COMMISSION OF EUROPEAN COMMUNITIES

AFORISM

A COMPREHENSIVE FORECASTING SYSTEM FOR FLOOD RISK MITIGATION AND CONTROL

Final Report

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EXECUTIVE SUMMARY

AFORISM is a research project aimed at the development of a comprehensive forecasting system for flood risk mitigation and control which was funded by the Commission of the European Communities under the aegis of the research programme EPOCH.

The project aims to integrate, within the framework of a unique decision support system, the input data and the models representing the meteorological, hydrological and hydraulic phenomena with the other elements contributing to the decision making process, namely:

- Data Acquisition Systems;
- Rainfall forecasts (deterministic and stochastic models);
- Rainfall-runoff forecasts (deterministic and stochastic models);
- Flood routing and flood plain models;
- Flood Impact Analysis.

AFORISM has been conceived, as a double common experiment:

- An inter-comparison of different approaches for rainfall measurement and modelling as well as for rainfall-runoff modelling as part of a comprehensive flood forecasting scheme aimed at mitigating flood hazards.

- A feasibility analysis using the Reno river as a case study, aimed at integrating all the innovative technologies in an operational decision support tool for flood forecasting and flood impact analysis.

DATA ACQUISITION SYSTEMS

At the present time, most data acquisition systems are based upon conventional telemetering equipment whilst the use of meteorological radars has not yet reached wide-spread applications. Also the Quantitative Precipitation Forecast estimates from satellite images have not yet reached an operational quality, except for extremely large

catchments in the tropical zone, for which NASA runs the Tropical Rainfall Measurement Mission program. AFORISM uses a dense network of hydro-meteorological stations (circa 50 rainfall stations and 20 temperature stations over the Reno river catchment area of 4,172 Km^2) to estimate the precipitation volume over the different sub-catchments and compare these estimates with those obtained from the Doppler radar available through the Servizio Metereologico Regionale Emilia Romagna.

In addition to the meteorological stations, there is a network of river flow measuring gauges supplying flow information on a frequent basis.

RAINFALL FORECASTS

A number of different approaches were used and forecasts were produced by:

- Deterministic Limited Area Precipitation Models
- Stochastic univariate models
- Stochastic multi-variate models.

The aim was to verify the possibility of using a Deterministic Limited Area Model for producing precipitation forecasts to improve flood forecasting.

RAINFALL-RUNOFF FORECASTS

Several approaches were tested on different catchments in France, Greece, Italy and Spain, with the objective of finding the most appropriate schemes for real time flood forecasting.

The approaches used extend from the extremely simple event type, through conceptual semi-distributed, to complex physically based models; rainfall-runoff models such as ARNO, TOPMODEL, SACRAMENTO, SHE, were used and in-depth investigations were made using the most appropriate for real time flood forecasting.

FLOOD ROUTING AND FLOOD-PLAIN MODELS

Given the need of computing downstream levels for flood control purposes, flood routing in real time was performed with appropriate hydraulic models, which take into account river geometry.

Flood maps were obtained by simulating the spread of water over the flood plain by means of a 2-Dimensional flood plain model and by recording the following quantities:

- Maximum water depth
- Maximum water velocity
- Time of residence.

FLOOD IMPACT ANALYSIS

Flood impact analysis is finally obtained by superimposing flood maps with GIS georeferenced spatial data on:

- Agriculture
- Traffic
- Constructions

and non-spatial data:

- Economic
- Social
- Environmental

and making use of multicriteria optimization schemes, Artificial Intelligence and Decision Support Systems to attempt to reduce the hazard and minimize the flood damage.

THE RENO RIVER CASE STUDY

In order to study the possibility of integrating the above concepts into a flood management system with an ability to be practically implemented the methodologies were applied using the Reno river basin as a case study.

The common experiment used the data from the flood event of November 25th 1990.

All the available elements were used in the experiment to simulate a real time flood forecast and flood impact analysis.

The results were remarkably encouraging, so much so that the River Reno authority has continued with the monitoring and is keen to start with a flow-up study. The WMO gave support and expressed considerable interest in AFORISM as was expressed by M. Kundzewicz whose address appears as the FOREWORD to the main report.

It is comforting and pleasing that the diverse organizations and individuals contributing to AFORISM were able to make a combined effort whose result was the realization of a practical tool from what started as a good idea.

ACKNOWLEDGEMENT

It is with gratitude that I wish to acknowledge the support, interest and cooperation of the following organizations and persons. It is only because of their collective commitment to the AFORISM project that what was a good idea became a workable reality:

- World Meteorological Organization

  for its continued interest and tacit support over the five years since the first AFORISM meeting;

- Regione Emilia Romagna
- Autorità di Bacino del Reno
- Presidenza del Consiglio dei Ministri - Servizio Idrografico e Mareografico

  for their collaboration and great interest in AFORISM and for supplying the data for the Reno test case;

- The raporteurs

  for their care in the selection of appropriate material and for making a meaningful mole-hill out of a potential mountain;

- The researchers and technical participants in the various areas which AFORISM addressed

  for their willing cooperation in turning research material into useful practical methodologies;

- Prof. Geoff Pegram

  for his personal support and dedication in taking responsibility for the editing of the final AFORISM document;

- Ms Dina Giuntoli

  for her selfless contribution, beyond what would normally be expected, in organizing the material, typing the many drafts as well as the final report and for physically putting together the figures and the pages in the right order.

I thank them all.

Prof. Ezio Todini
Bologna,
April, 1996.

CONTENTS

FOREWORD

Z. W. Kundzewicz (WMO) - Statement for the Opening Session of the final meeting of the AFORISM Project, Bologna, 9-10 June 1994

Let me start by conveying WMO's thanks for being invited to this meeting and the Organization's best wishes for its success. It is my pleasure to do this on behalf of Professor Obasi, the Secretary General of WMO and of Dr. Rodda, the Director of WMO's Hydrology and Water Resources Department, who is the senior water-man in the house.

WMO recognizes the enormous importance of the area of flood forecasting and flood mitigation. The Organization was very much involved in preparation of the World Conference on Disaster Reduction convened by the General Assembly of the United Nations in Yokohama in May this year. The conference clearly proved that the worldwide losses caused by natural disasters have been continuously growing throughout the last decades as measured by the material damage, the number of deaths, and the number of persons affected. The material losses reach now the level of 60 billion US$ a year. Among the natural disasters it is floods which are most devastating at the global scale. Floods hit both developing and developed countries in a very serious manner, as evidenced by the example of Mississippi - Missouri flood of 1993 causing the losses in the range between 15 and 20 billion US$. During the last three decades (1963-1992) Europe has suffered as much as ten floods with the number of deaths in excess of 100 per event, and four floods in which the number of affected people exceeded 1% of the national population (data from the Information Paper No. 4 for World Conference on Natural Disaster Reduction).

WMO has been invited and its representatives have attended two earlier working meetings of the AFORISM Project held in Grenoble and Newcastle upon Tyne, respectively. WMO is interested in the Project because of a long tradition of intercomparison projects in the Organization. As early as 1974 WMO successfully completed a project on the intercomparison of conceptual rainfall-runoff models used in operational hydrological forecasting. The aim of this first project had been to compile an inventory of such models and to compare their basic structure, data requirements, computational requirements and accuracy of simulation. Since the success of the first endeavour of this type WMO has conducted a number of further intercomparison exercises embracing such elements as models of snowmelt runoff, simulated real-time intercomparison of hydrological models, and methods for estimating areal evapotranspiration.

The idea of launching a project on the intercomparison of models using remotely sensed data and quantitative precipitation forecasts (QPFs) had been put forward by the WMO Workshop on Simulated Real-time Intercomparison of Hydrological Models, held in Vancouver in 1987. In 1989 this idea was endorsed by the Eighth Session of the WMO's Commission for Hydrology as being the natural sequel to the project on the simulated real-time operation of models. However, such a project was recognized as being far more complex than those which the Organization had carried out before. Its implementation was therefore delayed while the matter was considered in some detail. WMO recognize with interest that the spirit of the concept, which is undoubtedly much needed by the hydrological community, was adopted as the core of the AFORISM Project, and that this would extend the classical rainfall-runoff perspective of hydrologists.

The AFORISM project integrates a number of components: precipitation forecasting, rainfall-runoff modelling, flood routing, and a decision support system for real time flood management. This ambitious endeavour was conceived to fill the existing gaps between the disciplines involved, e.g. between meteorology and physics of the atmosphere on one side and hydrology, soil physics and engineering, on the other side, and also between science and decision making. In addition, the horizontal aggregation included intercomparison of the different approaches to rainfall-runoff modelling and their use within real time flood forecasting schemes.

The Ninth Session of the WMO's Commission for Hydrology, held in January 1993, decided that the WMO Secretariat should monitor the progress of the AFORISM project and advise the Tenth Session of the Commission of the results. In addition, the CHy Rapporteurs on Application of Remote Sensing, on Areal Modelling and Hydrological Forecasting, and on Precipitation Estimation and Forecasting, are to jointly review the results of the AFORISM Project and make recommendations to the forthcoming CHy-X on the need for further work. In effect, WMO applauds these who launched and have worked on AFORISM and has held back from undertaking any similar work so as not to interfere with the work of this Project and, above all, to avoid expensive duplication of effort.

We congratulate the project participants, and in particular its coordinator Professor Todini, on the choice of this important though difficult topic and on its execution which has led to the preparation of the project report. We believe that the project report will not be just shelved but that it will offer practical advice to regions and countries, who may benefit from the results. We also hope that the work in the project area will continue also after the termination of this project, thus contributing to the improvement of human preparedness for floods - the natural disaster which worldwide takes the highest toll of material losses and human suffering.

1. INTRODUCTION AND SUMMARY OF AFORISM

1.1 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 the 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 extremely simplified event models, through continuous lumped semi-distributed models to 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 Mentue (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 under the auspices of the World Meteorological Organization 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.

This final report edited by Prof. E. Todini, with the assistance of Prof. G. G. S. Pegram, describes all the research work that was caried out during the project which, for the sake of clarity, is divided into the following sections:

- Rainfall Modelling and Forecasting (Rapporteur P. E. O'Connell)
- Rainfall Runoff Modelling: Fundamentals and Process Representation (Rapporteur Ch. Obled)
- Rainfall Runoff Modelling: Operational Use (Rapporteur I. Nalbantis)

- Flood Routing: modelling and forecasting (Rapporteur P. Lamberti)

- Decision Support System (Rapporteur Ph. O'Kane)

- System Integration: the Reno River Cases Study (Rapporteur E. Todini).

The Report is briefly out-lined and summarized in the following sections of this introductory chapter.

1.2. 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 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 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^{o} 39' N, 11^{o} 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. The sections are intended to capture the ideas, not necessarily matching the chapter headings.

1.2.1 Hydro-Meteorological Data Acquisition Systems

Most hydro-meteorological data used in the project were provided by conventional data acquisition systems which are widely spread throughout 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 whose 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 coefficients A=500 and B=1.5 (Joss et al., 1970) 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. 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 (1981). Because this 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 was a field experiment performed in June 1990 (Buzzi et al., 1991). 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 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.

1.2.2 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) (Messinger, 1973, Black, 1988, Janjic, 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 in 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 the 2 month period, June 1990 and January 1991. The Reno flood event which 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 (Black, 1988) (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 (1991(a) and (b)), of the National Meteorological Centre (NMC) of the USA. 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 with baroclinic disturbances. In the AFORISM case, where intense precipitation forecasting is of particular importance, There is interest in also breeding 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 at 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.

1.2.3. 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 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 for calibrating the MTB model.

NTUA-DWR developed a scaling model for the temporal structure of univariatee (single gauge) 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 accumulated rain.

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

1.2.4 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 (Dunne, 1978 and Freeze, 1980). Many efforts have been made to schematise the whole process in order to develop mathematical models (Dooge, 1957 and 1993, Amorocho and Hurt, 1964, Freeze and Harlan, 1969 and Todini, 1989). 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 (Abbott et al., 1986a,b, Bathurst, 1986, Beven et al. 1987), and to the three-dimensional representation of all the exchanges (Binley et al., 1989). Taken together, these latter kinds of model comprise the broad category of distributed differential models (Todini, 1988); 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 (Beven, 1989). 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 (1965), from the early sixties a large number of these models came to light from the Stanford Watershed Model IV (Crawford and Linsley, 1966) to the SSARR (Rockwood and Nelson, 1966), the Sacramento (Burnash et al., 1973), the Tank (Sugawara et al., 1983), 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 by linking together process components which described physical concepts, on the assumption 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 need to be estimated on the basis of objective functions to be minimised (for example the sum of squares of deviations) which exercise generally leads 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 can not always be guaranteed (Sorooshian and Gupta, 1983).

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 dynamic variation, within the catchment, of the saturated areas extent. Indeed in recent years, a general consensus has been reached on the fact that it is this dynamic variation (a function of the accumulation and horizontal movement of the soil moisture storage (Franchini et al., 1996 and Todini, 1995)), which is mostly responsible for the highly non linear behaviour of catchment response to storm events. Most conceptual modelers tried to compensate for the inadequacy of their models by adding more and more process components as well as parameters but they failed to reproduce the actual phenomena and expanded 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. These conclusions were highlighted in the WMO (1975) inter-comparison of conceptual models 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 (Natale and Todini, 1977).

More recently, newly developed conceptual models have assumed the soil moisture replenishment, depletion and redistribution mechanisms to be directly responsible for the dynamic variation of the source areas contributing to direct runoff and consequently for 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 (1977) and in Moore and Clarke (1981), or the distribution of a topographical index, as in TOPMODEL (Beven and Kirkby, 1979). The advantage of these models lies in their capability of reproducing the phenomena with a smaller number of physically meaningful parameters (Franchini and Pacciani, 1991).

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 to small and medium-sized headwater basins. Among the models of this category were chosen those that have the common structure used in the Unit-Hydrograph modelling context, namely they comprise of a first part called the production function and a second part, the transfer function. The production function summarises all hydrologic processes involved in an idealised soil column representation 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 assumed to be reasonably linear thus satisfying the assumptions of the Unit Hydrograph. In a recent paper (Duban et al., 1993) 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 (Burnash et al., 1973), and the TANK model (Sugawara et al., 1983).

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. This report discusses the methodology used, precisely defines the variables, provides the detailed calculation procedures, illustrates the procedures with numerical examples performed by hand, defines the various modules with their functions, the input information and the output coming out of the modules and, finally, provides 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 (Abbott et al., 1986) 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 (Franchini et al., 1996). Both the TOPMODEL and the ARNO model were calibrated on the Reno river catchment and the results showed a slightly 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. 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 if values of parameters as measured in the field are used, however numerical fitting leads to satisfactory results. The analysis of the model objective function response surfaces indicates relatively flat optimum areas. This provides a certain robustness in the parameter estimation phase. TOPMODEL requires some improvements, especially a general transfer (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 transfer function approach was successfully adopted.

1.2.5 Flood Routing and Flood Plain Modelling

At times of impending or possible flooding, predicting the future behaviour of a river requires extrapolations in space and time. The circumstances at such times are difficult for decision makers because they are carrying a heavy responsibility in an emotionally charged crisis situation, where communications may be failing and loss of life is a possibility. In such a reality, accurate prediction is a great help in buying time to make decisions. A vital link in this prediction process is an efficient flood routing module which can calculate future flows and levels dowstream of an information gathering site in order to anticipate whether to advise civil defense personnel to increase their level of alertness.

The development of flood routing schemes has been tackled in the past mostly by hydraulic engineers who are 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; by contrast, in real-time applications, both computation time and stability of results become of the utmost importance.

On the other hand, hydrologists have proposed extremely simplified models, as storage routing (Puls, 1928 and Goodrich, 1931), Muskingum routing (McCarthy, 1938), Lag and K routing (Linsley et al., 1949), Kalinin and Miljukov (1958) routing, linear reservoir and channel cascade routing (Maddaus, 1969), 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.

In the line of the comprehensive and detailed description of flood routing procedures which can be found in Fread (1985), 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) (Todini and Bossi, 1987 and Todini, 1991) 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 reach 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 damage of flooding, 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 (Cunge et al., 1980). 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. (1985), 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. (1991) and Katopodes (1980, 1984).

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. (1995) a mixed 1/2-D model, also described in Todini and Venutelli, 1991, was used for verifying the design of the Montalto di Castro Power Plant. The scope of the research at UNIBO-ICI was concentrated on 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 (Di Gianmarco et al., 1995) (originally introduced in heat transfer and flow in porous media calculations (Patankar, 1980)), which allows for conservation of mass and energy at the global as well as at the local scale.

1.2.6 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 from his/her decisions. This can be done by providing the Decision Maker with a Decision Support tool that allows him/her to rank the different alternatives in stead of finding 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 optimal control whereby the expected path taken by the upstream Reno through its state space is computed, given the non-stationary transition probability matrix. From the pilot version of this optimisation scheme, those controls which modify the upstream flow as it passes through the barrier are found which minimise flood damage downstream.

1.2.7 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 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 lines 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, so that it is capable of handling structural patterns of topography such as roads (break lines) and surface depressions where water remains stagnant. The model is then 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 (Di Gianmarco et al., 1994).

1.2.8 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 investigation has started in order to assess the capabilities of the system, which allows for real time control actions.

1.2.9 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 digitisation. After digitisation the data were checked and validated by comparison with the original graphs; in addition the recorded data were sampled at one hour sampling intervals 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, which at the time were the only major floods on record available for this study. The fitting was 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 reality, 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 also discretized into meaningful classes, and these have been also distributed accordingly over the grid elements . The grid has 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 simulated. 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 for simple models (thus avoiding the complex distributed physically based ones). In addition, due to the difficulty of estimating the initial soil moisture conditions and given the availability of continuously recorded real time data, continuous type models were chosen. The ARNO model and the TOPMODEL, were 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 relates to the more uniform performance of the model during verification periods. The second relates to the fact that the ARNO model is already imbedded in 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, now 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 the PAB flood routing scheme;
- Display of the flood levels in comparison with dike elevation.

Calibration of the ARNO rainfall-runoff model on the Reno river was successfully obtained by using the historical record (1990-1991). In order to perfom the calibration, 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, showed up 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, which was due to a dike failure in order to compare the results with recorded data. The model, which is based upon the Integrated Finite Difference approach, was originally developed at UNIBO-ICI. Within the frame of AFORISM, in collaboration with EPFL-IATE, the package was then modified in order to allow for inclusion of breaklines (such as dikes, roads etc), as well as 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.

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 a 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.

1.3 DISCUSSION OF THE 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, (whose remarks appear in the foreword to this report) 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 disciplines that must confront themselves with the problem of flood forecasting and warning.

First of all it gave the possibility of analysing indepth the most important features to be retained in a real time rainfall-runoff flood forecasting model, which have now been identified as 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 with the high credibility and reputation gained by the group among the Regional, National and 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.

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.

1.4 CONCLUSIONS AND RECOMMENDATIONS

AFORISM has been 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. However 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. In addition, the user should have access to geo-related documentation tools making available information on manpower and materials, on administrative and legal boundaries and on the people in charge.

Finally, given the increasing interest of the public in participating in making decisions that involve the essential safety and quality of life, it was thought essential to analyse the socio-economical impact and the public acceptance of flood risk mitigation plans as well as the implementation of flood warning dissemination schemes.

These points become, in essence, the objectives of a new round of research in which all the contributors to AFORISM wish to participate and are eager to address.

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2. RAINFALL MODELLING AND FORECASTING

2.1 INTRODUCTION

The past decade has seen a major upsurge in research on rainfall estimation, modelling and forecasting on space-time scales of interest to hydrologists engaged in real-time flood forecasting. The spectrum of research activity has been broad, and ranges from developments in the dynamic modelling of rainfall using mesoscale atmospheric models to advances in the stochastic modelling of rainfall in space and time. No attempt is made here to review the extensive literature describing this research; for this, the reader is referred to excellent reviews by Foufoula-Georgiou and Georgakakos (1991), Georgakakos and Foufoula-Georgiou (1991) and Foufoula-Georgiou and Krajewski (1995). However, some comments on contemporary research activity relevant to AFORISM research in this field are included, to place the latter work in context.

The classical deterministic approach to weather/rainfall forecasting is through a dynamic numerical model based on a set of partial differential equations describing the conservation of mass, momentum and energy in the atmosphere. Applied on a global scale, such models do not have anything like the required spatial resolution for hydrological (and other) applications, and so much recent effort has been devoted to the development, testing and comparison of limited area models (LAMs). These models are typically applied to mesoscale areas and derive their time dependent boundary conditions from a previously integrated global atmospheric model. Examples of such models are the Colorado State University - Regional Atmospheric Modelling System (CSU-RAMS), the National Centre for Atmospheric Research - Mesoscale Model Version 5 (NCR-NM5) model, and the University of Bologna limited area model (LAMBO) employed within AFORISM which is based on the University of Belgrade/NOAA-National Meteorological Centre of Washington model. Such models typically need convective parameterization schemes which are the subject of continuous research efforts (see Molinari and Dudek, 1992 for a review), since they exercise a major influence on the predicted timing, location and amount of precipitation.

Although the ability of such models to produce accurate simulations of rainfall on the scales of interest is limited, several applications of such models to a variety of hydrometeorological problems have been reported in the literature (Foufoula Georgiou and Krajewski, 1995). Moreover, major advances in workstation technology and communication systems enhance the prospects for real-time applications to quantitative precipitation forecasting (Cotton et al, 1994). However, as observed by Foufoula Georgiou and Krajewski (1995), the performance of such models in this role remains largely unknown. The work carried out in AFORISM with the LAMBO model is thus timely and addresses two important questions: (i) can increasing spatial resolution in the model lead to better forecasts and (ii) can the model be used to produce an ensemble of forecasts reflecting forecast uncertainty? These questions are explored within the framework of a case study for the Reno basin (Section 2.2).

In the absence of a well proven, operationally feasible, LAM modelling approach at the present time, alternative approaches are needed to meet the current need to extend the lead-time of flood and flash-flood forecasts. One interesting approach in this regard is to couple dynamic hydrological and meteorological model components at the catchment scale within a state estimation framework (Georgakakos, 1986a, b; 1987). Such models may be classified as stochastic dynamic models where the conservation of mass couples the two model components through both the dynamic model equations and state estimator feedback. The importance of coupling and the worth of various types of hydrometeorological data in flood forecasting have been demonstrated as a function of the ratio of forecast lead time to basin response time (Georgakakos and Foufoula-Georgiou, 1991). Improvements in short term quantitative precipitation forecasting using an enhanced stochastic dynamic model are discussed by Lee and Georgakakos (1992). This approach has not been applied within AFORISM, but is mentioned here as an important area for future development.

The stochastic modelling of rainfall in space and time has also seen important developments within the past decade. Early work on the use of point process models to describe the temporal structure of rainfall at a point (e.g. Rodriguez Iturbe et al, 1987) has given way to scaling approaches which seek to describe the spatial statistical structure of rainfall over a wide variety of scales with relatively few parameters. Scale invariance implies that small and large scale statistical properties are related to each other by a scale changing operator involving only the scale ratio. Developments in this field are reviewed by Foufoula-Georgiou and Krajewski (1995) who note that the current state-of-the art in scale invariant rainfall models revolves around multiplicative cascades which have their origin in the statistical theory of turbulence. Various methods of parameter estimation and multifractal field analysis and simulation have been developed based on this approach (e.g. Gupta and Waymire, 1993; Over and Gupta, 1994; Kumar and Foufoula-Georgiou, 1993 a, b). However, such models are still in the realm of theoretical development and their practical application would appear to be some way off.

Given the current state-of-the-art of stochastic modelling, one of the questions which AFORISM has sought to explore is whether or not ensemble or scenario forecasts from such models might prove useful in extending the lead time of flood forecasts from a rainfall runoff model. Existing empirical rainfall forecasting procedures are often very crude (e.g. assuming that future rainfall will replicate that observed in recent time periods). They may also involve the selection "analogue" of rainfall sequences from observed past events, but it is never clear which part of the past event should be used as an acceptable `forecast' of the current event. They are sometimes based on statistics extracted from past data (e.g. Schultz, 1994) but, in this case, the quantile curves do not display anything like the temporal variability of the actual rainfall.

The most straightforward and well developed area of stochastic rainfall modelling is for temporal rainfall at a point: this univariate modelling approach should also be applicable to rainfall averaged over an area. Rainfall runoff models with spatially averaged rainfall inputs have been found to perform well in many real-time flood forecasting systems, providing some justification for a univariate approach. Two different univariate approaches are employed in AFORISM: a renewal process model and a scaling model of a storm hyetograph which assumes scale invariance in the time domain. Ensemble forecasting procedures are developed for both approaches which involve conditioning on rainfall observed up to the current time point (Section 2.3.1).

As catchment areas increase, the assumption of spatial averaging of rainfall becomes more questionable, and so it may be necessary to employ a multivariate approach in which rainfall is modelled at several points (or for several sub-catchments), which would involve reproducing the cross-correlation as well as the temporal structure of point rainfall. Alternatively, a multi-dimensional rainfall field model could be employed to characterize rainfall at all points in the catchment domain, not just those where measurements exist. However, such models are not easy to parameterize, and the necessary data are frequently not available. Although radar data are normally required to parameterize a rainfall field model, the possibility of doing so using data from a relatively dense network of raingauges is explored in Chapter 3.

A key question impinging on the choice of stochastic model concerns the level of spatial averaging of rainfall inputs to a flood forecasting model that can be tolerated before a significant loss of forecast accuracy results. To gain some insight into this issue, simulation experiments with the rainfall field model and a physically-based distributed model are conducted in Chapter 3.

2.2 DETERMINISTIC RAINFALL MODELLING AND FORECASTING

In modern weather prediction practice it has long been accepted that the most successful method to predict quantitative rainfall on time scales from 12 to 36 hours or more (as opposed to predicting the probability of the rainfall event) is to use numerical limited area weather prediction models (LAMs) based on the primitive equations and complemented by suitable parametrizations of moist processes. Such LAMs are usually scaled versions of the same model codes used to produce global forecasts on the same timescales, but integrated not on the entire globe but on limited portions of it. This allows much higher horizontal resolutions to be used, resulting hopefully in much improved local forecasts. LAMs use as lateral time-dependent boundary conditions (made necessary by their limited spatial domain) the results of previously integrated global forecasts usually available, however, on much coarser horizontal grids than those used by LAMs. The production of rainfall in LAMs is normally the task of the so-called physical parametrizations, and in particular of deep convection and large-scale rainfall parametrizations, each attempting to model the rainfall produced by different physical processes. Here, the LAM used for the AFORISM project is described briefly, followed by a review of the results of the experiments carried out with the LAM. Additionally, the attempt to generate an ensemble of forecasts of precipitation (and thereby introducing a stochastic element into the otherwise purely deterministic LAM forecasts) is then described and the results compared with those of the single deterministic forecast.

2.2.1 The Limited Area Model used in AFORISM

The meteorological limited area model employed in the AFORISM project (and used by both SMR-ER and by UNIBO-ADGB) is a grid-point primitive equations model, originally developed in its older adiabatic form in Belgrade (during the early seventies) as a co-operative 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 developed and 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) (Mesinger et al,1988; Black, 1988; Janjic, 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 model used for AFORISM is the version dated 1989, further upgraded in some parts of the physical parameterization schemes, with a new radiation code (from Meteo France: Ritter and Geleyn, 1992) and completely reformulated in its pre- and post-processing sections. This model has also been operational at the SMR-ERSA since September 1993, and is referred to as LAMBO (Limited Area Model Bologna).

As already mentioned, LAMBO is a grid-point, primitive equations limited-area model. In such models the only basic approximation, well justified by the scale analysis of the vertical component of the momentum equation, is the hydrostatic approximation, which assumes pressure at any point is simply equal to the weight of the unit cross-section column of air above that point. 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 (separately for dry air and moisture) and using the law of ideal gases. Such a set of seven scalar differential equations in the seven field unknowns u,v,w,T,ρ,q (or combinations of them) constitute the initial and boundary value problem, the solution of which provides the future state of the atmosphere. The precise final mathematical form of the set of equations used by the model is closely related to the choice of vertical co-ordinate.

The equations of motion are solved in practice using finite difference methods and all model variables are defined on the so-called Arakawa E-type grid. Particular numerical schemes were developed to integrate on the E-grid the parts of the equations related to adiabatic processes and precisely to horizontal advection (Janjic, 1984) and geostrophic adjustment (Mesinger, 1973; Janjic, 1979).

The SMR/ERSA version of the ETA model has a full complement of physical parameterizations. Parameterizations are modules of the model code which attempt to represent the effects on model prognostic (dependent) variables of those processes which cannot be explicitly resolved during model integration, principally because they would need much higher (sometimes, as in the case of radiative exchanges, almost infinite) spatial resolution. Such processes include, in general, moist processes, vertical turbulent exchanges, radiative exchanges (including cloud-radiation interaction), lateral diffusion, surface exchanges of moisture, heat and momentum, mountain-generated gravity wave drag, and so on.

Vertical turbulent exchanges of heat, moisture and momentum are parametrized in LAMBO using the Mellor-Yamada closure schemes, levels 2.5 and 2, respectively, for the Boundary Layer and Surface Layer (Mellor and Yamada, 1974). Usually, the surface layer is treated with a theoretically simpler first-order closure scheme based on the Monin-Obukhov similarity theory, which is assumed to be valid within the first few tens of meters nearest to the ground. Since when using the eta vertical co-ordinate (the so-called step-mountains) the depth of the lowest layer near the ground is not constant but depends on terrain elevation; over mountains, the theoretical requirements for this type of closure to be justified are not satisfied and another approach (e.g. that of Mellor and Yamada, 1974) becomes necessary.

