscent of those that would be obtained in practice. By considering a set of configurations of rain gauges which become gradually less ideal, the threshold at which estimates of the raincell parameters of the MTB Model cease to be of use has been determined, hence design criteria for a minimum network have been established.

NTUA-DWR developed a scaling model for the temporal structure of rainfall events which is modelled by a self similar (simple scaling) model. The model is based on the hypothesis that the rainfall process at any time position in the interior of a storm of a certain duration is a simple scaling process with a constant scaling exponent. Thus, the processes of intensity in two events with different durations are proportional (in distribution) to each other, under appropriate scaling of time determined by the ratio of the durations, with the proportionality ratio being a power of the ratio of durations with exponent equal to the scaling exponent. UNIBO-ICI has developed a Bayesian univariate stochastic rainfall model and tested a stochastic generator in order to generate conditional series of future rain . The results of the generator seem effective, and the number of parameters may be reduced by accounting for the self-similar structure of cumulated rain.

IMG-LTHE has done extensive testing on a stochastic univariate rainfall generator based on the renewal processes approach.

The Rainfall-Runoff Models

The literature contains many works that summarise the level of understanding of the physics of the complex problem of rainfall-runoff transformation (9, 10). Many efforts have been made to schematise the whole process in order to develop mathematical models (11, 12, 13, 14, 15). This ranges from the simple calculation of design discharge to the two-dimensional representation of the various processes based on suitably and reciprocally conditioned mass balance, energy and momentum equations (16, 17, 18, 19), and to the three-dimensional representation of all the exchanges (20). Taken together, these latter kinds of model comprise the broad category of distributed differential models (21); they are frequently referred to as "physical models" to highlight the fact that their respective parameters are (or should be) reflected in the field measurements (22). Given their nature, they are mainly used in investigations and research as a mathematical support for the interpretation of physical reality.

Another category of models, which was mainly developed for operational purposes, is that of the complex "conceptual models" better known as "semi-distributed conceptual models". Starting from a very simple model developed by Dawdy and O'Donnell (23), from the early sixties a large number of these models came to light from the Stanford Watershed Model IV (24) to the SSARR (25), the Sacramento (26), the Tank (27), etc., which represented in different ways the response mechanism of the various phenomena, but mostly by means of non linear reservoirs and thresholds, directly connected or linked by means of linear transfer functions.

The reason for developing these models was the idea that one could represent the hydrologic cycle linking together process components which described physical concepts, on the presumption that the model parameters would also bear physical meaning, so that they could be assigned values without reference to the observed data. In other words, conditionally upon the structure of the models, it was assumed that most of their parameters (such as storage coefficients, roughness coefficients or thresholds present in the various sub-components) could be defined from the physiographic characteristics of the basins. In reality the parameters needed to be estimated on the basis of objective functions to be minimised (for example the sum of deviation squares) which generally lead to groups of unrealistic parameters which incorporate both data measurement errors and the errors present in the structure of the model itself; in addition the observability conditions could not always be guaranteed (28).

It is now understood, also as a result of AFORISM, that the basic failure of these models is essentially due to their lack of capability in reproducing the dynamical variation, within the catchment, of the saturated areas extent. Indeed in the last years, a general consensus has been reached on the fact that it is this dynamical variation, a function of the accumulation and horizontal movement of the soil moisture storage (29, 30), the major responsible for the highly non linear behaviour of catchment response to storm events. Most of the conceptual modelers tried to compensate the inadequacy of their models by more and more adding process components as well as parameters but they failed in reproducing the actual phenomena and reduced the models to extremely complex black-boxes with an exceedingly high number of parameters (frequently larger than 20) to be estimated from the available records, as it clearly emerged from the WMO inter comparison of conceptual models (31) where the results of all the different models did not appear to be significantly better than those produced by the Constrained Linear Systems (CLS) model, a simple piece wise linear black-box model (32).

More recently, newly developed conceptual models have regarded the soil moisture replenishment, depletion and redistribution mechanism directly responsible for the dynamical variation of the areas contributing to direct runoff and consequently on its greater or lesser incidence on flood flows. From this concept a number of models were originated which use a probability distribution of the soil moisture content, as in Zhao (33) and in Moore and Clarke (34), or the distribution of a topographical index, as in

TOPMODEL (35). The advantage of these models lays in their capability of reproducing the phenomena with a smaller number of physically meaningful parameters (36).
Within the frame of AFORISM several approaches have been implemented and tested in order to answer questions ranging from: which type of model should be used? deterministic or conceptual?, event based or continuous time?, lumped, semi-distributed or distributed?
NTUA-DWR limited the analyses in the calibration of continuous-time lumped rainfall-runoff models which are widely used in flood forecasting for small and medium-sized headwater basins. Among the models of this category we have chosen those that have the common structure used in the Unit-Hydrograph modelling context, namely they comprise of one first part called production function and a second part, the transfer function. The first part summarises all hydrologic processes involved in an idealised soil column representative of the whole basin and yields the runoff volume or effective rainfall for each time step. The transfer function encompasses all transfer processes within the catchment and is reasonably assumed linear thus satisfying the assumptions of the Unit Hydrograph. In a recent paper (37) a new approach for calibrating lumped rainfall-runoff models, called FDTF-ERUHDIT was presented. Based on the Unit Hydrograph concept, the method performs a simultaneous identification of the effective rainfall series and the First Differenced transfer function or Unit Hydrograph through an alternate iterative procedure without presupposing any runoff production function or applying any arbitrary base flow removal. The FDTF-ERUHDIT method was a key element in the analyses. Two well-known rainfall-runoff models were selected for the analyses, the version of the SACRAMENTO model adopted by the U.S. National Weather Service known as the Soil Moisture Accounting (SMA) of the U.S. National Weather Service River Forecast Service or SMA-NWSRFS (26), and the TANK model (27).
ISA-DER developed a distributed physically based model to be used as part of the inter comparison of rainfall runoff models. Before writing the code, a detailed report about the model was prepared. Such report discusses the methodology used, define precisely the variables, provide the detailed calculation procedures, illustrate the procedures with numerical examples performed by hand, define the various modules with their functions, the input information and the output coming out of the modules and, finally, provide a dictionary of equivalence between the mathematical symbols and the names of the variables in the selected computer language.
At UNUT-DCE the physically-based distributed catchment modelling system SHE (16, 17) has been calibrated on the Upper Reno catchment using limited but highly distributed data sets in order to analyse the effect of spatial variability of rainfall fields.
At UNIBO-ICI, the ARNO model and the TOPMODEL were both tested on various data sets. This comparison has been performed in collaboration with the IMG-LTHE who provided the data for the Réal Collobrier as well as the computer program for the TOPMODEL. The detailed analysis of the TOPMODEL, by means of the available digital terrain models of a number of different catchments (Réal Collobrier, Reno River, Arno River and all the Tuscany Region sub-catchments), in order to understand the representativeness of some of its elements, has been completed and a final report has been prepared (29). Both the TOPMODEL and the ARNO model were calibrated on the Reno river catchment and results showed a better behaviour of the ARNO model when used on split sample tests .
At IMG-LTHE the FDTF-ERHUDIT approach has been further developed and the problem of the invariance of the transfer function has been addressed by using data from the Réal Collobrier and of the Sieve In addition the study of a loss function based on TOPMODEL has been performed as well as the verification of the TOPMODEL at

hillslope scale. Furthermore a simplified version of TOPMODEL has been set up for operational purposes and tested.
IATE-EPFL carried out a deep investigation on the flood generating mechanism at different scales, with particular reference to the TOPMODEL mechanism and a number of conclusions have been determined. In particular it appears that the TOPMODEL does not adequately represent flood processes in the Haute Mentue watershed. However, numerical fitting leads to satisfactory results. The analysis of the model response surfaces indicates relatively flat optimum areas. This provides a certain robustness in the parameter estimation phase. TOPMODEL requires some improvements, especially a general routing function. This somehow reflects the findings of UNIBO-ICI on the uncertain determination of a characteristic catchment topographic index function as well as on the need of an appropriate routing function; at UNIBO-ICI the parabolic approach was successfully adopted.

Flood Routing and Flood Plain Modelling
Flood routing is an essential component in real time flood forecasting when flood stages have to be compared with warning or flooding levels at a downstream section.
The development of flood routing schemes has been tackled in the past mostly by hydraulic engineers mainly concerned with the design of hydraulic structures and the analysis of their effectiveness. This has lead to the implementation of a number of computer programs, based on the numerical integration of the partial differential equations describing the flood routing phenomenon. These efforts have mainly concentrated on the detailed description and accurate simulation of the propagation of a flood wave in a more or less complex channel reach. In general, computation time of the programs has not been considered as a limiting factor to their practical use, while in real-time applications both computation time and stability of results become of the utmost importance.
Alternatively, hydrologists have proposed extremely simplified models, such as storage routing (38, 39), Muskingum routing (40), Lag and K routing (41), Kalinin and Miljukov routing (42), linear reservoir and channel cascade routing (43), etc., which do not describe the propagation phenomenon, but allow for the computation of discharges in a given downstream section as a function of discharges known at an upstream section. These models require virtually no running time, but can only describe the overall effect of a channel or river reach, and do not allow for the simulation of hydraulic structures inserted within the reach. They tend to give what Dooge calls the "external" description as, opposed to the "internal" description of the system, provided by the full dynamic models.
On the line of the comprehensive and detailed description of flood routing procedures which can be found in "Channel Routing" by D.L. Fread (44), extensive investigation in this domain was carried out at UNIBO-ICI which showed that most rivers do not require the integration of the full De Saint Venant equations and simplified approaches can be used. Given its flexibility and the capability of accounting for downstream conditions, the Parabolic and Backwater model (PAB) (45, 46) was used for the main reach of the Reno River, while a Muskingum-Cunge model was developed on the main river tributaries, as part of a procedure aimed at transferring to the main rach the upstream forecasted flows.
Unless the water overtops dikes and spreads over the flood plain, rendering the one-dimensional description inadequate, the one-dimensional assumption is reasonably accurate for describing channel flow, but for the purpose of AFORISM, in order to assess the possible damages of flooding, the two-dimensional flood plain inundation or overland flow had also to be studied. Quasi-two-dimensional models can be found in the study of flood events; in these the flooded area is described by a series of reservoirs and

channels whose position may correspond more or less to their exact spatial arrangement in the area in question (47). In parallel with this, a large number of numerical solutions for two-dimensional models have been developed which can broadly be distinguished according to the type of spatial discretization employed: the mesh can be structured (with nodes arranged on a straight-line grid or adapted to the boundaries by appropriate geometrical transformations) or non-structured (irregular and composed of triangles quadrangles or polygons). Structured meshes are usually associated with finite difference equation (FD) discretizations; non-structured meshes are generally found in integrated finite differences (IFD) or in finite element (FE) discretizations. Hromadka et al. (48), among others, developed a finite difference model based on an integrated finite difference version of the nodal domain integration model, in which the discretization in polygons (control volumes) is based on an irregular triangular discretization. Alternative solutions for the two-dimensional overland flow problem using the FE approach can be found in Galland et al. (49) and Katopodes (50, 51).
Mixed one-two dimensional (1/2-D) approaches (i.e. two-dimensional (2-D) flood plain and one-dimensional (1-D) channel flow models dynamically linked by matching their respective boundary conditions) are used to describe flood plain inundation problems, in order to deal with the whole domain by defining a unique mathematical problem to be solved at each time step. The mixed 1/2-D approach also affords approximation of bends, expansions and contractions of the river bed, flow breakouts, and the general main flood carrying area. Furthermore, when rivers are characterised by accentuated meandering, a flood may overtop the banks and change the preferential flow direction, originally described with the 1-D approach, thus becoming fully 2-D. As a consequence, a major advantage of a mixed one-two dimensional description is that the construction of the model does not require "a priori" knowledge of the main direction of propagation which may vary in time, provided that the model is supplied with the necessary topographic information. In Anselmo et al. (52) a mixed 1/2-D model, also described in Todini et al. (53), was used for verifying the design of the Montalto di Castro Power Plant. The scope of the research at UNIBO-ICI has been concentrated in the extension of a model based upon the Integrated Finite Difference to problems encountered in practice, in collaboration with EPFL-IATE, and to the development of a mixed 1/2-D overland flow model based upon the Control Volume Finite Element discretization method (54) (originally introduced in heat transfer and flow in porous media calculations (55)), which allows for conservation of mass and energy at the global as well as at the local scale.

Multicriteria Optimisation

The decision making process for managing flood control structures, such as those present on the Reno River, requires that the Decision Maker analyses the different impacts or consequences that may result as a consequence of his decisions. This can be done by providing the Decision Maker with a Decision Support tool that allows him to rank the different alternatives more than to find an "optimal strategy". At UNIBO-ICI, the Compromise Programming Method was analysed in order to function as the basis of the decision support system to be used by the Decision Maker, and two reports were prepared on the subject. In addition the need for the development of Decision Support System, such as for instance the one that appears from the findings of the University of Cork, requires both the acquisition of an expert system shell and the training on the development and use of expert systems.
For these reasons a workshop on "Expert Systems for Water Resources Management" was organised in Bologna by the Institute for Hydraulic Construction of the University of Bologna and the Centro IDEA, with the sponsoring of : UNESCO, IAHS, ENEA, ISMES and POSTER.

At UNUT-DCE a new approach was sought for the optimal control whereby the expected path taken by the upstream Reno through its state space is computed, given the non-stationary transition probability matrix. Then those controls which modify the upstream flow as it passes through the barrier are found which minimise flood damage downstream.

Geographical Information Systems

The development of an integrated decision support system for the management of floods and the alleviation of flood risk requires a simulator which will estimate the impact of the different proposed strategies under the uncertain climatic conditions.
The basis for this simulator are (i) the availability of a Geographical Information System (GIS), comprising not only the Digital Elevation Model of the terrain, but also all the information needed for the estimation of the flood impact, and (ii) a two-dimensional flood routing model which will allow for the estimation of the water flow velocity, the water depth and the water time of residence.
On this line a collaboration with the EFPL-IATE was established and a two dimensional model for flood plain inundation studies was developed in Bologna by means of two different integration schemes: the Integrated Finite Differences and the Control Volume Finite Elements. The model was modified in collaboration with EPFL-IATE in order to make it compatible with the requirements of flood mapping in flat areas, that is capable of handling structural patterns of topography such as roads (break lines) and surface depressions where water remains stagnant. The model is then to be used in combination with the GIS in order to estimate damages and losses. EPFL-IATE also developed GIS prototypes for flood mapping and assessing flood impacts on road traffic, agricultural areas and built up regions. Prototypes to evaluate flood impacts on traffic network, agricultural practice and built up areas have been developed. Conceptual dynamic data bases have also been implemented (56).

Decision Support Systems

UCC-CORK studied the feasibility, the configuration and the requirements for the development of the Expert System as part of the Decision Support System. UCC-CORK performed a series of structured interviews in order to identify the needs of the various parties involved in the decision making process both in Ireland and in Italy. The findings were considered under the following groups: Operational managers in Italy, Civil Response managers in Italy, Operational managers in Ireland and Civil Response managers in Ireland.
Operational managers were defined as those dealing with the physical infrastructure of flood control such as dam operations and pumping decisions etc. Civil Response managers were defined as those responsible for reacting to a flood event once it has occurred by carrying out temporary works, organising evacuations, attempting to minimise economic and social costs etc.
The results of these interviews were taken as the basis for the definition and the structuring of the Decision Support System and a proposal has been made with a set of rules encompassing not only flood management but also, more general quantity and quality management.
UNIBO-ICI has acquired the G2 Expert System shell and deep investigation has started in order to assess the capabilities of the system, which allows for real time control actions.

The Reno River Common Experiment.

