European Commission, Directorate General XII

FLOOD aware

Prevention and forecast of floods

Floodaware
Final report
August 1996 / July 1998

Floodaware
ENV4-CT96-0293

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Floodaware

Programme Environment and Climate 1994-1998
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Abstract

The prospect of the Floodaware project is to build a European methodology for flood management and damage mitigation with accepted standards, especially on vulnerabilities and risk maps implementations (risk = vulnerability x hazard). The objectives are to implement into models and tools new synthetic approaches developed in water sciences and management. The flood management policy must be treated with carefulness toward the water resources and ecological aspects. This knowledge has deep implications in social and economic behaviour. So, a structured effort is made to present this new knowledge under a "negotiable" form : negotiations for water volumes, and/or for land uses, between the different communities and owners living all along a river.

The Inondabilité methodology deals with synthetic models in hydrology, hydraulic modeling, hazards parameters, vulnerabilities, crossed maps... All these concepts are devoted to a dynamic slowing down producing simultaneously hazard mitigation and resources improvement with socio-economic interfaces. First results have already been obtained for a quantification of the hazard and works are done for an estimate of the objectives of protection against floods.

A synthetic Heuristic approach is developed, for prevention and forecasting. This methodology will be confronted to Inondabilité, as an alternative procedure for data management, more adapted to tumbling rivers with unstable beds. Data are collected and treated for simulations and some first results will be available soon.
Research is done in the field of Regionalization in hydrology, in the field of rainfalls, extreme rainfalls and discharges evaluations, including reservoir management rules devoted to hazard mitigation, when water resources are critical. Theoretical results will be soon available and tested on data sets.

The aim of this project is to give effective answers to help decision-makers, engineers and researchers to develop solutions to their specific problems in flood risk prevention and forecasting.

Résumé

Depuis quelques années, et apparaissant comme une des principales priorités en environnement, de nouvelles approches synthétiques sont développées en sciences et en gestion de l'eau. Une des raisons d'une telle évolution est les liens étroits entre le climat, les régimes hydrologiques, et l'occupation du sol. Pour cela, les politiques environnementales doivent évoluer d'un état de connaissance actuel qualitatif ou trop compliqué vers des éléments objectifs et transférables.

Les inondations étant le processus le plus structurant des problèmes liés à l'eau, elles doivent être traitées en priorité par les concepts proposés ici. Pour utiliser ces concepts et ces outils, des cas tests sont nécessaires. La perspective est de construire, pour la gestion des inondations, et une diminution des dommages, une méthodologie européenne avec des standards reconnus, notamment pour l'établissement de cartes de risques et de vulnérabilité.

De plus, les politiques de gestion d'inondation doivent être prudentes face aux ressources en eau et plus généralement aux problèmes écologiques. Ces aspects doivent être pris au moins comme une contrainte, au plus comme un objectif supplémentaire. La gestion des inondations ayant un impact social important, et certaines réticences étant observées parmi les acteurs qui doivent prendre en compte ces réalités, des efforts doivent être fournis pour présenter de nouvelles méthodologies sous forme de négociations : négociations sur les volumes d'eau, et/ou sur l'occupation du sol, entre les différents acteurs concernés.

Ce projet est essentiellement consacré au développement de ces nouveaux concepts pour la gestion des inondations, tenant compte des connaissances déjà existantes.

Sommaire

A Corinne.

Foreword

The prospect of the Floodaware project is to build a European methodology for flood management and damage mitigation with accepted standards, especially on vulnerabilities and risk maps implementations (risk = vulnerability x hazard). The objectives are to implement into models and tools new synthetic approaches developed in water sciences and management. The flood management policy must be treated with carefulness toward the water resources and ecological aspects. This knowledge has deep implications in social and economic behaviour. So, a structured effort is made to present this new knowledge under a " negotiable " form : negotiations for water volumes, and/or for land uses, between the different communities and owners living all along a river.

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A synthetic Heuristic approach is developed, for prevention and forecasting. This methodology will be confronted to Inondabilité, as an alternative procedure for data management, more adapted to tumbling rivers with unstable beds. Data are collected and treated for simulations.
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NEEDS OF THE SOCIETY

The extreme climatic events of the last years in Europe have shown that flood management is a necessity and a priority to mitigate/avoid serious damages and disorders in social and economic terms.

When we analyse the operational needs of the Institutions and Services in charge of the flood and inundation management, we have to face the following items :

- A flood warning system ;
- The management of hydraulic structures ;
- The survey of hydraulic structures ;
- The forecast of the discharges for various needs ;
- The knowledge of the hydrological regime, and the short term meteorological events ;
- The knowledge of the vulnerability (social and economic stakes) of the major bed to design and operate, if necessary, some evacuation programs ;
- ... more ...

The scientists and the researchers who work in the fields of Hydrology and Hydraulics are able to make short or long term scientific proposals to improve the methodologies and the models used for flood management.

But it won't be sufficient to deal only with the improvement of the different items of a flood management system, without having previously defined and designed a global and general strategy, a conceptual framework, in which all the operational means, and the present, as the future, institutions will take place, and will be better developed. The scientists have, as a first task, to design and to propose a consistent methodology for flood and inundation management, then to derive from it, in a coordinated way, some tools, in particular modelling tools, for the Operational Services in charge.

OPERATIONAL METHODS AND TOOLS

The flood risk can be defined by disintegration between hazard and vulnerability components, which are more or less independent.

The flood hazard is measured from hydrological parameters transformed in hydraulic characteristics.

The vulnerability is strongly related to land use and economical stakes.

Usually, hazard doesn't change very much through the time (hydrological regimes are relatively stable at long term scale), except when structures' buildings change the hydraulic characteristics. On the contrary, vulnerability generally increases due to more and more major bed urban occupation.

Some concepts and methodologies such as the « Dynamic Slowing Down » or the « Inondabilité method » can take into account the consequences of the planned programs on the water resources generally speaking (in both terms of quality and quantity, and in terms of quantified elements of negotiation to exchange water volumes), and especially when low flows/severe low flows occur. They bring, at this stage, some interesting element for the general analysis. These methods can be modelised in technical tools (softwares including multi-media).

A mapping of the flood risk (hydraulic hazard and vulnerability) has to be planned as a decision making tool, and also as an information tool for the concerned public. Such maps, allowing a clear and detailed diagnostic at any scale, allow negotiations and the adequate decisions to be taken, both on hazard (for hydraulic measures, crisis management included) and on vulnerability (progressive evolution in land use, and short term crisis measures included, like population evacuation).

Forecasting and crisis management are more efficient in a context where flood prediction and prevention are well developed.

Hydrological and hydraulic models allow to modernise flood warning system (the social request is easily expressed as the need of a flood plain forecast system, even when the actual need is more on land management), and to evaluate the consequences of future hydraulic works or the human influences.

RIVER MANAGEMENT

When we deal with rivers, we have to take into account many components of its functioning. As they are essentially used for their water resource, we have to study the impact of the water withdrawals especially during low flow period. Moreover rivers also overflow sometimes and people that have settled near have to be protected ; we have then to know about high and extreme flows. Finally, rivers are the place of life and we have to preserve their biological wealth.
Unfortunately, people that worked on rivers used to consider these components without relationships. That means that they usually solve problems without taking into account the other aspects. And the impacts generated by this way are sometimes very negative. For example, hydraulics engineers drilled the river beds to prevent from floods. These hydraulic works have huge effects on the availability of the water resources and on the ecosystem due to the lowering of the water level.
So, in order to provide river management, people try now :

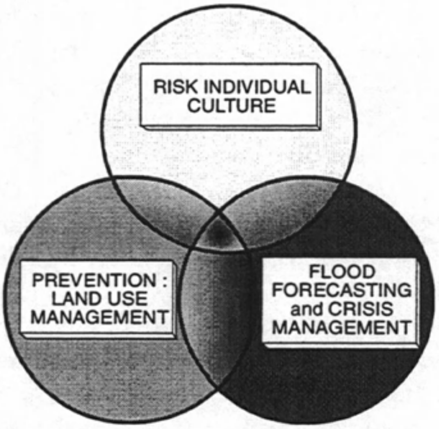
- to propose an integrated river management that takes into account the global functioning of the river basin and the use of it
- to preserve future with action that take into account next generations : a sustainable management.

When people integrate all the components of the rivers for better solutions, it appears that it is very complex. Each discipline is usually well known but the interactions between them are not as easy as we could firstly think. That is why we have to develop new concepts and tools to give better answers.

FLOOD MANAGEMENT

To mitigate the consequences of the floods, there are several methods : prevention, forecasting and promotion of risk culture. They have to be used all together.

It is not possible to suppress inundations. The hydro-meteorological processes will always generate floods, because the volumes of water are incompatible with the size of the minor river bed. We cannot avoid the flood water volumes to return to the sea.
In a short term management, we can try to forecast the propagation of the flood and to take all the measures to save people's life and goods. We are dealing with flood forecasting and crisis management.
In a long term management, we can try to move in space and time the flood volumes, with the natural constraints. We are then dealing with prevention.
At last, we need to inform and to sensibilise concerned people if we want them to accept and follow proposed measures. We are dealing with risk culture.



Flood management

Flood forecast or crisis management

The first known services of flood forecasting appeared in Egypt. In the 14th century, some systems existed in China. On the old continent, they appeared in the 18th century in Central Europe, on river Elbe. All these systems were based on a

transmission to downstream (by boat, rider or cannon fire) of a flood's arrival. It is only from the middle of the 19th century that start the first forecasting calculations from hydrometric and pluviometric data.
The stakes in flood forecasting were at the beginning essentially agricultural. They became later urban.

The missions of flood forecast have now changed : it is now "flooded areas" forecast. The demand is much complete. It is not enough to announce a flood arrival ; the information has to concern the arrival time of the discharge peak, the duration and the stretching of the inundation. The flood forecasting services have a increasingly complex work.
Moreover, flood forecast can quickly become crisis management. Over a certain threshold (of flow discharge, volume or duration), people need help or emergency assistance more than forecast.
We need in any case flood forecasting in already built areas that are vulnerable and potentially flooded..

Prevention

Prevention deals with long term management.
For ages, people have worked on rivers to mitigate floods, with often structural measures : chenalization, dike building... Taken at a very local scale (village), they had usually perverse effects downstream.
Flood risk prevention has to be understood as a management tool at catchment scale. It allows an integrated management taken into account other river functions as water resources, aquatic ecosystem...

Risk culture

Prevention and forecast cannot be efficient if we don't develop people's awareness and sensibilisation.
It remains little traces of an event because it has a high return period (by definition, a natural disaster happens very rarely). The geological and natural records are not always lisible. The time or the rebuilding often erase the material and historical archives.
We have to contribute to a living memory of the events. We have to develop this risk culture for a better understanding of prevention actions and crisis management. This sensibilisation has to begin in the early life at school and continue for all the life.

These three means to mitigate flood damages (prevention, prevision and promotion of risk culture) have different time scales and specific tools. Nevertheless, these measures are complementary and they should be applied all together.
Within the Floodaware project, we deal with flood prevention and prevision.

The Floodaware contract has been signed by the European Commission on July 1996. The formal start of the project is the 1st August 1996 and its duration is 2 years. Several work meetings have been organised within the Floodaware project :

- Lyon, 20 November 1995
- Torino, 12 March 1996
- Valencia, 16 July 1996
- Gembloux, 13-14 January 1997
- Dublin, 18-20 June 1997
- Madrid, 19-20 January 1998
- Barcelona, 29-30 June 1998

This book presents the results obtained within the project Floodaware.

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The Inondabilité method

La méthode Inondabilité

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Abstract

To deal with flood risk management, it is now accepted to consider the risk as the comparison between vulnerability and hazard. The Inondabilité method uses this concept to provide tools for river management. The vulnerability, attached to the land use, determines the susceptibility to floods. We promote an expression of this component with hydrological variables: return period (T), duration (d) and water depth (p) of flood. The hazard is attached to hydro-meteorological phenomena and their consequences to the water flow; it is characterised by its discharge, its frequency and its duration, calculated by hydrological and hydraulic models. To compare the two notions of the vulnerability and the hazard, we use a discharge-duration-frequency (QdF) hydrological model, allowing the transformation of the two previous components in the same unit, a return period. The definition of the risk as a difference implies a search of an acceptable solution instead of an optimised solution, usually impossible to reach. These new concepts and methods should improve risk mitigation and lead to a better acceptable risk level in the potentially flooded area.

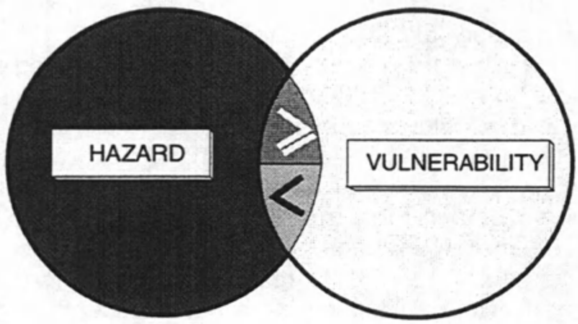
Résumé

Une partie de la réponse aux impacts économiques, sociaux et humains des inondations réside en une meilleure gestion de l'occupation des sols. La méthode Inondabilité permet d'apporter une réponse opérationnelle aux acteurs en charge de la gestion et l'aménagement des cours d'eau. Elle permet de mesurer dans la même unité et de comparer les deux facteurs indépendants que sont l'aléa et la vulnérabilité, pour aboutir à une quantification objective du risque. Sa mise en œuvre sur un bassin versant consiste en une modélisation de l'hydrologie grâce aux modèles Débit-durée-Fréquence, de l'hydraulique ainsi que de l'occupation du sol pour aboutir à une représentation cartographique du risque. L'originalité de la méthode Inondabilité tient à la quantification de l'aléa et de la vulnérabilité en une même unité, une période de retour qui permet une comparaison objective de deux grandeurs très différentes. De plus, la quantification du risque est estimée à l'aide d'une différence contrairement aux approches traditionnelles qui privilégient souvent un produit, permettant ainsi la définition d'un risque acceptable.

1 Introduction

Risk analysis may be approached by a first conceptual model made up of 2 components: hazard and vulnerability (sensitivity of the land use). It is particularly true for flood events: we practically never speak about flood risk neither in an alluvial forest or in a district situated at the top of a hill. Alluvial forests are regularly flooded (hazard), but with no prejudicial consequence; and at the top of a hill, whatever the stakes (vulnerability), any flood would never occur.
This first level of modelling (breaking the risk down into 2 parts, the hazard and the vulnerability) simplifies a complex reality, but grows away from the common citizen intuitive perception. So, we have to define very precisely the vocabulary used, to ensure a consistent dialogue between scientists, engineers, citizens and their elective representatives.

Conceptual model of the risk notion



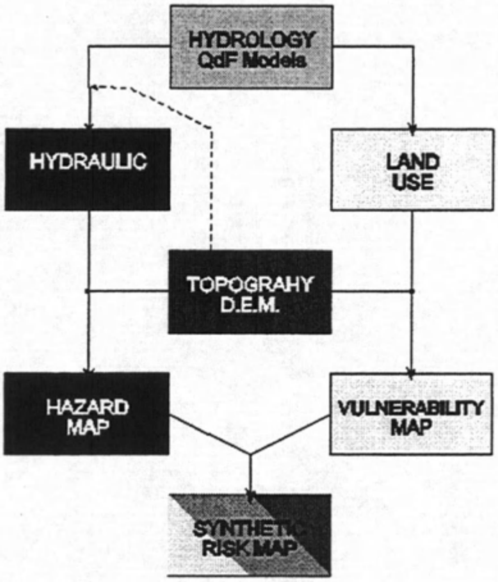
The Inondabilité method aims at assessing quantitatively the risk, through a quantified modelling, parallel and independent of the two variables that are the hazard and the vulnerability. The comparison of these two dimensions allows defining an objective and rational measure of the risk, for each parcel. This summarised definition infers numerous hypotheses. Indeed, to achieve such a result, the hazard and the vulnerability must be quantified in the same unit of measure, that is to say with the same physical parameters (convertible into an equivalent measure). To apply that in a given place, we need a spatial modelling of these parameters. The method aims to be fitted to various geographic contexts, taking into account the local specificities without being dependent of them. So an objective quantification is necessary, and will also help to establish a real negotiation between the different involved people.

Thus, through a quantitative risk unit, the method defines the parcels over protected or under protected, following the sign of the risk:

1. positive sign = areas with a deficit of relative protection (high level of risk)
2. negative sign = areas with a credit of relative security (low level of risk).

Then, the two variables - the vulnerability and the hazard - and the results of their crossing - the risk -, will be mapped clearly, and will become a basis for the negotiations (synthetic maps of the results are a readable way to make them understandable both by managers and inhabitants).

Chart of the Inondabilité method



So as to take into account the upstream and downstream interactions, and the hydraulic constraints of the river, it is necessary to work on an adapted geographic mesh, that is to say the whole linear of the considered river. Then the whole basin's inflows can be integrated, and the potential diversion of water from the upper part to the low part of a catchment might be tested.

The river linear has also to be significant in order to obtain a global view, at the basin scale, of the risk situation.

2 The concept of risk

The following detailed flowchart shows the different parts of the Inondabilité method, through 4 main subsets:

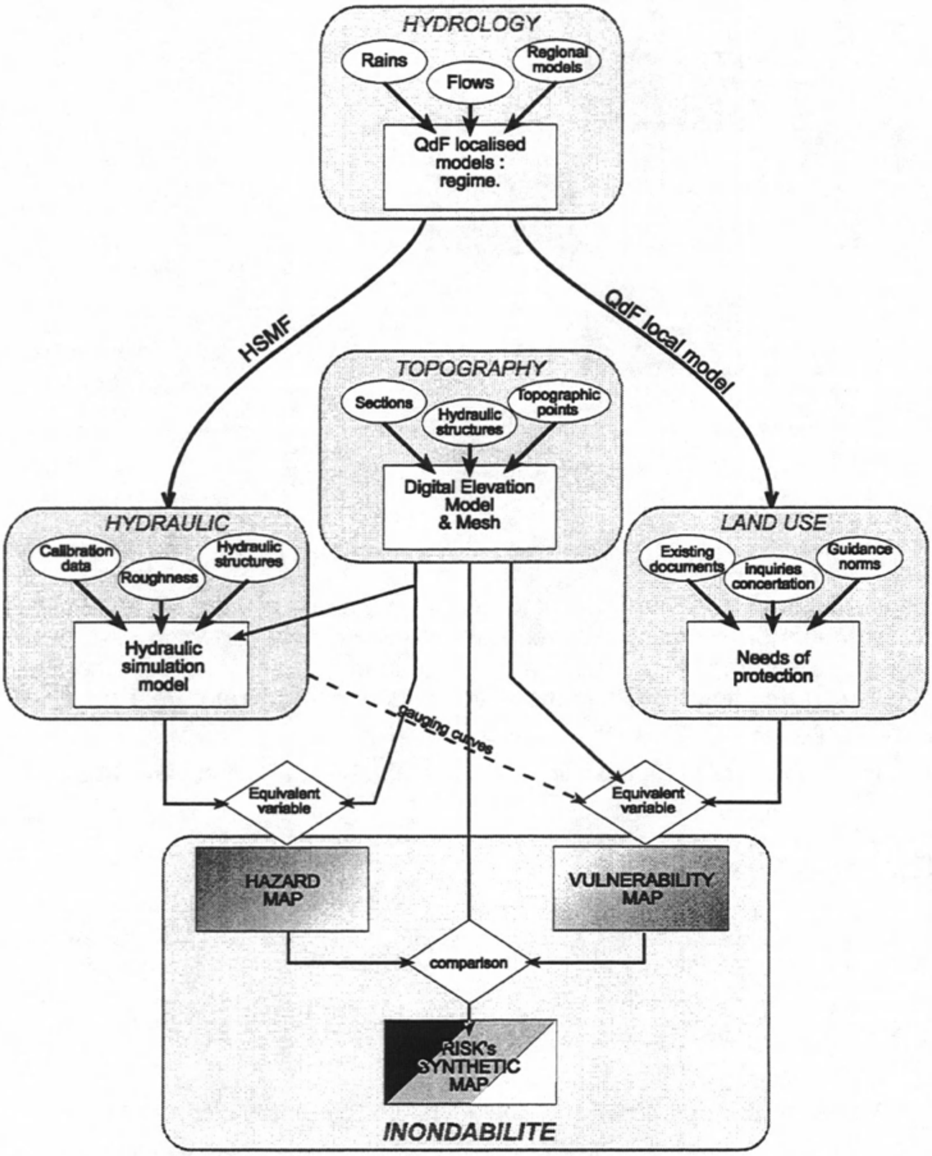
1. the hydrological "box"
2. the hydraulic "box"
3. the land use "box"
4. and the cartographic "box", including the topographic one's.

We can point out that these different sub-models are not sequentially ordered, since they will be put as well into the hazard analysis, as into the vulnerability one.

2.1 Analysis of the Hazard

The hazard represents here a specific natural constraint: the inundations, caused by the river floods. The Inondabilité method is only interested in the river flooding

Detailed chart of the method Inondabilité



(but it could be partially extends to other cases like the urban surface runoff, with some adapted tools).

The hazard analysis should end in a knowledge of this constraint, as objective as possible, so as to ensure its quantification and its spatial distribution. It implies to modelize the phenomenon, to be able to apply it everywhere on the territory and rely it on observation calibrations to ensure a significant representation.

The hazard analysis is today a classical and known step in the flood risk studies.

Different forms of spatialized analyses of the hazard exist.

First, for a given event, we might determine the hazard characteristic parameters, like the flood duration, the water depth, or the water velocity, that varies with the considered parcel. Then, by making up these different physical parameters, it becomes possible to define a scale of the hazards, allowing a classification of the parcels. But a difficulty remains, linked to the kind of the different parameters which are not easily comparable, e.g. what is the worst situation between "a water depth of 1 meter during 2 days every 25 years on average, or a water depth of 25 cm during 1 hour every 5 years on average" ? This tricky comparison can begin to make sense by looking at the situation in a one-dimension space equivalent to this three-dimension space.

Second, it is also possible to define a single parameter as the mean return period of the just flooding discharge for each parcel, and consider that, due to the bijective properties stemmed from the theoretical hypothesis of the method and being at the root of the synthetic hydrological model QdF, this mean return period is equivalent to the previous physical parameters.

A measure through a single variable allows an objective and rigorous classification of the hazard, since the classification in increasing order is automatic (without combining different kind of variables). This variable, that takes a single value in any given place, and quantifies the hazard, was named TAL. It is defines as the mean return period of the actual just flooding discharge. Its unit of measure is the year.

TAL: measure of the hazard in any given place, defined as the mean return period of the just flooding discharge on this area

The synthetic hydrological model QdF (discharge Q, duration d, frequency F) allows the construction, for each return period, of a monofrequency synthetic hydrograph, representative of the flood regime. A hydraulic transient monodimensional model enables to represent the river flows, and allows also to calculate the flooded area for each mean return period.

Close of these calculations, we obtain a spatialised representation, on a common scale variable (the minimum mean return period of a flooding discharge) of the hazard allowing the allocation of a representative value everywhere. This value, measuring the hazard, represents the sensitivity of each parcel to the flood natural phenomenon.

More simple hydraulic models might be used, like permanent monodimensional models, or models with a parameterised geometry, allowing a brief analysis of the hazard useful for a preliminary study (diagnosis).

2.2 Analysis of the Vulnerability

Like for the hazard, the vulnerability analysis set out to obtain a spatialised representation of this risk component. It has to take into account the existing land-use diversity, and to identify a measuring scale to classify, at least in relative value, the various land-use characteristics, and to impute to each parcel a value representative of its vulnerability, in a common system for the entire considered area.

Classically, vulnerability analyses rely on a cost estimation of the potential damages induced by the characteristics of a given flood. But other values, less economic and more sociologic, have to be integrated, like the emotional value associated to a parcel, or the different individual perceptions of the vulnerability.

Vulnerability analysis shows a great variability between different geographic areas: for the same flood, causing equivalent economic damages, the vulnerability of the same housing site could be different whether it was situated in the north or in the south of France, due to the local risk culture. So, if it is useful to work on the basis of common standards, it is also necessary to adapt them locally after a specific survey. A diversified analysis will allow the determination of a maximal risk level acceptance, or demanded (minimum) level of protection, and integrating the local and individual specificity's of the risk perception, due to a process of dialogue where everyone may express its point of view.

To do that, we suggest to let people express their minimum demanded level of protection, with the parameters already used to describe the hazard, that is to say the flood probability (or its mean return period), the flood duration, the acceptable water depth. Using the hydrological synthesis discharge-duration-frequency model it is possible to translate the triplets frequency-duration-depth (T,d,h) into an equivalent parameter: the mean return period equivalent to the demanded level of protection. The parameter that took a single value in each parcel was called TOP, since it quantifies the demanded level of protection in term of probability, with the dimension of a return period. Its unit of measure is the year.

TOP: measure of the vulnerability, imputed to a parcel and defined as the mean return period equivalent to the demanded level of protection.

It is then sufficient to transfer on a map this measure of the vulnerability, to obtain the vulnerability map.

Just as for the hazard, we can imagine some declined forms of the vulnerability analysis, avoiding the parcel scale and working on the basis of great homogeneous schemes. In this case, the use of general standards characterising the vulnerability remains efficient. In the same way, we won't obtain a detailed spatialized analysis of the vulnerability, but only a first rough estimate, useful to do the spadework on the problem.

The seasonal factor could also be of importance, particularly concerning the rural area vulnerabilities. It is possible to lead a seasonal analysis and built seasonal hydrological synthetic QdF models.

2.3 Synthesis of the risk

As we have this spatial distribution of hazard and vulnerability parameters, it becomes possible to compare these two values (TAL and TOP), since the proposed modelling of these two components, made from the QdF hydrological models, are compatible: hazard and vulnerability are expressed in the same unit, the mean return period.

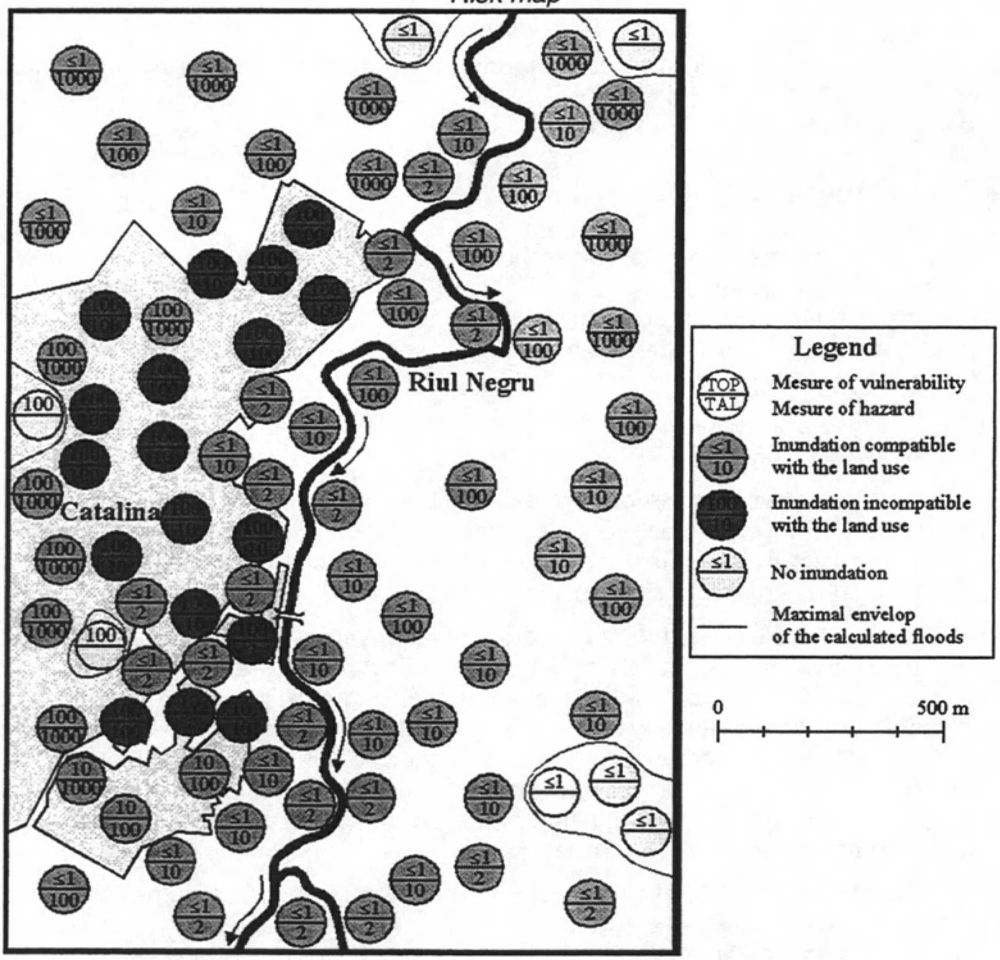
The comparison, for each area enables an objective view of the risk situation all along the river.

It underscores areas where problems exist, and, on the contrary, areas with a safety margin. Moreover, the difference between the two variables gives an estimate of the risk extent or the safety margin, and thus, contains intrinsically some elements to a global answer to the problem.

We have chosen 3 colours the map representation: yellow, green, and red. A parcel coloured in yellow represents a parcel, which is not exposed to the hazard (within the limits of the hazard modelling). A parcel in green is subject to a hazard compatible with its demanded level of protection. A parcel coloured in red is affected by a too high hazard - corresponding to a small TAL - considering the demanded level of protection. In this last case, the hazard level is not acceptable and we have to improve this situation. This kind of codification allows obtaining some documents very easy to analyse.

This synthesic view of the risk level, at the parcel scale, is then a summary of the basin ës hydrology, the floods propagation, and the kind of land-use as well. It enables an efficient diagnosis of the situation and the proposition of solutions in terms of hydraulic or land use management. Furthermore, the cartographic representation makes easier the comprehension by the whole concerned people, even if they aren't specialists.

Risk map



3 Theoretical basis

3.1 Objectives of the Inondabilité model

1. The first purpose of the Inondabilité model is the water resource improvement: to maximise the availability of the water resources, by reducing a useless water resources disposal downstream, and finally to the sea, where they become unusable nor for the continental aquatic ecosystems or for the human society. So, Inondabilité model is also an efficient tool to fight against... the droughts, by floodwater discharging, slowing down the fresh water disposal to the sea.

2. The second purpose of the method is the flood awareness and mitigation, helping the decision and negotiation processes, adapted to a changing environment, and respecting the water resources. It should be an efficient and reasoned long-term process, at the basin scale (taking into account the whole river length), fitting the risk to the need of protection against flooding.
3. The third purpose is a clear display of the results on the whole potential flood plain along a river, with on the one hand a map of the hazard aspects, on the other hand a map of the vulnerability aspects. Finally, a synthetic crossed form - the risk map - determines the areas with flood problems, and the areas not flooded or "over protected". Such synthetic maps resume the whole knowledge about a risky situation, including socio-economy and hydrology, and suggests the water management aspects (options of management solutions, either through hydraulic works, and/or through land use changes).
4. The aim is to have, after comparison between the diversified vulnerabilities and the flood hazard parameters, some clear negotiation tools for managing spatially and temporally the volumes of water in excess.
5. The fourth purpose is the adaptability of the model. The model must be adapted to follow the strong and continuous, observable or foreseeable, developments (such as hydraulic structures, hydrological regimes, social needs, and even the climate change). Thus, the maps, quoted above, should be updated.

According to these purposes, this model has a great ambition, and could, finally, becomes a basic model for the continental water management, being applicable in any place. Indeed, floods constitute the main phenomenon of the hydrological regimes (in terms of volume, discharge, erosion, water suppletion...), so it appears essential to begin by managing floods before looking after less severe and less structuring phenomenon like medium water yields or low water.

3.2 Hypothesis, principles and constraints

3.2.1 Existence of a representative local model zdF

If:

6. z is a water level (corresponding with a depth),
7. d, the duration during which z is exceeded,
8. F, the z(d) non-exceeding frequency, i.e. z linked distribution, knowing d,

in that case, we do the realistic hypothesis, often confirmed, that a z-d-F law exists in any limited place of the territory, monotone decreasing with z(d), monotone increasing with z(F), and either stationary compare with the known or able conditions (geometry, hydrological regime...) of the site, or with some possible modelling drifts if we have suitable knowledge. Furthermore, the monotone aspect is considered as exploitable in bijectivity. The bijection is mainly applied to the basic relation between the 3 variables F[z(d)]. In corollary, some inverse relations, like $z_d(F)$ or $d(z_F)$, won't be optimal, but still exist mathematically, and remains significant for the phenomenon we have to represent.

The main points of the concerned territory belong to the major beds of the river, but may also concern the minor beds (for hydrobiological or sedimentological applications of the model), or the temporary river beds like that are created in the micro-talweg and depression at the occasion of local runoff.

The implementation of these knowledge and tools, allowing the real modelling of such zdF functions in any given place of the territory, belongs to the hydrologists and hydraulic engineers.

3.2.2 Existence of a representative local rating curve Q(z)

It is usually possible, in every given point of the territory, to approximate a relation Q(z) between the water level z and its main discharge Q. This rating relation is more often monotone increasing, then usable in bijectivity. It could be considered as stationary, or subjected to modelling trends in measurable environment conditions.

Few cases of non-bijectivity may be found (hysteresis in dynamic, downstream conditions, hysteresis in continuity). In these cases, instead of the rating curve Q(z), we will consider the pseudo-rating curve QX(zX) linking the maximal discharge QX(tQ) and the water level zX(tz) by event pairs (floods), that is to say concomitant in the sense of a same flood (tQ and tz belong to the same event), but not necessary concomitant in the sense of a current time strictly equal (tQ and tz are structurally out of line in these cases of non bijectivity of q(z) rating).

Sometimes, it doesn't exist any significant rating or pseudo-rating curve: these average ratings are too far from the real rating and prevaricate the results up to the point where they loose their interest. It is one of the rare hypotheses, which could put in check the model, as it runs presently, on certain limited reaches. In the real application cases of the method, any situation invalidating the method hasn't occurred.

3.2.3 Feasibility of the building of a representative local model QdF

The both previous hypotheses have a hydrological corollary:

It exists, in every point of the territory, a QdF law (the frequency F is the Q(d) one's), monotone decreasing in Q(d), monotone increasing in Q(F), so exploitable in bijectivity (2 to 2, with the previously quoted reserves), supposed stationary (or with modelling trends...) subjected to environment condition description.

Some areas could be submitted to generic multiple QdF. That is the case of some humid areas, supplied by 3 relatively independent regimes: overflowing of the main river, groundwater layer rising, and independent little lateral basin. In this case, the single QdF searched is the frame or these generic QdF, giving the most constraining hazard and/or vulnerability conditions, that is to say qualitatively the most flood damaging "z-v" (water level z and velocity v) combination (practically, the most severe zdF).

The main advantage of the QdF models is their scale and spatial validity field, potentially very large, comparative to the zdF totally linked to the local geometry of the site surrounding the concerned place.

3.2.4 Objectives of protection

Another constraint of Inondabilité model is the possibility to take into account some diversified demanded level of protection, fitted to the diversity of the land use (today and in the future), in every points of the river major bed.

We can say that it exists, in every site, a reasonable demanded level of protection against the floods, focused on a maximum beyond that it becomes unrealistic to ask for a protection (e.g. financial, technical, or ecological reasons). This maximum isn't a single optimum, due to the criterion multiplicity.

So, it exists, in every site, a risk, which must be known and assumed. A goal of Inondabilité model is to define this risk as exactly as possible, and then, to make the flood acceptable. It means to assume an acceptable risk, and to accept that, for a more rare flood event than previously determined, some damages could occur and be compansed for by another type of measure (insurance, indemnity...).

3.2.5 Existence of a synthetic, representative and Mapbase local parameter

The preliminary works to Inondabilité model have shown that, due to the physical processes at the origin of a flood, a standardizable variable, continuous and defined in every points of the major bed should exist to represent the local hazard regime. Subject to be able to interpret the local vulnerability with the terms already used for the hazard, the local asked level of protection should also be synthesised in such a representative local scalar. In corollary, it might allow a direct and quantified comparison between the subjected hazard and the vulnerability.

If we want to succeed in obtaining readable results, and following the basic hypotheses already described, the maps must display only one single variable to represent the hazard, and a single one to represent the vulnerability (social request). These two variables, having the same nature, expressed in the same unit, may then be compared and allow a clear and objective qualification of the local risk, favouring a reasoned decision-making process.

The previous hypothesis being checked, the QdF offer the following potentialities:

- express in a one-to-one way, for a given point of the major bed, the main flood hazards in terms of depth z(Q), velocity v(z), duration d(F,Q) and frequency F(Q,d);
- except the damages calculations, the social need of protection could more often be expressed by a combination of the same hazard terms;
- their monotone character, with their bijectivity relations, allows (by a QdF internal projection) to link to each (F,Q,d) triplet, an equivalent and only one (F_{eq},Q_{eq},d_{eq}=0+) triplet, where the duration d is nullified, corresponding to an instantaneous discharge equal to Q_{eq}, with a frequency F_{eq} different

from F. This new triplet respect the possible interval between the original triplet and the QdF (then zdF) regime of the floods in the given place;
Here is certainly the key of Inondabilité method, and its main original feature.

- same here, their monotone and bijective properties, linked to a rating curve Q(z), also bijective, allows to link to each (F,Q(z),d) triplet, an equivalent and only one (F_{eq1},Q_{eq1}(z=0+), d) triplet, corresponding to the "just flooding" discharge for the given place, with the same duration d and frequency F_{eq1} different from F. This new triplet respects the possible interval with the QdF regime (then zdF) of the floods in the given place. We may note that this derived triplet (F_{eq1},Q_{eq1}(z=0+), d) brings back to the previous case, i.e. might itself be brought back to such a (F_{eq},Q_{eq},d_{eq}=0+) triplet, linked to the equivalent instantaneous discharge.

The frequency F_{eq} (result of these transformations) squares with the instantaneous discharge (i.e. with a zero duration) equivalent to the demanded level of protection, and thus synthesises the information contained in the initial (F,z,d) triplet.

The interpretation of this (F,z,d) triplet, corresponding to the demanded level of protection may be expressed as following:

- refusal to accept a flood longer than d, more water depth than h (directly inferred from z) during this duration d, for a frequency highest than F, with as corollary:
- the flood is "accepted" if it is more rare.

3.2.6 Simulation of the hazard z-F

The theoretical and rigorous solution is based on a permanent regime modelling for a discharge Q with a given mean return period T corresponding to a non-overflooding frequency F like $T = \frac{1}{1-F}$.

An operational option, enabling the simulation of the possible developments with their effects on the hazard regime (hydrology and hydraulic), is based on a transient mode, supplied with representative operators of the discharge regime (monofrequency synthetic hydrographs).

In both cases, to simulate the hazard level in a given place, we just need to calculate the water levels for different discharges Q, so as to sweep the whole necessary range. It allows to observe the position, in relative value, of the demanded level of protection related to the subjected hazard, particularly by assessing the mean return period of the first flooding flow of the site.

3.2.7 Contribution of hydraulics

The hydraulic modelling in transient mode provides a necessary support to the hydrological part and to the determination of the vulnerabilities and their assessment. Obviously, it allows simulating how the hydraulic works could change the hazard distribution. But, above all, it will help the hydrologists in the following case: the hydrological regime, that is to say the main simulated river's QdF are sometimes not well known. This case is frequent for the rivers supplied by tributaries and contributing areas with very various regimes. In this case, hydrology may benefit by the transient model which is able to make efficient compositions of tributary hydrographs (taking into account the whole contributing areas), including the classical damping phenomenon by diffusion and reservoir routing. In a first stage, the single QdF of the affluent basins have to be available (boundary conditions). The studied river QdF will be inferred from the hydraulic model outputs, after propagation and possible corrections. In this case, the need of protection will then be defined and map-made only after the end of the hydraulic stage. The composition of such tributary discharges outlines the problem of their probability composition.

3.2.8 Unicity of the hydraulic model

The results displayed by the hydraulic model have to be very credible, whereas the hydraulic model is used, on the one hand, to go locally from the QdF to the zdF (and each other), and on the other hand, to simulate a range of hazards practically always extremely wide (from 0+ to 100 or 1 000 years). This variability is linked to the diversity of the land use, and thus, the diversity of the minimal demanded level of protection. But the hydraulic model, as the hydrological one's, are subjected to different uncertainties, sometimes wide or not well known. Furthermore, the different assessments of hazard and vulnerability will be intercompared. So, it means very efficient hydraulic models, and need some new developments.

3.2.9 Ergodicity of the spatiotemporal processes

The ergodicity property is attributed to the processes having simultaneously a certain spatial and temporal variability and a certain spatiotemporal independence of the studied events, so as the observation of a great space overcomes the briefness of the observations. This allows replacing a part of the temporal analysis by a suitable spatial analysis.

An objective of Inondabilité model is to enhance the basin unity concerning the flood problems, but the model is also directly interested in a maximal spatial extension, to have as quick as possible some observation arguments to flush out any non-problem. This model is then quite adapted to the required or wished "regional" scale, without loosing any significance at the local or individual scale.

3.3 Difficulties concerning the velocities

The whole thought on flood risk regulation underlines the need to take into account the velocity as a factor to describe the risk. Indeed, we have to take into account the high flow velocities at the origin of tearing risks or drowning accidents, and also a short alert time induced by a reduced flood rise time. These two factors are probably not independent.

A good integration of the velocity factor into the Inondabilité method implies to check some additional hypothesis. We have to find a bijective relation between the local velocity V and one of the other parameters already used, as the water level z or the discharge Q. This relation V(z) [or V(Q)] has to present the same qualities of monotony and bijectivity as the other relations used within the method. The existence of such a V(z) [or V(Q)] relation will enable to define the need of protection from a velocity V, a depth associated to a water level z, a flood duration d, and a frequency F; the bijective relations linking these variables two by two (as already shown for z,d,F) will allow to end in an equivalent frequency following the previous methodology. In this case, the definition of the need of protection in term of velocity will allow defining an objective of protection by the mean of an equivalent level of water, which could be lower or higher to the level of water fixed as an objective. Then, we will choose the most constraining solution that is to say that, for an equal frequency, it has the lower water level.

4 A tool for water management

4.1 Water management scenarios

Within the previous chapters, we have described the bases and the directions for use of the Inondabilité method, through its different components (hydrology, hydraulics, socio-economy, topography and cartography) fitted together like that:

- hydrology supplies
  - ⇒ the hydraulic with upstream boundary conditions
  - ⇒ and the socio-economy to give an equivalent measure of the vulnerability;
- hydraulic allows
  - ⇒ to do the simulations needed to calculate the hazard
  - ⇒ and to provide the local rating curves required for the vulnerability calculation;
- topography is used
  - ⇒ as an input for the hydraulic model (boundary condition)
  - ⇒ and as an input for the cartographic model required for the spatial representation of the hazard;
- cartography is used to display the results
  - ⇒ from the hydraulic part, that is to say the parameter characterising the hazard
  - ⇒ and from the socio-economy, that is to say the parameter characterising the vulnerability
  - ⇒ to, finally, end in synthetic maps summarising this whole knowledge on the spatial distribution of the risk all along the river.
  - ⇒ And to make easier the comparison of different development scenarios.

4.1.1 Evolution of the catchment

The basin development in terms of waterproofing or high modification of the hydrographic network may affect the hydrological regime and then the discharge-duration-frequency models.

This type of development allows thus to simulate the hydrological regime evolution and its consequences on the risk situation all along the studied river. Nevertheless, the quantification of these influences remains difficult as soon as the basin size overcome a few tenth of square kilometres.

4.1.2 Hydraulic management

The usual hydraulic developments (recalibrations, embankments, dams, ...) lead to a hydraulic modification of the river, able to be modellized by the used hydraulic models.

Some hydraulic simulations integrating these modifications allow an updating of the hazard maps with these new conditions, and a test of their effects on the risk situation all along the river.

Generally, we consider that these hydraulic modifications have no effect on the hydrological regime of the river itself. If such developments become more important within the hydrographic network, we will have to review the hydrological regime of the river.

4.1.3 Evolution of the vulnerabilities

Some land use modifications within the valley lead to a modification of the vulnerability. Such scenarios may be simulated by a projection of the possible evolutions, their translation in an equivalent variable of the vulnerability, and their impact in term of risk all along the river.

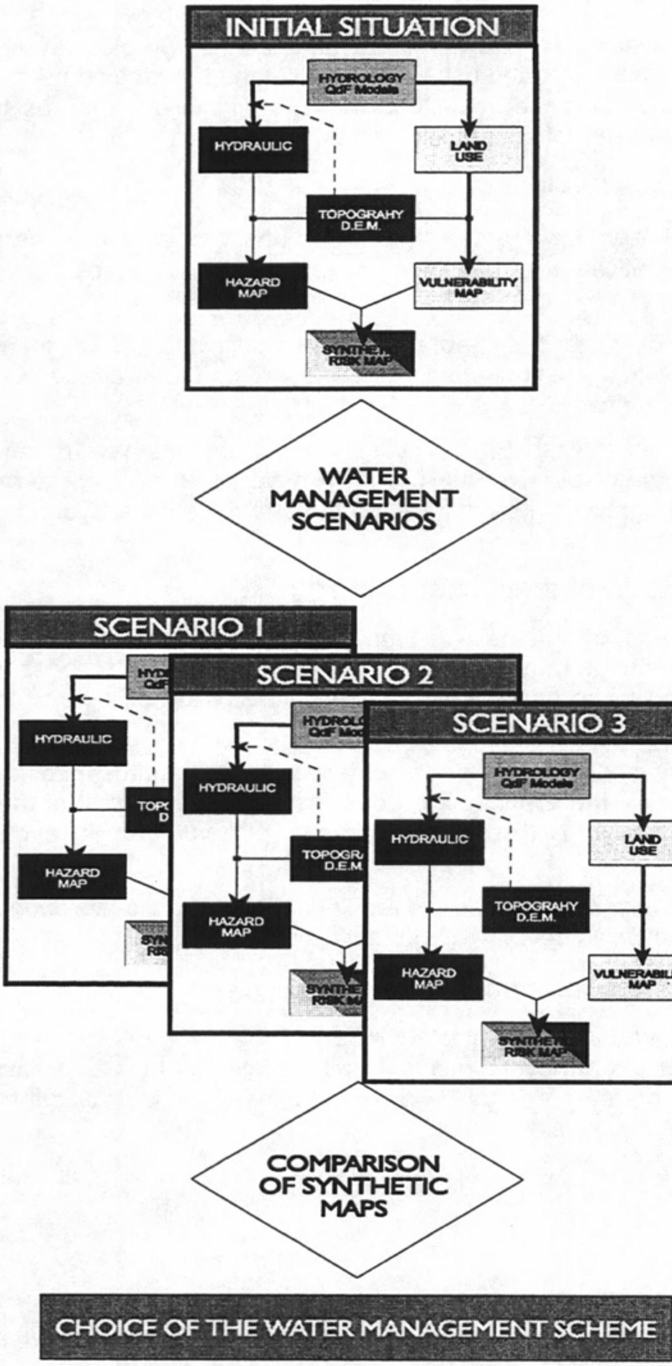
These modifications does not lead to any hydrological regime modification considering that generally the alluvial plain doesn't form the main part of the studied river basin. So we can really dissociate the impact of a vulnerability evolution from the regime evolution.

Such modifications may also be the result of joint hydraulic evolution (e.g. intensification of the activities beyond the protective dikes).

4.1.4 Comparison of scenarios

The synthetic maps allow a quick comparison between different scenarios, and a simulation of different developments, in a first time just by a clear display and a visual effect on the red-green-yellow area evolutions, and later by quantification.

Comparison of water management scenarios



4.2 The Golden Rule of the Dynamic Slowing Down

The golden rule of the Dynamic Slowing down consists in supporting water storage during flood periods wherever we can in order to favour natural lamination of flows, fitting hydraulic constraints (frequency, duration, depth, and velocity) to a more realistic need of protection linked to each land use type.

This rule aims at:

- improve the efficiency of the whole developments already realised
- reduce the costs, the investment one's and those devoted to the maintenance of the structure works.
- favour the natural balances, in the field of geomorphology, geochemistry, biology...

For these different reasons, this rule should be set up on the whole basin, and at the time of each processes of development able to have an impact on the origin of the flows (sanitation developments, town planning processes, river management...). The generalisation of the major bed concept to every situation inducing runoff, even occasional, should allow the satisfaction of a reasoned protection against the floods, respecting the local social request, without given the water resource linked to the basin functioning up. The enhancement of the whole land use diversity within a catchment and all along a river will be a source of efficiency for a general flood damage mitigation policy. Thus, we think favour the emergence of efficient and sustainable solutions, expressing a kind of application of the "caution rule" within the regional development.

Inondabilité method proposes an operational mean to apply this rule on really objective basis.

5 Research for the future

5.1 Hydrological references

The generalisation of the regional hydrological methods (like the QdF's), which we have shown the interest to improve the dimensioning and design of the structures, will probably go through the setting up of regional hydrological references, enhancing the whole collected data, particularly by the way of the public services.
Such studies, led systematically at a regional scale, following some validate comparable and regularly updated (every 10 years) methodologies, should allow:

- a better enhancement of investments in data collection,
- an homogenisation of the structure dimensioning methods and used hydrological references,
- a steady follow of the hydrological regime evolution, with the development incidence,
- a more efficient capitalisation of the available data and progress in the field of hydrology.

That is the single way to achieve a more objective analysis of the real or supposed modifications of the hydrological regime, and thus, an improvement of the water resources management.

5.2 Automatic cartography of flooded areas

The expansion of automatic cartography tools, interfaced with hydraulic modelling tools, is a necessity to hold maps, which may be updated, as new developments will be realised. Due to the complexity linked to the abundance of data to manage (topography, hydrology, hydraulic, land use...), it becomes necessary to develop advanced interfaces helping the end-user and making its intervention more significant to solve the true questions: what will be the good development, respecting as well as possible the conflicting stakes around a river ?

Some specific research programs are required in this mind, using data processing. Furthermore, these developments should also end in educational tools using the multimedia techniques, in order to support the risk culture so as to increase the recommended measure efficiency.

5.3 Socio-economic quantification of the vulnerability

The proposed method, even operational, still suffers a few imperfections concerning the socio-economic consideration of the risk. The suggested standards are based on a general expert assessment and a present state of the knowledge, and we know the limits of this operational approach. To improve this part of the Inondabilité method, it is essential to work jointly with some economic, human and social science representatives.

Due to the difficulties linked to an interdisciplinary work, real common research programs on these fields, financed as such, are essential to encourage the searchers to work together (develop collaborations).

5.4 Development of the signification of the Δ(TOP, TAL)

The assessment of the risk situation results from the comparison of two variables: TOP and TAL. The interval between them constitutes a measure of the risk intensity (if it is positive, i.e. actual risk) or of the available safety margin (if it is negative, i.e. credit of relative security). This interval could probably be correlated to the water volumes (in excess if the risk is positive, available for the storage of excess water in another place, if the risk is negative).

Otherwise, for a given area, the interval between its hazard and its vulnerability measures its "credit of security". The further developments to realise (hydraulic structures or change in the land use) will only change the distribution of these "risk points" among the different areas of the river major bed.

Thus, we may design a "risk market" at the basin scale, enabling to manage the flood volume, from an area with a severe deficit of relative protection to another with a low level of risk (in term of duration, depth, velocity, of frequency).

The process of negotiation to enter into the different areas should be based on this "exchange money" subject to a previous agreement between the different partners on the rules enabling the establishment of the needs of protection, that is a basis for the risk assessment. But it won't be judicious to enter a negotiation into the single hazard level, this one being mainly set by the real natural phenomenon (hydro-meteorological processes) and being only one part of the risk complexity. So, the "money" could be the vulnerability levels and/or a financial compensation.

It seems to be the best way to achieve a basin solidarity, in mobilising all the diversity and the potential of the landscape (natural polders, forests, ...), to promote a better individual risk culture, and finally, to avoid damage in implementing a better land use management policy.

5.5 Developments for low flows

Finally, a coupling with the biological models should enable to consider, within the same mapping system, some more environmental objectives. Indeed, as we are able to quantify the need of protection (or maximal risk level acceptance) in order to take into account the flood risk, it may be possible to define a "minimal need of flood" allocated to each kind of ecosystem linked to a river (particularly the wetland areas), and thus to check the adequacy of the hydrological regime to the ecosystem. Thus, we would reconcile the objectives of flood damage mitigation with the need to keep a quality natural environment.

6 Conclusion

The conceptualisation of the flood risk as resulting from the crossing of a hazard (the physical phenomenon of the river flood) and a vulnerability (the land use sensitivity to this phenomenon) isn't itself a novelty. But the main originality of the Inondabilité method is that we have the mean to translate these two concepts into two quantifiable variables in the same nature, so objectively comparable. It means to translate the socio-economic data into a hydrological kind of variable (contrary to most of the method that try to translate in monetary term the hydrological knowledge of the river functioning). It is then easier to take into account the probabilistic knowledge of the river flood regime, as well as the numerous non-market values characterising the local vulnerability.

The conceptual model expressed by Inondabilité method may be significant to improve the thought in the field of regional development subjected to flood risk. The method may thus be declined into different accuracy levels, according to the available financing, the acquired knowledge of the basin, and the identified stakes. It has to be used in every cases of river developments where come out some uses conflicts, or land ownership pressure on area liable to flooding, or environmental problems. The availability of the Inondabilité maps and their notification to the general public should lead to a general awareness of the need to respect the "natural" functioning of the river, in order to favour the preservation of a diversified environment, rich and sustainable in the interest of the community and its individuals.