Precipitation is parametrized as that which is of large scale (stratiform) and that which is of convective origin. The large scale precipitation scheme is quite conventional and, layer by layer, condensation occurs when relative humidity exceeds a predetermined threshold (usually set at a value somewhat lower than 100%), in order to allow partial cloudiness over the grid box. In this version of the model this threshold is set to 95%. In addition to the process of condensation, the precipitating water is allowed to evaporate in unsaturated underlying layers up to their saturation value or until all of the precipitating water is evaporated.

Deep (precipitating) and shallow (non precipitating) convection is parametrized using the Betts and Miller (1986) scheme. This method is based on the simultaneous adjustment of temperature and moisture vertical profiles of the unstable atmosphere toward observed reference profiles. Such adjustment occurs during a pre-determined relaxation period; in our case this period has been set equal to approximately thirty minutes. Two different reference thermodynamic profiles are used for shallow and deep convection, together with different energy integral constraints. For the shallow convection, the scheme constrains the vertical integral of sensible heat and moist static energy to be constant during the adjustment process; for deep convection the same constraint is applied to total enthalpy (Lazic and Telenta, 1990).

Radiation was originally parametrized using the NMC version of the GLAS radiation scheme (Harshvardhan and Corsetti, 1984). During the last year of the AFORISM project, a new radiation package from Meteo France has been implemented into the model on the grounds of a combination of performance, economy of integration resources and simplicity of formulation (Ritter and Geleyn, 1992).

The model includes also fourth-order non-linear horizontal (lateral) diffusion, with the diffusion coefficient dependent on flow deformation and on the level of turbulent kinetic energy. The exchanges of mass, energy and momentum between the lower-most atmospheric model level and the underlying surface are parametrized using a simple two-layer soil model.

2.2.2 Rainfall Forecasting

Quantitative precipitation forecasting (QPF) is considered to be amongst the most difficult tasks to be performed by a limited area forecasting model. The very small spatial scale (at the limit of horizontal model resolution) on which precipitation processes tend to organize themselves make it very difficult for the model dynamics to interact correctly with parametrized local convective processes so to correctly generate and evolve such organized structures. Here, the performance of the LAM in producing local QPFs is first analyzed through a series of single, purely deterministic forecasts of increasing horizontal resolution. An attempt is then made to quantify possible improvements in such QPFs by considering small ensembles of forecasts starting from (supposedly) equiprobable initial conditions (the technique of Ensemble Forecasting).

2.2.2.1 Deterministic Forecasts

This forecast experiment has been performed from initial conditions of 24.11.1990 at 12GMT in an attempt to predict the intense precipitation which occurred mostly during the 25th of November over the catchment basin of the Reno river in the Emilia Romagna region of Northern Italy. This case has been extensively described from a hydrological point of view elsewhere in this report and only a brief synoptic account of the meteorological development of the event is given here.

Synoptic description of the case study

The European Center for Medium-Range Weather Forecasts (ECMWF) analysis of 25 November 1990 at 12 GMT shows a trough over France with a geopotential height minimum of 850hPa located north of the Alpine mountains (see Fig. 2.1a). The frontal system is clearly evident in the Meteosat image of 10.30 GMT (see Fig. 2.1b), with the warm front crossing the Tirrenian Sea and the Apennine chain. This strong meridional advection induced very intense rainfall over Northern Italy, in particular in the Tuscany Region (upwind of the Apennine chain) and in the Lombardia Region (upwind of the Alpine chain), as can be inferred by consulting the relevant Synop messages (see Fig. 2.2 for observed synoptic network precipitation data; panel 2.2a shows precipitation collected in the 12 hours from 891024 18GMT to 891025 06GMT, panel 2.2b shows precipitation collected from 891025 06GMT to 891025 18GMT).

Regarding the Reno River basin in particular, the largest rainfall amounts occurred in the mountain area, where some stations of the National Hydrographic Service recorded more than 280 mm of rainfall in 36 hours, while the rainfall in the plain land area was generally less than 30 mm during the same period (see Table 2.1 and Fig. 2.3). 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 November. In the late afternoon of the 25th November a severe flood was recorded in the mountain town of Porretta and its neighbouring areas.

Station Code	Height m	Precipitation mm	Station Code	Height m	Precipitation mm
1	741	240	25	51	22
2	1043	283	26	340	79
3	627	155	27	841	86
4	806	213	28	187	35
5	1100	69	29	276	18
6	480	181	30	177	32
7	349	133	31	286	0
8	915	233	32	871	0
9	640	216	33	422	145
10	804	98	34	741	128
11	890	166	35	845	8
12	710	237	36	165	32
13	500	142	37	658	72
14	240	82	38	195	27
15	195	63	39	73	6
16	850	144	64		9
17	830	211	65		20
18	747	0	66		11
19	620	70	67		74
20	130	34	68		26
21	727	61	69		0
22	596	60	70		12
23	317	43	71		27
24	286	28	72		22

Table 2.1 List of rainfall recording stations in the Reno river basin (also shown in Fig. 2.3), with rainfall accumulated over the 36 hours period from 90/11/24 12GMT to 90/11/26 00GMT

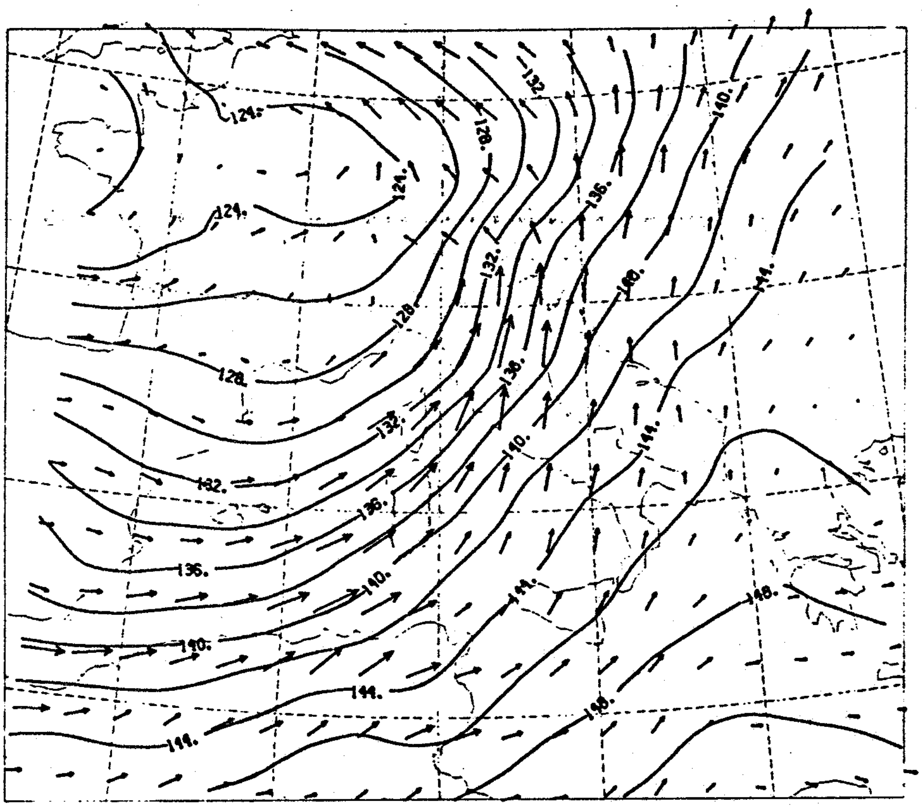


Figure 2.1a - ECMWF analysis at 25.11.90.12GMT of 850 hPa geopotential height and wind; isolines every two decameters

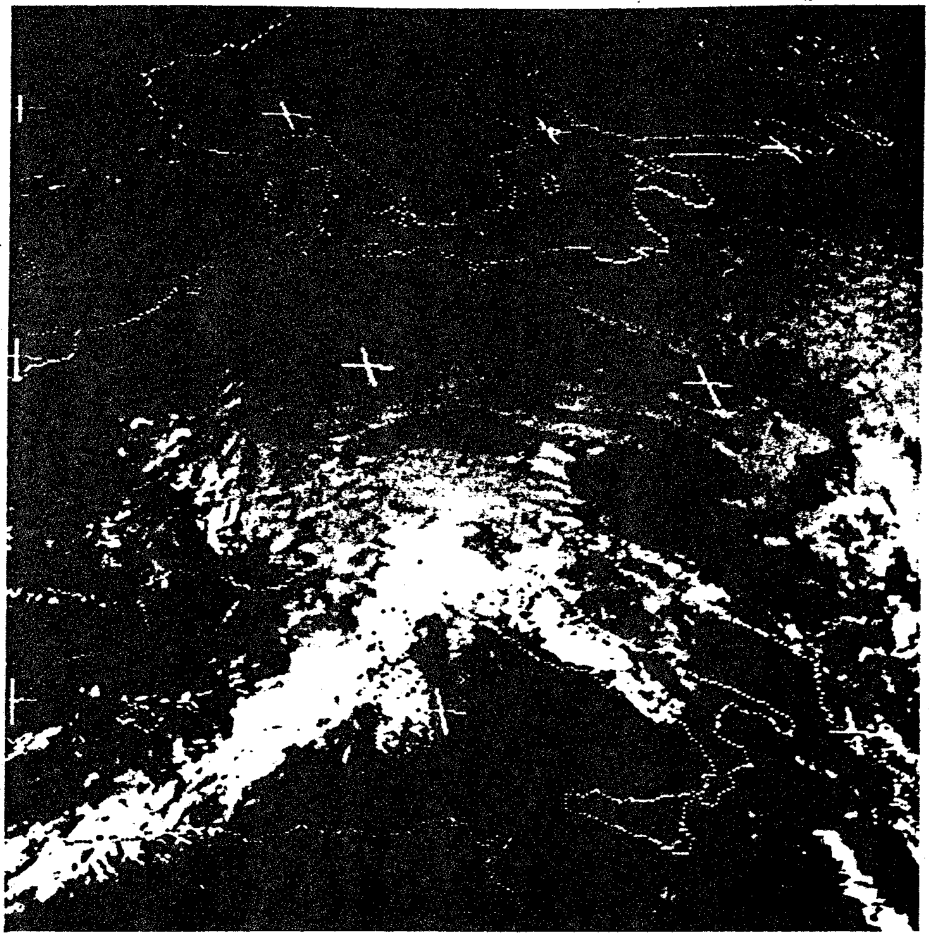


Figure 2.1b - Meteosat image in the visible channel of 25.11.90 at 10.30 GMT.

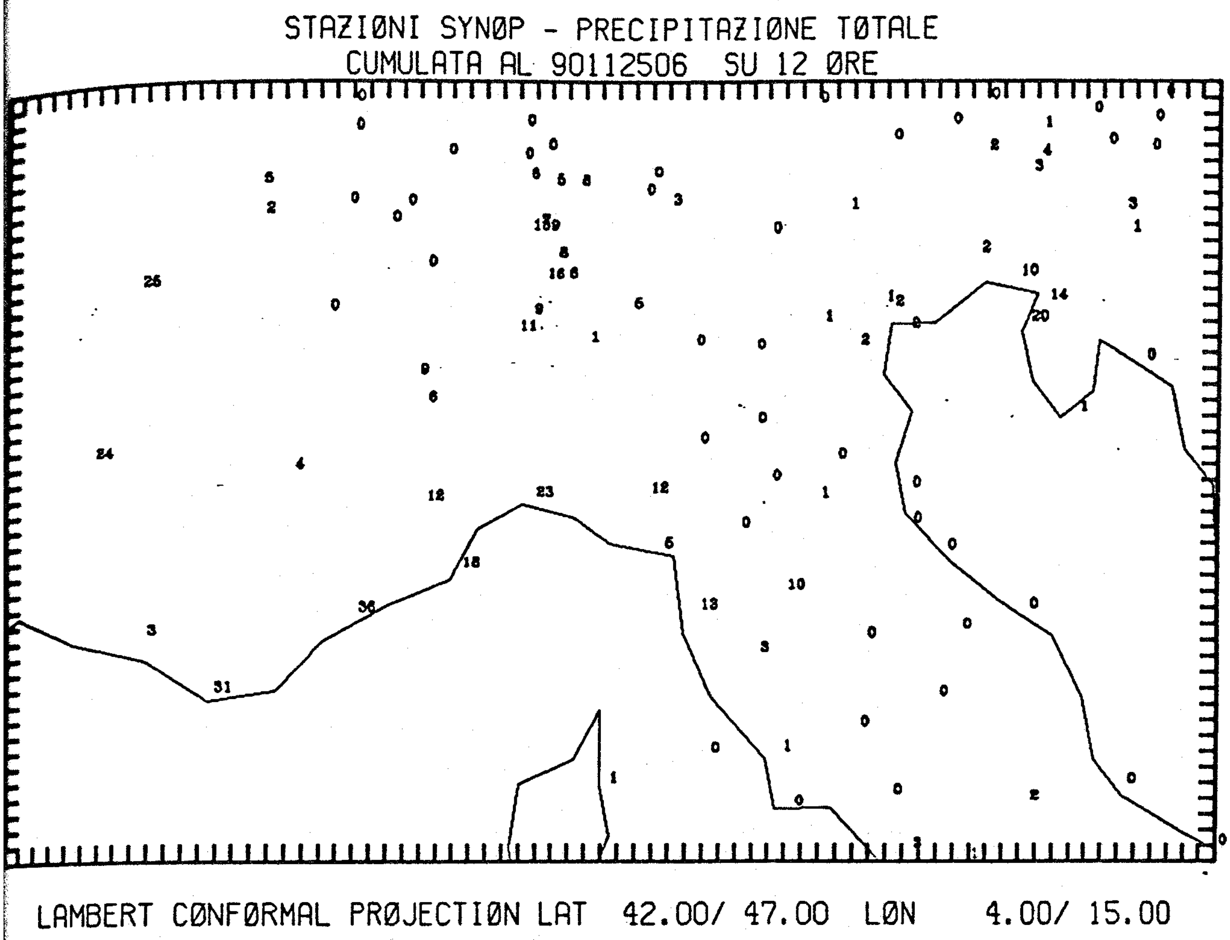


Figure 2.2a - Observed 12 hour accumulated precipitation from 24.11.90.18GMT to 25.11.90.06GMT.

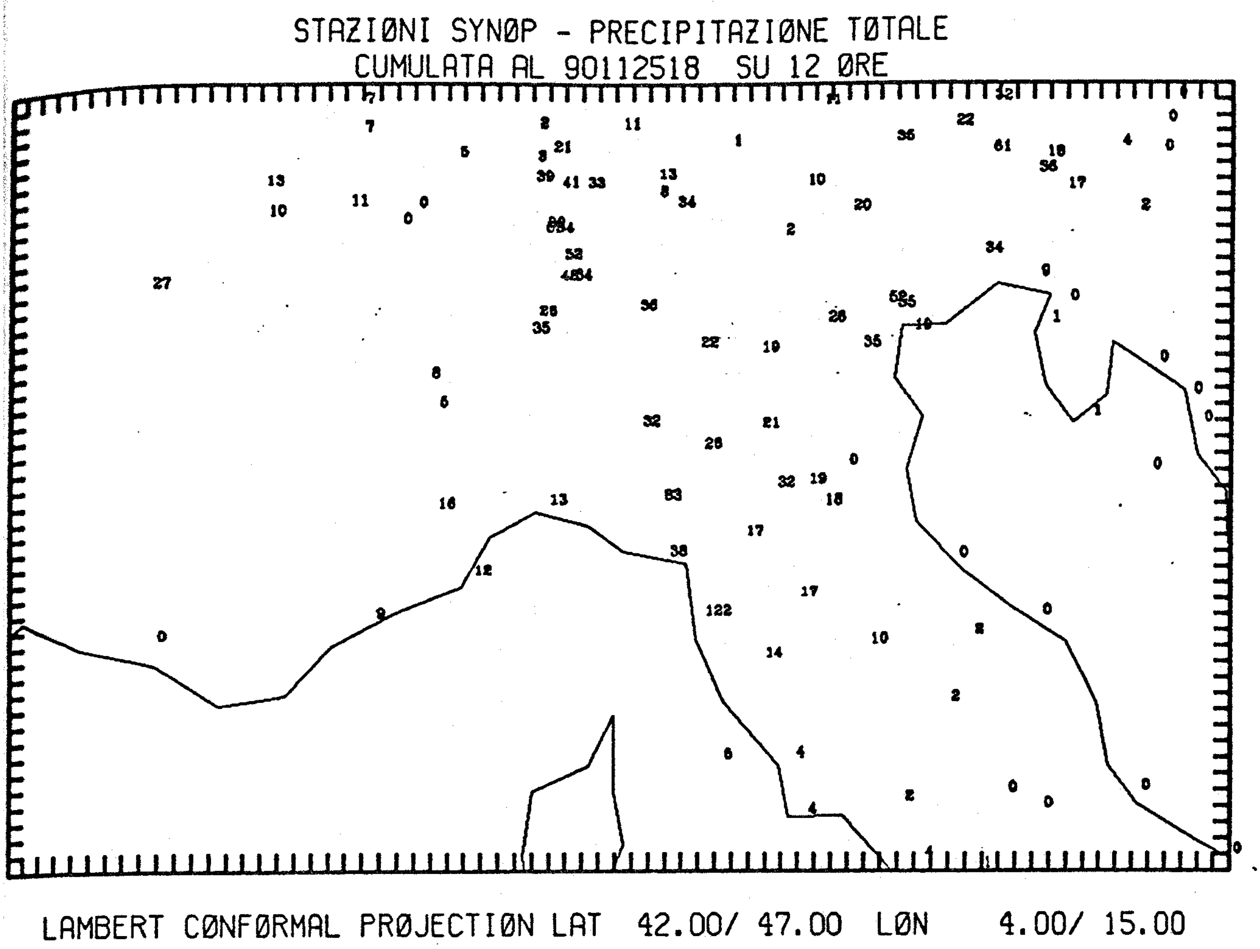


Figure 2.2b - Observed 12 hour accumulated precipitation from 25.11.90.06GMT to 25.11.90.18GMT.

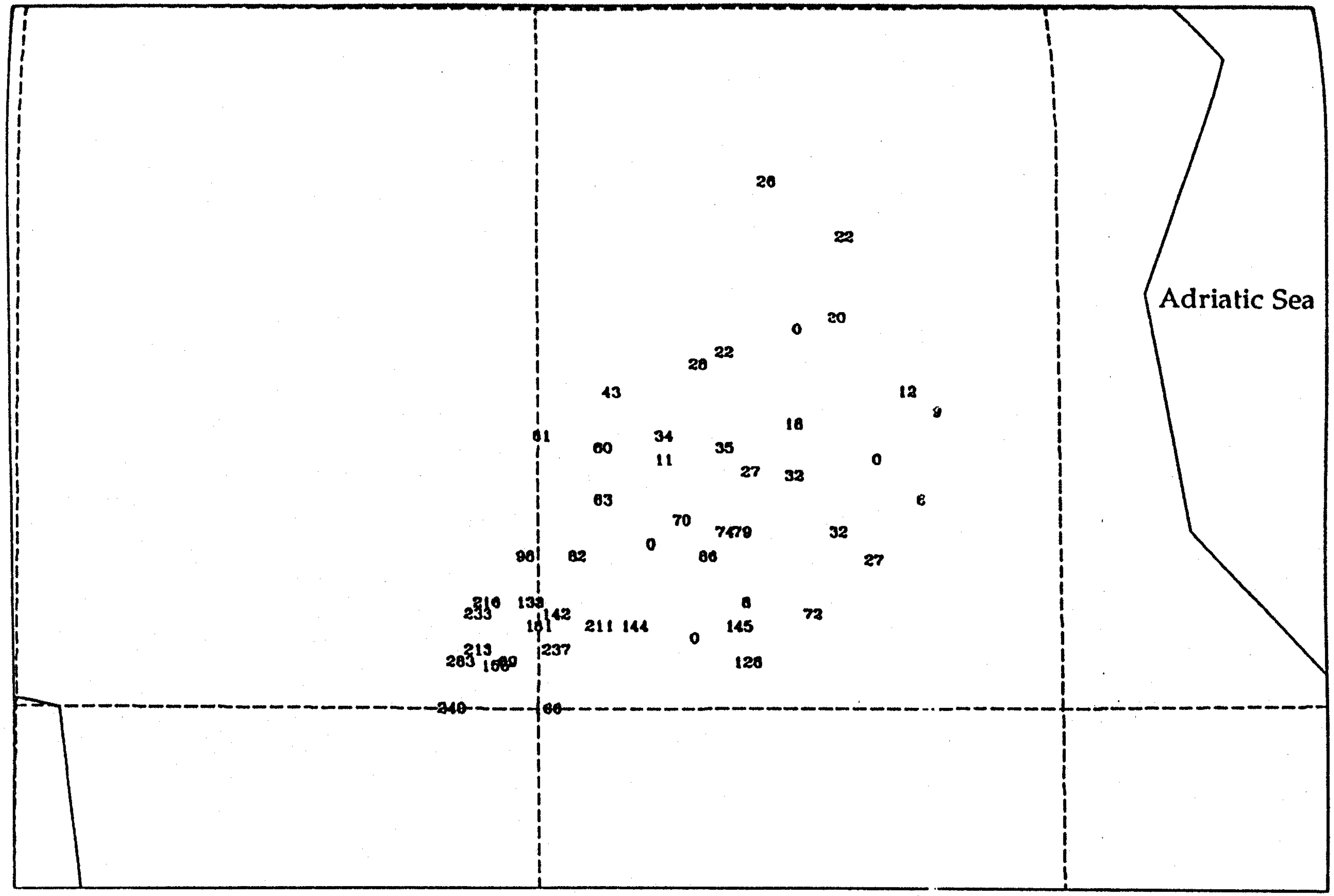


Figure 2.3 - Total precipitation accumulated over the period 24.11.90.12GMT to 26.11.90.00GMT at the raingauges of the National Hydrographic Service network within the Reno river Basin (see black dots in panels of Figure 2.4 for geographical location).

Analysis of modelling results

A considerable proportion of any limited area modelling effort directed toward quantitative precipitation forecasting usually goes towards the identification of the optimal configuration of the LAM to be used for forecasting, in particular as far as the QPF quality is concerned. In AFORISM this has been achieved by means of a systematic statistical verification of the daily LAM forecast performance over the entire one-month period of June 1990 (Pelosini and Paccagnella, 1993; Paccagnella and Pelosini, 1993). This month was chosen because of the MATREP co-ordinated data collection campaign which took place in the North Italian region in the same period (Buzzi, Morgan and Tibaldi, 1991).

This extensive model verification effort, which was further extended to a second one-month period (January 1991), highlighted some model problems, affecting particularly the forecast of surface parameters. For this reason, some model code development became necessary, particularly in relation to the parametrization of radiative processes and to the turbulent exchanges closure scheme and vertical diffusion. As a consequence of this, a new radiation package from Meteo France (Ritter and Geleyn, 1992) was implemented and calibrated and the surface exchange scheme was updated to the more recent 1993 version used by the NMC operational Limited Area Model. As a consequence of such modifications, the model (which was in principle built to be easily integrated using both ETA and SIGMA vertical co-ordinates) had to be integrated only using sigma vertical co-ordinates. All runs reported here (which necessarily refer to the third year of activity) have therefore been performed using sigma as vertical co-ordinate only.

After the preliminary base work of optimizing the general LAM configuration, the main task of the deterministic QPF experimentation work has been performed by integrating the model at different horizontal and vertical resolutions to evaluate the impact of resolution on QPF values. The model was integrated three times for 36 hours, starting from initial conditions of 24/11/90 at 12 GMT, in the following different model configurations:

ExpLR (Low resolution experiment):

horizontal resolution:	.25x.25 degrees in rotated co-ordinates (equivalent to about 40 Km resolution)
vertical resolution:	20 vertical levels in sigma co-ordinates
time step:	120 sec
initial conditions:	ECMWF objective analyses, 24.11.1990 12GMT
boundary conditions:	ECMWF operational forecasts; updating every time step by interpolating in time, ECMWF forecast available every 12 hours.

ExpHR (High Resolution experiment):

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

ExpVHR (Very High Resolution experiment):

horizontal resolution:	.0625 x.0625 degrees in rotated co-ordinates (equivalent to about 10 Km resolution)
vertical resolution:	32 vertical levels in sigma co-ordinates
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 both very similar to the operational configuration of SMR/ER (Paccagnella, 1994).

The most evident and important conclusion emerging from the comparison between all these experiments is the large impact of horizontal and vertical model resolution on forecasted precipitation pattern. The precipitation field produced by progressively higher resolution experiments is increasingly more structured and the absolute values of precipitation maxima are measurably enhanced and nearer to observations (Fig.2.4a and 2.4b).

In particular, in the Appennine and Po-Valley region, the increase in horizontal resolution produces an increase in the upwind (presumably mountain-induced) 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. This is also, to a lesser degree, as observed.

A closer look at Fig. 2.4c reveals that the Reno river basin observational network (black dots) is located right on the boundary of the largest model precipitation feature. This fact alone makes the evaluation of the model QPF in comparison to the observed precipitation as perceived by the Reno river basin network, an exceedingly sensitive operation, sensitive, that is, to the exact area used for space averaging. This is unfortunate and is a factor which penalizes the evaluation of the model performance.

2.2.2.2. Ensemble Forecasts

The purpose of producing an ensemble of forecasts is twofold: firstly, it is hoped that the ensemble mean forecast will provide a better forecast that a single, purely deterministic, integration. Secondly, the internal spread within the ensemble could provide an a priori measure of the uncertainty of the forecast (a so-called forecast of the forecast skill). However, the existence of this latter relationship, so far investigated only in a global forecast context, has often been questioned, and an exploration of its existence in the context of limited area QPF was one of the purposes of this part of the AFORISM project.

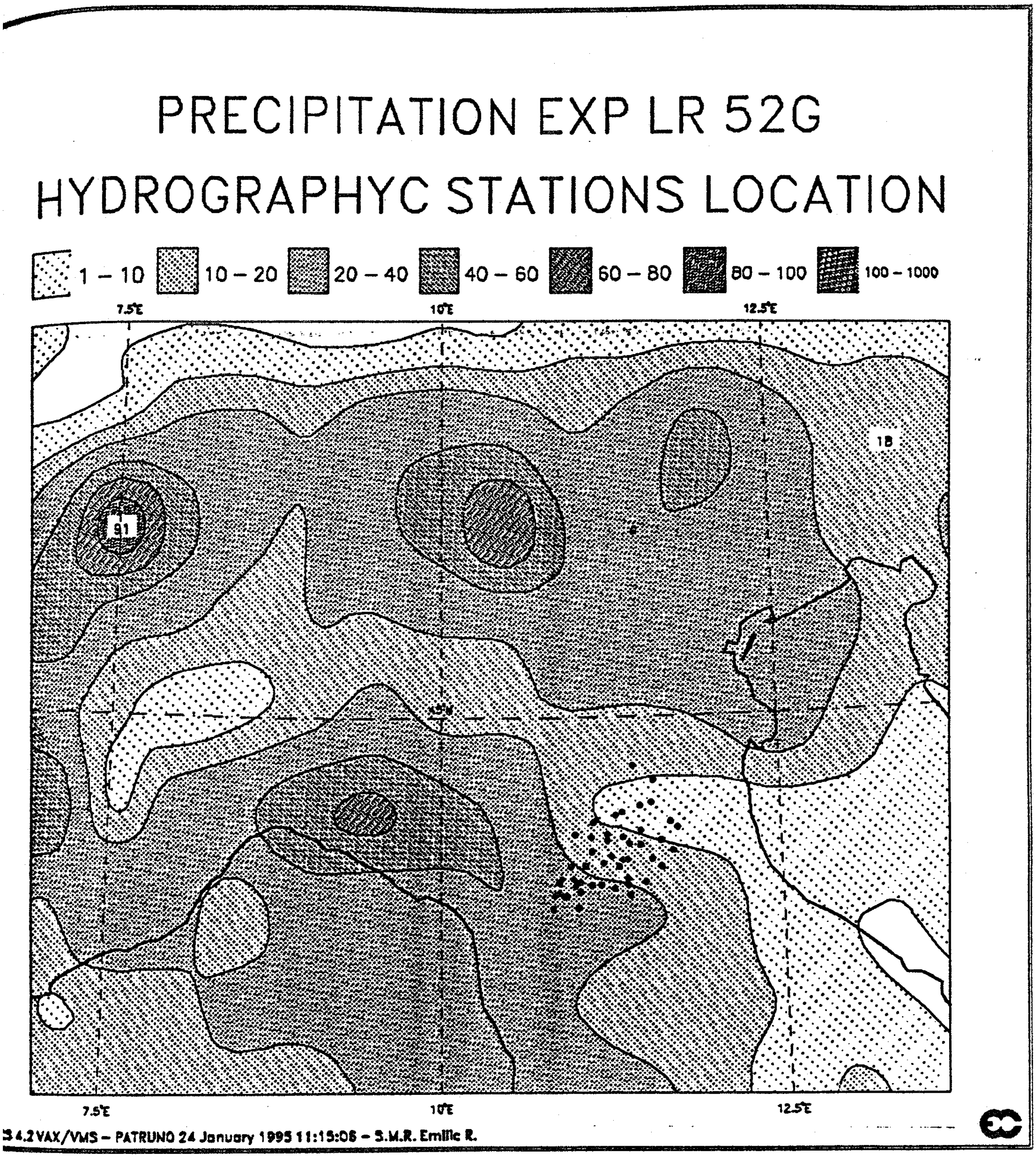


Figure 2.4a - Total precipitation accumulated during the 36 hours of model integration for expLR. Black dots indicate the Reno-river station network of the National Hydrographic Service.