As it was mentioned earlier in order to assess the capability of integration of all the components a common experiment was launched on the Reno river. The preparation of the data sets for the common experiment was a major responsibility of UNIBO-ICI. In order to allow for the common experiment the topographical computerised maps of the Reno river acquired from the Regione Emilia Romagna have been completed with data acquired from the Tuscany Region and a digital elevation model of the terrain in the upper part of the Reno river was established. In addition three years (1990-1992) of continuous records for precipitation (48 stations), temperature (15 stations) and water levels (22 stations) were provided to the project by the Servizio Nazionale Idrografico e Mareografico. Most of the data were on graphs which required long time consuming digitalisation. After digitalisation the data were checked and validated by comparison with the original graphs; in addition the recorded data were sampled at one hour sampling interval and all the missing data were reconstructed by means of a Kalman Filter approach (Todini, 1995)

The MTB model was fitted to five storm events which were observed on the Reno catchment around the time of the only major flood in the records available for this study. The fitting has been done in such a way that the depth, time of arrival, and duration of these storms is reproduced, on average, by realisations of the model. This means the production of 'alternative' storms which, although never having happened in practice, may with equal probability have happened instead of the five observed events. It is therefore possible to produce an ensemble of flood-producing rainfall scenarios which can be used to investigate the effects of incomplete sampling of rainfall fields in the domain of the Reno catchment. At UNUT-DCE the physically-based distributed catchment modelling system SHE has been calibrated on the Upper Reno catchment using limited but highly distributed data sets provided by UNIBO-ICI. A digital elevation model (DEM) was used to derive grid square elevations, and river widths and depths were derived from limited information on channel sizes. The soil types, land coverage and vegetation types have been discretized into meaningful classes, and these have been distributed accordingly over the grid elements also. The grid size itself is to 800 metre resolution, and covering an area of about 40 by 60 kilometres, comprises 2196 computational elements. Monte-Carlo experiments have been performed with the MTB and SHE models whereby a large number of synthetic rainstorm events are sampled according to hypothetical rain gauge networks consisting of 3, 6, 12, 18, and 24 rain gauges distributed approximately evenly about the catchment, and the rainfall field has also been sampled on a grid of the same spatial resolution as the catchment model. All the storms, in all the sample configurations, have then been input to the SHE model and the resulting runoffs assimilated. These results have been analysed in order to determine the nature and magnitudes of the errors (i.e. differences in runoff arising from the same storm but with different sampling arrangements).

As a result of the comparison of different rainfall-runoff models to be used for real time flood forecasting a general consensus was reached on the need of simple models (thus avoiding the complex distributed physically based ones). In addition, due to the difficulty of estimating the initial soil moisture conditions, continuous type models were chosen, also given the availability of continuously recorded real time data. The ARNO model and the TOPMODEL, where analysed as possible candidates and were calibrated using the 1990 rainfall and runoff data. The final choice was for the ARNO model for two reasons. The first one relates to the more uniform performance of the model in verification periods, and the second one relates to the fact that the ARNO model is already imbedded into an automatic real-time flood forecasting system, known as the European Flood Forecasting Operational Real Time System (EFFORTS), which was developed within the frame of a R&D project funded by the CEC and has been extensively used in practical applications, nowadays being operational on several rivers (Fuchun, Po, Arno, Tiber, Adda, Oglio, Danube); EFFORTS includes a suite of several programs capable of accepting real time data and performing the following operations:

- Display of the catchment and of the stations;
- Verification of the real time acquired data;
- Automatic reconstruction of missing data;
- Sampling of data at constant time steps;
- Computing average precipitation and evapotranspiration;
- Computing flows at a number of pre-set locations by means of the ARNO model;
- Computing the levels in all the river cross sections, by means of PAB flood routing scheme;
- Display of the flood levels and comparison with the dikes elevation.

Calibration of the ARNO rainfall-runoff model was successfully obtained by using the historical record (1990-1991).

In order to calibrate the flood routing model for the Reno river, a number of problems had to be solved. In particular the rating curves provided by the Hydrographic Office in Bologna needed verification: this was done by establishing a measurement campaign on the upstream cross sections, while using an original technique for estimating the downstream ones.

The cross sections available for the river Reno were used for calibrating the flood routing Parabolic and Backwater (PAB) model selected. The results of calibration, although reasonably good have shown the inadequacy of the available cross sections. The Reno River Authority was informed and the operational decision was taken of performing, in due time a new measurement campaign. As previously stated the results were good enough for the purpose of the project and this calibration was then used within the EFFORTS package.

In addition, the setting up of the real-time flood forecasting system required the following operations to be performed:

- Digitisation of the basin map and measurement point location;
- Structuring of the necessary system definition files;
- Calibration of the real time automatic data reconstruction models for precipitation, temperature and level stations;
- Calibration of the Kalman Filter based rainfall extrapolation models;
- Calibration of the Kalman Filter based real time updating noise models.

The entire set of operations was successfully performed bringing about a system which can be used for operational flood forecasting in real time.

In order to analyse the effects of possible real time decisions a 2-D model was then calibrated and used in combination with dike failure hypotheses, in order to simulate the inundation event of November 26th, 1990. The model, which is based upon the Integrated Finite Difference approach, was originally developed at UNIBO-ICI. Within the frame of AFORISM, the package was then modified in order to allow for breaklines (such as dikes, roads etc), as well as for other hydraulic specific elements which are currently encountered in practical applications in collaboration with EPFL-IATE.

The model was calibrated by comparing the actual flood map with the model results and the results were demonstrated in an animated succession by means of a GIS.

Finally a joint experiment was set up in collaboration with the ERSA-SMR group. Nine quantitative precipitation forecasts up to 24 hours were generated by ERSA-SMR on the basis of an operational Limited Area Precipitation model with 10 x 10 km^2 grid. The forecasts were aggregated at the scale of the subcatchments used in the flood forecasting model and compared, for the first 12 hours, with the precipitation calculated by using the available rain gauge system. After applying a correction factor, the precipitation estimates were used as input to the rainfall-runoff model. The results showed interesting possibilities, although scaling problems between the precipitation forecasted by the model and that measured at the rain gauges, still exist. Further investigation should be devoted to this approach, which seems extremely promising, by developing an improved post-processor for the precipitation estimates.

3. DISCUSSION ON RESULTS

All the results of the three years research were presented in Bologna in an International Workshop organised under the auspices of the World Meteorological Organisation. UNIBO-ICI in collaboration with the Centro IDEA, provided the organisation and the logistic for the seminar. The Seminar was held in Bologna on June 1994 with more than 80 participants from European, Italian National and Local authorities dealing with flood forecasting and warning. The results of the project were very well accepted by the participants; in particular highly positive comments were issued by the representative of the World Meteorological Organisation, as well as by the Director of the Italian National Hydrographic and Mareographic Service.

It has been recognised that the project has been extremely successful, and indeed one should recognise that AFORISM was a very ambitious and complex project, partly scientific and partly trying to solve communication problems among the different subjects that must confront themselves with the problem of flood forecasting and warning.

First of all it gave the possibility of deeply analysing the most important features to be retained in a real time rainfall-runoff flood forecasting model, which have now been identified in the dynamical variation of the directly contributing saturated surfaces, in combination with the filling and depletion of the soil moisture storage.

The second achievement has been the setting up and calibration of a prototype for the real time flood forecasting system of the Reno river, with the identification of all the interconnections needed and the pitfalls to be resolved for the development of an operational system which would make best use of the available data by extrapolating the precipitation measurements on the basis of the Limited Area Precipitation model forecasts and to assess the effect of decisions by means of flood plain modelling and impact analysis as a support to the decision makers.

The third and most important achievement has been the strong interaction associated to the high credibility and reputation gained by the group among the Regional, the National and the International Authorities. One of the project outcomes is the decision expressed by the Director General of the National Italian Hydrographic and Mareographic Service as well as by the Secretary General of the River Reno Authority to establish the Reno river as the Italian National sample catchment for flood forecasting experimentation and to proceed to a new phase in which all the work carried out under AFORISM will be operationally implemented.

Indeed much work has still to be done, but already a draft proposal for the definition of the forecasting system, as well as for the reorganisation and standardisation of the Flood Warning and Civil Protection procedures has been circulated with the intent of proceeding to its implementation within the frame of the next few months.

4. CONCLUSIONS AND RECOMMENDATIONS

AFORISM has been in our view the first phase, the feasibility study of a complex comprehensive tool to be developed in order to support both planning and forecasting. The first action to be taken is to capitalise on the extremely high interest expressed by the

Authorities and to operationally implement the system. This would allow for a thorough experimentation of the possible benefits arising from its use.
Additional work has to be performed in order to improve the precipitation forecasts using the Limited Area Model on the basis of the radar and of the conventional precipitation gauge network.
On the other hand several other aspects, which were not taken into consideration in this first phase, and which were pointed out by the World Meteorological Organisation, have still to be analysed in order to complete the operational tool.
The first aspect relates to the possible use of Quantitative Precipitation Forecasts derived from satellite images. Indeed recent advances in this domain make the investigation appealing.
The second aspect relates to the necessity of providing the user with the possibility of taking advantage of a unified standard manual of procedures as well as with the availability of geo-related documentation tools in order allow information on manpower and materials, on the administrative and legal boundaries and on the people in charge.
Finally, given the increasing interest of public in participating to decisions that involve the essential safety and quality of life, it was sought essential to deeply analyse the socio-economical impact and the public acceptance of flood risk mitigation pre-defined plans as well as the implementation of flood warning dissemination schemes.
This are in essence the objectives of a new round of research which all the participant to AFORISM are eager to address.

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

UNIBO-ICI, University of Bologna
Institute for Hydraulic Construction

Research Contract n°: EPOCH-CT90-0023

Contract n° : EPOCH-CT90-0023

Contractor Institution : UNIBO-ICI, University of Bologna - Institute for Hydraulic Construction

Project Leader : Prof. Ezio TODINI (Co-ordinaor)

Other Institutions cooperating:

- University of Bologna, ADGB
- Ente Regionale di Sviluppo Agricolo
- University College Cork
- University of Newcastle Upon Tyne
- National Technical University of Athens
- Ecole Polytechnique Federale de Lausanne
- Instituto Superior de Agronomia
- Institut National Polytechnique de Grenoble

Starting date: June 1st, 1991

Title of the project: A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

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1 MAIN OBJECTIVES

The main objectives of the research carried out by the University of Bologna group during the third year of research can be listed as follows:

- Coordination
- Setting up of the real-time flood forecasting system
- The Reno river common experiment development
- Organization of International Seminar for the presentation of final reults.

2) METHODS AND MATERIALS

Methods

The methodology used for the development of the real time flood forecasting model of the Reno river is based upon the EFFORTS package (European Flood Forecaasting Operational Real Tyme System) which was developed within the frame of the "REAL TIME MONITORING SYSTEM FOR OPTIMAL COMPUTER CONTROL OF THE FUCHUN RIVER HYDROPOWER STATION RESERVOIR" a CEC funded R&D contract n.CI13-0004-I, and which proved to be adequate for the purpose.

The flood plain analys was performed on the basis of a 2-D flood plain model based upon an integrated finite differences (IFD) approach, originally developed at UNIBO-ICI and modified, in order to be effectively applied to real world problems, in collaboration with EPFL-IATE.

The GIS used for the tratment of the spatial data and the generation of the Digital Terrain model is the IDRISI package.

Materials

The following materials were used:

HP9000/710 under UNIX
Fortran Compiler
C Compiler
HP Soft Bench
G2 Expert System
AUTOCAD
ARC-CAD

4 PC 486 under Microsoft Windows
Microsoft Fortran Compiler
Plot88
Statgraphics
Media Cybernetics Halo Professional

3) RESULTS

In the third year, the work in Bologna was carried out along fthe following lines:

a) Co-ordination
b) Development of the rainfall-runoff model for the Reno river
c) Developmet of the flood routing model
d) Setting up of the real-time flood forecasting system
e) Modelling the effects of flooding by means of a 2-D flood plain model
f) Forecasting floods by means of Limited Area Precipitation model results
g) Organization of International Seminar for the presentation of final reults.

a) Co-ordination

The following co-ordination meetings were orgnized and attended during the third year:

CORK, September 1993
NEWCASTLE, February 1994
BOLOGNA June 1994

b) Development of the Rainfall-Runoff model for the Reno River

As a result of the comparison of different rainfall-runoff models to be used for real time flood forecasting a general consensus was reached on the need of simple models (thus avoiding the complex distributed physically based ones). In addition, due to the difficulty of estimating the initial soil moisture conditions, continuous type models were chosen, also given the availability of continuously recorded real time data. The ARNO model and the TOPMODEL, where analysed as possible candidates and were calibrated using the 1990 rainfall and runoff data.

The final choice was for the ARNO model for two reasons. The first one relates to the better performances of the model in verification periods, and the second one relates to the fact that the ARNO model is already inserted into an automatic real-time flood forecasting system, known as EFFORTS, which includes a suite of several programs capable of accepting real time data and performing the following operations:

- Display of the catchment and of the stations;
- Verification of the real time acquired data;
- Automatic reconstruction of missing data;
- Sampling of data at constant time steps;
- Computing average precipitation and evapotranspiration;
- Computing flows at a number of pre-set locations by means of the ARNO model;
- Computing the levels in all the river cross sections, by means of PAB flood routing scheme;
- Display of the flood levels and comparison with the dikes elevation.

Calibration of the ARNO rainfall-runoff model was successfully obtained by using the historical record (1990-1991).

c) Development of the flood routing model.

In order to calibrate the flood routing model for the Reno river, a number of problems had to be solved. In particular the rating curves provided by the Hydrographic Office in Bologa needed verification: this was done by establishing a measurement campaign on the upstream cross sections, while using an original technique for estimating the downstream ones.

The cross sections available for the river Reno were used for calibrating the flood routing Parabolic and Backwater model selected. The results of calibration, althogh reasonably good have shown the inadequacy of the available cross sections. The Reno River Authority was informed and the operational decision was taken of performing, in due time a new measurement campaign.

As previously stated the results were good enough for the purpose of the project and this calibration was then used in the EFFORTS package.

d) Setting up of the real-time flood forecasting system

The setting up of the real-time flood forecasting system required the following operations to be performed:

- Digitization of the basin map and measurement point location;
- Structuring of the necessary system defnition files;
- Calibration of the real time automatic data reconstruction models for precipitation, temperature and level stations;
- Calibration of the Kalman Filter based rainfall extrapolation models;

- Calibration of the Kalman Filter based real time updating noise models.

The entire set of operations was successfully performed bringing about a system which could be immediately used for operational flood forecasting in real time.

e) Modelling the effects of flooding by means of a 2-D flood plain model

In order to analyse the effects of possible real time decisions a 2-D model was calibrated and used in combination with dike failure hypotheses, in order to simulate the inundation event of November 26th, 1990.

The model, which is based upon the Integrated Finite Difference approach, was originally developed at UNIBO-ICI. Within the frame of AFORISM, the package was then modified in order to allow for breaklines (such as dikes, roads etc), as well as for other hydraulic specific elements which are currently encountered in practical applications.

The model was calibrated by comparing the actual flood map with the model results and the results were demonstrated in an animated succession by means of a GIS.

f) Forecasting floods by means of Limited Area Precipitation model results

A joint experiment was set up in colaboration with the SMR-ER group. Nine quantitative precipitation forecasts up to 24 hours were generated by SMR-ER on the basis of an operational Llimited Area Precipitaiton model with 10 x 10 km^2 grid. The forecasts were aggregated at the scale of the subcatchments used in the flood forecasting model and compared, for the first 12 hours, with the precipitation calculated by using the available rain gauge system.

After applying a correction factor, the precipitation estimates were used as input to the rainfall-runff model. The results showed interesting possibilities, although scaling problems between the precipitation forecasted by the model and that measured at the rain gauges, still exist. Anyway, further investigation should be devoted to this approach which seems extremely promising.

g) Organization of International Seminar for the presentation of final reults.

All the results of the three years research were presented in Bologna in an International Workshop organised under the auspices of the World Meteorological Organization. UNIBO-ICI in collaboration with the Centro IDEA, provided the organization and the logistic for the seminar.

The Seminar was held in Bologna on June, 1994 with more than 80 participants from European, Italian National and Local authorities dealing with flood forecasting and warning.

The results of the project were very well accepted by the participants; in particular highly positive comments were issued by the representative of the World Meteorological Organization, as well as by the Director of the Italian National Hydrographic and

Mareographic Service.

4) CONCLUSIONS

From the point of view of the UNIBO-ICI the project has been extremely successful.

First of all it gave the posibility of deeply analysing the most inmportant features to be retained in a real time rainfall-runoff flood forecasting model, which have now been identified in the dynamical variation of the directly contributing saturate surfaces in combination with the filling and depletion of the soil moisture storage.

The second achievement has been the setting up and calibration of a prototype for the real time flood forecasting system of the Reno river, with the identification of all the interconnections needed for the development of an operational system which will use Limited Area Precipitation model forecasts as well as flood plain modelling and impact analysis.

The third and most important achievement has been the intention expressed by the National Italian Authorities an by the River Reno Authority to establish the Reno river as the sample catchment for flood forecasting experimentation an dto proceed to a new phase in which all the work carried out under AFORISM will be operationally implemented.