As demonstrated, some scientific and technical results confirm the operational nature of innovative methods to ensure a better integrated river management, reconciling the flood damage mitigation objectives with water resource improvement and natural environment preservation. Inondabilité method was developed in this mind, and, in spite of still expected progresses, it achieves today an operational level, as demonstrated through real practical cases on several catchments.

Inondabilité method proposes objective bases to enter into a true and necessary negotiation at the basin scale, around flood problems. This negotiation level is essential to propose acceptable development means for the whole concerned actors of the basin. Some accompaniment measures will be required, to help the local inhabitants to accept the hydraulic constraint modifications.

Therefore, new researches are still required to improve and complete this approach, and make it more efficient in the future: stabilisation and better definition of the hydrological regime concept, improvement of the knowledge on the processes at the origin of these phenomenon, integration of socio-economic and biological data, consideration of the water quality criterions.

Study and research for the implementation of an Alert Prototype System (APS) in mountainous catchments in north-west Italy

Étude et recherche pour la mise en place d'un Prototype de Système d'Alerte (APS) dans les bassins montagneux du nord-ouest de l'Italie

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Abstract

The research study aimed at the set-up of an Alert Prototype System (APS) functional to catchment characteristics and requirements, to support decision-making. Important side objectives are: a) the assessment of factors relevant to catchment response; b) assessment of hydrological parameters enhancing flood warning; c) determining procedures for flood warning and for the APS.

A full APS has been successfully developed and tested in the Sesia river (Piemonte, north-west Italy) in collaboration with the Geological Survey of the "Regione Piemont" (in charge of flood management). This enables the achievement of the main objective of the research study and leads to interesting future developments.

A first screen analysis of different catchments characteristics has been carried out to select the suitable catchments; the catchment choice depending on: a) amount and reliability of data; b) its significance among the different type of flood behaviour which can be observed in mountainous areas. The preliminary screen analysis has been carried out by taking into account of existing literature and recent studies carried out in Piemonte. Moreover, the most common numerical model based methodologies routines have been screened to select a "commercial" modelling tool to be inserted in the APS for hydrological and hydraulic routines. Three catchments (Sesia, Tanaro and Toce) were selected at first, not only because floods frequently affect them but also for their dense population and the economic importance. This allows us not only hazard level assessment but also risk evaluation. Only two of them have been studied: a) the Sesia, a typical Alpine catchment characterised by high altitude and significant snow flow regime; b) the Tanaro, a typical Apennine catchment, characterised by pluvial flow regime and high sedimentation/erosion rate. Here, two sub-catchments have been selected: Belbo and Bormida. The two rivers have many problems of flood and erosion /sediment transport. The behaviour of Toce is very similar to the Sesia, showing a clear man-made flow regime with reservoirs and many other diversions that deeply affect the natural transfer of

peak discharges. The catchment does not represent a natural behaviour. For this reason the Toce river has been then excluded from the study. For what the Tanaro catchment concerns, it was not possible to carry out the same deterministic approach based on numerical model as for the Sesia. This is due of the lack of data at our disposal on Belbo and Bormida at the end of the study.
The rainfall-runoff transformation module (NAM), the hydrodynamic module (HD) and flood forecasting module (FF) of the model MIKE11 have been used in the study. The choice has made from the authors' experience developed with this model, its reliability and the friendly use of the package[1]. The numerical model has been extensively used in the Sesia and Tanaro catchments. In the Sesia the alert procedure has been developed with the use of NAM (for long and short period simulation), HD (for flow simulation in the river network) and FF (for real time flood simulation). In Tanaro river only the rainfall-runoff transformation and the hydrodynamic simulation have been carried out to represent synthetic events on the catchment, to define different contribution from tributaries in relationship with different rainfall patterns and to assess general flood behaviour.
The present study shows how it is possible to develop a real time forecasting system for a natural mountain catchment taking into account of both modelling techniques for hydrological and hydrodynamic simulation and threshold values for defining vulnerability and risk parameters. The study underlines also the difficulties normally encountered when studying and forecasting floods in mountainous areas. This is particularly evident in Piemonte where climatic, physiographic and morphological characteristics vary very much within single catchment.

Résumé

Le projet de recherche a pour ambition la mise en œuvre d'un prototype de système d'alerte (APS) adapté aux caractéristiques et besoins du bassin, destiné à apporter une aide à la décision.
Les principaux objectifs sont: a) l'estimation des paramètres pertinents de réponse du bassin, b) l'estimation des paramètres hydrologiques améliorant l'annonce des crues, c) la détermination de procédures pour l'annonce des crues et pour l'APS.
Un APS complet a été développé avec succès et testé sur la rivière Sesia (Piemont, Nord-ouest de l'Italie) en collaboration avec le "Geological Survey" de la Région Piemont (en charge de la gestion des crues). Cela permet d'atteindre le principal objectif de la recherche et conduit à d'intéressants développements futurs.
Le présent travail montre comment il est possible de développer un système de prévision en temps réel pour un bassin montagneux naturel en prenant en compte à la fois les techniques de modélisation pour les simulations hydrologiques et hydrodynamiques, et des valeurs seuils pour la définition des paramètres de vulnérabilité et de risque. Les travaux soulignent aussi les difficultés normalement rencontrées lors de prévisions de crues dans des zones montagneuses. Cela est particulièrement vrai dans le Piemont où les caractéristiques climatiques, physiographiques et morphologiques varient énormément sur un seul bassin.

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1 *Note that the present research study supports the realisation of a friendly use and possibly commercial APS. Such a system should include a tested commercial tool, of very high class, available today in the market.*

1. Overview of theoretical concepts

Real time hydrological forecasting is the prior estimating action of future states of hydrological phenomena (like floods) and is based and includes quite number of activities: network design, data processing, remote sensing, modelling, telecommunication, operational use of computer, etc.

Hydrological forecast needs to be viewed as an economic activity involving different actors, decision makers and expertise's.

1.1 The traditional approach to flood forecasting

In the past flood forecasting or flood plain management were never considered as a powerful tool for flood prevention. It was in fact assumed that structural measures (construction of dams, dikes and levees) were the unique correct disaster-mitigation action.

The approach has changed in the time and it is today well accepted the sentence: "not to keep the water away from the people, but people away from the water".

Proper flood plain management that include flood forecasting have been developed extensively in Europe and in the world, to decrease vulnerability to flood damages. Also the importance of real time flood forecasting is today more in the focus of local and national authorities. In facts, a flood-oriented hydrological forecasting system inserted in a disaster prevention programme would lead to a better planning and prevention of floods and efficient intervention.

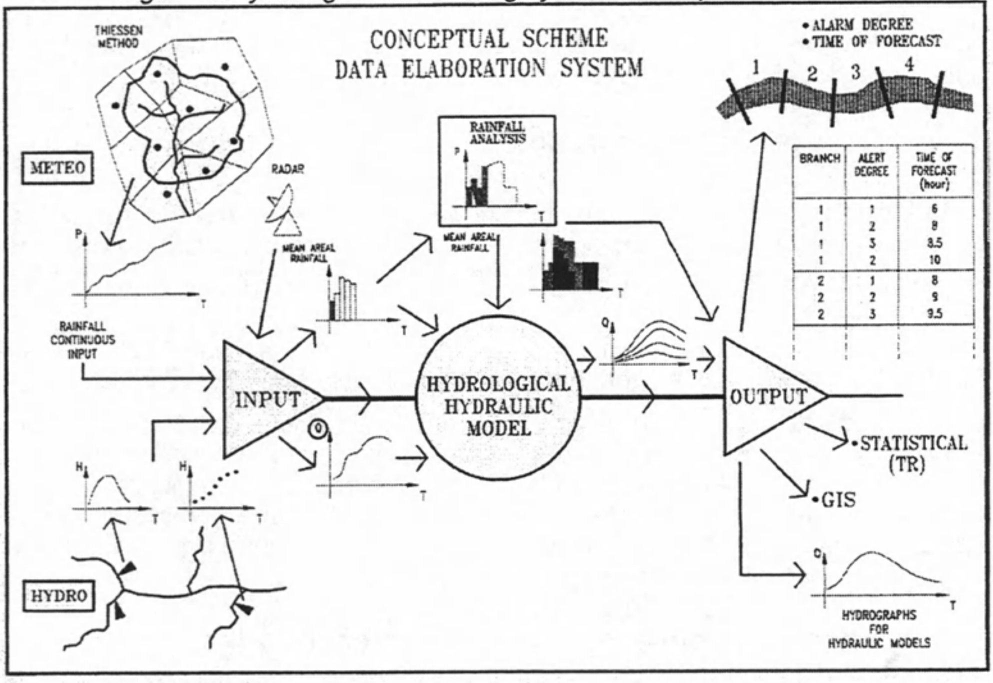
1.2 A new methodology for flood forecasting techniques

A modern flood forecasting system (Fig.1) is generally part of a larger management system tools (1) foreseen in a basin and includes a number of subroutines:

- real time monitoring of the hydro-meteorological, hydrological and water quality data;
- a forecasting software system which enables the simulation of hydrological scenarios, the flood evolution and support possible management intervention during the event. This system is constituted by sophisticated and reliable simulation software, calibrated models and databases. It is managed by a specific management software component, which ensures also the flow of information and data through the interfaces with other elements;
- decision-aid or "expert" system that evaluates the quality of forecast and translates it into a more explicit frame of changes and need of intervention;
- catchment operational management routine, based on the knowledge of present and future situations. It forwards information to local administration, civil protection unit, communities and population for decision. This element of control loop is essentially based on human decision, which cannot be reasonably replaced by a computer;

- telecommunication system capable to transmit in real time all the data, information and results coming from the various elements of the main system. This is the most vulnerable part of the whole system because it depends upon the local technological and natural conditions.

Fig. 1 - A hydrological forecasting system: conceptual scheme



The system developed in such a way enables the representation of various hydrological situations; but it needs to be calibrated for each of those situations.

It is known that a catchment can show different hydrological-hydraulic situation during the flood event. Therefore, it is necessary to characterise different "ambits" in a catchment where the degree and type of alert is different during the flood event (Fig. 2).

1.2.1 Pluviometric ambit

It is referred to the highest part of the catchment, mainly the header of the subcatchment, characterised by step streams and where the alert is based on a very short concentration time (1 or 2 hours). In this case, only rainfall intensity threshold values can be used as warning parameters.

1.2.2 Pluviometric and hydrometric ambit

It is represented by the area where the river network transfers the subcatchments contributions downstream. The concentration time is longer (3 to 18 hours), this is due to the diminishing of river slope and its morphology. The main alert parameters are: rainfall intensity and discharge or hydrometric thresholds.

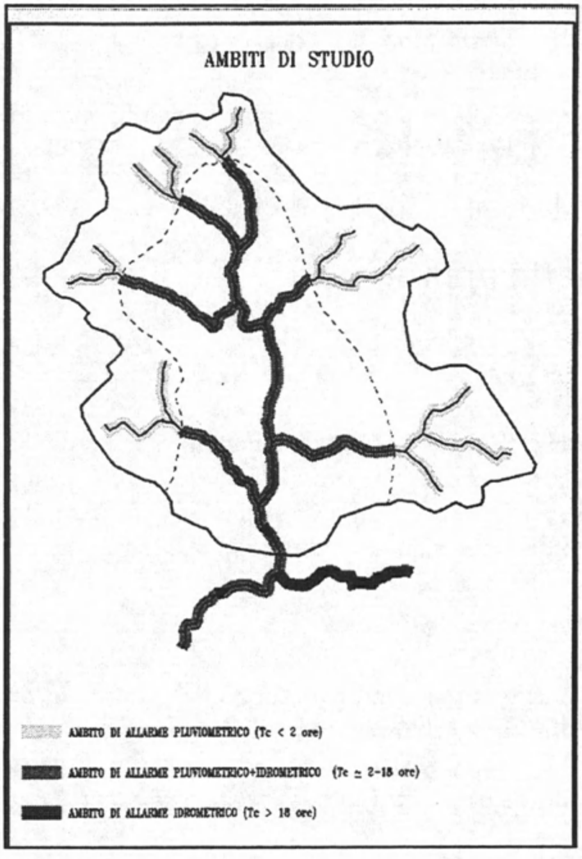
1.2.3 Hydrometric ambit

It is represented by the main river network, where the concentration time is over 18 hours, and where discharge and hydrometric values can be used as alert parameters. A specific hydrodynamic model can simulate the transfer of peak discharges and produce a flood forecast downstream along the river.

Generally, the classical flood forecasting approach does not integrate hydrological and hydrodynamic elements, especially in real time conditions.

Moreover, most of the existing alert systems are related to pluviometric and hydrometric ambit, especially in Italy. On big rivers, as the Po river, the flood forecasting is based on discharges and hydrographs records and the prevision of the river behaviour is conducted by taking into account of water levels variations recorded along the river. Many other examples of local pluviometric alert systems are known and are all referred to very local conditions and short time of warning, especially where critical hydrogeological conditions are known.

Fig. 2 - Hydrological forecast "ambits"



Contrarily, the goal of the present research study is more focused on the hydrometric ambit, where hydrological factors and river hydrodynamics are the most significant for flood forecasting analysis.

1.3 Flood characteristics in mountainous catchments

Several critical situations are known in Piemonte: recent floods (a.e.: November 1994) demonstrated that almost all the Alpine and Apennine catchment shows high risk (2). Typical mountainous rivers have still many problems of flood forecasting. These problems are mostly related to:

- exceptional fast runoff , allowing only a very short time to decision makers to intervene in case of hydrological critical conditions;
- instability of numerical models because of super-critical flow simulations, caused by the very high streams and river slopes;
- presence of snow and glaciers that cover large parts of the catchments and are not easy to be simulated. This is due to the generalised lack of data (temporal and spatial information);
- insufficient meteorological and hydrological real time information. This is due to the high altitude and severe weather conditions for locating and installing gauging stations;
- heterogeneity of spatial information, due to high degree of heterogeneity of the catchment physical characteristics.

The Piemonte offers a wide variety of mountain catchments with very different hydrological and meteorological characteristics. The results obtained in the present study on two selected areas (Sesia and Tanaro) are certainly the starting point for the establishment of similar approaches to other European areas.

2. The heuristic approach

2.1 Project structure

The work package HEURISTIC is subdivided into three sub-packages:

- CATCHMENT

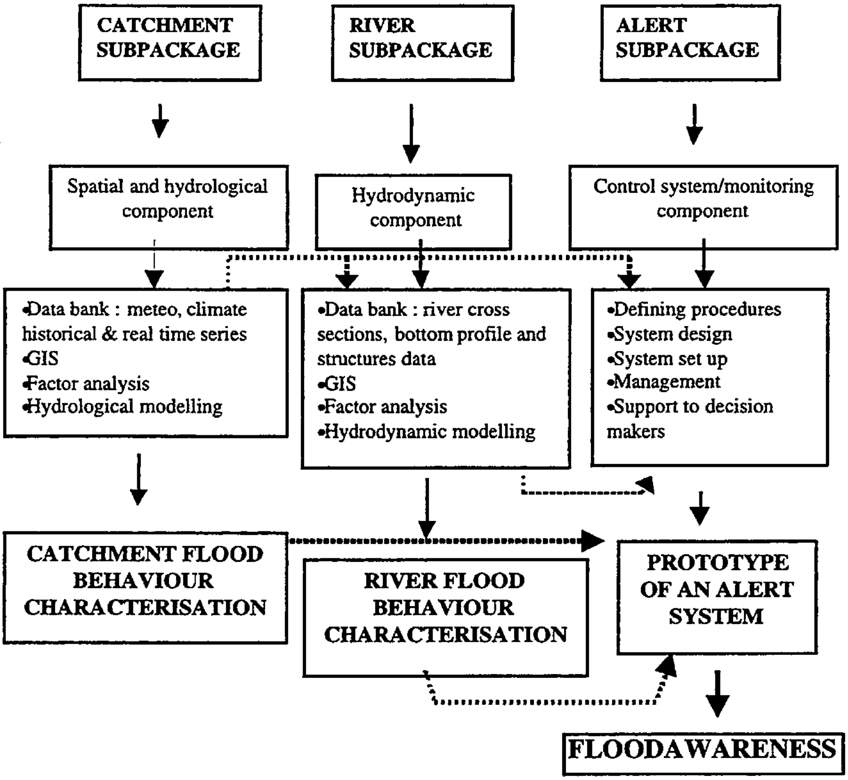
  It describes the land phase of the hydrological cycle and allows seeking the relationship between rainfall and runoff.
- RIVER

  It describes the river hydrodynamics.
- ALERT

  To define and test the operative flood alert system in the pilot catchment, with the purpose to extent the system to other alpine catchments.

The sub-packages "Catchment" and "River" are related to the physical setting of the catchment and have been carried out in both Sesia and Tanaro. The third subpackage "Alert" has been implemented only in the Sesia. The project scheme and the links among the packages are shown in Fig. 3.

Fig. 3 - Project scheme



2.1.1 Subpackage "Catchment"

The objectives are:

- calibration and validation of the land phase part of the numerical model and the production of hydrographs (which can be used as input for the hydraulic part of the model);
- identification of the importance of the different catchment related factors influencing rainfall-runoff relationships: land use, soil type, vegetation, morphology, temperatures,.etc.

The activities are:

- collection of data: catchment data (morphology, soil type, soil use, lithology),
- collection/acquisition of meteorological data (precipitation, temperature, snow levels) and hydraulic data (measured water levels);

- transformation of the meteorological and hydraulic data into time series database;
- determination of the hydrological model parameters (using empirical formulas, values from literature and experience);
- calibration and validation of the model and simulation of different scenarios;
- analysis of results.

2.1.2 Subpackage "River"

The objectives are:

- to obtain a well calibrated hydraulic model and interpreting the results of the Flood Forecasting system;
- to identify the hydrodynamic behaviour of main river and tributaries.

The activities are:

- collection of data (cross-sections, flood plains, river bed roughness, location and characteristics of existing hydraulic structures, morphologic characteristics);
- calibration and validation of the hydraulic model and simulation of different scenarios;
- calibration of Flood Forecasting model parameters;
- analysis of results and estimate of the river morphology development.

2.1.3 Subpackage "Alert"

The subpackage is meant for a particular alpine ambit given by catchments with average dimension and hydrological behaviour conditioned, partly, by both slope contributions (rainfall-runoff transformation) and hydrographs hydrodynamic composition along the river network (flow routing).

It is very important to stress the experimental character of the research that distinguishes our Subpackage "ALERT" from other numerous studies on the same matter which have been developed mostly on theoretical base. Our ALERT is implemented.

The general structure of "ALERT" is constituted by a data acquisition-interpretation system, a real time input and model interface, a numerical model for real-time simulations of flood (based on monitored and foreseen hydrological conditions) and by a section for the interpretation of final simulations. "ALERT" is connected to "CATCHMENT" and "RIVER".

"ALERT" set up has been interactive with the experimentation of the whole procedure and with the updating of the sub-packages "CATCHMENT" and "RIVER", which give information for the development and the calibration of the modelling tools.

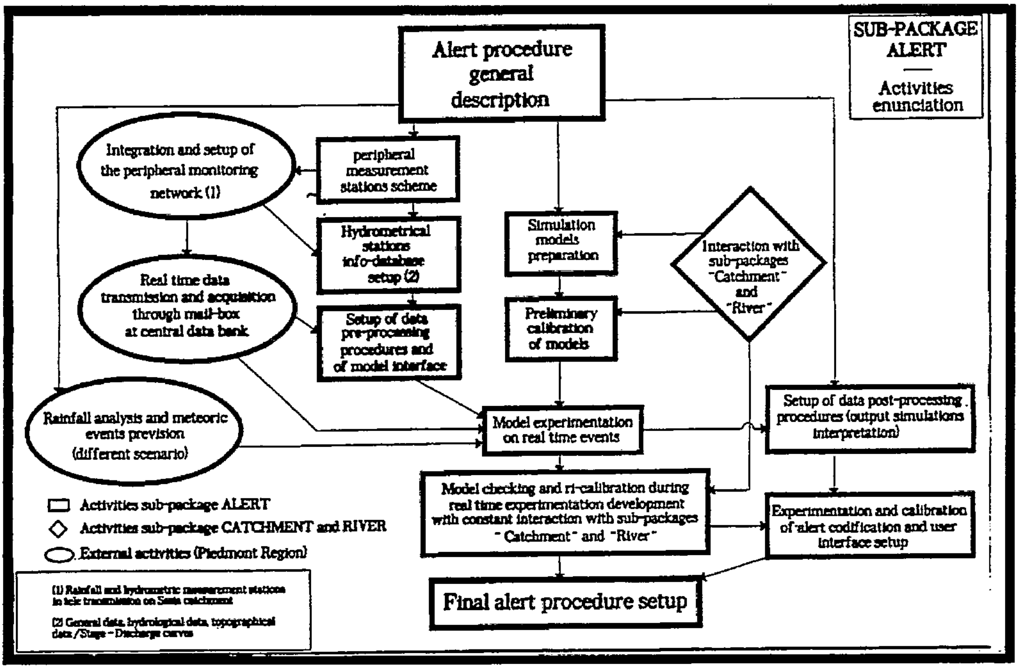
2.2 Design of the Alert Monitoring System (AMS)

The main objects of the experimental AMS procedure are:

- set-up of the hydrological-hydraulics simulation model;
- to integrate the calculation module with an organised input data system, especially during the real-time management of critical event;
- to apply the forecasting procedure on real events, verifying and optimising times and data management and pre-processing;
- to study an output of the model compatible with the effective needs of alert by the civil protection unit in the area.

In Figure 4 the main phases of the alert procedure are summarised. The main components are shortly described here after.

Fig. 4 - Alert activities



<u>INPUT</u> - Software packages and control/managing procedures have been developed to set up a real-time routine interfaced with the local rainfall and hydrometric measuring network and the data pre-processing analysis (a.e.: integration-extrapolation of historical series of data, transformation of hydrometric values into discharge values through stage-discharge curves or hydraulic modelling, elaboration of flood development scenario using rainfall data analysis and comparison with previous flood events).

<u>HYDROLOGICAL-HYDRAULIC MODELLING</u> - The simulation model is used in accordance with the complexity of the catchment situation, a.e. the extension and

articulation of the considered hydrographic ambit, the data availability and the concentration time for the forecasting. The main function of numerical modelling (composed by rainfall-runoff lumped model combined with hydrodynamic model for the wave propagation) allows the extent of the information on flood development from the gauging points to the whole hydrographic network. This is possible by calculating modalities and concentration times and hydrographs transfer after a certain rainfall event.

<u>OUTPUT</u> - The results of the hydrologic-hydraulic simulations are interpreted by taking into account of the risk index and the time of forecast at each cross section of interest (values referred to the real event and to the theoretical forecast). Statistical parameters are defined to characterise the event (in terms of return period) and consequent output data are produced for their use into other modelling applications downstream the river network connected with the hydrological catchment. The synthetic values generated by the output module of the ALERT procedure go to fill the issued floodaware reports and are used for the development of territorial operation management and protection measures.

Referring to the general scheme of ALERT, the main activities conducted for the definition of the entire procedure are described hereafter.

2.2.1 Connection to peripheral networks

Location of the peripheral monitoring network and the interface with the ALERT's operational centre. The set up of ALERT takes place into the current Programme of co-ordination of the different monitoring networks on the territory (national and regional), through a gradual development of Agreements for data sharing and for the maintenance services.

In order to receive real-time data flowing from the external monitoring network, ALERT must be connected with a "Data Concentration Point" that works interactively with the main peripheral gauges.

In our case, data are acquired by the Geological, Meteorological and Seismic Prevention Department of the Piemonte Regional Authority.

2.2.2 Data pre-processing

Acquired data must be transformed into suitable data for modelling. A first step elaboration is conducted for temperature and rainfall raw data and hydrometric data which must be transformed into discharge values. Gauge sections and the whole river present unstable conditions. This being due to: -) morphological natural changes; -) deposit-erosion processes; -) artificial conditioning; -) infrastructures near the gauges. It is therefore necessary a continuous control of the new physical changes and possible developments at the gauging point/sections.

The implemented database must be therefore very flexible to the continuous updating. The deep knowledge of the gauged sites (a.e.: hydrographic localisation, hydrometric reference, characteristic of the instrumentation, hydrological characteristics, hydraulic characteristics and stage-discharge relationships, data of previous flood events, topographic and bathymetric survey data at the gauge cross section and other geometrical elements) must be at full disposal to support the real-time interpretation of flood phenomena.

2.2.3 Rainfall data analysis

Two different data analysis have been conducted:

1. the interpretation of real rainfall data, comparing the recorded value with the threshold value defined in terms of rainfall intensity or total cumulated rainfall depth;
2. the extrapolation of real time recorded events for the elaboration of the evolution scenarios.

2.2.4 Simulation modelling

The numerical core of ALERT is the hydrological-hydraulic model. The model MIKE 11 is the chosen software-integrated package that can reproduce most of the natural phenomena on territory; its structure being based on different simulating modules.

2.2.5 Analysis of the hydraulic vulnerability

The analysis is carried out by using data from the sub-package "RIVER". Both data related to minor flood events (with return period of 2÷5 years) for the activation of the alert procedure and data related to major flood events are necessary to interpret the simulation model output.
Significant water levels at some critical sections having flooding problems are used also for comparison with planning bonding rules like "fluvial pertinence bands".
Each river where an alert system is to be developed is subdivided into characteristic branches. Critical water level values, corresponding to certain degrees of alarm, are assigned to each branch, by considering: events frequency, the presence of vulnerable structures or building up areas and downstream risk induced.

2.2.6 "Alert bulletin" definition

Output results from models must be interpreted and transformed into data suitable for dissemination, broadcast of alert issue and description of critical event evolution. The information is planned be collected into an "Alert Bulletin" issued with a defined frequency. The Bulletin is structured together with the end-users (Regione Piemonte and Civil Protection Department) accordingly with their needs. The output data interpretation procedure begin with the comparison between data (rainfall, discharge, hydrometric level) coming from the activities above. This phase is supported by simple calculation routines. The compared results are transformed into index-values for each cross section of interest or each branch, taking into account of: -) degree of alarm; -) event's return period estimation; -) rainfall return period estimation. The index values must be considered for both the instantaneous moment during the event and the forecasted flood scenario.

2.2.7 Activation and management of ALERT procedure

The organisation of "ALERT" activities, in normal conditions and during flood events, must give answer to the different issues coming from various end-users.

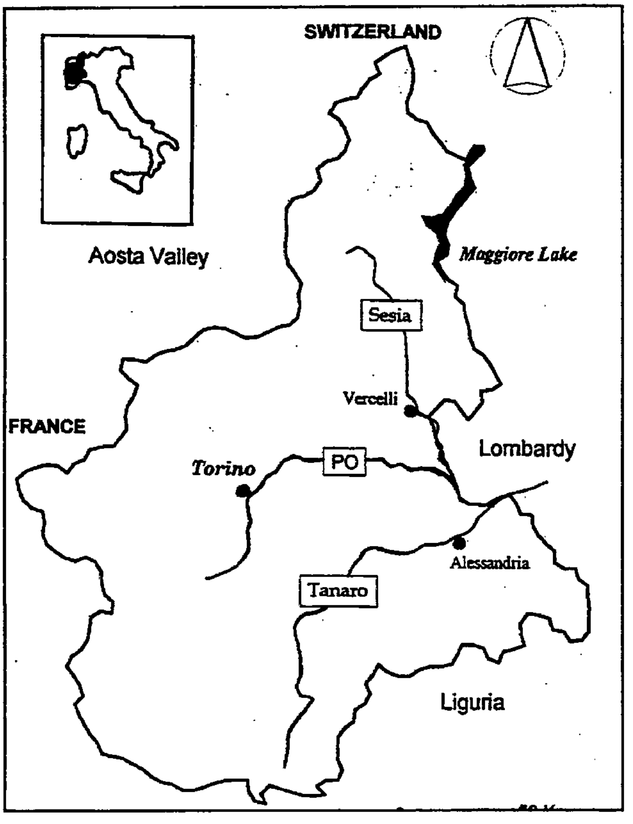
The entire procedure is to be tested and improved on the base of real applications. A determining element of the entire procedure is concerned with the activation modality of the flood service. On this argument research is still on.

2.3 The studied catchments: main characteristics

Both Sesia and Tanaro are tributary of the Po respectively at km. 209th and 222nd (Fig. 5). The following table shows the main characteristics of the catchments at the main gauge before the confluence with the Po river.

name of the basin	*Maximum altitude*	*Average altitude*	*surface*	*Mean rainfall*
Sesia at Vercelli	4559 m a.s.l	884 m a.s.l.	227 km^2	1754 mm
Tanaro at Montecastello	3297 m a.s.l.	663 m a.s.l.	7985 km^2	1018 mm

Fig. 5 - Piedmont Region and the studied rivers



The main tributaries of Sesia are the Mastallone, Sessera, Sermenza in the higher part of the basin and Cervo and Elvo in the lower part.

In the Tanaro the Belbo and Bormida subcatchments are the main "Apennine Type" subcatchments while the Stura Demonte is the main "Alpine type" tributary.

The pluviometric regime in Piedmont is characterised by a maximum in autumn and spring and two minimum rainfall periods in summer and winter. The Alpine catchment Sesia receives much more rain than the Alpine/Apennine Tanaro.

The Tanaro river network is highly branched and produces huge discharges in its lower part during intensive precipitation.

During the last 150 years several flooding events happened in the Tanaro catchment particularly in the main Apennine tributaries Belbo and Bormida. The most severe floods occurred in September 1948, October 1857, November 1968, May 1879 and November 1994. The event of 4-6 November 1994 was very exceptional (3) (4). For example at the Montecastello station a discharge of 3500 m^3/s has been measured. Compared to the discharge of the event of November 1968 (2700 m^3/s) the former is 30% higher.

The Sesia catchment can be subdivided into two parts: the lower southern part is a flat area (the river has a typical fluvial behaviour) and receives much more precipitation than the higher northern part where, on the contrary, precipitation falls often under the form of snow.

Rainfall intensity patterns are very heavy during late spring and early summer. In this period rains falls on the snow cover causing great amount of runoff in the internal tributary subcatchments. The snow component plays an important role in the catchment analysis of Sesia. In the Sesia catchment the most important flood events occurred in June '51, November '68 and September '93. The event of November 1994 was less critical than in previous years.

The two catchments present different lithology. The Tanaro's lithology varies from marls, sandy-marls, sands to clay, calcarenites and alluvial deposits (4). The morphology is terraced, and some old gravel alluviums, sometimes sandy and loamy; old gravel alluviums, recent gravel deposits and Holocene deposition on river bed are present. The Sesia, on the contrary, is basically constituted by hard rock geology: schists associated with limestone, micaschists, gneiss, basic granulites and associated amphibolites, kinzigites. Significant ancient glacial deposits are present downstream to the catchment.

The Sesia is covered predominantly with forest and natural pasture while the Tanaro is much more cultivated.

2.4 Phases of work

The whole research has been developed in two years. During the first year (June 1996-July1997) the activities carried out are divided into four phases:

1. phase 1: review of existing literature and state of the art on flood forecasting system (numerical models and application cases);

2. phase 2: check of the existing monitoring system and models interfaces; collaboration with the Regione Piemonte for data collection; data validation and pre-processing;
3. phase 3: modelling with NAM and HD models on the Tanaro and Sesia catchment; set up of models parameters and schematisation; calibration of NAM model on long period simulations; calibration of HD model for different scenarios;
4. phase 4: definition, in collaboration with the Regione Piemonte, of a first step alert procedure scheme (activation and management of input and output - "alert bulletin").

During the second year the research has focused on the APS for the Sesia catchment. The FF module has been used, tested and applied for some alert situations, both meteorological forecasting and other warnings (rainfall and hydrometric threshold values). Particular attention has been given to rainfall-runoff transformation in the Sesia catchment for the snow effect on the resulting discharge during both long period and real time simulations. The snow effect has been investigated with more regard, the snow parameter showing as to be important in a catchment like Sesia. This gave us also the opportunity to check the robustness of the new NAM-SNOW module provided in the MIKE 11 package. The NAM-SNOW module is based on a conceptual routine that can be carried out with limited available information and calibration parameters, but also include the possibility to account for important processes like change in the albedo and snow area coverage. The NAM-SNOW module calculates melt water in a number of altitude zones using an advanced degree-day-factor (or index) approach. Since in many cases the hydro-meteorological information from mountain basins is normally badly distributed, the module includes also facilities for distribution of the meteorological information with altitude. On the basis of the standard NAM input and a set of calibrated model parameters the module performs separate snowmelt calculations for each altitude zone. The melt water is routed through the NAM model for simulation of runoff from the whole catchment. Unfortunately, the NAM-SNOW module could not yet be interfaced with the FF module. In this case, a new empirical approach (that considers minor contributing basin surface when the air temperature is low) using the simple NAM model has been adopted to simulate the snow effect on discharges in the upper part of Sesia catchment during "ALERT" simulations.

3. Case studies: analysis and results

With reference to the project structure and considering the three subpackages, the following analysis has been conducted.

3.1 The Sesia catchment

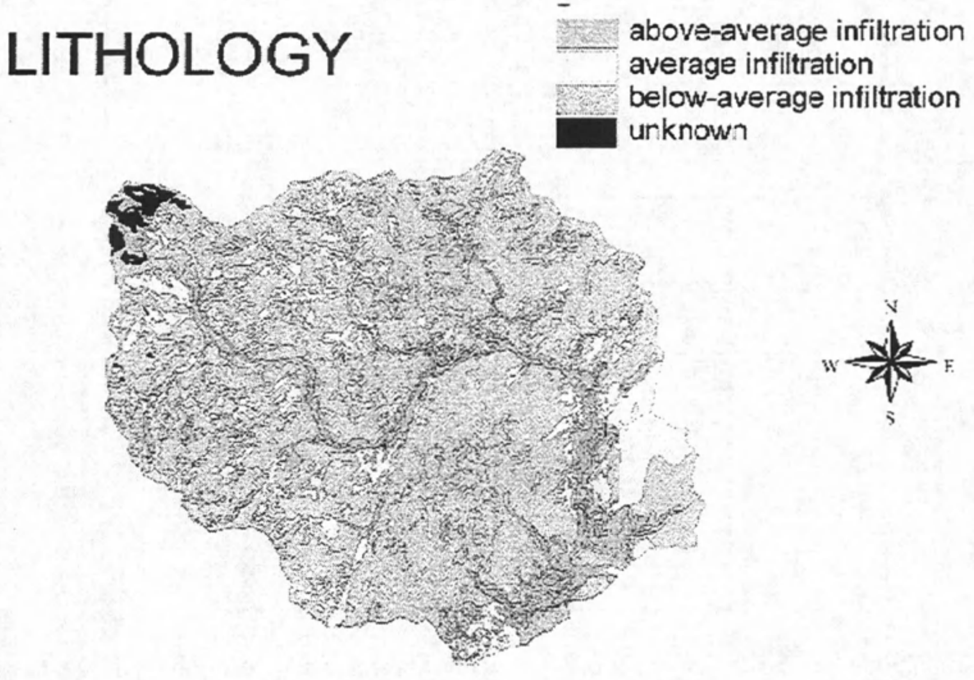
The main research efforts have been concentrated in Sesia catchment, where all the working packages have been deeply developed.

The analysis of the hydrological behaviour (subpackage "Catchment") has been carried out in the upper part of the catchment down to the main hydraulic section at

Borgosesia (downstream of confluence with the Sessera river) before the Sesia river flows into the flat area. The most important precipitation occurs normally in this part of the catchment. The NAM model has been implemented and tested considering: -) long and short period simulations; -) discharges, rainfall and temperature data supplied by the Meteorological Service of the Regione Piemonte (daily data of 1995 for model set up, daily data of 1996-1997 with some hourly events during 1997 for model calibration, real time hourly data from November 1997 to May 1998 for flood forecast simulation).

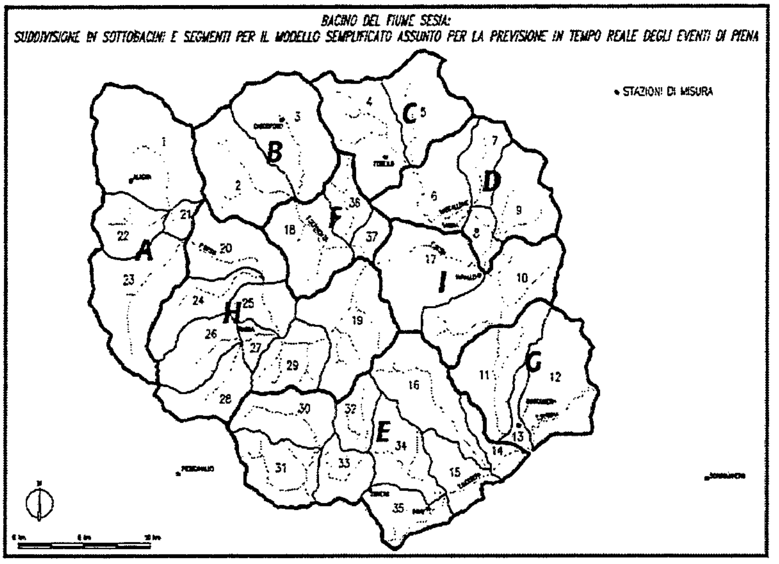
Soil use and lithological maps (Fig.6) and DEM have been provided by the Regione Piemonte Authority and used to define catchments main physical characteristics to be transformed into model main parameters values.

Fig. 6 - An example of numerical map on Sesia catchment



A scheme of the subdivision of Sesia alpine basin into sub-catchment is shown in Fig. 7; a simplified model based on 10 subcatchments has been established for real time simulations.

Fig. 7 - Sesia catchment subdivision and main parameters values obtained from physical data and model calibration analysis (Umax, Lmax, Runoff coefficient and CK1 are the main NAM model parameters)



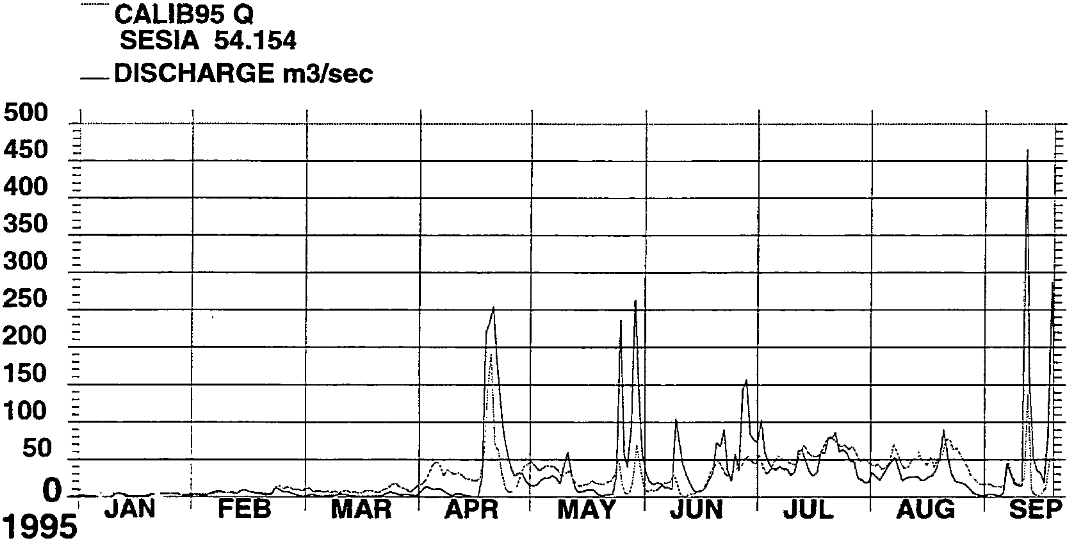
Sub-catchments main parameters					
Name	Area	Umax	Lmax	Runoff Coef.	CK1
	(km^2)	(mm)	(mm)	(-)	(hour)
A	120.3	3.3	33	0.76	1.6
B	81.7	4.6	46	0.74	1.7
C	73.5	5.4	54	0.72	1.9
D	80.9	6.7	67	0.71	1.5
E	178.3	6.4	64	0.69	1.8
F	49.7	6.6	66	0.71	1.3
G	89.2	6.8	68	0.61	2.4
H	173.7	5.8	58	0.70	1.3

Simulations of the upper network between Alagna and Borgosesia have been made by coupling NAM with HD to better describe tributary confluence and contributions. This upper part of the Sesia show very impulsive regime. Upstream confluences are quite similar (in time and contributions) and flood problems are very often related to hydrogeological vulnerability problems and not only to hydrological and hydrodynamic aspects.

Results of long period simulations shown in Fig. 8 have been very useful to establish initial model conditions (like catchment antecedent soil moisture conditions that

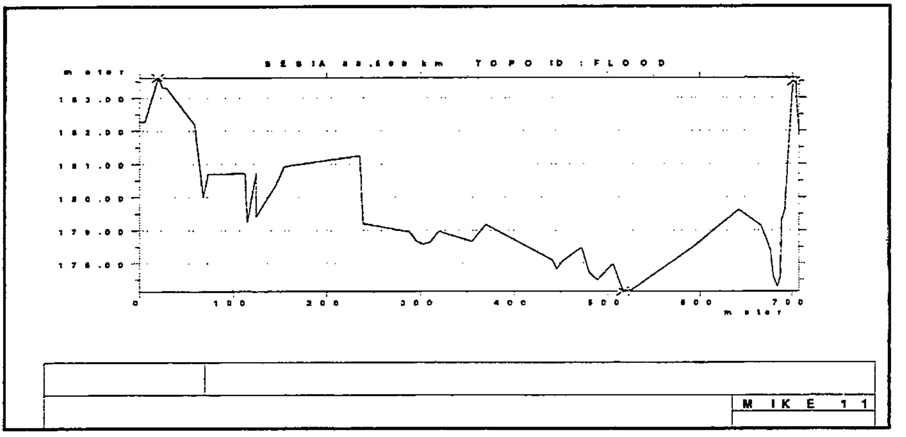
Results of long period simulations shown in Fig. 8 have been very useful to establish initial model conditions (like catchment antecedent soil moisture conditions that affects very much the resulting peak discharge values) as soon as the alert system has been set up for real time simulation.

Fig. 8 - Comparison between measured and simulated discharges at Borgosesia for the period 1/1/1995 - 30/9/1995



The analysis of the downstream sector of the Sesia (subpackage "River") has been carried out considering the hydrodynamic aspects of flood behaviour, using the HD module. Some more detailed description of hydraulic sections has been used to underline peak discharge propagation problems related to the presence of flood plains and embankments (Fig. 9). The information obtained from simulations regards mainly: peak discharge values along the river, maximum water levels and velocities, branches characterisation to define critical points (bridges, embankments, riverside populated or industrial sites). A great deal of the hydrodynamic information has been transferred to the project partner "Regione Piemonte" for the definition of the risk map.

Fig. 9 - Sesia River cross-section (survey 1992)



Some hydrometric threshold values have been defined for alert or alarm water level. These values are used to activate the APS when meteo-forecasting is not provided.

SESIA AT BORGOSESIA		
Discharges	h (m)	H (m a. s.l.)
QTR 2 years = 860 (m^3/s)	**2.15**	338.45
QTR 5 years = 1350 (m^3/s)	**2.88**	339.18

SESSERA AT PRAY		
Discharges	h (m)	H (m a.s.l.)
QTR 2 years = 193 (m^3/s)	**2.37**	---(*)
QTR 5 years = 318 (m^3/s)	**2.84**	---(*)

(*) hydrometric zero not still correctly known

SESIA AT PALESTRO		
Discharges	h (m)	H (m a.s.l.)
QTR 2 years = 690 (m^3/s)	**3.10**	112.15
QTR 5 years = 1635 (m^3/s)	**3.76**	112.81

As we have already above the subpackage "Alert" in its whole has been developed in Sesia river. After analysing the river behaviour from an hydrological and hydraulic view point, the whole procedure has been tested on real meteorological alert. This happened after the modules/models calibrations, the establishment of threshold values for critical conditions along the main river system, the development of the alert procedure the issue alert bulletins in collaboration with Regione Piemonte.

The main work consisted of:

- meteorological data acquisition (from individual rain gauges and Meteosat);

- hydraulic data acquisition from measured discharges and/or water levels to define actual conditions and rainfall patterns forecast. All this information have been transmitted in real time first to the Central Computer of the Regione Piemonte and then our Centre;
- model calculation.

The simulation results, coming after about 1-2 hours from the first data acquisition consisted of discharges and water levels for different forecasting time spans and for different places along the river. These results were then interpreted with the help of statistical analysis. Some alarm levels in the downstream part of the Sesia, that are critical for the urban and industrial setting in the flood plain, have been previously defined. The comparison between these alarm levels and the forecasted results by Mike11 has enabled the system to predict where and when the situation would become critical.

Alert bulletins are issued every 12 hour with or without forecast, following rainfall data acquisition (every 10 minutes) and model evaluations.

The procedure tests have been conducted on the only significant and real event occurred in the two years project, in November 1997. The event has not resulted heavy. Nevertheless, some previous and more critical events have been reproduced in similar way. In the winter '97-'98 and in the early spring 1998 conditions have been very dry.

The format of the Alert Bulletin issued for the November '97 meteorological warning is shown in Fig. 10.

Fig. 10 - Alert Bulletin

da: Risorse Idriche — a: Regione Piemonte Sala Situazione Rischi Naturali

SISTEMA SPERIMENTALE DI PREANNUNCIO DELLE PIENE
- FIUME SESIA (tratto Borgosesia - confluenza Po)

BOLLETTINO PREVISIONALE del ...6/11/97.... ore.14:30 (previsione meteo del 06/11/97 ore 12:00)

Tratto del Sesia		**portata prevista**				**portata di riferimento**	
		Qrain			Qmeteo		
codice tratto	descrizione	portata di picco (mc/s)	classe di portata 1per TR<2 anni 2per: 2<TR<20 3 per: TR>20	giorno/ora del raggiungimento della classe 2 o 3	portata di picco (mc/s)	Q tr2 (mc/s)	Q tr20 (mc/s)
S0	da Borgosesia a monte della confluenza T. Sessera		1	0/00/00 alle 0:00	**227**	**1100**	**2070**
S1	da confluenza T.Sessera a valle di Romagnano		1	0/00/00 alle 0:00	**271**	**1500**	**2880**
S2	da valle di Romagnano a Ghislarengo		1	0/00/00 alle 0:00	**253**	**1420**	**2830**
S3	da valle di Ghislarengo al ponte autostrada A4 TO-MI		1	0/00/00 alle 0:00	**237**	**1320**	**2770**
S4	dal ponte autostrada A4 TO-MI a monte confluenza T.Cervo		1	0/00/00 alle 0:00	**229**	**1150**	**2720**
S5	da confluenza Cervo a Vercelli		1	0/00/00 alle 0:00	**238**	**1370**	**3270**
S6	da valle di Vercelli a Palestro		1	0/00/00 alle 0:00	**227**	**1300**	**3000**
S7	da Palestro alla confluenza Po		1	0/00/00 alle 0:00	**211**	**1150**	**2500**

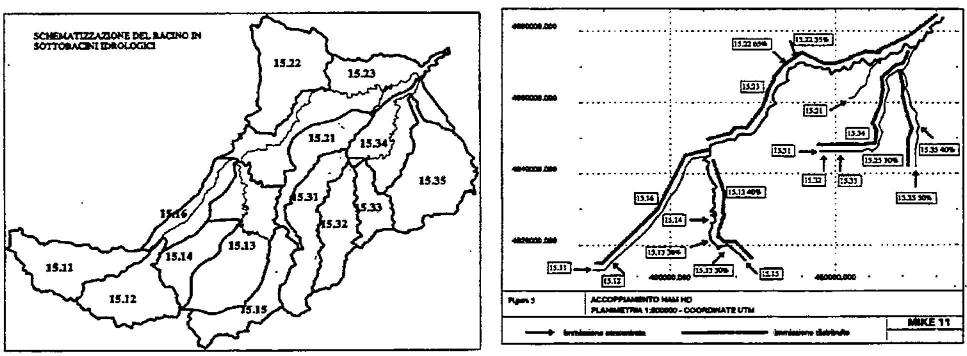
3.2 The Tanaro catchment

The Tanaro has been modelled for more than 100 km together with the Stura di Demonte, Belbo, Bormida and Orba tributaries. For the rainfall-runoff simulations the catchment has been divided into 14 subcatchments. The model has been calibrated for the event of November 1994. One has to noticed that the calibration over such a short period is generally not enough to define a model representative of all other periods. Nevertheless, the calibration has proved to be representative for flood simulations.

In the Tanaro catchment, the final goal is not the set-up of a real-time forecasting system and an APS. The catchment area of 9000 km^2 is to big for this purpose with the time constrains imposed by the project. Thus, the study has been limited to the factor sensitivity analysis with the scope of determining the effects and the catchment behaviour when changing NAM model parameters. This has allowed the most proper re-adjustment of the model. A second step study has focused on the effects of different precipitation patterns on the whole basin. This has lead to a better insight of the behaviour of the river and has allowed a preliminary assessment of discharges which can be expected and their time of arrival.

Moreover, it has been shown that a deterministic model like MIKE11 can be used - indeed - with good result in flood forecasting management. The hydrological-hydraulic scheme adopted for Tanaro is shown in Fig. 11.

Fig. 11 - Tanaro river hydrological-hydraulic modelling scheme



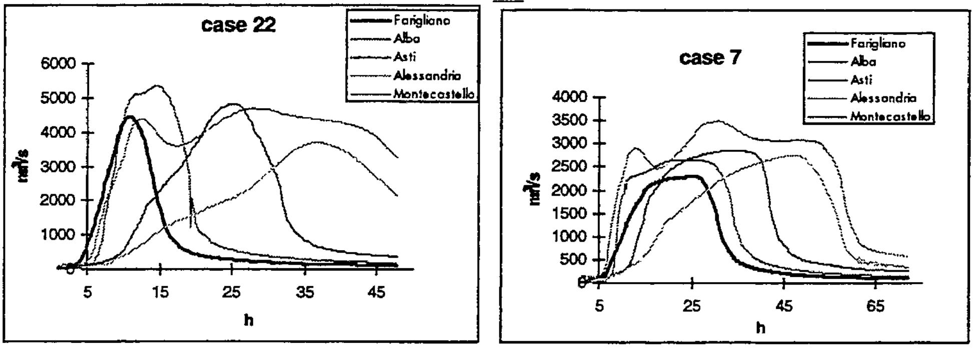
After calibrating the complex hydrological and hydraulic model on the whole Tanaro catchment considering the critical event of November 1994, and carrying out a "sensitive analysis" to better know the effect on model results based on different model parameters, a better knowledge on different subcatchments' flood behaviour has been established.

Generally, when the discharge from the upper part of the Tanaro arrives, the peak coming from Belbo and Bormida has already passed. In fact, a reduction of the concentration time in the upper part of Tanaro catchment or the augmentation of this parameter on Belbo and Bormida (in order to have peaks arriving at the closing section of Montecastello at the same time) does not produced the expected effect. The peak discharge resulted only in 1% higher.

A more detailed analysis on subcatchments behaviour has been conducted considering the response to different rainfall patterns (spatial different distribution and intensity conditions). Synthetic rainfall events have been used considering uniform rainfall precipitation on each subcatchment, with quantity of rain corresponding to specified return period and duration. The time duration has been established on the values of different concentration times related to some particular location along the river (from 12 to 48 hours).

The idea was not to simulate any possible events in the Tanaro catchment, but to demonstrate the way in which the results can be used to analyse the whole catchment flood behaviour. The results of the analysis (22 simulations) consisted mainly in the calculation of the maximum discharges in 5 cities along the Tanaro river and the time of arrival of related peaks (Fig.12).

Fig. 12 - Example of resulting peak hydrographs for 5 control locations along the Tanaro river considering different duration and intensity rainfall patterns



For each scenario the following elements are given: -) the value of the peak discharge; -) their difference compared to a fixed delay chosen as to be the situation where the rain duration on each sub-catchment is equal to the respective concentration time. Also the time of arrival of the peak discharge and the 'delay' in comparison to the same reference are given.

By analysing the HD model results it was also possible to define some critical time duration in respect to the flood severity. The use of specific rainfalls in specific areas of the basin has allowed the definition of a range of hours for the forecasting of a flood from an upstream location to another location downstream. Different rainfall patterns can produce an increase of peak discharge in some control sections and, contemporaneously, a discharge decreasing in other control sections due to the time shift of the events.

4. Conclusions

The research study has produced some important results Modelling integrated to new technologies for data acquisition and elaboration proved to be a good tool to assess flood forecasting systems on also in mountainous catchments. Different flood predictors like -) sudden hydrometric variations; -) critical weather forecasting and rainfall intensity pattern analysis; -) snow coverage linked to temperature; -) catchment physical characteristics, can be easily taken into account when setting up an Alarm System Procedure.

On the other hand, when establishing a real time flood forecasting, attention must be paid for all those factors that affects flood genesis and fate. This is particularly important in mountainous catchments where run-off time is very short. In typical "second level ambits" the time left for forecast is not more that few hours.

The complete approach to the problem of flood forecasting and alerting has been implemented for the first time in the Sesia catchment.

It is worth to mention the relatively low cost of such an operation, to activate different levels of alert system on the territory, using real time data and simulation tools for forecasting different flood scenarios (and not only floods!).

Considering our current experience and results achieved, a further research on how to better develop interfaces between real data, general informations and modelling tools is strongly recommended.

In the alpine catchments, the snow component must be carefully taken into account when simulating the hydrological behaviour and carrying flood forecasting analysis. The NAM-SNOW module has shown to be a consistent tool for real application but needs to be coupled with the Flood Forecasting routine for an easiest and more reliable real time simulation.

For other type of catchments, where flood genesis is not due only to slope runoff contributions in the upper part of the catchments but is also (or mainly) due to the concomitance of contributions along the river network, the hydrodynamic analysis must be more detailed and must consider also very local problems/physical settings, in order to correctly define vulnerability and risk.