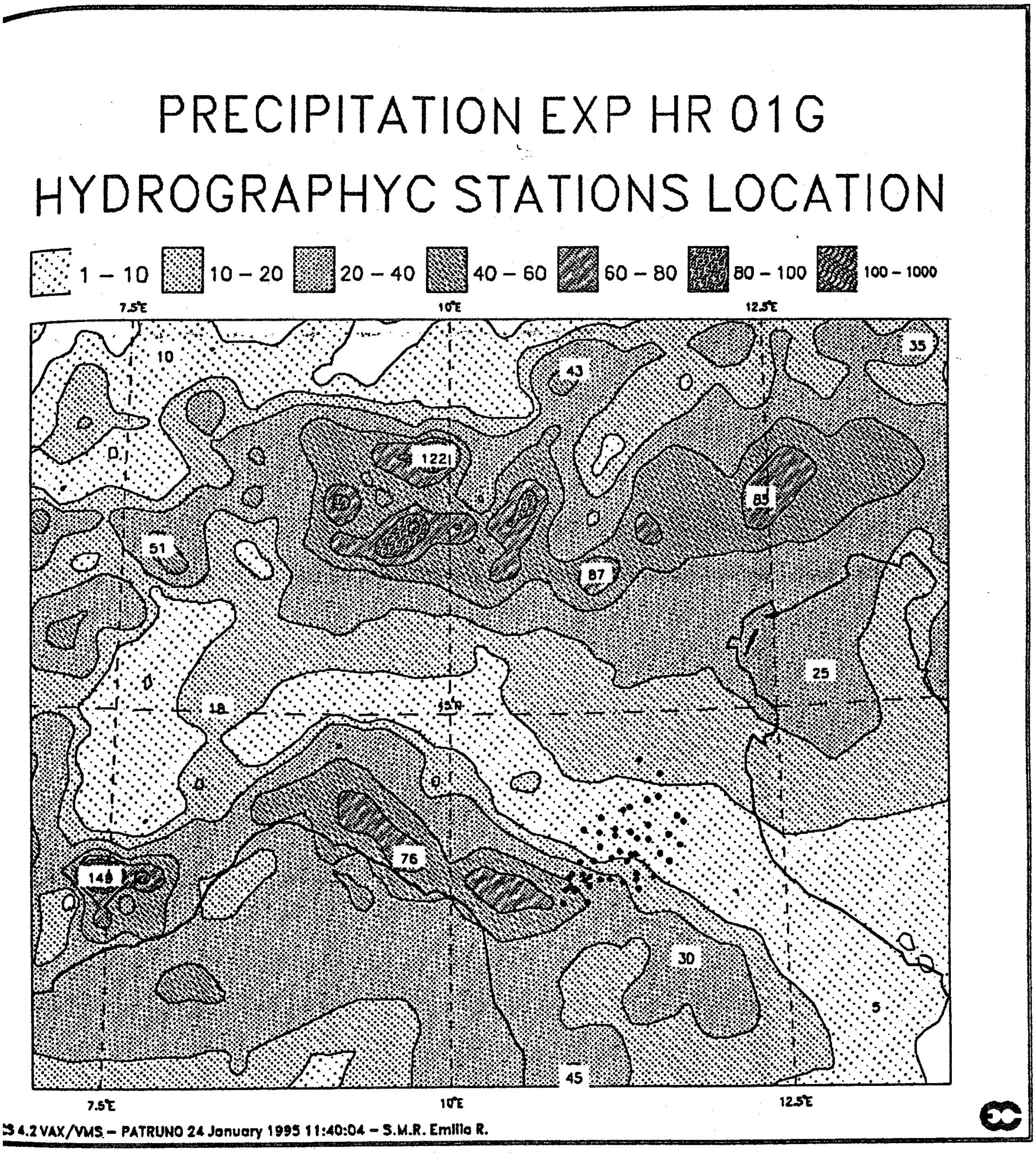


Figure 2.4b - Total precipitation accumulated during the 36 hours of model integration for expHR. Black dots indicate the Reno-river station network of the National Hydrographic Service.

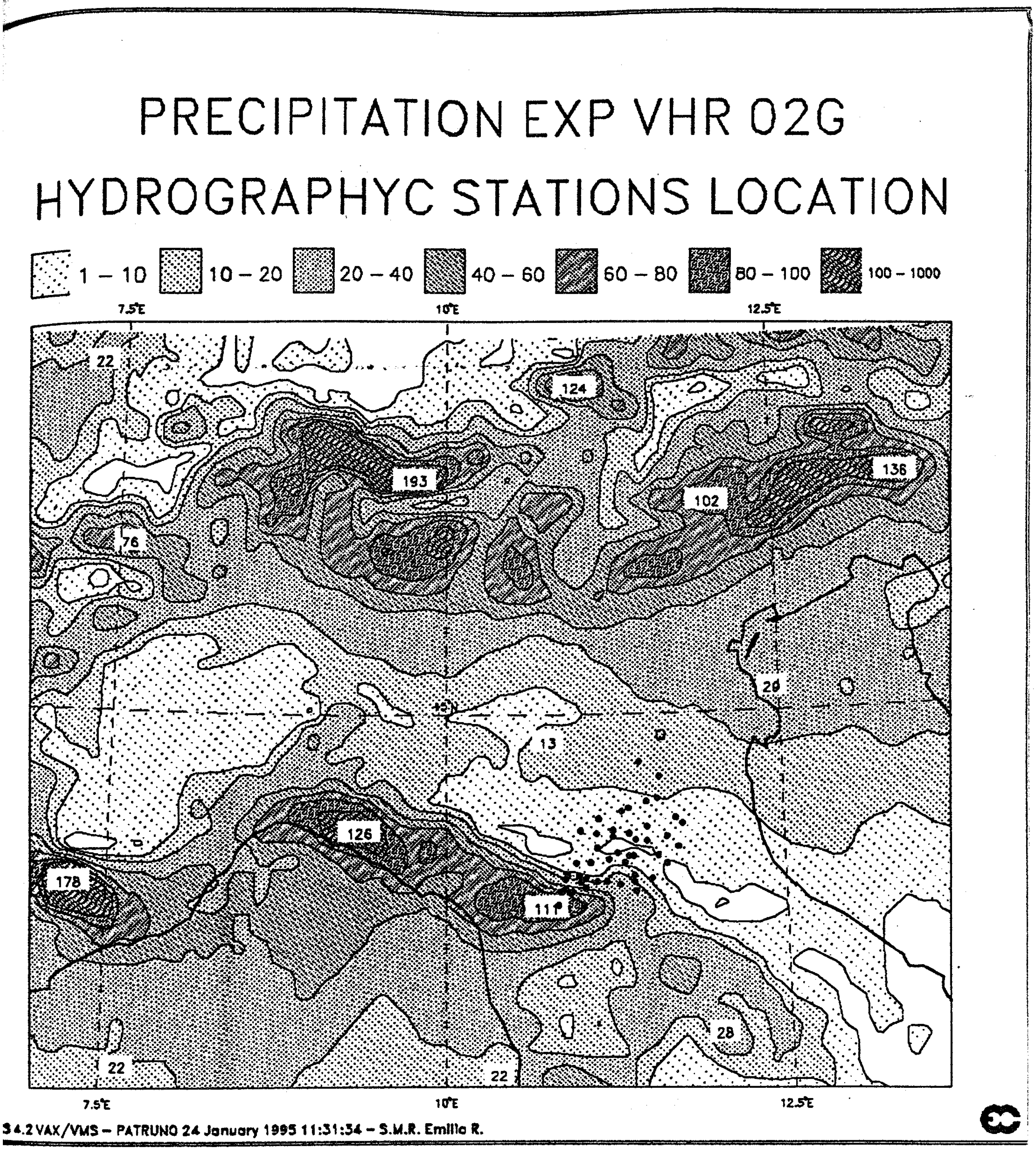


Figure 2.4c - Total precipitation accumulated during the 36 hours of model integration for expVHR. Black dots indicate the Reno-river station network of the National Hydrographic Service.

One of the essential prerequisites of the alternative initial conditions to be used, together with the available analysis (the 'central' analysis, from which the so-called 'central' forecast will be produced) is that they be almost equiprobable. This means that they have to be affected by an analysis error approximately of the same order of magnitude as that of the central analysis. In the past, several techniques for producing such an ensemble of initial conditions have been developed. The very first attempt (Hollingsworth, 1979) was made by adding small, completely random (and therefore dynamically unbalanced) perturbations to the central analysis. It was soon found that geostrophic adjustment and dissipative processes would very soon damp out such perturbations, producing an ensemble of forecasts, all almost identical to the central control forecast. Hoffmann and Kalnay (1983) proposed Lagged Average Forecasting (LAF) as a possible and economic alternative in the global medium-range context, and this was tried with some success by many groups (e.g. Molteni et al, 1986; Tracton et al, 1987). Murphy (1988) proposed a simple alternative method also found to work in the medium-range, global context, which consisted of adding to the central analysis a given proportion of another global analysis chosen at random from a suitable database for the same season.

More recently, two further methods have been proposed, one based on singular vector analysis and adjoint techniques (see, for example, Palmer et al, 1994) and one called Breeding of Growing Modes (BGM, Kalnay and Toth 1991a,b). All these methods are essentially untried in the LAM context (with the sole exception of the work of Vukicevic, 1991, and especially in the QPF context, for which, in principle, the problem can be expected to be still harder, since the meteorological structures responsible for quantitative forecast error have small spatial scales and can be at least in part be associated with fast gravity-inertia modes. Although the Lagged Average Forecasting technique produces results which are generally very satisfactory, in this context its applicability seemed very limited, since the difference in time between two different forecasts of the ensemble, i.e. at least 6 hours, is too large and is in fact, of the order of the lead-time of the forecast itself (max. 36 hours).

Additionally, the criteria forming the basis of the choice of methods for the generation of suitable perturbations to be added to the initial central analysis should be strongly related to the growth rate of the modes one is interested in simulating. These modes should project most efficiently on those dynamical instabilities which are supposedly mostly responsible for important forecast errors on the timescale of interest (in this case 12-36 hours).

The most promising method, also considering its practical ease of implementation, appeared therefore to be the already mentioned Breeding of Growing Modes (BGM) approach. The BGM is based on the breeding of an initial random perturbation by means of subsequent very short range forecasts. A detailed description of the method is reported by Kalnay and Toth (1991a,b), together with examples of applications in the context of the global NOAA-NMC data assimilation cycle. Their main purpose was to breed high-energy, relatively fast growing modes associated with large-scale baroclinic disturbances. In this case interest centres on also (and in fact even more) the very rapidly growing, smaller scale, modes associated with unstable moist convection. These modes, however, saturate typically at much lower energy levels.

Application of the BGM technique

For the AFORISM ensemble forecasting experiments, the model configuration is very similar, as far as the area covered and the horizontal resolution are concerned, to one of those used for the single deterministic forecast experiments (ExpHR), see Section 2.2.2.1 above. The main differences worth mentioning are the vertical resolution (here 20 levels instead of 32) and the data used to update the boundary conditions (here ECMWF analyses, instead of forecasts). The case study chosen is also the same case study used for the deterministic experiments and briefly described above in Section 2.2.2.1.

The application of the BGM experimented with in this AFORISM case study can be schematically described 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 as 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 the breeding cycle, the final perturbation is added to (and subtracted from) the 'central' analysis to produce one of the perturbed initial conditions needed for the ensemble forecast. Since every initial perturbation is both added and subtracted from the central unperturbed analysis (on the grounds 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 (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. Figure 2.5 shows an example of a perturbation field used for BGM.

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 with the generation of gravity waves. Both during the breeding cycle and the ensemble forecasting, the coefficient for the damping is kept to the minimum possible value. The breeding cycle is repeated for each member of the ensemble. For this case study, 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 was evaluated by comparing the BGM ensemble with an ensemble forecast based on not-bred Murphy-type perturbations with the same number (nine) of individual forecasts.

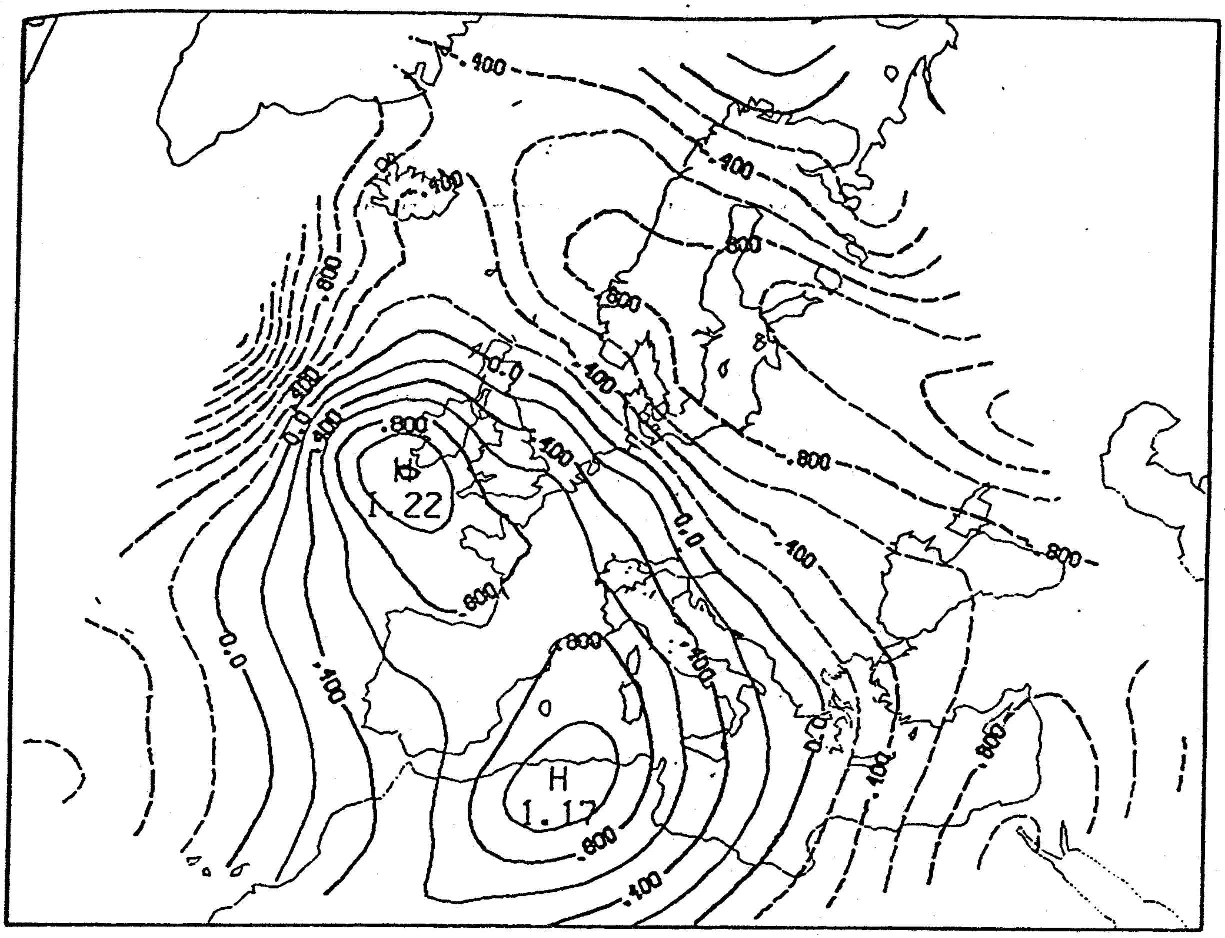


Figure 2.5 - Example of perturbation of 500 hPa geopotential height to be added and subtracted to the central analysis field to construct two perturbed initial states of the breeding ensemble.

Results from the breeding experiment

A quantitative analysis of the characteristics of the BGM perturbation 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. This work has however been necessary 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, and to help determine the optimal model configuration for the breeding experimentation. Here only a general description of the breeding experiment results will be given.

From the results of the ensemble experimentation (Figure 2.6 shows 36h accumulated precipitation for the control, Kalnay ensemble and Murphy ensemble experiments) 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. This is 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 point-measured precipitation is an impossible goal for the available observing system.

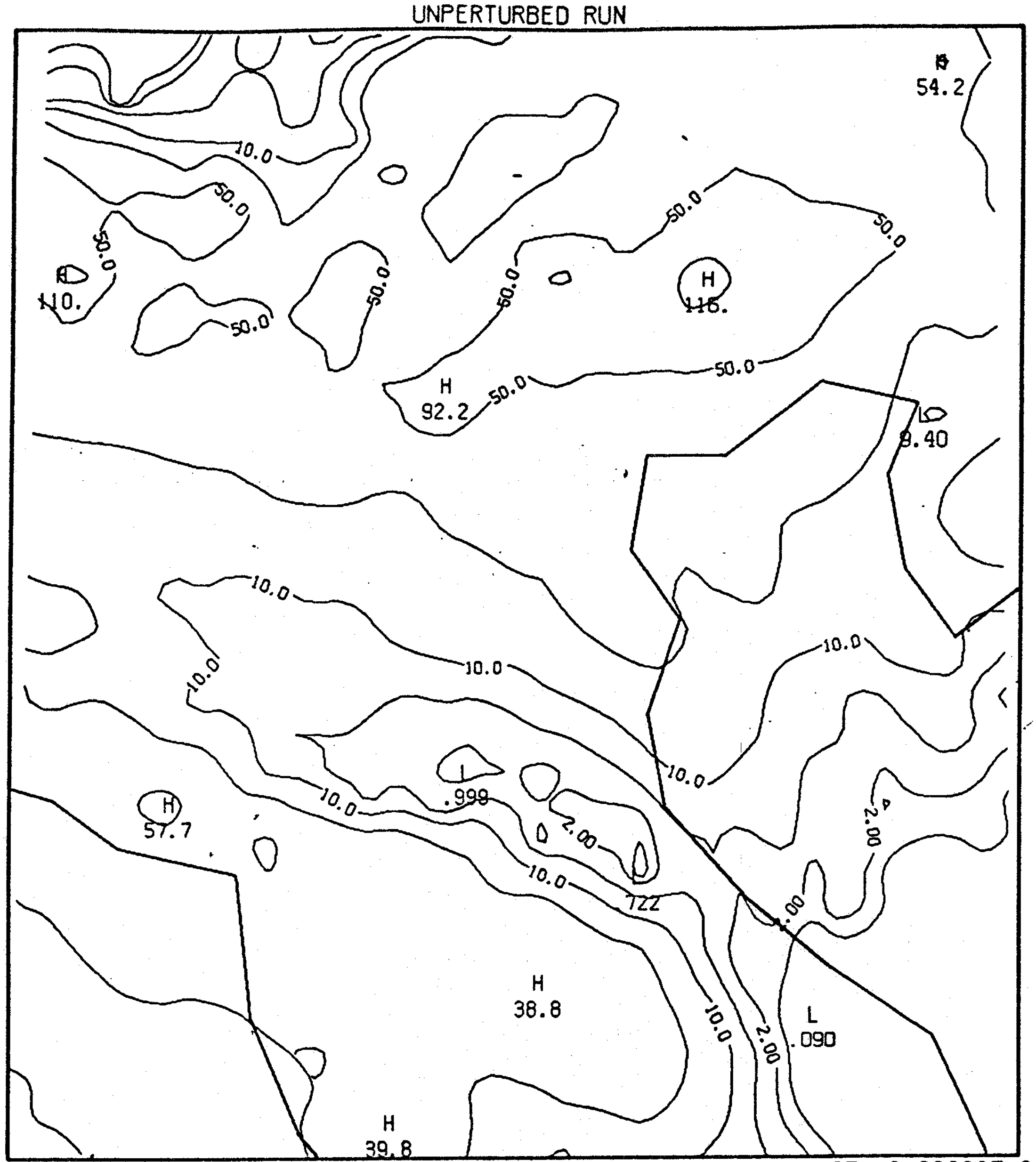
It should however be noted that, among the three forecasts of comparable horizontal resolution compared in this report (central deterministic, BGM ensemble and Murphy ensemble, the results are always relative to ensembles of nine members), the one making the best attempt at localizing the local maximum 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 (Fig. 2.6b). 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 generate 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.

From an overall analysis of the results of both the deterministic and ensemble experiments, it appears 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 BGM ensemble (two members indicating a much higher precipitation than all the others, therefore indicating the possibility of the occurrence of an extreme event was confirming the necessity for a state of alert. There obviously is much scope here for investigating further whether the implied potential contained in this single case study could be transformed into a viable operational QPF capable of consistently indicating the possibility of extreme events.

Concerning the investigation of possible relationships between ensemble spread and possible forecast error (a type of forecast skill forecasting system), scatter diagrams (not shown here of forecast skill (RMS error of rainfall forecast) against forecast spread internal to the ensemble failed to show evidence of any useful spread-error correlation. This was true within both BGM and Murphy-type ensembles. It must therefore be concluded (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 over short lead-times, appears to be useful only as a tool for producing estimates of possible extreme forecasts and not as an a priori 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 into monitoring and further intensified forecasting of the event.

CØNTRØL EXPERIMENT
UNPERTURBED RUN



CØNTØUR FRØM 1.0000 TØ 100.00 CØNTØUR INTERVAL ØF 0.00000E+00
LAMBERT CØNFØRMAL PRØJECTIØN LAT 43.00/ 47.00 LØN 9.00/ 14.00

Figure 2.6a - Total precipitation of the control run integrated over the 36 hours of forecast.

MEDIA KALNAY ENS 9

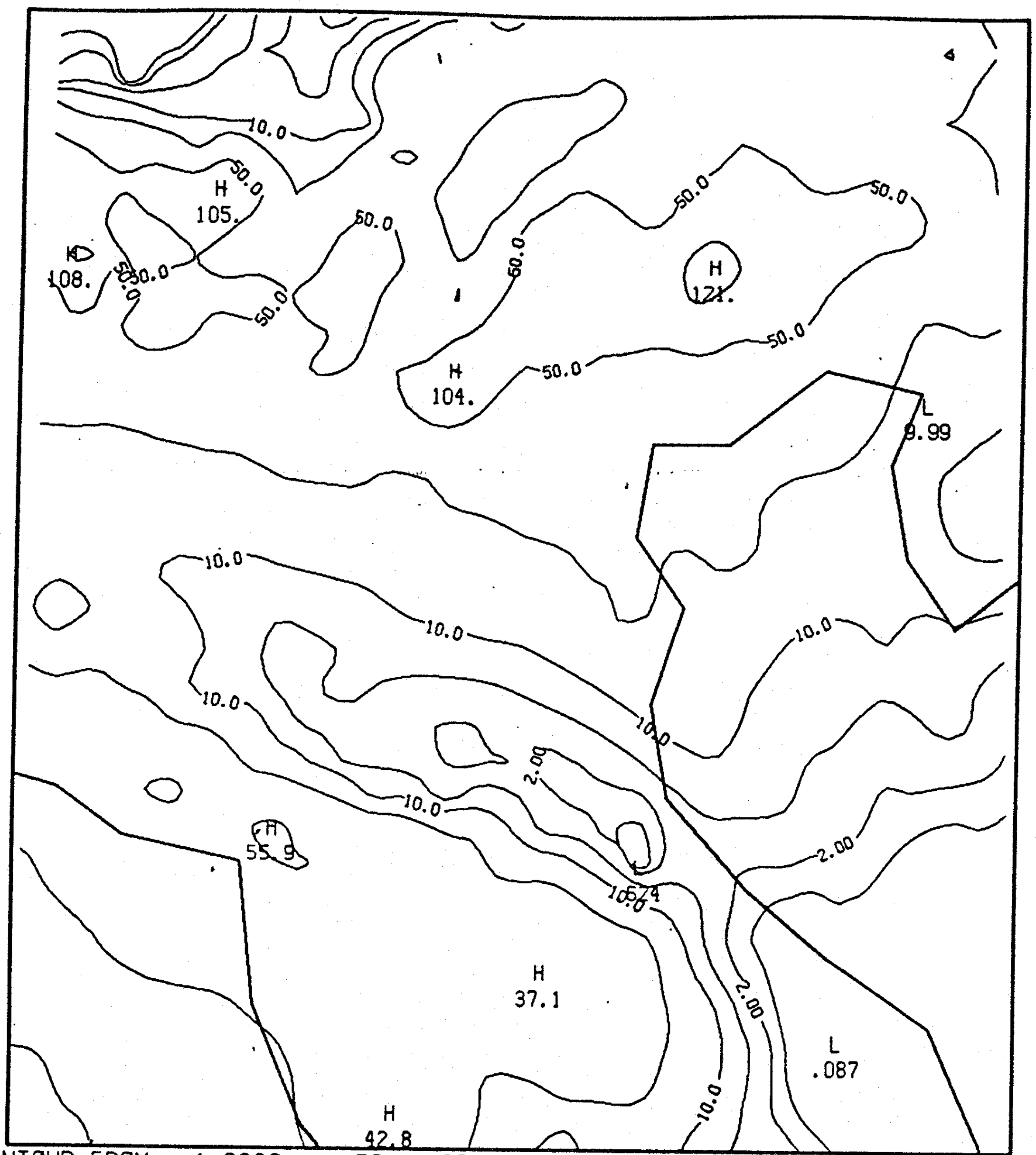


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Figure 2.6b - 36h accumulated total precipitation for BGM and Murphy ensembles respectively

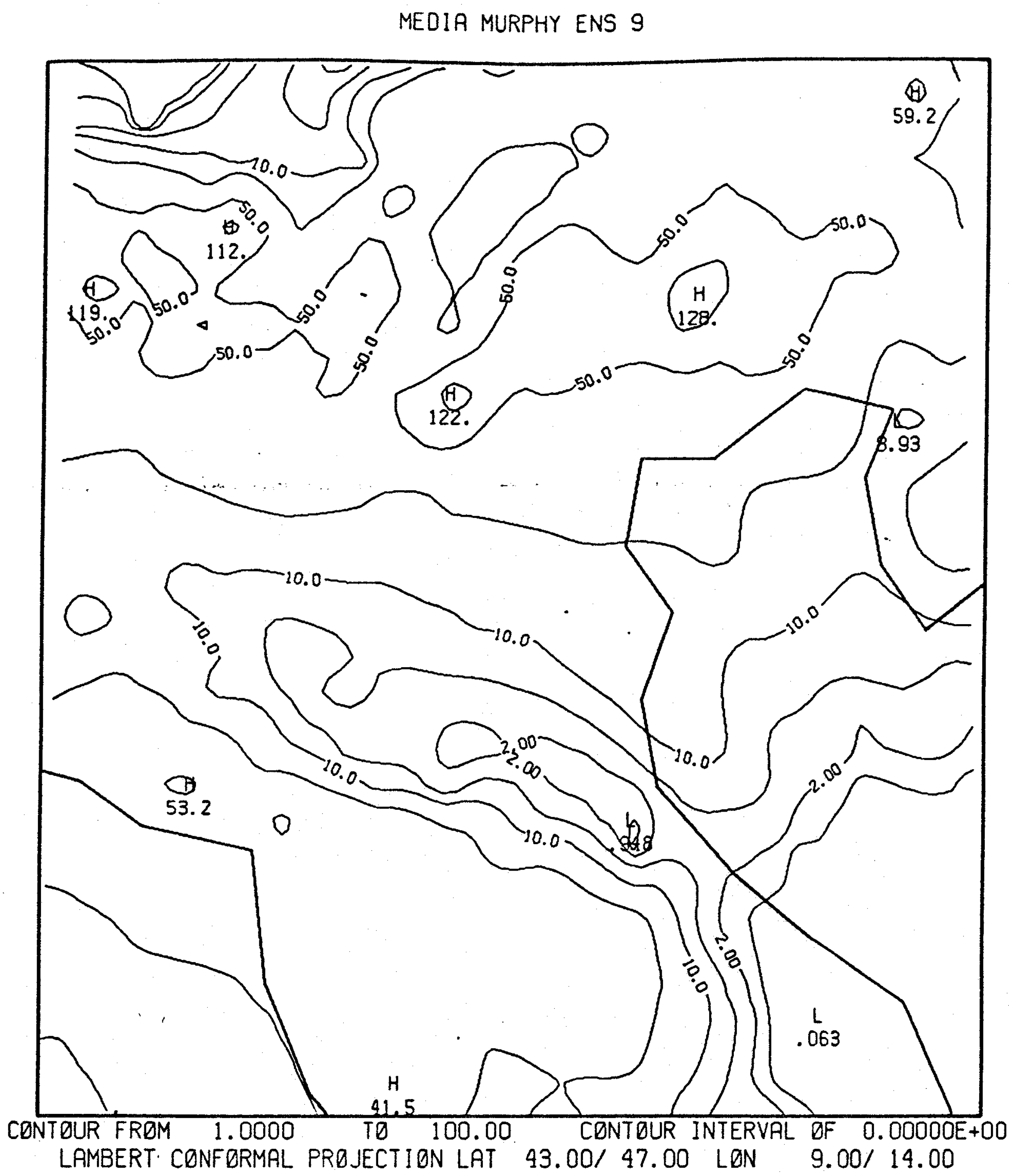


Figure 2.6c - 36h accumulated total precipitation for BGM and Murphy ensembles respectively

2.3 STOCHASTIC RAINFALL MODELLING AND FORECASTING

2.3.1 Univariate Models

2.3.1.1 Justification for a Univariate Model

Before adopting a univariate stochastic model for forecasting the rainfall input to a lumped rainfall-runoff model, it is appropriate to consider how much information might be lost in comparison with a multivariate approach. Specifically, a multivariate rainfall model describing the rainfall depths at several points in the basin or in neighbouring basins can be beneficial, if strong lagged cross correlations exist between rainfall depths at those points. This is because, in such cases, it could be possible to convey information from rainfall occurring over neighbouring areas to improve the forecast.