5) PAPERS PRODUCED DURING THE THIRD YEAR

1) Todini E. (1993) - Un filtro di Kalman per la ricostruzione automatica dei dati mancanti - Stachem '93 - Venezia.
2) Di Giammarco, P., Todini, E. (1994) - A Control Volume Finite Element Method for the Solution of 2-D overland flow problems In: P. Molinaro and L. Natale (Eds), Modelling of flood propagation over initially dry areas., Proc. of the Specialty Conf. ENEL-DSR-CRIS, Milan, 171-185.
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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

UNIBO-ADG, University of Bologna
Department of Physics, Atmospheric Dynamics Group

Research Contract n°: EPOCH-CT90-0023

Contract n°: EPOCH-CT90-0023

Contractor Institution: UNIBO-ADG, University of Bologna, Department of Physics, Atmospheric Dynamics Group

Project Leader: Prof. Stefano TIBALDI

Other Institutions cooperating:
- University of Bologna ICI
- Ente Regionale di Sviluppo Agricolo
- University College Cork
- University of Newcastle Upon Tyne
- National Technical University of Athens
- Instituto Superior de Agronomia
- Institut National Polytechnique de Grenoble
- Ecole Polytechnique Federale de Lausanne

Starting date: June 1st, 1991

Title of the project: Ensemble forecasting of precipitation with a high resolution) Limited Area Model

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1. MAIN OBJECTIVES

The main objective of this project is to improve deterministic quantitative rainfall modelling with ensemble (Montecarlo-type) techniques and provide stochastic-dynamic evaluation of the uncertainty of the rainfall forecast. This is done by generating a spectrum of future possible precipitation traces. The ultimate aim of the AFORISM project is to simulate and forecast, by means of rainfall-runoff models, a variety of future runoff scenarios.

The specific objectives of the research are:

a) Improve deterministic QPF (Quantitative Precipitation Forecasting) performed with dynamical numerical limited-area models (LAMs) with the aid of mixed stochastic-dynamical methods of the Montecarlo type. This will be done by generating a spectrum (approximately order ten) of approximately equi-probable initial conditions for the limited area model, integrate the model for each of them and consequently generate a spectrum of QPFs. Investigate whether this (mini)ensemble contains more information (is a better forecast) than the purely deterministic forecast (the "central" forecast).

b) Assess whether the spread within the ensemble is a valuable measure of forecast error (and, therefore, value).

2. DETAILED PROGRAMME AND METHODS

The above objectives have been reached through the following working programme:

a) A study has been performed (in a way much resembling previous similar studies performed with global weather forecasting models) on the optimal way to compute equiprobable initial conditions for the LAM; alternatives considered included perturbing the "best" available analysis either in wind or in temperature fields (or both) with a random noise of variance comparable to the estimated local analysis error; use, instead of random noise, a suitable proportion of a correspondent meteorological field chosen at random from a climatological archive (of the same season); breed a randomly chosen 'synoptic' perturbation by allowing it to grow in very short range predictions (BGM technique).

b) Once the "best" way to obtain the ensemble of initial conditions had been chosen, the LAM (UB/NMC was used) has been integrated for up to 36 hours starting from all individuals in the ensemble. All different integrations will yield different QPFs fields over the region of interests (essentially the Reno river basin in the Emilia-Romagna region of Northern Italy).

c) The ensemble of QPFs so obtained has been examined, diagnosed and verified against observations, and the ensemble average forecast has been evaluated against the "best initial analysis" purely deterministic forecast (the "central" forecast). The changes (improvements?) in QPF have been assessed quantitatively.

d) The variability (the "spread") within the ensemble has been evaluated and correlated with the forecast quality in order to test the usual assumption that difficult (and therefore unreliable) forecasts are associated to highly unstable initial conditions (and therefore to high spread within the ensemble), while conversely trustworthy forecasts come from stable situations leading to low spread within the ensemble. This check has been carried for the available case study.

3. RESULTS

The work during the third year of contract has consisted in the application of the BGM (Breeding of Growing Modes) technique to the case study to test the validity of the this technique, both in terms of improving the single deterministic forecast and to provide an apriori estimate.

The work can be schematically divided in three parts:

a) <u>the analyses of the perturbations,</u> performed in order to identify the dynamical nature of the bred modes and to evaluate the sensitivity of the bred perturbations to the amplitude of their initial values, to the length of the breeding interval and to the damping factor used in the breeding model (this part of the work, which turned out to be lengthy and time-consuming, will be highly summarized here, leaving the details to an appendix of the overall final project report);

b) the generation of the ensemble QPFs and the verification of the improvements by checking against observed precipitation in a realistic case-study;

c) the investigation of possible spread-skill relationships, i.e. the search for the existence of a correlation between the spread amongst the individual forecasts forming the BGM ensemble and the forecast error, existence of which would allow a prediction of the forecast skill; this was also done for the same realistic case-study.

We recall that the application of the BGM technique that was applied here can be schematically summarized as follows:

a) The beginning of the procedure takes place 24 hours before the start of the forecast (total breeding time = 24h);

b) a small perturbation is added to the initial atmospheric objective analysis;

c) the model is integrated for 6 hours from both the unperturbed (control run) and perturbed initial states (breeding interval = 6h);

d) the 6-hours control forecast is then subtracted from the perturbed forecast;

e) the difference field so obtained is scaled down so to have the same RMS variance of the initial perturbation;

f) the perturbation is then added to the following analysis as in a) and the process is repeated forward in time up to 24 hours.

At the end of this breeding cycle, the final perturbation is added to (and subtracted from) the 'central' analysis to produce one of the perturbed initial conditions needed to the ensemble forecast. Since every initial perturbation is both added and subtracted from the central unperturbed analysis, (on the ground of the essentially linear nature of the growing process, positive and negative perturbations should be equally likely) each breeding cycle produces two final perturbed analyses.

Regarding the choice of the initial perturbation, the method suggested by Murphy (Murphy 1988) has been used; in this method the perturbed field is constructed adding a given proportion (percentage) of a different analysis set randomly choosen and suitably scaled. The scaling factor for the geopotential height perturbation is taken so that the perturbation acquires an amplitude equal to an average analysis error (Hollingsworth and Lonnberg, 1986). The wind field perturbations are determined using a geostrophic balance with the geopotential perturbations. The specific humidity field is perturbed with the same scaling factor as for geopotential height. Since the model prognostic variables include temperature, instead of geopotential, and surface pressure, the perturbations on these two parameters are determined consistently with the hydrostatic assumption.

During each step of the breeding cycle the lateral boundary conditions are kept fixed and the renormalization of the perturbations is performed directly on the model levels. Additionally, the momentum equation of the model includes a term for divergence damping to avoid the amplification of the noise associated to the generation of gravity waves. Both during the breeding cycle and the ensemble forecasting, the coefficient for the damping are kept to the minimum possible value. The breeding cycle is repeated for each member of the ensemble (ensembles are formed by nine members). Each integration of the ensemble is then carried on for 36 hours.

The final impact of the breeding technique on the ensemble forecasting are evaluated by comparing the BGM ensemble with an ensemble forecast based on not-bred Murphy-type perturbations with the same number of individual forecasts. The model configuration is therefore the same used for the single deterministic forecast experiments, i.e. European integration domain (see Fig. 10), .125 x .125 degrees horizontal resolution, equivalent to about 19 km mesh size, 20 vertical levels in sigma coordinates and initial and boundary conditions from ECMWF operational objective analyses.

The entire work has been performed, to ease the comparison, on the same case study used for the deterministic QPF predictions Project carried out at the Regional Weather Service of Emilia Romagna Region (SMR-ER). This case study is briefly described synoptically in the following section.

3.1 Synoptic description of the case study

The European Center for Medium Range Weather Forecast (ECMWF) analysis of 25 November 1990 at 12 GMT shows a trough over the France with a minimum in the mean sea level pressure located north of the Alpine mountain. The frontal system is well evident in the Meteosat image of 10.30 GMT, with the warm front which crosses the Tirrenian Sea and the Apennine chain. This strong meridional advection induces very intense rainfall over Northern Italy, in particular in the Toscana Region (upwind of the Apennine chain) and in the Lombardia Region (upwind of the Alpine chain), as it can be inferred by consulting the relevant Synop messages.

As regards the Reno River basin in particular, the largest rainfall amounts occurred in the mountainous area, where some stations of the National Hydrographic Service recorded more than 200 mm of rainfall in 24 hours, while the rainfall in the plain area were generally less than 20 mm in the same period (see Table 1). The National Hydrographic Service reported that, in mountain stations, 90% of the rainfall amount occurred in the 18 hours from 05 GMT to 23 GMT of the 25th. In the late afternoon of the 25th a severe flood was recorded in the mountain town of Porretta and its neighbourings.

STATION	HEIGTH (msl)	DAILY RAINFALL (mm)		TOTAL (mm)
		24-25 08 GMT	25-26 08 GMT	
Piastre (PT)	741	32.4	236.8	269.2
Maresca (PT)	1043	65.0	219.8	284.8
Orsigna(PT)	806	56.0	250.6	306.6
Spedaletto (PT)	775	53.2	159.8	213.0
Pracchia (PT)	627	26.4	137.2	163.6
Porretta (BO)	345	11.2	130.8	142.0
Bologna (Bo)	49	0.0	19.0	19.0
Settefonti (Bo)	336	1.0	23.0	24.0
S.Pietro C(Bo)	10	0.0	18.0	18.0

TABLE 1 Rainfall during the period 24-25-26 October 1989 recorded at various stations of the Reno river basin.

3.2 The ensamble forecast

In this report, only a general description of the main results will be given. For a more complete account of the details of the study and for a more comprehensive account of the results, reference is made to the complete AFORISM scientific report, and to its Appendices.

a) The analysis of the perturbations to be used for the BGM technique

A quantitative analysis of the characteristics of the BGM perturbations fields is a difficult task, in particular due to the fact that the behaviour of the growing perturbations has to be analysed during the breeding cycle. For this reason it was decided to study the character of the perturbations applying a bi-dimensional Fourier spectral analysis on the quasi-horizontal model levels. The technique suggested by Errico (1985) was used and the analysis was performed directly on the rotated grid of the model.

The spectra of the perturbations for the fields of surface pressure were computed at beginning, in the middle and at the end of the breeding cycle (+00, +09 and +18 hours respectively) for two experiments named BL and BS, i.e. two experiments differing only for the amplitude of the initial perturbation to be bred, see Table 2 for a summary of experiment names and characteristics (in this case the randomly chosen situation providing the Murphy-type perturbation is 01.01.1991 12GMT). The impact of the initial perturbation of different amplitude during the breeding cycle has only been examined in the context of perturbation breeding. Actual forecasts have only been performed with small amplitude perturbations.

Experiment BL (Breeding, Large amplitude) has an initial perturbation characterized by a reference RMS equal to the assumed analysis error (the "given proportion" mentioned above is therefore 100%), while the reference RMS of the experiment BS (Breeding, Small amplitude) has been reduced to 1% of the assumed analysis error. This reduction has been applied following the idea of Kalnay and Toth (1991) that very small initial perturbations will breed into structures more associated to mesoscale convective systems. These experiments have been compared with the corresponding elements of not-bred Murphy-type ensembles, again generated with large amplitude and small amplitude perturbations (respectively experiments ML and MS).

	Murphy-type perturbation	Breeding Perturbation
Small amplitude perturbation	MS exp	BS exp
Large amplitude perturbation	ML exp	BL exp

TABLE 2 List and characteristics of ensemble forecast experiments.

In both the cases a sudden decrease of the energy associated with larger scales takes place. In exp BL, at the end of the breeding cycle, the energy tends to be still confined in a narrow spectral region at very high wavenumber, associated with horizontal spatial scales between 30 and 60 km. on the contrary in exp BS, at the end of the breeding cycle, the energy has been transferred back to the mesoscale, indicating that the perturbation has succeeded in projecting onto more meteorological modes. This behaviour, however, takes place also when breeding initial perturbations obtained from different random situations, suggesting that the amplitude of the initial perturbation is a factor more important than the spatial details of the perturbation patterns.

As previously mentioned, the BGM ensamble forecast from the BS perturbations will now be compared with a parallel Murphy ensemble generated from an unbred set of perturbations of the same amplitude (MS) and with the central deterministic forecast, all of them starting from 24.11.1990 12GMT.

b) Results from the ensemble forecasts

From the results of the ensemble experimentation it appears rather evident that, similarly to what happens for the purely deterministic central forecast, the two ensembles (BGM and Murphy) fail rather substantially to capture the very fine spatial details of the observed precipitation field, also de facto unresolved (but not completely undetected) by the conventional synoptic network, where isolated values of much higher precipitation than that measured in the surrounding stations (and in particular in the area of the Reno river catchment) make it evident that the spatial detail of pointmeasured precipitation is an impossible goal for the available observing system.

It should however be noted that, among the three forecasts of comparable horizontal resolution compared in this report (central deterministic, BGM ensemble and Murphy ensemble, the results are always relative to ensembles of nine members), the one having the best attempt at localizing the local maximum of the precipitation nearest to the area of interest, together with the indication of the largest probability of extreme values (as measured by the standard deviation fields), is the BGM ensemble forecast. This forecast also provides the best indication of low rainfall in those Northern Italian areas where observed rainfall was indeed lowest.

The information contained in the BGM ensemble standard deviation map (not shown here), when added to the highest resolution deterministic precipitation map, would have probably been sufficient to enter an alert situation. In an ideal situation, this would then have caused a hypothetical operational flood forecasting centre to enter a continuous monitoring situation, with continuous reruns of the LAM 6, 12, 18 and 24 hours later, and provide possibly improved quantitative precipitation forecasts.

It is also evident from these time graphs that the sum of the information contained in the set of increasing resolution deterministic experiments (models of higher resolution predicting consistently a higher precipitation) and that contained in the BS ensemble (two members indicating a much higher precipitation than all the others, therefore indicating the possibility of occurrence of an extreme event) was confirming the opportunity for a state of alert. There obviously is here much scope for investigating weather the implied potential contained in this single case study could be transformed in a viable operational QPF capable of consistently indicating the possibility of extreme events.

c) The search for possible spread-skill relationship

Concerning the investigation of possible relationships between ensemble spread and possible forecast error (a type of forecast skill forecasting system), scatter diagrams (for both BS and MS ensembles, panel a and panel b respectively) of forecast skill (RMS error of rainfall forecast) vs. forecast spread internal to the ensemble failed to evidence any useful spread-error correlation. This was true within both ensembles, BGM and Murphy type. We must therefore conclude (conscious however of the large limitations imposed by the single case study) that ensemble forecasting, in the context of limited area numerical forecasting of quantitative precipitation at the short range, appears to be useful only as a tool to produce estimates of possible extreme forecasts and not as an apriori predictor of forecast error. This could, in turn, provide the basis for deciding whether to enter an alert condition, and increase accordingly the effort put both in monitoring and further intensified prediction of the system.

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

SMR-ER, Regional Meteorological Service

Research Contract n°: EPOCH-CT90-0023

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Contractor Institution: SMR-ER(ERSA), Regional Meteorological Service

Project Leader: Dott. NUCCIOTTI

Other Institutions cooperating:
- University of Bologna ICI
- University of Bologna, ADGB
- University College Cork
- University of Newcastle Upon Tyne
- National Technical University of Athens
- Instituto Superior de Agronomia
- Institut National Polytechnique de Grenoble
- Ecole Polytechnique Federale de Lausanne

Starting date: June 1st, 1991

Title of the project: Deterministic QPF (Quantitative Precipitation Forecasting)

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1 MAIN OBJECTIVES

1.1 QPF

The main goal of the project is to perform short-range forecast of precipitation on a small area of Emilia-Romagna Region using a limited area model', LAMBO, now operational at SMR/ER. The forecasts have been tested with particular attention over the Reno River Basin by comparison with observations and forecasted precipitations have been furnished to UNIBO-ICI as input to run successive flood models.

1.2 RADAR DATA ANALYSIS

The analysis of precipitation estimates, provided by the GPM 500 C radar, collected during the period September-December 1993, is compared to the precipitation data recorded by the SMR (Regional Meteorological Service) automatic network.

A case study of a supercell storm occurring during the MATREP experiment has been analysed in detail, looking both the environmental conditions and the morphology of the cell evolution; with reference to the radar rainfall estimates the application of an objective analysis scheme drastically reduced the error in the direct radar estimates.