Design discharge calculations and flood plain management

Estimation de débits de projet et gestion des plaines inondables

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Abstract

A study of floods on a European level, both as regards calculation methods and design discharges, is one of the aims of the project, and others include the implementation of non-structural methods and the preparation of risk maps.

The contribution of CEDEX has been divided in two main groups of activities entitled: Design Discharge Calculations and Flood Plain Management.

The first part consisted in a compilation of the different methodologies that are currently being applied in design discharge calculation, special attention being paid to the accessibility of the basic information required, together with the problems faced when it comes to their application. The methods were grouped into two main categories: hydrometeorological and statistical and the methodologies described were applied to the Spanish basins of the Rivers Velillos, Llobregat and Noya.

A calculation of the maximum discharges associated with different return periods was calculated for the River Velillos, through the use of hydrometeorological methods, and the rainfall-runoff process was simulated on the basis of rainfall data and certain physical characteristics of the basin.

In the case of the Rivers Llobregat and Noya, statistical methods were used, based on the direct treatment of instantaneous discharge data and, where the River Llobregat was concerned, different historical references to past floods were also used. In river Noya, calculation was also made by applying the so-called modified rational method.

The second group of activities was devoted to Flood Plain Management. In Spain, as in other Mediterranean countries the combination of extreme rainfall events together with the occupation of flood plains has produced catastrophic floods. In this report an assessment of two of these flash floods is made: Biescas (1996) and Badajoz (1997), both produced in the period of development of the Floodaware project.

Non-structural measures do not act upon the floods themselves, but serve to reduce the damage these phenomena cause by means of a management rather than a construction policy. Biescas and Badajoz are examples showing that the use of this type of measures must be on the increase. Between other factors, it has been realised that structural measures enhance the implantation and development of communities because they feel safe, in places close to rivers, and where flooding is inevitable.

Spanish flood plain management situation at present has been also described, followed by a proposal of planning criteria for flood areas. These criteria were applied to a case study in the Spanish River Cinca.

Résumé
L'un des objectifs de ce projet est d'étudier les crues à une l'échelle européenne, d'un point de vue à la fois méthodologique et quantitatif d'estimation des débits de projet. Cela comporte également la mise en œuvre de méthodes non-structurelles et la réalisation de cartes de risque.
La contribution du CEDEX a consisté essentiellement à l'estimation de débits de projet, et à la gestion des plaines inondables.
La première partie a permis de faire le point sur différentes méthodologies couramment utilisées pour l'estimation des débits de projet, en portant une attention particulière sur la disponibilité des données de base requises et les problèmes qui peuvent se poser lors de leur utilisation. Les méthodes ont été regroupées en deux catégories principales: hydrométéorologiques et statistiques; et les méthodologies décrites ont été appliquées aux bassins espagnols des rivières Velillos, Llobregat, et Noya.
Le calcul des débits maximum associé avec différentes périodes de retour a été réalisé pour la rivière Velillos à l'aide de méthodes hydrométéorologiques, et le processus pluie-débit a été simulé à partir de données de pluie et de certaines caractéristiques physiques du bassin.
Pour les rivières Llobregat et Noya, des méthodes statistisques ont été utilisées, basées sur le traitement direct des données de débits instantanés, et, pour la Llobregat, différentes références historiques aux inondations passées ont été utilisées. Pour la rivière Noya, le calcul a aussi utilisé la méthode dite rationnelle modifiée.
La seconde partie du travail a été consacrée à la gestion des plaines inondables. En Espagne, comme dans d'autres pays méditerranéens, la combinaison des événements de pluies extrêmes avec l'occupation des plaines inondables a conduit à des inondations catastrophiques. Dans ce rapport, une évaluation de deux de ces crues éclairs est proposée: Biescas (1996) et Badajoz (1997).
Les mesures non-structurelles n'agissent pas sur les crues elles-mêmes, mais permettent de réduire les dommages causés par ces phénomènes grâce à une politique de gestion plutôt que de construction. Biescas et Badajoz sont deux exemples qui montrent que l'utilisation de ce type de mesures peut être généralisé. Entre autres, il a été montré que les mesures non-structurelles favorisent l'implantation et le développement des populations qui se sentent en sécurité, bien que proches de la rivière et en zones inondables.
La situation actuelle de gestion des plaines inondables en Espagne a été décrite, et suivie d'une proposition de critères de planification pour les zones inondables. Ces critères ont été appliqués à un cas d'étude sur la rivière espagnole Cinca.

1. Design discharge calculations

1.1 Calculation methods

As a first step of the job carried out by CEDEX, a summary of main used calculation methodologies was described in detail in "Mid-term report (August 1996/July 1997)".

The *hydrometeorological methods* simulate the rainfall-runoff process, on the basis of rainfall data and the basin characteristics, thereby making use of the advantage of the greater length and spatial density of the rainfall network when compared to the gauging network.
Several topics about these methods were described:

- Basic data needed:
  - Maximum Rainfall data
  - Maximum intensity or temporal distribution
  - Hydrological parameters
- Description of Aggregate method for Maximum Discharge Calculation
  - Estimation of concentration time
  - Calculation Formula
  - Obtaining the value of the intensity from intensity-duration curves
  - Estimation of runoff coefficient
- Distributed Method for calculating flood hydrographs
  - Net rainfall estimation
  - Obtaining the surface runoff hydrograph
  - Propagation of hydrographs in riverbeds and reservoirs

Several problems related with the applicability of these methods were identified:

- The use of hydrometeorological methods is commonplace in the estimation of design discharges associated with a particular return period, owing to the fact that there are not sufficient gauging data to allow for the estimation of the flood from a direct analysis of such information. Although these methods are easy to apply and can be compared experimentally at gauging stations, they do cause a series of problems, as regards both the approach to the methodology and the basic information required for their application.
- This methodology poses the difficulty of relating the probabilities associated with the rainfall and the consequent discharges, mainly owing to the fact that it is necessary to start with simplifying hypotheses for both the spatial and temporal definitions of the storm associated with a particular return period, and with the considerable variation with respect to the initial moisture of the net rainfall estimation parameters.
- The irregular spatial and temporal distribution of the maximum rainfall data for 24 hours, which is used as basic information in a local rainfall study, constitutes

the main problem when estimating the amount of rain associated with a return period. The same happens with the temporal distribution or maximum intensity of the storm, so, in the case of the Rational method, intensity-duration curves are used to determine the intensity value associated with an interval of duration t, equal to the concentration time. However, where the methods based on the unit hydrograph are concerned, it is necessary to start with synthetic storms to define a temporal distribution, if no data are available for shorter periods than 24 hours for defining a historic storm, and this is fraught with uncertainty.

- With respect to the hydrological parameters, runoff threshold (P_0) and concentration time (T_c), used in the two methodologies explained in the study, it is necessary in the first of these, to define the prior and characteristic moisture situation in the basin if the calculation value is to be obtained. In practice, if gauging data are available, this is done through calibration, and if such information is not forthcoming, edaphological, land use and slope studies have to be undertaken; these are used to estimate an initial value for this parameter, which will later be rectified on the basis of the prior moisture situation.
- As the concentration time (T_c) has a direct influence on the estimation of the design discharges, both in the Rational method, when calculating the uniformity coefficient (K) and the intensity (I), and in the unit hydrograph method, when defining the lag time (T_{lag}), it is necessary to tighten precautions when choosing between the existing empirical formulae, so that the best one is selected for estimating the characteristic time that is to measure this delay (delay, peak, lag times, etc.).

The *statistical methods* are based on the direct processing of instant discharge data, with the correct use of historical references where these are available. If this methodology is to be applied, the type of distribution has to be chosen first, as well as the method for adjusting parameters and quantiles and the procedure, where appropriate, so the historical data can be used.
In «Mid-term report (August 1996/July 1997)», several aspects were analysed:

- Basic information required and its analysis and completion
- Parametric methods for calculating flood discharges
- Use of historic references
- Description of Log-Pearson III (LP3) Law, LMOM Methods with Historic Information

Several problems related with the applicability of statistical methods were identified:

- The use of statistical models to estimate design discharges associated with a particular return period, requires that maximum instantaneous discharge information be available with a length of records which is sufficiently long and reliable. Such a situation is not very common at most gauging stations, and this often leads to the application of other methodologies.
- Discharge estimation is generally approached using parametric methods, given that subjectivity problems are inherent to the methods based on manual adjustment of a curve. However, it is always advisable to carry out a graphic contrast of the results, with the available data duly represented. The use of these parametric methods implies the selection of both the model to be used and the

method for estimating its parameters. It is not easy to select the model to be used, because there is a wide variety of statistical models. Neither is it easy to choose the method for estimating the parameters, given that there is a high degree of uncertainty when only one sample is involved, and there is normally only one.

- Finally, it ought to emphasised that it is important to use historic information outside the system record period, because it helps to reduce uncertainty in the estimation of the high discharge values. This use of historic references is always to be recommended, in spite of the errors that usually exist with these historic discharges.

1.2 Hydrometeorological calculation methods. Case study: River Velillos

Fig. 1 shows the catchment area of the River Velillos at the gauging station E-42: River Velillos at Pinos Puente.

Fig. 1 - River Velillos Basin at gauging station E-42 (code 5042)

The physical characteristics of this basin are:

Area (Km^2)	358
Length of main course (Km)	35.5
Slope of main course (m/m)	0.00986

Although the particular characteristics of gauging station E-42 data could allow for the use of statistical methodologies to obtain the discharge frequency law, the fact

that the series of records were short and that there was a lack of instantaneous discharge data, meant that hydrometeorological calculation methods were used.
The study carried out at station E-42 for the River Velillos, yielded the following maximum daily rainfall data for the following return periods:

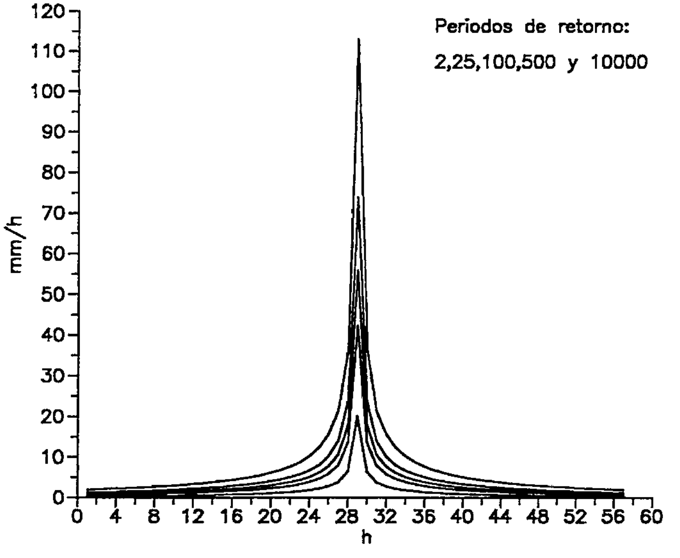
T (years)	2	5	10	25	50	100	500
Pd (mm)	45	63	75	94	109	124	163

The above results were obtained from a study of a maximum daily rainfall statistical model on a national scale (CEDEX, 1993). This data have to be reduced to take into account the effect of the rainfall not occurring simultaneously throughout the entire basin. Thus, daily rainfalls used are:

T (years)	2	5	10	25	50	100	500
Pd (mm)	37	52	63	78	90	103	136

When a flood is at its initial stage, not only the total amount of rainfall is an influencing factor, but also its distribution at smaller time intervals. This temporal distribution must be defined with greater or lesser detail as a function of the hydrological simulation method that is used. In this sense, when applying the rational method, it is only necessary to determine the average intensity for a duration that is equal to the basin concentration time. However, the use of a synthetic hyetograph is forced by the use of the unit hydrograph, because there is a lack of rainfall records for the zone. So, it is necessary to construct a hyetograph which fulfils the intensity-duration law for all the intervals centred with respect to the maximum intensity, and this can be seen for the River Velillos, in Fig. 2.

Fig. 2 - Hyetographs for different return periods



The method used to obtain the net rainfall is the one proposed by the Soil Conservation Service (S.C.S.), based on a extensively used "curve number" concept.

Taking into account the average slope maps for the basin (Fig. 3), as deduced from the digital terrain model, the basin soil-types - obtained from a cover provided by EUROSTAT which includes a classification of textures, with which a soil classification has been obtained that is equivalent to the S.C.S. one, (Fig. 4) - and the land uses adapted to the S.C.S. classification, from those included in the CORINE LAND-COVER (Fig. 5), a runoff threshold value of (P_o) has been reached - curve number distributed in the basin that is shown in Fig. 6, considering there to be average moisture conditions in the ground - whose areal integration yields a value of 13.5 mm.

Fig.3 - Slope map

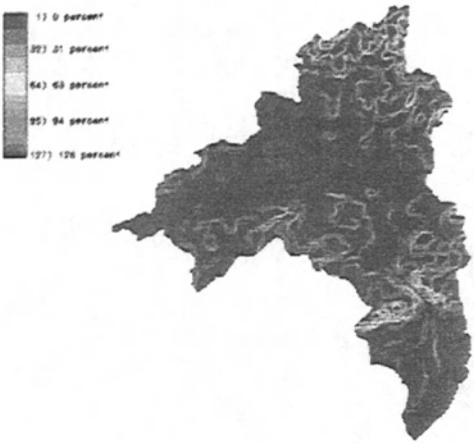


Fig. 4 - Soil types (3: C type, 4: D type)

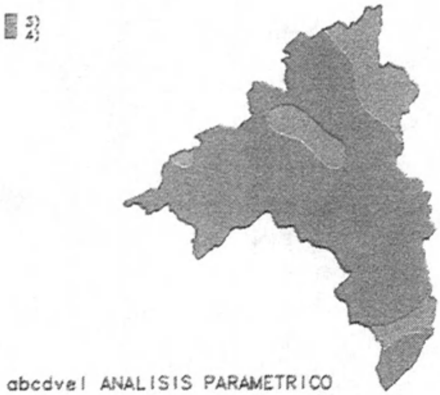


Fig. 5 - Land uses

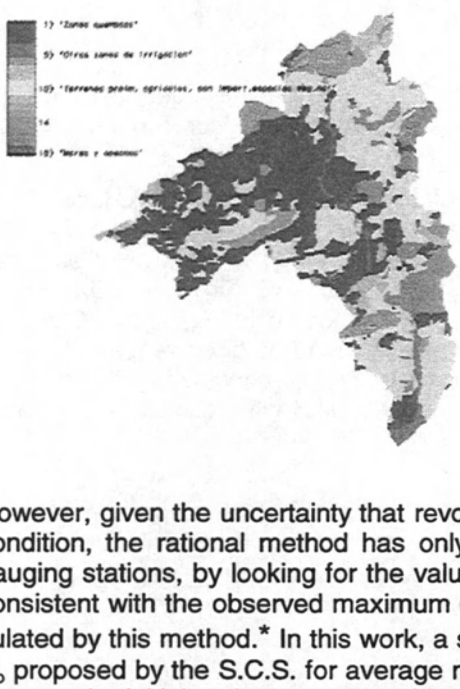
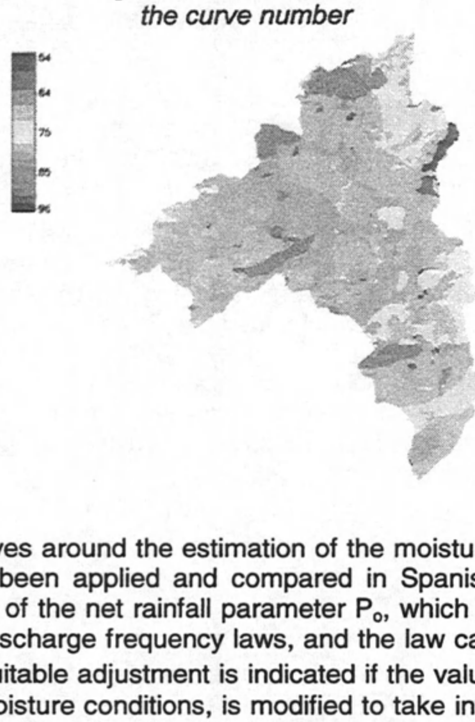


Fig. 6 - Distributed map of the curve number



However, given the uncertainty that revolves around the estimation of the moisture condition, the rational method has only been applied and compared in Spanish gauging stations, by looking for the value of the net rainfall parameter P_o, which is consistent with the observed maximum discharge frequency laws, and the law calculated by this method.* In this work, a suitable adjustment is indicated if the value P_o proposed by the S.C.S. for average moisture conditions, is modified to take into account the initial moisture expected in the zone, for the period during which floods

* *Témez, J.R. (1991): Extended and Improved Rational Method. Version of the Highways Administration of Spain. Proc. XXIV IAHR Congress. Madrid (España) 1991. Vol. A., pp 33-40*

normally occur. In this sense, the assumed modification, consists of a multiplicative factor of the parameter P_0, which ranges from 1 in the wet area of Northern Spain, to about 2 in the Central Zone and the Northern Mediterranean. This condition is consistent with the definition and the relationship existing between the moisture conditions of the S.C.S.: I and II.

Under this hypothesis, parameter P_0 for the Velillos zone, would by given by multiplying the value obtained by 2, and the eventual value calculated would be 27 mm.

The rational method formulae are extremely simple, which explains why this method is the most commonly used in cases where it is only necessary to obtain the peak discharge for the purpose at hand. In this work, the rational method is applied so that the results can be compared with the maximum discharges obtained through application of the unit hydrograph.

It is generally accepted that the return period for the flood calculated is the same as that for the rainfall used as basic data. However, this hypothesis must be compared with the gauging data available, especially with the overall hypotheses that have necessarily been carried out in the pluviometric definition: intensity-duration law, temporal distribution of the storm, etc.

By applying the two methods mentioned (rational and unit hydrograph) to the basin where the gauging station is located, users will not only be able to compare their results, but also make a comparison between these and existing gauging data. The discharges (m^3/s) obtained for the return periods under consideration, are summarised in the following table.

T (Years)	**2**	**5**	**10**	**25**	**50**	**100**
Rational	30	97	159	262	361	469
U.H	15	67	125	232	334	454

The following conclusions can be reached by comparing the discharges measured at the gauging station and the results obtained by applying the rational method and the unit hydrograph:

a) the results given by both methods are similar, except for low return periods, in which case the rational method shows greater discharges.

b) there is good agreement, especially in the case of the rational method, between the discharges calculated and those observed, at least as regards detail which allows for the use of an empirical formula such as Fuller's.

The best adjustment shown by the rational method is the one in which the runoff coefficient is modified to take specific account of storms on a small scale. In this respect, the results of the rational method are considered to be more reliable for low return periods, and these results are also more conservative.

1.3 Statistical calculation methods. Case study: Rivers Llobregat and Noya

Fig. 7 shows the basins of the Rivers Llobregat and Noya, in Martorell, both of which lie to North West of Barcelona, their surface areas falling within the boundaries of the provinces of Girona, Lleida, Barcelona and Tarragona.

The catchment of the River Llobregat covers a surface area of 4,561 Km^2 at gauging station E-5: Martorell, and at station E-23: Castellvel it is 3,291 Km^2. The altitudes range from elevation 44 m., at E-5 to 155 m. at E-23, up to an elevation of 1,936 m, at the source. The length of the main river is 129 Km. at E-5 and 96.5 Km at E-23.

The catchment of the River Noya at its confluence with the Llobregat, in Martorell, has a surface area of 929 Km^2, whereas, at gauging station E-4: SAN SADURNI DE NOYA, it is 726 Km^2. The altitudes range from elevations of 47 m., at Martorell and 121 m. at E-4, up to 870 m. at the source. The length of the main river is 66.5 Km. at its confluence with the River Llobregat and 48.5 Km at the gauging station.

Fig. 7 - Basins of the Rivers Llobregat and Noya

The basic rainfall data were obtained from a study of a maximum daily rainfall statistical model on a national scale (CEDEX, 1993) in similar way as in Velillos basin. The maximum instantaneous discharges from the following stations, were used as basic gauging data:

NUMBER	NAME	RIVER
E-4	San Sadurní	Noya
E-5	Martorell	Llobregat
E-23	Castellvell	Llobregat

Maximum annual instantaneous discharge data going back to 1972-73, are available for Station E-4. Data concerning the average daily maximum discharges, go back as before 1930, but they have not been taken into account, not only because their reliability is considered to be dubious, but also owing to a degree of uncertainty that exists with respect to a basin of this size, when it comes to transforming such data into maximum instantaneous discharges.

Maximum instantaneous discharges have been available for Station E-5, since 1955-56, with the exception of a small gap of two years, which has been completed through the "Study of the influence of the Baix Llobregat Dual Carriageway on the flooding of the River Llobregat (Baix Llobregat Dual Carriageway Project)" CEDEX 1990.

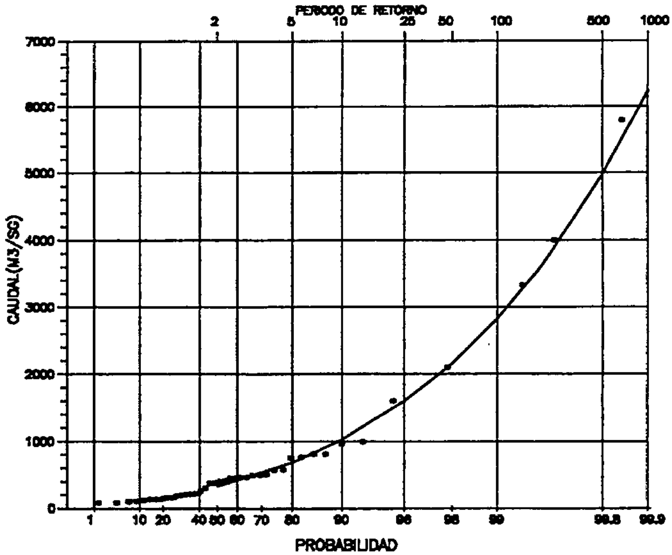
A limnigraph has been installed at station E-23, and this means that a series of maximum instantaneous discharges have been available from 1940-41 to 1995-96, with an occasional gap which has been filled in by assuming that the discharge is equivalent to that recorded at Station E-5, located downstream from the former.

The historical information lying outside the systematic recording period comes from the "Study of Past Floods. Potential Risk Map. Eastern Pyrenees Basin and the national Commission for Civil Protection". All the written references that have been found concerning the floods that have taken place in the Eastern Pyrenees river basin, are included in chronological order in that study.

It is considered that station E-5 is representative for obtaining the frequency law, and it is on the River Llobregat in Martorell. The reason for this is that it has a series of systematic records that goes back long enough in time, and it also has historical information and includes the River Noya, at its confluence with the River Llobregat.

The statistical analysis of the gauging records at that station, was conducted using distribution model LP3, the available historical data being suitably incorporated. The theoretical formula is defined in detail in Mid-term report. It is assumed that knowledge exists about the three most serious floods since 1617, these being much greater than the rest: the floods of 1617, 1740 and 1907, and that the systematic records (with the exception of the 1970 flood) are representative of the remaining years. With this hypothesis, Fig. 8 shows the obtained results in graphic form, together with the data concerning the corresponding instantaneous discharges, to which a sample probability have been allocated using Gringorten's formula, modifying the order number «i» for the joint use of systematic records and historical references. This order number «i» must be obtained by suitably weighting the data yielded by both procedures.

Fig. 8 - Maximum discharge frequency law for the River Llobregat at E-5



The difficulties that arise in the case of finding the maximum discharge frequency law in river Noya, is twofold:

- The series of instantaneous discharge data for gauging station E-4, do not go very far back in time.
- The difference in a catchment area, between this gauging station: 726 Km^2, and the River Noya at its confluence with the River Llobregat: 929 Km^2, has meant that it has been necessary to use the rational method, and then to graphically compare the results with the data available in a manner which is suitably representative.

The discharges obtained using the rational methodology for the different return periods considered, are summarised in the following table:

T (years)	2	5	10	25	50	100	200	500
Q (m^3/sec)	117	312	506	812	1085	1430	1784	2322

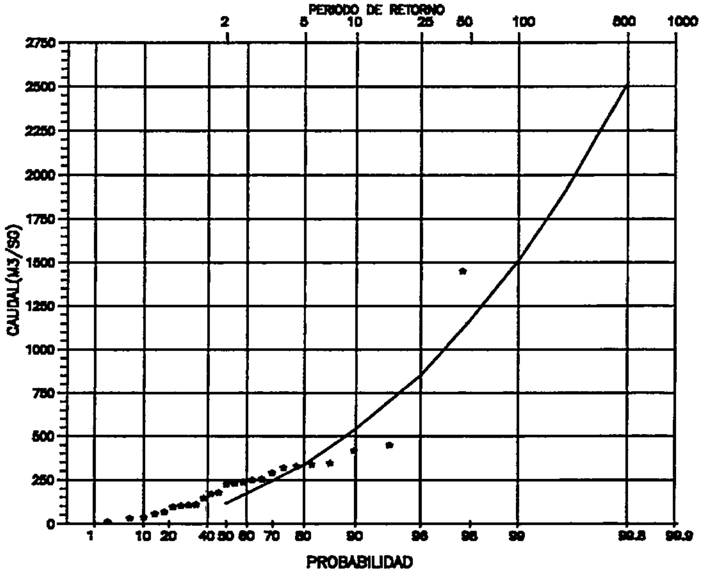
Fig. 9, shows a graphic comparison between the frequency law for the maximum discharges calculated, with the value of the parameter P_o = 30 and the recorded series of the maximum annual values. The adjustment is considered sufficient if the value of this parameter is adapted and consequently if the frequency law is adapted to the one that has been calculated.

If the whole of the River Noya is considered, it is necessary to carry out a discharge transfer between the gauging station and that point. The criterion that is used to do this, is the square root of the ration between areas, and the following is obtained:

$$Q_R = Q_E\sqrt{\frac{A_R}{A_E}} = 1,13\ Q_E$$

Given that the difference between area is only slight, the approximation made is considered to be sufficient.

Fig. 9 - Maximum discharge frequency law for the River Noya



The laws obtained for both rivers, are summed up in the following table:

Discharges for different return periods in rivers Llobregat and Noya

T (years)	2	5	10	25	100	500
R. Llobregat (m^3/sec)	329	685	1025	1600	2823	4981
R. Noya (m^3/sec)	119	338	540	856	1510	2522

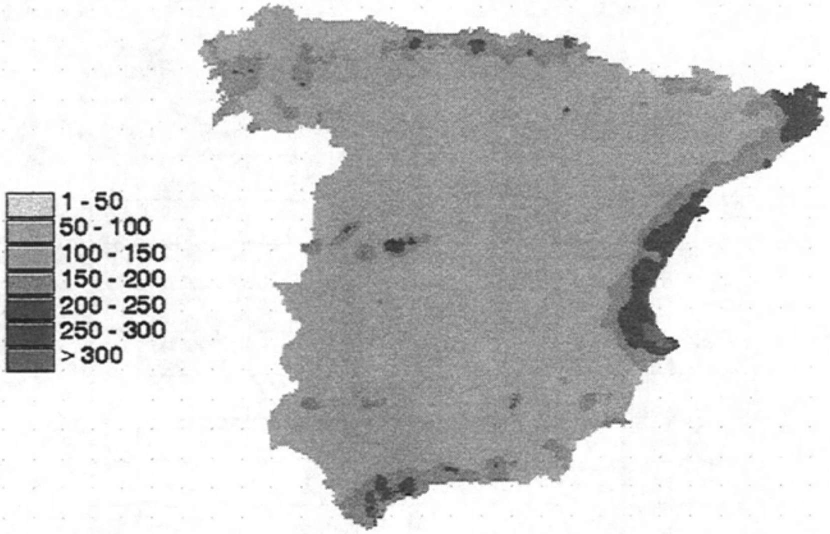
2. Flood Plain Management

2.1 An assessment of late flash floods events in Spain

In both, Mediterranean area and Europe, floods are the most common natural disaster and, in terms of economical losses the most costly. For example, in Spain, average annual economical losses produced by floods are estimated in about 350 Million Ecus.

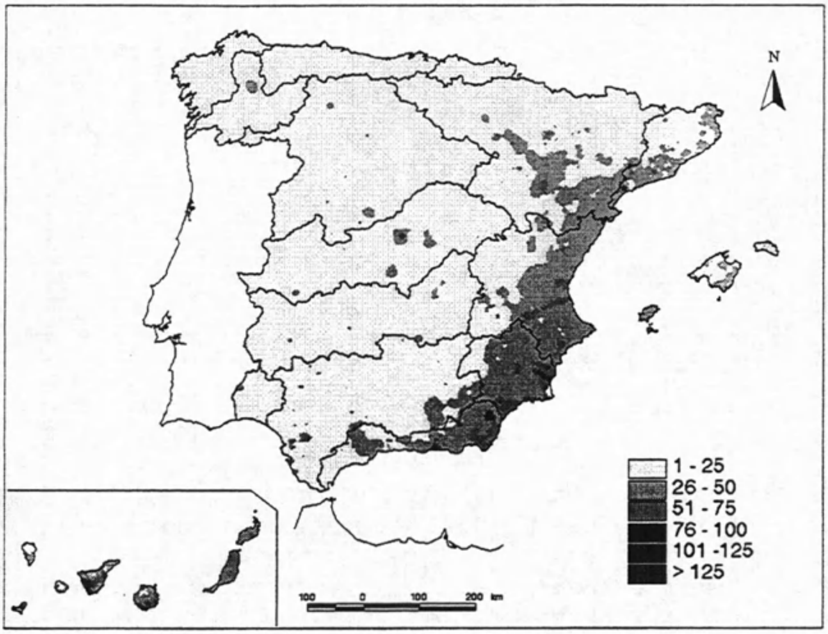
The following map shows maximum daily rainfall in Spain. In several regions, especially in the Mediterranean coast, values reach more than 300 mm.

Fig. 10 - Maximum daily rainfall in Spain



The following map that shows the relationship in percentage between maximum daily rainfall and mean annual rainfall in the period 1940/41-1995/96 gives an idea of the extremity of these values.

Fig. 11 - Relationship (%) between maximum daily rainfall and mean annual rainfall (1940/41-1995/96)



Flash floods are usually associated with this type of isolated and localised intense rainfall events generally associated with Mediterranean areas and, as a general rule, produces a high number of human victims, particularly because they are originated in basins with a short response time, where the surprise factor is the main cause of death.

In contrast, in large water basins, the hydrograph is long based and peak discharges are maintained over days. Usually high material losses are produced.
Two examples of these different types of floods are shown in figures 12 and 13.

Fig. 12 - River Rhine during flood 1995. Basin surface: 190.000 km². Peak discharge 12.000 m³/s during about one week

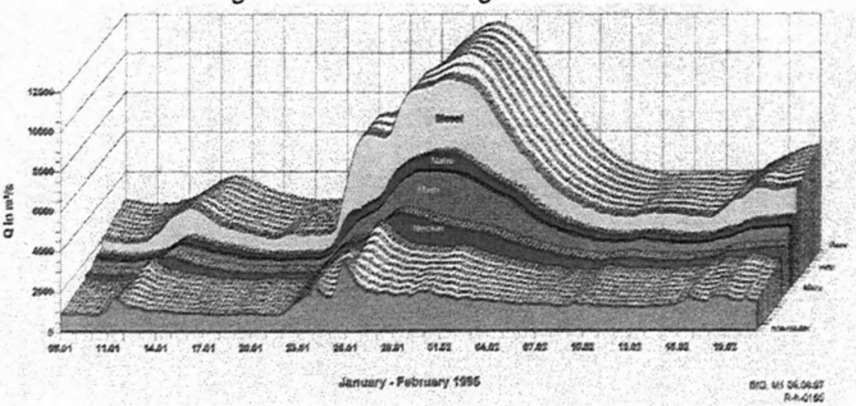
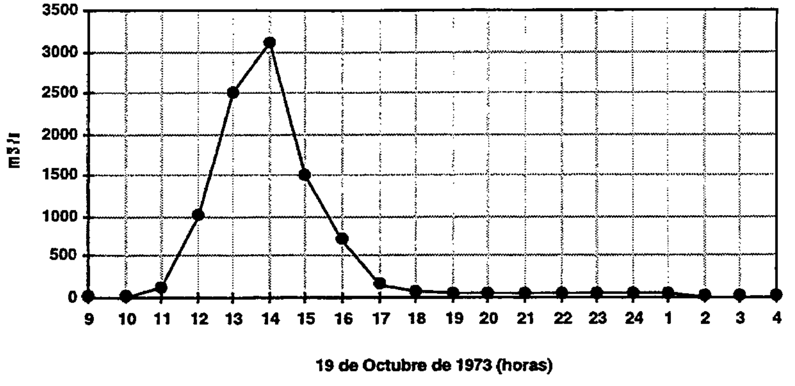


Fig. 13 - River Almanzora (South East of Spain) during flood 1973. Basin surface: 1.100 km^2. Peak discharge 3.100 m^3/s. Discharges biger than 2.700 m^3/s during about one hour



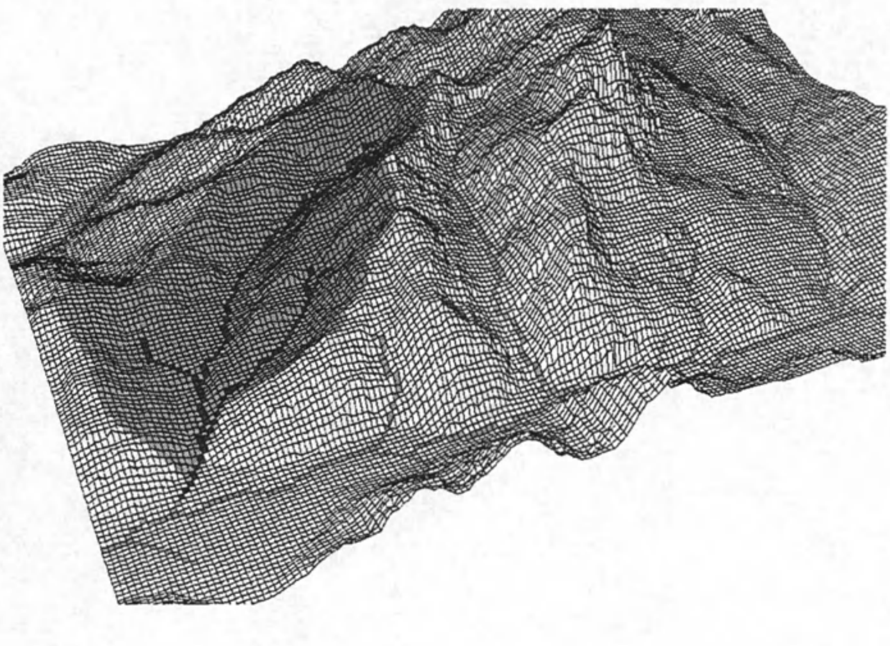
Therefore, there are two distinct flood types, which can be classified according to the damage they cause: those that are responsible for a high number of victims, largely because they take place in open spaces in mountainous basins, where there is a short response time (in many cases less than three hours), where the surprise factor is the main cause of death. However, these phenomena hardly ever cause major material losses. The second type, is the phenomenon that usually occurs in large rivers, where major flooding takes place in urban areas. As they do not take place suddenly, without any warning, there is usually time for real time forecasting, and the population can be alerted and evacuated in advance.

2.2 Case study: Biescas (1996)

The catastrophic flood of Biescas (7th August 1996. 83 victims) is shortly described below. To evaluate the flood hydrograph a distributed model developed in collaboration by CEDEX and Universidad Politecnica de Valencia was used.

Fig. 14 - View of affected area. Camping location close to a river chanelisation

Fig.15 - Digital Terrain Model of the cathment of River Arás in Biescas



Location:	River Arás in Biescas
Date:	7^{th} August 1996 (18:30)
Cathment area:	18.61 km^2
Major stream lenght:	9.14 km
Average slope:	14,4 %
Concentration time:	2.33 hours
Mean areal precipitation:	243 mm in 5 hours. 146 mm in first 1.5 hour

Figures 16, 17, 18 and 19 shows main information used in modelisation. Figure 20 shows isochrones field and simulated hydrograph.

Fig. 16 - Rainfall Isohyets map

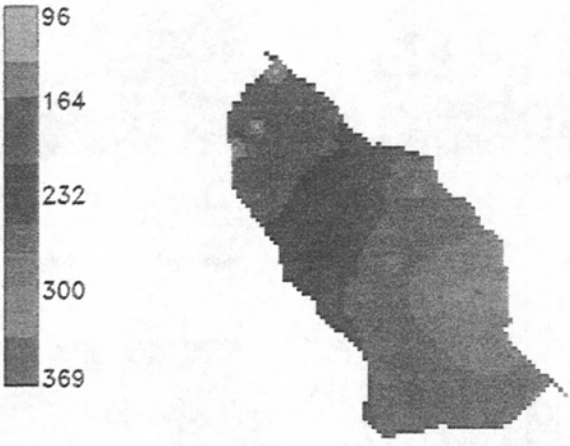


Fig. 17 - Soil Type (According S.C.S.)

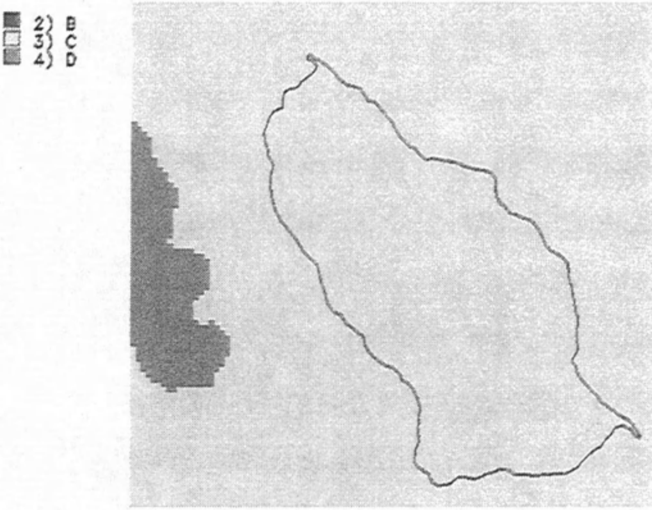


Fig. 18 - Land Use (Source: Corinne Land Cover)

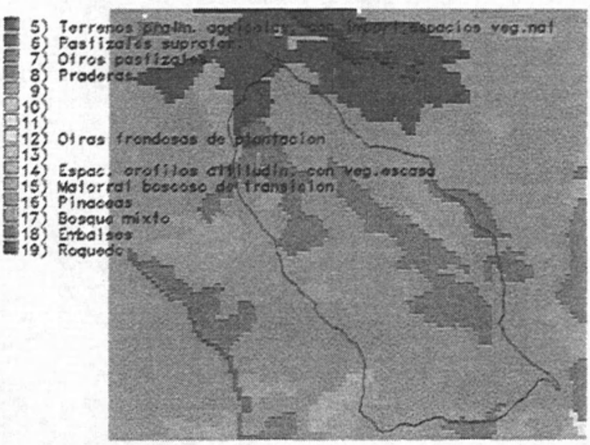


Fig. 19 - Curve number: 63 in average

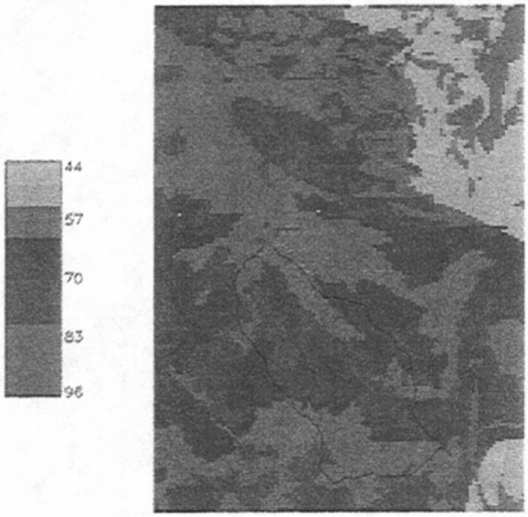
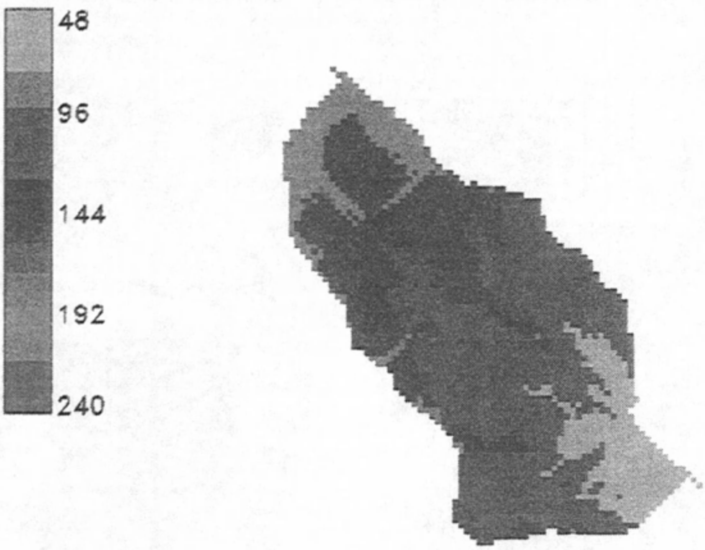
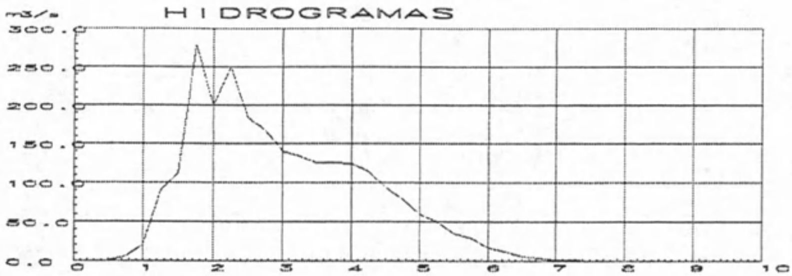


Fig. 20 - Isochrones field (hours x 100) and simulated hydrograph





2.3 Case study: Badajoz (1997)

In a similar way to Biescas flood, Badajoz (6th November 1997. 18 victims) is shortly described. To simulate the flood the model mentioned above was also used.

Fig. 21 - Area mainly affected by the flood

Basic information to simulate the flood is shown in following figures. Figure 26 shows the simulation results.

Date: 6th November 1997 (0:30)
Location: Rivers Rivilla and Calamón (Guadiana Basin)
Cathment area: 319 km^2
Major stream lenght: 32.33 km
Average slope: 0.57 %
Concentration time: 13,44 hours
Maximum recorded rainfall: 136 mm in 24 hours. About 60 mm. In last two hours

Fig. 22 - Digital terrain model

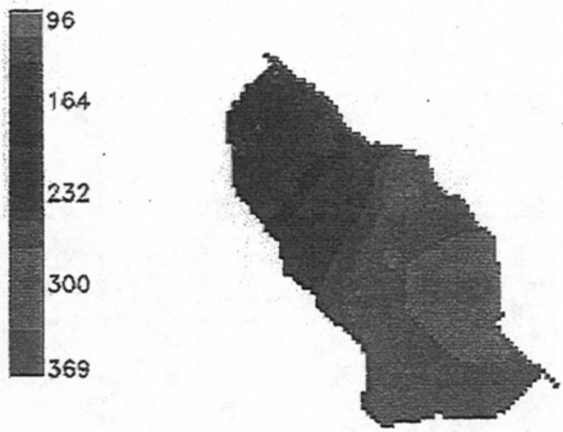


Fig. 23 - Soil Types (According S.C.S.)

Fig. 24 - Land use (Source: Corinne Land Cover)

Fig. 25 - Curve number (Av. Value 71)

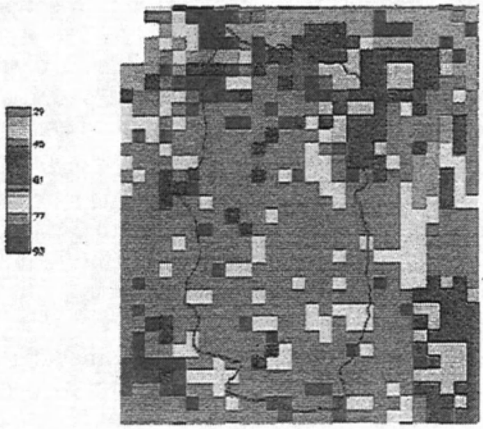
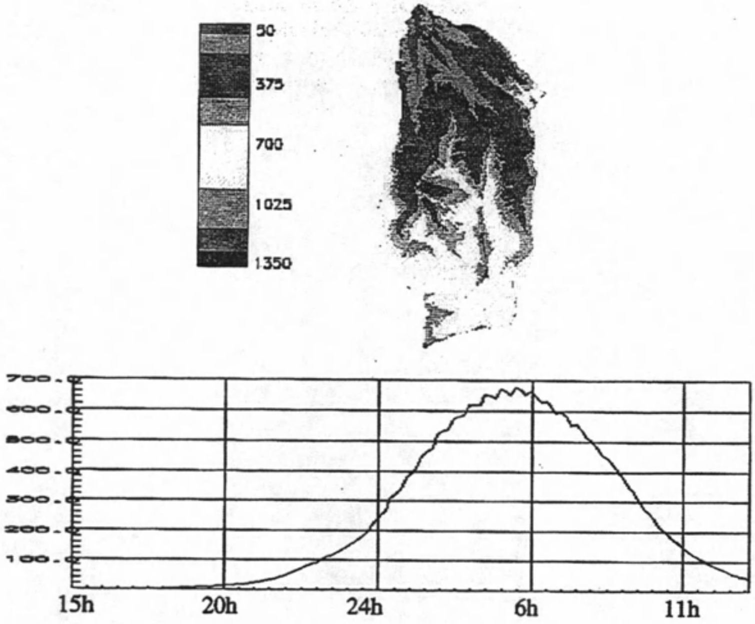


Fig. 26 - Isochrones field (hours x 100) and simulated hydrograph



2.4 The use of non-structural measures

Traditionally, the so-called structural measures have been used in flood prevention schemes, and this implies the construction of works that influence the mechanisms that cause flooding.

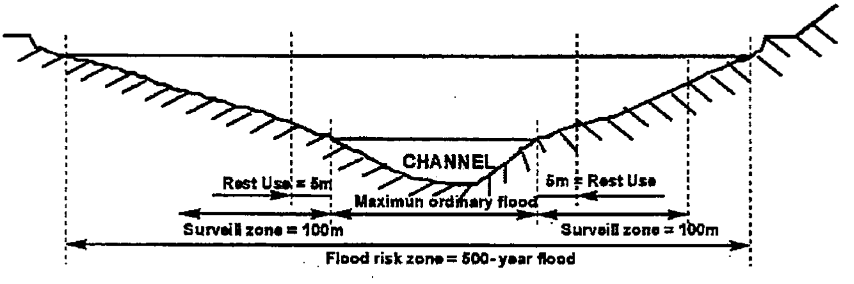
Otherwise, non-structural measures do not act upon the floods themselves, but serve to reduce the damage these phenomena cause by means of a management rather than a construction policy. At present, the applying of non-structural measures is on the increase, because it has been realised that structural measures enhance the implantation and development of communities, because they feel safe, in places close to rivers, and where flooding is inevitable.

In many cases flood monitoring and forecasting in real time is not sufficient due to very short time response. Among others non-structural measures that should be mentioned, are those regarding the management of the future development of the areas susceptible to flooding, for example, the planning (zonification and land use) of a floodplain.

Planning of flood areas in Spain is included in the Water Act and some of his regulations. They deal with the planning of river channels and overbanks. The concepts of restricted use, surveillance and flood risk areas are contained therein, and a series of general considerations are made, which must be supplemented and defined in the Hydrological Plans for each basin.

The legislation provides the following zonification of channel and overbanks (Fig. 27), together with the land use restrictions in each zone.

Fig. 27 - Floodplain zonification according Spanish Water Act and regulations



There are four main zones:

- Channel: Defined by the so-called maximum ordinary flood: average of maximum annual non-altered discharges during a period of ten years that could be representative of the hydraulic behaviour of the stream
- Restricted-use zone: A five meters strip on either side of the channel. Specific authorisation is required from the basin Water Board to plant trees and, above all to truct, this latter activity being rarely allowed.
- Surveillance zone: This is a 100 m. wide stretch on both sides of the channel. Here again, authorisation is required from administrative bodies for any kind of constructions. The limits of this zone can be modified on the initiative of the Local, Regional, or State Administration, but is the Basin Water Board that has the jurisdiction to carry this out.
- Flood risk zone: This is defined by the theoretical levels that the waters would reach during floods with a return period of 500 years, unless the Environment Ministry defines to the contrary.

As a previous step on the risk assessment, there is another flood plain zonification included in the so-called Basic Criteria on Civil Protection that defines three types of zones: frequent, occasional and exceptional flood zone according the water levels reached during return period floods of 50, 100 and 500 years.

The flood frequency itself is not sufficient in many cases to define the hazard concept. Thus some flood zonification criteria introduces additional information as depths during floods. This is the case of the criteria used by the Regional Government of Valencia. Three zones are defined:

- High risk zone: Areas with depths above 0.4 m. with return period of 25 years or 0.8 m with return period of 100 years.
- Reduced risk zone: Areas in which flood is produced with return period higher than 25 years and 100 years flood depths are lower than 0.4 m.
- Moderate risk zone: Areas in which situation is intermediate between both above mentioned.

Another criteria include also velocity considerations. That is the case of the CEDEX planning criteria for flood areas in Spain.

2.5 Planning Criteria for flood areas in Spain CEDEX proposal

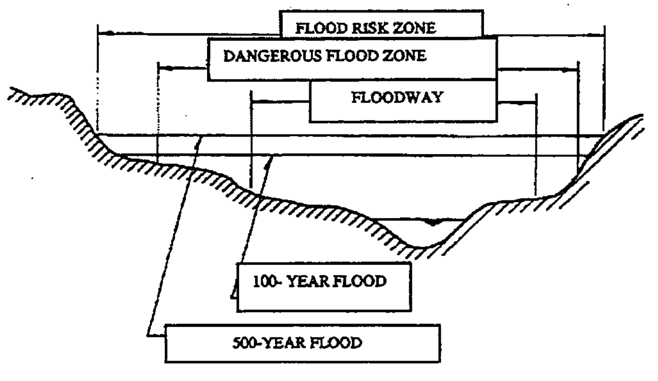
The main aim of these flood areas planning criteria is twofold: to prevent or reduce personal damage and damage to third parties. Other additional objectives as environmental protection or creation of open spaces for public use are also achieved.

These criteria are based on the F.E.M.A. (Federal Emergency Management Agency) standards, already put into practice in the U.S.A. but with major modifications such as defining the dangerous flood zone.

The zonification criteria proposed for flood areas is based in the following considerations:

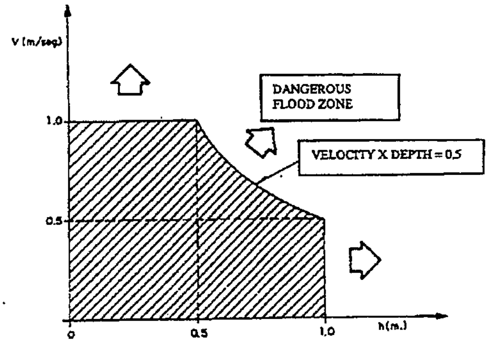
- Two zones must be distinguished in the flood area: a) flood risk zone, which includes a zone defined as a dangerous flood zone and b) floodway zone (Fig. 28).

Fig. 28 - CEDEX zonification



- The limits of the flood risk zone will correspond to a return period of 500 years.
- The dangerous flood zone is that area lying in the flood risk zone that could give rise to serious damage (human and material) in the eveny of a 500 years flood. In order to establish it, one or more of the following criteria must be met (Fig. 29): h (depth) > 1 m., v (velocity) > 1 m/s or hv > 0,5 m^2/s.

Fig. 29 - Criteria for delineation of dangerous flood zone



- The floodway is determined in such a way that a 100-year flood can take place without there being a height increase greater than 0,3 m. with respect to the elevation that would occur with the same flood considering the whole floodplain. This height increase could be reduced to 0,1 m. if the flood increase were to cause serious losses and, in addition, alternative locations for new constructions could be found off the zone, when these were deemed to be both economically and practically viable. On the other hand, this level could be raised by up to 0,5 m. in such cases where damage was limited and difficulties arose in finding other development areas in the affected communities.
- When the flow analysis shows more than one preferential channel, a multiple floodway consisting of several strips, will be established; one of such strips will correspond to the main channel and the rest will be different routes or preferential channels for the overflow water.
- There will be a tendency towards a minimum width for the floodway or floodways.
- The hydrological and hydraulic studies required to determine the different zones, must be based on the existing conditions, both as regards the extreme discharge regime and the floodplain characteristics.
- When there are dikes on the floodplain, they will be regarded as the floodway limit, as long as the increases in level to let the water from a 100-year flood flow away, is no greater than 50% more than acceptable for establishing the limits for the floodplain in the hypothetical absence of a dike. On the other hand, if dikes are to be taken as the limits at a flood risk zone, they must be capable of letting a 500-years flood flow away with a safety margin of 0,5 m. or without a safety margin, if the dikes can cope with small spillages over the crest. The dikes must receive adequate maintenance and preservation.

2.5.1 Extension to Spanish Water Act Surveillance Zone

This is the zone under the jurisdiction of the Basin Water Board, and where this body can restrict land use without resorting to a Governmental Decree. The width of the surveillance zone is generally fixed at 100 m., and in many cases, this standard strip excludes a substantial percentage of the area in which land use ought to be limited in accordance with strict technical criteria. The legislators, aware of this fact, permit the Local, Autonomous or State Administration to suggest a modification to the corresponding Water Board, and this body will then make the decision.