To investigate this possibility, some tests were performed using rainfall data from the Reno River basin, and some example results are presented in Table 2.2, where it can be observed 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 the lag-zero cross correlation is also included (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 long rainfall events).

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: $Y_t = b_4 X_t + W_t$.

Table 2.2 Gain from the use of various types of information for modelling hourly point rainfall at a site in terms of reduction in variance.

Thus, it may be concluded that it is impractical to convey information from neighbouring stations to improve the real-time stochastic forecast of rainfall. This justifies well the use of univariate rainfall models, in the case that a lumped or semi-distributed rainfall-runoff framework has been chosen. It should be noted, though, that in the analysis leading to this conclusion, all rainfall events have been considered together, regardless of their specific characteristics. It is likely that this conclusion could be different if, for instance, only the events with a constant direction of propagation or velocity were considered. However, the univariate rainfall models even then remain convenient and simple tools that can provide adequate inputs to lumped or semi-distributed rainfall-runoff models.

2.3.1.2. The Scaling Model of a Storm Hyetograph

This model has been developed within the framework of AFORISM at NTUA-DWRHME (Athens). The Scaling Model of Storm Hyetograph (Koutsoyiannis and Foufoula-Georgiou, 1993) is a stochastic model describing the temporal distribution of rainfall within a storm event, based on the theory of self-similar (scaling) processes. 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

$$\{\xi(t,D)\} \stackrel{d}{=} \{\lambda^{-H}\xi(\lambda t,\lambda D)\} \tag{2.1}$$

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 parameterisation 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 the 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 the modelling of intense rainfall events. Finally, the model was applied to the areally averaged data of the Reno River basin where it was found to fit all storms throughout the year regardless of the season (wet or dry) using only one parameter set. An indication of the fit to the characteristics of the total rainfall depth is given in Figure 2.7. It is remarkable that the fit 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 (see Figure 2.8).

A common property of rainfall data, which was also validated for 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 (see for example Figure 2.7 where it is shown that the mean and standard deviation of the total depth are related to duration). This part can be as high as about 50% for the total depth but it drops to 2-4% for the hourly depth. In an attempt to further lower the unexplained part of the variance of these variables, the general meteorological patterns that produce the specific events were examined, applying a certain classification of storm events by weather type.

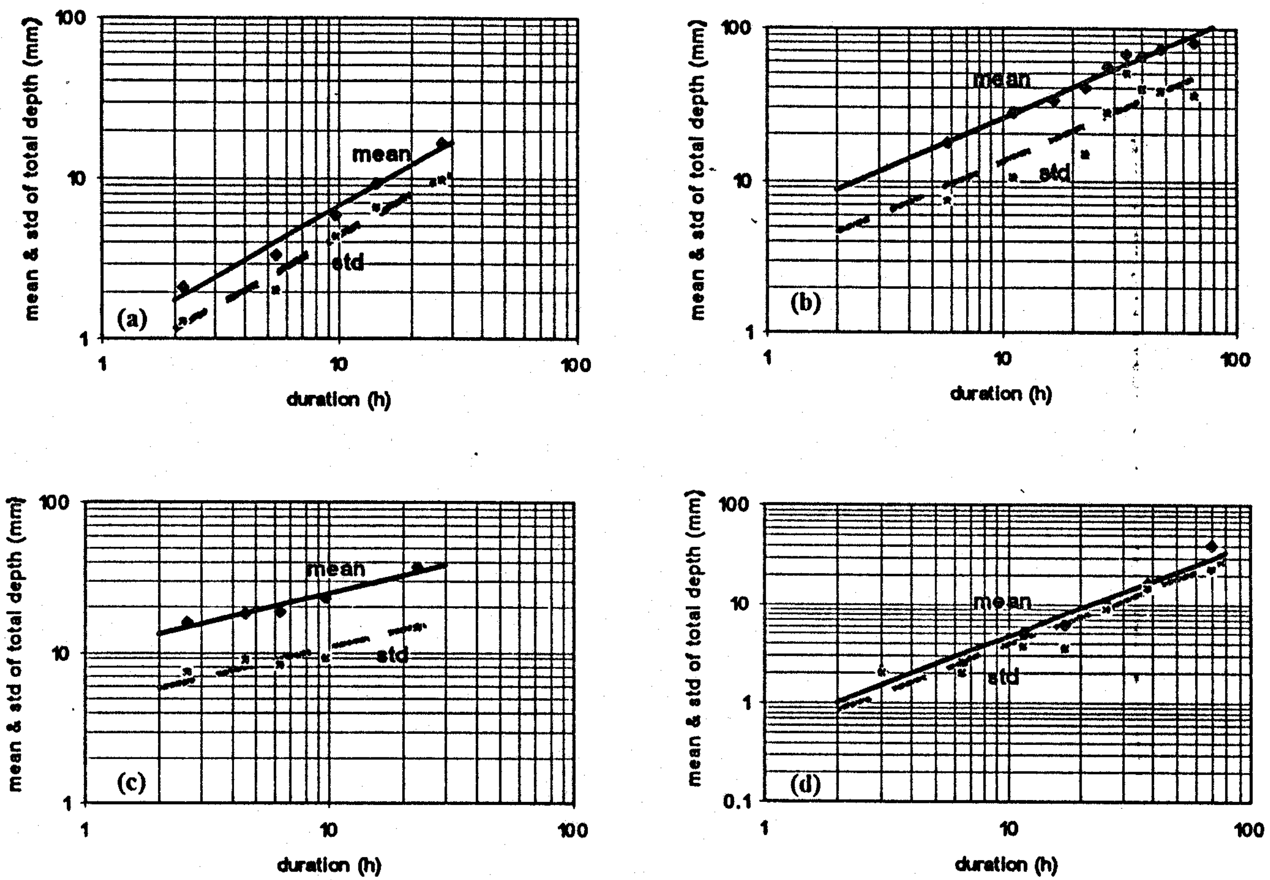


Figure 2.7 - Empirical and theoretical means and standard deviations of total storm depths as functions of duration for the scaling model and four different data sets: (a) all events of point rainfall at Aliakmon river basin for April, (b) and (c) intense events of point rainfall at Evinos river basin for the rainy and dry period, respectively, and (d) all events of areal rainfall at Reno river basin for the whole year.

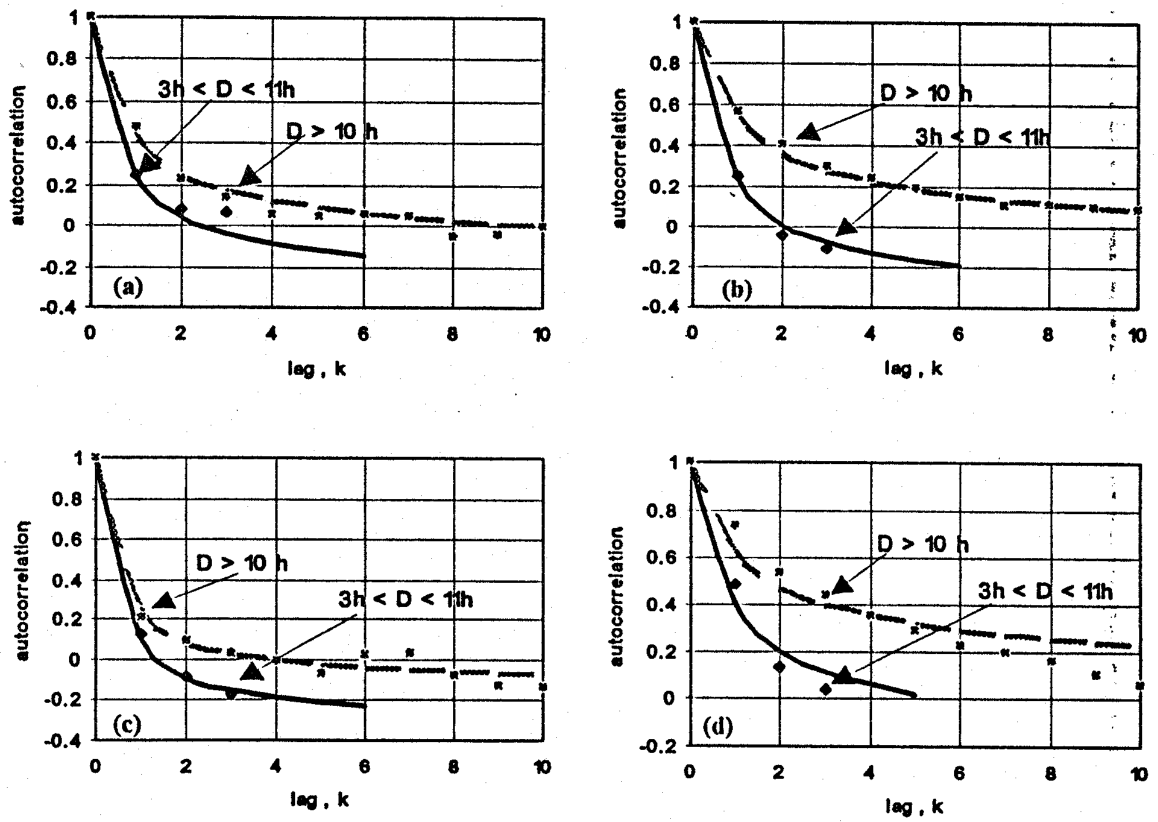


Figure 2.8 - Empirical and theoretical autocorrelation functions of hourly rainfall depths for large and small rain durations. The theoretical functions are calculated by the scaling model for four different data sets: (a) all events of point rainfall at Aliakmon river basin for April, (b) and (c) intense events of point rainfall at Evinos river basin for the rainy and dry period, respectively, and (d) all events of areal rainfall at Reno river basin for the whole year.

In this analysis, the data set of intense rainfall events for the Evinos River basin was used. The rainfall events for 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% for each one), while the 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 event 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 the characteristics of different weather types (Mamassis and Koutsoyiannis, 1993). Thus, the introduction of weather types does not explain a high proportion of the variability of rainfall (for example, it explains only 10-20% of the variance of the total depth, depending on the season, wet or dry).

The implementation of the scaling model for generation of synthetic rainfall events involves two steps. First, the duration of the event is generated. Second, either the consecutive incremental depths within the event are generated directly or the total depth is generated and disaggregated into incremental depths. To this end, 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 an arbitrary time step less than the duration. The sequential form of the model is based on the generalised matrix relation

$$X = QV \tag{2.2}$$

where X is the vector of incremental depths inside the event, V is a vector of independent variables and Q 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 Q 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 time scale rainfall disaggregation. Other models such as that of 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 model developed here is generalised to 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 model in continuous time and a Markovian model in discrete time). The results of the model application and testing for 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 data for 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. In 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 ($j = k+1, ..., D$), 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 $D > k$, 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 for Medium Range Weather Forecasts (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.

An indication of the performance of the conditional generation scheme is displayed in Figure 2.9, which is concerned with the application of the model to the rainfall event of 9-10 January 1994 in the Evinos river basin. The 50% and 95% probability levels of the future rainfall depths, extracted from 1000 synthetic hyetographs generated by the model, are compared with the historical hyetograph. It is observed that, in the case that only the conditions of the first category are used (known past) and the conditional simulation is performed for an unlimited lead time, the stochastic forecasting of the evolution of the rainfall process is poor (Figure 2.9a). This is due to the high coefficient of variation (> 1) and the low autocorrelation of hourly depths. The stochastic forecast is improved if the lead time is confined to 1 hour (adapting to the information in the recorded hyetograph every 1 h), even when the information of the first category is known only (Figure 2.9b). The situation is also improved for the case where the information of the second category (estimates for the total duration and depth) is available (Figure 2.9c). The range of the probability limits of the forecast is still wide in both improved cases. However, when the hyetographs are routed through a rainfall-runoff model, this range will be reduced to a significant extent (depending on the catchment and the specific rainfall-runoff model).

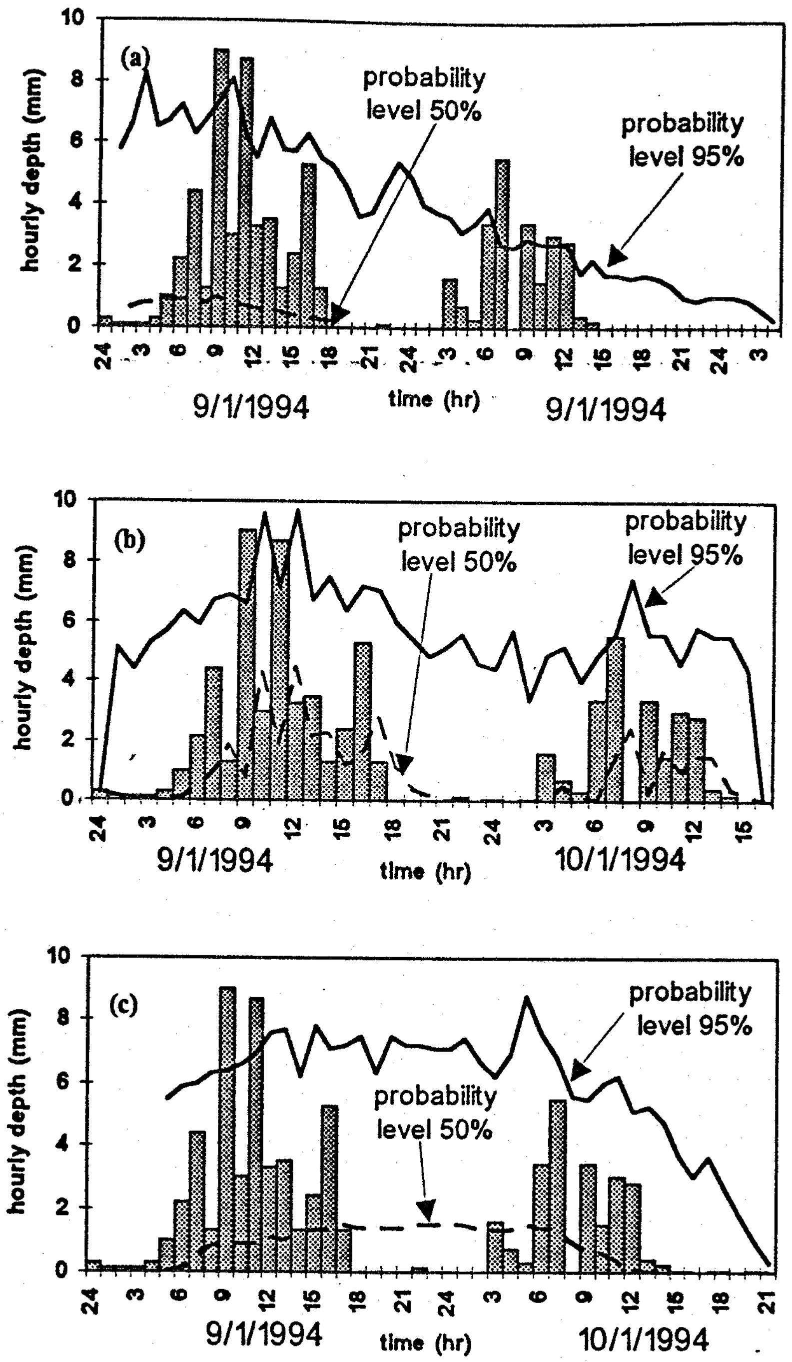


Figure 2.9 Comparison of forecasts derived by the scaling model running in conditional simulation mode with the observed hyetograph at Evinos basin. The model has run using: (a) conditions of the first category and unlimited lead time, (b) conditions of the first category and one hour lead time, and (c) conditions of the first and second category and unlimited lead time. The estimates of duration and total depth in case (c) were adapted from the ECMWF prediction by assuming error components 20% and 30% in the given predictions of the duration and total depth, respectively. The probability limits of the stochastic forecasts were extracted from records of 1000 synthetic hyetographs.

2.3.1.3. The Renewal Process Model

The objectives of this work, performed at INPG-LTHE-Grenoble, were as follows:

- to develop a stochastic rainfall generator, which would reproduce temporal rainfall variability for an area of some few hundred square kilometres and provide input data for a rainfall-runoff model,
- to link this rainfall generator to a rainfall-runoff model (e.g.Topmodel), in order to generate in real-time possible future discharge scenarios
- to test the system by using data for a real catchment (the Gardon d'Anduze catchment in South East France).

The second and third objectives are addressed in Chapter 4, while here only the development of a rainfall generator is reported.

The stochastic rainfall generator selected belongs to the renewal process approach. The idea was first proposed by Croley et al. (1978) for a single rain gauge station. It is based on a simple physical description of the shape and characteristics of rainfall events typically taken at an hourly time step although a similar structure applies down to 5 minute time steps. (cf. Figure 2.10).

A rainfall event is defined as a meteorological wet period and is made up of several sequences of rainfall, which are called storms, separated by interstorm periods. These storms are defined as a succession of rainy time steps with only one maximum of intensity each.

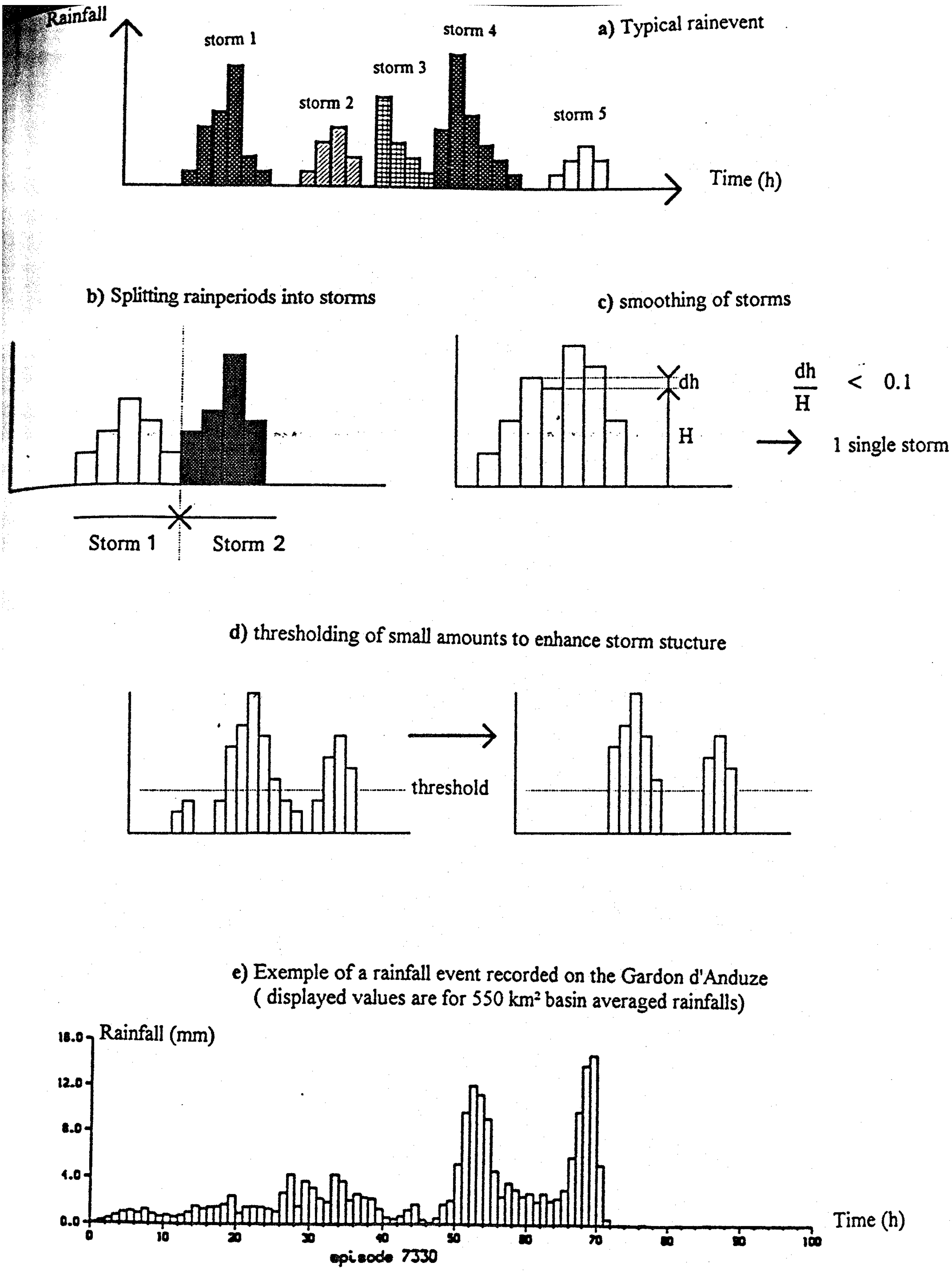


Figure 2.10 - Data preparation for the rainfall modeling by renewal process

The model may be summarised as follows: in a given rainfall event, there are a random number of storms NS. Each of them is described by the following variables:

- the storm duration SD
- the time interval between the present and the next storm ISD (which can be equal to 0)
- the total storm volume SV
- the position of the peak of maximum intensity within the storm duration
- the value of this maximum intensity.

Assuming that a rain storm has approximately a triangular shape (a reasonable assumption largely verified on the basis of historical record screening), these six physical variables describe entirely the succession of storms in a rainfall event.

This model was first proposed and tested as a point process model, to generate rainfall at a single station. In this case the storms may be associated with either mesoscale raincells or rainbands passing over the station. However, it can be adapted to basin average rainfall as long as its temporal structure is consistent with the assumed structure. This has been tested here for the spatially averaged rainfalls over the Gardon d'Anduze catchment (550 km^2). Hourly rainfalls were extracted from a hydrological data set of 13 years of Autumn seasons, which represented more than 3000 hourly data. This data set consists of point rainfalls at 36 gauges located in the catchment area or in its immediate surroundings. So the spatially averaged rainfalls were easily estimated by fitting a spline and integrating over the basin area.

The first step has consisted of verifying that the point model structure was still appropriate for basin averaged values, where "storms" are obviously smoother and longer lasting than at the point scale. This has required some changes in the model consisting of (cf. Figure 2.10):

- not considering small rainfall amounts which prevents clear separation between storms. Here, a threshold of 0.5 mm was selected below which the rain is considered as drizzle or a stratiform storm tail;

- defining new independent variables by combining some of the 6 physical variables (for example storm volumes and storm durations). Indeed, the generation process is based on the use of statistically independent variables, so that they can be generated separately.

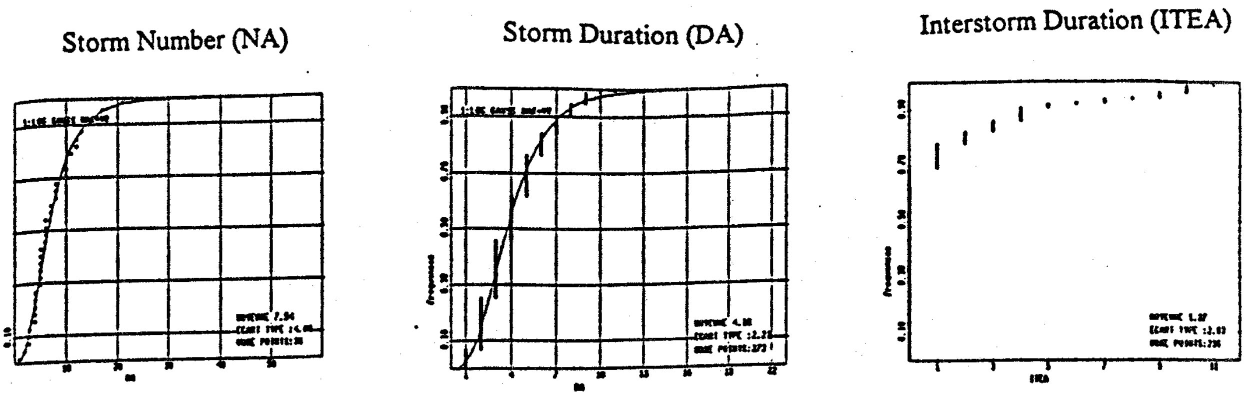
The calibration of the "marginal" generator (as opposed to "conditioned" - see below) was performed as follows:

- fitting analytical expressions to the observed CDF for each of the independent variables
- generating random values of these independent variables, and then recovering the physical variables describing the event.

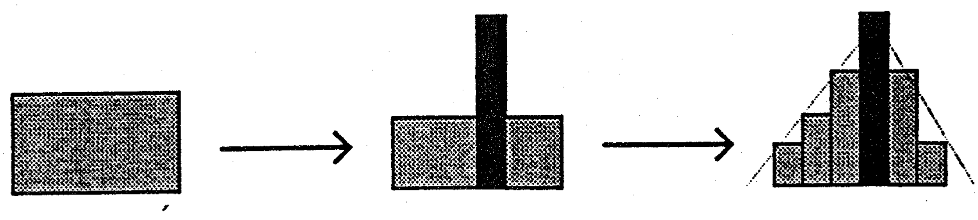
The generation process was first used to generate complete independent rainfall events (Figure 2.11). Statistics from the observed data set and from generated events were compared, first for the variables used by the model, to detect any bias in the generator itself. Thereafter, variables not involved in the generator were also checked, in order to see if the generator remains consistent with observation. Examples are provided for the serial correlogram, the distribution of rain event totals and the distribution of overall rain event durations (see Figure 2.12). They all showed very good agreement between generated and observed data, suggesting that the temporal pattern of rainfall was reproduced overall.

Then, the model was "conditioned", i.e. adapted to provide scenarios that extrapolate over the next 12 or 24 hours the currently observed rain event. In this case, the generator must respect both the climatological rainfall structure, as before in independent generation runs, but it must also take into account the specific and already observed sequence (number of storms, current storm in progress, etc.).

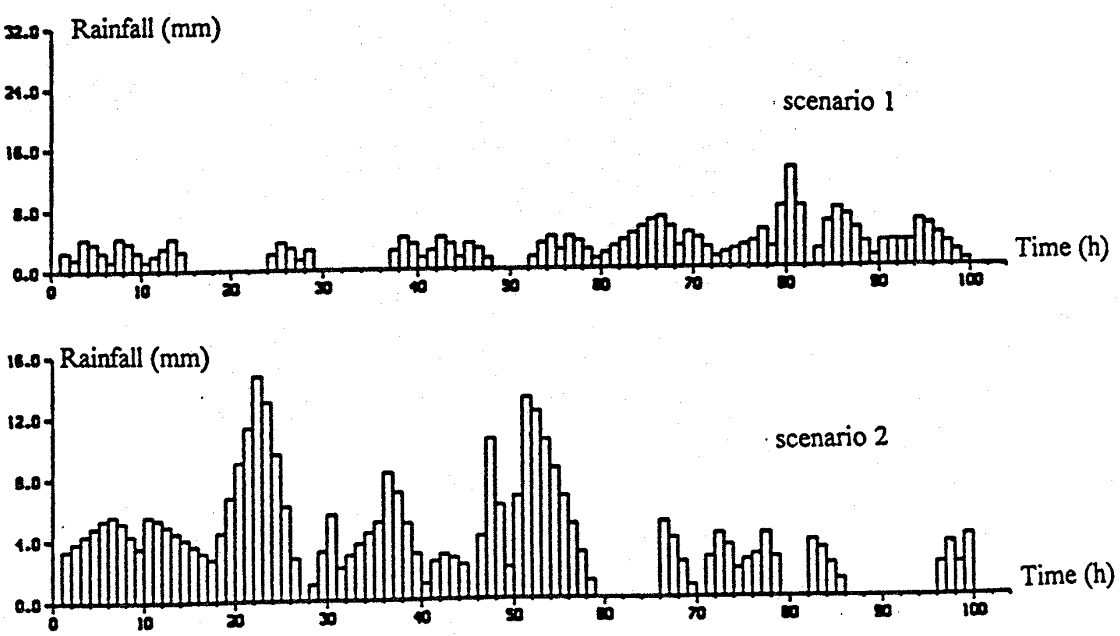
This means that, at each time step of a real rain event, the model is run to produce rainfall scenarios that are kept compatible with the already observed one (e.g. if a storm has been developing for 3 hours, only storm durations equal or larger than 3 hours are considered; the same holds for the volume if a total of 23.6 mm has already been collected, etc.). The model becomes, therefore, conditioned by the immediate past history of the event.



a) Typical cumulated distribution functions used

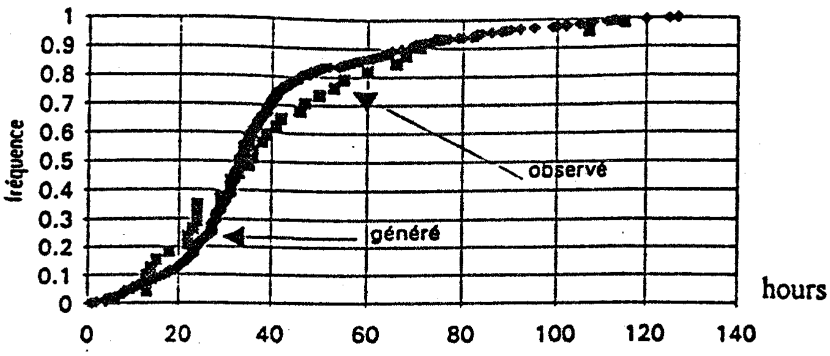


b) distribution of rainfall intensities within a storm

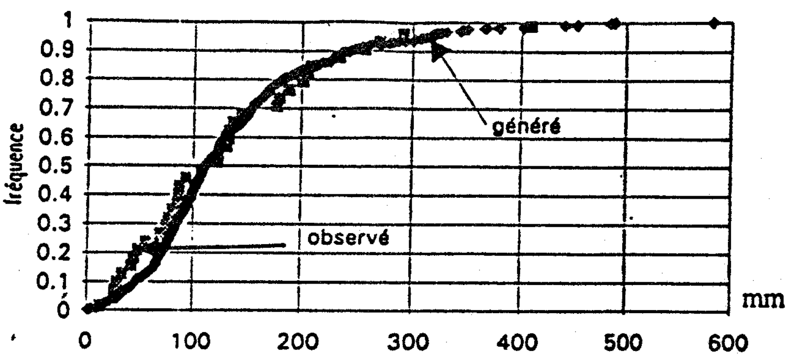


c) exemples of generated events

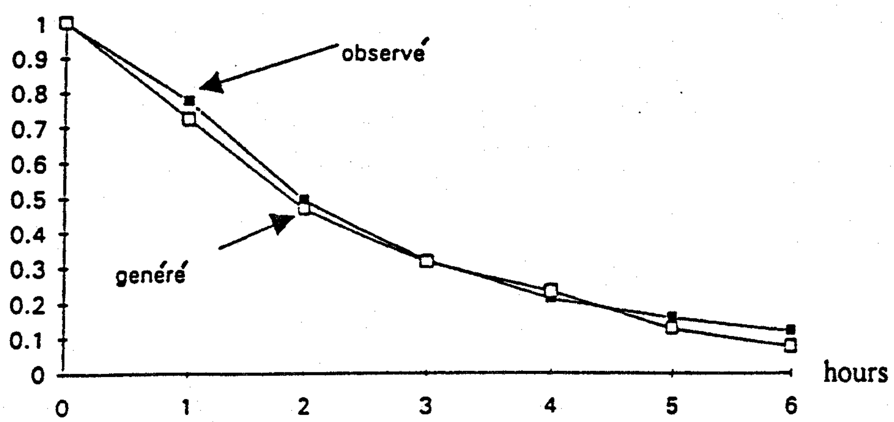
Figure 2.11 Rainfall generation by the renewal process approach



a) Comparison of observed v.s. generated C.d.f. for event durations.



b) Comparison of observed v.s. generated C.d.f. for event totals.



c) Comparison of observed v.s. generated serial correlations between hourly rainfalls.