2. METHODS AND MATERIALS

2.1 Methods

2.1.1 QPF

A primitive equations limited area model, LAMBO (Limited Area Model Bologna), has been employed to produce high resolution forecasts of precipitation within the AFORISM Project (LAMBO is now running operationally at SMR-ER since September 1993). In general a primitive equations model is a model in which, assuming that the atmosphere is in hydrostatic equilibrium, motion is predicted by applying the principles of conservation of momentum, energy and mass and using the law of ideal gases.

LAMBO is based on a model originally developed in its older adiabatic version in Belgrade (during the early seventies) as a cooperative effort between the University of Belgrade and the Hydrometeorological Institute of the former Yugoslavia (HIBU model).

During the last decade, several improvements in the formulation of the adiabatic part of the code have been implemented. Furthermore a complete physical package has been included in the model, in the framework of a cooperation between the University of Belgrade and the National Meteorological Centre of Washington (NOAA-NMC) (Mesinger et al,1988; Black, 1988; Janijc, 1990). This version of the model, referred to as the UB-NMC /ETA model, is at the time of writing the operational limited area model of the NOAA-NMC. The version dated 1989, recently upgraded is some parts of the physical parameterization schemes and completely reformulated in its pre- and post-processing sections, is the above mentioned operational model LAMBO.

2.1.2 Radar Data Analysis

The SMR radar of S. Pietro Capofiume (44ø39'N 11ø37'E, 11 m msl) became fully operational in the second part of 1992 and until spring 1993 only the polar volumes of intense rainy events were recorded. Since May 1993 a new archive has been created, which collects the precipitation intensity estimates worked out from the daily polar volumes recorded every thirty minutes. The CAPPI (e.g. PPI taken at Constant Altitude) of reflectivity Z computed at 500 m. altitude is converted in precipitation intensity by means of the Marshall and Palmer relationship Z=200*R1.6 (where R is precipitation intensity in mm/hr) and further averaged on a regular 5*5 km2 grid. The area covered has 125 km range. To eliminate the contribution of clutter, determined by orography and secondary lobes, the typical reflectivity value, drawn from a data set referring to days with no precipitation and with standard propagation, is deducted from each CAPPI elementary pixel (grid size resolution equal to 250 m).

The precipitation intensity estimates obtained in this way are then temporally integrated to compare them to SMR automatic network raingauge hourly cumulated data.

Although partly operating, the radar partecipated during the month of June 1990 to the field experiment MATREP which had the aim of monitoring the thunderstorm activity in the Po Valley of northern Italy. In such specific case the comparison of radar rainfall estimates and the raingauges data was performed using the scheme proposed by Koistinen and Puhakka (1981). Because of such technique combines in a weighted scheme the uniform spatial adjustment and the objective analysis of the adjustment factor (that is the ratio between the raingauge observation and the radar estimation in the same point), it produces satisfactory results in situations of small and non uniform raingauge density, like the situation of the Regional Meteorological Service network.

2.2 Materials

VAX 6310 computer under VMS - SMR/ER
CRAY C90 under UNICOS - CINECA (University Computer Centre)
NCAR Graphycs Package
DISSPLA Graphycs Package
Scientific Software developed at SMR/ER

GPM 500 C weather Radar
MOTOROLA 88100 computer under UNIX

3 RESULTS

3.1 Quantitative Precipitation Forecasting

During the previous years of activity within the AFORISM project an effort was made to identify the optimal configuration of the Limited Area Model, in particular as far as the QPF quality is concerned. This has been achieved by means of statistical verification of the LAM performance over a 1 month period, June 1990 (Pelosini and Paccagnella, 1993; Paccagnella and Pelosini, 1993). This period was chosen because the MATREP coordinated data collection campaign took place in this region in this period (Buzzi, Morgan and Tibaldi, 1991).

This extensive model verification effort , together with the same statistical verification during January 1991, highlighted some model problems, affecting particularly the forecast of surface parameters. For this reason during the third year of the project some model code development was needed, in particular in relation to the parametrization of radiative processes (a new radiation package from METEO-FRANCE was implemented and adjusted) and to turbulent exchanges closure schemes and vertical diffusion (updated to the more recent 1993 version of the operational NMC Limited Area Model). As a consequence of such modifications, the model (which during the previous year of the project have been easily integrated both using ETA and SIGMA vertical coordinates) had to be integrated only using sigma vertical coordinate. In conclusion, all runs reported here and referred to the third year of activity, have been performed using sigma as vertical coordinate.

Numerical integrations have been performed in the attempt to predict the intense precipitation, associated with strong meridional advection, which occurred mostly during the 25th of November 1994 over the catchment basin of the Reno river in the Emilia Romagna region. This precipitation was particularly intense in the Toscana Region (upwind of the Apennine chain) and in the Lombardia Region (upwind of the Alpine chain).

As regards the Reno River basin in particular, the largest rainfall amounts occurred in the mountainous area, where some stations of the National Hydrographic Service recorded more than 200 mm of rainfall in 24 hours, while the rainfall in the plain area were generally less than 20 mm in the same period.

After the above mentioned model upgrading the numerical experimentation has been addressed to:

a) run the model at different horizontal and vertical resolution to see the impact over the precipitation values

b) run the model several times with successive 6 hours lag in the start of the integrations to try a post-processing of the model precipitation output

As regards point a) the model run three times, for 36 hours starting from 24/11/90 at 12 GMT, in the following model configuration:

<u>exp LR (Low resolution experiment):</u>

horizontal resolution:	.25x.25 degrees in rotated coordinates (equivalent to about 30 Km resolution)
vertical resolution:	20 vertical levels in sigma coordinates
time step:	120 sec
initial conditions:	ECMWF objective analyses, 24.11.1990 12GMT
boundary conditions:	ECMWF operational ferecasts; updating every time step by interpolating in time, ECMWF forecast available every 12 hours.

<u>exp HR (High Resolution experiment):</u>

horizontal resolution:	.125x.125 degrees in rotated coordinates (equivalent to about 20 Km resolution)
vertical resolution:	32 vertical levels in sigma coordinates
time step:	60 sec
initial conditions:	ECMWF objective analyses, 24.11.1990 12GMT
boundary conditions:	from expLR by means of a nesting procedure developed at ERSA-SMR; updating every time step by interpolating in time expLR, forecast available every 6 hours.

<u>exp VHR (Very High Resolution experiment):</u>

horizontal resolution:	.0625 x.0625 degrees in rotated coordinates (equivalent to about 10 Km resolution)
vertical resolution:	32 vertical levels in sigma coordinates

time step:	30 sec
initial conditions:	ECMWF objective analyses, 24.11.1990 12GMT
boundary conditions:	from expLR by means of a nesting procedure developed at ERSA-SMR; updating every time step by interpolating in time expLR forecast available every 6 hours.

The first two model configurations, expLR and expHR, are almost the same model configurations of the operational runs of LAMBO at SMR/ER (Paccagnella 1994)

The most evident feature emerging from the comparison between these experiments is the strong impact of horizontal and vertical resolution on the predicted precipitation pattern. The precipitation field produced by higher resolution experiments is progressively much more structured and maxima of precipitation are measurably enhanced. Concentrating the attention on the Appennine and Po-Valley region, the increase in horizontal resolution produces an increase in the upwind precipitation, with maxima still underestimated but approaching observed values, while in a narrow region in the eastern part of the valley precipitation tends to decrease.

Detailed results are presented in the final report .

As regards point b) nine 24 hours forecasts have been performed starting at 24/11/90 00GMT and repeating the forecast every six hours as shown by the following scheme:

```
24             25             26             27     November 1990
00 06 12 18 00 06 12 18 00 06 12 18 00          GMT
 ----------------->
   ------------------->
      ------------------->
         ------------------->
            ------------------->
               ------------------->
                  ------------------->
                     ------------------->
                        ------------------->
```

The configuration of these run is the same of expHR equivalent to the highest resolution operational run of SMR/ER.

Results of the use of these run as input of the flood forecast model are presented in the UNIBO/ICI report.

3.2 Radar Data Analysis

September-December 1993 data have been examined: during this period the monthly precipitation amounts recorded in the radar area were comparable with the climatological values. During September and early October the rain was mostly convective, on the contrary it was stratiform during the rest of the period.

The comparison between radar and rain-gauge data has been carried out computing the bias and the mean square error (rms) for each station. The bias was defined as the mean value of the radar estimate (R) computed in the corresponding grid square minus the rain-gauge (G) value, considering only the hourly precipitation occurrance (i.e. G>0.2 mm).

As a general results the precipitation events have been under-estimated by the radar and the errors increase with distance: the bias of the most of the stations is between -0.4 and -0.9 mm while the rms ranges from 1 to 2 mm (Alberoni et al. 1994a). Further a gradual improvement in bias and rms from September to December was observed in the month analysis of precipitation events.

Some stations with bias values lower than -1 mm or with rms values higher than 2 mm show an evident anomalous behaviour. We guess that the more important causes of errors could be the following:

a) sampling error

b) over-estimated declutter

c) partial blocking

In a more detail the sampling error may be due to time integration, which is obtained by three radar volume scans carried out every 30 minutes: these acquisitions are not enough frequent to describe the fast evolution of convective rain events. During September, in fact, some storms occurred and locally produced very heavy precipitation, such as 48.4 mm recorded on 1st September at 03 GMT in Martorano station. The corresponding radar rainfall estimate was only 4.5 mm. In this case a more detailed analysis of the three radar maps revealed that the problem originated from the time lag between the radar acquisition times and the position of the precipitation intensity maxima with respect to the grid-square corresponding to the rain gauge.

Referring to declutter, the algorithm implemented in standard propagation conditions with no rain eliminates completely the orography and secondary lobes clutter echoes. The limits of this procedure are particularly evident in light rain conditions, when the signal does not differ from the one due to the clutter: in these cases the minimum detectable value is assigned to each pixel. The hilly station of Settefonti is particularly subjected to clutter, with declutter values converted to 10 mm/h "precipitation intensity": this may partially explain the strong under-estimates observed throughout the period. The situation is different for Malborghetto station, which is located in the plain and is affected by the second scale echoes coming from the Alps: they are in part responsible for the observed anomaly.

The partial blocking effect finally reduces even the precipitation radar estimate of the stations located in the Apennine. Using the high resolution orography of a regional Digital

Terrain Model and the theoretical computation of radar signal propagation mean path, it was deducted the blocking percentage of the radar beams: such values range tipically from 28% to 60% in the worst case, meaning that the visibility of the radar is reduced more than 50% for some stations.

Some final results can be summarized as follows:

1) radar precipitation general under-estimates in comparison with rain-gauge data: during the period under examination (September-December 1993) a gradual improvement, due to the best spatial-temporal homogeneity of winter stratiform precipitation compared to convective precipitation (occurred mainly in September), has been observed;

2) very high error values occur with heavy storms: the half hour sampling frequency is not adeguate to describe the raincells evolution during the convective systems lifetime.

During the field experiment MATREP (an italian acronym for the monitoring of thunderstorm in the Po Valley region of Northern Italy) some severe storms occurred in the target area, producing heavy rainfall and sometimes large damages.

On 8th June 1990 a supercell thunderstorm originated in the eastern part of the Po Valley and ended near the Adriatic Sea, about 100 km far away from the origin site.

The case study of 8 June has been analysed in a more detail (Alberoni et. al, 1994b), considering the synoptic situations and the mesoscale features which fed the devolopment of a supercell storm.

The termodynamic environment has been studied taking into account the temperature, humidity and wind profiles deducted from a radiosounding performed at S. Pietro Capofiume during the hours of the supercell lifetime. In particular the medium and upper troposhere wind profile match quite well with the profiles shown in the literature for the supercell storms; instead the profile in the boundary layer shows significant difference from the typical ones. This result was due to the different surface circulation between the radiosounding site and the area affected by the supercell path (which were more or less 70 km far away), as the analysis of the ground data in the two areas have shown.

The radar maps show the characteristic elongated area (greater than 70*20 km2) in the middle lifetime, with the maximum reflectivity gradient in the south-west upwind flank. In this position the radar detected a hook-echo pattern, which is a well-known marker of a tornado presence: this was even confirmed by the local newspapers eptember-October), has been observed;

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

UCC-CORK, University College Cork

Research Contract n°: EPOCH-CT90-0023

Contract n° : EPOCH-CT90-0023

Contractor Institution : UCC-CORK - University College Cork

Project Leader : Prof. Philip O'KANE

Other Institutions cooperating:

- University of Bologna ICI
- University of Bologna, ADGB
- Ente Regionale di Sviluppo Agricolo
- University of Newcastle Upon Tyne
- National Technical University of Athens
- Instituto Superior de Agronomia
- Institut National Polytechnique de Grenoble
- Ecole Polytechnique Federale de Lausanne

Starting date: June 1st, 1991

Title of the project: A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

THE DECISION SUPPORT SYSTEM

An overall flood warning and control system has been defined to meet the needs of the Reno stakeholders. The 3 groups of people participating in the system are: meteorologists/hydrologists, operational managers and civil response managers. The communications links that will be required between these 3 groups have been examined. The total warning system consists of 2 parts: a technological part and a social part.

The **technological subsystem** is run by meteorologists and hydrologists and consists of rain gauges, river gauges, and meteorological forecasting systems, which together provide data for hydrological and flood-forecasting models, and decision support tools. These are, in turn, made available to the **operations managers**. The data, models and decision support tools are interrogated by the operations managers to meet both their own needs and other requests. Relying on this, the operations manager may issue warnings to the **civil defence manager**.

The civil defence manager interacts with the media, the police, other officials and the public, both directly and indirectly. This forms the **social subsystem** of the overall total warning system.

While AFORISM has not been charged with investigating the social subsystem, the success of the technological system is critically dependant on a clear view of the social subsystem and is needs. Consequently, general lessons from the sociology of hazards must be borne in mind.

LESSONS FROM THE SOCIOLOGY OF HAZARDS

The following lessons from the sociology of hazards are important for the design and operational success of the technological subsystem of AFORISM. These are:

- Warnings must be clear.
- Warnings must also specify what is the appropriate response.
- The source of the warnings must be credible.
- Warnings must be reinforced locally.
- The medium used in issuing the warning must be suited to the circumstances of the specific case.
- The type of appeal to the public must be tailored to the public audience.

The lessons which derive from this an AFORISM decision support system are two-fold:

- Models, user-interfaces etc., must present clear, unambiguous, predictions, and courses of action.
- Specific instructions for the appropriate response to be taken, must accompany all warnings.

OUTLINE DESIGN OF THE TECHNOLOGICAL SUBSYSTEM

Outline data flow diagrams for meteorologists, operational managers and civil response managers have been prepared. These diagrams show the capture, storage, filing, processing, display and delivery of data to the relevant group of managers. They provide the starting point for the detailed design/selection of the operational computer hardware, which is required for the realisation of the decision support and forecasting system. An Expert System will form one part of this and is the object of the UCC AFORISM contract.

EXPERT SYSTEMS

A standard expert system consists of a number of parts: a knowledge base (1) - rules and facts stored in a working memory (2) - accessible to an inference engine (3) controlling inferences drawn from the knowledge base, and to which a knowledge acquisition subsystem (4) may add knowledge from experts or the system developer. The basic structure of the expert system is completed with a user interface (5), and an explanation subsystem (6). The knowledge acquisition subsystem, the user interface, and the explanation subsystem, all rely on the inference engine.

The knowledge base and the user interface are the most important parts of the expert system, for the purposes of this report.

USER REQUIREMENTS ANALYSIS

The first step in constructing an expert system and its user interface in particular, is to determine the requirements which may be placed on the system by Flood Managers.

A user requirements analysis has been carried out for two contrasting catchments both subject to flooding, one in Italy and the other in Ireland. The most important difference is the presence of a relatively large hydro-electric reservoir in the centre of the river Lee catchment in Ireland and the absence of a similar storage reservoir in the Reno catchment.

The importance attached to their requirements by the two groups of operations managers and civil response managers, has been estimated on a rough scale from 0 to 10. The results are presented in table 1. It can be seen that the relative importance of the requirements differ substantially between the two catchments. Consequently, no general set of conclusions is possible which is valid for all flood control situations.

However, two tentative conclusions may be suggested:

- large water authorities requiring short warning times, may have the highest need for a formal decision support system, and in contrast,
- small authorities with a long warning time requirement, may have a low demand for a formalised decision support system.