The surveillance zone is linked to the floodway concept because according to the Water Act, the control of activities and land use therein, is conducive to current regime protection as well as hydraulic public property. Therefore, a proposal is made to extend the surveillance zone so that it is identified with the floodway, i.e. the flow concentration or greatest risk zone, for the purposes of both personal and third party damage. In cases where the general 100 m. criterion on both sides of the channel were more restrictive than for the floodway, the surveillance zone would not be modified.

2.5.2 Land Use Recommendations for Each Zone

2.5.2.1 Floodway

The uses permitted in this zone will be such that: a) potential flood damage is minor, b) they do not obstruct the flood and c) they do not require structures, embankments or the permanent storage of equipment or goods. In no case may they have an adverse affect upon the floodway or cause serious personal damage.

In the light of the above, the uses may be as follows: a) Agricultural use; tilling, pastureland, horticulture, grape growing, lawns, nurseries and wild plants, b) Industrial-commercial use; temporary storage, parking of vehicles, etc, c) Residential uses; lawns, gardens, parking zones, recreational zones, etc. y d) Public and private recreational zones; golf courses, open air sports tracks, rest areas, swimming, natural and game reserves, hunting and fishing zones, equestrian or excursion activities, etc.

2.5.2.2 Flood Risk Zone

In the flood risk zone lying beyond the floodway, land use restrictions are not designed to conserve the current regimes, but rather to prevent extensive damage. The following restrictions are specified: a) The ground floor or basement, where applicable, of future constructions of a residential nature must lie above the level affected by the 100-year flood, and in the event of a 500-year flood, the dangerous flood condition is not applicable and b) Non-residential constructions (industrial, commercial, etc.) must be high enough to prevent the 100-year flood elevation reaching over 0.50 m., except where waterproofing has taken place to a greater height.

2.6 Case Study: River Cinca in Fraga

The purpose of this study to analyze the zonification criteria described in a real case, the River Cinca floodplain in Fraga, Spain. It has the following characteristics: a) there is an urban zone within the floodplain, b) structural measures have recently been adopted (construction of dikes), and c) there is a one-dimensional flow regime in flood situations.

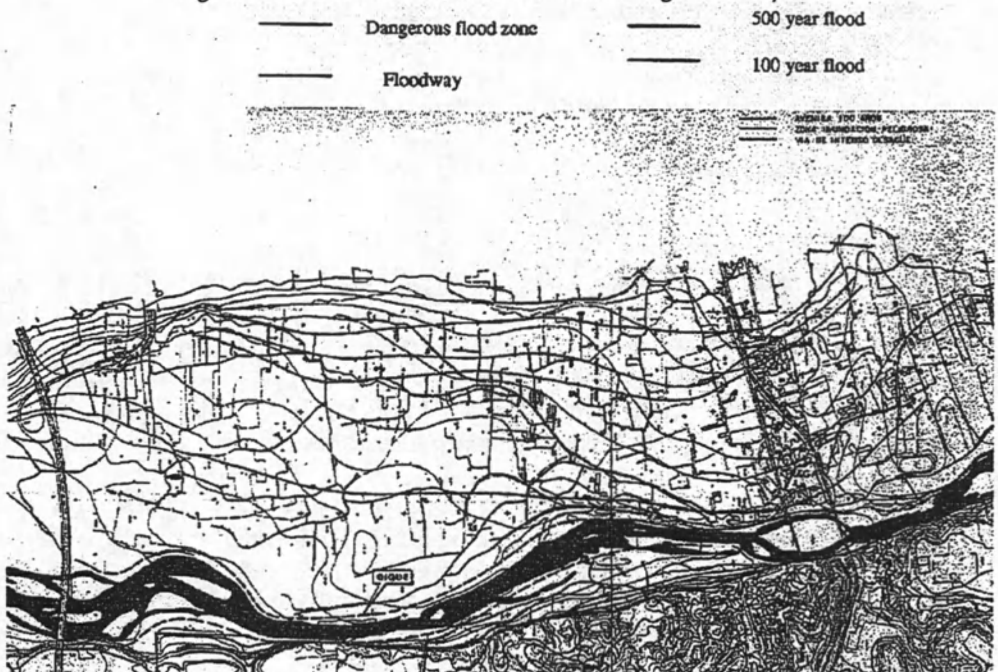
The town of Fraga lies on the River Cinca just before its confluence with the River Segre, and the sub-basin has catchment area of 9,612 Km^2. This century, Fraga has been flooded several times, the most outstanding occasions being those of 1907 and the most recent flood, in November 1982.

The dikes were constructed upstream and downstream on both river banks, after the 1982 flood. The mathematical model HEC-2, was used to calculate the water level profiles in the river. The model was calibrated with the flow ($Q = 2750\ m^3/sec$) and the references for the 1982 event. It was deduced from the simulations carried out on the calibrated model, that the dikes only protect against flooding to a level below the 100-year return period.

With the limits that they define, it is possible to let that flood flow with an average height increase of 0.8 m. with respect to the elevation that would exist if the whole floodplain were to be considered. This value is far above the necessary (1.5 x 0.3 m = 0.45 m.) for the limits to be regarded as floodway, according to the proposed criterion.

Figure 30 shows the zonification carried out. The limits of the diverse zones spread along the right overbank, because the left overbank slopes steeply.

Fig. 30 - Zonification of river Cinca in Fraga Flood-plain



A brief description of the criteria followed in.each zone can be seen below: a) Flood risk zone. This is defined by the 500-year flood, b) Dangerous flood zone. The dangerous condition criterion is defined as ($h > 1.0$, $v > 1.0$ or $h.v. > 0.5$) for the 500-

year flood. In this case, the restrictive variable was the depth, and c) Floodway. It was obtained in such a way that a 100-year flood can flow through its limits without a height increase of over 0.3 m. occurring, with respect to the elevation that would take place if the whole floodplain were considered. On the other hand, and for reference purposes, the 100-year flood limits are shown although, in isolation, they do not determine any zone.

The following conclusions can be drawn from an analysis of the results obtained: a) The floodway forms part of the dangerous flood zone, a circumstance which is not always the case, b) The floodway has an average width of 600 m., so it is identified with the surveillance zone, the latter being considerably wider than that referred to in the Water Act (100 m. on either side of the channel) and c) There is an extensive zone within the floodplain where, in spite of the absence of a considerable flow concentration, the condition of dangerous flood does exist and therefore, there is a serious material and human risk. In this case the conditioning variable was the considerable depths.

2.7 Conclusions of flood plain management

- Flash floods are common in Mediterranean rivers and in contrast with large rivers in other European regions produces peak discharges mantained only hours or even minutes.
- These floods usually produce a high number of human victims with recent examples in Spain as biescas (1996) or Badajoz (1997).
- In both cases structural measures produced a false sensation of safety in places close to rivers.
- Due to short response time, real time forecasting systems are not entirely useful.
- Land use planning in flood areas should be on the increase, but a real problem is what to do in already urban consolidated zones (i.e. Badajoz).
- The planning of the future development of a flood zone must not only be geared towards attenuating the direct damage to goods and the people who are going to be within the area (personal damage), but also thought of with a view to preventing damage to others (third parties damage) as a result of altering the flood flow conditions (current regime).
- In order to protect the current regime and prevent further significant damage to third parties, it is necessary to severely restrict land use within the strip or strips where the flow concentrates during the reference flood. These strips can be referred to as floodways. The surveillance zone is closely linked to the floodway concept because, according to the Spanish Water Act, the control of activities and land use is designed to protect the current regime as well as hydraulic public property.
- On the other hand, to prevent considerable personal damage (human and material), a dangerous flood zone can be defined, on the basis of the flow and velocities and depths corresponding to the 500-year flood return period.

Model and Spatial Database to Assess Design Peak Flow Rates in the Walloon Region (Belgium)

Utilisation d'un modèle hydrologique et d'une base de données cartographiques pour la prévision des débits de projet en région Wallonne (Belgique)

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Abstract

Managing and planning rural catchments require the setting up of efficient hydrologic tools. To this end, the Laboratoire de Télédétection et d'Hydrologie of the Faculté Universitaire des Sciences Agronomiques de Gembloux has combined a Geographic Information System, covering the whole Walloon Region, with the hydrologic model SWRRB-WQ adapted to the Belgian conditions.

Associating the model with the GIS provides us with geomorpho-hydrologic information, spatially distributed on the studied basins, as well as design peak flow rates and daily flow rates. Let us underline that soil moisture is one of the variables of the model SWRRB-WQ and that it has an influence on the runoff rate, through a digital parameter: CN (Curve Number coming from the American Soil Conservation Service [SCS]). Using the geographic database together with the model allows us to carry out a regional analysis which is linked to the catchment planning. Examples of simulation analyses show the effects of land use and the links between sub-basins.

Résumé

La gestion et l'aménagement des bassins versants requièrent la mise au point d'outils hydrologiques efficaces. Dans ce but, le Laboratoire de Télédétection et d'Hydrologie de la Faculté Universitaire des Sciences Agronomiques de Gembloux a combiné un Système d'Informations Géographiques, couvrant l'ensemble de la Région Wallonne, avec le modèle hydrologique SWRRB-WQ adapté aux conditions belges.

Cette association entre un SIG et SWRRB-WQ nous permet d'obtenir sur les bassins étudiés aussi bien des informations géomorpho-hydrologiques spatialement distribuées que les débits de pointe et volumes journaliers de projet. Soulignons que l'évolution de l'humidité du sol est une variable du modèle et que celle-ci a une

influence sur le taux de ruissellement à travers le paramètre CN (paramètre de ruissellement 'Curve Number' définit par le Soil Conservation Service [SCS]). L'utilisation conjointe de la base de données cartographiques avec le modèle hydrologique nous permet de prendre en charge des analyses régionales liées à l'aménagement des bassins versants. Des exemples montrent les effets des changements d'occupation des sols ainsi que les liens entre sous-bassins.

1. Introduction

These last years, the Laboratoire de Télédétection et d'Hydrologie of the Faculté Universitaire des Sciences Agronomiques de Gembloux in collaboration with the concerned ministries of the Walloon Region[1] and with the help of the OSTC[2] and the European has studied, simulated and characterised the volumes, flow rates and peak flow rates through the use of an efficient tool consisting of a GIS (Geo-Information-System) and a semi-distributed conceptual model.

Using this tool, namely on the Lesse basin in Gendron (1284 km^2) and its sub-basins allows the confrontation of the observed values with the values simulated by the SWRRBWQ-mod (without adjustment). Moreover, the reliability of this model and its help in detecting the potential particularities of catchments have also been established.

2. Implements and Method

2.1 Cartographic Database

Two softwares have been used to elaborate the GIS (ARC/INFO and ERDAS-Imagine).

The main info layers are: the Digital Elevation Model DEM (derived from the hypsometric maps at a scale of 1/50.000 - Institut Géographique National), the simplified pedological map at a scale of 1/500.000 (70 types of soil), the digitalized hydrographic network and the land uses map coming from satellite images (hydrologic classification of vegetation according to the SCS method).

The derived info layers are, among others: the hydrologic types of soil (SCS method), the map of slope classes, the map of CN classes for different conditions of soil moisture, the map of soil roughness classes, ... Other derived maps (parameters of Wischmeier's equation, ...) can be produced starting from this database.

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1 SETHY: Service d'Etudes Hydrologiques du Ministère wallon de l'Equipement et des Transports (M.E.T.)
DGRNE: Direction Générale des Ressources Naturelles et de l'Environnement du Ministère de la Région Wallonne

2 OSTC: Belgian Federal Office for Scientific, Technical and Cultural Affairs

2.2 Hydrologic Model (SWRRBWQ-MOD)

The hydrologic model used is the SWRRB-WQ (Simulator for Water Resources in Rural Basins -Water Quality) [Arnold J. G. *and al.,* 1991], developed by the United States Department of Agriculture and modified by the *Laboratoire de Télédétection et d'Hydrologie* (UHAGx - FUSAG) in order to take into account the particularities of the Walloon catchments (SWRRBWQ-mod). It is a conceptual model which is global or semi-distributed according to the option. It is physically based and works at a daily time step, at the scale of rural basins. It is based on the methodology defined by the United States Soil Conservation Service (modified SCS method taking account of soil moisture among other aspects). It can simulate long periods in order to realise frequency analyses.

The model uses daily weather data and statistical data that enable the simulation of the design peak flow rates and daily volumes. The main processes are surface runoff, percolation, hypodermic flow, evapotranspiration, storage in reservoirs and ponds, soil moisture evolution and melting of snow.

The validity of the SWRRBWQ-mod model for Belgian conditions has been established by our studies for basins from 10 to 1500 km^2. Some adaptations were necessary, namely on the formulation of the base flow rate, vegetation grow and percolation (Mokadem A.I. *et al.,*1989; Laime S., 1994; Moeremans B., 1995).

3. Application

The watershed of the Lesse river at Gendron is situated in the provinces of Namur and Luxembourg (Belgium) (1,284 km^2). Its vegetation is composed of more than 60% forest, more than 25% grass and the rest is farming. Urbanization is weak. The elevation spreads from 110 to 588 metres. Karstic phenomena can be seen on the Lesse (Atlas du Karst Wallon - Commission Wallonne d'Etude et de Protection des Sites Souterrains). We have divided this watershed in 8 sub-catchments.

3.1 Simulations

Each basin undergoes a simulation on 28 years, which corresponds to a maximum of 28 years of weather data (from 1968 to 1995). A first check is made on the mass balance, through the comparison of the observed and simulated yearly average runoff coefficients. The results enable us to note a good match between the observed and the simulated values. (Figure 1).

Then the maximum daily flow rates, the ones observed as well as the simulated ones, have been classified, following the Gumbel method. For the stations being upstream the karstic area, we can notice a good match between the relative adjustments to the simulations and observations (example Figure 2). Thanks to the model, we can identify the basins influenced by the karstic areas (example Figure 3) and by a natural reservoir (subterranean network of 12 km of galleries) (Figure 4), because of a divergence between the observed and the simulated flow rates.

All these findings as well as the analysis of the chronological flow rates seem to prove that the well-known weakness of the base flow in these karstic zones don't benefit a quantity loss, but rather the daily flow rates.

The process associated with the karstic areas is not explicitly described by the model; therefore, an adjustment is necessary. We can note that the reductions of the travel time of hypodermic and base flow are adequate for the stations where the karsts are present upstream (Figure 3).

The simulations allow us to reconstitute complete series of design daily flow rates corresponding to different time lengths and return periods (QDF curves) (Figure 5) and also, to re-create the simulated flood hydrographs (daily values) for different return period (Figure 6).

SWRRBWQ-mod also allows the simulation of design instantaneous flow rates. Their introduction in QDF curves give good results for three of the five tested basins (Figure 7). An overestimation is observed for the other two basins (Figure 8). Nevertheless, the obtained results are still acceptable; they enable, namely, to extract a trend or even to estimate, in a first step, a design peak flow rate, especially when no gauged point is available.

3.2 Effects of Land Use Changes

Different values of housing and corn crops surfaces are introduced, in order to analyze, with the model, the effects of land use changes replacing grassland and forests. These changes in land use correspond to a rise in soil imperviousness. The comparison of the results coming from SWRRBWQ-mod is based on the volumes and flow rates calculated by the model by introducing input values which correspond to the soil occupations areas identified by satellite images.

Figures 9 to 12 illustrate, for two different studied basins, the evolution of peak flow rates, with a return period of 50, 25 and 15 years, in function of the relative increase in urbanized or corn crops surface. The second axis Y also shows the corresponding modification of average yearly *surface* runoff. (namely the total amount of flow rate minus the hypodermic and base flow rates).

The simulation of the daily peak flow rates is carried out by SWRRBWQ-mod, using random parameters. This kind of calculation makes design peak flow rates fluctuate around a certain trend. The variations simulate the effect of the incertitude level of the observed data and of the model.

The hydrologic analysis of the simulated data shows that flows of a rare frequency are sensitive to the replacement of grassland (through urbanization or increase in corn crops) only above a certain level. This level varies according to the surface area of the studied basin (a basin is the more sensitive when it is of a smaller surface) and according to the kind of substitution realized (basins are more sensitive to urbanization than to corn crop increase). The curves indicate that, for Gendron (watershed of 1284 km^2) the values of urbanization or rise in corn crops have to be superior to 55-60% to allow the observation of a significant increase in floods of rare frequency whereas the same values go down to 35% urbanization and 40% rise in corn crops for Ochamps (basin of 10 km^2).

The curve of average *surface* runoff mainly shows a higher sensitivity to land use modifications; a rise by 10% in annual *surface* runoff happens when increasing urbanization by 6-7% and corn crops by 11-12 %.

The different sensitivities between floods of rare frequency (less sensitive) and yearly average *surface* runoff (which represents average floods - more sensitive), tend to support the statement developed in the recent following text coming from the "Plan d'Action Inondations Meuse" and published by France together with the Walloon and Flemish Regions of Belgium and with The Netherlands":

> *« Perméabilité et rétention*
>
> *La perméabilité du sol est limitée surtout en Ardenne. Lorsque la capacité d'infiltration est atteinte et que le sol est saturé, les précipitations ruissellent directement vers le réseau hydrographique. L'extension des zones urbaines peut accroître cet écoulement direct lors de faibles précipitations. Des barrages-réservoirs ont été aménagés sur quatre affluents (Eau d'Heure, Vesdre, Warche et Rhur); l'une de leurs fonctions est de contribuer à l'écrêtage des crues. Les effets de l'urbanisation se manifestent surtout au niveau de la pointe et de la forme des crues d'importance moyenne: lors de précipitations engendrant des crues moyennes, une partie de ces précipitations s'écoule plus rapidement qu'avant l'urbanisation en raison des revêtements imperméables. Dans le cas des crues élevées, l'ensemble du bassin versant est généralement saturé, si bien qu'il réagit hydrologiquement comme un revêtement imperméable. A ce moment, les effets de l'urbanisation locale sont peu perceptibles. »*

Moreover, to give a comparison, the results of observation made in the United States by the Urban Drainage and Flood Control District - Denver Colorado in 1983 during 2 years (Figure 13) in Maidment, 1992 show different measured values of the *surface* runoff coefficient in function of the mesured variation in impervious, which confirms the trend et the variability of this link.

4. Conclusions

On the basis of comparisons between simulated and observed daily values, the daily flow rates calculated by the model SWRRBWQ-mod adapted by the *Laboratoire de Télédétection et d'Hydrologie of the Faculté Universitaire des Sciences Agronomiques de Gembloux* for the Walloon region, are close enough to the reality in order to justify the pertinence of this model, working without adjustment. The significant particularities of behavior among the observed flow rates, which, in this case, are due to natural phenomena (buffer effect of the natural reservoir, karstic areas effects) are identified. The technique used here, given the QDF curves (Flow rates - Duration - Frequency) and the flood hydrographs, can be applied to every point of the river and, therefore, does not require any gauged point.

The simulated peak flow rates can also be estimated with a acceptable precision when no gauged point is at hand.

As to the flow rates of rare frequency, in the current state of knowledge, the simulations show that it is hazardous to analyze small variations of land use within a basin. It is to be underlined that a basin is the more sensitive to such a change when it is of a small surface (tested basin: from 10 to 1284 km^2). Differences only become significant, for the tested basins, when the variations, which consist in replacing grassland and forests through urbanization or increase in corn crops, are as high as 35% or 60% depending the basin size and the type of change. Nevertheless, the effects of land use are much more noticeable on average floods.

5. Figures

Fig. 1 - Yearly Average Runoff Coefficients (Simulated / Observated)

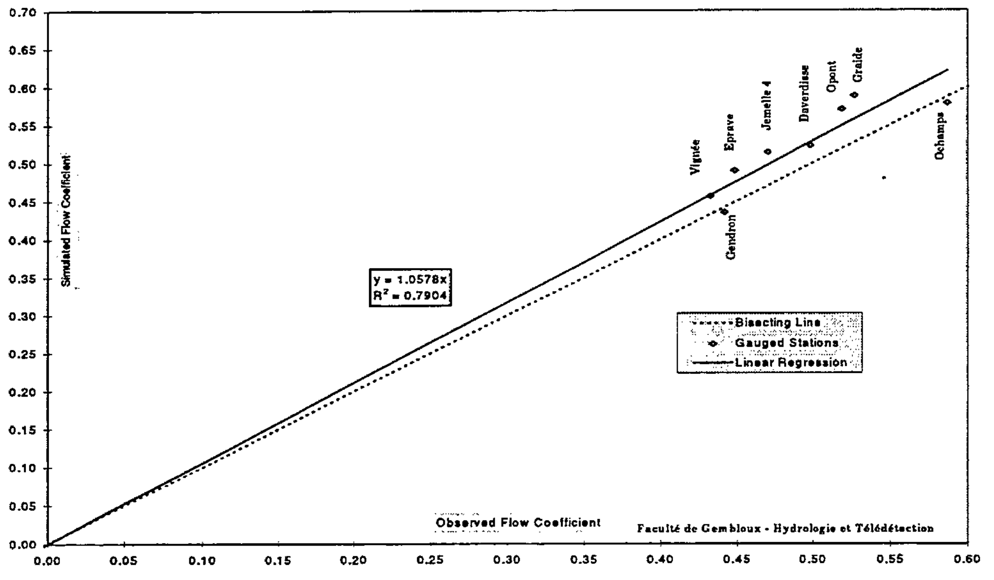


Fig. 2 - Observed and Simulated Maximum Daily Flow Rates Classified Following the Gumbel Method - Opont Station (70 km²)

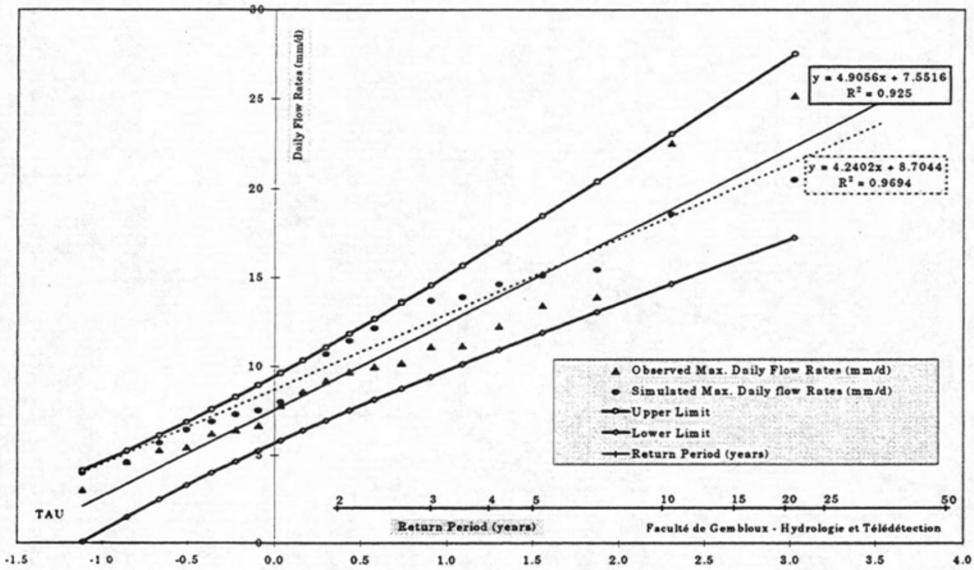


Fig. 3 - Observed and Simulated Maximum Daily Flow Rates Classified Following the Gumbel Method - Gendron Station (1284 km²)

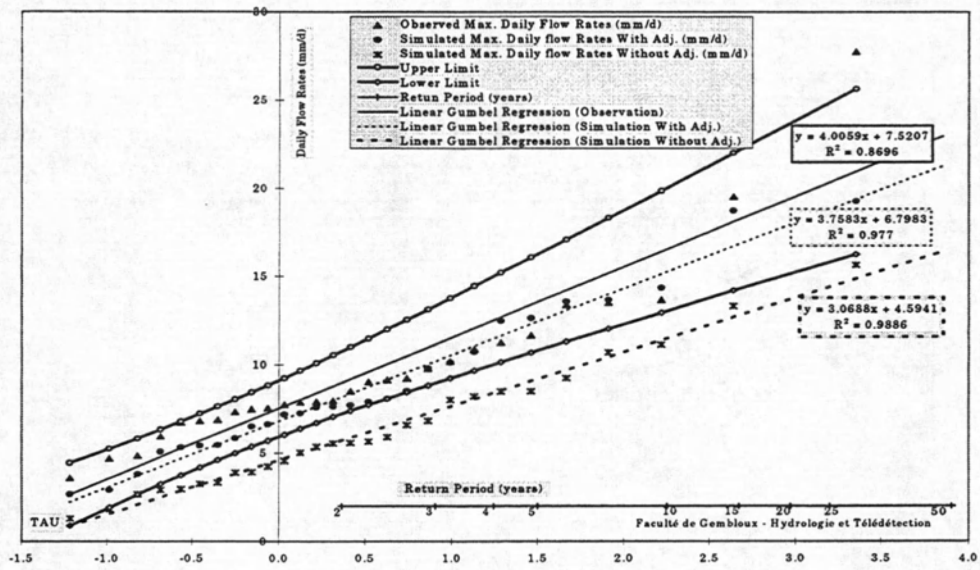


Fig. 4 - Observed and Simulated Maximum Daily Flow Rates Classified Following the Gumbel Method - Eprave Station (418 km²)

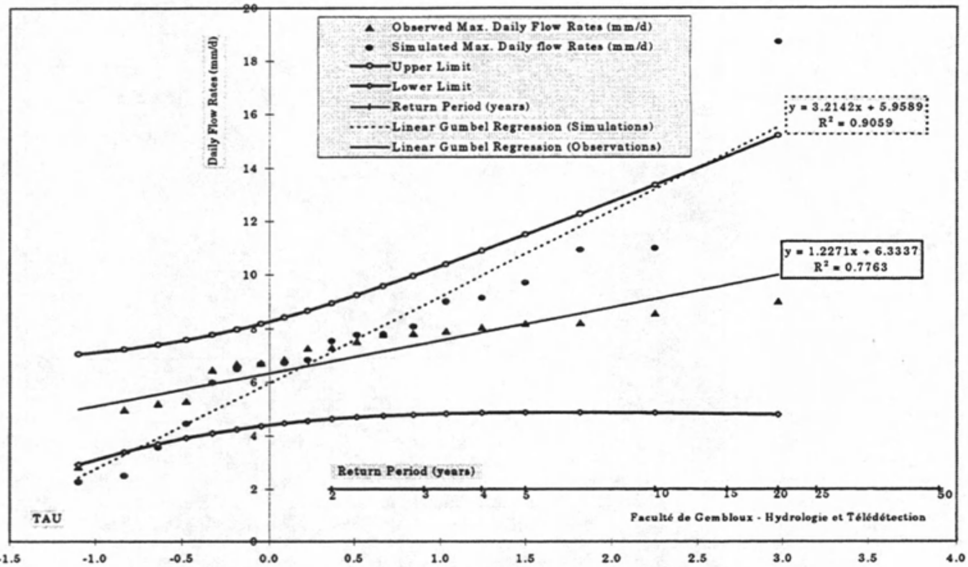


Fig. 5 - Observed and Simulated QDF curves for Opont Watershed (70 km²)

(QDF = Flow Rates - Duration - Frequency)

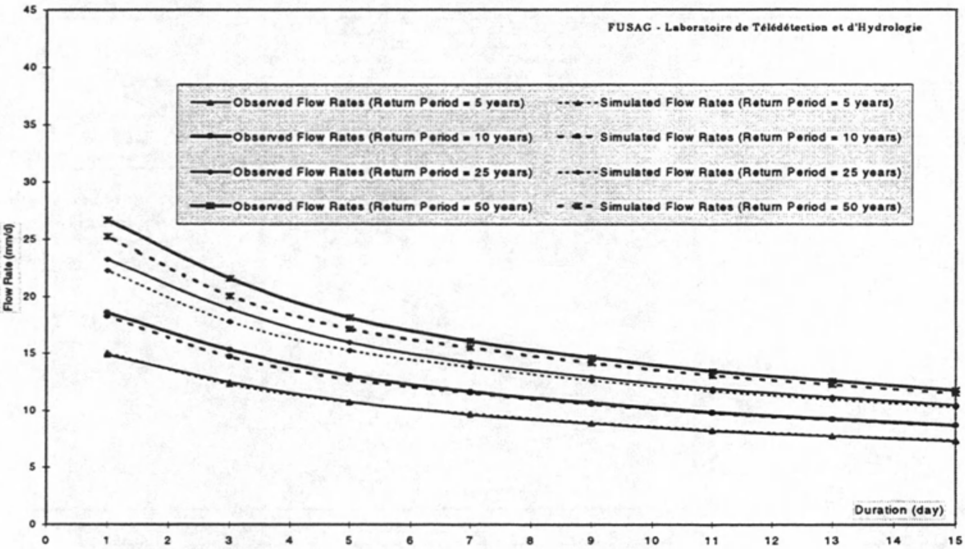


Fig. 6 - Observed and Simulated Design Floods (Return Period = 50 Years) for Opont Watershed (70 km²)

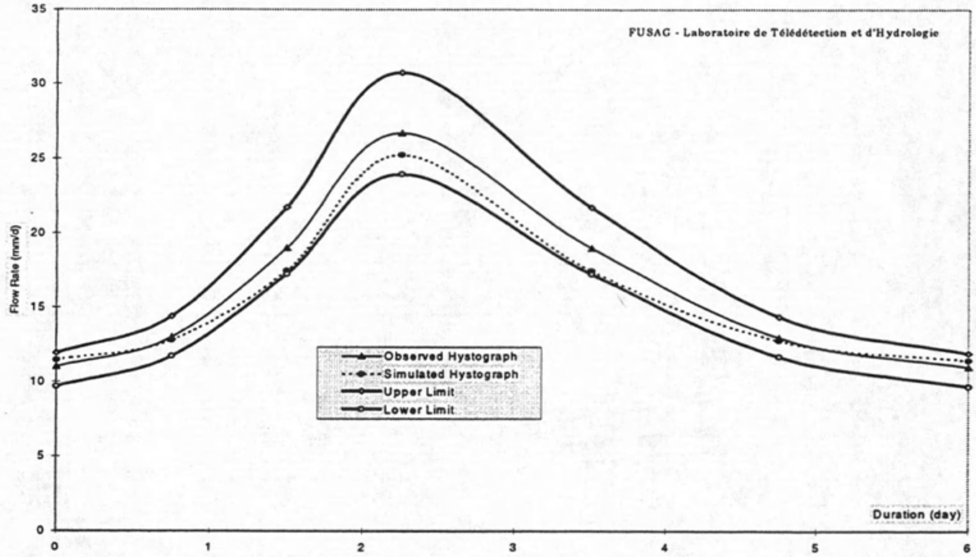


Fig. 7 - Observed and Simulated QDF curves for Gendron Watershed (1284 km²)
(QDF = Flow Rates - Duration - Frequency)

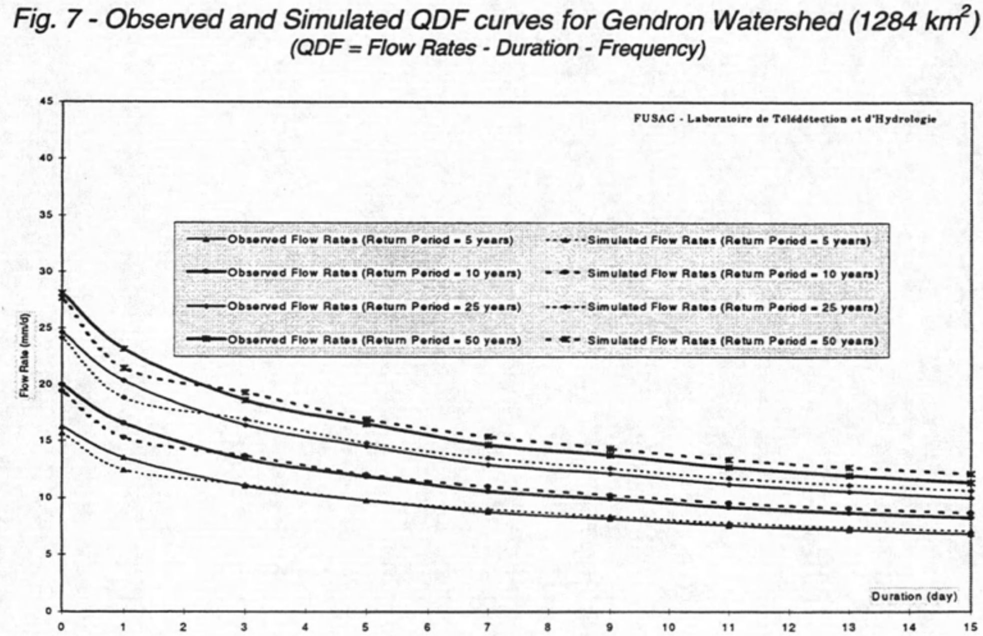


Fig. 8 - Observed and Simulated QDF curves for Daverdisse Watershed (300 km²) - (CN=70)
(QDF = Flow Rates - Duration - Frequency)

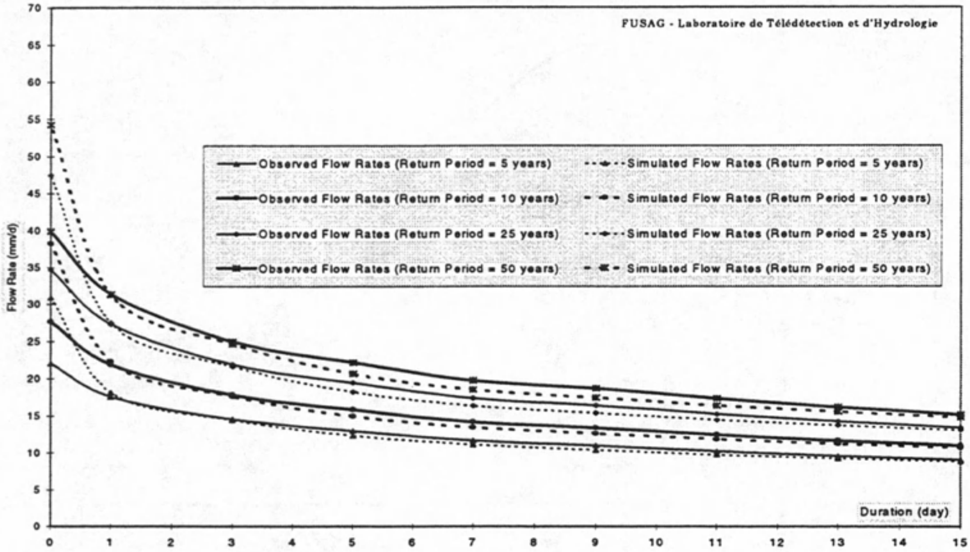


Fig. 9 - Evolution of the Simulated Rare Frequency Floods (Q50, Q25, Q15) and of the Simulated Yearly Average Surface Runoff (as an Average Flood Indicator) in Function of an Increase in Urbanization against Grassland and Forest (Gendron Watershed – 1284 km²)

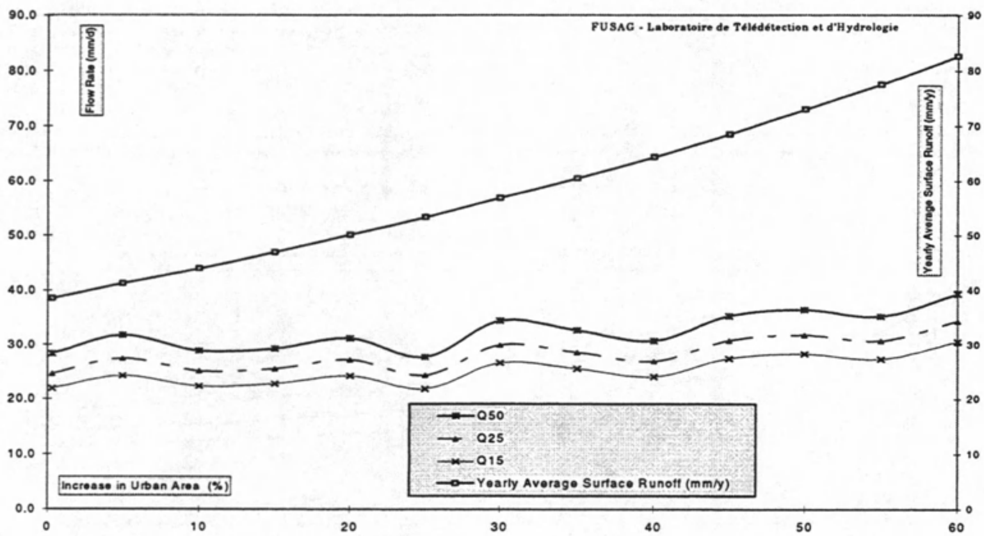


Fig. 10 - Evolution of the Simulated Rare Frequency Floods (Q50, Q25, Q15) and of the Simulated Yearly Average Surface *Runoff (as an Average Flood Indicator) in Function of an Increase in Corn Crops against Grassland and Forest (Gendron Watershed – 1284 km²)*

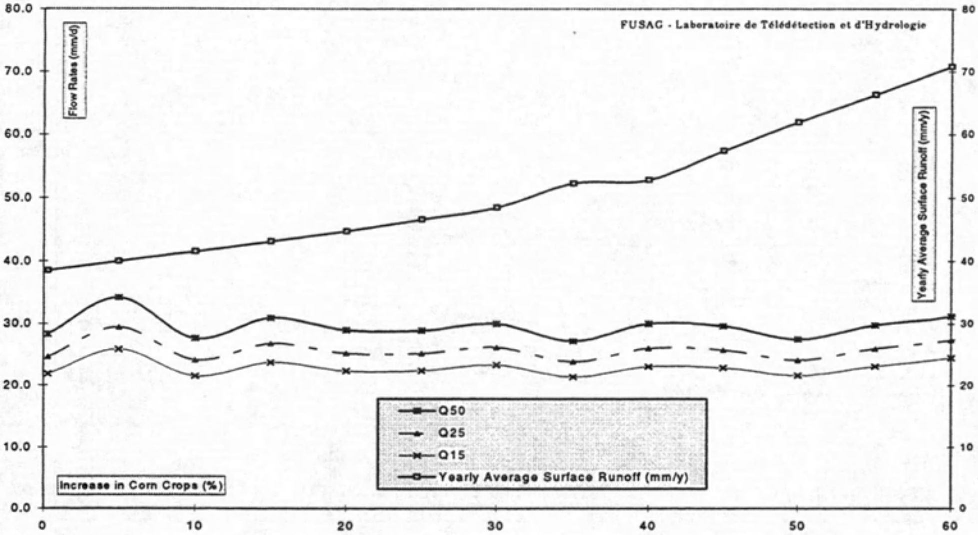


Fig. 11 - Evolution of the Simulated Rare Frequency Floods (Q50, Q25, Q15) and of the Simulated Yearly Average Surface *Runoff (as an Average Flood Indicator) in Function of an Increase in Urbanization against Grassland and Forest (Ochamps Watershed – 10 km²)*

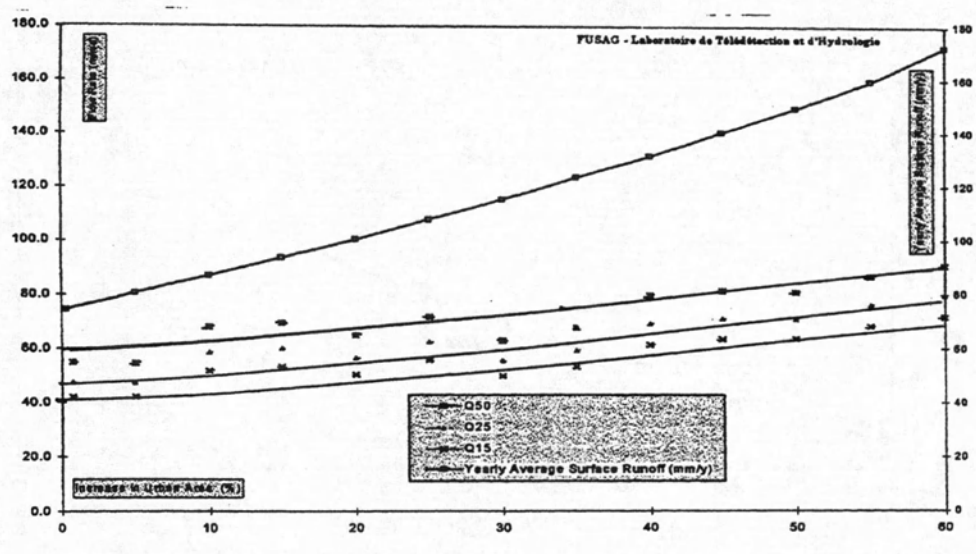


Fig. 12 - Evolution of the Simulated Rare Frequency Floods (Q50, Q25, Q15) and of the Simulated Yearly Average Surface *Runoff (as an Average Flood Indicator) in Function of an Increase in Corn Crops against Grassland and Forest (Ochamps Watershed – 10 km²)*

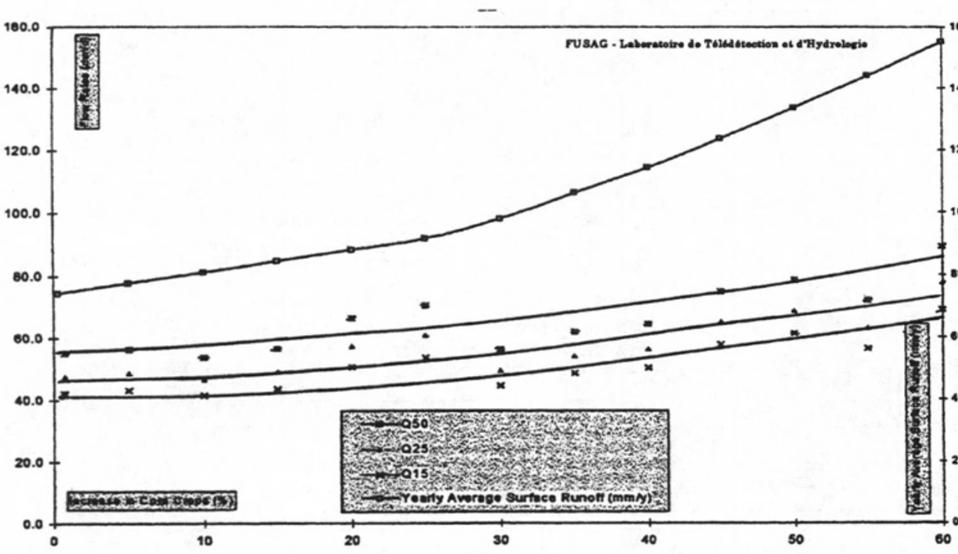
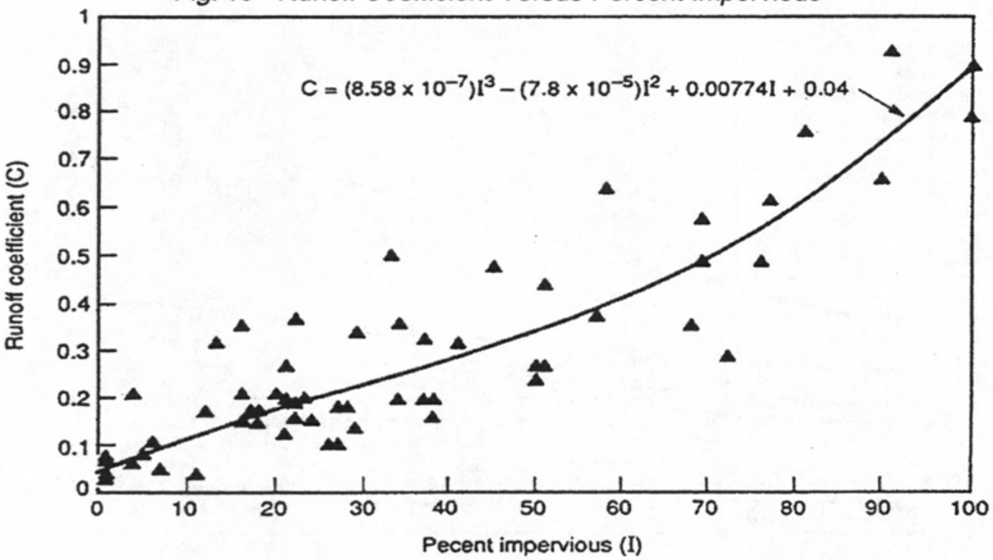


Fig. 13 - Runoff Coefficient Versus Percent Impervious



Rainfall analysis and regionalization computing intensity-duration-frequency curves

Analyse des précipitations et régionalisation des courbes intensité-durée-fréquence

Ms. Ilona Vaskova under direction of Dr. Félix Francés
Ms. Vaskova, Ph.D candidate fully supported by this project

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Abstract

The intensity-duration-frequency curves (from now IDF) represent for a given non-exceedence probability (or usually in terms of the return period in years) the variation of the maximum annual rainfall intensity with the time interval length. Obviously, for a given return period, the IDF curves decrease with increasing time interval.

Minor attention has been paid in the past to improve current techniques of data analysis. Actually, in most cases design practice is based on unproved or unrealistic assumptions concerning the structure of rainfall in space and time. The traditional method to construct IDF curves has three main steps. From the raw data, the first step is to obtain annual maximum intensity series for each time interval length. Then, for each time interval a statistical analysis has to be done to compute the quantiles for different return periods. Lastly, in order to smooth these values, the IDF curves are usually determined by fitting a specified parametric equation for each return period to the quantiles estimates, using regression techniques.

This traditional methodology has an important problem: a high number of parameters is involved, which makes it non-parsimonious from the statistical point of view. Usually, for each time interval there are at least two parameters for the fitted distribution function, and two or three for each smoothing curve. And this is one of the main objectives of this work: the reduction of the number of parameters to be estimated in order to increase their reliability. The other main objective is to reduce the estimation process to one single step.

Some regularities in hydrological observations, such as scale invariance, has been detected on storm records in the past (Rosso and Burlando, 1990). Present study deals with the estimation of IDF curves using the scaling properties observed on data of extreme storm intensities. Using these properties it will be possible the joint estimation of the IDF model using the Maximum Likelihood (or ML) estimation method and with a few number of parameters.

Two rainfall data series measured in Valencia and in Barcelona has been used in this study. These two raigauges are located in the eastern coast of Spain. The Valencia data series consists of 62 storm events, which has been measured during the last 43 years (1951-1993), but only the 43 most severe events have been taken

into account. In the Barcelona series a continuous data set of rainfall precipitation measured with a non fixed time interval in the period 1927 to 1981 was used. After some manipulations in both cases the final time discretization was ten minutes.

Résumé

Les courbes intensité-durée-fréquence représentent pour une probabilité de non-dépassement (usuellement exprimée en terme de période de retour) la variation de l'intensité annuelle maximum des pluies avec la durée de l'intervalle de temps. Bien entendu, pour une période de retour donnée, les courbes IDF décroissent avec l'augmentation de l'intervalle de temps.

Par le passé, peu de travaux ont été consacrés à l'amélioration des techniques courantes d'analyse de données. En fait, dans la plupart des cas, la pratique est basée sur des hypothèses non prouvées ou irréalistes de la structure de la pluie dans le temps et dans l'espace. Les méthodes traditionnelles de construction des courbes IDF suivent trois étapes principales. A partir des données brutes, la première étape consiste à obtenir des séries d'intensités maximum annuelles pour chaque pas de temps. Ensuite, pour chaque pas de temps, une analyse statistique a été conduite pour calculer les quantiles des différentes périodes de retour. Enfin, afin de lisser ces valeurs, les courbes IDF sont généralement déterminées en ajustant à l'estimation des quantiles, pour chaque période de retour, une équation paramétrée, en utilisant des techniques de régression.

Cette méthodologie classique comporte un important problème: elle requiert un grand nombre de paramètres. En général, pour chaque pas de temps, il y a au moins deux paramètres pour l'ajustement de la fonction de distribution, et deux ou trois pour le lissage de chaque courbe. L'un des principaux objectifs de ce travail est donc la réduction du nombre de paramètres à estimer afin d'accroître leur précision. L'autre objectif majeur est de réduire le processus d'estimation à une seule étape.

Des régularités dans les observations hydrologiques, telles que des stationnarités d'échelle, ont été relevées sur des enregistrements d'orages dans le passé. (Rosso and Burlando, 1990). Les études actuelles traitent de l'estimation des courbes IDF en utilisant les propriétés de l'échelle observée sur des données d'intensités d'orage extrêmes. Grâce à ces propriétés, il devient possible d'avoir une estimation commune du modèle IDF utilisant la méthode d'estimation des probabilités maximum et avec un petit nombre de paramètres.

Deux séries de données de pluies, mesurées à Valence et à Barcelone, ont été utilisées dans cette étude. Ces deux stations sont situées sur la côte Est de l'Espagne. La série de données de Valence comporte 62 événements orageux qui ont été mesurés au cours des 43 dernières années (1951-1993), mais seuls les 43 événements les plus forts ont été pris en compte. Dans la série de Barcelone, on a utilisé un jeu de données continues de précipitations mesurées avec un intervalle de temps non fixe sur la période 1927-1981. Après quelques manipulations dans les deux cas, le temps de discrétisation final était de dix minutes.

1 Traditional method

1.1 Statistical analysis

Since the late 1930's the applications of the extreme value distributions have grown to the fields of hydrology for studying maximum rainfalls, flood flows etc. Important papers in the flood frequency analysis were written by Gumbel in the forties and by Jenkinson in the fifties, obtaining the general solution of the functional equation that must satisfy the extreme values, which is called General Extreme Value (GEV) distribution function (Raynal-Villasenor, 1985). The GEV distribution can be described by the following expression of the cumulative probability distribution function (c.d.f.):

$$F(x) = e^{-\left[1-\frac{\kappa(x_2-v)}{\alpha}\right]^{1/\kappa}} \qquad \kappa \neq 0$$

where α is the scale parameter, β the position parameter and κ the shape parameter.

For the estimation process, the most recommended method in the literature for this distribution is the probability weighted moments method, or PWM. The procedure of this method was developed by Greenwood *et al.,* (1979). Hosking (1985) later applied the PWM method for the GEV distribution. The simplicity and robustness of this method is the reason of its common use (Ferrer, 1996).

The Gumbel distribution function is a particular case of the GEV when the shape parameter is equal to zero. The Gumbel distribution function was first used by Gumbel (1958) for the distribution of annual maximum river flows, and it has been widely used for rainfall depth-duration-frequency studies (Hershfield, 1961, mentioned in Haan, 1977). Its c.d.f. is given by:

$$F(x) = \exp[-\exp(-\alpha(x-\beta)]$$

where α is the scale parameter and β is the location parameter. For non small samples the most recommended method for parameter estimation is the ML (Lowery and Nash, 1970, Cunnane, 1989).

Statistical analysis of the Valencia and Barcelona intensity data series has been done using these two distribution functions of extreme values and others such as the SQRT-ET max (Etoh and Murota, 1986) and the Log-normal III. However only good results were obtained with the GEV and Gumbel distributions.

Figures 1, 2 and 3 show the Gumbel and GEV fitted to the Barcelona data series for the time intervals of 10 minutes, 1 hour and 8 hours, using for the plotting positions the expression given by Cunnane (1978) for a Gumbel population. The hypothesis that series follow the GEV or Gumbel distribution has not been rejected for all time intervals in Valencia and Barcelona using the Kolmogorov-Smirnov test with a significance level of 5%.

Fig. 1 - Comparison between plotting position and the fitted GEV and Gumbel for t = 10 min in Barcelona

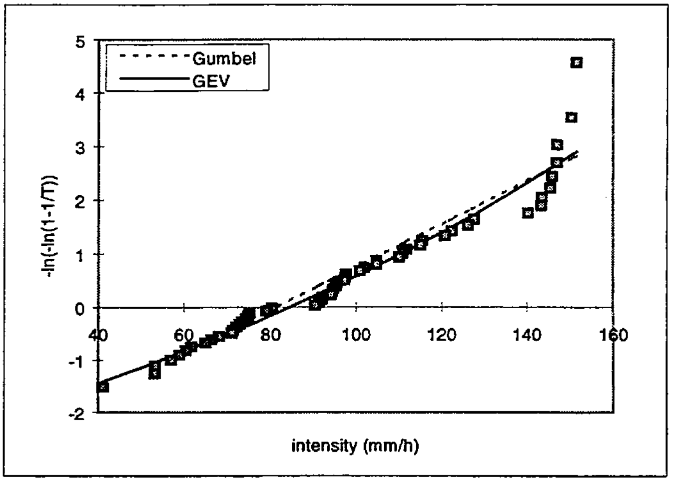


Fig. 2 - Comparison between plotting position and the fitted GEV and Gumbel for t = 60 min in Barcelona

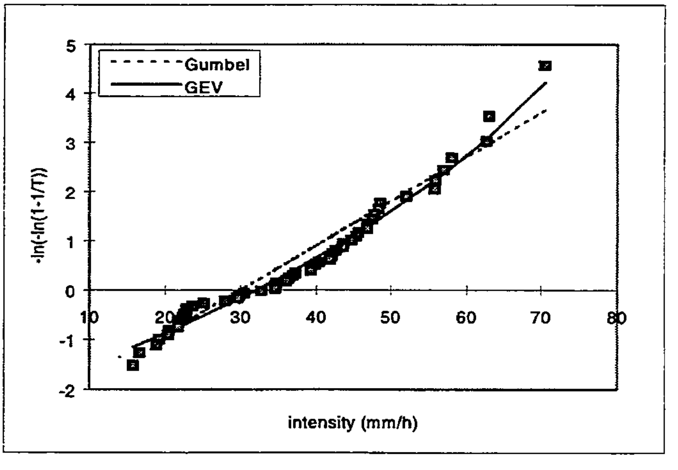
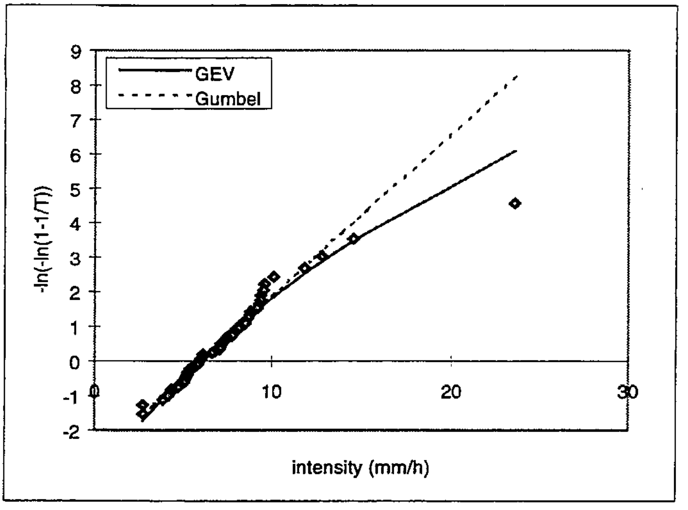


Fig. 3 - Comparison between plotting position and the fitted GEV and Gumbel for t = 8 h in Barcelona



1.2 Quantile somoothing cuves

The most general form for the most widely used quantile smoothing curves is a power function with three parameters (or TPP), given by:

$$I(t) = \frac{A}{(t+B)^C}$$

where *t* is the time interval length , $i_T(t)$ is the mean intensity, and *a, b, c* are the parameters. The well know Montana equation is a TPP particular case with *b* equal zero. Usually the parameters *b* and *c* are constant, and only the parameter *a* depends on the return period. The least square estimation method has been used. Figure 4 shows a very good fitting of the TPP function to the Barcelona 100 years quantiles obtained by the GEV distribution. However, there isn't any physical meaning for the observed dependence between the parameter *a* and the return period (Figure 5).