Figure 2.12 - Validation on independent variables (not used in the generation)

The first step consists of analysing the current characteristic of the event, and determining the current value of its 6 physical variables and of the related independent variables. Then, new values of these independent variables are generated for the coming time-steps, which are kept compatible with the observed values (generated values not compatible are rejected and new ones generated until acceptable). This conditioned process generation was empirically validated. At each time point of an observed event, generated scenarios were compared to the unique observed one, showing that there were always scenarios very similar to this observed one (cf. Figure 2.13). Furthermore, it has been established that a set of 500 generated scenarios at each time step was sufficient to represent a reasonable range of likely future rainfalls, with a good probabilistic meaning (Figure 2.14). It is believed that this generation process is not so time-consuming and could be performed "in real-time". While a rainfall event develops, rainfall scenarios can be generated at every time step for the required lead time (eg 12 hours), taking into account the latest information about the observed rainfall. This has been simulated off-line and used in connection with an operational rainfall-runoff model, as discussed in Chapter 4 (see Section 4-3-4).

2.3.2 Rainfall Field Modelling

A key question investigated within AFORISM is the extent to which incomplete sampling of rainfall by a raingauge network can lead to errors in predicted catchment runoff. A rainfall field model (the Modified Turning Banks (MTB) model) is coupled with a physically-based distributed modelling system (SHETRAN) to investigate this issue. The results of the simulation experiments carried out are reported in Chapter 3; here, two separate studies are described which relate to the calibration of the MTB model and the generation of the rainfall fields used in Chapter 3. The first study, carried out using autographic raingauge data from a network in the Mentue and Broye catchments in Switzerland, investigates the usefulness of such data in calibrating the raincell parameters (velocity, lifetime and width) of the MTB model. The second study describes the use of the MTB model to generate space-time storm rainfall scenarios which are conditioned on properties of the major historical storm which occurred over the Reno Basin around 25 November 1990. A brief description of the MTB model below is followed by a summary of the results of the above two studies.

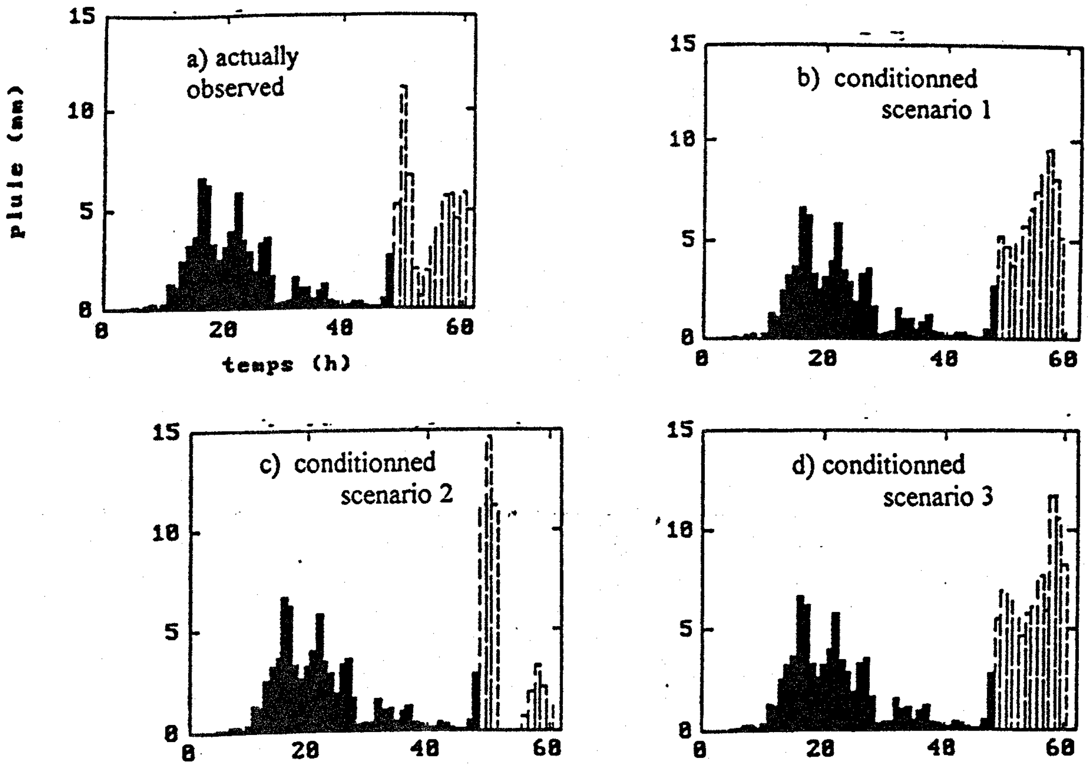


Figure 2.13 - Conditional generation: example of 3 conditionned scenarios with the observed one (for event 7730)

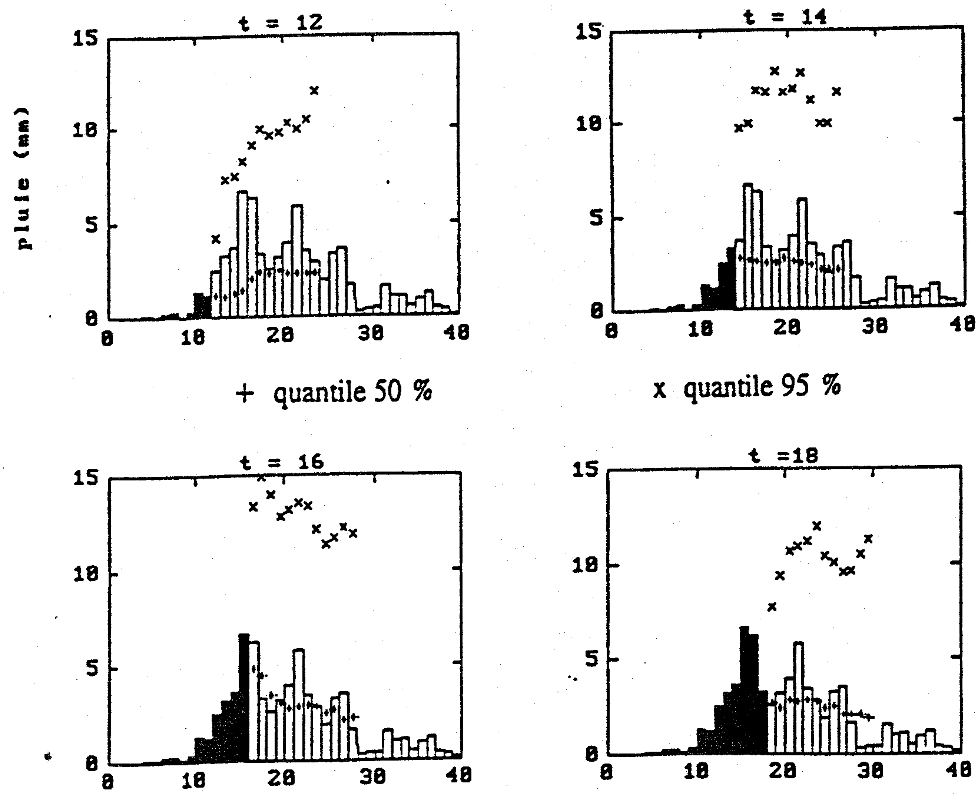


Figure 2.14 - Conditional generation at time 12, 14, 16, 18 of a given observed event

2.3.2.1 The Modified Turning Bands (MTB) Model

The structure and mathematical properties of the MTB model are presented in Mellor (1995), while algorithms for parameter estimation using radar data are described in Mellor and O'Connell (1995) and Mellor and Metcalfe (1995). A brief summary of the MTB model is furnished here.

The construction of the model begins with the placement of two sets of parallel parabolic prisms at random in (x, y) space, as indicated in the bottom layer of Figure 2.15. The two sets are at different angles to the storm velocity vector (which points from left to right in Figure 2.15). The prisms slide along with a common velocity for each set which is perpendicular to the axes of the prisms, and are added together where they intersect.

Next a modulating function derived from the superposition of two sinusoids is applied to the aggregated prisms as indicated in the second layer from the bottom in Figure 2.15. This slides over the model domain with the velocity of the storm, and the individual oscillations inside also slide along with their own velocity. This modulates multiplicatively the sums of the parabolic prisms described above, and results in a storm profile which decays gradually to the edges, and contains inside a banded structure which may travel faster than the storm itself so that rainbands appear at the back edge of the storm, grow and decay as they pass through, and eventually die out at the leading edge of the storm. This is realistic behaviour which has also been observed in radar images (see for example Hobbs and Locatelli, 1978).

The field resulting from the combination of the above features, displayed in the third layer from the bottom of Figure 2.15, is taken to represent the expected density of raincells at each point in the region. More precisely, an inhomogeneous, non-stationary Poisson point process is realized in the three dimensions of (x, y) space and time with the rate function given above, and raincell births are centred on the occurrences of points of this process. These raincells are circular with a parabolic rainfall intensity profile which is a maximum at the centre and decays to zero at the edges. The intensity also grows and decays quadratically in time, starting from zero at birth, reaching a peak halfway through the lifetime, and then returning to zero when the lifetime of the raincell has expired. Again, the raincells slide over the domain with some common velocity during their lifetime which is independent of the storm and rainband velocities.

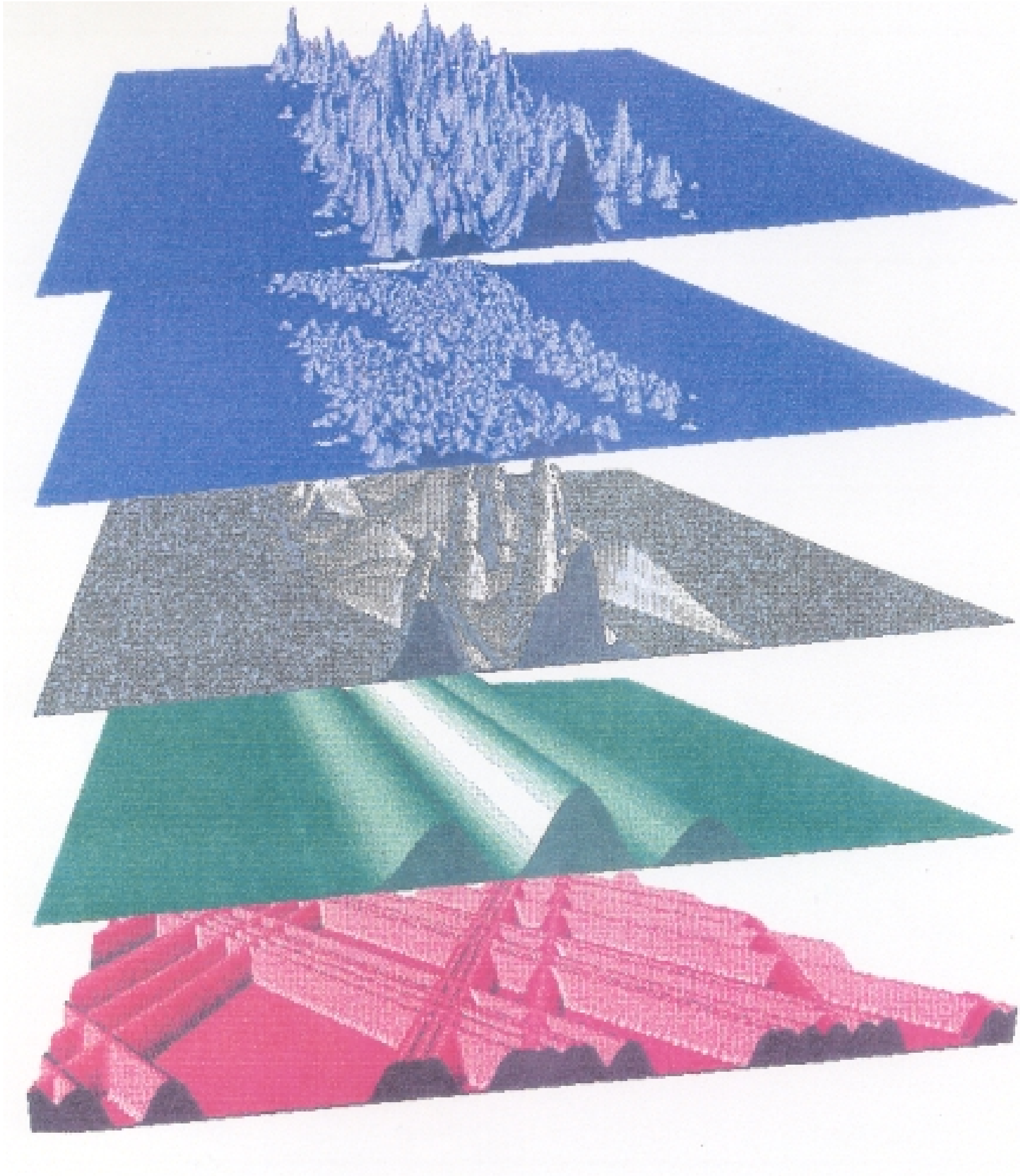


Figure 2.15 - Construction of an MTB model simulation, showing from bottom to top, the placing of two sets of parallel parabolic prisms, the storm/rainband modulating function, the resulting potential function of raincells, a distribution of raincells and the final rainfall field on summing the contributions of all the raincells.

The resulting field of raincells is summed in the domain to produce the final rainfall intensity field in the top layer of Figure 2.15, which is seen to be a kaleidoscope of phenomena simulating storms, rainbands, cluster potential regions, and raincells, and which reproduces realistically their various interactions and motions.

2.3.2.2 Density and configuration of raingauge network required for estimation of MTB raincell parameters

The theory of the MTB model is well developed for the analysis of radar data (Mellor and O'Connell, 1995; Mellor and Metcalfe, 1995). For AFORISM, the requirement is to be able to calibrate the parameters of the model as far as possible using raingauge data so that the synthetic storms used for the simulation experiments in Chapter 3 are realistic. The three scales of rainfall phenomena which the MTB model explicitly reproduces are the raincells (roughly of the order of 10 kilometres in space, 20 minutes in time), cluster potential centres (~20 kilometres, 40 minutes), and rainbands (~100 kilometres, 6 hours). Given that a raingauge network needs to span an area larger than the phenomenon under investigation, it is seen that most realistic raingauge networks will only be able to observe the raincell structures of a rainstorm, and none of the larger details. Given the high resolution provided by raingauge observations in time, this makes dense raingauge networks particularly suited to the investigation of raincells. The work here aims to establish the density and geometry requirements of a raingauge network for this purpose.

The basis for this work is the raingauge network present in the Broye and Mentue catchments, Switzerland (Figure 2.16). It is initially desired to assess the usefulness of this particular network for the purpose of determining the raincell characteristics of any one storm event. While the emphasis here is on the velocity of the raincells, the results are generally applicable to any of the characteristics of the raincells (velocity, width and lifetime), as these all take on values at the same scales of space and time.

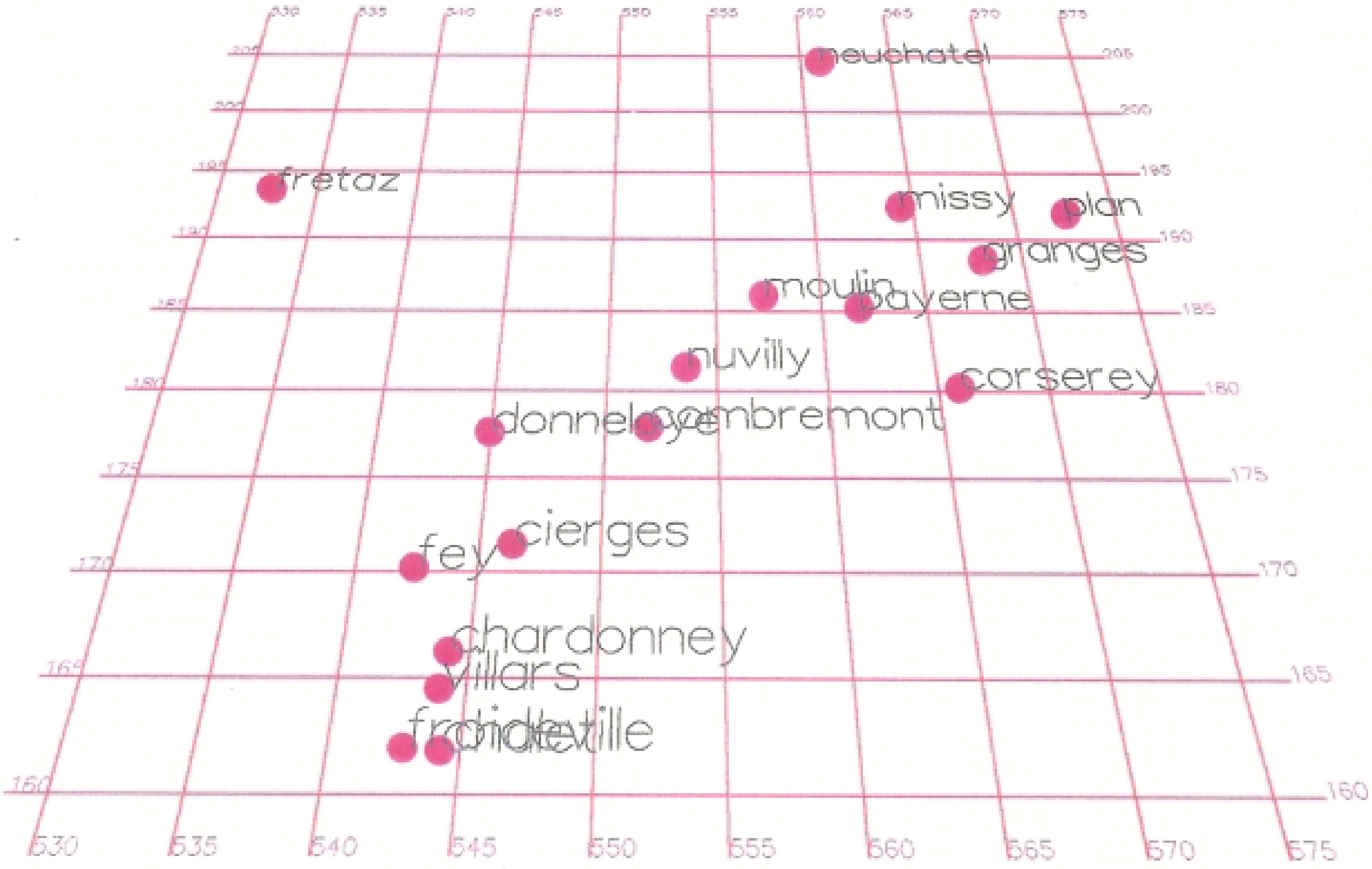

neuchatel
fretaz
missy
plan
granges
moulin
payerne
nuvilly
corserey
donneloye
combremont
cierges
fey
chardonney
villars

Figure 2.16

Two methods were developed for the determination of the raincell velocity from networks of raingauges. The first was a development of methodology previously used for velocity estimation from radar data. This entails the identification of the peak in a temporally lagged spatial correlogram. The displacement of this peak from the origin indicates the distance a typical raincell has moved in the interval of time corresponding to the lag of the correlogram. However, this method should only work well when the observations of the rainfall field are made on a rectangular grid so that cross-correlations of time-series can be averaged over several pairs of raingauges at each spatial lag over which the correlation surface is computed. This results in more reliable estimates of the correlations and thus a more consistent surface from which the peak may be identified.

The alternative method developed here also relies on the cross-correlations between pairs of raingauges, but in this case the correlations are produced at a set of lags in time separately for all pairs of raingauges. Then the distance of the peak in the cross-correlogram from the origin indicates the time taken for a raincell to travel from the site of one raingauge to the other. This 'time of flight' is used to infer the raincell velocity, which is then averaged across all the possible pairs of raingauges that can be taken.

Unfortunately, it has been found that the alternative method is not useable because the velocity estimates obtained from the different pairs of sites do not give consistent results, and the average is not representative of the velocity of the raincells in the region. The former method, however, is known to work well with radar data, and so an investigation was conducted using synthetic data from the MTB model and a hypothetical network to establish the network requirements (density and geometry) for the successful application of the method. Before this method is applied to raingauge data, the spatial co-ordinates of the raingauges are adjusted to the nearest grid point, with no adjustment being made to the observed data themselves. The effect of this has also been investigated and the results are summarized below.

Experiments were conducted with a hypothetical network of 100 "autographic" raingauges initially covering an area of 20 km x 20 km with 2 km spacing. Storms were generated with the MTB model with specified parameters and translated across the network with the prescribed storm velocity; the model parameter values were chosen on the basis of previous analyses of radar data and experience with the model. This network was then diminished in stages in various ways, so that the effect on the bias and variance of the estimate of raincell velocity could be determined. Four separate experiments were conducted as follows:

(i) the spacing between the raingauges and overall span of the network were expanded. The results indicate that a spacing of 2-5 km is desirable for accurate velocity estimation, with the smaller spacing being preferable.

(ii) the spacing between the raingauges was expanded but the number of raingauges decreased so as to maintain the 20 km x 20 km span. The results reinforced those obtained under (i) above.

(iii) raingauges were randomly removed from the network. Here it was found that up to eighty gauges could be removed from the network without any significant influence on the estimate of rainfall velocity. This rather surprising result implies that nothing is gained by having more than 20 raingauges within the area i.e. a density of one per $20km^2$.

(iv) raingauges were chosen at random and displaced a random distance from their initial, regular-grid positions, so that the network became gradually more irregular. Before the lagged correlation analysis technique can be applied to an irregular network of gauges each gauge must first be shifted to the nearest regular grid node. The bias in the raincell velocity estimate (underestimation) was found to increase rapidly with "integrated displacement", defined as the sum of the individual gauge displacements, up to about a value of 10 km above which the estimate is unusable.

It has also been found that the bias in the velocity estimate associated with the integrated displacement is the same as that observed when the grid spacing is varied by a similar amount, with these effects being additive.

If a network is to perform a useful role in estimating raincell velocity, the following design criteria are suggested, based on the simulation experiments conducted with the MTB model:

(i) adopt a minimum density of one gauge per 20 km^2;

(ii) locate the gauges on a regular grid as far as possible, with a spacing of 2-3 km, but deviations are tolerable up to a total grid spacing plus integrated displacement of about 5 km.

(iii) the overall span of the network should be not less than 20 km.

2.3.2.3. Model calibration and the production of synthetic rainfall scenarios for the Reno River Basin

Model calibration on the Reno storm events of 25th November 1990

The intense rainfall episode which occurred mostly during 25 November 1990 over the Reno River Basin has been discussed in Section 2.2.2. Half-hourly rainfall data for this period for 24 sites in the upper Reno basin were available for the study carried out here. Point rainfall values, for a selected gauge, are plotted in Figure 2.17.

Before any analysis of the raingauge data is carried out, 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 identified from the data before the model can be calibrated. For this purpose, a storm is defined as a period of rainfall in which the longest dry spell (i.e. with no recorded rainfall), is no longer than five hours, and there must be dry spells 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 is based upon previous experience of picking out meaningful periods of atmospheric activity to which the MTB model can be fitted. It is on this basis that five storm events occurring 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 are used as a basis for fitting the MTB model and are reproduced, on average, in the synthetic rainfall fields produced by the model. Since the MTB model does not currently deal with orograhic influences on the rainfall field, a procedure was devised for dealing with the effects of orography during model calibration.

The annual average rainfall map for the upper Reno was digitized, and annual averages computed for the Thiessen polygons associated with the raingauge sites.

The site observations were scaled to have the same annual average rainfall, and then used to fit the MTB model. Simulated MTB storms were then rescaled with the annual average rainfall values to simulate the effects of orography.

Rainfall field simulations

The MTB model has been used to simulate 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 storm fields travel from west to east across the catchment, which is the predominant direction for storm movement. The simulations last as long as there is any rainfall within this area.

A spatial snapshot of rainfall intensity within a simulated storm is shown in Figure 2.18, while temporal point profiles for 3 simulated storms are presented in Figure 2.19. The latter relate to the same gauge as Figure 2.17 and show that the characteristics of the observed storms are being reproduced. These storms can be regarded as equally likely realizations in space-time of the storm which occurred around the 25 November 1990.

For the purposes of the computational experiments carried out in Chapter 3, the rainfall was sampled at the prescribed sampling points and then aggregated to hourly values.