	ITALY		IRELAND	
Operations Managers	*Consorzio Bonifica Renana*		*Elect Supply Board-river Lee*	
	Aggregation of waves below barrier	9	Volume of rain	6
	Aggregation of waves above barrier	9	Timing of flood waves	5
	Access routes	8	Legal implicates and costs	5
	Ecological effects	6	Environmental Water Quality	5
Civil response Managers	*Protezione Civile*		*Local Authority*	
	Integrated data of potential hazards	8	Better flood forecast in time	7
	Data bank and risk maps for floods	7	Better forecast accuracy	6
	Data bank for actions	7	Decision support dam Break	5
	Data bank for priorities	6		

Table 1

THE RULE BASE

Since the last annual report, further work has been carried out on the rule base. A revised set of rules has been established for the issue of a pre-alert notice and the operation of the Reno Barrier. These are presented below, as an appendix, together with

- three ecological rules derived from the general ecology literature on the possible effect of river flow variations on plants, invertebrates, fish and birds,
- a set of channel and bank maintenance rules for enhanced conservation, and
- two legal rules.

CONCLUSION

Our research has produced a rule base with 20 rules, which is far below the power far current computerised KBS (Expert System/Knowledge base) technology.

Further rules may be envisaged in the areas of

- aggregation and propagation of flood waver
- overtopping of banks
- growth and decline of flooded areas
- integrity of the dykes

all of which require extensive modelling and the collection of field data. This work should be carried out in a follow-on phase of AFORISM.

APPENDICES

REVISED RULE SETS:

General rules:

IF level at Casalecchio > or = 0.8 meters
THEN the flood service of the Reno Special Office is activated

IF level at Casalecchio > or = 1.4 meters
THEN give Pre-Alert

IF level at Casalecchio > or = 1.00 meters
AND River high downstream
THEN give Pre-Alert

IF aggregation of flood waver upstream, even small waver
AND river high downstream
THEN give Pre-Alert

IF PRE-ALERT given
THEN consider using Reno Barrier

Rules for Barrier Operations:

IF Reno level at Barrier > = 22.00 meters
THEN Adjust Barrier to minimise aggregation risk.

IF lever high upstream for many hours
THEN adjust the Barrier to keep level even > 22.00 meters downstream.

IF level > 22.00 meters downstream for many hours
THENconsider possible overflow though GALLO spillway.

IF want to use flow diversion into NAPOLEON CANAL
THEN adjust to Barrier quickly to provide an overfow level, irrespective whether the level in the downstream Reno is stabilised at 22.00 meters or not.

Channel & Bank Maintenance Rules for enhanced conservation

can, or should, the channels be left entirely untouched?

If **YES**:

Consider structural solutions

flood banks,
flood storage,
flood bypass channels, and multi-stage channels.

Consider biological solution

tree planting
to shade out plant growth

If **PARTIALLY**::

Consider structural solutions

partial dredging,
conserving riffles and pools, and
meander conservation

Consider biological solution

weed cutting and dredging

If **NO**::

Consider structural solutions

reinstating pools,
riffles,
shallow bays,
shallow water berms,
groynes and water deflectors,
los stone weirs,

Consider biological solution

establishing aquatic plants.

can, or should, the banks be left entirely untouched?

If **YES**:

Consider structural solutions

flood banks,
flood storage areas,
flood bypass channels, and
the off site dumping of poil

Consider biological solution

fencing, and the bank top planting of alders

If **PARTIALLY::**

Consider structural solutions

multi-stage channels,
partial dredging,
meander conservation,
working from one bank,
vertical earth bank protection,
islands,
soil spreading,
spoil disposal in banks, and
spoil disposal and trees

Consider biological solution

timimng the mowing of bank vegetation,
patch cutting of bank vegetation,
working through scrub, headges,
marking trees to be treated,
working between and around trees,
coppicing trees and scrub,
retaining trees within flood banks,
minimal tree and scrub removal for otters,
marking and retaining holt trees for otters.

If NO::

Consider structural solutions

reinstate shallow water berms,
shallow bays, stumps and logs, spiling,
wire mesh and willow, hurdles, natural stone,
gabions, fabric and mesh revetment materials,
cellular concrete revetment materials,
fish shelters, artificial otter holts,
bat roosting boxes, nesting banks for kingfisher and
sand martin.

Consider biological solution

reed planting for bank protection,
natural re colonisation, seed mixtures,
transplanting turf, tree and scrub planting.

FLOODING	NUMBER OF SPECIES	FLOW VARIATIONS	
PLANTS	1000s	Positive effect	Very Negative effect
INVERTEBRATES	1000s	No effect	Very Negative effect
FISH	10s	No effect	Very Negative effect
BIRDS	10s	No effect	Very Negative effect

ECOLOGICAL RULES:

Rule 1. Mitigate high flows as much as possible

Rule 2. Ignore normal variations

Rule 3. Keep up a minimum base flow

LEGAL RULES:

1. "The authority owes a duty of care to all persons, members of the public and others, that may be effected by its actions".
2. "Provided the effect of the actions of the authority have a mitigating effect on the severity of natural hazard, then the authority can claim the defence of inevitable accident".

RULES		REMARK
OPERATIONS	10	Reno alert rules
ECOLOGY	2	Doesn't give rules for each species
MAINTENANCE	6	Relevant for day-to-day activities
LEGAL	2	Doesn't include individual cases.

TOTAL = 20

Power of contemporary KBS technology

COMMISSION OF EUROPEAN COMMUNITIES

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1. MAIN OBJECTIVES

The main objectives of the University of Newcastle group are:

(a) an evaluation of the errors in runoff predictions deriving from the inadequate sampling of the rainfall process in space

(b) the development of algorithms which will support decision-making in identifying optimal flood mitigation and control measures

The third and final year of this project has seen the implementation of a highly distributed catchment response model, the Systeme Hydrologique Europeen (SHE) on the Reno river system. This has been used in conjunction with the Modified Turning Bands (MTB) model for space-time rainfall which was developed in the early stages of the project to investigate in some detail the effects of the incomplete sampling of the rainfall field in time and space on predicted catchment response, and to show the nature of the errors in runoff predictions.

Under objective (b) two lines of work have been pursued: the further investigation into the Dynamic Expectation Control Theory (DECT) developed in the second year of the project, and the development of a more classical dynamic programming (DP) approach, as now explained.

The DECT control theory has been investigated using a simplified model of the Reno catchment. Unfortunately, it has been found that there is still much basic development work that needs to be done on this, putting a working methodology out of reach of the current project. Suggestions for further development of the system have been made which could be undertaken within the framework of a further phase of the project.

The more classical DP approach developed presents a rational framework for the management of the canal/dyke system. An objective function suitable for this type of river defence system is derived. An existing computer program which implements the Parabolic and Backwater (PAB) method (which applies De Saint Venant's partial differential equations for gradually varied unsteady flow) is used to propagate the flood wave over a time horizon representing the reliable forecast interval. The objective function is then applied in a dynamic programming model to derive the optimal policy. The benefits of this system are illustrated by comparison with the existing method of operation.

2. METHODS AND MATERIALS

2.1. Methods

The MTB model has been fitted to five storm events which were observed on the Reno catchment around the time of the only major flood in the records available for this study. The fitting has been done in such a way that the depth, time of arrival, and duration of these storms is reproduced, on average, by realizations of the model. This means the production of 'alternative' storms which, although never having happened in practice, may with equal probability have happened instead of the five observed events. It is therefore possible to produce an ensemble of flood-producing rainfall scenarios which can be used to investigate the effects of incomplete sampling of rainfall fields in the domain of the Reno catchment.

The physically-based distributed catchment modelling system SHE has been calibrated on the Upper Reno catchment using limited but highly distributed data sets. A digital elevation model (DEM) was used to derive grid square elevations, and river widths and depths were derived from limited information on channel sizes. The soil types, land coverage and vegetation types have been discretized into meaningful classes, and these have been distributed accordingly over the grid elements also. The grid size itself is to 800 metre resolution, and covering an area of about 40 by 60 kilometres, comprises 2196 computational elements.

Monte-Carlo experiments have been performed with the MTB and SHE models whereby a large number of synthetic rainstorm events are sampled according to hypothetical raingauge networks consisting of 3, 6, 12, 18, and 24 raingauges distributed approximately evenly about the catchment, and the rainfall field has also been sampled on a grid of the same spatial resolution as the catchment model. All the storms, in all the sample configurations, have then been input to the SHE model and the resulting runoffs assimilated. These results have been analyzed in order to determine the nature and magnitudes of the errors (i.e. differences in runoff arising from the same storm but with different sampling arrangements).

2.2. Materials

14S HP9000/710's under UNIX
UNIRAS graphical subroutine library

FORTRAN, C and C++ compilers
Dedicated HP9000/715-50 workstation

3. RESULTS

The investigations into the effect of the incomplete sampling of rainfall in time and space on catchment response for the Reno consist of the following three parts:

a) development of the space-time rainfall model

b) development of the SHE catchment model

c) integration of the two models and Monte-Carlo simulations

which are now described in detail.

a) Development of the MTB Space-Time Rainfall Model of Reno Storms

The only information available to this study on how the Reno responds to extreme rainfall events are data from a flood event which occurred around 25th November, 1990. This is the only time in the three year record available that flooding occurred, and the calibration of both the rainfall and catchment models is specific to this event. It is therefore unlikely that the calibration of the models performed here will be suitable for the simulation of the behaviour of the catchment under ordinary circumstances. It is also for this reason that none of the other rainfall-runoff events contained in the three year record have been used for the calibration of the models to deal with extreme rainfall.

The rainfall data made available by Centro IDEA comprise time-series observed at 48 sites around the Reno catchment for three years, 24 of the sites being in the upper part of the catchment. The data are to a resolution of 60 minutes, but not all the raingauges were operational at all times.

Before any analysis could take place of the rainfall data which have been obtained for the Reno river system, the notion of a storm event must be clarified. This is because the MTB model is an event-based model, and therefore individual storms must be extracted from the data before the model can be calibrated. A storm is defined as a period of rainfall in which the longest dry spell, *i.e.* no recorded rainfall at all, is no longer than five hours, and there must be periods of no rainfall lasting at least five hours both before and after the event.

This choice of five hours as the threshold between inter-storm dry periods and inner-storm dry periods is rather arbitrary, but based upon previous experience with rainfall data which demonstrates that the method is successful at picking out meaningful periods of rainfall to which the MTB model can successfully be fitted. It is on this basis that five storm events around 25th November, 1990 have been identified, and the lifetime of each event, number of rainbands and total volume of rainfall determined. These aspects of the storms were reproduced, on average, in the synthetic rainfall fields produced for this work.

For each of the raingauges in the catchment, an altitude correction factor was computed which allows for the scaling of time-series produced from the MTB model calibrated as if over a flat landscape. This was necessary because the MTB model is not currently able to deal implicitly with orographic influences on the rainfall field. The annual average rainfall field was supplied in the form of a paper-based contour map for the entire Reno catchment. This was optically digitized for the upper part of the catchment. To determine the altitude correction factors, the average annual rainfall was computed for the whole catchment, and for the cells of the Thiessen polygons around the raingauge sites, this being done separately for each of the configurations of raingauges considered. The MTB model was then calibrated to give statistics reminiscent of the catchment average (that is, the observations at the sites were scaled so that they all had the same annual average rainfall and the MTB model was fitted to these scaled data), and the results at the simulated raingauges were scaled back to re-introduce the effects of altitude.

The MTB model was used to produce rainstorms in a rectangular area just large enough to enclose the catchment. In the case of the Upper Reno this is 40 kilometres east-west by 60 kilometres north-south. The simulations lasted as long as there was any rainfall inside this area. This done, time-series were extracted from the full spatial data set at each raingauge site, at a resolution of S minutes which was subsequently aggregated to one hour.

It is to be noted at this stage that the model is making no attempt to reproduce the observations that were made at the time of the flood, but to produce other extreme events equally likely to have happened instead. These events have the same overall characteristics as the observed events on average (the same total volume, durations, and relative arrival times), but each individual event is unique.

It is to be noted also that the synthetic storms produced by the MTB model all travel from west to east. This is the predominant direction for the movement of storm features in the Reno basin, hence the results should indicate the modal behaviour of the catchment in this respect, but may not represent the average effect, and may underestimate the variability in runoff hydrographs which occurs in practice. It will not, for example, display any enhancement in runoff which would occur if the storm travels down the catchment.

On a Hewlett-Packard 715/50 workstation it took less than one minute to generate a synthetic rainfall event in space, and about one further minute to sample the time-series from this. The complete generation of the succession of five rainstorms, and the sampling of time-series from the catenation of these events takes no more than three minutes.

b) Catchment modelling

The SHE catchment modelling system centres around a distributed, physically based model. This requires the preparation of a large amount of data, and the preprocessing and management of this, including conversion to a form which can be used directly by the SHE model, was time consuming. The final model provides a completely distributed description of the physical landscape (altitude, soil depth, vegetation type) and models a river system whose geometry varies continuously as it meanders down the sides of mountains and branches intersect with the main stream.

In order for this amount of detail to be prepared for input to the system, comprehensive preprocessors have been developed for the SHE system which accepts the raw data in simple 'flat' file formats, performs spatial interpolation/rescaling where necessary, checks the integrity of the results (for example, it ensures that there are no pits in the DEM landscape caused by the discretization which would fail to convey water in the proper manner, that no river links run uphill, and it ensures that no negative or excessively small or large soil depths occur). The details of the fitting procedure are now described.

The first requirement was to reach a compromise in the representation of the Reno catchment between a discretization which is as fine as the data available, and hence resolves spatial heterogeneity as far as possible, and a discretization which is computationally feasible given the processing power, core memory and disk storage capacity of the available computers, and logistically feasible given the time and manpower available for the processing of the data. The coarsest data set was the altitude data obtained from a digital terrain model supplied by Centro IDEA, which was at 400 metre resolution. The smallest multiple of this which leads to a distributed model which is feasible is 800 metres, resulting in a model with 50 grid squares in the east-west direction and 75 squares in the north-south (the upper Reno catchment is about 40 kilometres east-west and 60 kilometres north-south). The total number of computational elements in this model is 1875, and there are 281 river links in all.

The river links and annual average rainfalls over the catchment were.originally digitized optically from paper maps, and this was done to a resolution of 400 metres in line with the resolution of most of the original data. Initially, enough river branches were used as required to drain each of the seven sub-catchments as identified by Wendling (1993), but it was found that part of the catchment became water-logged, and inspection of the river map indicates that this part of the catchment indeed has a channel, and this was subsequently put in.

The only information supplied as regards the size and shape of the river channel network is that it is about 20 metres wide and 2 metres deep at the top of the catchment, and 100 metres wide and 3 metres deep at the bottom (the outlet from the catchment~. Thus the network has been set up so that the width and depth increase in proportion to the 0.4th power of the total upstream run length (this is in agreement with the UK Flood Studies Report). If there is a merging of two branches of the river, then the downstream elements are taken to have upstream run lengths composed of the sum of the run lengths of the two upstream branches. The channel was everywhere assumed to have a rectangular cross-section. The alternative method of making the size of the channels proportional to the distance of each link element from its source was also tried, but lead to some difficulties with localised overland flooding where branches came together and the downstream section was not sufficiently wide to take the combined upper fluxes.

The altitude of each channel link was initially taken to be such that the bank-top was at the same elevation as the lowest of the two adjacent land elements. However, in places this causes the river to run uphill, hence the 'lower' river link is lowered so that it is 10 metres below the 'upper' one, with a subsequent modification being made to the downstream links where necessary to make the network flow everywhere downhill.

Information about the land cover came from land-use data obtained from the Forest Authority of the Emilia-Romagna region at a 200 metre resolution. These data indicate whether a land element is built up, pasture, woodland, or bare rock, with many subdivisions within these main classes. It was seen that most of the surface of the land was either grass or forest, hence two vegetation types were defined for the SHE model. The parameters for these vegetation types were chosen based on previous experience at Newcastle.

No information on the soils was available. The catchment was assumed to be homogeneous in this respect, and the soil parameters were based on previous experience at Newcastle. The only information on the soil depth was that the impermeable bed-rock is everywhere very close to the surface, the surface area of the land where the depth is more than 10 metres being less than 10 km^2, and this only in the river plains of the lower catchment. Information on the bedrock could also be extracted from the land-use data, as this indicated the points on the ground where the bedrock reaches the surface. With these considerations in mind, then, the depth of the bedrock below the ground was allowed to vary from 0.1 to 0.5 metres, with the shallowest soils being at the points where the bedrock was observed at the ground, and the soils increase linearly in depth as one goes away from the bare rock element, so that the deepest soils were located at the points most remote from anywhere the bedrock had been observed at the ground level.