Fig. 4 - TPP curve fitted to the 100 years GEV quantiles in Barcelona

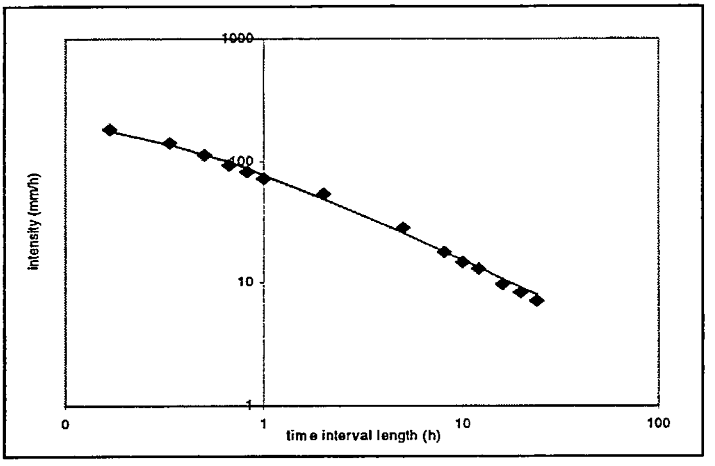
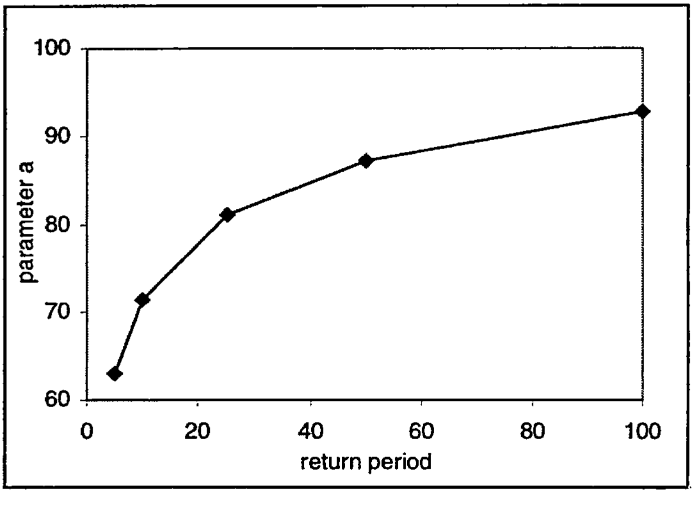


Fig. 5 - Evolution of the parameter a as a function of the return period in Barcelona



2 Joint estimation

Study of the rainfall scaling properties in space and time is of great importance in hydrometeorology. The statistical dependence structure of the precipitation has been shown to be closely tied to scale (Rodriguez-Iturbe *et al.*, 1984). Lovejoy and Schertzer (1985) introduced the ideas of scale invariance and fractals into rainfall modelling through evidence that rainfall may be scaling. Rodriguez-Iturbe *et al.*, (1989) have studied storm rainfall in detail and have found evidence of deterministic chaos in the process. Gupta and Waymire (1990) studied rainfall spatial variability by introducing the concepts of simple and multiple scaling to characterise the probabilistic structure of the precipitation process. The scaling properties of temporal rainfall have shown to dictate the form of the IDF curves (Burlando and Rosso, 1995).

The parameters of the IDF curves depend on the frequency level *q*. Rosso and Burlando (1990) showed that power function (TPP with *b*= 0) becomes from the assumption that storm rainfall is scale invariant. Gupta and Waymire (1990) defined such property as «*simple scaling*».

Gupta and Waymire (1990) demonstrated if a random variable X_t is time scaling, i.e.:

$$X_{\lambda t} \overset{d}{=} \lambda^n X_t$$

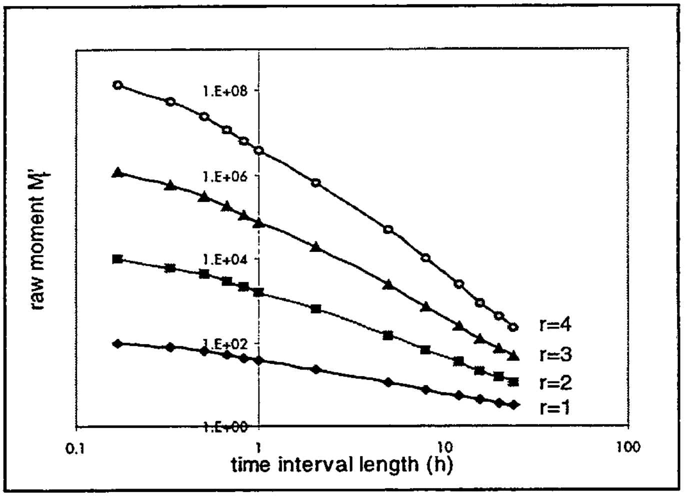
then also the quantiles and the raw moments of any order are scale invariant, i.e.:

$$\xi_q(\lambda t) = \lambda^n \xi_q(t)$$
$$E\left[X_{\lambda t}^r\right] = \lambda^{rn} E\left[X_t^r\right] = \lambda^{\alpha_r} E\left[X_t^r\right]$$

where $\overset{d}{=}$ means identity in the probability distribution, λ is a scale factor, *n* is the scaling exponent, and *r* is the order of the moment. This property is called "*wide sense simple scaling*".

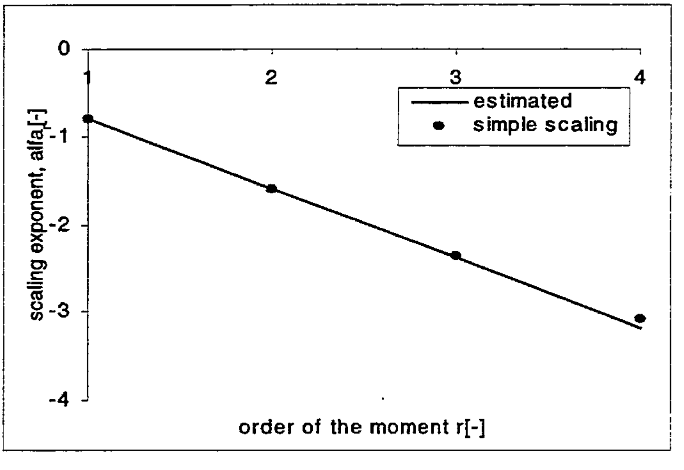
In figure 6 the sample estimates of the Barcelona raw moments have been plotted against the corresponding time interval on a double logarithmic scale. The slope of the fitted line to those points gives us the value of the scaling exponent α_r for each order of the moment *r*. However only in the range from 1 to 24 hours the fitted curve can be considered as an straight line. Similar results were obtained for the Valencia data. Therefore, from now only this time interval range will be considered.

Fig. 6 - Sample raw moments for the Barcelona data series



As it can be shown in figure 7 for the Barcelona data, the scaling exponent α_r has a linear dependence with the order of the moment for time intervals larger than 1 hour. Therefore the Barcelona data can be considered wide simple scaling, and the IDF curve can be constructed by developing a model which estimates a common scaling exponent *n* for any frequency level. This idea has been applied to the Gumbel and GEV distribution functions.

Fig. 7 - Wide simple scaling of the scaling exponent with respect to order of the moments for the Barcelona data series



3 Application of simple scaling to the Gumbel distribution function

If both parameters of the Gumbel distribution follow a power function:

$$\alpha(t) = \alpha_0 t^a$$
$$\beta(t) = \beta_0 t^{-b}$$

Then the quantiles are given by:

$$\xi_q(t) = \beta_0 t^{-b} - \frac{1}{\alpha_0 t^a}\ln(-\ln q)$$
$$\xi_q(\lambda t) = \beta_0 (\lambda t)^{-b} - \frac{1}{\alpha_0 (\lambda t)^a}\ln(-\ln q)$$

Therefore, $|a| = |b| = n$, in order to have wide sense simple scaling. In this case, the description of the IDF curve can be carried out by the joint estimation of only three parameters for the total time interval range. The Maximum Likelihood method is proposed for this joint estimation. The log-likelihood function will be:

$$\ln L(\alpha_o, \beta_o, n) = NM\ln\alpha_o + Nn\sum_{i=1}^{M}\ln t_i - \sum_{i=1}^{M}\sum_{j=1}^{N} x_{j(i)}\alpha_o t_i^n + NM\alpha_o\beta_o - \sum_{i=1}^{M}\sum_{j=1}^{N} e^{\alpha_o\left(\beta_o - x_{j(i)}t_i^n\right)}$$

where M is the number of time intervals, N is the number of years. The parameters α_o, β_o and n can be obtained by the maximization of this expression. The *Powell* method has been selected in this case, using a IMSL library algorithm from the Microsoft Fortran Power Station package.

In figures 8 and 9 we can see a perfect agreement between the α and β parameters obtained by joint estimation and the α and β estimated for each time interval, assuming a Gumbel distribution function. On the other hand, figure 10 shows us the IDF curve obtained by the joint estimation method and the quantiles estimated for each time interval based on the Gumbel distribution function.

Fig. 8 - Parameter α obtained by joint estimation and estimated for each time interval in Barcelona assuming a Gumbel distribution

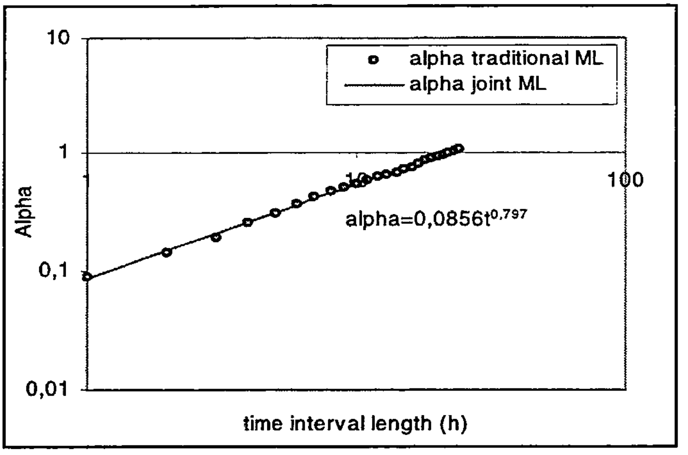


Fig. 9 - Parameter β obtained by joint estimation and estimated for each time interval in Barcelona assuming a Gumbel distribution

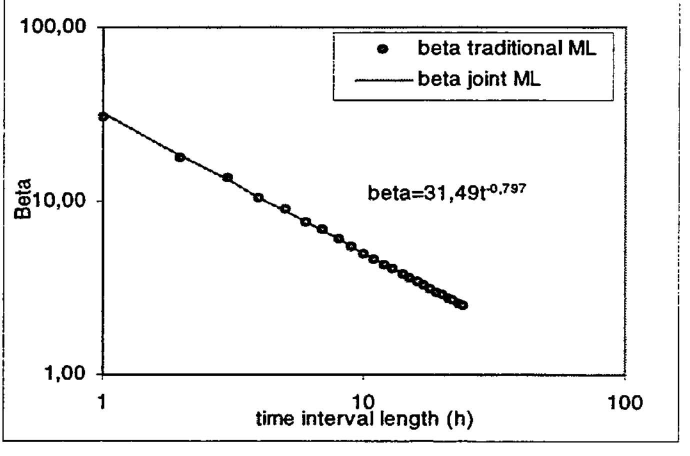
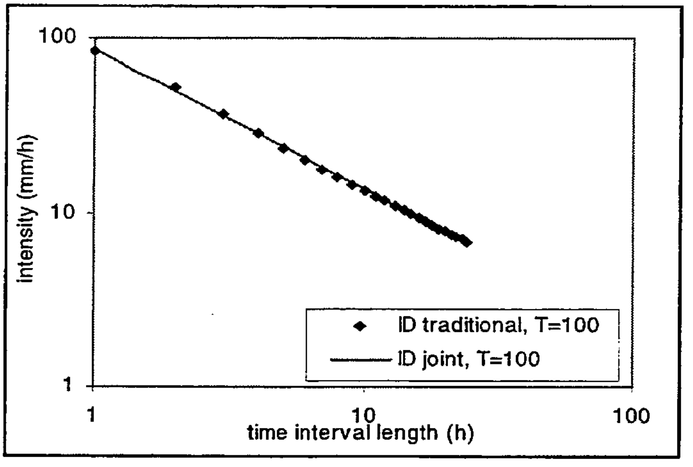


Fig. 10 - IDF curve for T=100 years in Barcelona by Gumbel joint estimation, compared with traditional quantiles



4 Application of simple scaling to the General Extreme Value distribution function

For the GEV distribution it can be demonstrated (in a similar manner to the Gumbel case), that in order to have simple scaling the scale and position parameters must follow the following expressions:

$$\alpha_t = \alpha_0 t^{-n}$$

$$\beta_t = \beta_0 t^{-n}$$

and the shape parameter κ must be constant. Therefore, the log-likelihood function can be defined by:

$$\ln L(\alpha_o,\beta_o,n,\kappa)=Nn\sum_{i=1}^{M}\ln t_i-NM\ln\alpha_o+\left(\frac{1}{\kappa}-1\right)\sum_{i=1}^{M}\sum_{j=1}^{N}\ln\left(1-\frac{\kappa x_{ji}}{\alpha_o t_i^{-n}}+\frac{\kappa\beta_o}{\alpha_o}\right)-\sum_{i=1}^{M}\sum_{j=1}^{N}\left(1-\frac{\kappa x_{ji}}{\alpha_o t_i^{-n}}+\frac{\kappa\beta_o}{\alpha_o}\right)^{\frac{1}{\kappa}}$$

In this case also the Powell maximization algorithm has been used to find the four estimated parameters.

In figures 11 and 12 we can appreciate a good agreement between α and β parameters obtained by joint estimation and the corresponding estimates for each time interval. However, in figure 13 we can see the assumption of a constant κ is not very good, mainly because there is a high variation of the skewness coefficient with the time interval.

Figure 14 shows us the IDF curve obtained by the joint estimation method and the quantiles estimated for each time interval based on the GEV distribution for the return period of 100 years in Barcelona.

Fig. 11 - Parameter α by joint estimation and estimated for each time interval in Barcelona assuming a GEV distribution

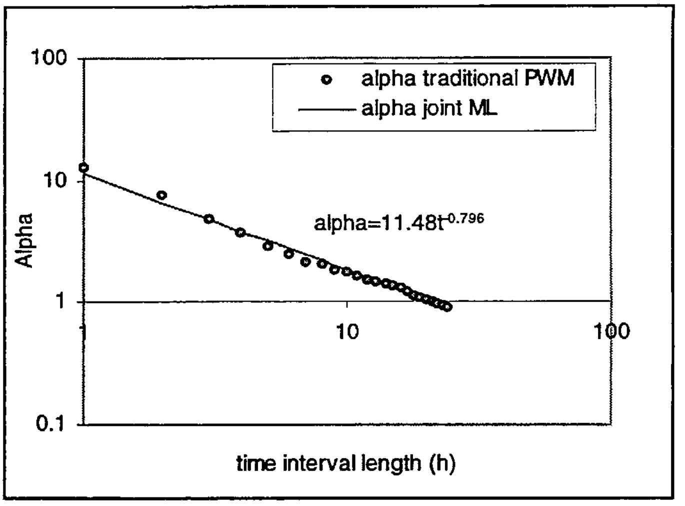


Fig. 12 - Parameter β by joint estimation and estimated for each time interval in Barcelona assuming a GEV distribution

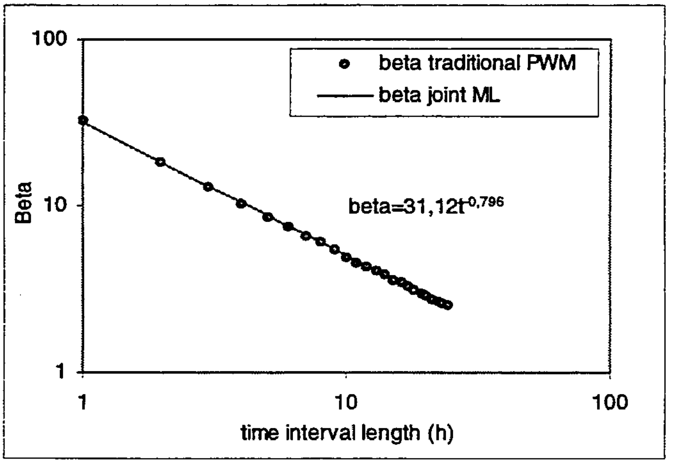


Fig. 13 - Parameter κ by joint estimation and estimated for each time interval in Barcelona assuming a GEV distribution

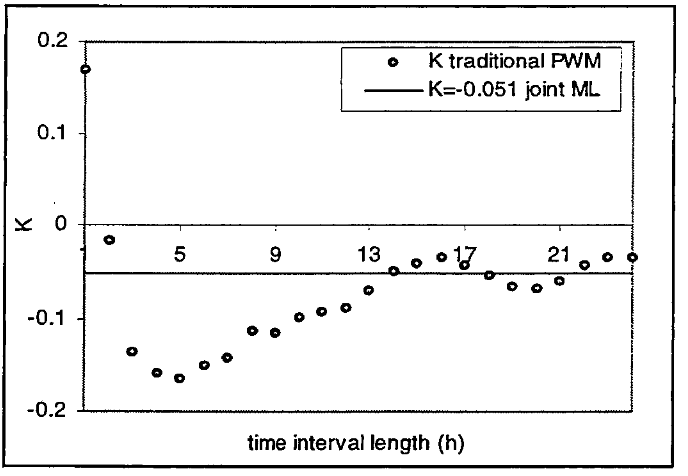
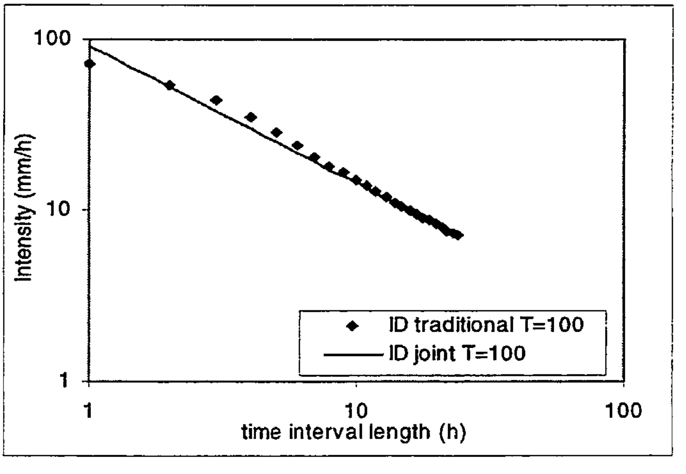


Fig. 14 - IDF for T=100 years in Barcelona by GEV joint estimation, compared with traditional quantiles



5 Conclusions

The analysis of extreme intensity data sets indicates that the seemingly irregular patterns exhibited by the storm rainfall, has a scale invariant structure. The raw moments calculated from the maximum intensity data series in Barcelona and in Valencia suggest the existence of wide simple scaling, but only for time intervals larger than one hour.

The assumption of simple scaling implies the distribution parameters must have certain properties. In the case of the Gumbel distribution, its scale and position parameters must be scale invariant with the same scale exponent. For the GEV additionally the shape parameter must be constant. In both cases all the IDF curves can be defined by a small number of parameters: three for the Gumbel distribution, and four for the GEV. Moreover, using these properties it has been possible to make a joint estimation of these parameters using the Maximum Likelihood estimation method.

The suggested IDF joint estimation method based on the scale properties of storm precipitation compared with traditional methodology is more parsimonious, improves robustness and provides a physically based synthesis of the storm precipitation mechanism in a point. The model implicates simple rules to the complex phenomenon of extreme precipitation and also a higher reliability of storm design in engineering applications.

Flow regionalization
A stochastic flow model for QDF analysis

Régionalisation des écoulements. Un modèle d'écoulement stochastique pour l'analyse QdF

Dr. Juan B. Marco with the help of Mr. Jesús Rodríguez Gimeno, undergraduate student with cooperation grant from this project

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Abstract

QDF curves are a concise and nevertheless rich method to present flood regime information of a river. It is well recognized that pure flood peak frequency description is not sufficient to answer many engineering design problems, specially if flood routing is involved. QDF curves, similar in idea to better known IDF curves of rainfall analysis, provide information on flows to be expected for a given duration.

QDF curves however, erase the stochastic nature of flows, focusing only on probabilistic aspects. A relationship however exists linking the hydrograph shape, the succession of events and its global probabilistic characterization. QDF curves as a probabilistic expression of the flow regime must be coherent with the stochastic structure and hydrograph shape.

Résumé

Les courbes QdF représentent une méthode concise et néanmoins riche pour présenter les informations sur le régime de crue d'une rivière. Il est reconnu qu'une seule description de la fréquence des pics de crue n'est pas suffisante pour répondre aux nombreux problèmes d'ingénierie, particulièrement dans la réalisation de modèles hydrauliques. Les courbes QdF, dont le concept est similaire à celui des plus connues courbes IdF d'analyse des pluies, fournissent des informations sur les écoulements prévisibles pour une durée donnée. Cependant, les courbes QdF gomment la nature stochastique des écoulements en se focalisant uniquement sur les notions de probabilités. Une relation existe cependant entre la forme de l'hydrographe, la succession des événements, et sa caractérisation probabiliste globale. Les courbes QdF, comme expression probabiliste du régime des écoulements, doivent être cohérentes avec la structure stochastique et la forme de l'hydrographe.

1 QDF Curves

Flow-duration frequency curves, were introducted on flood analysis by Galéa and Prudhomme (1993). These type of curves were long time used in their empirical form, since the beginning of this century for hydropower analysis, and without any type of probabilistic analysis. They were known as classified flow curves. Reason for this was that engineers were mostly interested on frequent and average flows to produce electricity and not on the extreme flows regime.

To obtain empirical QDF, a duration is selected, and the worst period from each flood hydrograph is located for which a flow is continuously surpassed. This flow is termed the threshold flow. In this fashion a sample of maximum threshold flows is obtained which can be statistically analyzed using either the empirical frequency analysis or fitting a suitable distribution. A number of percentiles for representation is chosen corresponding to different return periods. The process for representation is chosen corresponding to different return periods. The process is repeated for each duration d and finally the curves are represented by uniting flows for all the duration range and the same return period. This is exactly the same process long term used for short term rainfall analysis in urban hydrology to obtain the intensity-duration-frequency curves to be used for rational method analysis. It is obvious that for d tending to zero, the flood peak frequency distribution is the departing point of QDF curves.

In this fashion, QDF curves represent a probabilistic picture of the flood regime from a river in both the flow and time dimensions.

However, Galéa and Prudhomme (1994, 1995) elaborated the QDF curve concepts by scaling through a suitable duration, and flow. They selected the characteristic rising time of the hydrograph D as time scale and the QIXA(10) that is the maximum instantaneous flow of 10 year return period as flow scale. In doing so, spatial and time scales of the basin are removed. So the QDF curves are rendered dimensionless. Galéa and Prudhomme (1994, 1995) found that dimensionless QDF curves obtained are very stable and constant over basins of different size, representing a blueprint of the climatic factors of a region.

Also Galéa and Pundhomme (1994, 1995) realized that from a single QDF curve, a synthetic hydrograph could be deducted containing the flows of each duration possessing the same return period. They termed it the Mono Frequency Synthetic Hydrograph, applying this concept on the dimensionless QDF curve. This idea is a logic development, since similarly from IDF curves for rainfall analysis a design hyetograph can be deducted for urban hydrology design of sewers. Also a design hydrograph was obtain from a similar concept as we will see later by Hiemstra (1974).

2 Stochastic flow models

Stochastic flow models, especially time series models have a long term established status in hydrology. However, stochastic models for flood analysis are very rare, the bulk of the literature seeing derroted to low and average flows. Instead, probabilistic analysis of floods is a standard tool. A stochastic model for flows, if we want to analyze the flow and duration regimes, must rely on the crossing properties of the series.

Crossing theory was introduced in time series analysis by the Swedish mathematician H.Cramer (1946). Their introduction in hydrology was made by Saldarriaga and Yevjevich (1970) and later by Millán and Yevjevich (1971). Mostly as a method to study drought characteristics. As explained by Yevjevich, run properties are very attractive to analyze persistency because they are distribution free and their properties stem only from serial dependence. But crossing theory has not been applied to floods. Stochastic analysis of floods is based on the partial duration series concept. The idea is to model only the flood peak series by truncating it and separating the average and low flows. The flow series is reduced to a series of peaks, associated with a point process, triggering each one a flood peak. The concept of partial duration series was first proposed by pioneers like Langbein (1949) Darlymple (1960) and Bernier (1967). However, its systematic treatment was consolidated by Todorovic in a series of Paper by him and his coworkers. (Todorovic and Zelenhasic, 1969; Zelenhasic, 1970; Todorovic and Woolhiser, 1972; Todorovic, 1978).

Todorovic model is essentially a marked poisson point process. Selected a certain base level Q_0, we denote by t_1, t_2, t_3... the duration of the exceedences, that is the time between a upcroassing and downcrossing of the base level Q_0, and Z_1, Z_2, Z_3 ... the times of local maximum of flow during these exceedances. Defining also

$$Q_{X_R}=Q\ (Z_R)-Q_0; \qquad k=1,2\ ...$$

the series of maximum value of excedances, this Q_{Xk} is called the partial duration series.

The point process, is defined by the counting process of points, $\{N_k;\ k = 0, 1, 2...\}$. If the occurrence of points is statistically independent, that is to say the occurrence of a point on a given interval is the same regardless of the occurrence in previous non-overlapping time intervals, the process is called a Poisson point process. The most important characteristics of Poisson point processes are that

(a) The probability distribution of the number of points v at a given time interval Δt follows a Poisson distribution

$$P(v)=\frac{e^{-\lambda\Delta t}(\lambda\Delta t)^{v}}{v!}$$

being λ the intensity of the point process.

(b) The waiting time between points follows an exponential distribution

$$If\ \ W_k=Z_{k+1}-Z_k$$

then, the distribution of W is

$$f(W)=\gamma e^{-\gamma W}$$

In fact, for flood analysis, if the base flow crossing level is selected sufficiently high (N.E.R.C. 1975) so that the number of peaks per year is less than 5, independence of flood peaks is granted. Hence the Poisson hypothesis is fully supported by all means of evidence, and has been adopted since Todorovic (1972) by all authors. Much less studied are the marks associated with each point. Todorovic (1978) assumed that marks, that is to say flood peaks Q_{x_k} are independent identically distributed random variables. He chose the exponential distribution

$$f(Q_x)=\alpha e^{-\alpha Q_x} \quad for\, Q>0$$

This was also the distribution selected by Cunnane (1979), North (1980) and Ashkar and Rouselle (1981). The exponential distribution was also chosen to model duration over a threshold

$$f(t)=\beta e^{-\beta t}$$

But all this group of researchers, assumed independence of t and Q_x. This is hardly justified since duration and flood peak are strongly correlated, over ρ = 0'70 usually. Also they analyzed only floods over a single threshold Q_0, without studying the relationship among properties at different crossing levels.

Choulakian *et al.*, (1990), took the Partial Duration Series Model of Todorovic, as departing point. They assumed the Poisson point process, but instead used as marks flood peak Q_x and duration t from a bivariate distribution, since both random variables are strongly correlated. They used Nagao-Kadoya (1971) distribution, which is a bivariate distribution with marginal distributions following the exponential law.

$$f(Q_x,t)=\exp\left\{-\frac{1}{1-\rho}\left(\alpha Q_x+\beta t\right)\right\}\frac{\alpha\beta}{1-\rho}\sum_{k\geq 0}\left[\frac{\alpha\beta Q_x t}{(1-\rho)^2}\right]^k\frac{1}{(k!)^2}$$

This distribution has very interesting properties. For instance, conditional expectations are

$$E(t|Q_x)=\frac{1}{\beta}(1-\rho+\alpha\rho Q_x)$$

$$E\left(Q_x|t\right)=\frac{1}{\alpha}(1-\rho+\beta\rho t)$$

increasing linearly with the conditioning variable, which is something observed in reality. Variances are also lineary increasing. But the most interesting result for us is the conditional distribution of durations given the flood peak.

$$f(t/Q_x)=\frac{\beta}{1-\alpha}\exp\left\{\frac{1}{1-\rho}(\alpha Q_x+\beta t)\right\}\frac{\alpha\beta}{1-\rho}\sum_{k\geq 0}\left[\frac{\alpha\beta Q_x t}{(1-\rho)^2}\right]^k\frac{1}{(k!)^2}$$

From this model they also derived the distribution of flood peak volume by assuming triangular flood hydrograph.

3 Objectives

Our objective is to establish the equivalence between QDF curves and a stochastic model of flood peaks.

A stochastic model of flood peaks has been built, belonging to the Partial Duration series domain, driven by a Poisson point process. The marks are of several types.

(a) Univariate marks of flood peak Q_x as random variable, but triggering a deterministic hydrograph. It will be triangular of

- Base duration proportional to the peak
- Base duration constant
- CEMAGREF MFSH which is intermediate

(b) Bivariate marks using Choulakian model.

Then conditional Probability distribution functions of duration for fixed threshold and threshold flow for fixed duration will be theoretically obtained. The extreme distribution of this latter is clearly the concept of QDF curves, so the equivalence will be theoretically obtained.

4 Stochastic flow model

The stochastic flow model contains several elements. First, a Poisson Point Process of flood peak occurrences. Second a probability distribution of flood peaks triggering different types of deterministic hydrographs. For each of these models, conditional probability distribution of duration for a given crossing level and crossing level flow for given duration have to be obtained. Also, a triangular hydrograph of random bivariate flood peak and duration will be researched. Finally, extreme distribution from the underlying ones, must be obtained.

5 A Poisson Point Process of Flood Peak Occurrence

Considering the time of peak occurrences, it is modeled according to a Poisson Point Process {N(t)} of a parameter λ.

In this fashion, the number of flood events for any time interval Δt follows Poisson distribution

$$P(N(\Delta t) = n) = \frac{(\lambda \Delta t)^n}{n!} e^{-n\lambda\Delta t}$$

Occurrence of floods on any disjoint interval is an independent random variable.

6 A probability distribution function of flood peaks

Flood peak Q_x at each point t_1, t_2... is considered an independent realization from an identically distributed random variable with probability distribution function $F(Q_x)$. In this fashion the stochastic process of flood peaks becomes a Marked Poisson Point Process. As a flood peak model, negative exponential and Gumbel distribution have been tested.

7 A dimensionless hydrograph

To each peak a shape of flows in time is associated to build the complete hydrograph. Several possibilities can be explored each one resulting in a different model. First we assume a mono frequency hydrograph, in other words assuming that only flood peak is random in nature, the whole hydrograph being reconstructed from its value.

(a) Triangular hydrograph with constant base time t_b

For this model, duration d over a threshold flow Q_0 can be obtained as

$$\frac{Q_x}{t_b} = \frac{Q_x - Q_0(d)}{d}$$

Hence

$$Q_0(d) = Q_x \left(1 - \frac{d}{t_b} \right)$$

(b) Triangular Hydrograph with base time proportional to peak flow

If we assume a characteristic flow peak Q and duration D as defining a triangular hydrograph, any hydrograph can be built proportionally. Hence

$$Q_0(d) = Q_x - d \frac{Q}{D}$$

Relationship between flood peak and volume is quadratic, non random.

(c) CEMAGREF Model

CEMAGREF Model assumes a MFSH of linear rising limb and constant time peak and an exponential decay of more complex construction.
We can express the duration over a given threshold in terms of the peak flow as

$$Q_0(d) = Q_x \left(\frac{\alpha d + \gamma D}{\beta d + \gamma D} \right) - \delta Q$$

Note that whilst for constant base time Q_0 (d) decreases linearly with d and Q_x and for proportional hydrograph Q_0(d) decreases independently from Q_x, in this case is somehow in between. Relationship between Flood Peak and Volume is also in between and not random since for each value of flood peak the volume is uniquely determined.

(d) Choulakian model hydrograph

Choulakian *et al.,* (1990) assumed a triangular hydrograph of random peak Q_x and base time t_b. Their hydrograph is hence.
So we have that, like in case a)

$$Q_0(d) = Q_x \left(1 - \frac{d}{t_b} \right)$$

but in this situation, t_b is not a constant parameter but a random variable.

8 Properties of the model for fixed crossing level Q_0

If a fixed crossing level Q_0 is set, properties of the duration run can be obtained. A new stochastic process is defined which has the structure of a marked renewal Poisson Point Process.

First we can compute the distribution of run duration d for a fixed Q_0 through derived distributions. If equations for Q_0 (d) are inverted, we can obtain

$$Q_x = \varphi_1 (d; t_b, Q_0, D, Q, \ldots)$$

where Q_x and d are the only random variables.
Conditional distribution of duration can be found.

$$f(d \mid Q_0) = f(\varphi_1(d \mid Q_0)) \left| \frac{dQ_x}{dd} \right| (1 - P(d = 0 \mid Q_0))$$

The new Poisson point process has smaller intensity λ' since if flood peak is smaller than the crossing level, d=0 and no point exists. This is called a p-thinning of a point process.

The new intensity can be obtained as

$$\lambda' = \lambda P (Q_x \geq Q_0)$$

Finally if we want to obtain the maximum duration d_x distribution for a period τ, for instance 1 year and given Q_0 through independence of the peaks within the period, we can obtain.

$$F(d_x|Q_0) = \sum_{N=1}^{\infty} \frac{e^{-\lambda T}(\lambda' T)^N}{N!} \prod_{n=1}^{N} \left(F(d|Q_0)\right)^n$$

First of all, conditional distribution of flow threshold Q_0 for a given duration can be found. Through derived distributions technique threshold flow expressions can be inverted as a function of duration and flood peak. Hence

$$Q_x = \varphi_1 \left(Q_0; d, t_b, D, Q, \ldots\right)$$

being Q_x and Q_0 the only random variables. Then

$$f(Q_0|d) = f(\varphi_1 Q_0|d)) \left|\frac{dQ_x}{dQ_0}\right| \bullet \frac{1}{(1-P(d>t_b))}$$

The last correction is due to the fact that if selected duration is larger than base time t_b of the hydrograph, no crossing level Q_0 is defined.
This expression can be obtained for the three hydrograph models under consideration.

If Choulakian model is adopted, in the expression

$$Q_0 = \varphi_1 \left(Q_x, t_b; d\right)$$

both Q_x and t_b are random variables. To obtain F $(Q_0|d)$ integration of the joint bivariate distribution f (Q_x, t_b) over the whole domain R for which $Q_0 < \varphi_1$ $(Q_x, t_b; d)$ is needed.

Hence, the conditional probability distribution of Q_0, given the duration d is

$$F(Q_0|d) = \frac{1}{1-\mathrm{Pr}\,ob(t_b \le d)} \int_d^{\infty} \left[\int_0^{\frac{Q_0 t_b}{t_b - d}} f(Q_x, t)\, dQ_x \right] dt_b$$

where f (Q_x,t) is the Nagao-Kadoya (1971) distribution

$$f(Q_x, t) \exp\left\{-\frac{1}{1-\rho}(\alpha Q_x + \beta t_b)\right\} \frac{\alpha\beta}{1-\rho} \sum_{k \ge 0} \left[\frac{\rho\alpha\beta Q_x t_b}{(1-\rho)^2}\right]^k \frac{1}{(k!)^2}$$

9 Probability Thinning of the Stochastic Process

When duration d of interest is fixed, it can be larger than the base time of a number of hydrographs. This fact is reflected in a p-thinning or probability deletion of a number of events.

The new point process has smaller intensity λ''.

$$\lambda'' = \lambda\left(1 - P(d > t_b)\right) = \lambda P(d \leq t_b)$$

10 Maximum threshold flow Q_{0x} distribution for a given duration d in a period τ

If we consider a period τ, for instance 1 year and compute the maximum flow lasting for a duration d, its probability distribution function can be computed from the Poisson process and the independence hypothesis.

$$F(Q_{0x}|d) = \sum_{N=1}^{\infty} \frac{e^{-\lambda''\tau}(\lambda''\tau)^N}{N!} \prod_{n=1}^{N} \left[F(Q_0|d)\right]^{r}$$

But this is exactly the concept of QDF curves for a period τ.

So, in other words, flood peak distribution marking a Poisson point process and Mono-Frequency Synthetic Hydrographs, define a process from which QDF curves can be obtained or conditional distribution function for duration over a given threshold. Methods can then be developed to obtain one formulation from another one. However estimation can be best performed from the model since a small set of parameters can be calibrated at once.

11 Application to a real case

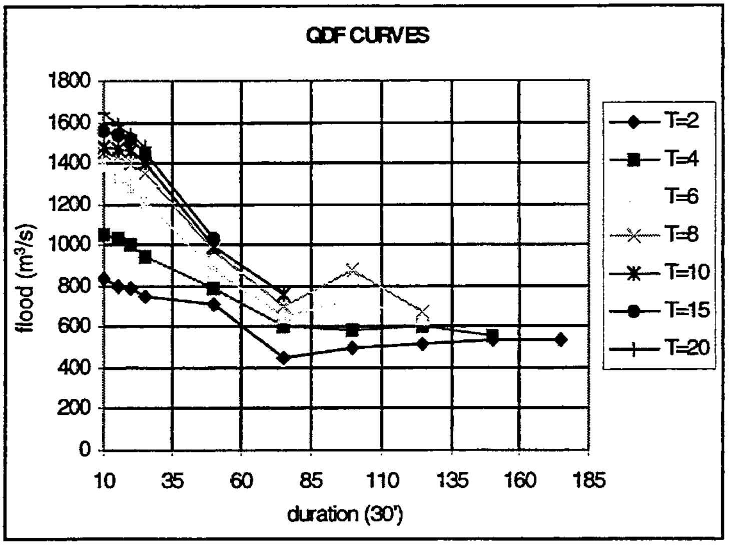
A series of floods was collected and analyzed for the Ebro river at Miranda. 13 Hydrographs were analyzed, from 28 years of records. This is not a systematic sample, the number of floods being smaller than the number of years. Results are affected by this fact, specially through the maximization procedure.

A computer package has been prepared to obtain both empirical and theoretical QDF curves. A number of options are available. First the probability distribution function for flood peaks can be chosen among the most commonly used ones: exponential, Gumbel- Rearson, etc. also the empirical PDF can be used. Then empirical QDF curves can be computed from the series. Theoretical QDF can also be computed acording to the hydrograph model selected: Proportional, constat base time, Cemagref MESH. Also empirical and theoretical curves of maximum duration given the threshold level can be computed.

Fithing flood peak distribution, three options were used: Exponential, Gumbel and the empirical curve. Exponential fit was discarded, because since the sample is not systematic, somehow a maximization process has been introduced. So the fact that the underlying flood peak distribution is already an extreme one, affects the results. The exponential distribution is not representative.

For each duration, conditional distribution of flow threshold given the duration can be computed, and also its theoretical extreme distribution. Empirical QDF curves were also computed. They are shown in figure 1.

Fig. 1 - Empirical QDF curves for the Ebro river



Theoretical QDF curves are shown for instance with constant base time $t_b = 200$ (100 hrs) and for proportional hydrograph with $Q = 1000\ m^3/s$ and $D = 100$ (50 hrs).

Fig. 2 - Theoretical QDF curves. Constant base time hydrograph

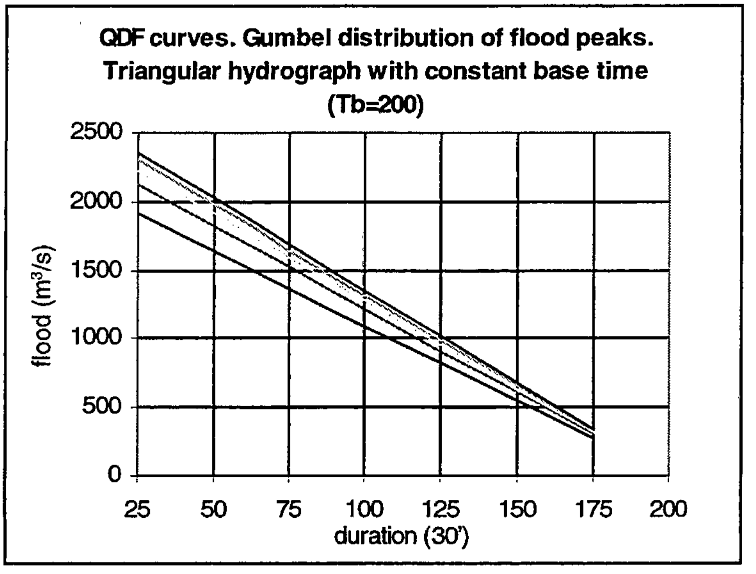
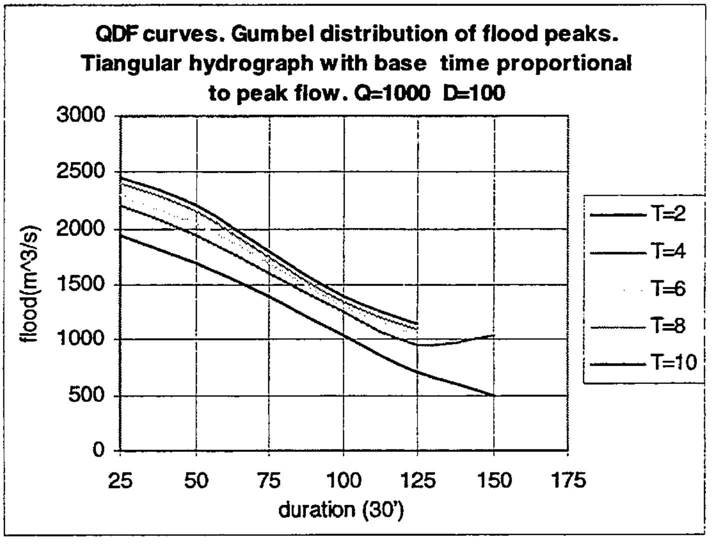


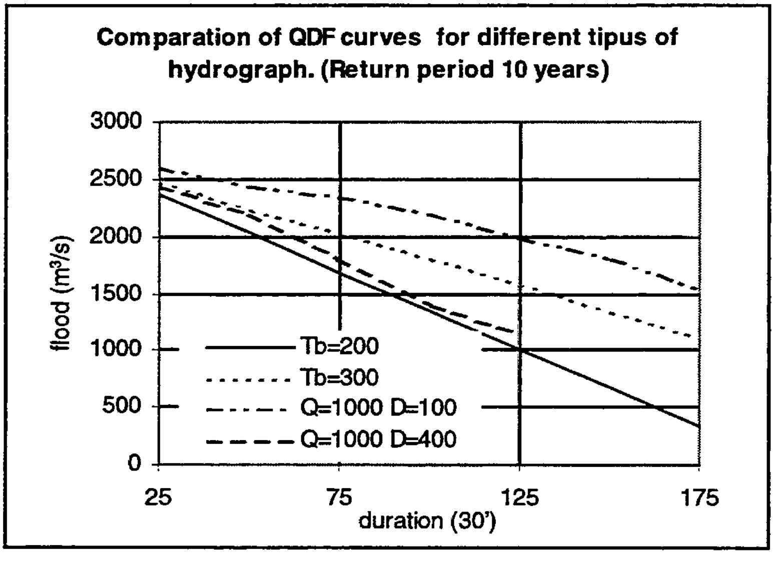
Fig. 3 - Theoretical QDF curves. Proportional hydrograph. Q=1000 m^3/s and D=100 (50 hrs)



It can be seen show the shape and slope of the empirical QDF curves are correctly reproduced, but not their absolute value. This is clearly a consequence of the flood sample selection which has already maximized the initial flood peak distribution, in fact a Gumbel one.

As for the hydrograph selection, we present in figure 4, four models and the empirical curve. Differences are very scarce. In fact it can be seen that curves for constant base time $T_b = 200$ (100 hrs) and Proportional hydrograph with $Q = 1000\ m^3/s$ and $D = 400$ (200 hrs) give both almost equed results. The peak proportion between flow and duration seems to be the single relevant variable determining the QDF shape.

Fig. 4 - Comparation of Theoretical QDF curves and empirical for several hydrograph models



Flood risk modification downstream from reservoirs

Modification du risque de crue en aval des réservoirs

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Abstract
Among all uses of large reservoirs, flood control has to be always taken into account. Flood peak reduction can be substantially reduced through previous empty space and the hydraulic characteristics of its spillway and intakes.
A flood can be as a first approximation characterized by its flood peak and volume. This is the minimal configuration to determine an input hydrograph. To obtain the risk downstream of a reservoir, we need first to characterize the transformation of flood peak and volume through its previous empty space and hydraulic parameters, and second we must characterize from a statistical point of view the incoming flow peak and volume. Since the incoming flood characteristics are strongly related, a bivariate probabilistic approach is needed.

Résumé
Parmi les différents usages des grands réservoirs, la fonction de contrôle des crues doit toujours être intégrée. La réduction des pics de crue peut être substantielle à travers des zones de stockage en amont et des ouvrages hydrauliques caractéristiques (prises d'eau et déversoirs).
En première approximation, une crue peut être caractérisée par son débit de pointe et son volume. C'est la configuration minimale pour déterminer un hydrogramme d'entrée. Pour obtenir le risque en aval d'un réservoir, nous avons d'abord besoin de caractériser la transformation du pic de crue et de son volume en terme de volumes de stockage et selon les paramètres hydrauliques. Puis nous devons caractériser d'un point de vue statistique le pic et le volume d'écoulement entrant. Comme les caractéristiques des flots entrant sont fortement liées, une approche probabiliste bi-variée est nécessaire.

1 Relationship between upstream and downstream flood characteristics

Flood characteristics are deterministically transformed when a hydrograph is routed through a reservoir. We will denote I_p and V the input flood peak and volume to a reservoir and O_p and V^1 as the corresponding output variables. Net effect from a reservoir is to damp the peak and retard its occurrence.

We look to characterize through a simplified approach amenable to statistical analysis the relationship between upstream and downstream variables. Namely we look for relationships of the type

$$O_p = h_1(I_p, V)$$

$$V^1 = h_2(I_p, V) = V - V_0$$

although obviously, V^1 is the input flood volume V minus the previous empty space V_0.

2 Properties f continuity equation

Water mass conservation can be expressed through the conservative systems equation

$$I(t) - O(t) = \frac{d\,S(t)}{d\,t}$$

relating three functions: Input hydrograph I(t), output hydrograph O(t) and storage within the system, S(t).

Equation for storage is related to the capacity curve of the reservoir

$$S(t) = A\,[h(t)]^b$$

where h(t) is water level.

Discharge equation, from spillway hydraulics is

$$O(t) = \alpha\left(h(t) - h_0\right)^\beta$$

where h_0 is the spillway crest level. Eliminating h(t), we can express O(t) as a function of S(t)

$$O(t) = \alpha\left[\left(\frac{S(t)}{A}\right)^{\frac{1}{b}} - h_0\right]^\beta$$

On the other hand, considering I(t) as known function, the storage equation can be expressed as depending of a single variable

$$\frac{d\,S(t)}{d\,t} = I(t) - \alpha\left[\left(\frac{S(t)}{A}\right)^{\frac{1}{b}} - h_0\right]^\beta$$

Despite is nature as a first degree ordinary differential equation, no explicit exact solution can be obtained to the reservoir mass balance equation. Numerical simulation is the standard tool to solve it. This is well known Puls method.

Covering through numerical simulation all the space of pairs of values of $\{I_p , V\}$ and obtaining the corresponding O_p values, we can represent this relationship and look for a simplified model amenable to statistical analysis. As will be seen later, linear relationships accomplish this quite well.

The numerical procedure above explained of numerical simulation over the whole space of $\{I_p , V\}$ combinations and linearization of the relationship $O_p = h_1 (I_p , V)$ with respect to I_p has been applied to several combinations of reservoir characteristics. A sensitivity analysis has been performed with respect to parameters A, b and α characterizing the reservoir geometry and hydraulics. β is generally 3/2 so it has not been changed.

Of course A, b and α depend from the considered reservoir, but in all researched cases, linear peak damping was proven to be sufficient for practical purposes, for fixed flood volume V.

3 Bivariate probabilistic model for input flood peak and volume to a reservoir

Since the simplest hydrograph needs to be characterized as a minimum by its flood peak I_p and volume V, and these random variables are strongly correlated, a bivariate approach has to be adopted.

At this point several options appear

1. To use a skewed bivariate distribution like the Marshall-Olkin or Farlie-Morgenstern
2. To build it from marginals, like Hashinomodel
3. To build the bivariate distribution from the marginal distribution of I_p and the conditional distribution of V given I_p.

$$f(I_p,V)=f(I_p)f(V \mid I_p)$$

This has seen the approach finally selected. It is very sound because $f(I_p)$ is quite well established, and correlation between I_p and V is very high.

As a model for the marginal $f(I_p)$ flood peak distribution, the most common ones in the hydrological practice have been used. These are Gumbel, log-normal with 2 and 3 three parameters and Pearson.

To model the conditional distribution $f(V \mid I_p)$, a normal distribution has been considered around the expected value, depending quadratically from I_p and a variance proportional to I_p. Then

$$V \mid I_p \_ N\left(c I_p + d I_p^2, f I_p\right)$$

being c, d, f constant. Hence the probability density function is

$$f(V \mid I_p)=\frac{1}{\sqrt{2\pi}\,\sqrt{c\,I_p}}\exp\left\{-\frac{1}{2c\,I_p}\left(V-c\,I_p-d\,I_p^2\right)^2\right\}$$

4 Derived distribution for flood peak and volume, downstream

In this situation, since the transformation is

$$\begin{cases} I_p=m^1(V)\,O_p+n^1(V) \\ V=V^1+V_0 \end{cases}$$

the Jacobian determinant is

$$J=\begin{vmatrix} \frac{\partial I_p}{\partial O_p} & \frac{\partial I_p}{\partial V} \\ \frac{\partial V}{\partial O_p} & \frac{\partial V}{\partial V^1} \end{vmatrix}=\begin{vmatrix} m^1(V) & \frac{\partial I_p}{\partial V} \\ 0 & 1 \end{vmatrix}=m^1(V)$$

Then, to obtain the new distribution, it is only necessary to substitute the transformation equations into the selected distribution and multiply by the $m^1(V)$ coefficient obtained from systematic simulation and linear fitting.

Once obtained both bivariate probability density functions, then the associated risk before and after dam construction can be computed and compared, by integrating their marginal distributions for a given flow q

$$P(I_p>q)=\int_0^q\int_0^\infty f(I_p,V)\,dv\,dI_p$$

$$P(O_p>q)=\int_0^q\int_0^\infty g(O_p,V^1)\,dV^1\,dO_p$$

where q is the flood peak we are interested in.

5 Application to a real case

The developed methodology has been applied to the Ardisa river basin. This is a tributary of the Ebro river in the Pyrenées. The basin has an area of mostly of woods and pasture, in mountain area. A sample of 28 flood hydrographs has been analyzed. Risk reduction through the Regajo reservoir has been considered.

The Regajo reservoir has a capacity of 6 Hm^3. Its capacity curve is in metric units.

$$S(t) = 8000\,[h(t)]^2$$

and its spillway rating curve

$$O(t) = 7'975\,[H(t) - 26\,]^{\frac{3}{2}}$$

First, marginal distributions for flood peak were fitted. Then, to model the conditional distribution $f(V \mid I_p)$ the Ardisa data were analyzed, to fit the model N $(c\,I_p + d\,I_p^2\,,\,f\,I_p)$.