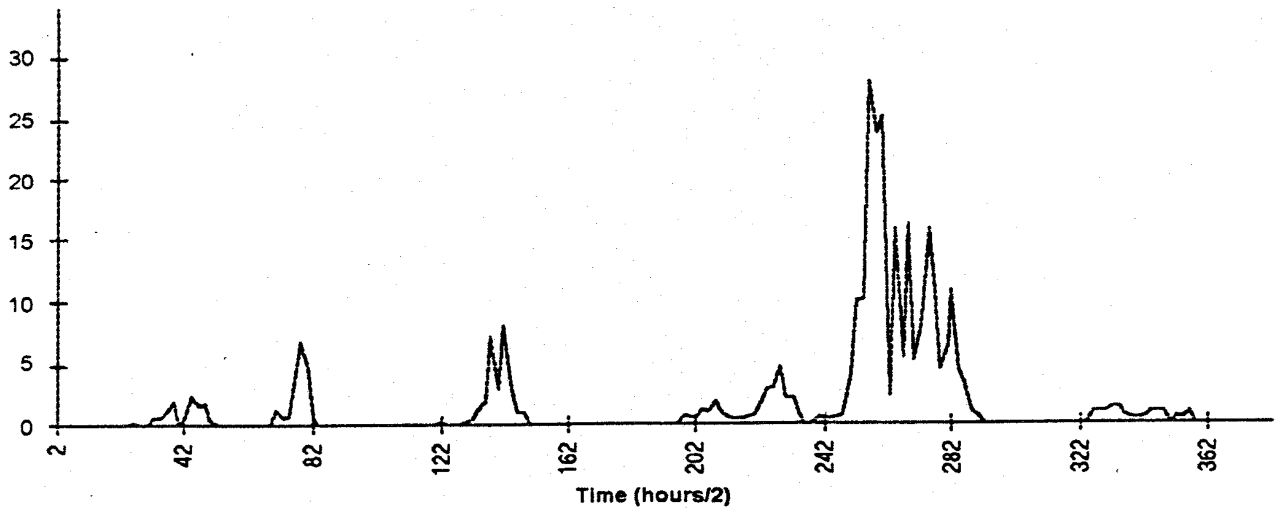


Figure 2.17

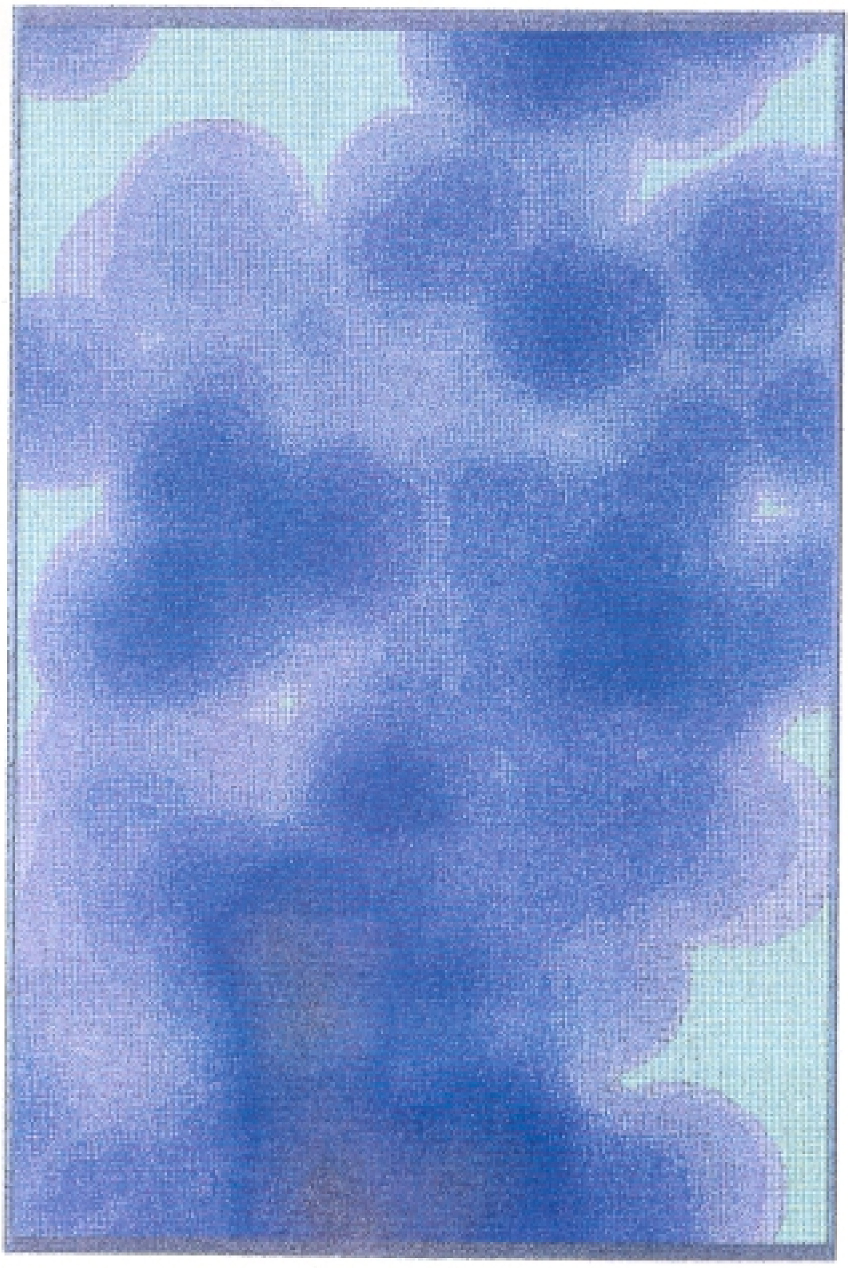
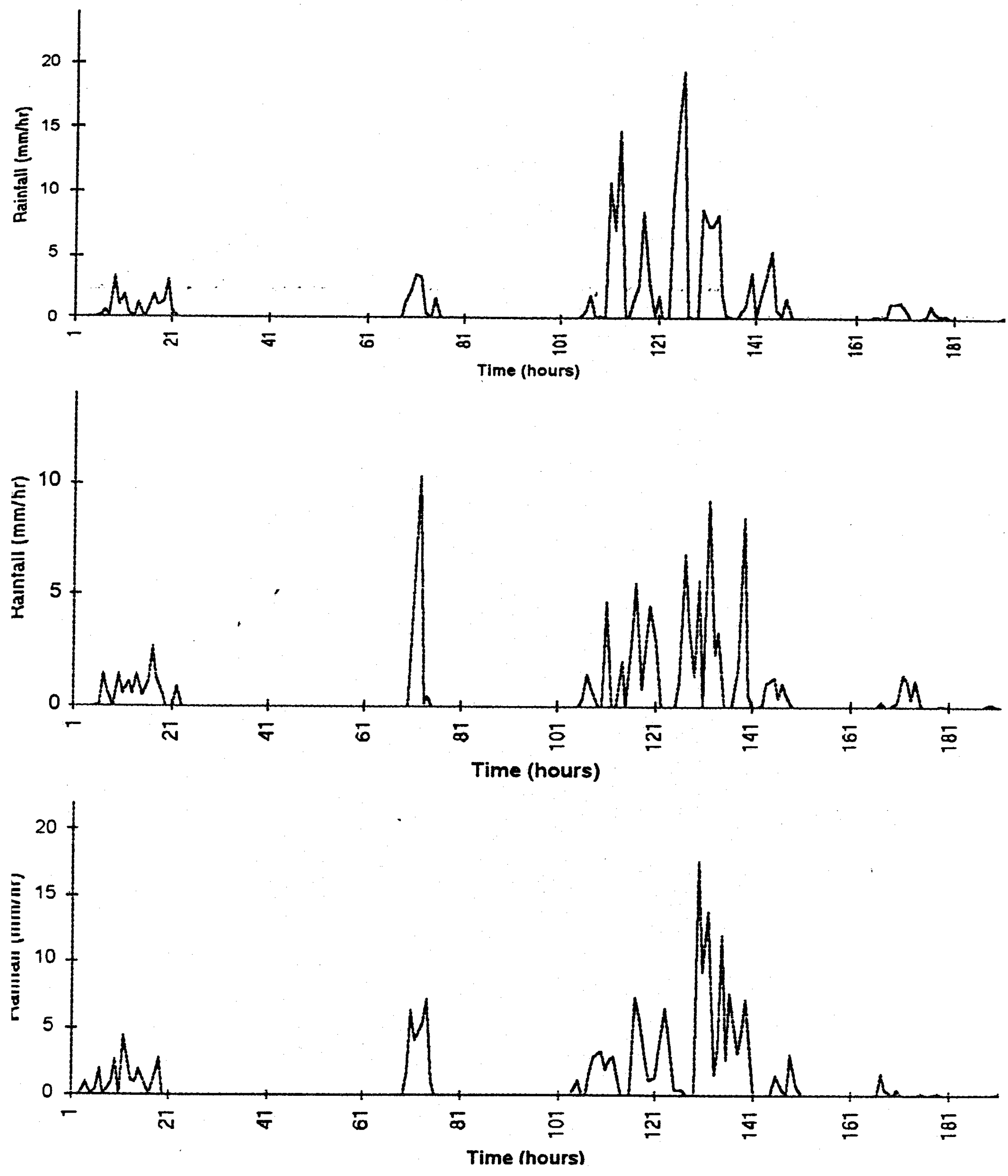


Figure 2.18 - A spatial snapshot of rainfall intensity within a simulated MTB storm. The intensity ranges form 0-9mm/hr, and the domain is the rectangular area enclosing the upper Reno catchment (60Km north-south x 40Km east west)


Rainfall (mm/hr)
20
15
10
5
0
1
21
41
61
81
101
121
141
161
181
Time (hours)
Rainfall (mm/hr)
10
5
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1
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41
61
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161
181
Time (hours)
20
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Time (hours)

Figure 2.19

2.4 CONCLUSIONS

The rainfall modelling activity undertaken in AFORISM has demonstrated advances in rainfall forecasting methodology in a number of areas. Firstly, off-line applications of atmospheric dynamic modelling at space scales of interest for real-time flood forecasting are now feasible, but the performance of such local area models (LAMs) in this regard has remained largely unexplored. However, the case study reported here suggests that increasing the resolution in a LAM model can lead to a better forecast of the observed rainfall pattern for a large storm. The use of this rainfall forecast within the Reno River case study is described in Chapter 7. However, further case studies and more extensive high density observational networks will be required to make a more comprehensive assessment of LAM capability in flood forecasting applications. The research conducted here with a LAM ensemble forecasting approach has indicated that, while such forecasts could provide an indication of a possible extreme event, the ensemble forecast is not a useful a priori predictor of forecast error.

Although the LAM dynamic forecasting approach clearly has long-term potential, LAMs are unlikely to see operational use within flood forecasting systems for some time to come, and so the potential of alternative forecasting procedures must be explored in the interim. Given the uncertainty inherent in any current rainfall forecasting approach, it is important that this uncertainty be quantified, which can readily be achieved within a stochastic modelling framework. The univariate stochastic models examined here have proved to be rather simple, easy to calibrate, and capable of resembling the temporal stochastic structure of the rainfall process. Although generally designed to generate rainfall sequences at a unique station, they can be easily adapted to represent a basin averaged value, as long as the basin is small enough for the same stochastic structure to still hold for the averaged variable. This has already proved very useful where a single lumped basin model is concerned (see Chapter 4).

The univariate models can easily be run in a conditional simulation form so as to provide a sort of stochastic forecasting of the evolution of a specific rainfall event. They can take into account the already observed part of the running event, as well as any external information, such as might be provided by meteorological forecasts. An apparent weakness of the stochastic forecast is the wide range of its probability limits. However this range is reduced when the rainfall input is routed through a rainfall-runoff model. In this respect, the value of the univariate stochastic forecasting method is that it can extend the lead time of a flood forecast (in the framework of a lumped rainfall-runoff model) by at least one or two hours, while also providing probability limits for the forecast.

If a rather large river basin is considered, such as the Reno basin for example (more than 4000 km^2), then it is usually subdivided into several lumped entities that are spatially connected to each other. In this case, the cross-correlations between them must be respected. This may require a multivariate rainfall model, where each basin corresponds to one variable of the multivariate set, therefore allowing the cross-correlations between those sub-basins to be accounted for. A more sophisticated approach is to consider a complete distributed rainfall field generator, even if lumped values at the scale of every sub-basin are to be derived afterwards by integration over each sub-basin.

The work carried out here with the MTB rainfall field model has not sought to develop the forecasting mode of the model. Rather, the main aim has been to assess the effects of rainfall sampling and averaging on simulated runoff response. In conducting such experiments, it is clearly desirable to calibrate the MTB model parameters as far as possible, to ensure that the simulated storms are realistic. While algorithms for calibrating MTB model parameters have been successfully developed for radar data, the work carried out here with real and hypothetical raingauge networks has shown that certain conditions must be fulfilled in terms of network density and configuration before the small scale MTB model parameters can be estimated.

As part of the Reno river case study, the MTB model has been fitted to selected features of the large November 1990 storm over the Reno basin. In fitting the model and generating rainfall field scenarios, the effects of orography were accounted for. The simulated rainfall scenarios are seen to reproduce realistic temporal and spatial features, and can be regarded as equi-likely realizations of the November 1990 storm. The results of the study of rainfall sampling/averaging effects on runoff are reported in Chapter 3.

Looking to the future, developments in LAM modelling and workstation technology can be expected to lead to the eventual implementation of such models within operational flood forecasting systems. In the shorter term, a potentially fruitful area for research is to explore how the information generated by operational atmospheric forecasting models can be used in conditioning the forecasts of stochastic models. The conditional forecasting mode of the MTB model is currently being developed; conditioning can be based on point rainfall data, radar data and forecasts from an atmospheric model. Similarly, the wide probability limits for forecasts observed here for simple stochastic models could be reduced by conditioning on an atmospheric model forecast.

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3. RAINFALL-RUNOFF MODELLING: FUNDAMENTALS AND PROCESS REPRESENTATION

3.1 OVERVIEW

This chapter is devoted to the identification of flood generating processes and their representation into hydrological models. A complementary task is the intercomparison of the different existing approaches in Rainfall-Runoff modelling, with both aims of scientific consistency and also of appropriateness for use within a real time flood forecasting scheme. However, the project wanted to contribute to the improvement of the tool itself, i.e. the Rainfall-Runoff model, not only by comparing but also by developing especially models in the context of Southern Europe, which means relatively smaller basins, often with marked relief and very intense rainfalls.

A number of recent rainfall runoff model intercomparisons (WMO 1975, Franchini and Pacciani; 1991, Chiew et al., 1993) have failed to convincingly demonstrate the superiority of any particular model and therefore to provide firm guidelines for model choice. These results are not surprising: O'Connell (1991) argued that, for time series and soil moisture accounting models, process representation and model structure are not unique and have not well established experimental basis. As parameter estimation relies exclusively on rainfall input and runoff output series, these models are confronted to problems such as parameter identifiability or poor performance outside the parameters calibration range.

There is a need for catchment models to be more firmly based on an adequate knowledge of active basin hydrological processes. Having in mind the necessary simplifications that will be required for operational purposes, even among these active processes, the potentially dominant processes during major floods have to be identified to make sure that they are correctly accounted for even in simplified models. This requires some feedback between field studies and models development in two directions: model structure evaluation and parameter estimation issues. In the recent past, field studies have essentially been performed in the context of temperate humid climate, showing that the development of variable contributing areas was probably the dominant process in natural rural catchments.

However such experimental results were very limited in the Mediterranean zone, where the Hortonian concept was still considered as dominant. Before undertaking an extensive modelling exercise in this zone, some field evidence was required, therefore the inclusion of an experimental part in the project.

Another concern was about the types of model that are necessary to represent such processes, and among them, which ones will be the most parsimonious. Physically based models attempt to fully take into account the complex interactions between the surface and subsurface flow systems which determined eventually the dynamics of the contributing areas. However they are computationally far too expensive to be used in present flood forecasting systems, and too much information demanding to be correctly provided with required basin characteristics. As Todini (1988) has pointed out, a promising direction in model development is to lump them so as to leave only the few essential parameters and make them computationally affordable.

Consequently, simplifying assumptions have to be made. They must be thoroughly compatible with fields observations, but more or less extended level of simplifications can be thought of and must be tested by numerical experiments.

Therefore, it was worth collecting recently proposed models and to compare them objectively on the same data sets representative of Southern Europe flood problems. The former experience of the coordinating group in Bologna in intercomparison of models has allowed to put all this model into perspective on several data sets made available by the different partners. However, before using a model, it is always worth to handle it by taking it down to pieces and putting in perpective its explicit but also implicit or hidden hypotheses.

As for the distributed differential models, efforts have been made essentially by the ISA-Lisboa group in trying to develop a version of SWATCH appropriate to the use of GIS. Some experiences have also been made with the SHE model.

However the most comprehensive effort has been devoted to semi-distributed models. For example, TOPMODEL, a very fashionable but also promising model has been studied by 3 groups within the project. The major role attributed to the topography looked very attractive, but had to be understood in relation with the quality of topographic information and in interaction with the other parametrisations involved in the model. Other groups have also focused on the ARNO and on the Sacramento model.

Heretoo, field research can contribute to solve modeling issues by providing additional possibilities to estimate model parameters. Many hydrological models, either process based or physically based have problems of parameter identifiability. This problem is particularly acute for distributed models. There is needs to constrain better model parameters. And this would hopefully increase prediction accuracy on independent data sets. The use of additional data on which to constrain the model (i.e. piezometer data, geochemical or isotopic tracer data) and the provision for independent estimate of some model parameters (e.g. hydraulic conductivity), would greatly enhance confidence in the modeling exercise. It will be seen that even if sometimes disappointing, these experiments allow to pinpoint some hidden properties in model structure and functionning.

Another important point in the Mediterranean zone is the spatial and temporal variability of rainfall and therefore understanding what should be the minimum requirements on rainfall information (Obled, 1989). It is often claimed that spatial variability of rainfall is determinant for the rainfall-runoff transformation, so that this information should be provided to and handled by the model, which conversely should have a structure allowing to manage this information which means the use of fully distributed, often complex, models.

However this affirmation has hardly been confirmed, even in extreme conditions like small urban catchments where the role of spatially varying rainfall should have been very important.

So it had been decided to study this aspect, for medium sized rural catchments, by two different ways: through the use of synthetic data, and the use of actually observed data.

Preliminary results of this chapter 3 are summarized hereunder.

Summary of results:

- First, an important result of our field studies on both the Réal Collobrier and Haute Menthue catchments is is that the variable contributing area concept is active not only in temperate humid climate, but is also a good candidate for generating quickflow in vegetated Mediterranean basins. Stormflow is mainly produced by saturation overland flow and shallow subsurface flow or interflow. Infiltration excess overland flow is active, and there always exist some impervious zones directly connected to the drainage network, but their importance is less than was previously accepted for this type of physio-climatological environment. Consequently, it cannot be expected that models structured and parameterised on the basis of the Hortonian concept could provide good results. Therefore, even a simplified forecasting model will have to explicitly account for the variable contributing area concept.

- Semi-distributed models which are able to represent this process, either explicitly or implicitly, are performing well. In particular TOPMODEL has been studied very deeply, allowing an original insight on the role of topography, and also on interception. The ARNO model shows some similarities with it and displays similar performances. The attempts made with fully distributed differential models have been less productive in term of tools for operational use, but very stimulating for process understanding. They still should be reserved for exploratory research works.

- Nevertheless, if field experiments and associated small scale modeling have proved extremely valuable to the qualitative understanding of catchment behavior, local measurement were not able to provide reliable parameter estimates for the hydrological models tested. We could not perform satifactory model validations with field estimated parameters, especially soil hydraulic conductivity. With respect to the scale of most measurements, hydrologic variables have a tremendous heterogeneity. Since the governing equations are non-linear, effective field parameters may not exist or be only loosely related to point values. In the absence of new measuring techniques working at basin scale, this situation is likely to continue. However, integrative techniques such as environmental tracing have proved promising on the Mentue catchment, although it is too early to conclude on the other catchments.

- Further to the physical notion of effective parameter at basin scale, there is the artefact caused by numerical effects and parameter interactions. Perhaps for the first time, a relationship has been sorted between a model parameter (i.e. the hydraulic conductivity) and the way "physical" information is provided to the model, (here, the topography input in TOPMODEL). Depending on the meshosize used, this causes a bias in the model representation of the basin that has to be compensated by the conductivity, which cannot any longer stick to its physical meaning and range of values.

- The intensive study of model sensitivity to spatially variable rainfall has shown that even with actually time varying rainfall patterns, the dampening capacity of the basin processes is sufficient to rub out these effects in the response variability. However, a very good basin average input rainfall remains necessary, and its proper estimation is affected by the spatial variability.

All these items will be developed hereunder.

3.2. EXPERIMENTS

3.2.1 Experiments on the Haute-Mentue catchment

The Haute-Mentue catchment (12.5 Km^2) is located in the Swiss Plateau region some 20 Km north of Lausanne. The climate is humid temperate with a slight continental tendency. Mean annual precipitation is around 1250 mm, and mean annual potential evapotranspiration about 600 mm. Altitudes range from 930 m above sea level to 694 at the outlet (Fig. 3.2.1). Topography is gently rolling with an average slope of 4°. Forest covers 55% of the basin. The remaining area is devoted to agriculture with mixed farming and permanent pasture. The soil layer is around 1 m deep. Soils can be classified as dystric cambisoils and luvic cambisoils. Iron and manganese oxidation and reduction traces are widespread over the basin at depths of 50 to 80 cm from the ground surface. Soils are moderately permeable sandy loams or loamy sands. Saturated hydraulic conductivities range from 4 to 40 mm/h at a depth of 50 cm. The underlying bedrock is made of low hydraulic conductivity sandstones, overlain by compacted morainic deposits of variable thickness.

In the field study we used a combination of point and integrative measurements. Inference of stormflow generating processes can only be made using such a combined experimental strategy. It must be pointed out that measurement accuracy was a first priority since it was considered a fundamental aspect for identification of hydrological models. Point measurements are essential as they provide information about hydrological processes that can not be uniquely inferred from integrative measurements. However, due to spatial variability, an intensive sampling is needed to assess the relative importance of processes at the catchment scale and to infer major physical controls. Some soil-water content, tensiometric and hydraulic conductivity measurements were performed (Jordan, 1992) and are pursued. More emphasis has been placed on the monitoring of a network of piezometers which is simple to maintain and thought to be particularly relevant for the processes active on the Haute-Mentue catchment. However it seems that point measurements, even piezometric ones, are of little use for hydrological modeling at the catchment scale. Therefore a special consideration was dedicated to integrative measurements. Currently a network of eight catchments with areas ranging from 2 ha to 1250 ha is being monitored. Environmental tracing is performed on up to three catchments in parallel.

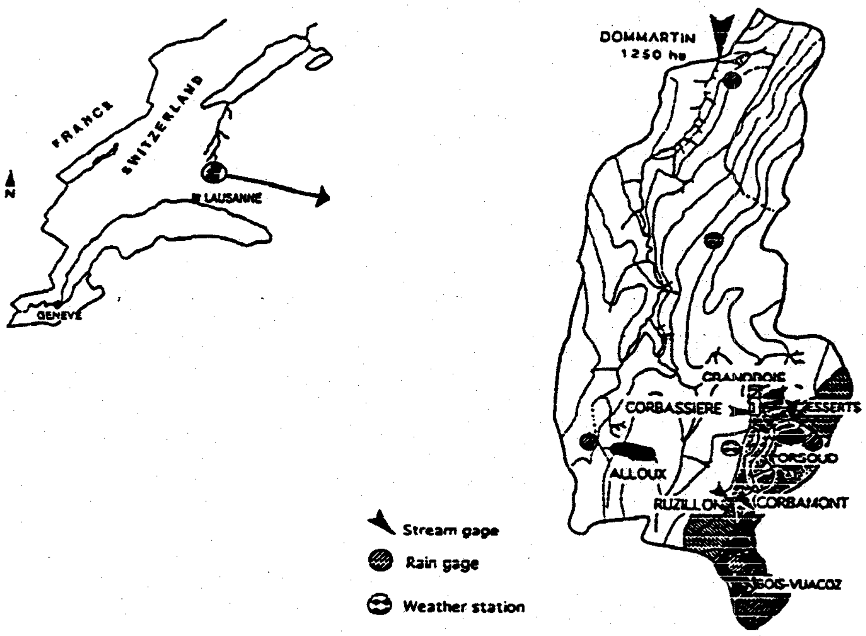


Figure 3.2.1 - The Haute-Mentue research catchment

In a first experimental period (1988-1991) the main objective was to test land use effects on hydrological response. This was related to an effort to parameterize physically based models such as SHE on the basis of land use characteristics. Four first order catchments with areas of 2-4 ha and rather homogeneous land uses were monitored. Two were under forest cover and the other two were devoted to agricultural practice. Two third order catchments (12.5 Km^2 and 1.85 Km^2) with different land uses were also monitored.

This experimental set-up did not permit one to identify a significant influence of land use on stormflow characteristics (Jordan, 1992). This clearly implies that for the Haute-Mentue catchment physical factors other than land use dominate hydrological response. Analysis of a storm sample showed that even for elementary catchments basin reaction was not correlated to short interval rainfall intensities (2' to 30') but rather to total rainfall and baseflow prior to event. Major events occur in wet catchment conditions and are triggered by prolonged, moderate intensity, frontal storms and not by high intensity summer convective storms. This allows one to infer with a certain confidence that the infiltration excess mechanism is not a dominant one. However, it is likely that for some areas high rainfall intensities can produce infiltration excess stormflow but with significantly lower return intervals than those of rainfalls.

Systematic trends were found between first order and third order catchments (Jordan and Iorgulescu, 1992) confirming the variable contributive area concept. This 'scale effect' is attributed to contributing areas which are located mainly on third order catchments during small to moderate events. These areas expand also to the monitored first order catchments for large events. Topography could qualitatively explain this behavior in the framework of the saturation overland flow mechanism. Elementary catchments are situated on straight hillslopes with little convergence, while third order catchments have a larger fraction of flat valley bottoms and convergent headwaters.

Isotope tracing attempted on one elementary catchment (Alloux, 3.6 ha) demonstrated the feasibility of this method in Haute-Mentue's conditions. Results (Jordan 1992) showed that baseflow contributions were important for moderate rainfalls falling on a wet catchment but were low for important events with high rainfall and/or high intensities. This also applies for events occurring in very dry antecedent conditions. The generating mechanisms for the 'new-water' can not be uniquely determined from hydrograph and tracer data. Infiltration excess overland flow mechanism seems dominant for one event while saturation overland flow is predominant for others.

It was decided that further work should concentrate on the role of the topographic factor. Consequently four forested sub-catchments (20-35 ha) with rather different topographic characteristics were monitored since 1992-1993. This experimental set-up allows a fairly objective evaluation of the role of topography.

Figure 3.2.2a presents an example of a summer event: a relatively intense convective rainfall (17mm in 45 min) falling on a dry catchment. Runoff coefficients are quite low varying between 0.2% and 1.7%. Figure 3.2.2b (note changes in scales) presents an example of a sequence of rainfall-runoff events in autumn. Frontal rainfalls have smaller intensities but longer durations. Catchments are wetter as higher baseflows indicate. Runoff coefficients are considerably higher than for the summer event and range between 15% and 30%.

There are indeed indications that topography may be an important control for catchment response. The topographic index $(ln(a / tan\beta))$, defined by Beven and Kirkby (1979) is a measure of the likelihood of a particular point to became saturated. Beven and Kirkby (1979) argue that the higher that ratio the wetter the point would be. For each catchment we calculated the average value of their topographic index (λ). The cumulative distributions of the topographic index for the studied catchments (Figure 3.2.3) were obtained using the multiple flow direction algorithm of Quinn et al (1991) and a DTM (Digital Terrain Model) with a grid size of 10 m.

It may be observed that ranking in catchment responses for the fall events tends to be positively related to the ranking for the topographic index average (λ). Note also that the ranking of catchment reactions tends to be inverse to that for the summer event. This is not unexpected from geomorphological considerations. In the study area catchments with steeper slopes have a narrow valley bottom with thin soils. Even in relatively dry conditions, slopes feed this valley bottom enough to maintain them close to saturation.

Furthermore, this geomorphologic configuration makes more difficult for saturated areas to extend upslope. In flatter and larger valley bottoms moisture deficits are more important in dry conditions but once they are filled saturation zones expand rapidly.

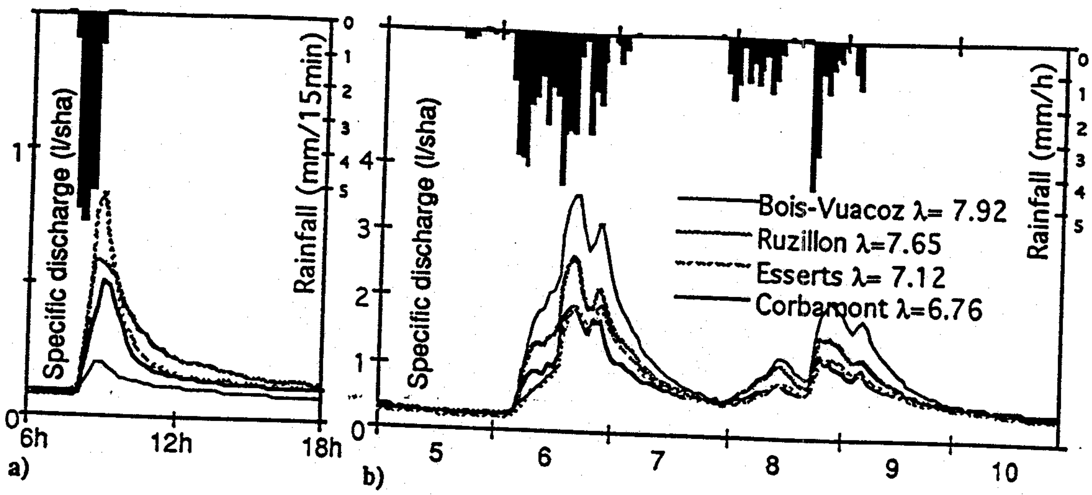


Figure 3.2.2 - Comparative hydrological responses a) June the 20th 1993, 6-18h. b) October 1993, 5 to 10. (a) and b) have the same legend but note changes in scales).

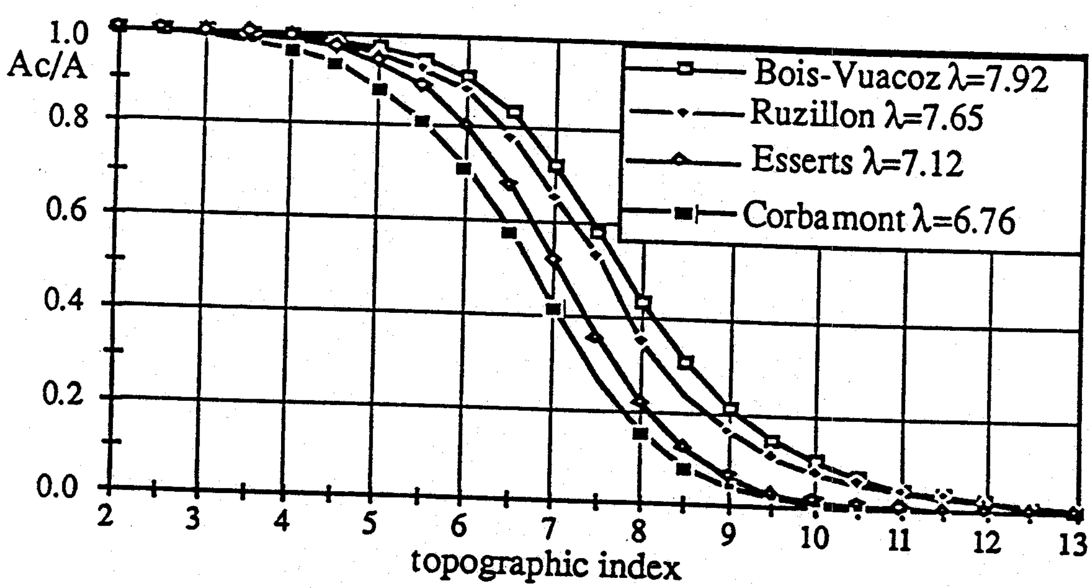


Figure 3.2.3 - Topographic index cumulative distribution for the studied catchments.