With a basic time-step of one hour, but a restriction so that no more than 0.1 mm of rain ever falls in one time step (the time step is reduced when this would otherwise occur), a model simulation including a large flood wave took approximately seven hours to run.

The bulk of the effort which went into the calibration of the SHE modelling system was in getting the represented shape of the land to reflect not only the average altitude of each grid square, for which there is sufficient data, but also to reflect the typical gradients present between two different grid squares. Information on the altitude of the land is not always sufficient to properly characterize the gradients, and it was found that some trial-and-error was needed to get this right. The main problems which arose are that when the altitude is sampled on a grid with a large spacing there are points on the ground which appear to lie in a hollow, and in the SHE simulations these collect water instead of propagating it further down the catchment. overall' the gradients of the land are underestimated by the coarse sampling of the land altitude. Also, small rivers and streams are not represented at all at coarse spatial resolutions, rather the overland flows are represented as simple overland shear flows. These have a much higher friction coefficient than flow which passes through a network of channels, again causing the simulations to occur as though the overland flow is unduly restricted. The solution of these problems is to make the Strickler coefficients slightly higher than observed, and to smooth out the shape of the land slightly so that there is a well defined path from all parts of the catchment to the outflow.

c) The numerical experiments

The experimentation was done in two parts, the first to determine if any patterns emerged in the errors in the runoff generated by inputting data observed at a network of raingauges into the catchment model, compared with complete information input, and to determine the nature of any consistency in these errors; the second part of the work is to investigate the dependence of these errors on the density of the raingauge network in use.

For the first part, the MTB model was used to generate 232 synthetic rainstorms, and these were fed to the catchment model both in complete spatial detail, and after being "sampled" by a network of 3 raingauges. The resulting runoff graphs were differenced, and then the results of this differencing were sorted into an order such that the square errors between successive difference graphs was minimized, i.e. the graphs were put into a sequence such that a slowly varying change of shape is seen from one graph to the next. The motivation for this is that if there is any repetition of the pattern of differences in the two runoff cases for each storm, then they will form a group in the ordered difference graphs of similar looking curves, which could be picked out by eye.

It was found that some patterns of differences did recur, but there was no one pattern which was clear and explicit enough, or frequent enough, to be useful in predicting future runoff. Thus it must be concluded that the method of predicting future runoff errors based on the recent past history of the success or failure of the modelling cannot be usefully implemented.

A common feature which did emerge from this analysis, however, was that the decay of the hydrograph after a severe storm event was almost always underestimated by the raingauge network input to the catchment model. Further, this discrepancy decayed with the same functional form after all storms as the runoff itself decayed, and the above results were used to estimate this function. This was done by shifting the peak runoff errors of all the difference graphs so that they coincided in time, and then averaging the remainder of the curves to give the average decay of runoff error after a peak flow. While this result will be of no use in predicting the onset of a flood event, it will at least allow for predictions of the withdrawal of the flood water to be improved, once the peak rainfall intensity in the storm has been observed.

For the second part of the work, the MTB model was used to generate 30 storms, and these were first fed into the catchment model so that each computational element of the model received a unique amount of rainfall as implied by the rainfall field. of the 24 raingauges present in the catchment, subsets of 6, 12 and 18 were selected so that each covered the entire catchment approximately evenly. Then the catchment model was run 4 more times with rainfall input as if sampled by the different sets of raingauges, i.e. the rainfall was sampled at the point in the field where a raingauge was located, and all the computational grid elements of the catchment model in the vicinity was done on a S minute basis, and then aggregated to the hour.

The complete experiment was performed on a network of 145 HP9000/710 workstations, so, while each individual run of the model took about seven hours, the whole experiment was completed in about three nights. For each storm event, and each collection of raingauges used, the runoff from the bottom of the catchment was stored.

It was seen that, in most cases the graphs of runoff obtained after the rainfall was input from a raingauge network was no different from the one obtained after input of the rainfall field in complete detail. However, in two out of the thirty cases it was seen that a large spike was observed in the runoff following complete information input which was not reproduced when input from any of the sets of raingauges was used, and in two other of the thirty cases spikes were present in the raingauge network case which were not in the complete case.

There was seldom any significant difference between the runoffs observed when different numbers of raingauges were used to sample the rainfall field. This is perhaps a surprising result, as one would expect a convergence of the runoffs as the number of raingauges tends towards a complete covering of the catchment, so that the raingauge network case and the complete information input case become indistinguishable. Clearly, this convergence does not set in until the number of raingauges in the network exceeds some value. This has not been investigated here, but could be the basis for further work in this area.

4. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

In general, a dense network of raingauges in the upper Reno catchment should be sufficient for forecasting the amount of water passing through Casalecchio via the Reno river. However, approximately once in every fifteen extreme events, a very large peak in the flow rate may be missed as a direct consequence of the incomplete sampling of the rainfall field in space, and the difference between the size of the unpredicted peak and the forecasted flow in this case will be a significant endangerment of life and property. This is perhaps justification for the use of a weather radar in conjunction with a dense raingauge network.

It has been found that the errors in the runoff predictions computed after the rainfall field has been sampled from a network of raingauges decay in a consistent way as the flood wave recedes, and this decay with time has been estimated so that it may be applied to real predictions of the recession of a flood wave to make them more accurate..The consistent peak difference in the errors is a significant part of the decay tail of the runoff hydrograph.

It is to be noted that while this work has been performed using the SHE model of catchment response as a test-bed river system, this is unsuitable for real-time prediction of runoff due to the large computational demands made. In practice, a simpler, less accurate model would be used, and so the results of this work should be taken as a lower bound on the errors which would occur, i.e. only the errors induced by the incomplete sampling of the rainfall field have been investigated here, not errors caused by the catchment model itself. Thus the experimental methodology developed above can be used to assess the errors caused by a raingauge network in isolation of any other sources of error, and can be used to determine optimal configurations of raingauge networks in this respect.

Further work needs to investigate the use of weather radar for forecasting rainfall in time and space, for the purpose of being input to a catchment response model so that flow forecasts can be produced. This would need to be accompanied by data from the dense raingauge network, and methodology would need to be developed for combining the two data sets in order to derive the most useful forecasts.

5. REFERENCES

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

NTUA-DWR, National Technical University of Athens

Research Contract n°: EPOCH-CT90-0023

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Contractor Institution: NTUA-DWR, National Technical University of Athens

Project Leader: Prof. Themistocles XANTHOPOULOS

Other Institutions cooperating:
- University of Bologna ICI
- University of Bologna, ADGB
- Ente Regionale di Sviluppo Agricolo
- University College Cork
- University of Newcastle Upon Tyne
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- Institut National Polytechnique de Grenoble
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Starting date: June 1st, 1991

Title of the project: A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

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1. MAIN OBJECTIVES

The research of NTUA-DWR has two basic lines within the framework of AFORISM: the study of intense, flood producing, rainfall and the study of rainfall-runoff models.

The study of intense rainfall includes:

(a) analysis and modelling of the temporal structure of storm events at a point and areal (lumped) basis,

(b) construction of a stochastic rainfall generator by using disaggregation techniques,

(c) application of the rainfall generator for generation of storm scenarios and testing of the model results.

The second line of research includes:

(a) evaluation of the performance of several rainfall-runoff models with emphasis on their runoff production part by treating the transfer to the watershed's outlet in a uniform way,

(b) addressing the problem of data inadequacy that arises from the gauging networks with non-recording devices; a methodology for integrating, in a continuous-time model, information from both daily and shorter time-step data is sought,

(c) investigation of the usefulness of the FDTF-ERUHDIT method in tackling the above problem described in b,

(d) examining the possibility of initialising continuous-time rainfall-runoff models through models of the same structure operating on a daily time basis, and

(e) gaining an insight on the above issues with the aid of synthetically generated data.

2. METHODS, DATA AND MATERIALS

2.1 Methods

Modern techniques, based on the theory of self-similar (scaling) processes are used for modelling of the time distribution of rainfall. In addition, the meteorological conditions of the area are considered in order to classify storm events by weather type. New disaggregation techniques with simple structure and reduced parameter sets, which can be combined with the stochastic rainfall model are developed.

For rainfall-runoff modelling two well-known conceptual rainfall-runoff models were applied. An analysis framework for model testing was set up to perform different model calibrations of the same model on different kinds of data and to link model operation on more than one time steps.

2.2 Hydrologic data

The Evinos River basin, Middle Greece, at Poros Righaniou with a total area of 884 km^2 was selected as the main study area. A database was constructed for the rainfall and runoff data for that basin. For the rainfall model development and parameter estimation the data of three recording rain gauges for a 20-year period were digitised on an hourly time basis. In addition, weather maps at the surface and 500 mb level for the same period were used. Some 500 intense rainfall events were isolated from the time series by using certain criteria for event identification and selection.

For rainfall-runoff modelling, the following data of the Evinos River basin were obtained:

(a) Hourly rainfall data of three rain recorders for a 20-year period.

(b) Daily rainfall of six rain gauges for an about 30-year period.

(c) Hourly runoff data at the outlet for 28 flood events.

(d) Hourly runoff data at the outlet and maximum and minimum daily temperatures for a 2-year period.

(e) Daily runoff at the outlet for a 8-year period.

(f) Daily mean temperature of 3 measuring stations, for a 8-year period (as in e).

Also, for rainfall-runoff modelling synthetically generated data for a 20-year period were used. In addition, data from two other real-world basins were used in the rainfall study. A rainfall data set of the Aliakmon River basin, province of Macedonia, Greece was used for the first period of rainfall model testing. Finally, a data set including two-year rainfall records of four raingauges (Firenzuola, Porretta Terme, Montecatone, Bologna o.s.i.) at the Reno river basin was used in the last year in order to calibrate and apply the rainfall model in this principal study area of AFORISM.

2.3 Materials

The FDTF-ERUHDIT identification package was obtained from French EDF within the frame of collaboration with the French partner. Initial FORTRAN code of the TANK model was provided by UNIBO-ICI and served as a basis to recode the model All the developed models have been programmed and run on a PC/DOS environment in Pascal programming language. No other software packages have been used.

3. RESULTS TO DATE

3.1 Rainfall modelling

A stochastic model describing the temporal distribution of rainfall within a storm event, based on the theory of self-similar (scaling) processes, was the theoretical background of the rainfall modelling. This model, developed in the framework of AFORISM, has been named the Scaling Model of Storm Hyetograph (Koutsoyiannis and Foufoula-Georgiou, 1993). The basic hypothesis of the model is that the instantaneous rainfall intensity process at any time position in the interior of a storm event of a certain duration D depends on that duration in a manner expressed by a simple scaling law with a constant scaling exponent H. Thus, the instantaneous intensities of two events with different durations, after appropriate scaling of time (determined by the ratio of the durations) and intensity (determined by the ratio of the durations raised to the scaling exponent), can have identical distributions, as expressed by

$$\{\xi(t,\ D)\} \stackrel{d}{=} \{\lambda^{-H}\xi(\lambda t,\ \lambda D)\}$$

where t denotes time ($0 \le t \le D$) and $\xi(t,\ D)$ is the instantaneous intensity. As a consequence of this hypothesis, the mean and standard deviation of total storm depth increase with duration each according to a power law with the same exponent; also, the mean and standard deviation of the incremental (e.g. hourly) depth increase with duration according to the same power law; the lag-one correlation coefficient of incremental depths increases with duration; and the decay rate of the autocorrelation function of the incremental rainfall depth decreases with the increase of duration. The model was implemented in its simplest possible mathematical structure with four parameters only, and in a modified form using five parameters. It was found to explain reasonably well the statistical properties of historical data, thus providing an efficient parametrisation of storms with varying durations and total depths. Also, it is consistent with, and provides a theoretical basis for, the concept of normalised mass curves. Furthermore, it was found that the scaling model is superior to other simple temporal rainfall models, which were unable to capture important statistical properties of storm rainfall. At the stage of initial model testing the rainfall data of the Aliakmon River basin (Macedonia, NW Greece) were used, and it was found that the model is in good agreement with those data. The model was subsequently applied to the data of Evinos River basin and calibrated separately for the storms of each of the two seasons (rainy and dry). The conclusion is that the scaling model fits the intense rainfall data in both seasons, thus providing a basis for modelling of intense rainfall events. Finally, the model was applied to the data of the Reno River basin in an areal basis where it was found to fit all storms of the year regardless of the season (wet or dry) using only one parameter set. It is remarkable that the fitting is also good for rainfall characteristics that were not used explicitly in the estimation of model parameters, such as the autocorrelation functions of hourly depth for lag > 1.

A common property of rainfall data, which was also validated from all data examined in this study, is the high coefficient of variation (usually greater than unity) of all variables associated with a rainfall event and mainly of the hourly depth. This property is apparently a serious obstacle in building a stochastic rainfall forecasting model. A part of the variance of these variables can be explained by the storm duration as inferred by the scaling hypothesis. This part can be as high as about 50% for the total depth but it drops to 2-4% for the hourly depth. As an attempt to further lower the unexplained part of the variance of these variables, we examined the general meteorological patterns that produce the specific events, applying a certain classification of storm events by weather type.

In this analysis, the data set of intense rainfall events at the Evinos River basin was used. The rainfall events of both rainy and dry seasons were initially classified into different weather types. The specific weather types examined were introduced by Maheras (1982). Their definition depends upon weather characteristics such as the location of centres of anticyclones, the main trajectories of cyclones and some special characteristics at the surface and at the 500 mb level. It was found that two of the weather types, namely the cyclonic types SW1 and NW1 give rise to the majority of intense rainfall events (about 30% each one), while other four cyclonic types (W1, W2, SW2, NW2) and one special type (DOR) produce intense rainfall less frequently. The main characteristics of the rainfall events (mean and variance of event duration and of total and hourly depth; lag-one autocorrelation coefficient of hourly depth) were calculated for each class of events that belongs to a specific weather type. By comparison of different classes, it was concluded that apart from the probability of occurrence of a storm, only few significant differences appear between characteristics of different weather types (Mamassis et Koutsoyiannis, 1993). Thus, the introduction of weather types does not explain high portion of the variability of rainfall (for example, it explains only a 10-20% of the variance of the total depth, depending on the season, wet or dry).

As another attempt to lower the unexplained part of the variance of the rainfall process (and thus to built better stochastic forecasting models), we examined the possibility to utilise the lagged cross correlations between rainfall depths at several points at a basin or neighbouring basins. If these lagged correlations are strong then it could be possible to convey information from rainfall occurring at neighbouring areas to improve the forecast.

To investigate this possibility we performed some tests using rainfall data of the Reno River basin to which several simple stochastic models were fitted. Examples of such tests are given in Table 1. We observe that the use of the lag-one autocorrelation of the hourly rainfall depth by means of an AR(1) model (Model 1) can lead to a variance of residuals significantly lower than the total variance of the hourly depth. However, incorporating the lag-one cross correlation with a neighbouring station (Model 2) does not reduce the variance further. This remains true even in the case where we also include the lag-zero cross correlation (Model 3), although there is a significant lag-zero correlation between the reference station and the neighbouring station (as indicated by the reduced variance of residuals of Model 4 for large rainfall durations).

Table 1 Gain from the use of various types of information for modelling hourly point rainfall at a site in terms of reduction in variance.

Reference rain gauge (with hourly rainfall depth Y_t)	Neighbouring rain gauge (with hourly rainfall depth X_t)	Duration of rainfall events examined	Total variance of hourly depth Var[Y_t]	Variance of residuals (Var [W_t]) for Model			
				1	2	3	4
Firenzuola	Porretta Terme	≤ 22 h	1.47	0.95	0.95	0.95	1.46
Firenzuola	Porretta Terme	≤ 22 h	2.53	1.31	1.24	1.23	2.09
Montecatone	Bologna o.s.i.	≤ 22 h	1.39	1.13	1.12	1.12	1.35
Montecatone	Bologna o.s.i.	≤ 22 h	1.88	1.27	1.24	1.17	1.38

Model 1: $Y_t = a_1 Y_{t-1} + W_t$, , Model 2: $Y_t = a_2 Y_{t-1} + c_2 X_{t-1} + W_t$, ,
Model 3: $Y_t = a_3 Y_{t-1} + b_3 X_t + c_3 X_{t-1} + W_t$, , Model 4: $Y_t = b_4 X_t + W_t$.