After this, having validated the analytical shape of the model, the parameters were scaled to produce hydrographs meaningful to be damped through the Regajo reservoir. In metric units we had.

$$N\,(6000\,I_p + 6'5\,I_p^2\,,\ 2'5\ 10^9\,I_p)$$

Once obtained the distribution of input flood peak and volume, to model damping, a hydrograph shape must be adopted. We selected a Gamma function, very classical in hydrology. For this function, the hydrograph is given by

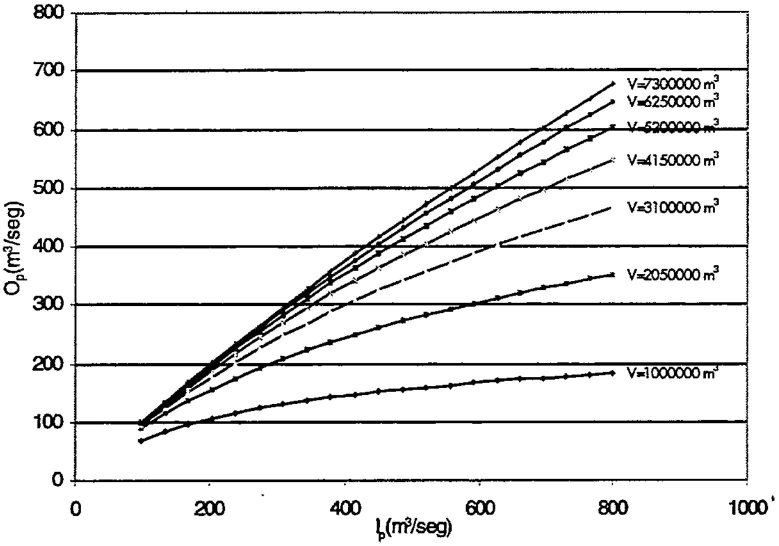
$$I(t) = I_p \left(\frac{t}{T}\right)^p \exp\left[-\,p\left(\frac{t}{T} - 1\right)\right]$$

where T is time to peak, and p a shape parameter.

A value p = 2'68 was adopted, because this produces the peak at 1/3 of the total duration of the hydrograph.

Through simulation, the relationship between I_p and O_p was obtained.

Fig. 1 - Relationship between input and output flood peak for different flood volumes



From this figure it is clear that relationship between I_p and O_p is practically linear. Linearity is more evident for large flood volumes. To verify this a few linear fitting were performed.

The linear relationship will be expressed as

$$I_p = m O_p + n$$

where m and n are functions of V for a given reservoir. This relationship is more practical to perform the change of random variables.

Different values of m and n have been obtained depending on V. To research this dependence, each parameter has been represented as a function of V.

All this process was also repeated for slightly different values of p, the shape parameter of the hydrograph, resulting on negligible differences. For all purposes, damping is practically independent of the shape of the hydrograph provided the flood volume is the same.

A sensitivity analysis has been performed with respect to the parameters, which describe the physical characteristics of the reservoir. These parameters are A and b, the parameters describing the geometry of the reservoir, and α, β and h_0 the parameters describing the hydraulic characteristics of the spillway.

The influence of h_0 is very clear and will not be explored, since for $h = h_0$ the stored volume is V_0, the previous empty space. Also the β parameter has been always set to $\beta = 3/2$, since all reservoirs used for flood control, have free surface spillways.

Simulations have been performed by setting two parameters and varying the third one. Three sets of simulations have been analyzed.

To model this relationship for a given reservoir, this family of curves can be expressed as

$$m = s - t \exp\{-r V\}$$

and for the intercept similarly

$$n = s^1 - t^1 \exp\{-r^1 V\}$$

After performing he change of variables, the probability distribution can be obtained as

$$g(O_p, V^1) = |m| f(m O_p + n, V^1 + V_0)$$

where m and n are functions of V^1, namely

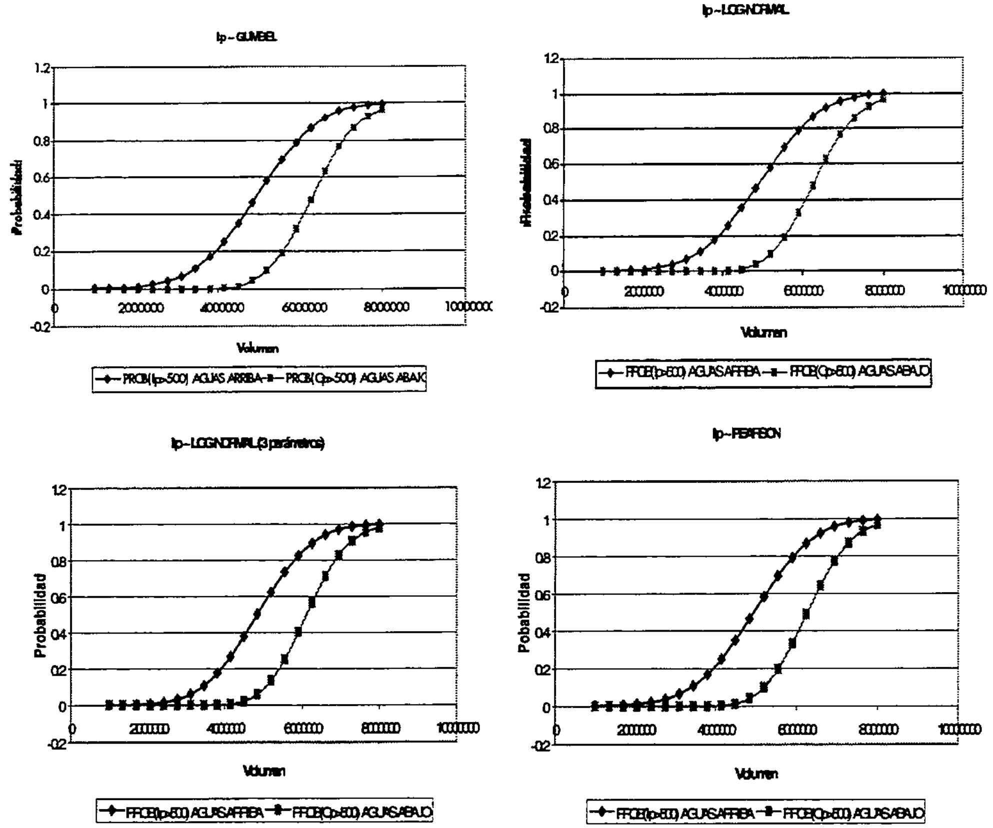
$$m = s - t \exp\{-r V^1\}$$

$$n = s^1 - t^1 \exp\{-r^1 V^1\}$$

So the transformation is fully determined by the six parameters r, s, t and r^1, s^1, t^1. Then, modified risk was computed.

Results to compare both risks for the Ardisa river, can be seen on figure 2. For the 4 marginal input flood peak distributions fitted.

Fig. 2 - Risk reduction for the Ardisa river



It can be seen how risk reduction is maximum for a certain flood volume interval. Floods under it change very little because water depth over the spillway is too small to store water in the reservoir. Large floods fill quickly the dynamic storage and peak reduction is also small. From this we can conclude that reservoir sizing has an optimum given the hydrological regime of the river.

Also it is very interesting that flood peak reduction is not sensitive to the probabilistic flood peak model chosen. It is almost distribution free. Much more important is to capture the volume variance around the expected input flood peak. Volume is the key variable for this problem.

A prototype of real time flood warning system in a Piedmont catchment

Un prototype de système d'annonce des crues en temps réel dans un bassin de Piémont

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Abstract
The Regione Piemonte and Risorse Idriche started the implementation and experimentation of a flood forecasting system in an average size basin. Planning and operating aspects linked to its development are dealt with. The system structure includes a hydrologic model linked to the network through telemetering and an operating structure that issues warning procedures. The components are integrated with a map of inundation risk.

Résumé
La Région Piemont et le Risorse Idriche ont commencé la mise en place et l'expérimentation d'un système d'annonce de crues dans un bassin de taille intermédiaire, y compris les aspects d'aménagement et d'exploitation liés à son développement. La structure du système comporte un modèle hydrologique qui intègre le réseau à travers la télémesure et une structure d'exploitation aboutissant à des procédures d'alerte. Les éléments sont intégrés à travers une cartographie du risque d'inondation.

1. Foreword

The defence from natural risks by means of traditional structural works, or through relocation of residents and industrial activities cannot often be applied due to technical and economical reasons. In these cases, damage can be limited by adopting emergency procedures aimed at preserving human life and reducing vulnerability of people living in risk-prone areas. The effectiveness of these means mainly depends on the timeliness of rescue operations set up during emergency situations, and therefore also on the capability to foresee the events.

In order to be able to efficiently forecast severe rainfalls, Regione Piemonte has been carrying out during the last few years a meteorological warning service designed for civil protection authorities. The service is operated by a bureau named Sala Situazione Rischi Naturali (SSRN, Natural Risk Control Room) that every day evaluates hydrogeologic risks on the Piemonte based on rainfall forecasts provided by meteorological models.

With the aim of enhancing this service and extending to flood events control, Regione Piemonte developed and experimented an operational system for real-time forecasting of floods in a pilot Piedmontese basin.

2. The basin

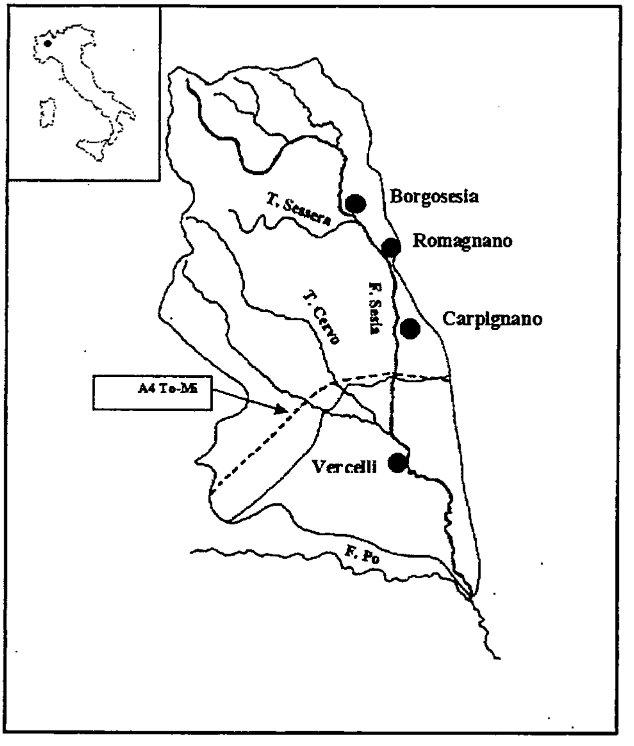
At the moment of planning the forecasting system, it was decided to choose a river whose hydrologic and hydraulic characteristics were representative on a regional scale with the presence of flood-prone towns in the area. The Sesia was chosen: a river whose headwaters are in the Western Alps at an altitude of 4.559 m (Mount Rosa). The outlet into the Po River is at about 90 m a.s.l., the stream length is 131 km, draining 3,100 sq km (Fig.1). The catchment of the Sesia River may be ivided in a mountain zone upstream of the town of Romagnano and a plain zone from Romagnano to the outlet.

The mountain basin, (980 sq km and an average elevation of 1,300 m) may be affected by very intense rainfalls (annual total precipitation ranges between 1,500 and 2,500 mm) due to the orographic effect on stormscoming from the Mediterranean sea. The basin has low permeability, and very short lag-time, due to steep slopes. More over rainstorms are generally located on the lower parts of the catchment, while the contribute of the mountain part is usually of minor importance. These features imply a hydrologic regime characterized by floods with high discharges. Furthermore, the evolution of floods is strongly influenced by the kind of precipitations (solid-liquid) and by snow melting.

On the plain between Romagnano and Vercelli, the Sesia river flows in a typically meandering bed with an average gradient ranging between 0.5% and 0.3% with no significant tributaries down to Vercelli where is located the confluence of the Cervo, a stream draining a catchment of 1,088 sq km. From here to the confluence with the Po river, the Sesia flows in a meandering bed with a slope of less than 0.1%. Almost the whole reach is without levees. During major floods, large overbank areas are inundated with a significant decrease in flood peak.

Flood forecasting is extended to the whole reach of the river from Borgosesia (695 sq km) to the confluence with the Po River.

Fig. 1 - Hydrographic basin of Sesia River



3. Flood forecasting

3.1 Flood forecasting capability

The amount of time needed for activating rescue operations depends on the degree of organization and coordination of the involved operative teams. The experience in the USA suggests that real-time flood forecasting requires at least six to eight hours of advance, so that forecasts can be effectively used in order to reduce the effects of floods and damages due to inundations. That is possible if well tested procedures are available; otherwise, it is more wise considering at least twelve hours of forecast advance (Todini, 1995).

The methodological approach for providing forecasting 12 hours in advance depends on to the basin size. In the largest basins (> 10,000 sq km), it is sufficient to know the water stage at the outlet of the mountainous area and to rout flood along the bed through the plain. In average size basins (1,000-10,000 sq km), the rainfall-runoff process has to be modeled, while in smaller basins, besides measuring precipitations, rainfall forecast is required.

Atmospheric forecasting models can be currently considered efficient instruments for "medium-term" rainfall forecasting (24-48-72 hours), even though they do not have sufficiently detailed spatial and temporal accuracy to forecast hydrologic dynamics at small scale (Brath, 1996). Not with standing, the ability to forecast floods in small basins with adequate advance is strictly correlated with the availability of rain-fall forecasts at small scale. The attempts to solve this problem include various types of approach: from non-hydrostatic high-resolution physical models (Gozzini, 1997) to the thickening of rain fields of limited area models using stochastic procedures (Lanza, 1998); however, at present, operating products to be used for real-time flood forecasting are not available.

3.2 Monitoring

Hydrologic monitoring is carried out by means of the meteo hydrographic network of Regione Piemonte integrated with the network of Servizi Tecnici Nazionali, the na-tional technical service (Fig. 2). Three different kinds of instrumentation were used: recording rain gauges, stream gauges and snowgauging stations.

Raingauges (n.14) are mainly located in areas with complex orography like the mountain valleys and the piedmont area; these stations are equipped with a tipping-bucket rain gauge and an electronic thermometer; solid precipitations (snow) collected in the 1000 cm^2 funnel are melted by means of an electric powered resistance-coil.

Hydrometric stations (n.3) are located in order to record water stage at the main tributaries outlets and on the Sesia river reach; at present, the Cervo is not gauged, but a hydrometric station is expected to be installed in the next future. The water level is measured by an ultrasonic sensor with continuous measurement of air temperature to correct the sound velocity in air.

In the upper basin, one snow-gauging station measures snow depth at 2,410 m of altitude. Technical features and sampling times of monitoring sensors are shown in table 1.

Fig. 2 - Stations for hydrologic monitoring of the Sesia river through telemetry

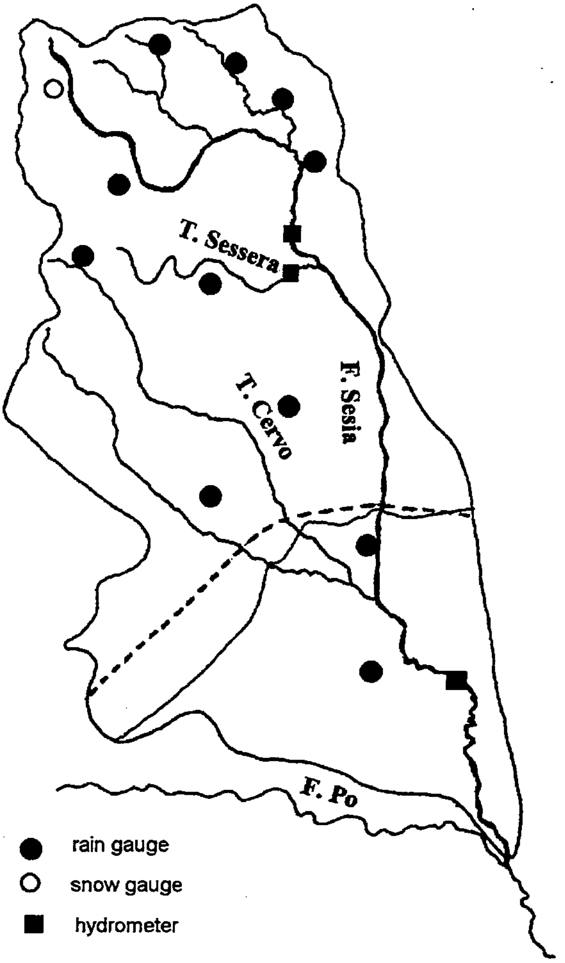


Table 1 – Technical features and sampling times of monitoring sensors

Sensor	measuring field	Sensitivity	total accuracy	recording time
Rain gauge	0 - 300 mm/h	0.2 mm	±0.1 mm/h max a 10 mm/h	10'
Termometer	-30/+50 °C	< 0.02 °C	±0.4 °C max	30'
Hydrometer	15 m	0.1 cm	±1.5 cm max	30'

The parameters measured at site are then transmitted to the Turin operating centre (SSRN) via tropospheric or satellite radio link. The data collection system automatically updates archives every 30 minutes, a management system displays data in graphic form and provides statistics on measured parameters and system operations.

3.3 The forecasting model

A hydrologic model (MIKE 11 of the Danish Hydrologic Institute) was implemented with the Sesia river data; input data from the monitoring network are supplied to the model in real time. The computation code has a modular structure; three models were used to reproduce the most important physical processes that originate floods: rainfall-runoff (NAM), hydrodynamic model (HD) and Flood Forecasting (FF).

NAM is the name of a hydrologic model with lumped parameters that calculates transformation of rains in surface downflow in the sub-basins of the catchment. Each sub-basin is associated with a set of 4 tanks (snow, surface accumulation, infiltration, layer) in which accumulation and release processes are combined to produce the flow hydrograh from each sub-basin. The combination of flood hydrograhs generated by single sub-basins and the calculation of the crest translation along the main fluvial reach are obtained inside HD solving the St. Venant equations (geometric and hydraulic (roughness) characteristics of the bed being known). Last but not least, FF optimizes real-time flow forecasting through self-adjustment of the model response in dependence on direct flow measurements.

The hydrologic response of the catchment to a rainfall event can vary greatly depending on the basin initial conditions (degree of saturation of soil, snow accumulation, etc.). In MIKE 11, this information is expressed assigning the degree of filling of the 4 NAM tanks. More specifically, the degree of accumulation of tanks is determined through continuous simulation of the cycle of transformation of inflows into downflows.

Hydrologic response of the Sesia river in the mountain part and in the first reach of the plain generally occurs in less than 12 hours and thus, keeping in mind the above considerations on the warning time span, the use of rain forecast appears to be wise. To this aim, meteorologists make use of precipitations forecast in the medium term by a limited area meteorological model that covers Italy, as a whole (Mephysto of ENEL, the Italian electricity company). Due to the unreliable matching of meteorological-hydrologic models, warning is based on the flow values caused by actual rainfalls, while flows obtained with forecast rainfalls only determine a pre-warning situation.

3.4 Warning bulletin

Results of the forecasting provided by the model are summarized in a flood warning bulletin. This bulletin provides informations about the forecast flows at selected cross sections along the Sesia stream, the warning level code and the time at which the code will be reached. The code is referred to several levels depending on the degree of danger:

Code	Forecast discharge return period (years)
1	< 2
2	≤ 20
3	> 20

Furthermore, the bulletin gives the peak value calculated with precipitation forecast by NAM and a pre-warning code if this exceeds the flow with a return time of two years.

4. Map of inundation risk degree

The approach to inundation risk mapping is based on the joint use of historical data and geomorphologic and hydraulic analysis. The method was applied to River Sesia and required three investigation phases.

In the first phase of the work, main flood events were analysed with the aim of reconstructing inundated areas, overland flow processes and related effects. To this purpose, aerial photos, historic documents and information taken from local interviews were used.

The second phase led to the assessment of the bed morphology and its evolution trend in the last century, and to the analysis of physiographic features of the area external to the bed that effects the dynamics of major floods.

The third phase concerned the assessment of the free boards for bridges and river banks through hydraulic profiles related to floods with a return time of 20 and 200 years. Eventually, the risk scenarios related to floods with different hazard rates were determined combining all the final results.

4.1 Historic analysis

The main events which affected the catchment in the last century are the following: May 1908, May 1923, August 1934, September 1948, August 1954, November 1968, October 1977, August 1978, September 1993, November 1994.

In the mountain reach, the most serious flood of which water stages are known, occurred on September 1948. Near Borgosesia (Aranco bridge – 695 sq km) a maximum flow of 3,070 cu.m/s was estimated from the stage-discharge relationship, which corresponds to a considerable unit area discharge (4.4 cu.m/s per sq km).

Near Vercelli (2,274 sq km) the maximum stage was observed in November 1968 with 3,900 cu.m/s (1.7 cu.m/s per sq km). Table 2 shows some major historic values.

Table 2 - Historic flood discharges (Q) and related hydrometric levels (h) of the Sesia river

Gauging site	August 1934		September 1948		November 1968		September 1993		November 1994	
	Q m^3/s	h (m)	Q m^3/s	h (m)	Q m^3/s	h (m)	Q m^3/s	h (m)	Q m^3/s	h (m)
Borgosesia	2990	7.5	3070	7.9	2150	6.8	2400	5.05	1800	3.37
Vercelli	2970	6.4	-	-	3900	6.9	3400*	5.68*	3200*	5.65*

** Palestro station (downstream to Vercelli)*

In order to compare these figures with floods with assigned return time, it is possible to refer to the values shown in the "Piano Stralcio per la difesa idrogeologica e della rete idrografica nel bacino del Po" (Autorità di Bacino del Fiume Po – 1997) and reported in table 3.

Table 3 – Flows of the Sesia river with assigned return time

Location	**Return Time 20 years**		**Return Time 200 years**	
	Q (m^3/s)	q ($m^3/s/km^3$)	Q (m^3/s)	q ($m^3/s/km^3$)
Borgosesia	2730	3.93	4220	6.07
Vercelli	3370	1.48	4900	2.15

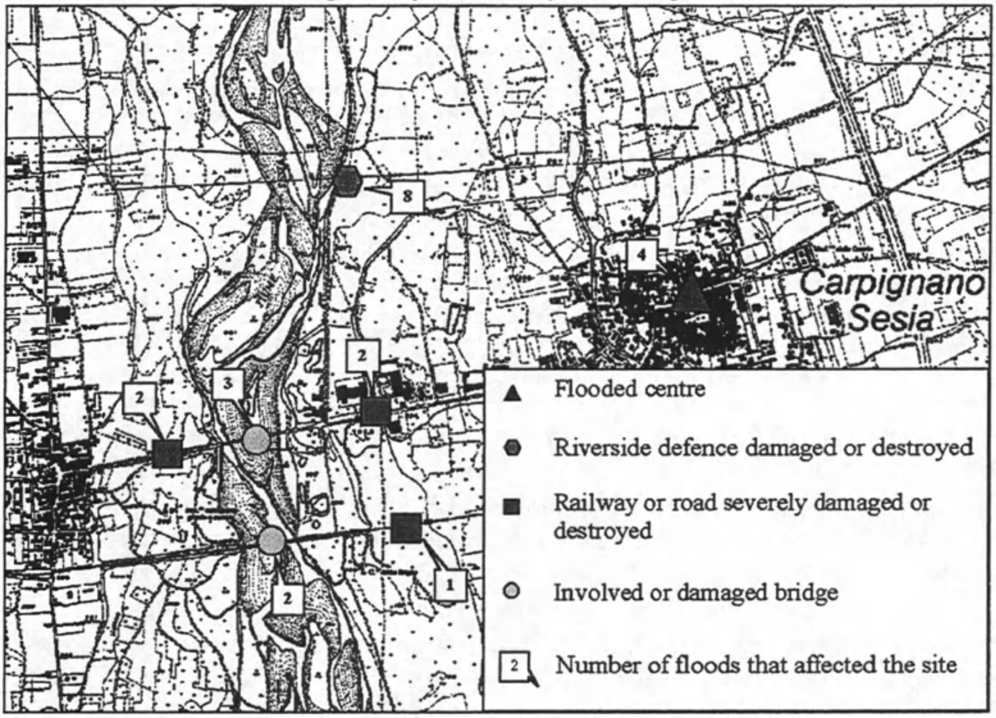
By comparing tables 2 and 3, it is possible to state that the flood of November 1968 was characterised by a return time well above 20 years, with the exception of the mountain reach. The flood measured in Borgosesia, even though not high, resulted in a considerable hydrometric level (6.8 m in Borgosesia, at the Aranco bridge, as compared with the stage of 5.05 m recorded in 1993). On that occasion, the Sessera stream, which flows into the Sesia downstream to the gauging station of Borgosesia, poured a big volume of water.

On the contrary, floods of August 1934 and September 1948 were characterised by a return time of more than 20 years in the upper part of the basin. The flood of September 1993 had a return time of some 20 years.

The consequences of historic floods were reconstructed by means of the analysis of aerial photos showing the most important inundations (1954, 1968, 1977, 1993) (Ramasco M., Giampani C., 1997). Remote sensing analysis led to identify the inundated areas and the flood effects (damages to roads and bridges, bank erosions, bank overflowing, and levee breaches). In particular, the analysis of the flood of 1968 stressed the influence of abandoned morphology on the pattern of downflows; on that occasion, the energy of the river stream in the overbank areas was higher along the abandoned fluvial beds. Thus, floods can have serious effects even in areas located very far from the active riverbed; such areas are sometimes developed with houses, rads and other facilities.

Areal data are matched with accurate informations retrieved from the geological database (the so called Geological Information System of Regione Piemonte) in form of cards. Information contained in the data base was completed with data found in the State Archives, municipal archives. In case of lack of official information, interviews to residents and technical staffs became the source of details. In order to derive both a spatial and a temporal representation of occurred damages, the data above described were put down on the Regional Technical Map subdivided into categories (Fig. 3) at the scale of 1:10000.

Fig. 3 - Synthetic map of damage



4.2 Geomorphological analysis

From Borgosesia to Romagnano, in the mountain part of the catchment, the Sesia river flows in a fairly narrow plain between valleys whose extension is limited by the side slopes of mountains which produces two narrow reaches at Borgosesia and Romagnano. Along the bottom of the valleys and in the plain, the river, which is characterized by a typically meandering pattern, flows between a series of nested alluvial terraces. In these areas there are the most important residential areas, as well as industrial and agricultural activities. In this reach of the river, the only defence works are those set up to protect the riverbanks.

South of Romagnano, on the right bank, a characteristic morphological element is visible: this includes a long continuous terrace, ranging between 4 and 7 m in height on the alluvial plain, that is interrupted at the South of Greggio. On the left bank, morphology is less evident, and terraces feature discontinuous escarpments with a height of about 1 m and surfaces characterized by ancient fluvial morphologies. These characteristics are visible up to Vercelli.

In the plain, downstream to Romagnano, defence works are represented by a system of almost continuous embankments on both riversides and other protection works positioned in the most critical points (Ramasco M., Giampani C., 1997).

The analysis of the trend in stream bed evolution allows the geomorphologists to transfer the historic information and analysis of past flood to the current situation of the river.

By comparing the pattern of the Sesia River in 1882 with those of 1994 it is possible to see that there has been a general reduction of its section in this last century. In particular, the studies carried out on modifications of the active bed of Sesia from 1954 to 1994 emphasized a general trend of the bed to narrow, due to erosive processes that could negatively affect stability of works in the bed (Ramasco M., Giampani C., 1997).

In order to define planimetric and altimetric variations of Sesia with more accuracy, in the context of this work, cross sections of the bed measured in different years were compared with correspondent hydrometric levels for reference floods. Available sections are those surveyed by the Magistrato per il Po (The River Po agency in charge of river works) in 1971 in the reach from Romagnano to the Turin-Milan motorway (11), and in 1992 from Romagnano to the Cervo stream (59). Furthermore, in order to understand the evolutive trend of the bed after 1992, six sections were surveyed in 1997.

Comparison between cross-sections in the reach from Romagnano to the Turin-Milan motorway emphasized a general increase of the bed conveyance because of the removal of large amounts of alluvium from 1971 to 1992.

This tendency is confirmed by comparison of hydrometric levels for reference floods. With reference to the 20 years recurrence discharge, the water surface elevation in the 1992 cross sections is 0.5 - 1 m lower than in the 1971 cross sections. (a significant example is shown in Fig. 4). These levels were calculated by means of the hydraulic model that compute the flood routing in the framework of the warning system (monodimensional approach).

In the same reach, comparison between cross sections of 1992 and 1997 shows an opposite trend, with deposition of material in the bed (Fig. 5).

Fig. 4 - Sections of comparison 1971-1992 of the Sesia river upstream to the Turin-Milan motorway and hydrometric levels for a flood with a return time of 20 years

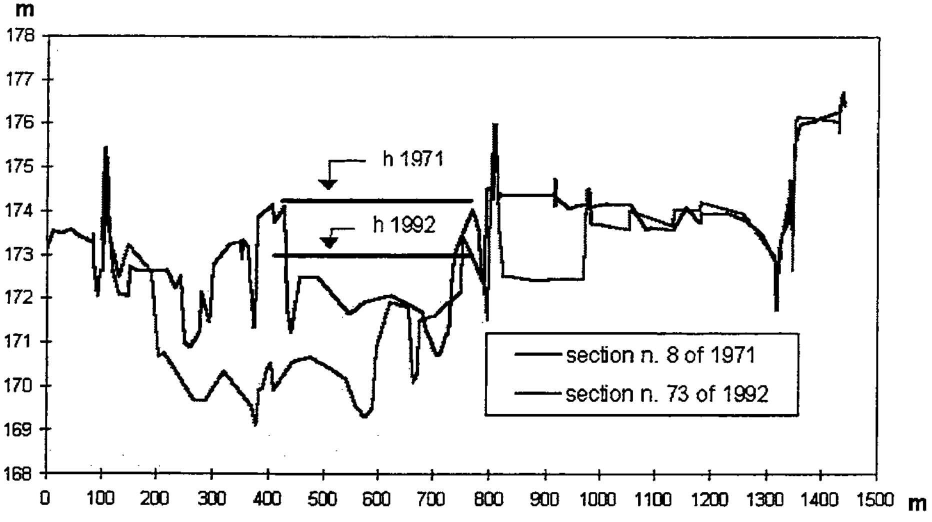
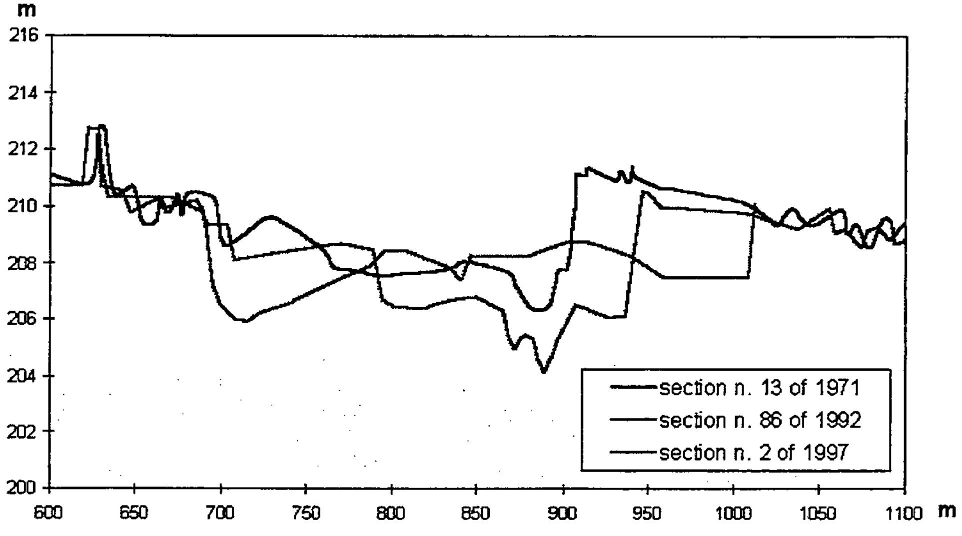


Fig. 5 - Sections of comparison 1971-1992-1997 of the Sesia river upstream to Carpignano



From Borgosesia to Romagnano and from the Turin-Milan motorway to the Cervo stream, it was not possible to make any considerations due to the lack of sections for comparison.

From 1971 to 1992, in the reaches examined, a general trend to the increase of conveyance of the river was observed, while current signs seem to indicate an opposite trend after 1992. Therefore, it can be assumed that should an event like that of 1968 occur again, the flooding could affect the same areas causing even higher damage, also considering that anthropic occupation has been increasing in the last few years.

4.3 Risk of inundation

In the framework of the afore mentioned flood forecasting system, forecast alluvial events are subdivided into two classes of danger. The first class, which refers to a flood with a return time up to 20 years, is associated with a "warning code 2; the second, which refers to floods with higher return time, has a "warning code 3".

Risk evaluation is carried out referring to these two levels of danger, in order to be able to associate flood forecasting with the relative risk class.

First of all, areas subject to risk of inundation with warning code 2 and 3 were circumscribed. Then urbanized areas and hydraulic as well as road facilities were defined and subdivided ac-cording to typology: civil settlements, industrial settlements, infrastructures and roads.

Bridges and vulnerable hydraulic works (banks prone to erosion, levees exposed to breaching, overflowing points) were defined according to the two levels of danger. Roads that hinder downflow of flood and intakes of derivation canals for which letting of uncontrolled flows could lead to the risk of inundation of villages located downstream were also identified.

All this information is represented on a map on a 1:10,000 scale (Fig. 6) that also includes explanatory tables (Fig. 7).

Fig. 6 - Map of inundation risk

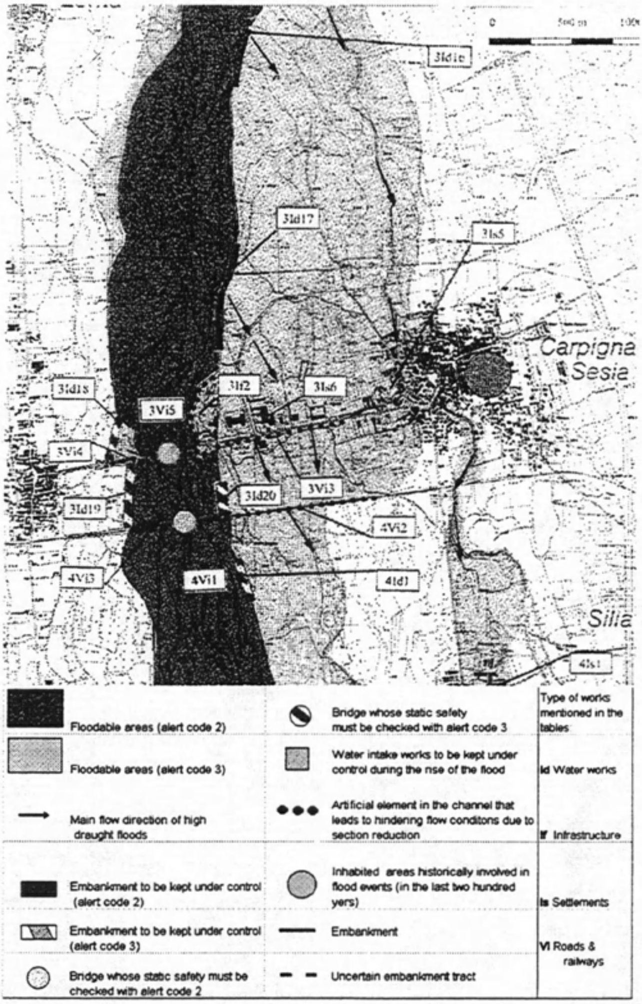


Fig. 7 - Table of scenarios associated with the map of risk

WORK							SCENARIO	
BRANCH	IDENTIFICATION INDEX	COMMUNE	PLACE	RIVERSIDE	TYPE	WORK DESCRIPTION	ALERT CODE	DESCRIPTION
3	Is5	Carpignano	inhabited area	left	settlements	civil	3	high water level due to overflow in Cavo Busca
3	Vi3	Carpignano	Provincial Route Ghislarengo-Carpignano	left	roads & railways	road bed	3	erosion corresponding to canal subways. These works hinder flood flow.
4	Vi2	Carpignano	Biella-Novara railway	left	roads & railways	ballast	3	possible erosions. The ballast hinders flood flow
3	Id17	Carpignano/ Ghislarengo	upstream industrial area	left	water works	embankment	2	embankment erosion
3	Id17	Carpignano/ Ghislarengo	upstream industrial area	left	water works	embankment	3	breach
3	Is6	Carpignano/ Ghislarengo	industrial area between Sesia River and Sant'Agata	left	settlements	industrial	3	high water level
3	If2	Ghislarengo	quarry	left	infrastructures	quarry	2	the quarry hinders flood flow
3	If2	Ghislarengo	quarry	left	infrastructures	quarry	3	flood
3	Vi3	Ghislarengo	Provincial Route Ghislarengo-Carpignano	left	roads & railways	road bed	3	erosion corresponding to canal subways. These works hinder flood flow.
3	Vi4	Ghislarengo	Provincial Route Ghislarengo-Carpignano	left	roads & railways	road bed	3	road bed erosion. The road bed hinders flood flow
3	Vi5	Ghislarengo	Provincial Route Ghislarengo-Carpignano		roads & railways	road bridge	2	lacking of an adequate free board/ bridge piers erosion
3	Vi5	Ghislarengo	Provincial Route Ghislarengo-Carpignano		roads & railways	road bridge	3	overflow
3	Id18	Ghislarengo	upstream road bridge	right	water works	embankment	3	overflow
3	Id19	Ghislarengo	between road and railway bridges	left	water works	embankment	3	breach
3	Id20	Ghislarengo	between road and railway bridges	right	water works	embankment	3	breach
3	Vi1	Ghislarengo	Biella-Novara railway		roads & railways	railway bridge	2	erosions localized on foundation works
3	Vi1	Ghislarengo	Biella-Novara railway		roads & railways	railway bridge	3	lacking of an adequate free board
3	Vi3	Ghislarengo	Biella-Novara railway	left	roads & railways	ballast	2	possible erosions. The ballast hinders flood flow
3	Vi3	Ghislarengo	Biella-Novara railway	right	roads & railways	ballast	2	possible erosions. The ballast hinders flood flow
3	Id1	Ghislarengo	downstream	left	water works	embankment	3	breach
3	Is1	Sillavengo	Cne. Gianotti	left	settlements	civil	3	flooding by overflow of roggia Falsina

Flood prone are as were delimited on the basis of inundation fields of historic floods integrated with accurate information on damage and morphological considerations.

The area prone to risk of inundations with warning code 2 was made to correspond to the zone hit by the flood of 1993, being extended up to the banks where these are not interrupted; downflow of flood mainly occurs inside the carved bed with possibility of reactivation of secondary channels that are nearer to the river and inundation of the lowest neighbouring areas. Some effects on structures and infrastructures facing the bed are forecast only at local level.

The area prone to inundations with warning code 3 originates from the integration of the area flooded during the inundation of 1968 and the bed of 1882; limits were further extended in those cases where the "map of damage" contains signs of frequent damage. The area prone to inundations with warning code 3 is, in some tracts, very wide, since it also includes reactivation of abandoned morphologies or uncontrolled propagation of flows through artificial intake canals.

Location of tracts of bank that are more prone to breaching was carried out based on historic information on breaching of banks (information concerning damage or aerial photos documenting effects) and on current state of maintenance of banks. The same criteria were applied in order to locate defence works that are more exposed to erosion.

Reaches of bank prone to the risk of overtopping were located by means of hydraulic analysis: comparison between the hiìghest elevation of the bank and the hydraulic profiles of two floods taken as a reference point. Floods with a return time of 20 years were related to the event with the lowest level of danger, floods with a return time of 200 years with the most dangerous event.

Hydraulic profiles were calculated by means of a flood routing models in the context of the forecasting system (monodimensional approach with bed geometry derived from sections surveyed in 1992 integrated with cross sections at bridge locations).

The degree of static safety of bridges, referred to the scouring of foundations, was evaluated in dependence of the efficiency of river works and the extent of erosion phenomena. The general bed degradation, previously described, is particularly evident near bridges; foundation plinths often show excavation effects that, in case of floods, could negatively affect static safety of the bridge itself.

The degree of safety of bridges, referred to the dynamic effect of the stream on the structure, was evaluated by comparing flood profiles with the bridge lower cord.

5. The alert management

Experimentation of the warning system is carried out by Regione Piemonte, through the SSRN, and by Risorse Idriche. Flood warning related to the pilot basin is derived from the meteorological warning, extended to Piemonte (Fig. 8).

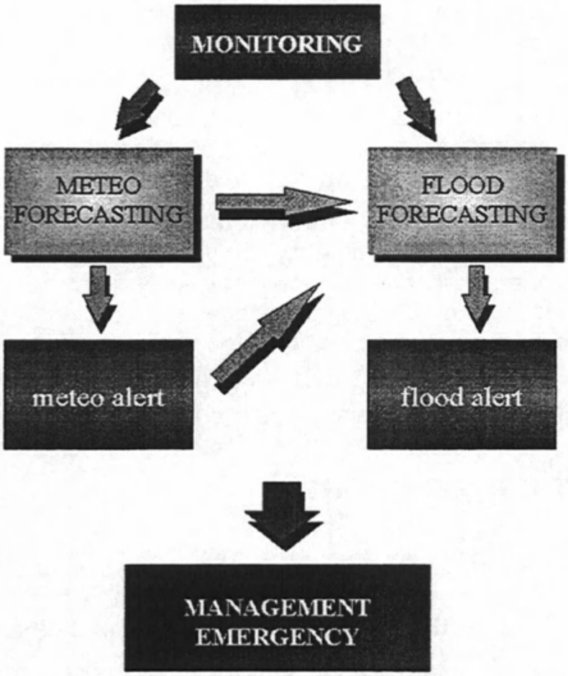
In normal conditions, usual activities include daily analysis of meteorological forecasts and hydrologic monitoring on the network via telemetry. Every day, a meteorological warning bulletin is issued that indicates the degree of danger of rainfalls forecast for the subsequent 48 hours on Piemonte.

The flood monitoring system on the Sesia River is activated when heavy rainfalls are forecast on this basin, or when pluviometric and hydrometric monitoring values ex-ceed the pre-established thresholds. This activity includes the preparation of the flood warning bulletin and periodic updating of data until the end of the warning phase.

This procedure was tested in real time on 5-6 November 1997 following meteorological forecasts of heavy rainfalls. Despite the fact that pre-processing of input data is not fully automatic, the whole procedure (data entry, forecast entry, simulation, bulletin issue) was carried out in a relatively short time.

On that occasion, downflows were moderate because precipitations mainly included snowfalls. The model overestimated flows, since the NAM module had considered excessive rainfalls. In these basins snow is a fundamental parameter of flood generation. In order to overcom the lack of accuracy, a new version of NAM was adopted in the successive analysis with satisfactory results. This module, named "rainfall-runoff module" with extended snow module (NAM-SNOW), determines the aggregation of precipitation (snow-rain) in every sub-basin on the basis of the air temperature measured by monitoring stations corrected according to the elevationin each sub-basin.

Fig. 8 - Scheme of warning activities



6. Conclusions

Forecast of river floods that drain fairly large catchments (a few thousand sq-km) can be carried out using only actions and procedures derived from the monitoring network. Short-term rainfall forecasts (less than 24 hours) are required for smaller streams, including a reach of the Sesia. Due to the high unreliability of joining hydrologic and meteorological models, the problem was approache integrating flood forecasting with the meteorological warning service. Results enable technicians to determine critical rainfall situations with 24-48 hours of advance and to alert authori-ties responsible for emergency services. In this way, operating times are con-siderably reduced and flood forecasting can even be issued 6-8 hours in advance. Testing of the system gave results that encourage its implementation in average size basins. However, the system will reach full efficiency only when rainfall forecasting will be provided in detail, at the scale of hydrologic events.

Study of extreme rainfalls

Étude des pluies extrêmes

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Abstract

The rainfall and hydrometeorological analysis project has been mainly devoted to three topics: "Regionalization of extreme rainfall events in the Mediterranean Area", "Classification of rainfall events to use it in hydrology" and "Analysis of spatial and temporal rainfall distribution in complex terrain". According with the first topic, the creation of a database referred to the monthly and highest rainfalls at different Mediterranean countries has been made and analysed. Along the second topic a system of rainfall events classification in basis to their hydrometeorological characteristics has been proposed. Recourse was had for this purpose to definition of two parameters, β and β^*, and their distribution throughout the rainfall rate series of Barcelona, Spain, (1927-1981). This classification allows improving the IdF curves and design hyetograms (although these results are not showed here) and it has revealed as a useful tool to characterise the extreme rainfall events. The third part has been the application of this classification to the rainfall recorded during the period 1997-1998 in Catalonia, using the 5.min rainfall rate recorded in 125 pluviographs. Related with the "forecasting" part of the project, the use of the thermodynamic analysis as a tool of prediction of extreme rainfall events, has been considered. Simultaneously, a regional floods case study using objective synoptic analysis and Meteosat images, has been done.

Résumé

Le projet d'étude pluviométrique et hydrométéorologique a été principalement dédié à trois sujets: "régionalisation des événements de pluies extrêmes en zone méditerranéenne", "classification des événements de pluie pour une utilisation hydrologique", et "analyse de la distribution spatiale et temporelle des pluies sur un terrain accidenté". Pour le premier sujet, une base de données rattachée aux pluies mensuelles les plus fortes dans différents pays méditerranéens, a été créée et analysée. Dans le cadre du second sujet, un système de classification des événements de pluie en fonction de leurs caractéristiques hydrométéorologiques a été proposée. Pour cela, on a eu recours à deux paramètres, β et β^*, et à leur distribution à travers des séries de données de pluies à Barcelone (Espagne, 1927-1981). Cette classification permet d'améliorer les courbes IdF et de concevoir des hyétogrammes (bien que ces résultats ne soient pas montrés ici), et elle s'est révélée un outil utile pour caractériser les événements de pluies extrêmes. La troisième partie du travail a consisté à appliquer cette classification aux pluies enregistrées en Catalogne durant la période 1997-1998, en utilisant des données de pluies de 5 mn *enregistrées sur 125 pluviographes. En lien avec la partie "prévision" du projet, l'utilisation des analyses de thermodynamique comme outil de prévision des événements de pluies extrêmes a été étudiée. En même temps, une étude de cas d'inondation régionale, utilisant des analyses synoptiques objectives et des images Meteosat, a été réalisée.*

1 Introduction

Floods have achieved the distinction in some countries of being the natural hazard that year in year out produces the most casualties. On the 7th of August of 1996, a flash flood which affected a camping placed in the Spanish Pyrenees produced 85 casualties, although the most catastrophic one recorded in that country was the flash flood produced in September 1962 in Catalonia with more than 815 casualties in less than 3 hours. In the South of France, the floods recorded on September, 22, 1992, produced 41 casualties on the Ouveze basin. The same event produced catastrophic floods on the NW of Italy and this region was affected too on September 1993 and November 1994 by extraordinary floods. This kind of extreme event has shown that flood management is a necessity and a priority to mitigate/avoid serious damages in social and economic terms.

There scarcely exists in the world a study of the climatology of floods, and still less of flash floods, and, when there is any such study of climatology, it usually relates to a very specific areas. The knowledge climatology of heavy precipitation events is more widespread and there are therefore more situations, which can be analysed, classified and used to draw conclusions. In view of the fact that one necessary though insufficient factor for the occurrence of a flash flood is the existence of heavy rainfall, the study of floods inevitably involves gaining knowledge of the processes which cause this to occur. Usually, heavy rains are identified with rains of high intensity, which are also persistent. This implies that the flow of water vapour drawn by convection is considerable and that precipitation efficiency is high. Although the concept of high rainfall rate can vary with the climatic characteristics of the rain for each location, the literature considers a high intensity to be that which exceeds 0.8 mm/min. Although not all precipitation of that intensity is convective, nor does all convective rain attain such an intensity it is usual to identify high rainfall with convective rainfall (see Llasat, 1997). This criterium has been used in this paper after a brief discussion.

This paper shows the results obtained by the Meteorological Hazards Analysis Team, (GAMA group, Mediterranean Hydrology Network) of the University of Barcelona, into the Floodaware project. Having in mind that it would be not possible to show all the results, the paper has been centred in the results obtained for Catalonia (Spain). On the other hand, calls to different papers written into the Project has been made in order to clarify or to provide more information about some topics.

2 Classification of rainfall events to use it in hydrometeorology

The objective of this part lies precisely in an attempt to find an objective method of rainfall events classification, which at the same time has a plausible physical interpretation and hydrological application. To this end recourse was had to the 1927-1981 series of 1-min rainfall intensities provided by the Jardí pluviograph which is situated in the Fabra observatory (Barcelona, Spain), on the slopes of Tibidabo mountain, at an altitude of 414 m a.s.l. and at a distance of 7.5 km from the sea (for more information see, Llasat and Puigcerver, 1997).

The first study carried out on the basis of individual analysis of each precipitation episode recorded on the Jardí pluviograph between 1960 and 1979 showed that more than 55% of the annual precipitation was of convective character, while 46% of it was convective and at some stage exceeded an intensity of 0.8 mm/min (Llasat and Puigcerver, 1997). For the same period it was found that the rain from episodes of non-convective character in which the intensity at some point exceeded that threshold accounted for less than 0.001% of total annual rainfall time, and in no case exceeded an intensity of 3 mm/min (Llasat, 1997). Consequently, the error involved in supposing that all those episodes in which the threshold of 0.8 mm/min was at some point exceeded are convective is, in general, negligible. Furthermore, rain from convective episodes beneath said threshold only accounted for 18% of total annual rainfall. Thus, the hypothesis of taking an episode to be convective when a threshold of 0.8 mm/min is exceeded at some point is not unreasonable, all the more so if it is born in mind that the problems (hydrological, radio links, rescue services, etc.) are not usually caused by low intensities. Finally, meteorologically speaking, convective systems of a certain size (from unicellular storms to mesoscale convective storms) usually give intensities exceeding that threshold, that is, exceeding 0.8 mm/min or 50 mm/h.
The discussion of the previous paragraph could be based on terms of a β parameter which related convective rain with total rainfall:

$$\beta = \text{monthly (yearly) precipitation exceeding a one-minute intensity of 50 mm/h / total monthly (yearly) precipitation}$$

Having in mind that the new measuring networks usually record the rain at intervals of 5 minutes or more, the threshold intensity can not longer be 50 mm/h, but must after the increase of time interval be reduced as a result due to the consequences of the attenuation provoked in the high-intensity peaks. It is possible to demonstrate (Montes, 1997) that a value of 35 mm/h will be taken as the 5-minute mean intensity threshold. From analysis of the 5-minute series it can be deduced that for 1.454% of the mean annual time for which it rains, the precipitation presents a mean 5-minute intensity exceeding 35 mm/h, responsible for 18.2% of the total annual precipitation.

The foregoing values relate to the monthly and annual distribution of convective precipitation. In order to model episodes, however, it would be useful to have a parameter for each one of them. The methodology proposed herein for resolving that objective is the introduction of a parameter designated as $\beta^*_{L,\Delta T}$ which, unlike the previous one, is of meteorological rather than climatic character. To calculate it, it suffices to use the expression

$$\beta^*_{L,\Delta T} = \frac{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)\theta(I - L)}{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)}$$

in which

- ΔT is the time-interval of accumulation of the precipitation, expressed in minutes
- N is the total number of ΔT integration steps into which the episode is subdivided
- $I_L(t_i, t_i+\Delta\tau)$ is the precipitation measured between t_i and $t_i+\Delta\tau$ divided by Δt, that is, the mean intensity in the said interval expressed in mm/min or mm/h
- $\theta(I-L)$ is the Heaviside function defined as:
  $\theta(I-L) = 1$ if $I>L$ $\qquad$ $\theta(I-L) = 0$ if $I<L$ $\qquad$ $\theta(I-L) = 1$ if $I=L$

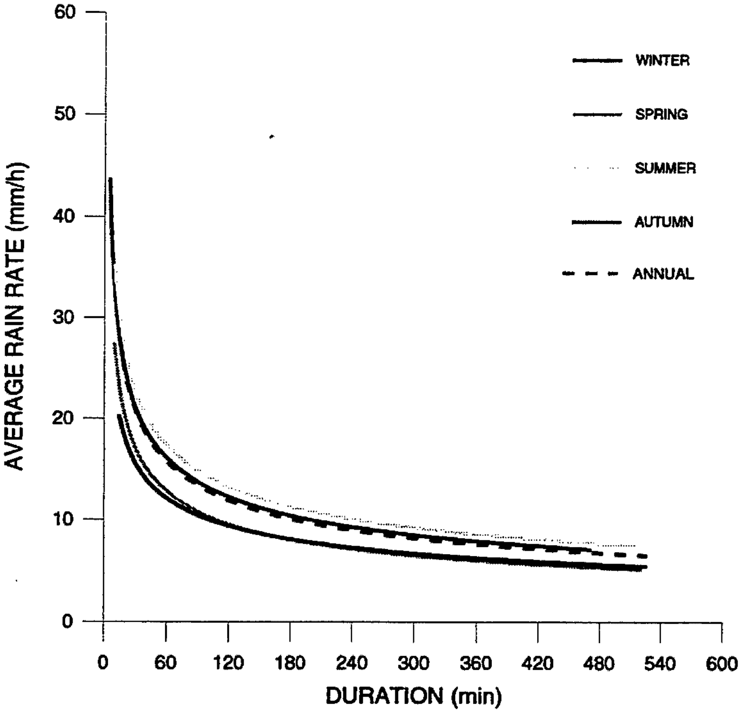
It is felt that it is possible to distinguish between two different episodes when the time which elapses between them without rainfall exceeds 1 hour, which permits an assurance that the two episodes come from different "clouds". Based on previous comments, we will hereinafter take ΔT=5 min and L=35 mm/h, simplifying the notation of $\beta^*_{35,5}$ which will be represented as β^*.

The monthly distribution of the percentage of rainfall events with β^* other than zero shows that the maximum pertains to the month of August, with 18.3%, followed by September with 15%. On the contrary, in February and March the percentage falls to 1.9% and 1.8%, respectively. Figures change considerably when percentages are refereed to quantity of precipitation: in August more than 60% of precipitation is provided by events with β^* other than zero, while in March only the 13.3% of the cumulated precipitation has this origin.