Isotope and chemical tracing was performed on three catchments in parallel. The objective is to relate differences in hydrological reaction to differences in storm water pathways and origins. This provides additional insight in the spatial variability of processes and enhances validation of process representation by hydrological models. Even if the differences in shape for the two events in Figure 3.2.2 suggest different dominant runoff generating mechanisms, in storm hydrographs alone there is not enough information to infer them. Environmental tracing is becoming increasingly used to provide much needed insights into stormflow origins and pathways. One of the main advantages of this technique is that it applies to the same scale as flow measurements. Storm hydrograph separation techniques are usually based on the following relationships:

$$C_{sj}Q_s = \sum_{i}^{m} C_{ij}Q_i \qquad j = 1,\dots n \qquad (3.1)$$

$$Q_s = \sum_{i}^{m} Q_i$$

where Q_s ($m^3\ s^{-1}$) is streamflow, Q_i ($m^3\ s^{-1}$) is the contribution to streamflow of component i, C_{sj} is the concentration of streamflow in tracer j, C_{ij} is the concentration of component i in tracer j, n is the number of tracers and m is the number of components (also called end-members). While the last equation ensures the conservation of water flow, the first n equations express the conditions for the conservation of the n tracers. This conservative mixing hypothesis is the basic assumption on which hydrograph separation models rely. The selection of tracers with such a conservative behavior is of major concern. These equations form a linear system with $n+1$ equations and m unknowns (Q_i). For this system to have a solution the rank of the matrix $\|C_{ij}\|$ must be equal to m. In order to secure that the solution is not too sensitive to spatial and temporal variability in C_{ij} the matrix should also be well conditioned. This is usually expressed as the condition for chemical (of isotopical) identity of components (Ogunkoya and Jenkins, 1993) or that the components be well defined (intra-component variability significantly lower than differences between components) as formulated by Christophersen et al. (1990).

For the Haute-Mentue catchment Iorgulescu et al. (1994) have shown that the most frequently used two component model ('old water' with baseflow signature and 'new water' with rainfall signature) based on a single isotopic tracer is inadequate. Soil-water, with a significantly different signature (chemical and isotopical) from that of deep groundwater, may have an important, even dominant contribution. Therefore a three component model which accounts not only for deep groundwater and incident precipitation, but also for soil-water is needed to explain stormflow pathways and origins. As implied by the discussion in the previous paragraph at least two independent tracers are needed for such a model. Theoretical considerations as well as a detailed field study identified dissolved silica and calcium as good candidates for this model. Silica serves to distinguish soil-water and deep groundwater which have relatively high silica concentrations (350 $\mu eq l^{-1}$) from throughfall with concentrations close to 0. Calcium helps to distinguish between the carbonate rich ($\approx$2450 $\mu eq l^{-1}$) deep groundwater in contact with the bedrock or the weathering zone, soil-water from the acid soils (dystric cambisoils) with concentration around 300 $\mu eq l^{-1}$ and throughfall (60 $\mu eq l^{-1}$).

In dry conditions weak catchment reactions can be explained as a mixture of deep groundwater and rainwatre. What differentiates tracer based hydrograph separation results from the Haute-Mentue catchments with respect to most similar studies in humid temperate limate is the relatively low proportions of groundwater in the stormflow hydrograph. This is noted for a large range of events. For dry antecedent conditions and high intensity rainfall events results from the present study corroborate those obtained by Jordan (1992, 1994) on the Alloux sub-catchment. He found contributions of 'new water' in the storm hydrograph of 90% for a high intensity storm (35 mm in 0.5 h) and 100% for a small event (.2 mm quickflow for 9.3 mm precipitation) in dry antecedent conditions. The most probable source areas are the wetter groundwater seepage zones and riparian areas.

The 7-14 September 1993 period offers an interesting example of temporal variability in catchment response (Figure 3.2.4). Following a sequence of three significant rainfall events with similar depths (45 mm, 52mm and 39 mm) and maximum intensities, falling on an initially dry soil, the catchment response substantially increased (runoff coefficients of 5%, 20% and 25%). The previously described three-component mixing model was used to infer stormflow pathways. There is some uncertainty in these separations, principally due to spatial and temporal variability in soil-water. However, qualitatively the results are well supported by the data. Moreover, chemical and isotopic results agree well and are further confirmed by piezometric evidence. Results suggest that soil-water which was previous to event in unsaturated conditions (as for the 7-8 September event) or in partly saturated conditions (as for the events of 9-10 and 13-14 September) significantly contributed to stormflow. The relative contribution of soil-water increased throughout the three events. The contribution of water with a baseflow signature followed an inverse trend, being maximum (however only about 33% of total flow) in the first event and subsequently decreasing. It is also believed that a part of the 'deep groundwater' contribution comes from soil zones were concentration in calcium has values between those for baseflow and soil-water. Samples from the riparian area show there are quite significant concentration gradients in soil-water both laterally and vertically. However these concentrations are bounded by the soil-water and groundwater components which justifies the use of the three component model.

Piezometric measurements (Figure 3.2.5) confirm that a considerable soil depth became saturated and further explain the temporal variability in catchment response. The group P1-P3 are located in valley bottoms or near foot slopes, while P4-P6 are in upper or middle slope positions. It may also be observed that in wet conditions piezometers except P1 and P3 showed rapid variations, recovering in 1-2 days pre-event levels. For one piezometer (P6) 30 mm of rainfall are needed on average to reach saturation at the ground level. At site P3 a piezometer installed at 30 cm and a nest of tensiometers indicate that an impeding horizon at shallow depth produces a perched watertable. This implies that, for a significant catchment area the topsoil layer has been able to temporarily store and transmit considerable amounts of water.

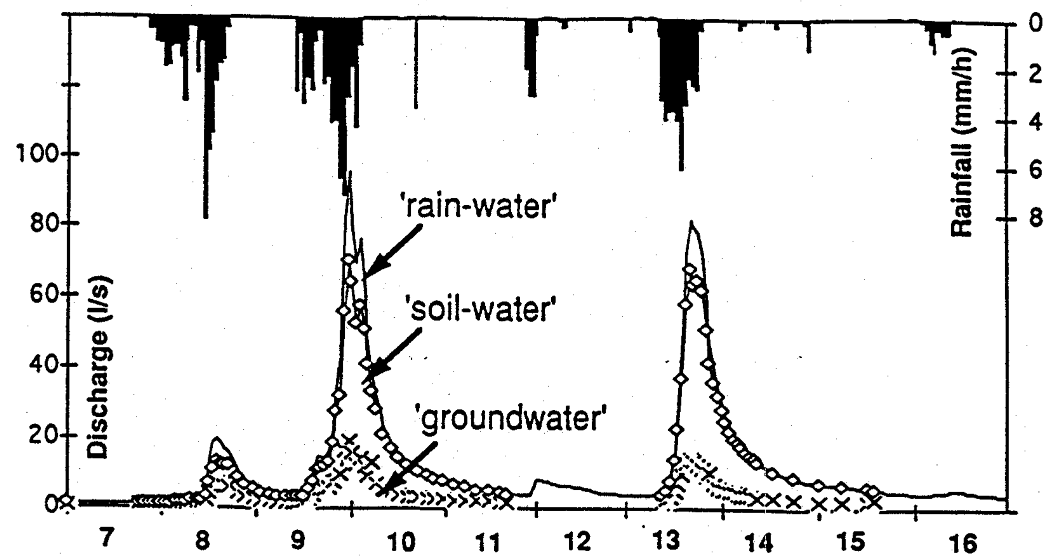


Figure 3.2.4 - Bois-Vuacoz 7-14 September 1993. Tentative identification ofstormflow pathways using a three component chemical mixing model.

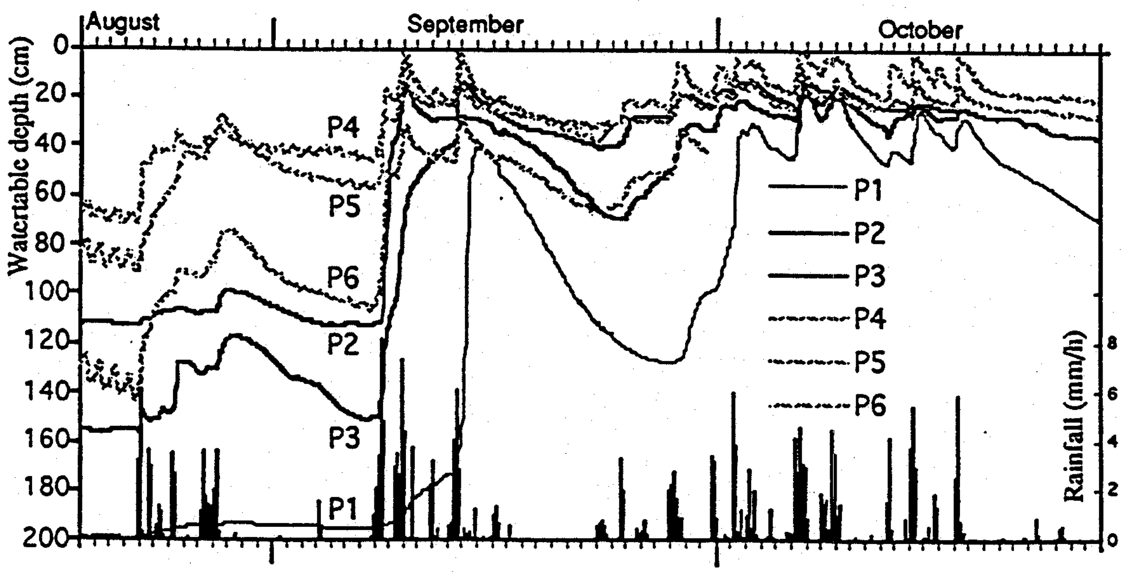


Figure 3.2.5 - Rainfall and water table depths for six continuously recording piezometers during the period 19 August - 27 October 1993.

Piezometric behavior also suggests that a significant part of rainfall followed subsurface pathways to reach the stream. This is confirmed by the chemical dilution of soil water samples with respect to pre-event values. Piezometer measurement show also supplementary evidence for the variable contributing area concept, as for some piezometers (as P4 or P5) about 40 mm of rainfall can make them become contributing areas, while for others (not shown in Figure 3.2.5), after the 160 mm of rainfall in the 7-14 September period, watertables didn't raise above 200cm.

The evidence already presented suggests the possibility to use the topography based hydrological model TOPMODEL to explain temporal and spatial variability in hydrological reactions at the catchment scale. Modeling results will be presented in the following sections. However piezometer data somewhat temper our expectations. TOPMODEL's theory implies a strong correlation between topographic index and watertable depths. The study of Jordan (1992, 1994) showed that, for a 25 piezometer network on an elementary catchment, this correlation was in fact quite weak.

In the present study a more sparse network of 30 piezometers was monitored (situated on what was considered as being 5 representative hillslopes) in an effort to capture the soil and topographic variability at a larger scale. Weak correlation between watertable depth and topographic index was also found, but watertables evolved in a temporally consistent manner (good correlation coefficients between observations made in time). Continuously monitored piezometers also show that low topographic index locations (P2 and P3) may have a behavior quite similar to higher topographic index locations (P4-P6). This suggests that factors other than the topographic index dominate behavior at the point scale. However, it is believed that at different scales different physical factors may dominate variability in hydrologic response. It is believed that piezometric measurements alone may not be a reason for rejecting TOPMODEL for catchment scale modeling.

3.2.2 Experiments on the REAL COLLOBRIER catchment

The purpose of these experiments was the coupling, over the same catchment, between experiments and modelling for a better identification and understanding of flood runoff generating mechanisms. As proposed in AFORISM, the catchment has been chosen to focus on small Mediterranean basins, more prone to flash flooding and characteristic of Southern Europe.

The modelling at basin scale will be discussed elsewhere in this chapter of the report, but it is worth noticing that a model specially studied by different groups (Bologna, Grenoble, and Lausanne) is TOPMODEL, first proposed by and developed in cooperation with the University of Lancaster. This model focuses on the role of quickly varying aquifers in creating variable saturated contributing areas. So the elementary feature considered in the basin is no longer a parcel but rather an hillslope, therefore the following experiments were designed to test these hypotheses.

The experimental part has considered an hillslope, as representative as possible of the catchment which was concurrently modelled, on the site available to the French partner: the Réal Collobrier experimental basin. This basin has been described elsewhere in this report *(see Section on available data sets)*. The experimental work has been performed over a subbasin of 8.5 km^2 called Les Maurets (see Figure 3.2.6), more intensively observed than the total catchment. Nearby the flow gauge, a sampler for isotopic and geochemical analyses had been installed by another research institution, from which a separation of flood flows into components was expected.

The contribution of INPG-Grenoble has consisted in the instrumentation of an hillslope to follow the build up of water content and eventually of a temporary aquifer into the topsoil layers. The selected site consists of a steep hillsope of some 160m followed by a gently sloping terrace 30 m wide, overhanging the river 2 m below (Figure 3.2.7). The purpose was the continuous monitoring of capillary pressures and groundwater levels during rainevents. During the spring and summer of 1992, several sites with nested tensiometers and piezometer were installed. Unfortunately, it has proved very dificult to capture manually continuous data during rainevents, so that later in the summer 1993, a data acquisition system was installed, financed by another contract.

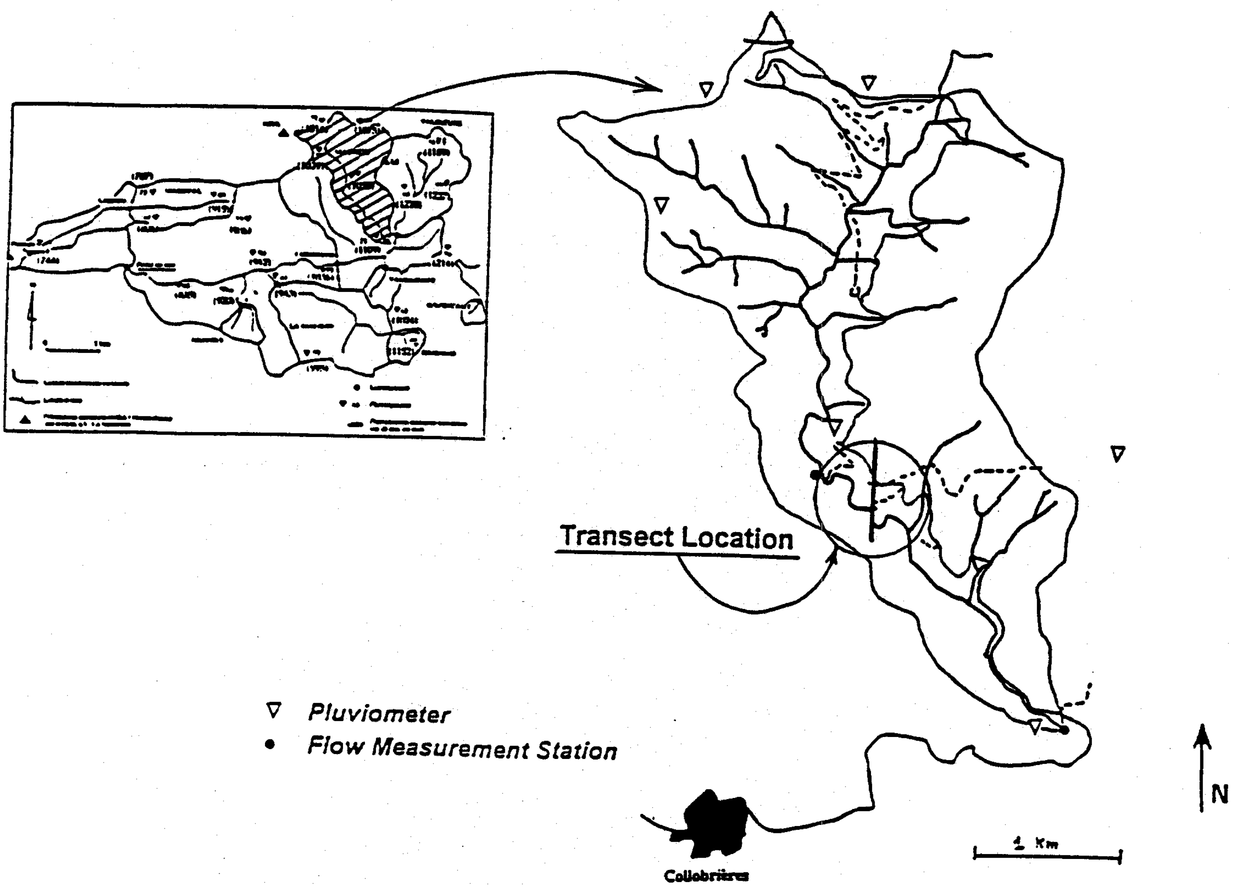


Figure 3.2.6 - Map of Maurets catchment (8.5 Km^2) within the Real Collobrier basin

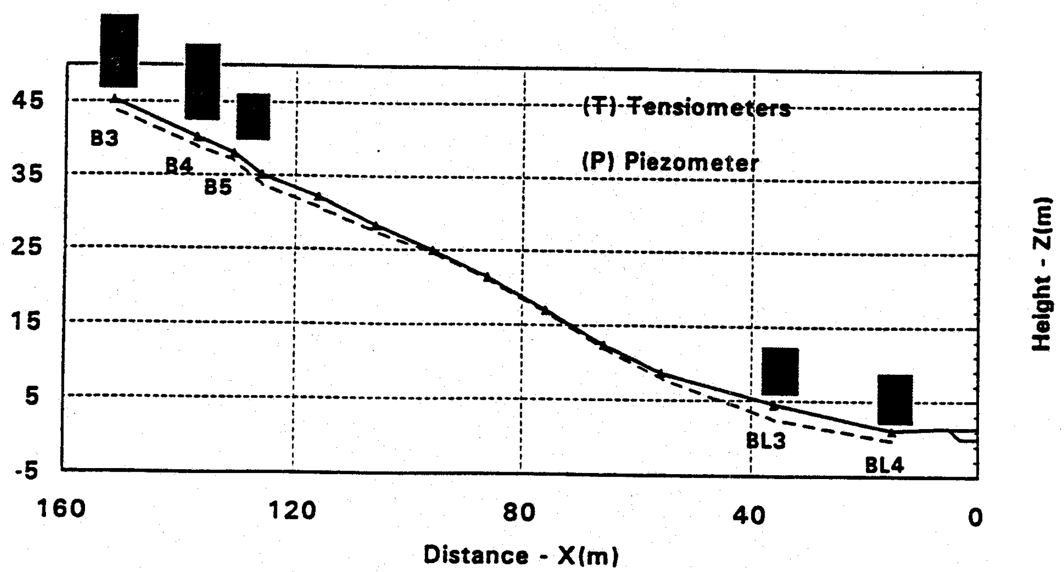


Figure 3.2.7 - Instrumented Hillslope cross-section

Meanwhile, extensive campaigns of soil characterisation have been performed since the beginning of the project, first to select the approriate site, and later to collect a good knowledge of the soil geometric and hydrodynamic properties: soil depths, porosity profile, saturated conductivity profile, and the relationship between succion and conductivity (Figure 3.2.8a, 3.2.8b, 3.2.8c). This has been performed with the help of a Guelph permeameter, although it was not adapted to near surface measurements. So more originally, a new disk permeameter called TRIMS (Triple Ring Infiltrometer with Multi Suction) with controlled negative suction has allowed to characterise the first cm of the soil. It has stressed the specific role of the top 20 to 30 cm layer, which can be associated with the root zone, where the conductivity is about ten times larger than in the underlying soil.

The use of Time Domain Reflectometry (TDR) has been tested during the stay of an ERASMUS students coming from the UNUT-Newcastle partner, but has not proved immediately usable. Some systematic differences were noticed between actual water content (measured by gravimetric methods) and values displayed by the TDR. So a new calibration technique for this device has been developed and has been used in the 1993 experiments (Figure 3.2.8c).

Surprisingly, the decrease in porosity (Figure 3.2.8a), and more specifically in conductivity (Figure 3.2.8b) is very similar to the one hypothetised by TOPMODEL. In spite of a rather large spatial variability, first it looks almost exponentially decreasing with depth, and next its characteristic depth of decrease lies between 15 and 20 cm and appears very consistent with the decrease parameter identified in TOPMODEL calibration.

Other measurements have been launched recently, with the help of a rain simulator, to estimate the friction characteristics of the actual overland flow on the vegetated hillslope. Although outside of this project, the first results confirm that the order of magnitude for speed on the slope is the cm/s (or some 10 to 100 m/h), while the first estimations within natural riverbeds are around .5 to 1m/s (or a few km/h). This too has proved helpful in understanding results of global, more operational approaches at basin scale, as will be discussed later in this section.

As a temporary conclusion, the AFORISM project has been the trigger of these intensive experiments. There has been some trial and error approach in selecting both the sites and the sensors, in spite of the helpful transfer of expertise collected from the EPFL-Lausanne partner. These experiments are now being pursued under other national contracts.

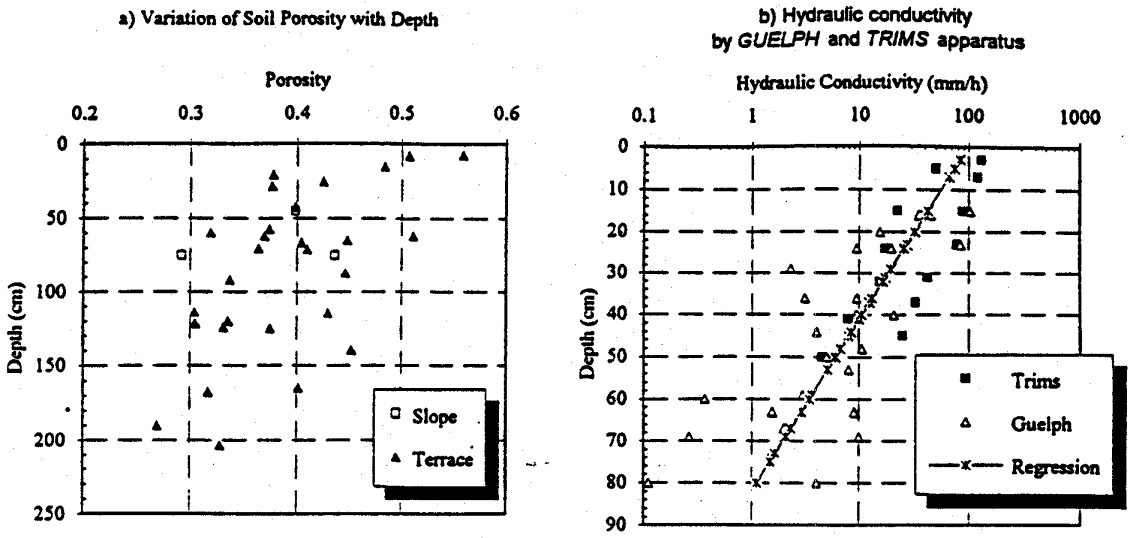
However, even during the AFORISM project, useful results collected on the field site have allowed a refined modelling of the hillslope. It is presented here in the experimental section, because it is more directly interconnected with the experimental work than with the more global approach at basin scale of the operational part of AFORISM, although there could be some connections in the future.

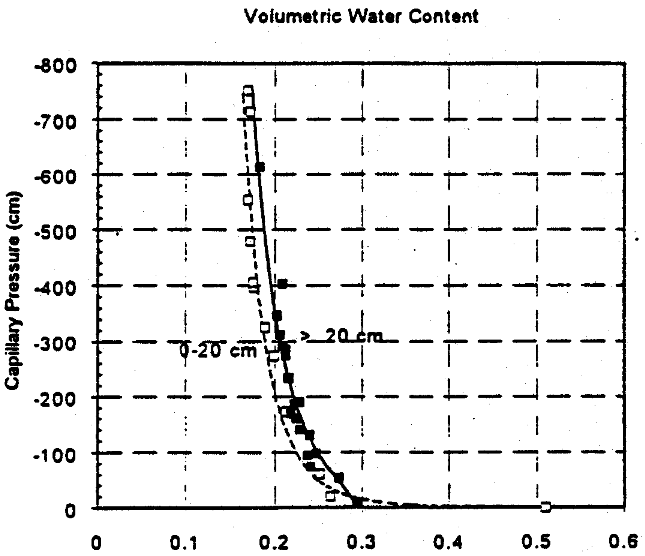
The initial idea was to design a refined mechanistic model of the whole hillslope, but it had to be restricted first to the modelling of its bottom part: the terrace lying by the river. A sketch of the domain modelled is shown on (Figure 3.2.9).

The model is based on the Richards equation for the unsaturated zone, applied to a two layer sloping soil, in order to simulate infiltration and the potential overland flow. These equations are coupled to a groundwater flow model when water pressures become positive. The numerical solution is performed by finite difference, using the actual hydrodynamic characteristics measured in the field.

Since it has not been possible to capture a complete event during the project, the model has been used for sensitivity analysis, trying to see if saturated area can reasonably appear in this context. Using the two layer model, with a 10% slope, it has been seen that under strong but not unusual rainfall intensities (30 mm/h), a temporary aquifer can develop within the toplayer, and that saturation from below may appear and extends sometimes very quickly. These numerical experiments are not fully realistic by now, since the boundary conditions are not either (no feeding of the terrace from the upslope).

However, it is comforting that, based on realistic values of soil parameters, this process of variable contributing areas appears acceptable even in this Mediterranean context.





c) Soil Hydraulic Properties
Water Content Measured by TDR

Figure 3.2.8 - Soil characteristics along the instrumentedtransect

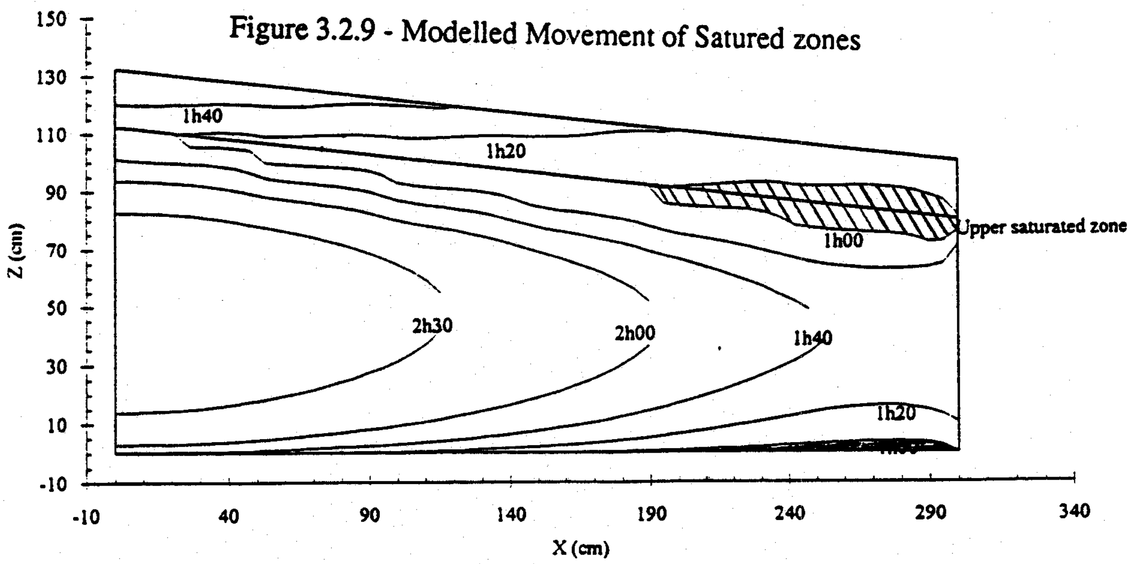


Figure 3.2.9 - Modelled Movement of Satured zones

Initially, it was hoped that field experiments would have allowed calibration of a complete mechanistic model of the instrumented hillslope which itself would have provided the time sequence of saturated zones expansion and decay along the slope. This deterministic simulation would then have been used to constrain the expansion and decay computed over the whole basin by the more simplistic and conceptual TOPMODEL.

It has not been possible to run completely this chained and logic approach, essentially because of practical problems in implementing a new instrumented site. However, the intermediate results have already proved useful for the project. And this work will be pursued under the funding of other projects.

3.3 VARIABLE CONTRIBUTING AREA MODELS

3.3.1 Introduction

At the very beginning of this project, a still open question was: is it thinkable for a Mediterranean basin to generate flood discharges following the variable contributing area mechanism? Experimental works described in paragraphs 3.2.1 and 3.2.2 of this chapter have now answered positively, but the associated question at that time was the availability of models based on this concept and their effective applicability to Mediterranean catchments.

Among them, TOPMODEL turns out to be completely driven by this mechanism. Nevertheless, according to its developers from Lancaster University, it had only been applied at that time in temperate humid basins never exceeding 10 km^2 or so. Therefore it was worth becoming familiar with it and applying it to typically Mediterranean and possibly larger basins. This has been done first by the EPFL group on the Mentue catchment, next by the INPG-LTHE group on the Real Collobrier watershed during the first half of the project.

Later, the model was transferred to UNIBO for intercomparison and further developments, so that in the end, the 3 groups have working concurently and cooperatively on different aspects of this model, as will be detailed in paragraph 3.4 of this chapter.

In parallel the ARNO model developed in Bologna from the Xinanjiang model, although not claiming explicitly being based on the variable contributing area concept, could easily be interpreted and adapted to match this concept.

So before presenting in paragraph 3.4 the respective developments and contributions performed in each group, it seems worthwhile to give a brief presentation of those two models.

3.3.2 Description of the TOPMODEL

A full description and analysis of the behaviour of TOPMODEL is given in Franchini et al. (1996). Much of the material given here is based on that paper.

Two components can be identified in all conceptual rainfall-runoff models: the first represents the water balance at soil level and the second the transfer to the basin outlet.

- The water balance at the soil level is the component which characterises the model and constitutes the most important part. Cordova and Rodriguez-Iturbe (1983) summarise this concept most succinctly, saying "..the problem is more *what* to route than *how* to route", a consideration broadly corroborated by the Franchini and Pacciani study (1991).

- The transfer component is generally divided into two phases: the first representing transfer along the slopes towards the drainage network and the second representing transfer along the drainage network to the basin outlet.