Thus, we conclude that it is impractical to convey information of neighbouring stations to improve the real-time stochastic forecast of rainfall. This justifies well the use of univariate rainfall models, in case that a lumped or semi-lumped rainfall-runoff framework has been chosen. The univariate rainfall models are convenient and simple tools that provide adequate input to lumped or semi-distributed rainfall-runoff models.

The next topic studied is the implementation of the scaling model for generation of synthetic rainfall events either in a marginal or a conditional manner. In the case of marginal generation, i.e. simulation of rainfall without any former information, the generation involves two steps. First, we generate the duration of the event. Second, we can either generate directly the consecutive incremental depths within the event or generate the total depth and disaggregate it into incremental depths. To this aim, an event-based rainfall generation scheme was developed which embodies two different generation forms: a typical sequential form and a disaggregation form (Koutsoyiannis, 1994). Both forms of the generation model are compatible and can be combined with either the scaling model or any other appropriate rainfall model and can perform with arbitrary time step less than the duration. The sequential form of the model is based on the generalised matrix relation

$$\mathbf{X} = \Omega \mathbf{V}$$

where **X** is the vector of incremental depths inside the event, **V** is a vector of independent variables and Ω is a matrix of coefficients. Given the marginal and joint moments of the incremental depths (e.g., as a consequence of the scaling model) the moments of **V** and the coefficients Ω can be easily determined.

On the other hand, the disaggregation model can divide the total depth of an event (with known duration) into incremental depths. The disaggregation technique is characterised by simplicity and parsimony of parameters. It assumes a random shape of the hyetograph and it is compatible with various rainfall models. It is well known that most disaggregation models in the literature (e.g. Valencia and Schaake, 1972, 1973; Mejia and Rousselle, 1976; Todini, 1980; Stedinger and Vogel, 1984; Pereira et al., 1984; Lane and Frevert, 1990; Grygier and Stedinger, 1990; Koutsoyiannis, 1992) are not applicable to short scale rainfall disaggregation. Other models such as the one by Koutsoyiannis and Xanthopoulos (1990) are especially designed for short scale rainfall disaggregation, but they are not so generalised as to be combined with any rainfall model, as they include certain hypotheses about the stochastic structure of the rainfall process. The developed model is generalised in a high degree as the only hypothesis it uses is that the incremental rainfall depths are approximately gamma distributed and not very highly serially correlated. With this assumption a simple two-step disaggregation method was established. At the first step the method uses the above mentioned sequential model without reference to the total depth, while at the second step an appropriate adjusting procedure is applied. It was found that the method gives good approximations of the important statistics of interest. Furthermore, under some ideal conditions the disaggregation method was shown to be exact in a strict sense, i.e., it preserves the complete distribution of the variables (Koutsoyiannis, 1994). Both generation techniques were combined with three alternative rainfall models (the scaling model, a Markovian in continuous time and a Markovian in discrete time). The results of the model application and testing at these three cases indicated very satisfactory resemblance of the important statistics of incremental rainfall depths (first, second and third order marginal moments, marginal distributions, and joint second order statistics).

Finally, the generation model was modified so as to form a conditional generation scheme of the future evolution of a storm, given the situation at the current time step k and the previous ones. This scheme can also incorporate (as a condition) any available information about the event. A conditional simulation scheme with two main steps was used for this purpose. At the first step the total duration D is generated from its conditional distribution, given any condition that is known for duration. The second step involves the generation of the sequence of incremental depths X_j ($j = k+1, \ldots, D$), given any condition that is known for depths. The latter step is performed either in a typical sequential manner or by disaggregation.

The conditions examined fall into two categories: The first category encompasses the information that is known from the past and it includes (a) the obvious condition $D \geq k$, and (b) the observed series of incremental depths $X_1, \ldots, X_k$. The second category includes information that possibly could be provided from meteorological predictions such as approximate estimates of (a) the total duration and (b) the total depth of the event or incremental depths (e.g., every 6 hours). Such estimates can be deduced from the quantitative precipitation forecasts of the European Centre Medium Range Weather Forecast (ECMWF). Since these forecasts have a great degree of uncertainty, they can be treated by the generation scheme in a probabilistic manner, i.e., the generation scheme can directly add random components to the ECMWF forecasts.

The above described conditional simulation scheme was applied in several cases and the obtained stochastic forecasts were compared with historical data. It was concluded that in case that we use the conditions of the first category only (known past) and perform the conditional simulation for an unlimited lead time, the stochastic forecast of the evolution of the rainfall process is poor. This is due to the high coefficient of variation (> 1) and the low autocorrelation function of hourly depths. The stochastic forecast is improved if the lead time is limited to 1 hour (adapting the conditions of the recorded hyetograph every 1 h), even when the information of the first category is known only. The situation is also improved at the case that the information of the second category (estimates for the total duration and depth) is available.

3.2 Rainfall-runoff modelling

Flash floods are frequently encountered in steep headwater basins of the Mediterranean zone. Small basin areas ranging from several tens to several hundreds km^2 give rise to very short response times (up to a few hours). This necessitates time steps for model operation within the range from a fraction of one hour to a few hours. For such a time-resolution of hydrologic data, recording devices are needed. However, during the design phase or the very early stages of operation of a flood forecasting system, a common situation in regard to data consists in the following: (a) a rather dense network of non-recording devices has been providing data for a long period (e.g. 20 or 30 years) mostly on a daily basis, (b) recording devices are much fewer and they have been providing discontinuous records in most cases related to some flood study. In such situations two modelling alternatives can be followed: (a) the use of the limited set of pieces of continuous charts to extract data for some flood events followed by a purely event-based modelling approach, or (b) the use of the charts in combination with the daily data in the hope to embody all available information in a unique model. It is the latter approach that we have chosen to explore within the AFORISM project. More specifically, two problems have been tackled. The first problem is model calibration based on inappropriate data sets in situations that have been described previously. The second problem concerns, always in the same context of data availability, the initialisation of event-based models in an operational context.

Our analyses refer to lumped conceptual rainfall-runoff models which consist of two parts: the production function and the transfer function. The production function summarises all hydrologic processes involved in an idealised soil column or hillslope that represents the whole basin. The transfer function encompasses all transfer processes within the catchment and is assumed linear by the Unit Hydrograph theory. A key element in our analyses is a new model calibration method, called FDTF-ERUHDIT (Duband et al., 1993). Based on the Unit Hydrograph concept, it performs a simultaneous identification of the effective rainfall series and the transfer function or Unit Hydrograph through an iterative procedure. It does not presume any production function nor it applies any baseflow removal.

A new methodology was developed to tackle the problem of model calibration based on inappropriate data. It involves the following steps:

(a) For a specific model structure (e.g. that of the TANK model) a daily model is calibrated based the long continuous-time data set that is available.

(b) The transfer function of the model is calibrated, on the time step that is suitable for the basin dynamics (e.g. one hour); event-based data are used together with the FDTF-ERUHDIT method.

(c) Based on the above identified model parameters, a new model, called the "derived" model; is constructed; its production function parameters are derived from those of the daily model while the parameters of its transfer function are directly identified (as described in b).

Parameter transformation from one time step to another was also studied. A certain number of cases were to cover most models commonly used in practice (see Nalbantis, 1994).

The second problem that was studied concerns the operational use of the derived model Two possibilities arise: (a) continuous-time run, and (b) activation only in flood periods or event-based approach. To tackle the problem of model initialisation that arises in the second case, we proposed the following methodology:

(1) The daily model is run as a continuous-time one.

(2) The derived model that operates on a shorter time step, is initialised through the daily model, whenever this is necessary. The initial values of the state variables of the derived model are provided by the daily model.

(3) The initial values of some state variables may be tuned to "correct" the model performance.

To validate the methodology proposed, we set up a framework for analysis which was applied to a Greek basin for a short time step of one hour. Two well-known rainfall-runoff models were selected for the analyses, the version of the SACRAMENTO model known as the Soil Moisture Accounting (SMA) model of the U.S. National Weather Service River Forecast Service or SMA-NWSRFS (Burnash et al., 1973), and the TANK model (Sugawara, 1976; Sugawara et al., 1983). The framework for analysis comprised the following steps:

(1) Identification, for comparison purposes, of a reference model on a continuous-time data set on a short time step; this data set is available only in our case study.

(2) Construction of the derived model as previously described.

(3) The performances of the two models are compared in continuous-time data sets to test the possibility of using the derived model as a continuous-time model.

(4) The effectiveness of the initialisation of the derived model through the daily model is tested for a number of historical flood events.

(5) The sensitivity of the whole composite scheme (daily + derived model) to the initial values of state variables is assessed and the effect of tuning some of these values is evaluated.

In the calibration phase, the hourly models showed efficiencies higher than those of the daily models (by 20% for the SMA-NWSRFS model and by 16% for the TANK model). The efficiencies of the two model structures (SMA-NWSRFS and TANK) were rather similar although the TANK model gave slightly lower values (by 1% for the daily time step and by 4% for the hourly time step). In the verification phase, performances remained close to those of the calibration phase. In all cases, the reduction in efficiency was less than 10% with the exception of the hourly SMA-NWSRFS model for which the reduction is 28%. So, one may claim that the TANK model performed more satisfactorily in our case study.

The performance of the derived model was compared to that of the corresponding reference model. Performance criteria are shown in Table 1. We easily observe that the derived model performed equally well to the reference one for the verification period (1985-86) and for both model structures.

Table 2. Comparison of performance of the reference and the derived model.

Model	Period	*EV*	R^2	Loss in R^2 (%)
SMA-NWSRFS				
reference	1980-81	0.847	0.847	
reference	1985-86	0.610	0.610	
derived	1980-81	0.663	0.662	21.8
derived	1985-86	0.616	0.615	-0.8
TANK				
reference	1980-81	0.818	0.812	
reference	1985-86	0.763	0.763	
derived	1980-81	0.777	0.757	6.8
derived	1985-86	0.780	0.769	-0.8

EV = explained variance, R^2 = Nash efficiency

As we have already stressed previously, the derived model can be used as an event-type model after it has been initialised through the daily model. To examine this possibility, the values of state variables obtained from each daily model were compared to those of the corresponding derived model for two continuous simulation periods and results showed that: (a) for the SMA-NWSRFS model structure very high values of R^2 were found for the tension water contents while for the other state variables results were less satisfactory, especially for those states that determine the fast baseflow and the interflow, and (b) for the TANK model analogous results were obtained i.e., very good agreement for all state variables except for that of the secondary subtank. Hence, a direct transfer of the states from the daily model to the derived model is perfectly possible with the exception of one or two state variables. Subsequently, four simulation schemes were compared on a single flood event:.(a) continuous run of the reference model, (b) continuous run of the derived model, (c) event-based run of the derived model after initialisation through the daily model, and (d) as in (c) with tuning of some of the initial states provided by the daily model. For the SMA-NWSRFS model structure R^2 dropped from 0.918 for the reference model to 0.502 for the continuous-time derived model and further to 0.285 for the derived model initialised through the daily model. A large number of trials revealed that tuning the two state variables of the upper zone is effective and may raise R^2 to 0.752. For the TANK model structure the reference model gave a rather low value of R^2 (0.697) which decreases very little ($R^2 = 0.679$) for the continuous-time derived model and the event-based derived model ($R^2 = 0.668$). Tuning of the state variables of the upper zone raised R^2 to 0.808.

The tuning procedure described is however difficult to implement in real time since the forecaster has to wait for the natural system to be sufficiently excited by the input rainfall. This is the reason why we examined another approach that involves residual treatment. The scheme proposed encompasses the following steps: (a) At each time t, a hydrologic-model-based forecast is calculated based on rainfall forecasts and a rainfall-runoff model which in our case is the derived model initialised through the associated daily model, (b) the residuals of this model from the previous flood are treated to yield parameters of an autoregressive-moving-average (ARMA) model called error model, (c) a prediction error forecast is calculated through the error model and then is added to that described in (a) to obtain the final forecast. This scheme was applied tor the Evinos catchment and for two different model structures, the SACRAMENTO and the TANK model. Autoregressive models of orders one, two and three were fit to the residuals with the aid of the Recursive Least Squares Linear Sampling (RLSLS) algorithm. This is an adaptive identification algorithm (Delleur and Obled, 1985) that allows efficient identification in real time through parameter updating. Problems of instability were encountered during the initial phase of the flood events. The whole scheme was also implemented with a continuous-time hydrologic model that is directly identified on a long continuous data set (i.e., the reference model previously defined). It appeared that: (a) an autoregressive model of order two is sufficient to model the residuals, (b) very high lag-one autocorrelation coefficients (> 0.95) are encountered, and (c) the derived model initialised through a daily one performs equally to a true continuous-time model when both are subject to residual treatment. The latter result is valid for lead times up to six hours but degrades thereafter.

A last series of tests that was carried out during the third year of the project, involves testing the methodology proposed on synthetically generated data. This was necessary due to the uncontrolled errors that are always present in real-world basins. Experience with tests on synthetic data had already been acquired in previous research work (Nalbantis et al., 1994) but within the AFORISM project a new framework for analysis was set up. It involved generation of true or reference data, contamination of the input rainfall with errors, and addition of errors to the model parameters. The error on the areal input rainfall was a white noise applied on the true values in a multiplicative manner while three values were considered for its standard deviation (10%, 50%, 150%). A short time step of one hour was selected for the tests. The series of tests involved:.

(1) Comparison of the true end-of-day values of state variables with those of the true hourly and the true daily model.

(2) Comparison, on synthetic flood events, of the performances of the reference and the derived model after initialisation of the latter through the associated daily model.

(3). Testing of the effect of errors on rainfall and of parameter uncertainty

A simplified version of the TOPMODEL was chosen for the tests

The main conclusions drawn from our study are:

(1) It is not an uncommon situation for many countries to dispose inappropriate hydrologic data during the early stages of design and development of a flood forecasting system; in particular, large amounts of daily data are usually available together with some event-based data sets.

(2) Although the most straightforward approach would be to follow a pure event-type approach, we propose an alternative methodology which integrates in a single model both daily and shorter time-scale information.

(3) A calibration procedure was developed which utilises the FDTF- ERUHDIT method for Unit Hydrograph identification while the runoff production function is derived from daily data.

(4) The resulting derived model performs well in continuous simulation and can be effectively initialised through the daily model; the performance of this scheme (daily + derived model) is very much improved through tuning of some of the initial values of the state variables.

(5) The methodology for integrating information from different time steps in a unique rainfall-runoff model was validated in a real-world case; further insight was gained through tests on synthetically generated data both error-free and contaminated with controlled errors on rainfall and the model parameters.

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

ISA-DER, Instituto Superior de Agronomia

Research Contract n°: EPOCH-CT90-0023

Contract n° : EPOCH-CT90-0023

Contractor Institution : ISA-DER, Instituto Superior de Agronomia

Project Leader : Prof. Santos PEREIRA

Other Institutions cooperating:
- University of Bologna ICI
- University of Bologna, ADGB
- Ente Regionale di Sviluppo Agricolo
- University College Cork
- University of Newcastle Upon Tyne
- National Technical University of Athens
- Institut National Polytechnique de Grenoble
- Ecole Polytechnique Federale de Lausanne

Starting date: June 1st, 1991

Title of the project: A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

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1. MAIN OBJECTIVES

The main objectives of the research carried out by the Instituto Superior de Agronomia can be listed as follows:

- Development, calibration and validation of a distributed and continuous rainfall-runoff model.

-Application of the developed model to the Reno River.

- Utilisation of a Geographical Information System for the manipulation of cartographic data (topography, soil type and land use), to be used in the construction of the input files of the developed rainfall-runoff model and using different space scales of representation of the watershed, in order to assess the effects of lumping and averaging the different hydrological phenomena at increasingly larger scales.

2. METHODS AND MATERIALS

2.1 Methods

Approximate analytical solution of the equations describing the simulated hydrological processes.

2.2 Materials

ALR Business VEISA, 20386, 33 MHz, Computer under DOS
Rowland Plotter (A0)
Hewlett-Packard Laser Jet III Printer
7012 Power Station IBM RISC/6000 under UNIX
AIX XL Fortran Compiler/6000
GraPHIGS Programming Interface software
ARC/INFO GIS software
CoDraw and CoPlot Scientific software
Calcomp Digital Tablet (A0)

3. RESULTS

3.1 Rainfall-runoff model development and application:

The code of the main program of the model is still being developed.