In order to obtain fuller information, the mean intensity of each episode has been represented in function of its duration for those cases in which $\beta^*>0$. With the exception of autumn, the durations are in general less than 240 minutes and that, where this value is exceeded, the mean intensities are lower than 10 mm/h. Stated another way, those episodes in which at a given moment the 5-minute intensity of 35 mm/h is exceeded, are of a duration generally less than 4 hours. In the case of autumn, this generalisation loses a certain amount of validity as a result of the by no means negligible number of episodes with $\beta^*>0$ and durations ranging between 4 and 8 hours. It should also be noted that neither in winter nor in spring is the mean intensity of 40 mm/h exceeded. Figure 1 shows the adjustment curves of the average intensity (mm/h) of the rainfall events with β^* other than zero in function of their duration.

Analysis of the maximum 5-min intensities achieved in those events with β* other than zero shows that, except for one case, in winter 75 mm/h has never been exceeded, which threshold in spring rises to 100 mm/h, in summer to 200 mm/h and in autumn to 225 mm/h. Similarly, all these extreme intensities are recorded in episodes with a duration of less than 1 hour (in autumn there is the occasional case which lasts two hours) and with values of β* close to one unit.

Fig. 1 - Distribution of the average intensity (mm/h) of the rainfall events with β other than zero in function of their duration*



It is thus possible to draw up a classification of the above episodes in the light of their greater or lesser convective character, according to:

- β* = 0 non-convective
- 0 < β* <= 0.3 slightly convective
- 0.3 < β* <= 0.8 moderately convective
- 0.8< β* <= 1.0 very convective

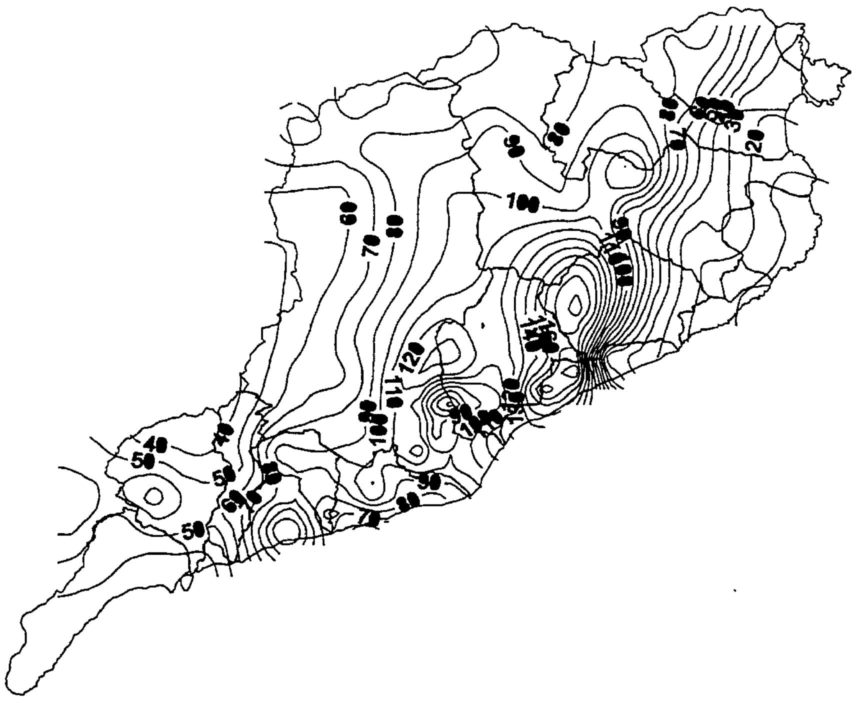
We can conclude this part saying that 8% of the rainfall events produced in Barcelona are convective and responsible of 36.5% of the total precipitation. 3.8% of the total rainfall events are slightly convective, 2.9% are moderately convective and 1.3% are very convective. It would be possible to show that the first class events last usually between 2 h and 8 h, 59% of them have maximum intensity inferior to 75 mm/h, and in some cases they can be related with floods produced after a long time period of low/moderate rainfalls. The second class events last usually between 1 h and 3 h, 63% of them have maximum intensity between 75mm/h and 125 mm/h, and occasionally can be related with catastrophic flash floods (Llasat and Puigcerver, 1994). Finally, the third class events last usually minus than 2 h, 55% of them have maximum intensity above 125 mm/h, and sometimes can be related with local flash floods. For more information about this topic, see Llasat, 1998.

3 Analysis of the orographycal influence in basis to the SAIH network

The SAIH (Sistema Automático de Información Hidrológica) of the Internal Basins of Catalonia (Spain) of Junta d'Aigües of the Generalitat de Catalunya is an automatic system composed by an automatic raingauges and gaugings network, which covers an area of 16000 km^2. This rainfall network is composed by 125 tipping-bucket automatic raingauges with a rainfall overttuning of 1.0 mm. The precipitation is accumulated and recorded every 5 minutes. The study developed in this part is based in the data obtained from the first day in which the network started to be operative (December, 1995) until December 1997. Before to start the hydrometeorological analysis, the raingauges calibration has been made in collaboration with Junta d'Aigües. On the other hand, all original data has been submitted to a quality control filter.

The hydrometeorological analysis has consisted in two parts. The first part has been devoted to some moderate-high rainfall cases study (days 7-11 and 15-16, December 1995; 9-10, 22-24 and 28-30 January 1996 and 1-2 February 1996). Three more cases (8^{th} August 1996; 14^{th} October 1996; 1^{st} June 1997) have been analysed using, besides the SAIH data, the rainfall EPA data that allows to analyses the altitude gradient. The EPA network is constituted by 9 tipping-bucket automatic raingauges (rainfall overtturning, 0.2 mm), some of them connected by phone, which cover an area less than 500 km^2. It is distributed along an axis that starts in the river Llobregat mouth and finish in the Sant Llorenç de Munt summit (1105 m a.s.l), on the Southwest of Barcelona city. In this way, this axis passes through the Litoral mountain range ending in the Prelitoral mountain range. In consequence is an area with a strongly mountainous orography with some slopes near 25%. For more information about the installation and general features, see Llasat *et al.*, 1997.

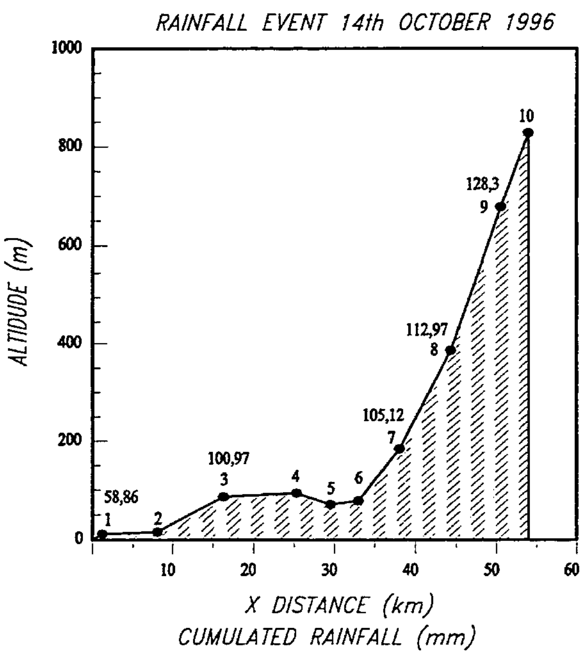
Fig. 2(a) - Rainfall distribution between 13th October and 16th October 1997



The Figures 2 (a), 2(b) and 2 (c) show the rainfall event recorded over Catalonia between 13th October and 16th October 1997. Figure 2 (b) shows the β* parameter distribution. Having in mind the previous classification, this event can be identifying as "moderately convective event". Finally, Figure 2 (c) shows the altitude gradient of the cumulated rainfall recorded in each raingauge of the EPA transect, during this event. The fact of the first precipitation was recorded in raingauge 3, placed towards the north of the Llobregat axis, shows a possible movement from NE to SW, corroborated by the rainfall distribution time evolution analysed using the SAIH data. The maximum rainfall was cumulated near the mountain summit (this feature is corroborated in the other cases analysis), with 128.3 mm, meanwhile the maximum intensity was recorded in points of medium altitude, with a maximum instantaneous value of 158.4 mm/h. The synoptic situation was characterised by the pass of a frontal wave related with a depression placed to the NE of the British Islands. A secondary low was developed over the Balearic Islands.

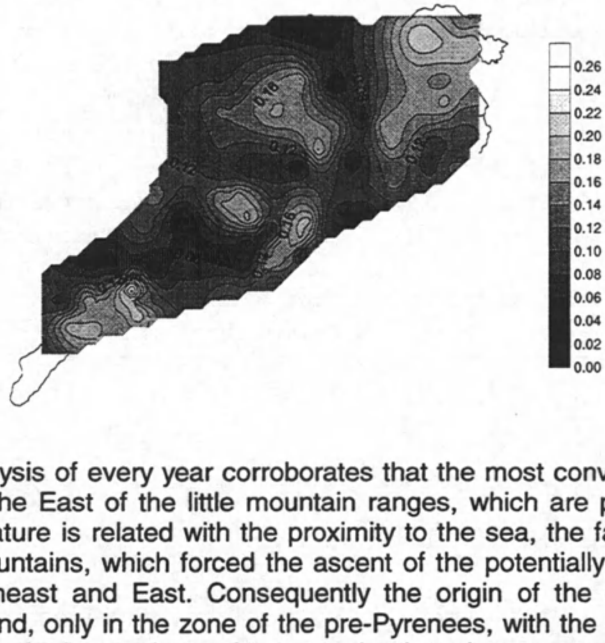
Fig. 2(b) - β distribution between 13th October and 16th October 1997*

Fig. 2(c) - Cumulated rainfall distribution over the EPA axe, between 13th October and 16th October 1997



The second part has been devoted to the "climatic" analysis. With this object monthly and yearly charts of β distribution has been done in order to identify the most favourable areas for developing convection and compare them with other regional analysis made previously for extreme rainfalls of convective precipitation. First of all, the wrong data have been eliminated: 3 of the 125 raingauges have been considered out of order. For the remaining 122 raingauges the β parameter has been calculated for every month, season, and year, and the result has been plotted and analysed using the Kriging method. Figure 3 shows the β distribution for the period 1996-1997. It is possible to see that the β values are comprised between 0.02 (a 2% of the total precipitation was convective) and 0.26 (a 26% of the total precipitation were convective). The maximum values correspond to the coastal zones, mainly at the north and south of the selected region., while a secondary maximum is found in the Pre-pyrenean area. On the contrary, absolute minima are placed over the Pyrenees and the SW region

Fig. 3 - Space distribution of β parameter for the period 1996-1997



The individual analysis of every year corroborates that the most convective rainfall is produced over the East of the little mountain ranges, which are parallel to the coast line. This feature is related with the proximity to the sea, the favourable orientation of the mountains, which forced the ascent of the potentially unstable wet air from the Southeast and East. Consequently the origin of the convection is mainly mechanic and, only in the zone of the pre-Pyrenees, with the main convection recorded during the late spring and autumn, the thermic component dominates.

The comparison of these results with the space distribution of the return periods (Gibergans, 1994) shows a good relationship between the zones with the maximum values of β and those zones with the minimum return periods for extreme rainfall events (100 mm/24 h, 150 mm/24 h and 200 mm/24h).

A second analysis has been made using the β* parameter in order to classify each rainfall event. In this part all the events with cumulated rainfall above 50 mm/day (from 0000 UTC until 2400 UTC) in one or more raingauges, have been selected.

Once the selection has been made the cumulated rainfall and the β^* parameter has been plotted and analysed using the kriging method. Simultaneously the meteorological maps (surface and 500 hPa at 1200 UTC) corresponding to each event, have been analysed. The classification has been made taking into account the localisation of β^* and R (rainfall) maximum values, the orographic distribution of β^* and R, and the main meteorological features.

Figure 4 shows the events selected and classified. Type A is called "Very Convective" because the maximum values of β^* are near of 1 and is placed in the rainfall structure centre (the isothets have a circular or an elliptic saphe). The zones with β^* maximum values coincides with those zones with the high values of cumulated rainfall, and, usually, with moderate altitudes. These kinds of events are produced during the warm season and have a local character. The meteorological situation in surface is not well defined and a talweg or low is located in the medium troposphere over the Iberian Peninsula.

Type B is called "Little Convective" because the maximum values of β^* are less than 0.3. In this case the nucleus are not well defined and the isolines of β^* are irregular. Rainfall usually affects all the region and there is not a coincidence between the zones with the maximum β^* values and the maximum cumulated rainfall. This kind of event is produced usually during the winter and is related with strong Atlantic lows.

Type C is called "Moderate convective" because β^* usually shows values comprised between 0.3 and 0.75. The zones with maximum values are not well defined and it is not possible to identify circular or elliptic structures in the β^* chart. Rainfall affects at the major part of the region and it is possible to distinguish between those events in which the maximum β^* values coincides with the maximum cumulated rainfall (Type Ca) and those others in which this coincidence is not founded. This kind of event is mainly produced during the warm season.
For more information about this topic see Montes, 1997 and Llasat and Montes, 1998.

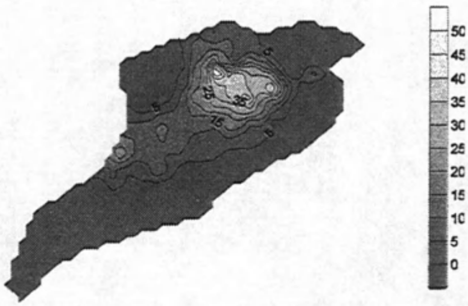
4 Regionalization of extreme rainfall events in the Mediterranean Area

In the previous paragraphs a classification in basis to the convective character of the precipitation has been proposed in basis to a long rainfall rate series from Barcelona (Spain). This classification has been used successfully over the 5 min-rainfall rate data obtained from 125 typing-bucket, during 1996 and 1997, and covering a region of 15000 km^2. Consequently, the next question would be related with the possible extension of the methodology and conceptual results to other regions. This possible extension would be more correct when more correlated were the rainfall of the other regions with the rainfall in the previously analyed area. However, the rainfall is a climatic variable characterised for its elevate time and space dispersion, mainly in the Mediterranean regions, where the convective component of the total precipitation is high. Consequently, bad correlations are waited and it is need to develop other tool to compare the rainfall features in the different regions. Finally, and taking into account the great seasonal variation, the use of monthly or daily data has been needed.

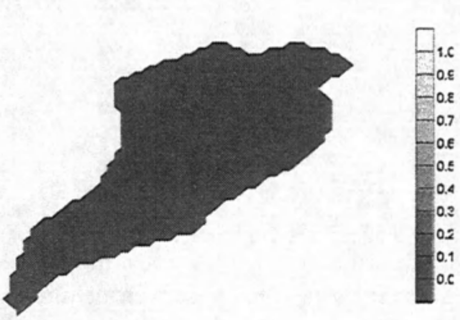
This part of the work has been made from the database developed by the AMHY/FRIEND project of UNESCO and from the data gathered by different members of that project and the FLOODAWARE project. Two kinds of data have been used. The first ones consist on daily or monthly rainfall series that is to say continuous data. The second ones refer to high rainfall events, and it is usually a discontinuous and heterogeneous information. Table 1 shows the monthly series used in the continuous data analysis. Table 2 shows the data used for the analysis of high rainfalls, together with the stations with daily rainfall of Table 1. Recently, the series of Valencia, Spain (1935-1996) and 20 stations of the Regione Piamonte, Italy (1913-1985), have been included.

4(a) - Distribution of β^* parameter for an event of type A

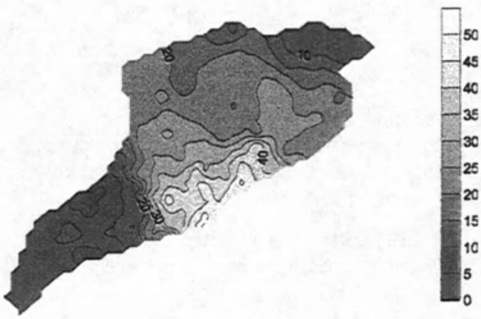
4(b) - Rainfall distribution for an event of type A



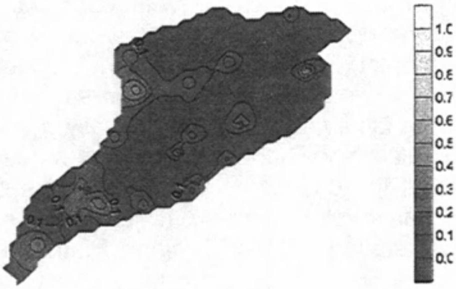
4(a) - Distribution of β^* parameter for an event of type B



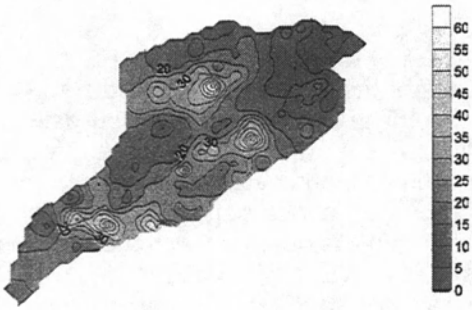
4(b) - Rainfall distribution for an event of type B



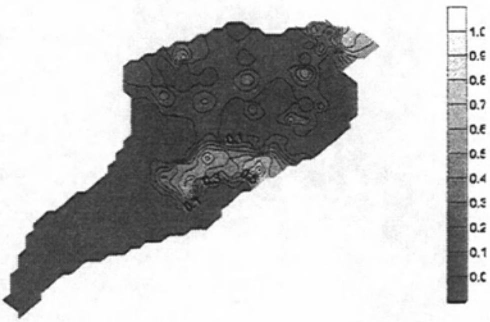
3(a) - Distribution of β^* parameter for an event of type Ca



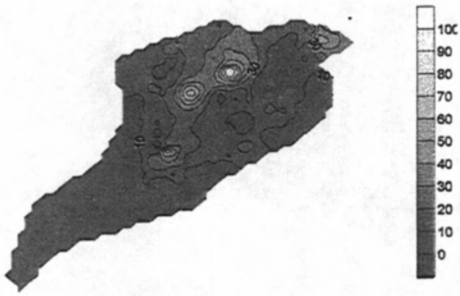
3(b) - Rainfall distribution for an event of type Ca



4(a) - Distribution of β^* parameter for an event of type Cb



4(b) - Rainfall distribution for an event of type Cb



The first part of this study has been the temporal analysis of the monthly precipitation of the stations showed in table I. The purpose here is to compare trends and anomalies of rainfall and the main precipitation features at the different stations during this lapse of time. This kind of analysis is the most useful one if we are interested in regional features, because it allows us to determine the differences and analogies in rainfall distribution from a spatial and temporal point of view.

*Table 1 - Stations with monthly rainfall series. The * does reference to those stations with daily data*

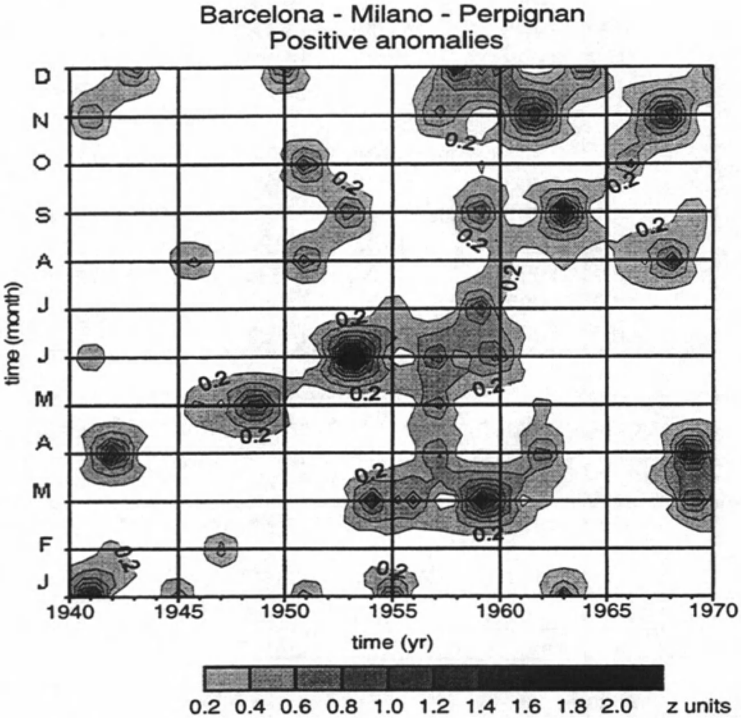
Station	Period	Latitude	Longitude	Altitude	Country
Athens Obs*.	1871-1990	37º59'N	23º44'E	107 m	Greece
Thessalonique*	1930-1990	40º38'N	22º56'E	40 m	Greece
Lugoj*	1930-1993	45º41'N	21º55'E	-	Romania
Timisoara*	1922-1993	45º45'N	21º13'E	-	Romania
Caransebes*	1921-1993	45º25'N	22º13'E	-	Romania
Barcelona*	1850-1991	41º22'N	8º00'E	10 m	Spain
Murcia	1942-1993	37º57'N	1º47'W	75 m	Spain
Sevilla	1923-1993	37º21'N	6º00'W	14 m	Spain
Ciudad Real	1866-1991	38º59'N	1º13'W	629 m	Spain
Perpignan	1850-1970	42º36'N	2º54'E	-	France
Milán	1850-1983	45º30'N	9º00'E	100 m	Italy
Roma	1782-1983	41º54'N	12º29'E	-	Italy
Belvedere Sp.*	1922-1987	39º12'N	4º26'E	330 m	Italy
S.Severina*	1922-1987	39º08'N	4º28'E	326 m	Italy
Rocca di Neto*	1922-1987	39º11'N	4º33'E	183 m	Italy
Crotone*	1922-1987	39º05'N	4º41'E	6 m	Italy
Ljubljana	1851-1994	46º04'N	14º33'E	-	Slovenia

Table 2 - Regions with data of maximum daily rainfall year by year and number of stations in every region. Number of years between 1940 and 1990 with maximum in 24 h above 200 mm and the most affected season

Country	Region/bassin	Num.	Period	N>200	Season max.
Portugal	Portugal	4	1940-1992	1	Winter
France	Herault	221	1883-1991	22	Autumn
Spain	Catalonia	66	1917-1990	28	Autumn
Italy	Calabria/Basilicata	100	1920-1987	39	Autumn
Yugoslavia	Montenegro	1	1923-1984	34	Autumn
Romania	Romania	9	1934-1980	5	Summer
Moldova's Rep.	Moldova's Rep.	5	1889-1994	0	-

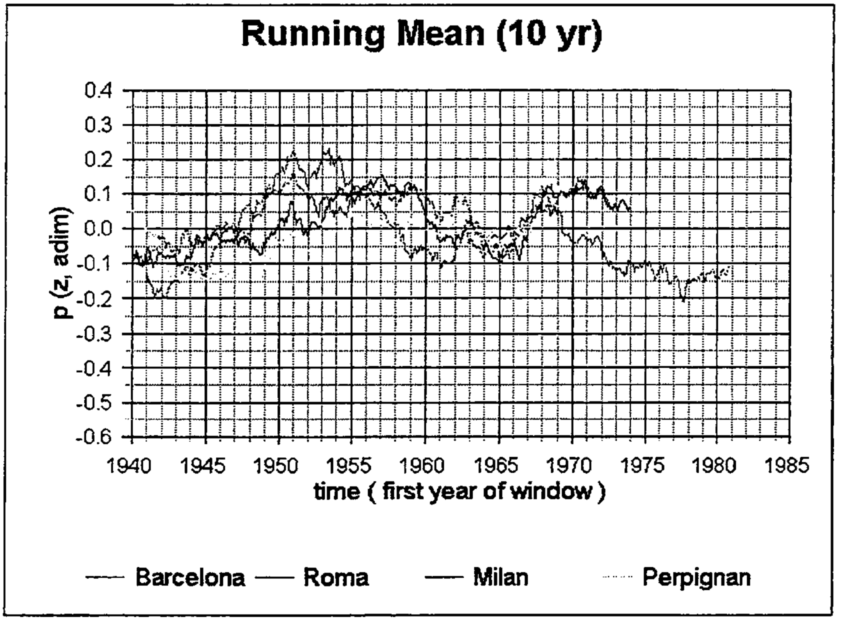
Secondly, the statistical properties of the series and their correlation have been considered. The results have showed a correlation coefficient above 0.8 between the monthly series of Calabria, and, above 0.5, in the cases of Ciudad Real/Sevilla, Lugoj/Timisoara and Barcelona/Perpignan. Although all the other coefficients of correlation are less than 0.5, Barcelona is the station the best correlated with the other stations placed in the West Mediterranean, mainly with Milan, Roma, and Perpignan. Once the correlation has been obtained, the data have been standardised month by month with respect to the monthly average at each station, in order to eliminate the specific characteristics of the annual position. The persistence of spells of precipitation which are either above or below average will be apparent in periods of positive and of negative anomalies that either extend through a period of successive months or prevail at the same season or part of a season but over a number of years. The two fields of positive and negative anomalies are analysed for each station and, afterwards, the common anomalies of all stations have been obtained. Figure 5 shows the common anomalies between Barcelona, Perpignan and Milan.

Fig. 5 - Common positive rainfall anomalies between Barcelona, Milan and Perpignan. They are plotted in standard deviations using 0.2 unit steps beginning at +0.2



Thirdly, the evolution of moving average using the technique of the mobile window of constant length L=10 years and cadence τ=1 year has been made. Such 'moving' statistics provide information on the evolution of the frequency distributions and the series tends, but, given their ability to summarise only the more 'ordered' or deterministic aspects of the distribution, they can provide little information concerning the random element. In order to solve this last question, the analysis of the entropy evolution in each station has been made. This kind of analysis shows the evolution of the non-periodic components of the signal: an increasing of extreme values implies an increasing of the entropy. The evolution of the running mean shows common dry or rainy periods for all the stations (Figure 6). It is also important to see that sometimes the rainfall recorded in stations which are far from each other shows more similar features that the one recorded in stations which are nearer to each other.

Fig. 6 - Time evolution of the running means of the Barcelona, Roma, Milan and Perpignan monthly precipitation series using monthly intervals over 10-year windows



From the analysis of the rainfall monthly distribution, the correlation, the anomaly distribution and the running means it is possible to define the following clusters:

- S.Severino, Rocca di Neto, Crotone, Spineto;
- Ciudad Real and Sevilla;
- Barcelona, Perpignan, and Milan;
- Athenes, Thessalonique;
- Lugoj, Timisoara;
- Caransebes and Murcia have a bad correlation with the other stations. However it is possible to stablish a little relationship between Caransebes/ Thessalonique and Murcia/Barcelona. Rome could be joined to the south Italian stations or the north Mediterranean clusters. It would be necessary to do a more detailed study to clarify its cluster position.

For more information about this topic, see Llasat and Rodriguez, 1997 (a), 1997 (b), Rodriguez y Llasat, 1997 and Rodriguez *et al.,* in press.

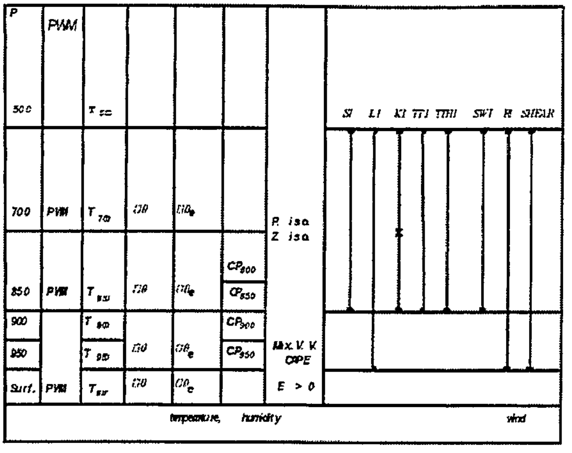
5 Diagnosis and forecasting of extreme rainfall events

In order to improve the forecasting of the extreme rainfall events, a good diagnosis of them are needed. This diagnosis has been made from two points of view. Firstly, the detailed analysis of the meteorological situation associated to the floods produced in the South of France and North of Italy between the 27^{th} and 28^{th} September 1992, has been done. The overlapping of meteorological maps and satellite images has shown that the occurrence of an Mesoscale Convective system in the western Mediterranean region could be related to the presence of the four key meteorological factors (water vapour convergence at 1000 hPa, quasi-geostrophic vertical forcing at 850 hPa, instability between 1000 and 500 hPa and CAPE values above 1800 J/kg) and to an intense flow which impinges perpendicularly to the coast and the nearby mountain regions, triggering the potential convection. Those results corroborate the conclusions obtained in previous works (Ramis *et al.,* 1994, 1995) about the zones for which there exists a potential risk of heavy rains. For more information, see Llasat, 1997, and Llasat *et al.,* in prep.

Secondly, the thermodynamic data as a tool to improving the forecasting has been analysed. Particularly the atmosphere's thermodynamic analysis makes it possible to obtain information about the possible existence of instability or about an auspicious environment for convection, the contents of water vapour as well as the possible formation and development of clouds, and the existence of wind's shear and jet streak. The thermodynamic analysis has a highly discriminating feature in those situations in which the synoptic situation does not allow to completely justify either the atmospheric phenomena or their distribution. In order to discriminate the high rainfall possibility from the other situations, it is need to work with a radiosounding data series. In this project, the initial information has been constituted by the notable levels of Palma's radiosoundings (1975-1989) and Nimes' radiosoundings (1954-1983) corresponding to 00 UTC and 12 UTC, for the period 1975-1989 , both to what temperature and humidity respects as well as wind. Those data have been submitted to a quality control, based on selecting only those radiosoundings that demonstrate the accomplishment of certain reliability features, either due to the quality of the information or quantity of it.

Once the wrong data have been eliminated, the average monthly conditions in all the tropospheric levels have been analysed. Later, the rainfall events have been classified in basis to the daily rainfall recorded in the selected areas of study. Then, the thermodynamic parameters showed in Figure 7, and their statistical distribution, have been calculated for the different samples. On the other hand, the correlation between the daily rainfall in Barcelona, and the data from the Palma radiosounding, has been calculated.

Fig. 7 - Thermodynamic parameters calculated in order to discriminate the high rainfall events



PWM : Precipitable Water Mass
T: Temperature
∂θ: Temperature potential gradient
∂θe: Temperature potential equivalent gradient
CP: Convective Available Potential Energy from different levels
P. iso : Pressure of isozero
Z.iso : Altitude of isozero
CAPE : Convective Available Potential Energy (Weisman and Klemp, 1986)
M.V.V : Maximum Vertical Velocity
E> 0 : Positive Energy or energy set free by the particle in its rising

SI: Showalther index (Showalter, 1953).
LI: Lifted index (Galway, 1956, Fujita et al, 1970).
KI: K index (George, 1960).
TTI : Total total's index (Miller, 1972).
TTH : Wet bulb potential temperature index (Pickup, 1982).
SWEAT : Severe Weather Advisory Trend (Miller et al, 1971)

RI : Bulk Richardson Number (Weisman and Klemp, 1986)
SHEAR : Vertical shear, defined as the difference between the wind averaged with the density of the 600 meters below and the wind of the 500 meters below.

Finally, artificial neural networks have been applied over the previous thermodynamic data for extreme rainfall event classification and forecasting. in Catalonia, Spain. We have tested different inputs (precipitable water mass, equivalent potential temperature, CAPE and so on) and different learning processes. The results obtained have allowed to select the most representative variables and to classify the different rainfall events in relationship with the thermodynamic variables. Although it is not possible to show here all the results it is interesting to say that the frequency of success when the neural network predicts rainfall if more than 50 mm is recorded is 96.7%. The frequency of success when the neural network predicts rainfall if more than 100 mm is recorded is 100%.

For more information about this topic, see Llasat *et al.* (b), 1997; Gibergans *et al.*, 1997, Gibergans and Llasat, 1998 and Gibergans, in prep.

6 Conclusions

Starting from a long but punctual rainfall rate series, we have showed that it is possible to draw up an objective classification of the pluviometric episodes in the light of their greater or lesser convective character, and this classification can be applied to a waste region. It would be possible to show that the physical features of those episodes which $\beta^*>0$ have a good relationship with the different kind of convective systems proposed by the literature. Besides this, it is possible to propose a possible threshold for the relationship average intensity/duration, which allows to discriminate the rainfall events with damages from the rest of the convective events:

$$I_{average} = 734.2\ D^{-0.6912} \text{ (Montes, 1997)}$$

Mapping of β^* values allows to find a good relationship between the type of event and the synoptic meteorological situation. The application of those results can improve the forecasting and management (it is not the same, for the Civil Protection, a local high convective event, that a more extensive one). On the other hand, zones with great β values coincides with the most flood prone areas. Although this result can be corroborated with more years of data, it is interesting to prevention tasks. In order to test in the future, the previous results in a more wide region, a rainfall regionalization has been made. Results have showed that the application to the Southeast of France and North of Italy would be interesting. Finally, thermodynamic and objective synoptic analysis has been made to improve the high rainfall events classification and forecasting.

This paper has showed the main results (to see all the results you can consult the different publications referenced) obtained into the Floodaware project in the field of prevention and forecast of extreme rainfalls. The objectives (Regionalization of extreme rainfall events in the Mediterranean Area; Analysis of spatial and temporal distribution in complex terrain; and Improvement of Idf and Gradex parameterization and regionalization by including meteorological analysis) have been achieved, although some of them are still open and can be object of future researches. The first topic, can be improved doing a systematic analysis of all the monthly and/or daily rainfall series (and working with more data series) from 1930 until 1990. The objective of this task would be a more detailed determination of homogeneous zones in which extreme rainfall (high or low) events or the main rainfall features are common, using other "tools" more appropriate for the analysis for the rainfall variable (developed into the Floodaware project). A secondary objective will be related with the impact of the climatic variability over water resources. In order to apply it to the forecasting of future scennarios, rdcourse to NAO and other climatic variables would be need. The second topic would be improved using the proposed rainfall events classification over other regions (starting for the stations placed in the same "pluviometric region" that Barcelona) and increasing the lapse of time used to test it in the Floodaware project (1996-1997). On the other hand, the application of this classification to IdF and Gradex parametrization. is still open. Finally, the analysis of rainfall distribution in complex terrain will be improved as we have more SAIH and EPA data.

These results will be presented, as a solicited paper, in the Conference Climate and Waterthat will be held in Espoo, Finland, on 17-20 August 1998

7 Acknowledgements

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A Case Study in the Gort/Ardrahan area of South Galway

Une étude de cas dans la zone Gort/Ardrahan du Sud Galway

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Abstract
The Gort/Ardrahan area of South Galway has been prone to severe flooding on relatively infrequent occasions up until the last six years. (Approximately 1 in 30 years). The recent floods (in 1990, 1991, 1994/1995) appear to be associated with exceptional rainfall rather than human influence such as farm drainage, afforestation or swallow hole blockage.
The hydrological/hydrogeological regime is only partially understood. There is a lack of data concerning detailed geology, flow rates, rainfall (particularly on Slieve Aughty), turlough levels, groundwater levels, groundwater flow paths, aquifer parameters, structural and geomorphological influences on the hydrogeological flow regime, and hydrochemistry. Over the last two years considerably more data has been collected for analysis. The lowland karst area of South Galway is environmentally very important both nationally and internationally and is one of few representative areas of its type in Ireland and even the World.
Local farming communities are very keen on land drainage as a solution to the problem of the deleterious effects of flooding on their livelihoods. Severe local disruption to the road network occurs during the flood events and large expenditures have been made in providing relief for livestock. Relatively few properties have been inundated but the anguish caused to those affected has been severe or even intolerable during the 1990s.
Currently considered engineering solutions are likely to prove uneconomical using standard cost-benefit analyses. Non-technical solutions are unclear at present but run the risk of social unacceptability. There is a need to reconcile the demands of agricultural development with those of ecological conservation.

Résumé
La zone Gort/Ardrahan au Sud de Galway a été soumise au cours des six dernières années à des inondations fortes mais occasionnelles (période de retour de l'ordre de 30 ans). Les inondations récentes (1990, 1991, 1994/1995) semblent correspondre à des pluies exceptionnelles plutôt qu'à une conséquence de l'influence humaine (drainage agricole, déforestation, embâcles).
Le régime hydrologique et hydrogéologique n'est que partiellement connu. Il y a un manque de données sur la géologie détaillée, l'écoulement, la pluie (en particulier sur la Slieve Aughty), les niveaux de turlough, les niveaux des nappes, les voies d'eau

souterraines, le régime des aquifères, les caractéristiques des aquifères, les influences de la structure et de la géomorphologie sur le régime hydrogéologique, et l'hydrochimie. Ces deux dernières années, de nombreuses données ont été collectées pour l'étude. La zone de karst des basses terres du Sud de Galway est très importante au plan environnemental, à la fois au niveau national et international, et constitue l'une des rares zones représentatives de ce type en Irlande voire même dans le monde.
Les collectivités rurales locales sont très favorables au drainage des terres comme solution aux incidences néfastes des inondations sur leur source de revenus. Les inondations entraînent de fortes perturbations locales du réseau routier, et d'importantes dépenses ont été initiées pour porter secours aux cheptels. Assez peu de propriétés ont été inondées, mais l'anxiété provoquée chez les personnes touchées a été très forte voire intolérables au cours des années 90.
Actuellement les solutions d'ingénierie étudiées semblent non valables d'un point de vue économique au vu d'analyses coût-bénéfice standards. Les solutions non structurelles sont encore peu évidentes et engagent un risque de non-acceptabilité sociale. Il est nécessaire de réconcilier les enjeux du développement de l'agriculture avec ceux de la préservation de l'environnement.

1. Objectives

This project has the following objectives,

- to define the current flooding problem
- to define the hydrological/hydrogeological processes
- to assess the effects of climate change
- to quantitatively define the flood hazard, in terms of land inundated for specific return periods, economic value and social implications
- to quantify and rank the environmental importance and economic value of the various turloughs, streams, land areas, wetlands etc.
- to propose engineering solutions, in terms of relative alleviation of risk and evaluate their economic costs, social and environmental implications. These might include drainage channels, dams, groundwater pumpage, diversion channels, afforestation and forestry management practices, swallow hole maintenance and improvement etc.
- to evaluate the economic and social impacts of non-technical solutions which might include land and property purchase, planning policy changes, turnover of designated areas to environmental uses, investment in tourism and academic pursuits and also compensation payments.

At a very early stage of project execution certain fundamental points became clear. These issues affected the emphasis and direction of the project work.

- The lack of sufficiently detailed topographic and cartographic data and incomplete coverage of the study area.
- The lack of hydrometric data concerning rainfall, surface water flows, groundwater levels and turlough water levels.

- Insufficient basic geological mapping, litho-stratigraphic correlation and subdivision of the Carboniferous Limestone's in the South Galway area.
- Paucity of ecological data.
- The importance of the rainfall.
- The complexity of the hydrogeological/hydrological regime and the importance of an integrated multi-disciplinary approach.

OPW developed a Geographical Information System (GIS) for this area in South Galway, Ireland.

The GIS will reflect the complex geology, hydrogeology and hydrology of the area as well as its environmental importance, notably the turlough systems that are prevalent throughout the lowland part of the catchment.

1.1 The Study Area

Figure 1.1 in the second year report outlines the extent of the catchment to be studied. It stretches from the southern portion of the Dunkellin River catchment to the Termon area and the northern extent of the Fergus River catchment. It is important to note that the hydrogeology and hydrology of neither the Fergus catchment nor the Dunkellin catchment can be included in the Project under current budgetary arrangements.

The impacts of either current or future technical or non-technical solutions on the adjoining catchments will not be assessed as part of this work.

2. OPW work programme for Floodaware

The first task was to set up a network of monitoring gauges to collect data to supplement those gaps in the existing data bank.

2.1 Hydrology/Hydrogeology

1. Install five new recording rain gauges on Slieve Aughty
2. Install five new stream flow gauges on the rivers from Slieve Aughty to the lowlands and Lough Cutra
3. Install a network of 18 - 20 recording stations with electronic loggers
4. Water resources modelling activities including:

4(a). development of a distributed rainfall model
4(b). development of a surface water model for the catchments of the Slieve Aughty
4(c). develop a ground water model

5. Expansion of existing geological mapping into the Coole, Ballylee, and Blackrock areas
6. Acquisition of field structural data including mapping of faults, folds and determination of the regional structure
7. Carry out preliminary surveys to locate fractures and karstified zones and to clarify the lithology drift and bedrock ridges

8. Water sampling and analysis of surface and ground water samples (hydrochemical data).

2.2 Environmental

1. Establish an ornithological database
2. Establish ecological value of turloughs
3. Establish baseline botanical information in areas likely to be involved in engineering flood water management proposals
4. Establish baseline studies for invertebrates, bats and marine biology.

2.3 Socio-Economic

1. Establish fundamental sociological and economic parameters of the study area from field surveys.

2.4 GIS

1. Set up GIS system incorporating all of the above information
2. Establish a detailed information database for topographical control of flooded areas, land use, and effects of flooding including inundation of farmland, road damage and blockage, effects on septic tanks and other treatment systems
3. Obtain aerial photography from Ordnance Survey Office (OSO) and Geological Survey of Ireland (GSI) and obtain radar satellite images for the period in 1994/95 when the area was subjected to severe flooding.

2.5 Catchment Description

The catchment area for this investigation is bounded on the east by the Slieve Aughty mountains and discharges to Galway Bay at Kinvara. The area is subject to periodic extensive flooding, a feature of which is the duration of such flooding. The flood of 1994/95, the most severe in memory, lasted from November 1994 to February 1995, with one local area remaining flooded until April 1995. Damage is caused to farmland, houses, schools, and commercial premises in the area. The extensive flooding isolates areas and threatens the livelihood of many people.

Burren Limestone underlies much of the low-lying area between the Slieve Aughty mountains and Galway Bay and it underlies the areas with the persistent flooding problems. It is usually present at or close to the ground surface with a thin cover of free draining sandy till in places. Rainfall reaction with pure limestones such as the Burren limestone creates distinctive features of relief, hydrology and hydrogeology, called karstification. Karstification in the Gort-Ardrahan area has reached the mature stage with extensive dissolution of the limestone and full development of an arterial underground drainage system with flows concentrating into zones of exceptionally high permeability. The main topographic features of karst areas are swallow holes, sparse and intermittent streams, bare rock, collapse features, caves, large springs and turloughs (temporary lakes). Other features include variable borehole yields and a high vulnerability to ground water pollution. The areas underlain by the Burren Limestone around Gort and Ardrahan can be classified as low land karst with all the typical karst features. This situation results in flooding of an unconventional type, for example, the backing up of sinking streams with inadequate underground channel capacity or the flooding of closed depressions by rising ground water. Successful drainage by conventional methods is difficult to achieve. The Gort-Ardrahan area has many natural features of scientific, conservation and heritage importance largely because of the unusual geological and water regimes in the area. This close and critical relationship means that any flood alleviation proposals must take account of the conservation aspects.

2.6 Monitoring Network

The complete lack of flow data, groundwater level data, and rainfall data in the Gort lowlands has meant that it was essential to set up a comprehensive monitoring network.

The continuously logged monitoring network (rainfall, river gauge, turlough/lake, groundwater level) has proved successful although the system was not completed as early in the study as could have been hoped.

As can be seen from the plots found in the Appendices to the report, the data is distinctive, of good quality and capable of interpretation.

The monitoring period was agreed to be extended to May 1997. Rain gauges and river gauging stations continued to be operated up to this period.

2.7 Topographic Surveying

In order to properly evaluate the flooding problem the volume of flood water held in storage has to be estimated. The recession of flood levels as the turlough levels fall need also to be evaluated so that estimates of input (and outflow for rising levels) to the groundwater system can be made. A Digital Elevation Model (DEM) has been created to cover the entire study area enabling contours at 1 m or 2 m intervals to be plotted across the whole area.

2.8 Geology

2.8.1 Solid Geology

It was recognised at the outset that the geology was not known in sufficient detail to allow the hydrogeology and karst system to be adequately evaluated.

A mapping exercise was instigated and a geological map has been produced by the Study geologist. This map represents a considerable step forward in understanding the geology and the possible geological controls on the development of the karst system.

2.8.2 Surface Geophysics

The very high resistivity of the limestones often proved a problem with electromagnetic methods and sometimes with resistivity but has enabled outstanding results to be attained with ground radar.

2.8.3 Drilling and Downhole Geophysics

Twenty-three boreholes were drilled for geological/hydrogeological purposes and have provided excellent water level/hydrochemical data to advance the conceptualisation of the water system. Cores have been used for geological correlation and control of mapping and geophysics. All these boreholes, plus several others have been geophysically logged.

2.9 Hydrochemistry

Hydrochemistry of the various waters that make up the hydrological system in the Study area provides a major qualitative contribution to the definition of the aquifer/surface water system. The extensive hydrochemical analysis and interpretation carried out has confirmed some of the major flow routes interpreted from other investigations, such as tracing, features mapping and water level monitoring.

2.10 Hydrogeological Field Investigations

Clearly all the investigations discussed thus far have implications for the hydrogeology of the Study area.
In addition to the investigations discussed above a number of other fieldworks activities have been carried out which do not adequately fit into the categories mentioned above. These have been grouped together within this heading and are discussed briefly below.

2.10.1 Karst Features Mapping

An inventory of karst features within the Study area was compiled during July and August 1996. The inventory characterises the features into ten categories. These have been input to the study GIS and the "Geological Survey of Ireland Karst Database".

2.10.2 Spot Gauging Programme

A programme of spot gauging has been carried out throughout the study period at the river gauging stations in order to measure flows at different hydrograph stages, for the purpose of generating stage-discharge rating curves.

Attempts were also made to quantify the spring flow entering Kinvara Bay. This flow gauging was carried out in conjunction with salinity monitoring of the Bay, but proved unsuccessful in establishing the coastal and submarine flows.

2.10.3 Tracing

Tracing investigations were carried out in late 1996 and early 1997, to identify the flowpaths of groundwater passing through the karst lowlands. 19 No. individual traces were carried out, sampling from 38 N° detection locations, using 5 N° types of tracer, including bacteriophage.

Tracing experiments were designed to investigate different possible flow route variations at different stages of water level and flow from the same input sites. This tracing was highly successful in identifying flow routes and represents probably the most complete tracing study carried out in Ireland to date. The use of bacteriophage represents a considerable advance in research using this technique for groundwater investigation.

2.10.4 Deep Karst Investigation near Kinvara

The existence of a deep karst (>40 mbgl) was identified at GFS 23 and possibly Kinvara PWS. An investigation was designed and executed to determine its existence (and significance to the flooding problems), at a site near Kinvara.

The investigations found three levels of karst, a shallow depth karst (15-25 mbgl), an intermediate (40 - 50 mbgl) and a deep (70 - 80 mbgl) karst in the Kinvara area. The shallower two appear to transmit rapid throughflow waters at high groundwater levels but are susceptible to saline intrusion at low water levels. The deepest karst appears to be a palaeo-karst and contained old groundwater.

2.10.5 Cave Diving Data

Literature reviews of speleological expeditions within the study area established records to exist for Polbeaghy and Polloughabo. These have been entered onto the study GIS database. No new diving surveys were commissioned as part of this study.

Other monitoring surveys and investigations include current metering at low tide in Kinvara Bay to assess freshwater spring discharge.

A conductivity survey of parts of Kinvara Bay has been carried out.

2.11 Analysis of Rainfall

The study of the rainfall patterns in the Gort area has had two main aims; firstly to investigate the extent to which unusually high rainfall was responsible for the flooding in the area during the 1990's, and secondly to develop a model for the rainfall in order to assess future flooding risks and to provide input to hydrological and hydrogeological models.

It is concluded that the major areal flooding of 1994/1995, was caused by a combination of very high rainfall over an extended period and the finite natural capacity of the karst flow system.

A study of the rainfall patterns in the area over the last 50 years has shown that the best statistical representations of the observed data indicate a change in the rainfall patterns. Winter rainfall in the area has been steadily increasing since the late 1960's. Two possible rainfall climate change scenarios best represent the observed data.

2.12 Ecology

The ecological work has resulted in a broad picture being obtained of the value and content of the lower part of the catchment. The vegetation survey suggests that several discrete types of wetland exist (the distinction between turlough and lake is difficult to sustain):

1. "Riverine" wetlands, for example Lough Coy, Blackrock, Coole and Caherglassaun where the annual plant communities on the flat silty shores are a reflection of frequent changes of water level through the growing season.
2. Marl-rich wetlands with a high watertable in summer, with or without peat accumulation, e.g. Lough Bunny, Kilmacduagh Fen, Frenchpark, Termon South.
3. Marl-rich sites that dry out in summer except for small pools e.g. Ballinderreen, Poulroe, Tulla, Ballinduff.
4. Basins in glacial drift, dry in summer, e.g. Killeenavarra, Roo East, Cahermore.

The survey of aquatic fauna shows that the southern groundwater-fed wetlands contain richer and more distinctive assemblages of species than the northern ones. As with other data Coole fits better with Lough Coy and Blackrock in terms of its crustaceans than with the (contiguous) Newtown turlough. It has richer populations of insects and other organisms however because of permanent water. Newtown, Hawkhill, Garryland, Roo West and Poulroe appear to be the most interesting sites.

Work on terrestrial invertebrates concentrated on the upper parts of wetland basins where potential impacts from water management will be the greatest. Rare species have been found but evaluation was based on the communities that occur. Thirteen sites have been sampled intensively for beetles to identify species. The spread of trapping for moths has been somewhat wider and it shows that the scrub zone at the edge of winter flooding has the highest diversity and density of species. Lower down there are quite large numbers, but of few species. The level of grazing on the vegetation is an obvious controlling factor for these plant-eating organisms.

The number of bats using caves in the study area appears to have declined sharply over the last few years and this may be a direct effect of the high floods.

2.13 Baseline Socio-Economic Analysis

2.13.1 Profile of Local Economy

The economy of the Study Area is based on its natural resources, with agriculture being the single largest sector. Farming in the area is primarily occupied with the development of drystock cattle and sheep with a limited amount of dairying. In terms of farm size, over 92% of farms are below 50 hectares, and 51% have fewer than 20 hectares. The average size of farm is almost 25 hectares, some 25% larger than the average of 19.7 hectares for Co. Galway. Farmsteads occupy a total of 55,361 hectares; 80% of which are arable and pastureland and 20% being rough grazing land.

In terms of forestry, the Derrybrien forest on the Slieve Aughty mountain accounts for a large proportion of forest land, covering approximately 4-4,500 hectares. Shell fishing is important in the Study Area and oysters are farmed at 4 locations. There has been a sharp downturn in oyster production in recent years. This was examined under the Marine Ecology component of the Study.

There are 34 Forbairt and IDA supported firms, operating mainly in the wood, furniture and engineering sectors. Tourism focuses on the heritage, cultural and natural resources of the area, with a concentration of cultural and historic sites in the immediate hinterland of Gort. The Study Area has a small accommodation base and development of this sector is affected by its proximity to Galway City. Ease of access to the area via the N6 and N19 will ensure that a large number of visitors will continue to pass through.

The Study Area is served well by both national and secondary roads. Improvements to the road network are planned which would benefit economic activity in the area. A comprehensive range of commercial, professional and socio-economic services are available in the area.

2.13.2 Impact of the Current Flooding Problems

The impact analysis focused on the impact of the 1995 floods in the Gort-Ardrahan area of South Galway. A total of some 300 questionnaires were distributed to affected households and farms. In total, responses were received from 240 farms and households, with a resident population of 966 persons.

In conclusion, a total of £9.5 million was estimated as representative of the cost of the damage caused by the 1995 floods. This excludes the impact of road closures, and the social and personal impacts. Making allowance for these exclusions would probably see the estimate rise to over £10 million.

2.14 Recommendations of the Study

- Implement non-technical planning controls within the 1994/95 flooded areas and the launch of a structured tourism initiative.
- Move to implement the modification and protection of key arterial and essential access routes in order to maintain vehicular access during flood events.
- Move to implement peripheral engineering solutions at Termon Mannin Cros if detailed environmental and cost-benefit investigations confirm viability.
- Continue to monitor flows and water levels at key locations within the study area.
- Collect and analyse rainfall data to confirm (or otherwise) climatise trends on cycles identified.
- Update and refine the design and calibration of numerical models.

Economic valuation of the maximum acceptable risk

Évaluation économique du risque maximum acceptable

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Abstract

Vulnerability plays a critical role in implementing the Inondabilité method. Its quantification is based on the concept of maximum acceptable risk, to be applied to each of the land uses in the floodplain. To define such a limit of risk on an objective basis requires to identify a level of maximum acceptable loss and to complete a microeconomic analysis of the activity as a whole, including its objectives, resources, restraints and results, at a more or less high degree of detail. More attention is devoted to the technico-economic background, the financial capacity and the system of information-perception-adaptation of the agent, which are the main factors influencing the level of maximum acceptable loss, and then the level of maximum acceptable risk as expressed by the agent in the public decision process. A methodology is proposed mainly for the case of an agricultural activity.

Résumé

L'analyse de la vulnérabilité occupe une place cruciale dans la mise en œuvre de la méthode Inondabilité. Sa quantification est basée sur le concept de risque maximum acceptable, appliqué à chaque type d'occupation du sol dans la plaine inondable. Pour définir une telle limite au risque sur des bases objectives, il est nécessaire d'identifier un niveau de perte maximum acceptable et de conduire une analyse micro-économique de l'activité, y compris ses objectifs, ressources, contraintes, résultats, à un degré de précision plus ou moins grand. Une grande attention est portée au contexte technico-économique, à la capacité financière, et au système information-perception-adaptation de l'agent, qui sont les principaux facteurs influençant le niveau de perte maximum acceptable, et donc le niveau de risque maximum acceptable exprimé par l'agent dans un processus de prise de décision publique. Une méthodologie est proposée, principalement pour le cas de l'activité agricole.