In the TOPMODEL, by its very nature, the flow in the soil is available directly along the drainage network, while the surface runoff component is usually made available to the drainage network inside each time interval: the saturation areas have, (or at least they should have in order to validate this assumption), a limited extension around the drainage network. Accordingly, in the TOPMODEL the presence of a refined hillslope transfer component is not necessarily justified, while the drainage network transfer component still has some importance.

In the original version this transfer in the river network is accomplished by a kinematic scheme. In Franchini et al. (1996) the kinematic transfer component has been replaced by a parabolic unitary hydrograph obtained by the analytical integration of the convective-diffusion equation of channel flow, a comprehensive description of which can be found in Todini and Bossi, (1986), and Franchini and Todini (1988) (cf. also Franchini and Pacciani, 1991). Still in Franchini et al. (1996), but also in Obled and Wendling (1991) it was decided to retain the convolution with respect to the hillslopes, since the extension of the saturation areas found in the different simulations was considerable, with peaks of around 50%: indeed the immediate transfer to the drainage network tended to produce, in the various simulations, a systematic anticipation of the flood events.

However, in recent versions of TOPMODEL, the channel routing was simply performed by a set of isochrones based on a constant speed in the channel (between 0.5 and 1 m/s). This appears sufficient, although the ignorance of an hillslope transfer also causes underestimation of the water delivery to the outlet. So an hillslope transfer function could be added but should have been made variable with saturated area extensions. In fact, it had been seen that a global transfer function Obled and Wendling (1991) that merges both hillslope and channel transfer is relatively time invariant and robust, in that it benefits from compensatory effect between extension of saturated areas over the hillslope and increasing speed in the channels (see also Chapter 4 and Gresillon et. al. 1994).

Below, focus will essentially be made on what represents the water balance component at the soil level and what actually characterises the TOPMODEL. Although it is always difficult to try to summarize TOPMODEL, a first paragraph as much equation free as possible will try to give the substance of TOPMODEL, while more detailed aspects will be given in the next paragraphs.

Assuming that aquifer rise is the driving mechanism to generate temporary impervious areas, saturated from below, TOPMODEL is essentially a simplified aquifer model. It attempts to capture the dynamics of the most reactive aquifer present in the catchment, preferably the permanent or temporary hillslope aquifers developing in the topsoil weathered zone.

The model itself works as a succession of stationary states, for which the level of the aquifer is computed at every time step both as a "subbasin" average, and more locally at the scale of a class of pixels similar in terms of hydraulic behaviour. This water level is expressed conversely in terms of deficit, i.e. the amount of water necessary to bring the aquifer to the soil surface (this includes the role of porosity). The sequence is to compute first the average deficit at subbasin scale, and then to distribute it. The average aquifer level, or deficit, is the result of a water balance between:

- the output, by aquifer drainage downslope into the river network
- the distributed input from the upper non satured soil by percolation
- and the fluctuation of the aquifer storage, expressed by its average level.

The input is itself the result of a more or less simple soil water balance, between incoming rainfall, depression and vegetation storage including interception loss, unsaturated zone storage and evapotranspiration loss. Hortonian flow may even be generated when rainfall intensity exceeds the infiltration capacity (saturation from above).

However, the cornerstone of TOPMODEL is the way method used to distribute the average aquifer level, or deficit, into a local deficit at any point i into the catchment. This is done by assuming a direct connection with an hydrotopographic index, first proposed by K. Beven and J. Kirkby (1979), defined at any point *i* as: $Ln(Ai / Ti.tg Bi)$. To understand this index, consider that, in quasi stationary conditions:

- the provision of water at any point is proportional to the drained area Ai
- while the drainage or removal of water through a unit length of the soil profile is controlled locally by the soil transmissivity Ti and the energy slope of the aquifer. This one is further supposed close to the local topographic slope $tg Bi$.

If the first factor overcomes the second one, the transfer can no longer take place within the soil profile, and the soil saturates: This ratio is therefore an index of the soil facility to become saturated. Preferential zones for easy saturation corresponds to large values of the index obtained when the drained area is large and/or when the local slope is low (e.g. bottom of hillslopes).

From simple physical and analytical derivations described in the next paragraphs, it may be shown that the local deficit to the aquifer d_i is inversely connected to the local value of the index $Ln(Ai / Ti.tg\, Bi)$, i.e. the larger the index, the smaller the deficit or the depth to the water table. Since any point i may be characterised by its index departure $Ln(Ai / Ti.tg\, Bi) - Ln(A / T.tg\, Bi)m$ to the average value of the index at subbasin scale, the local aquifer level is distributed accordlingly around its average value at time t, $dm(t)$, by taking $di(t) - dm(t)$ negatively proportional to the index departure. (see Figure 3.3.1).

Moving from time step t to time step $t+1$ implies:

- first to compute the new average status $dm(t+1)$ of the aquifer, as a function of its drainage to the river and of the recharge from above.
- then to determine the local deficit $di(t+1)$ from this average value and from the local index departure $Ln(Ai / Ti.tg\, Bi) - Ln(A / T.tg\, Bi)m$
- finally, a check must be made for those point where the deficit becomes positive, which means that the supposed aquifer level has overtopped the soil surface, therefore producing contributing areas saturated from below. Over those variable contributing areas, overland flow is generated and routed to the river, and then to the outlet.

This paragraph will come back on the following components that have been identified:

- vegetation interception capacity,
- surface runoff due to saturation excess,
- surface runoff due to infiltration excess and, finally,
- the flow in the saturated zone.

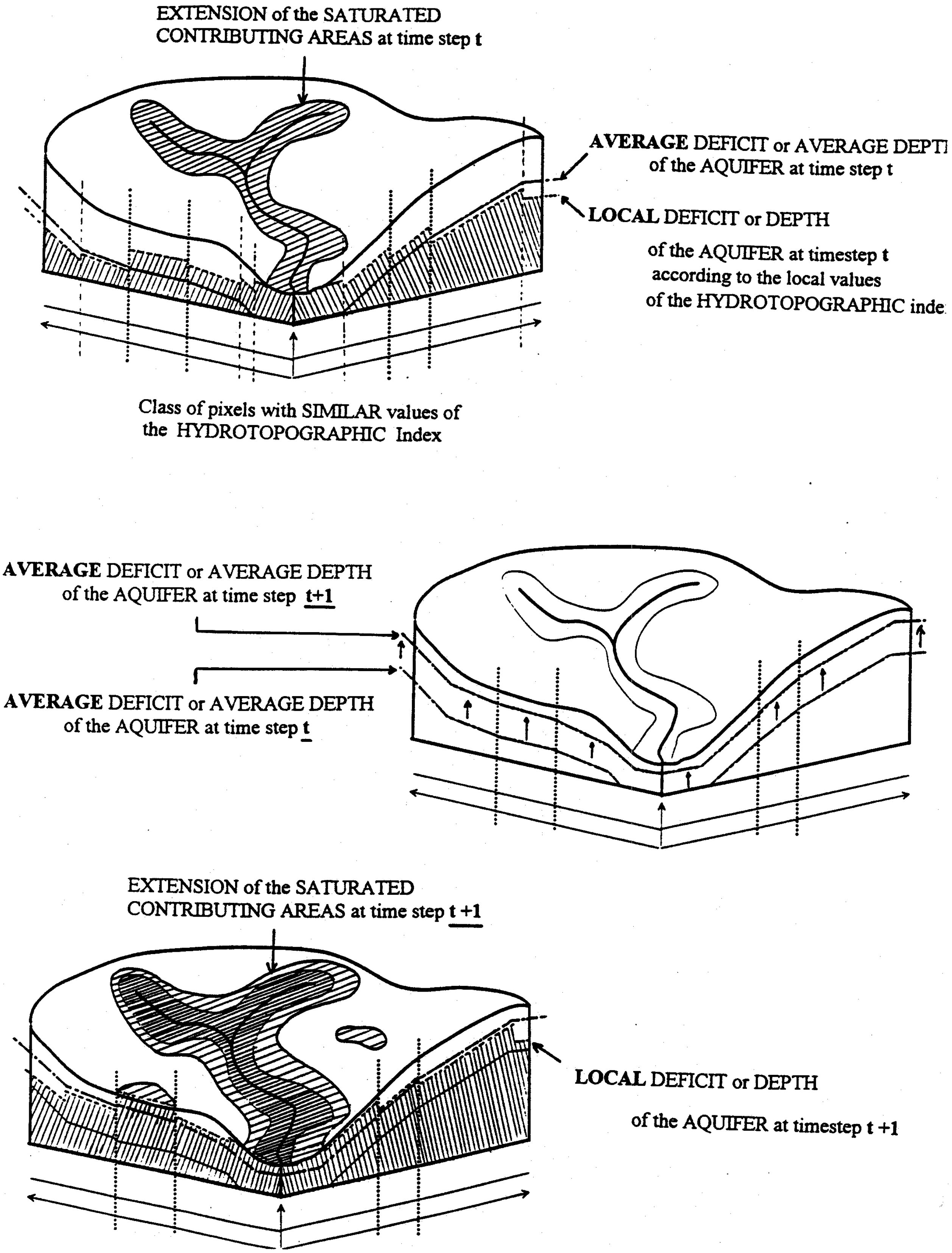


Figure 3.3.1 - Functionning of the dynamic aquifer in TOPMODEL
(Transition from time step t to time step t + 1)

But at this stage it is worth making a few remarks on the vegetation's interception capacity and the calculation of surface runoff from infiltration excess:

- What is refered to here as the vegetation interception capacity and indicate by the symbol SR_{max} is described in many other papers as "soil root capacity" (cf. for example Durand et al., 1993). In fact this component is not involved in the exchanges between unsaturated and saturated zone and its sole purpose is that of accumulation from which the water is extracted by potential rate evapotranspiration. Its very "starting position" in the chain of calculations inside the "programme" (or "code") basically assigns to it the role of intercepting available precipitation. This is why the name "canopy interception capacity" is preferred to "soil root capacity". Obviously, in computational terms nothing changes in either case.
- The surface runoff due to infiltration excess is the component described in Sivapalan et al. (1987) and is based on the Philip scheme (1957). This description is provided for the sake of completeness in the presentation of the model.

The calculation of the surface runoff component due to saturation excess and flow in the saturated zone has been made, in the version used for the analysis of the TOPMODEL, on the assumption of constant hydraulic conductivity over the whole basin. This does not however affect the validity of the equations presented, which are formulated with reference to the more general case of space-variable hydraulic conductivity, but which are easier to manipulate in this way, thereby simplifying the separation of the topographic information from that regarding the nature of the soil.

The presentation of the TOPMODEL version used is accompanied by a description of the sequence of calculations within the programme, the definition of the starting conditions and the index curve calculation procedures.

Canopy interception capacity

The canopy interception capacity is represented by a reservoir with a capacity of SR_{max}. Water is normally extracted from this reservoir on the basis of the rate of potential evapotranspiration, although a modification has been proposed to account for direct evaporation, or interception loss during rainhours; the net precipitation (represented by the difference between precipitation and evapotranspiration) in excess of the capacity SR_{max} reaches the soil and comprises the input for the subsequent model components.

Surface runoff due to saturation excess

In the TOPMODEL the saturated hydraulic conductivity of the soil follows a negative exponential law versus depth:

$$K_s(z) = K_0 \exp(-fz) \tag{3.2}$$

z : depth in the soil (z-axis pointing downwards);

K_0 : hydraulic conductivity at ground surface. Held to be constant over the entire basin;

f : decay factor of K_s with z, held constant over the entire basin.

This equation will sometimes be written: $K_s(z) = K_0 \exp(-fz) = K_0 \exp(-\frac{z}{M})$ where M has the dimension of length and is equal to the depth at which the conductivity is divided by $e \approx 3$

The "watertable is parallel to the soil surface" (cf. Sivapalan et al., 1987) (see Figure 3.3.2).

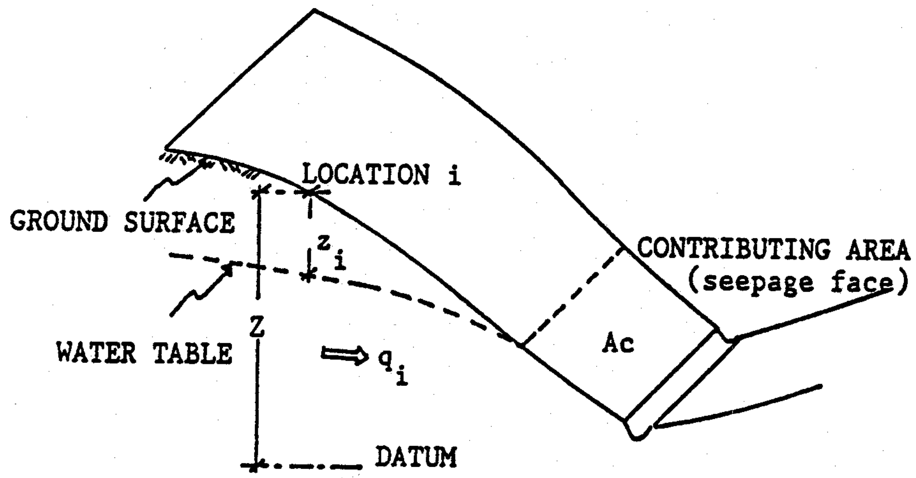


Figure 3.3.2 - Schematic representation of a valley and formation of runoff according to the TOPMODEL. A_c: contributing area to the surface runoff; q_i: interflow corresponding to an area drained per unit contour length.

More precisely, in the calculation of the interflow beneath the watertable positioned at the depth z_i, in steady state conditions, the hydraulic head is approximated by the corresponding slope of the soil surface:

$$q_i = T_i(z_i)tg\beta_i \qquad \text{(Darcy's Law)} \tag{3.3}$$

$tg\beta_i$: surface slope of soil at point *i*.

$T_i(z_i)$: transmissivity at point *i*.

The value of $T_i(z_i)$ is given by integrating equation (3.2) over the vertical:

$$T_i(z_i)=\int_{z_i}^{Z} K_s(x)dx = \frac{K_0}{f}[exp(-fz_i) - exp(-fZ)] = \frac{1}{f}[K_s(z_i) - K_s(Z)] \tag{3.4}$$

Generally it is possible to assume that the saturated hydraulic conductivity at large depth z becomes negligible compared with the conductivity at depth z_i. Substituting (3.4) in (3.3) we get:

$$q_i = \frac{K_0}{f} tg\beta_i\, exp(-fz_i) = T_0 tg\beta_i\, exp(-fz_i) \tag{3.5}$$

where $T_0 = K_0 / f$ is the transmissivity of the fully saturated soil which, like K_0 and *f*, is assumed constant over the whole basin.

Referring to steady state conditions, it is possible to write the continuity equation:

$$a_i R = T_0 tg\beta_i\, exp(-fz_i) \tag{3.6}$$

where:

R : uniform recharge rate to the water table.

a_i : area draining through location *i*, per unit contour length.

Making z_i explicit in (3.6) we get:

$$z_i = -\frac{1}{f} ln\left(\frac{a_i R}{T_0 tg\beta_i}\right) \tag{3.7}$$

By integration over the entire area of the basin we obtain the mean value of the variable z_i:

$$\bar{z} = \frac{1}{A}\int_A z_i dA = \frac{1}{fA}\int_A \left[-ln\left(\frac{a_i}{T_0 tg\beta_i}\right) - ln R \right] dA \tag{3.8}$$

where it is allowed that equation (3.3) continues to hold also for negative values of z_i.

By combining eq.(3.6) with eq.(3.8):

$$\bar{z} = \frac{1}{f}\left[-\frac{1}{A}\int_A ln\left(\frac{a_i}{T_0 tg\beta_i}\right) dA + f z_i + ln\left(\frac{a_i}{T_0 tg\beta_i}\right)\right]$$

and therefore:

$$f \cdot (\bar{z} - z_i) = \left[ln\frac{a_i}{T_0 tg\beta_i} - \lambda \right] \tag{3.9}$$

where: $$\lambda = \frac{1}{A}\int_A ln\frac{a_i}{T_0 tg\beta_i} dA$$

Lastly:

$$z_i = \bar{z} - \frac{1}{f}\left[ln\frac{a_i}{T_0 tg\beta_i} - \lambda \right] \tag{3.10}$$

It is worth noting at this point that in the case of constant transmissivity the expression for λ becomes:

$$\lambda = \frac{1}{A}\int_A ln\frac{a_i}{T_0 tg\beta_i} dA = \lambda^* - ln T_0 \tag{3.11}$$

where:

$$\lambda^* = \frac{1}{A}\int_A ln\frac{a_i}{tg\beta_i} dA \tag{3.12}$$

represents the average value over the area of the basin of the variable $x = ln\frac{a}{tg\beta}$.

Thus, eq.(3.10) becomes:

$$z_i = \bar{z} - \frac{1}{f}\left[ln\frac{a_i}{tg\beta_i} - (\lambda + ln T_0) \right] = \bar{z} - \frac{1}{f}\left[ln\frac{a_i}{tg\beta_i} - \lambda^* \right] \qquad (3.13)$$

In other words the calculation of the depth z_i of the "groundwater" is determined only by the parameter f and the topographic index $x = ln\frac{a}{tg\beta}$. Note now that if $z_i \leq 0$ then the "water-table" is at least level with the surface of the soil and therefore at this point -i- the saturation condition has been reached. All the points with $z_i \leq 0$ generate the basin fraction in saturation conditions where the rainfall produces direct surface runoff. The equation (3.13) shows that if x^* is the value of x which produces $z_i = 0$, then all the points with $x \geq x^*$ are in saturation conditions. The basin percentage with $x \geq x^*$ is then defined on the basis of the index curve which in turn represents the probability distribution of the variable x. The method used of computing the index curve, based on a Digital Elevation Model (DEM) is described later.

Before concluding the descrption of the basic equations of the TOPMODEL it is worth adding that in other papers (e.g. Beven et al., 1988) the reference variable is not the depth of the "water table" z_i but the "moisture deficit" S_i, which is nevertheless linked to the variable z_i through the equation $S_i = (\vartheta_s - \vartheta_r)z_i$, where ϑ_s, ϑ_r represent, respectively, the moisture content in the saturated soil and the residual moisture content. The equations characterising the model written in terms of S_i are entirely identical to the preceding ones (cf. Beven et al. 1988, Wood et al., 1988) except that z_i is replaced by $z_i = S_i / (\vartheta_s - \vartheta_r) = S_i / \Delta\vartheta$, or, as more frequently happens, z_i is substituted by S_i and the parameter $m = \Delta\vartheta / f$ is introduced. Below, unless specified otherwise, reference will nevertheless be made to the equations written directly in terms of depth z_i and transmissivity $T_0 = K_0 / f$. This means that the porosity (or rather $\Delta\vartheta$) is supposed to be equal to 1. This position certainly produces an underestimation of the "water table" depth but it does not influence any consideration developed in the analysis of the assumptions underpinning the model and on the sensitivity of the TOPMODEL to the index curve.

Surface runoff from infiltration excess

In the most recent versions of the TOPMODEL the infiltration excess computation is based on the Philip equation (1957):

$$g = cK_0 + \frac{1}{2} S t^{-1/2} \tag{3.14}$$

where g is the potential infiltration capacity, S the "sorptivity", and K_0 the saturation hydraulic conductivity at the soil level. The "sorptivity" S is linked with K_0 as follows:

$$S = S_r K_0^{1/2} \tag{3.15}$$

In the most recent versions (cf. Sivapalan et al. 1987) K_0 may be considered randomly variable over the whole basin while S_r and c are regarded as constant coefficients.

However in this study K_0 is considered as constant. Moreover, as is clear from the results of the simulations described in Franchini et al. (1996), the values of K_0 obtained during calibration are so high that no type of Hortonian mechanism was activated. In these circumstances the behaviour of the infiltration mechanism in the TOPMODEL can be entirely ignored.

Calculation of the flow in the saturated zone and sequence of calculations in the TOPMODEL

The equation (3.13) permits the estimation of the saturated basin fraction on the basis of the knowledge of the current value of $\bar{z}$. The value of $\bar{z}$ is updated at every t on the basis of the following equation:

$$\bar{z}^{t+1} = \bar{z}^t - \frac{\left(Q_V^t - Q_B^t\right)}{A} \Delta t \tag{3.16}$$

where:

Q_V^t: Recharge rate of the saturated zone from the unsaturated zone over the time interval $t, t+\Delta t$;

Q_B^t : "Base flow", connected to the flow in the saturated zone, over the time interval $t, t+\Delta t$;

A: Area of the basin;

Δt: Time interval.

The quantity Q_B^t can be defined analytically:

$$Q_B^t = \int_L Q_{B_i}^t dL = \int_L T_0 tg\beta \, exp\left[-f \, z_i^t\right] dL \qquad (3.17)$$

where L is twice the length of all stream channels. Bearing in mind eq.(3.13), this becomes:

$$Q_B^t = \int_L T_0 tg\beta \, exp\left[-f \, \bar{z}^t - \lambda^* + ln\frac{a}{tg\beta}\right] = T_0 \, exp\left[-f \, \bar{z}^t\right] \cdot exp\left[-\lambda^*\right] \cdot \int_L a \cdot dL$$

Since:

$\int_L a \cdot dL = A$ (total area of basin)

than:

$$Q_B^t = A \cdot T_0 \cdot exp\left[-\lambda^*\right] \cdot exp\left[-f \, \bar{z}^t\right] = Q_0 \cdot exp\left[-f \, \bar{z}^t\right] \qquad (3.18)$$

with: $Q_0 = A \cdot T_0 \cdot exp\left[-\lambda^*\right]$

Now, Q_V^t can be thought as the sum of the contribution of all the grids measured from the Digital Terrain Model (DTM) covering the basin:

$$Q_V^t = \sum_{i \in A} Q_{V_i}^t = \sum_{i \in A} \alpha_i K_0 \, exp\left[-f \, z_i^t\right] \qquad (3.19)$$

where α_i is the area of the *i-th* grid. The equation assumes that the transfer from the unsaturated to the saturated zone is controlled by the conductivity at the depth of the "perched water table", under unit vertical hydraulic gradient (Beven, 1986). Naturally eq.(3.19) holds good when the current water content in the unsaturated zone is not a limiting factor; otherwise the contribution is calculated on the basis of the actual amount of water available. Lastly, it is worth stressing that eq.(3.19) extends to all the grids where $z_i \geq 0$.

Initial conditions

The continuity equation (3.16) is initialised assuming that the simulation begins after a long dry period; in other words the unsaturated zone is held to be totally dry and the flow observed at the basin outlet is deemed to have been generated only by the "base contribution":

$$Q_V^1 = 0$$
$$Q_B^1 = Q_{ob}^1$$

Recalling eq.(3.18):

$$Q_B^1 = Q_0 \exp(-f \cdot \bar{z}^1)$$

and therefore:

$$\bar{z}^1 = -\frac{1}{f} \ln\left(\frac{Q_{ob}^1}{Q_0}\right) \tag{3.20}$$

With eq.(3.13) it is possible to define the initial depth of the "perched water table" in each grid.

Description of the computational procedure for $x = \ln\frac{a}{tg\beta}$ in each grid square

In order to calculate $x = \ln\frac{a}{tg\beta}$ in each grid the contributing area for that grid must be calculated and divide by the tangent of the slope relevant to that grid. Only the downward directions are considered below. If it is assumed that all the directions have the same water transportation probability, then the area drained by contour unit of length can be calculated as (Quinn et al.,1991):

$$a = \frac{A}{nL} \tag{3.21}$$

where:

$n =$ number of downstream directions;

$L =$ effective contour length orthogonal to the direction of flow ($L = \frac{GS}{1+\sqrt{2}}$, with GS, Grid Size of the DTM.);

$A =$ total area drained by current grid (total upslope area).

One possible representation of $tg(\beta)$ is:

$$\overline{tg(\beta)} = \frac{1}{n}\sum_{i=1}^{n} tg(\beta_i) \tag{3.22}$$

where $tg(\beta_i)$ is the slope of the line connecting the current grid with the furthermost grid in the *i-th* downstream direction. Therefore:

$$\frac{a}{\overline{tg(\beta)}} = \frac{A}{L\sum_{i=1}^{n} tg(\beta_i)} \quad \text{and} \quad ln\left(\frac{a}{\overline{tg(\beta)}}\right) = ln\left(\frac{A}{L\sum_{i=1}^{n} tg(\beta_i)}\right) \tag{3.23}$$

The amount of A that contributes in each downstream direction i is thus calculated as:

$$\Delta A_i = \frac{A \cdot tg(\beta_i)}{\sum_{i=1}^{n} tg(\beta_i)} \tag{3.24}$$

The procedure is repeated on all the DTM grids proceeding downstream.

Summary

It turns out (Franchini et al., 1996) that the soil (as distinct from the transfer) component of TOPMODEL can be described by three parameters: f, K_0 and SR_{max} in addition to a measured topological index. This parsimony makes it relatively easy to calibrate with real rainfall-runoff data compared to some other conceptual models.

3.3.3 Description of the ARNO Model

A full description of the ARNO model can be found in Todini (1996) from which much of the following material is taken.

Soil Moisture Balance Module

The soil moisture balance module of the ARNO model derives from the Xinanjiang model developed by Zhao (1977, 1984), who expressed the spatial distribution of the soil moisture capacity in the form of a probability distribution function, similar to that advocated by Moore and Clarke (1981) and Moore (1985). Successively, in order to account more effectively for soil depletion due to drainage, the original Xinanjiang model scheme was modified by Todini (1988), who originated the ARNO model within the frame of the hydrological study of the river Arno.

The basic assumptions expressed in the soil moisture balance module of the ARNO model are:

- the precipitation input to the soil is considered uniform over the catchment (or sub-catchment) area;

- the catchment is composed of an infinite number of elementary areas (each with a different soil moisture capacity and a different soil moisture content) for each of which the continuity of mass can be written and simulated over time;

- all the precipitation falling over the soil infiltrates unless the soil is either impervious or it has already reached saturation; the proportion of elementary areas which are saturated is described by a spatial distribution function;

- the spatial distribution function describes the dynamics of contributing areas which generate surface runoff;

- the total runoff is the spatial integral of the infinitesimal contributions deriving from the different elementary areas;

- the soil moisture storage is depleted by the evapo-transpiration as well as by lateral sub-surface flow (drainage) towards the drainage network and the percolation to deeper layers;

- both drainage and percolation are expressed by simple empirical expressions.

A sub-basin of given surface area S_T (excluding the surface extent of water bodies such as reservoirs or lakes) is in general formed by a mixture of pervious and less pervious terrains, the response to precipitation of which will be substantially different. For this reason the total area S_T is divided into the impervious area S_I and the pervious area S_P :

$$S_T = S_I + S_P \tag{3.25}$$

In order to derive the expressions needed for the continuous updating of the soil moisture balance, let us first deal with the amount of precipitation that falls over the pervious area. Given that from equation (3.25) the entire pervious area is:

$$S_p = S_T - S_I \tag{3.26}$$

if one denotes by $(S - S_I)$ the generic surface area at saturation, x, defined as:

$$x = \frac{S - S_I}{S_T - S_I} \tag{3.27}$$

will indicate the proportion of pervious area at saturation. Zhao (1977) demonstrated that the following relation holds reasonably well between the area at saturation and the local proportion of maximum soil moisture content w/w_m, where w is the elementary area soil moisture at saturation and w_m is the maximum possible soil moisture in any elementary area of the catchment.

$$x = 1 - \left(1 - \frac{w}{w_m}\right)^b \tag{3.28}$$

This can be inverted to give the cumulative distribution for the elementary area soil moisture at saturation, shown in Figure 3.3.3 and defined as:

$$w = w_m\left[1 - (1 - x)^{\frac{1}{b}}\right] \tag{3.29}$$

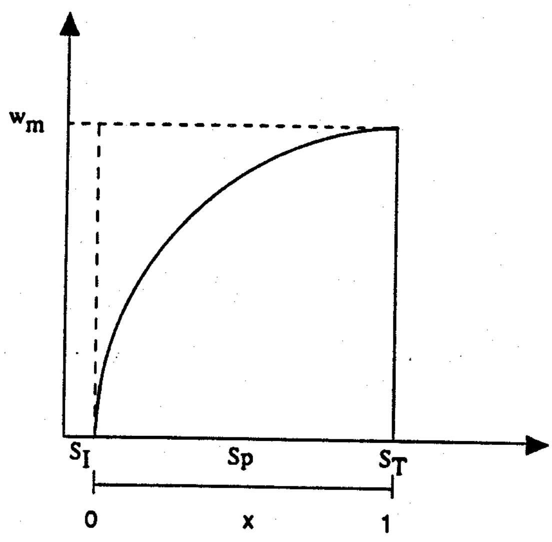


Figure 3.3.3 Cumulative distribution for the elementary area soil moisture at saturation

In the ARNO model, an interception component (Rutter et al., 1971, 1975) is not explicitly included. Nevertheless in order to allow for a substantially larger evapotranspiration when the canopies are wet (without obviously explicitly accounting for the disappearance of the stomatal resistance (Shuttleworth, 1979)), the following succession of operations is followed. If the precipitation P is larger than the potential evapotranspiration ET_p, the actual evapotranspiration, for the reasons expressed above, is assumed to coincide with the potential, i.e.:

$$ET_a = ET_p \tag{3.30}$$

and so an "effective" meteorological input M_e, defined as the difference between precipitation and potential evapotranspiration, becomes:

$$M_e = P - ET_p = P - ET_a > 0 \tag{3.31}$$

With reference to Figure 3.3.4, the surface runoff R generated by the entire catchment is obtained as the sum of two terms, the first one is the product of the meteorological effective input and the percentage of impervious area while the second one is the average runoff produced by the pervious area, which is obtained by integrating the soil