A detailed analysis of the subroutines that perform the calculations for the simulation of the different hydrologic processes is being done.

The simulation of the overland flow process has been carefully analysed. SWATCHP model (Matias, 1992) simulates the overland flow using the kinematic wave equation, which is solved analytically by an approximate procedure. The simplified hypothesis utilised in the analytical solution of the kinematic wave equation are: constant initial water depth in the overland flow plane, D_0 zero water depth at upstream of the plane, for all time (boundary condition) and an excitation designated by effective artificial rainfall rate, which is equal to the sum of the throughfall rate to the mean overland flow produced, during the time step, at the upstream plane (reduced to velocity dimensions), minus the mean infiltration rate during the time step. As an alternative, the water depth correspondent to the mean overland flow produced at the upstream plane could be added to the initial water depth. In this case, the effective artificial rainfall rate is only the difference between the mean throughfall and infiltration rates, during the time step.

Those two different ways of handling the upstream overland flow were compared. In order to perform the comparison an analytical exact solution of the kinematic wave equation was needed. In fact, two exact analytical solutions were utilised, both considering a constant rainfall rate: the first corresponds to the case of one impervious plane, derived by Morel-Seytoux (19), and the second corresponds to the case of two impervious planes, both with a rating curve exponent of 2, and with the slope of the upstream plane being 4 times the slope of the downstream plane, derived by Morel-Seytoux (1989 and 1994, not yet published). In addition, another model was utilised, in order to compare the performance of the approximate analytical solutions of SWATCHP against the numerical solution of the kinematic wave equation. The utilised model was the KINEROS model (Woolhiser *et al.*, 19). The obtained results are (and should be soon published):

- when using SWATCHP, it is better to add the mean overland flow produced at the upstream plane to the effective artificial rainfall rate than to update the initial uniform water depth in the plane.

- The SWATCHP solution improves when using a large time step. The opposite happens with the numerical solution. It is to be mentioned that, due to convergence problems, there is a limit in the utilised time step when using the numerical solution. Given that this limit does not exist with SWATCHP, this model can run much faster than the numerical solution.

- The increase of the number of overland flow planes improves the solution of SWATCHP and worsens the numerical solution. It is to be noted that when using several overland flow planes, the utilisation of a short time step in the numerical solution does not provide good results.

- In SWATCHP mass balance is respected, while in the numerical solution serious errors can occur which can be detected but that are corrected.

From that analysis it seems that the approximate analytical solution of SWATCHP is best suited to be incorporated in watershed modelling, given its efficiency and accuracy. Efficiency means that it can be run as a widely distributed model with relatively small time steps (say 10 to 20 minutes) and run over long horizons of time (say a few years). Clearly then one cannot use purely numerical schemes which would require too much computer time and cannot be very accurate by their very nature whenever changes in time or space are rather abrupt, which tends to be the cases of interest (e.g. floods or droughts i.e. extreme situations). Accuracy means that it describes correctly the essence of the physical processes so that the model can be used to extrapolate to low frequency events once it has been calibrated on historical records and be used to asses changes in management of the basin system. Accuracy does not mean that for every point in time and space the predictions meet a certain error tolerance. SWATCHP is not a model of kinematic wave theory. It uses a technique of solution for the simplified equations of overland flow to be integrated in the much broader purpose of prediction of discharge at the catchment outlet, given rain over long periods of time.

Since the model is not operational it was not possible to apply it to the Reno River.

3.2 GIS utilisation:

The work consisted essentially in learning UNIX and beginning to understand how to use some modules of ARC/INFO.

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

IMG-LTHE, Institut National Polytechnique de Grenoble

Research Contract n°: EPOCH-CT90-0023

Contract n° :	EPOCH-CT90-0023
Contractor Institution :	IMG-LTHE - Institut National Polytechnique de Grenoble
Project Leader :	Prof. Charles OBLED
Other Institutions cooperating:	- University of Bologna ICI - University of Bologna, ADGB - Ente Regionale di Sviluppo Agricolo - University College Cork - University of Newcastle Upon Tyne - National Technical University of Athens - Instituto Superior de Agronomia - Ecole Polytechnique Federale de Lausanne
Starting date:	June 1st, 1991
Title of the project:	A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

This report covers the last year of the project, which was initially planned for two years. This third year has been granted without funding to allow those partners that have had some troubles in starting up their work to fulfill their contribution.

1. MAIN OBJECTIVES

The contribution of the IMG-LTHE was organized around two main lines of research.

The objective of the **first line** is the development and improvement of rainfall-runoff models appropriate for operational use in real-time flood forecasting, especially for mediterranean streams. This line can be subdivided into:

- improvement of a methodology for the simultaneous identification of transfer-function and excess rainfall series, including sensitivity to input and output data.

- development of a new loss function, based on the contributing area concept used in TOPMODEL. This includes some separate tests on fully physically-based hillslope models, to improve understanding, as well as testing the worth of including information about spatial variability of rainfall.

The objective of the **second line** is more devoted to the practical aspects and operational use of such models. It consists of three main subjects:

- design of a minimal configuration for operational models, in term of data requirements both for hydrometeorological variables or for basin characteristics,

- the use of Kalman filtering to update the initial or the current state of a simple model

- the use of information on future rainfall to extend the lead time of a forecast. This aspect is limited to the use of rainfalls scenarios provided by simple stochastic rainfall simulators.

The project was supposed to converge on the data of a unique test catchment: the RENO river, on which every group would apply its methodology. Our objective, for the IMG-LTHE group, was to provide rainfall-runoff forecasts at the outlet of the mountainous part of the catchment (Casalecchio di Reno, just upstream of Bologna, ~1000km^2)

2. METHODS, MATERIALS and STAFF INVOLVED

2.1 Materials needed for the research

2 Microcomputers COPAM PC/AT 486 SBX 200C under DOS
2 APPOLO HP Workstations N° 400 under Unix
A color printer HP 1200c
DPFT identification Package (Electricité De France)

2.2 Elaboration of a Database

Further to the AFORISM databases collected during the first two years, our contribution has consisted, during this last year, in focusing on:

1-) the "SIEVE" basin (Italie) .

In order to wait for the RENO data, while working in similar hydroclimatic conditions, the SIEVE basin had been used for testing our methodology.

The initial SIEVE data set (used by Franchini & Pacciani, 1992) was of good quality, but somewhat restricted in size.

So data published in the ARNO report of 1978 have been collected by INPG-IMG from UNIBO-IDEA, allowing to extend the number of events set at Fornacina station to more than 50.

However, major inconsistencies have been detected for some events, requiring a careful and extensive processing and some corrections due to heterogeneities in the data.

2-) Data on the RENO River basin have been proposed by the coordinator at the February 93 meeting in Grenoble. They consisted of a 2 year continuous record (1990 & 91) for all available stations in the total basin (~4000 km^2). Some work has started on these data, but it has soon appeared that there was no hope to apply our methodology on the RENO data during the few remaining months because:

- our Tranfer Function identification technique requires some 20 to 30 independent floods to allows the derivation of a robust unit hydrograph. This usually means around 10 years of data, while only two were available for the Reno...

- similarly, our rainfall generator must be based on a long serie of hourly rainfalls, hopefully 30 years but at least 10. This is especially true if we wanted to work on basin averaged rainfalls, which requires the availability of enough stations over ten years to compute a robust estimate of the basin rainfall.

Thanks to the coordinators, a few long series of hourly rainfalls have been collected in the form of graph records, but the time required for data criticism and digitisation would have overpassed the duration of the project.

2.3 Staff Involvement

This paragraph insists on how the work has been organised during this third year of the Project.

PROF. Ch. OBLED has continued to work on the project at IMG-LTHE. However, the initial team based of Ph.Ds students (Dr. J. WENDLING and Dr.P. LARDET) has been dispersed, as the project was initially planned and funded for two years only.

Hopefully, those two Ph. Ds have joined other AFORISM partners for a postdoctoral stay (J. WENDLING in Bologna, and P. Lardet in Newcastle/T).

During this period G.M. SAULNIER, who got engaged in a thesis in September 1992, has worked on topographic analysis. But he has devoted much of his time in designing the TOPSIMPL 1.0 operational package for implementing the chain gathering the TOPMODEL+FDTF approaches.

2.4 Interactions with other AFORISM members

The program has tried to stick as far as possible to the real time aspects of the system and several demo's were presented.

Also related to the interactive aspects between AFORISM members, G.M. SAULNIER has staid some months in LANCASTER working on TOPMODEL with Prof. BEVEN, and has been welcome in Lausanne for some months.

The major interaction during this last year has been the preparation of the final report, for which Prof. OBLED has been in charge of coordinating with Prof. TODINI the Chapter 3 and 4 on the fundamentals and operational aspects respectively of Rainfall-Runoff modeling.

There has been two meetings, one in CORK (November 1993) where the structure of the final report has been launched and one in NEWCASTLE/T, (in March 1994), where the first draft of the report has been presented and some chapters extensively reorganised.

A last meeting has been held in Grenoble in April 1994, thanks to the EGS genral Assembly, which has allowed a last concertation between members.

Many papers have been presented, among which a general presentation od the project by the coordinator Prof. E. TODINI.

As for the Grenoble group, at least four communications or posters have been presented in connection with AFORISM, and a special session devoted to Flashfloods and Mudflows has been chaired by Prof. Ch. OBLED.

3. RAINFALL-RUNOFF MODELLING

3.1 Development about the FDTF-ERUHDIT identification method

The major point addressed during the third year has still beenthe Invariance of the Transfer Function. The work has been finished on the Sieve catchment, (840 km^2), where a partitionning of the event has been performed based on peak discharges (50 to 150 m^3/s, 150 to 300 m^3/s, and larger than 300 m^3/s), this splitting being reasonnably consistent with a ranking by runoff coefficient.

The effect has shown a transfer function less peaky and delayed by almost 2 hours when moving from the first to the second group. But the third group showed a recovering in response time and becoming even slighty shorter than in the first group. This has been interpreted as the result of a competition between channel and hillslope processes occurs.

Globally, this means that the gross invariance of the transfer function is only the result of counteracting influences. Some variability is definitely present, but in spite of the large range of peak discharge, an average invariant transfer function may usually be selected although this requires a specific checking on every catchment to be processed.

3.2 Development of a loss function based on TOPMODEL

In the U.H. terminology, the transfer function or U.H. performs the routing of water, while the soil moisture accounting part of the model is performed by a loss function.

In the recent past, TOPMODEL has been tested as a way of generating runoff by considering the dynamic development of a temporary aquifer, and therefore of "variable contributing areas" saturated from below. In this work, it has been shown that this process allows reasonable and perhaps better simulation, and can be easily included in a simple operational model. Reference is made for these aspects to the first and second year annual report.

The third year has been devoted to the development of a user friendly tool comparable and complementary to the package developped by EDF for the ERUHDIT transfer function identification technique.

3.3 Developing a complete modelling "chain" (FDTF+TOPMODEL)

During this period, the approach advocated above has been applied "operationnally" to 2 new test basins (the SIEVE and the PAILLON), in the following sequence:

- identification of the transfer function (and of likely excess rainfall series) by the FDTF approach

- fitting of simplified Topmodel as a loss function in connection with these previous T.F. and excess rainfalls.

It seems that a non experienced user can now perform a reasonnably good fitting and testing within 3 to 6 months depending on the data quality problems encountered. Those improvements are to be included into the package written in connection and maintained by Electricity of France (DTG - Sce Ressources en Eau).

In order to allow comparisons between event based and continuous simulation, an experiment has been set up, based on the Sieve data set. The Bologna group has calibrated continuously the TOPMODEL and the ARNO model on the december 1959 data, while January to March were used as the validation set. The Grenoble group has calibrated the above "chain" on nine events extracted from december 1959 and tested the results on events from february and march 1960.

In fact, it has appeared that the results obtained on events, thus using only the dynamic part of the hydrographs, are very close to those got from continuous simulation, although in this last case the inclusion of long slow varying recession tends to improve the criteria of performances.

4. CONCLUSIONS

For the INPG group, this second year has allowed to fulfill almost all the objectives fixed for our contribution in this project. Special opportunities (sabbatical leave, postdoctoral stay, european grants, etc...) have allowed for effective interactions with other partners, which was part of the objective.

These results will be finalised in the third extra year of this project by trying to apply them to the Reno River data and providing them to the decision-making framework designed by other partners.

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COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

EPFL-IATE, Ecole Polytechnique Federale de Lausanne

Research Contract n°: EPOCH-CT90-0023

Contract n° :	EPOCH-CT90-0023
Contractor Institution :	EPFL-IATE Ecole Polytechnique Federale de Lausanne
Project Leader :	Prof. André MUSY
Other Institutions cooperating:	- University of Bologna ICI - University of Bologna, ADGB - Ente Regionale di Sviluppo Agricolo - University College Cork - University of Newcastle Upon Tyne - National Technical University of Athens - Instituto Superior de Agronomia - Institut National Polytechnique de Grenoble
Starting date:	June 1st, 1991
Title of the project:	A Comprehensive FOrecasting System for Flood RISk Mitigation and Control (AFORISM)

1. INTRODUCTION

IATE/EPFL is involved in two major research topics within the EPOCH-AFORISM project. These are:

- Rainfall-Runoff modeling.
- GIS applications for hydrologic modeling, flood mapping and flood damage assessment.

The present document briefly describes the main results obtained until June 1st, 1994.

2. RAINFALL RUNOFF MODELING

2.1. objectives

a) Study flood generating mechanisms at different scales.

b) Identify dominant flow processes and explaining parameters (topography, geology, soil types, etc.).

c) Collect valuable and pertinent hydrologic data (flows, rainfall, water table levels, soil water contents, isotope tracing, etc.).

d) Validate conceptual representation of catchment hydrologic response. Test operational models for real time flood forecasting.

2.2. Results up to date

a) A three component chemical mixing model (throughfall, soil-water and deep groundwater) based on two tracers (Calcium and Silica) was successfully applied on several sub-catchments. This model capitalizes on the hydrochemical contrast between the carbonated bedrock, acid soils and throughfall and the very low silica concentrations in throughfall.

b) Due to sometimes important contribution of soil water which may be isotopically different from groundwater, the accuracy of the classical "new" vs. "old" water separations may be seriously affected.

c) Tracer data (both chemical and isotopic) shows significant differences with respect to other studies in humid temperate climate. A relatively low proportion of previous-to-event baseflow in the stormflow hydrograph is found.

d) There is a convincing body of evidence that a mixture of pre-event shallow soil-water and rain-water rapidly passing through the soil makes a major contribution to stormflow, especially for wet antecedent conditions and moderate rainfalls.

e) The three component chemical mixing model satisfactorily explains the link between spatio-temporal variability of hydrological and hydrochemical response.

f) TOPMODEL was applied on four catchments in parallel with the same soil parameters. Topography alone, has been able to satisfactorily explain a considerable spatial and temporal variability in hydrological response.

g) Model parameter estimation on multiple catchments significantly improved the performance on independent data sets.

h) The use of tracer data for model parameter identification needs further work.

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3. GIS, FLOOD MAPPING AND FLOOD DAMAGE ASSESSMENT

3. 1. Objectives

a) Develop a two dimensional hydraulic model compatible with the requirements of flood mapping in flat areas capable of handling structural patterns of topography such as roads (break lines) and surface depressions where water remains stagnant.

b) Develop GIS prototypes for flood mapping and assessing flood impacts on road traffic, agricultural areas and built up regions.

3.2. Methods and materials

GIS systems: Data base system Dbase4, raster GIS IDRISI and vector GIS MapInfo (MSDOS 6.0 under WINDOWS 3.1 environment).

3.3. Results to date

- The prototypes to assess flood impacts to built-up areas, agriculture and traffic network were improved and are now operational in a WINDOW 3.1 MSDOS PC environment.
- The theoretical method to construct the Triangular Irregular Network, needed for the derivation of the Digital Terrain Model on which hydraulic computations are based, was established.
- Preliminary implementations into more sophisticated GIS packages running under UNIX were attempted (ORACLE, VISION).
- An interface with a Swiss institutional Geographic Data Base was achieved.
- A Data Conceptual Model (Dynamic and Static) for the purpose of AFORISM was developed.
- A 2-D hydraulic model was tested and validated in the Broye river catchment. Equations for hydraulic structures were improved.
- Stability criteria and recomenditions for selecting optimal time steps were preliminarly proposed.

3.4 References

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