1 Context

1.1 The study-and-decision process

1.1.1 The general setting

Here one considers a public study-and-decision process devoted to define a flood management scheme and following the Inondabilité method, developed by Cemagref (henceforth named written "IM"). The core of this approach consists of quantifying the level of flood risk born on each land in the floodplain, by directly comparing its level of hazard (a physical phenomenon) and this of vulnerability (land-use). Economic valuation of MAR is a part of the vulnerability study, but is also only one on the several contributions by economics within the full prevention process, the (chronologically) first one but also the more basic and original, since it conditions the others.

The economic valuation of maximum acceptable risk (henceforth named written MAR) is a major part of a broader field that could be named *"econometrics of prevention"*, i.e. the economic quantification of (mainly public) actions in flood risk management at the watershed level (general scheme, local projects). These actions are evaluated by reference to a status quo situation or/and more or less preventive vs curative alternatives.

1.1.2 Concerned stages of this process

In order to locate accurately the valuation of MAR, it is necessary to ***apprehend the whole process of study-and-decision*** for a preventive management of flood risk, as represented in the figure 1. This process is easily structured by sequencing (time ↓) separately several fields (columns) and interrelating them (arrows). These fields are:

- two domains for ***study***: ❶ water sciences, ❹ economic and social sciences,
- and two spheres for ***public decision***: ❷ management of flood risk, ❸ management of other stakes. These last, linked with water or not, may have connections with the management of flood risk, especially in a perspective of long-term prevention.

This structure reflects the complexity which underlies every problem of flood prevention. It is best suggested by reference to a comprehensive (i.e. non purely technical) definition of the IM:

(a) a method for flood plain management (i.e. a system of models: hydrologic, hydraulic, geomatic),

(b) producing two parallel mappings and quantifications: hazard, vulnerability,

(c) confronting them to generate a synthetic information on risk levels and to locate parcels which are under-protected and these over-protected,

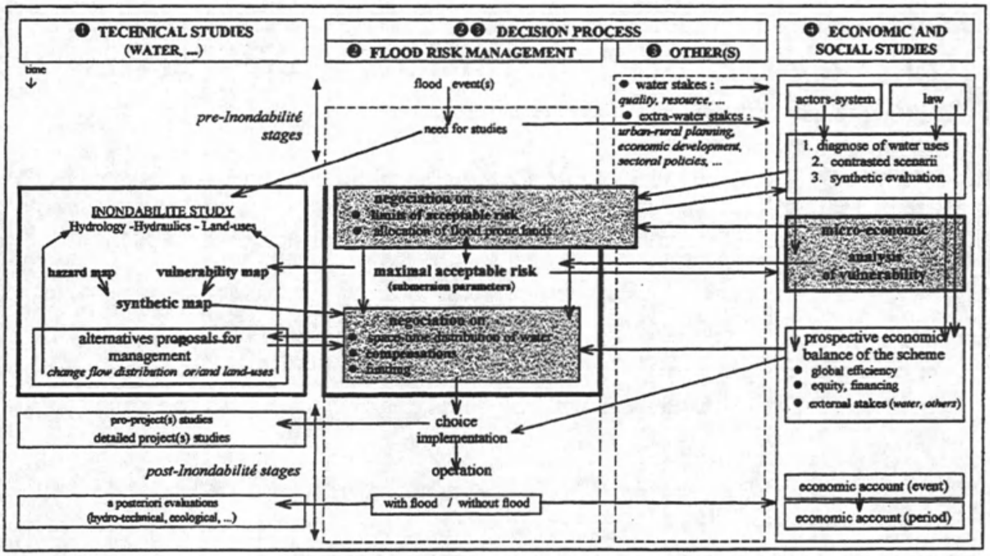
(d) to help local actors to negotiate a change of the existing space-time distribution of floodwater,

(e) capable to satisfy the protection demands,

(f) while respecting at the maximum the operation of the hydrosystem, in its several components (resource, ecosystems, recreation, landscape…) and the related social demands.

The valuation of MAR locates upstream of the element (b) of the above definition, and takes place in the diagram within the cell called **micro-economic analysis of vulnerability** (as a major part of it; the other portion is the calculation of [effective or potential] damages, not included in this chapter).

Fig. 1 - The maximum acceptable risk within the study-decision process



Other evaluations can be made in relation with one or several elements (d), (e) and (f), and take place in an other sub-process (before the strictly called MI one, and after it), as suggested by the diagram (resp. above and below the bold zone).

1.2 Nature of the question requiring an economic evaluation of the MAR

The main objective of this evaluation is to ease every owner (or user) of flood-prone land to express as ***objectively*** as possible a limit of submersion he can accept at the maximum on his parcel in a given type of land-use or activity. This objectivity is a condition for the fiability of several subsequent operations:

- the best quality of information which will enter as an input of the ***vulnerability map***,
- a maximal fiability of the ***synthetic map of risk***,

- a fair ***identification of the potential*** for augmenting locally the submersion in order to reduce it elsewhere.

A similar evaluation of MAR locates at the moment when the public decision-maker considers a possible (basin) scheme or (local) project (or several alternative ones) to retain more floodwater on some identified lands, and will have to negotiate an financial agreement with the potentially concerned owners.

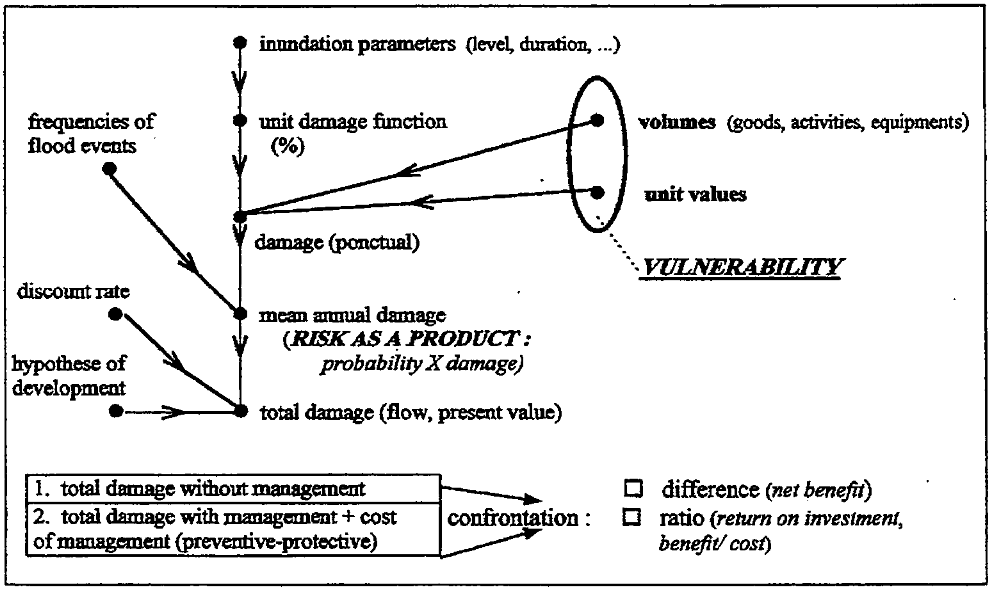
In both contexts, the question is: by which methodology can we identify and measure this need for protection or his potential to accept water, in such a way both:

1. to reflect realistically the "objective" ***local economic conditions*** of its activity,
2. to ***relate*** this need or potential to the ***physical parameter(s) of flooding*** (depth, duration...) ?

2 On vulnerability in general and maximum acceptable risk in particular

Before exposing the proposed methodology for quantification, it is essential to specify the meaning of *"maximum acceptable risk*" and "*vulnerability*", two concepts which receive in the IM an innovative definition, with some major implications in both theoretical and practical terms.

Fig. 2 - Vulnerability as a macro-economic magnitude



2.1 The ways to deal wih vulnerability

2.1.1 In the existing risk management studies

The dominant view of vulnerability has been developed in connection with the elaboration of synthetic maps of natural risks and especially of flood risk. It consists of a global volume of flood-prone wealth (dwelling units, economic activities, equipments) that a socio-economic community may expect for a year without flood. This amount can be used to assess the economic opportunity of a preventive policy; then, vulnerability is one of the variables of a damage model, as the product of volumes of assets or/and activities **Q** by unit monetary values **v**, as represented on figure 2. Notice that the damage associated to one given flood will be equal to the product of **Q.v** and a rate of loss, **l**, and the risk, in terms of mean annual damage, results from the product of the **Q.v.l** with the frequencies of floods, **p**. We can summarize the main features of vulnerability by saying that it is a ***macro-economic*** concept, i.e. a global amount (in physical terms: houses, bridges...) or value (in monetary terms) of wealth exposed to flooding.

In some more recent studies, this same concept is named *"stakes"*, and then the word "*vulnerability*" indicates not an amount but a relationship, where the inputs are stakes, hazards and adaptative resources, and the output is impact of floods, next transformed in damages. This terminologic change aims at focussing on the evaluation of stakes instead of the conventional accent on evaluation of damages, whose results appear in pratice to be subject to excessive uncertainties and misinterpretation by politicians and public opinion. But whatever the word, the essence of stakes concept remains this of a global amount of flood-prone wealth.

2.1.2 In the Inondabilité method

By contrast with this conventional view, the concept of vulnerability developed by the IM is innovative on three respects.

1. Vulnerability is totally ***deconnected from hazard*** for defining a synthetic concept of risk. While hazard (linked to the regime of the river and the topography of the valley) is an objective data, vulnerability (since depending on the nature of the land-use or activity and its socio-economic characteristics) is a mental artefact. Both are separate as two components of the concept of risk, and they represent also two different ways to design prevention actions, as suggested on figure 1: either by changing the statistical distribution of water (i.e. the hazard) or by modifying the uses of flood-prone lands (i.e. the vulnerability).
2. Hazard and vulnerability are ***quantified in the same unit***. Thanks to the QdF model, every triplet of flood parameters (depth-duration-frequency) for a given location within the watershed (for instance, one parcel) can be transformed in a synthetic indicator, in terms of equivalent return period (here written **T** for the hazard, and **T*** for vulnerability). This commensurability allows to confront them directly through their difference (**T**

- T*). Notice the contrast with the classical definition of the level of risk as a product (**Q.v.I. p**) (as suggested on figure 2).

In this framework, vulnerability is designed not as a damage (effective or hypothetic, either the mean annual one or this associated to some particular extreme event taken as a reference), but as a limit of acceptability: each individual may make this limit explicit by asserting that he could not tolerate submersion more than some level ***h**** or/and duration ***d**** once every ***n**** (next traduced in some value of **T***). This is the MAR, with three practical and interrelated aspects:

- ***Technical-cartographic*** aspect: the individual MAR expressed by people allow the engineer to calculate T* for each parcel (or homogeneous zone) and then its specific position as over- or under-protection, to be mentioned on the vulnerability map.
- ***Socio-political*** aspect: technically speaking, individual MAR could be expressed in a more or less bilateral and confidential. In the contrary, the main benefit from quantifying MAR consists of initiating a ***collective confrontation*** of the occupants (between themselves and with the public decision makers). Then, more than the absolute values of inundation parameters, the relative ones are the important consideration, since they will result in (a) an ***explicit hierarchy*** of priorities in protection and (b) a ***social consensus*** on this hierarchy: this can be a decisive factor to warrant ***credibility*** to the resulting new plan, its implementation and future operation.
- ***Technical-engineering*** aspect: the hierarchy adopted by the actors on the set of parcels or zones to be more or less inundated will inspire the engineer for ***designing the optimal mix of measures*** (structural or/and nonstructural) to be proposed for a management global scheme and local projects.

2.2 Micro-economic nature of maximum acceptable risk

2.2.1 Vulnerability: a synthetic and subjective concept

Such as defined as above, vulnerability in the IM meaning (i.e. MAR) appears to be in essence quite different from vulnerability in the conventional meanings (i.e. either total exposed wealth or mean annual damage). While wealth and damage correspond to ***objective*** magnitudes, subject to measurement by an external observer (at least theoretically; in fact, quantification raises great difficulties: multiple components of wealth, confidentiality...), in the contrary MAR as a limit of acceptability has no sense out of a ***personal valuation*** made by the economic agent himself. But before being able to express this limit, he will have to build a reasoning, either simplistic or a more or less sophisticated one, but in every case to appreciate his ***situation as a whole***, his present one but also the potential in case of flood event, including his objective(s), resources, restraints, etc., and not only to consider the hydrologic parameters and the physico-technical characteristics of his land directly connected to these parameters.

Several features have to be continuously kept in mind when considering MAR:

1. ***secondarity***: a maximum level of risk (acceptable by a given economic agent) cannot be defined and identified as an absolute value, but only derived from a global evaluation of the individual activity,
2. ***syntheticness***: MAR depends altogether on a plurality of elements, mainly: (a) his prime economic objective while occupying a land in the floodplain, i.e. some net benefit, (b) his various restraints (flood risk and others), (c) the resources devoted or/and devotable to adapt to flood risk,
3. ***subjectivity***: it depends also on an appreciation to be formulated of his overall situation, and not only on the factual observation of technical elements,
4. ***systemicity***: the most important thing in searching an expression of a limit of acceptable risk is the process followed by the individual to generate this limit, and therefore the way to be followed by the observe to represent this as a system.

Because of this synthetic and subjective character, no external observer can ***measure*** vulnerability in a ***direct*** and ***quantitative*** way, as something pre-existing and simple: all what he is able to do for making this limit explicit and objective, will consist in designing a ***model of the whole process*** and collecting or/and generating data, relations and judgments, following more or less indirect and selective ways.

For describing the operation of an activity and the generation and implementation of judgments and decisions by an individual, a discipline is available: ***micro-economics***. [Remind: Micro-economics is the discipline which explains how the individual agent (producer, consumer, public entity) makes a good decision (the optimal or - more extensively - a satisfying one) by considering ***the whole set*** of his objectives and restraints, especially on available resources; all that, by contrast with simple technico-economic response.]

2.2.2 From acceptable risk to acceptable loss

From a micro-economic point of view, the reference to a global evaluation of the individual situation amounts to assert that the economic agent identifies a limit of acceptability in terms of loss, that we call a ***maximum acceptable loss*** (MAL). Even if it cannot be observed as a pre-existing objective magnitude, a level of MAL does normally exist: it is an alternative way of saying that the economic agent has ***risk-aversion***. This last itself results from an concept of ***ruin*** and the idea that, if he occupies a parcel in the floodplain, it is because he evaluates his activity on it as globally optimal (or satisfying). His benefit may be in monetary terms (net income, capital appreciation) or in non monetary ones (pleasure, conveniency, mental health, etc., all that in non-market economics is globally named "amenities").

Of course, this judgment is not absolute and definitive, but relative to the informations available to the agent at a given time. They include flood risk but also every pertinent element entering in his activity, more or less numerous, uncertain and changing, for instance: land price, transportation cost, road accessibility, community taxes, etc.

From this classical micro-economic principle, there is a level of loss so high to put in question this interest, and that we call ***maximum acceptable loss*** (MAL). Notice that if the concept of MAL has sense, by contrast the concept of MAR has not. It is nonsense saying that some level of risk is "acceptable" (or not) in an absolute meaning, but only as this level of risk ***associated with the global option*** which is the best (or the most acceptable) for the agent.

In spite of a somewhat abstract formulation, practical implications appear quite evident.

2.3 Methodological implications for quantifying maximum acceptable risk

First, we must remind that the objective of the IM at the pre-cartographic stage does not consist of obtaining explicit limits of loss (in monetary terms) but limits of risk (in terms of T). In other words:

- an objective expression of vulnerability in terms of the ***how much*** (some level of MAR) - i.e. the result of the ***vulnerability process*** - lies primarily on a sound identification of the ***how-why***, i.e. the essential structure of this process (logical sequencing, factors influencing the MAR),
- within this process, a central role is played by the MAL, but this does not demand per se in every case a direct ***evaluation of the loss*** itself.

Therefore, from this acceptable risk-acceptable loss dichotomy, two implications may be inferred as basic general rules before trying to specify a fair (i.e. both pertinent and feasible) methodology for the various land-uses.

2.3.1 Looking for a global approach from several main components

What the study man needs for getting an MAR by an agent and which would be the most objective, is to "explain" this expression by reference to a ***global "model" of the agent*** (at least in the comprehensive meaning of "mental representation"). An approach to elaborate this representation consists of following a sequence, made of three levels. Each of them corresponds to one of the main groups of factors, we have identified from a comprehensive survey of world literature about human behavior and attitudes toward flood risks (mostly north-american, in several disciplines, mainly: human sciences, geography, agricultural economics).

1. The approach begins with the ***technico-economic characteristics of the activity***, because they include the most "objective" and generally available informations. For an agricultural instance: which are the precise motives to assert that a vineyard is able to bear **h** centimeters of water during **d** days within the season **s** every **t** years, while an hectare of salads is not ?

2. A second level of investigation comes close to the ideas of loss and ruin: it involves an appreciation of the ***financial capacity*** of the economic agent to absorb the impact of flood(s). In the agricultural example: of two farmers in a similar locations and thus prone to the same level of hazard, and making the same crop, one has achieved the stage of maturity and will be able to bear the cost of a given flood, while the second cannot because of a maximal indebtness and a survival monetary surplus.

3. Finally, a level of MAR identified from the levels 1 and 2 can yet be affected by the knowledge of risk by the agent, the way of taking it in account and the resources he affects, or intends to affect, to adapt for reducing the impacts and his lossn and thus augment the limit of acceptable hazard. That can be named the ***information-perception-adaptation system*** (of this individual). For an industrial instance: a multi-site firm, which has been physically damaged by floods, prefers to keep its factory located in the floodplain, but develops a new preventive plan including the temporary transfer of manpower and stocks to another site external to the plain.

In summary, the basic idea of this reasoning is that several ***parcels*** with the same land-use may, since they have been related to ***the economic unit*** to which they belong respectively, have different vulnerabilities, and the study man will have to make these disparities explicit and explain them by reference to differences in the respective micro-economic systems.

Of course, for implementing this global approach, there cannot exist a unique protocol for all the types of land-use, i.e. pertinent and feasible altogether for agricultural farms, industrial firms, resident households, market tertiairy services, public utilities networks, non market services and natural zones. Moreover, for each land-use, the practical has to be adjusted to the degree of expected accuracy in the result and to the delay available for study. Therefore, a second rule is formulated below.

2.3.2 Associating interactively several sources of information

At the ground level, it is judicious to use informations from four types of source, in necessarily interactive ways, since each of them appears to be more or less partial or/and time costly.

1. The engineer refers to values of MAR seeming "reasonable", i.e. coming from ***experts*** or/and ***literature*** or/and other ground ***similar past experiences*** following the IM, and propose them to the occupants as an introductive proposal, to be discussed and modified via rational arguments.

2. The study man fulfills ***direct inquiries*** to the land-owners, at least via a series of sectoral samples covering the different existing types of land-use. This way represents a priori the most pertinent one, but its feasibility can be limited by the size of the concerned region and the diversity of the human occupations.

3. For that reason, he has to exploit many informations from ***indirect sources*** (such as sectoral or regional various statistics, files, data bases). They have the great advantage to be existing and generally simple to access. As a counterpart and similarly to the canal 2, they need a basic model for structuring the collection of data and the processing of them.

4. The ***actors of the floodplain*** express their level of MAR. The likelihood of a subjective and strategic attitudes is present, but can be minimized by a true confrontation and reference to external references and economic reasoning. A benefit can emerge from such a discussion if a true pedagogic-democratic process can be initiated, by showing to every participant that the society cannot protect everybody equally and "fully" and that priorities have to be explicited for the common interest.

The proposals below concern the 2 and 3 canals, but their possible combinations with the two others must not be forgotten.

2.3.3 Organizing production and circulation of information on MAR

In the present state of basic knowledge on flood risk behaviors and of the vulnerability analysis in a IM context, designing a series of ready-to-use sectoral (agricultural, industrial...) models seems premature: these will better come progressively along with various real-time applications. Therefore, a priority should be given to installing a simple and flexible system for framing the basic information and MAR results, the existing ones, the production of new results, and for valuing them by transfers.

Three would levels have to be separated but also interconnected:

1. ***Basic knowledge*** yet to be acquired: it concerns mainly the study of relations between (a) one component of the system (of an economic agent), which is not directly observable in its whole (for instance: system: farm → component: financial capacity) and (b) some observable magnitude to be selected as an indicator (in this example: the age class of the farmer, as linked with an indebtness ratio). Producing these informations is not incumbent upon study man or engineer engaged in a local process, but on research centers.
2. Other informations fall under a ***storage-and-comment*** device in a ***database***. It could be visited by the study man, but symmetrically augmented from local studies, especially via an adequate and selective return of vulnerability local meetings (final results, course, arguments).
3. Finally, some informations to be produced within the local process itself, from two sources:
    - either a ***simple method***, based on maximal indirect information and most selective direct inquiry,

- or/and a ***detailed and global approach***, to be limited to some parcels, zones or economic agents but justified by any reason binded, for instance, to the likely size of some economic stake or to a major uncertainty about the limit values.

3 Valuation of maximum acceptable risk in agriculture

3.1 Specific importance of agriculture for flood risk management

3.1.1 Reasons for evaluating vulnerability in agriculture

The prior interest for ***agricultural*** vulnerability is based on several reasons, whose the two first are basic, associated with two differents steps of the study and decision process in floodplain planning.

1. The main use of this quantification is not specific to agricultural land-use and has already benn mentioned. It locates at the first stage of the process, when each riparian (farmer or not) has to express his protection need, as a basis for the ***cartography*** of vulnerability. Here, connecting this expressed value to the economic activity it reflects is a sound way to insure more fiability to the cartography of both vulnerability and (synthetic) risk. Similarly, at a later stage, this measure will allow more realism in estimating the global ***potential*** for water storage (in terms of volume, i.e. of surfaces X depths).
2. More agriculture-specific, the second basic reason concerns the ***design of a flood management*** scheme or project. In the perspective of a watershed-wide management of flood risk, agriculture represents quite a strategic activity, because most of the areas, potentially available for storing floodwaters at the upstream of these to be protected (because more and less urbanized ones), are in fact occupied by crops, meadows and forest. Therefore the public decision-maker cannot escape from a ***financial negotiation with the potentially concerned and-owners-farmers***. In this quasi-market context, the quantification of MAR (a physical one, but related to its economic basement) and, better, a tentative valuation of MAL itself (then in monetary terms) affords a useful information to the public decision-maker.
3. Independantly from Inondabilité studies, agriculture is the most direct illustration of the general approach to vulnerability as a acceptable limit. In this sector, the concepts of ruin and of ***probability of ruin***, as a restraint to profit maximization by the farmer is relatively familiar.
4. In every country ***agricultural damages*** from floods, their importance in absolute value and in relative one (meaning both: versus non-agricultural damages, and in terms of rate of net loss) is a subjet for recurrent debate and controversy. Therefore a microeconomic approach to vulnerability can contribute to a better basic knowledge, by illuminating the actual processes of loss and response at

the level of the farm as a whole. One subquestion of this fourth reason is the relative contribution of different types of events: moderate and frequent vs. extreme, on viability and profitability of the farm in a short or long term perspective.

For all these reasons, primarily the (a) and (b) ones, we have designed a method to identify the level of flood frequency-duration-depth upto which some floodwater could be "deposited" on a given parcel while ***remaining economically acceptable by the farmer.***

3.1.2 A practical perspective

- The main objective has not been primarily theoretical, but practical: identifying the types of ***information***, the various potential ***sources*** and the ***treatments*** suitable with the Inondabilité format. But facing the synthetic and subjective character of the MAR and MAL concepts, the response needed some detour and to refer to a ***global view of the farm***, and for that, to question the micro-approach to farm economics at its most basic level.
- As in the general presentation of vulnerability, a clear separation has to be made between the ***mean annual damage*** (MAD) and the ***maximum acceptable loss*** (MAL), as conceptually different. Of both only the second plays a critical role in implementing the IM. However, since several informations are common (damage functions, technico-economic farm data) and damage is an attractive item for actors, the calculation is summarized for the reader in an extra-text box.

3.2 Basic features of vulnerability in agricultural activities

Following the basic principles exposed in 2.3.1, the limit value of submersion parameters to be identified on a given agricultral parcel depends on the ***micro-economic and social characteristics of the farm*** to which it belongs to, as a whole, and not only on the local characteristics of this land.

3.2.1 Approaching the farm as a whole

In a first approximation, this proposition could be viewed as trivial since, finally, it does not represent more than another way to say that vulnerability is a micro-economic concept. From then, this would seem to be recognized by most of the many ***models of farm economics under risk*** from the (mostly anglo-saxon) literature during the last decades. They consider the farmer as profit-maximizer, who has to allocate resources to parcels for alternative or/and complementary activities (crops), subject to various restraints. Some of theses restraints can include a limit of acceptable risks [flood, other non-flood, or general], especially via a ***probability of ruin***, i.e. probability of having a given critical loss not greater than a given limit.

But in fact, by focussing onto the formal procedure to select an optimal scheme of crops in a given context (as an application of the standard optimization model of the firm), this approach fails to consider the farm in itself, as a comprehensive system. Really, several other technical, financial or/and social components may appear to be more or less complex and decisive factors from a case to another: thus they have to be considered in themselves, from an ***integrated point of view***. From this principle and the review of this voluminous literature, we conclude that micro-economic optimization models, while potentially interesting as a subpart of a comprehensive approach of the farm, represent an excessively ***reductive*** way-of-thinking to be considered as affording by themselves a pertinent tool for evaluating agricultural vulnerability.

By contrast, the modern (french) methodology for ***global farm management*** seems to offer positive potentialities in his respect. The following paragraph contains a brief outline of it.

3.2.2 A systemic view on farm management

Several decades of experience in extension of farm management (with its shares of various success and failure) lead to the major conclusion that the observer is able to understand the operation of a farm only if he considers it as a system. This mainly two methodological golden rules.

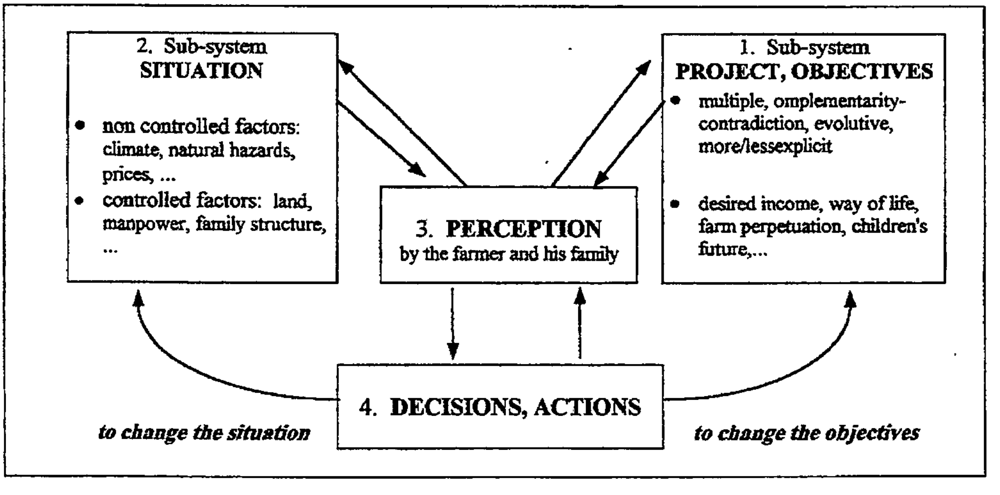
❶ Study must not be limited to the ***global economic-financial*** result, it has to include first the other aspects:

- ***technical*** (agronomic, zootechnic), through technological choices, use of inputs and results in physical terms (production, yield),
- ***social***, through (a) a labor force from family, (b) a desired level of net income and (c) a future perspective for children or/and the farm.

❷ Before analyzing the elements in detail, he must consider the set, by focussing on (a) the ***actor*** (a mix of firm and family), with (b) some ***objectives***, (c) a (overall but more or less explicit) ***project*** and (d) a system of ***governance***.

By contrast with the conventional micro-model and derived management tools, which reduce farm operation to a simple and uniform model of optimization, this way-of-thinking defines a global coherence from the ***type of adaptative behavior***. This view is illustrated by the diagram on figure 3.

Fig. 3 - The farm operation as an adaptative system



1. The farmer has a ***project***, in reference to which his behaviors and attitudes should be interpreted. It contains ***objectives***, which can be multiple, more or less coherent and evolutive. In any case, the project reduces to a simple profit-maximization, and can include social items (in terms such as family income, way-of-life, perpetuation).
2. ***Situation*** is the set of the restraints limiting potential actions, but also of positive levers (some items can play either as a restraint or as a lever: it depends on the project).
3. The ***perception*** the farmer has of his project and situation is always imperfect, but can react to evolution in 1 or 2 and be modified by action.
4. ***Actions*** may consist of modifying some elements of the situation (structural ones, or practices) or/and adjusting the objectives.

The main idea developed in this framework is that the "why" must be prior to the "how much", i.e. the ***successive technico-economic and social choices*** made by the farmer are the key to explain the periodic financial-economic results, and to imagine what could happen in some hypothetic events (such as floods). This view contrasts with the conventional theory and practice of farm management, where only the ***financial-economic result*** has importance.

On this foundation, one can analyze with a more or less detailed degree several subsystems: decisional (objectives, control), operating (technico-economic), social-financial (generation and distribution of income, capitalization).

Calculation of Agricultural Mean Annual Damage

The method summarized below considers first the case of a *little-size floodplain* (or any reduced part of it), so little enough to carry out a "complete" investigation (including a direct inquiry at the farm) reasonably within the usual professional (vs. academic) delay for river studies. The objective is to identify possibilities and difficulties, and concludes on the feasibility of the approach at this level. In a second stage, one considers a simpler method, which would be devoted to the case of a medium- or great-size floodplain (or part of it). It consists of exploiting the many existing agro-economic data from public and professional sources, thus minimizing the direct collection from the farmers themselves. It is named *regional approach*, by contrast with the previous one, named *local approach*.

LOCAL LEVEL

<u>Basic data on the agricultural space</u>. A prior step consists of collecting and treating the basic information on the local agricultural space, in order: (a) to identify and quantify the land-domain and associated farms, and (b) to structure it by connecting parcels to farms. One starts from the map of hazard and this of land uses and, through several intermediate operations (not described here), builds the *table of the concerned farms* (mentioning: identification, list of parcels, associated crops and corresponding hectares).

The calculation of the MAD *for each farm* has to follow five steps.

<u>*Step 1: calculation of flooded acreages*</u>. It is the most important from an hydrologic-hydraulic point of view. One uses hazard map and land-use map for identifying and estimating the *surfaces submersed in each type of crop* by floods corresponding to various given frequencies. The analysis from QdF model and flow-level curve (giving the overflowing flow for each section of the bed), usually annual, can be made seasonal if justified by the time-profile of damage to crops.

Step 2. One applies to the hectares flooded in each crop a *loss of yield* (%) according to several parameters of submersion: primarily duration and time, which are reputed to play a critical role on most of crops. On the other hand, to convert unit (i.e. per hectare) yield losses into unit gross income loss (following step 3) appears easily feasible as soon as ***regional technico-economic standards*** are available, including output prices and operational expenses, in each type of farms and size class. (Of course, a direct inquiry may always be performed specifically on the concerned farms, if the manpower and time are available. But in fact existing agro-economic statistical databases include the pertinent information.)
Subsequent steps. From there, the total income loss per farm is calculated for various returns periods (step 4), and finally mean average damage (step 5).

REGIONAL LEVEL
The above method, which is normally adequate for little territories, is no longer feasible as soon as the number of parcels or/and of farms exceeds a reasonable level, which would remain compatible with the usual sequence of a study-and-decision process. Especially, an important section of the valley or the whole of it, an estimation of regional MAD is possible via a shorter method, at leat as a first approximation.
For step 0, one exploits indirect statistical data on the agricultural economy at the level of local communities and farms, to identify homogenous zones , and validates them by farm sampling. In step 1, the hectares flood are calculated by zone instead of by farm. For the subsequent steps, the sequence is unchanged.

LIMITATIONS
Non-relevance towards the Inondabilité method. The basic weakness of MAD lies on its conceptual nature: MAD expresses *the value of effective losses* associated to the observed statistical distribution of the hazard, or the value of potential losses if considering a given alternative distribution (for instance the one linked to a given modification of runoff). But both are essentially different from the concept of vulnerability developed in the Inondabilité method, i.e. as a *limit of acceptability*. On a both logical and practical ground, this dichotomy implies that it is not necessary to estimate MAD in order to make MAL explicit.
A synthetic but simple indicator. Nevertheless MAD cannot be completely by-passed from consideration. In the broader context of the Inondabilité method, discussions between partners may also take place surrounding the amount of actual or/and potential losses. In this respect, the conventional and unique indicator to refer for representing these losses synthetically (instead of punctual reference to some given particular flood) is MAD. But it must be recalled that a mean value of damage is far from reflecting the whole loss linked to the flood risk for the economic agent: it does not includes the loss specifically associated to (a) the *dispersion of alternative events* (especially: rare events vs. frequents ones) or (b) some particular *parameter* of inundation, or (c) some *particular value or interval* of this parameter - all other considerations than the simple mean and that the economist tries to include through the concepts of *risk aversion* and *ruin*, and he globally designates as the *cost of risk* or *cost of risk-bearing*.

3.3 Main items to be included in vulnerability assessment

From the above considerations the characteristics of a farm which would seem pertinent next to vulnerabiliy to flood pertain to three levels (ordered but interactive, as shown below).

3.3.1 Technico-economic conditions for the agricultural activity

They include inputs, outputs and the relationship between them. They can be taken as given restraints but also considered as levers and evolutive. A major of subset of information concerns the ***sensitivity of crop yield to various levels of the inundation parameters***; the perception of this sensitivity can also change with the actual experience of floods, and with the resources (or to be devoted) to adaptation.
At a second level, outputs and corresponding inputs are traduced in gross income and expenses, as usual.

3.3.2 The ability to absorb financial shocks

A second level of evaluation must consider the financial aspects of farm operation, as related to two objectives:

- ***social*** objective(s), in terms of a given level of desired net income for the family,
- ***economic*** objective, in terms of some level of productive capital to be achieved or maintained within a given time horizon, or of rate of capitalization.

The qualification of a farm in this respect is summarized by reference to a ***life-cycle*** principle: as a human being, every farm follows a vital cycle including some stages, defined in terms of capitalization (such as: elaboration → transition → stabilization-growth → fall or revival). To each of them, on can associate a more and less typical profile of financial outlays (occasional investments, recurrent debt payments, family intakes...) and incomings.

In this financial context, the ***impact of (effective or hypothetic) flood(s)*** takes place and eventually affects the previous evaluation of acceptable risk, based on a gross economic result from 3.3.1 above. Of two farmers supposed to have the same technico-economic profile (including total size, floodprone areas and identical hazards) and gross income:

- one will resist to the consequences of flood(s) [delay to obtain effective payment from insurance, net cost of damage, new investment for preventive adaptation] because he holds reserves (no longer debts, cumulative net savings),
- while the other cannot, because of a maximal debt ratio or/and familial needs, or/and potential from depressive prices.

Therefore, vulnerability must also depend on ***the potential for financial resistance.*** This judgment amounts to position the farm at some stage of its life cycle and identify the impact of hypothetic flood(s) and flood losses on this positioning.

3.3.3 Information-perception-response

Finally, the level of MAR depends on the specific way the farmer takes the hazard in account, in three steps:

1. which ***information*** (in quantity and quality) does he hold concerning the frequency of floods and other parameters, through personal experience of previous events or/and external sources,
2. for a given information system, does he ***perceive*** corresponding stake, to the point of having a willingness to include any consideration of flood risk in his "situation" (as either controlled or/and non controlled factors?) and his objectives?
3. in case of a positive perception, has he already acted, or would he intend to act to ***preventively adapt*** his farm and thus reduce his vulnerability. In other words, adaptation amonts to change the existing relation between MAR (in terms of parameter) and MAL (in terms of money), in order to allow:
    - either a greater MAL for a given MAR,
    - or a grater MAR for a same MAL.

3.4 Maximal method

3.4.1 The problem

On the ground level, a proposal of a general method for application in connection with the IM arouses two main symmetric difficulties: ***pertinence, feasibility.*** As the above considerations demonstrate, if the prior objective is full ***pertinence***, the micro-approach requires information on elements on the farm operation system - much more than those for calculating an MAD. The main point consists of relating a maximum acceptable ***risk*** (in terms of parameters) to a maximum acceptable ***loss*** (in monetary terms or percentage on it) via a series of intermediate variables and subrelations. These either can be (more or less) ***observable*** or/and inferred by a ***micro-economic reasoning***, or must be substituted by ***assumptions***. In each case, a choice has to be made by the user, according to both (a) the desired degree of accuracy and (b) the available delay for study and resources. Therefore we first propose a ***general scheme***, summarized as follows:

- the level of MAR (on a agricultural parcel) is defined as the limit value of inundation parameters such as the resulting ***loss of income*** would be equal to a ***given loss threshold***, depending mainly on the ***relative size of the parcel*** within the whole farm and on the ***technico-economic*** conditions of this,
- then this first result can be adjusted or if the ***financial potentiality*** of the farm is weak or high,
- similarly, a new adjustment can be introduced to include ***adaptative actions*** (effective or anticipated) in response to the flood risk as known and perceived by the farmer.

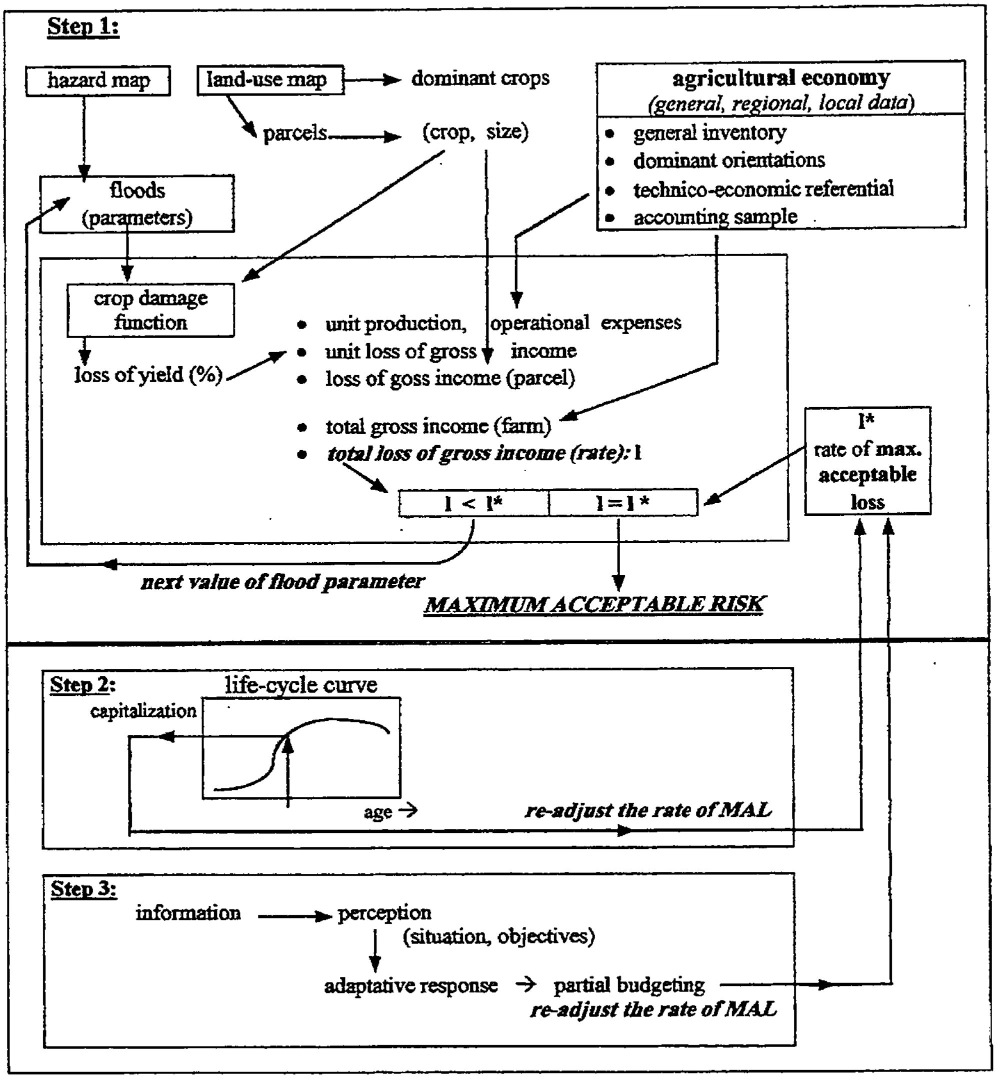
3.4.2 Main steps

The process is summarized as follows and synthetized on the figure 4.

❶ In a basic step, the ***level of MAR*** on a given parcel is defined as the limit value of inundation parameters such as the resulting ***loss of gross income*** would be equal to a ***given loss threshold.***

- The impact of inundation is captured through crop damage functions (in terms of rate of yield loss).
- The rate loss of gross income for the farm results from (a) the loss of gross income of the flooded parcel (i.e. variation of unit (per hectare) operational expenses and income X size of the parcel) and (b) the total gross income of the farm (estimated from the economic orientation and total land size).
- The loss threshold can be specified from general financial-bank ratios.

Fig. 4 - Identification of a maximum acceptable risk on an agricultural parcel from a micro-economic method



❷ In a second stage, the ***financial capacity*** of the farm is identified, and the previous loss threshold will be adjusted following whether this capacity is considered as significatively weak or high. This change of maximum loss restraint leads to revise the procedure 1 and produce a new level of MAR.

❸ Finally, the observer may have any reason to think that the farmer is (actually or potentially) sensitive to floods (as an actual or/and potential challenge for his economic-financial equilibrium), flood risk (through a synthetic appreciation) and flood risk management (with more or less preventive issues and a corresponding direct or indirect response), and that these considerations can take place in his situation or/and his project. Then a third step has to be implemented. It may consist in making ***scenarii of hazard*** and associating a method of ***partial budgeting***. This approach may identify an ***adaptative response***, for instance by reducing the actual loss for a given hazard (i.e. to change the damage relation), and thus to adjust the level of MAR upward.

3.5 Reduced method

3.5.1 Practical need

If the objective is to produce an initial information within a much more limited time restraint, the study man will probably not have time to engage an thorough investigation on every farm concerned by flood-prone parcels. Moreover, perhaps he will not need it, for instance since he has arguments to consider the whole floodplain or some portions of it as ***homogeneous***. Then he will limit such detailed study to a representative sample.

Indeed, the approaches may strongly contrast depending on the objective of the study in the decision process:

- if the need is to produce a synthetic value for great floodplain, the method can be reduced to a ***simple and largely indirect routine***,
- if, for any reason, the expected evaluation has to be much ***more accurate but spatially limited*** (for instance, to a little number of properties as object for a local negotiation), then one must implement a detailed inquiry, a more or less complex treatment and more or less interactions with the farmers themselves.

In conclusion, the study man will generaly have to ***adapt the ideal scheme***.

3.5.2 Practical rules

Therefore some practical and simple rules have to be formulated for this adaptation. They concern the ways to ***mix several sources of information***:

- direct inquiry at the farm level,
- indirect statistical information on farms,
- assumptions.

1. In every case, it is efficient to ***mobilize first the existing informations*** on farms at a local-regional level, coming from several sources:
    - standard general agricultural inventory: best accessibility, but random pertinence following the good or weak homogeneity of the local (community) agricultural land-use,
    - non standard analytic or synthetic studies from academic, administrative or professional sources.

2. While the step 3 needs a direct inquiry at the farm level in every case (at least in every case where it seems to afford a useful additional information), steps 1 and even 2 can be processed via a ***progressive procedure***, in order to benefit from the existing data from ***indirect sources***, supplemented by ***explicit assumptions***, each of them being next discussed, revised or/and (when feasible) substituted by new ground or sample data. For instance, to simulate a loss of total gross income by floods (step 1), one shall suppose that:
   - the dominant crops in the flood plain are the same as in the whole community,
   - the concerned farms are crop-oriented identically to the representative farm of the regional category,
   - the concerned farms have the same values of technico-economic items (crop yield, operational expenses, prices) as the mean (or other reference) farm of the category,
   - the rates of yield loss associated to the values of inundation parameters for the various crops are identical with those mentioned by the literature,
   - etc.
   - Similarly, in step 2, the age class of the farmer can be taken as a first proxy for a debt-ratio.
3. In every case, the study man will have to appreciate the degree of confidence of the results, by using ***sensitivity analysis***, and confront the accuracy of vulnerability results with this of the hazard ones.

To conclude, only many experiments can suggest a fair balance between the requirements more feasibility and the care for keeping the response pertinent.

4 Other items about the quantification of vulnerability

4.1 Non agricultural land-uses

Agriculture represents a polar case of good pertinence and feasibility for designing and applying a micro-economic approach to the maximum acceptable risk. Some reasons have already been mentioned in 3.1, but also others more technical but basic arguments will appear below. Concerning the other land-uses one usually meets in a more or less diversified flood-plain, what are the respective issues? They are summarized in the table of the figure 5.

The numerous non-agricultural land-uses or activities in a flood-plain (columns) have been grouped in six categories: ❷ to ❼. [The global typology, the particular items (designation, content and delineation) and their proposed ordering would deserve points and discussion, appealing to economic and non-economic, conceptual and pragmatic, detailed and general arguments.]

In order to explicit accurately the "profile" of each of them, a series of ***criteria for pertinence of a micro-economic approach*** are enuntiated (rows) in a sequence, almost similar to a lexicographic order. The agricultural case ❶, since now well known by the reader, can be taken as a reference. The agenda row draws conclusion. Notice that the qualification "*non pertinent*" relates only to the micro-economic approach to the MAR (i.e. via the concept of MAL) but, of course, not to the MAR itself. Moreover this last could perhaps find an objective justification from another approach than the strictly economic one, for instance by contributions in human or/and other social sciences (psychology, sociology, political science), but this perspective outpasses the field of the economist. (See LATEC, 1998a.)

4.2 The uses of vulnerability valuations

The above text has focussed on the identification of MAR from a micro-economic approach of the land-uses, especially of the agricultural one. But, as suggested in the figure 1, econometrics of prevention also includes utilizations of these measures in the study-and-decision process. This may cover a variety of contributions, enunciated in the table of the figure 6. (See Latec, 1998b and 1998c.)

Notes ot the figure 5
Rows: ④* Such as an inter-institutional special governance or coordination committee. ** Such as local (community or intercommunity) entity, general or sectoral.
Columns: ❶❻❼ Including some forests. ❹ Including transportation. ❻ Except the "true" natural zones, included in ❼. ❺ * Willingness-to-pay (contingent valuatin method (CVM) applied to risk). ❻ ** Recreation and sport grounds. ❼ * If physical data and relations fiable.

Fig. 5 - Micro-economic approach to maximum acceptable risk: test of pertinence for the different categories of land-uses

Criteria	❶ Agri-culture	❷ Industry	❸ Tertiary, market	❹ Utility networks	❺ Residence	❻ Non market services*	❼ Natural zones
① Does this land-use represents a major potential for a global and negotiated management of floodwaters?	Yes, essential.	No, except locally.	No, except locally.	No, except transportation	Globally: no.	No, except for some, locally **.	Yes.
② Has the activity an essentially market character?	Yes.	Yes.	Yes.	Mixed.	No.	No.	No.
Does it generate major (rel. to direct) indirect economic losses ?	-	Needs case studies.	Needs case studies.	Yes.	Intangibles, traduced in monetary terms (WTP*).	Needs case studies.	Some but not major.
③ Has a general concept of ruin a sense in the governance of the decision unit?	Yes.	Yes.	Yes.	Needs case studies.		No.	No.
Or a concept of non monetary loss ?	-	-	-			Needs c.s.	Perhaps yes.
④ Is there any identifiable agent?	Yes.	Yes.	Yes.	Yes + politicians and users.	Yes.	Yes + policitians and users.	Diverse.
If not, is there any secondary actor (ad hoc* or pre-existing**)?	-	-	-		-		
⑤ Does the activity imply specific require-ments toward submersion **parameters**?	Yes.	Needs case studies.	Needs case studies.	Yes.	Yes for tangibles, perhaps no for intang.	Needs case studies.	Negative (needs for floods).
Generated by whom: the actor ? experts ? scientists ?	The three.	In the present state: empty.	Present state: empty.	1.		Dispersed.	3.
⑥ Is it pertinent to relate hazard and (effective or hypothetical) loss?	Yes.	Needs case studies.	Needs case studies.	Yes.	A priori yes via a CVM procedure.	Needs case studies.	Needs case studies.
and to confront loss to an acceptable limit?	Yes			Yes if yes in ③.			
Agenda	**Quasi-operational**	**More ground-level research.**			**Non pertinent, except CVM (pioneer research).**		**Same as ❺ ❻. Benefits of floods.***

Fig. 6 - Utilizations of vulnerability results in the study-and-decision process

Stage of the study-and-decision process (*)	Use of vulnerability results
Pre-cartography of vulnerability	MAR as input to the vulnerability map.
Elaboration of alternative proposals for a new management scheme	MAR ordering of parcels gives a hierarchy of priorities for submersion by floodwater.
Same	Identification of economically feasible local storages of floodwater.
Same	Estimation of the total potential volume (and next: corresponding mitigation of downstream physical impact, and associated benefits in reduced damages).
Alternative scenarii for space-time distribution of floodwaters	Comparing benefit-cost potential performance, including agricultural losses (maximum acceptable, or/and mean, or/and flood-specific).
Negotiation between the public entity and the farmers concerned by a pre-project or project of flood levelling	Estimation of the maximum compensation the farmers would demand for accepting water on their lands.
Elaboration of local projects for preventive risk management	Benefit-cost analysis. Calculating (financial or other equivalent) fair compensations and including them as a cost element.
Post-flood or/and periodic retrospective evaluation of the global scheme and local projects	Confronting the actual losses and the expected ones, and assessing the efficiency and equity of compen-sations and of funding.
Water and watershed planning (including other stakes: resource, wetland conservation, recreation...)	Including the economic measures or/and qualitative arguments on vulnerability in global evaluations (at the hydrosystems level), as one of the cost elements, parallel with benefits elements (including benefits from floods, private and social)[if physical data and relations are fiable].
Parallel debates on urban-rural planning and various public or private sectoral projects at the regional and local levels	Similar inclusion, at the level of a specific pertinent region and decision system.

(*) *Following chronological order partially.*

Application of the Inondabilité method to the Riul Negru catchment (Romania)

Application de la méthode Inondabilité sur le bassin versant roumain du Riul Negru

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Abstract

The Inondabilité method, developed by the Cemagref, has been applied successfully on several French catchments. But the concept had not been tested in other countries before this case study on the Romanian Riul Negru basin.
This study shows that we can use with efficiency the QdF models and it put in evidence in this specific case an hydrological regime's change due to hydraulic works. The hydraulic modelling allows a description of the spread of the different floods (TAL), function of their return period. The land use is described in seven categories (urban zone, scattered settlement, forest, field, meadow, fallow and wetland) reduced to three categories of equivalent return period of objective of protection (TOP). The comparison of the hazard and the vulnerability in order to have the risk level shows a rather good situation, except for some local areas.
The concept of the Inondabilité method (Risk description, hydrological modelling, analysis of the land use) can be transferred without problem in such a basin. The lack of this study is that it has been built without local contacts: it should have been more benefit if the local authorities have been involved in this research.

Résumé

Cet article montre l'influence des aménagements sur le régime des eaux. L'analyse hydrologique montre qu'au-delà d'une variation des descripteurs hydrologiques, nous avons un réel changement de régime qui se traduit par de nouveaux modèles. Aussi, avec un régime climatique stationnaire mis en évidence par les analyses des stations pluviométriques, nous pouvons clairement identifier l'impact des travaux sur le régime hydrologique du Riul Negru. Ceci a notamment été possible par une situation bien particulière: des aménagements très lourds réalisés de façon ponctuelle. Cette situation est en quelque sorte caricaturale, mais bien significative.

1. Introduction

Forever in the world, people have settled near the rivers. They benefit essentially from the water resource. But floods are also part of the river regime. The floods produce then many economic damages but also some human losses.
To mitigate the consequences of the floods, there are several methods: prevention, forecasting and promotion of risk culture and they have to be used all together. The local specificity favours one but the others have to be taken into account. Here, we only deal with prevention, with the Inondabilité methodology. Its aim is to propose some land-use management to mitigate flood risks.

2. The Inondabilité method

The description of the flood risk in the Inondabilité method is based on several hypotheses and concepts:

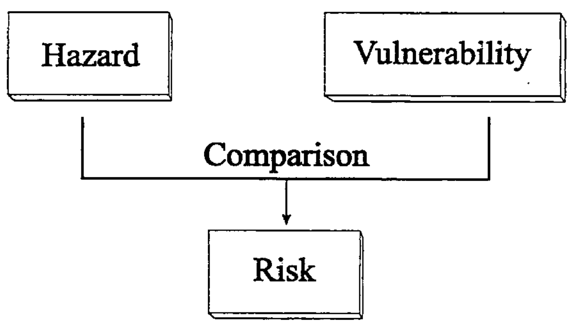
We can divide the risk in two components: hazard and vulnerability

$$Risk = \Delta\left(hazard, vuln\acute{e}rability\right)$$

Whenever all along the river, it exists a local zdF model.
Whenever all along the river, we have a biunivoque relationship between the discharge Q and the water depth z.
The hydrological phenomenon is continuous.

2.1 The concept of the risk

Fig. 1 - Definition of the Risk



The Inondabilité method is based on a decomposition of the risk in two components. The hazard that describes the natural hydro-meteorological events, usually expressed with hydrological parameters as their return period. It depends only on the flow regime of the river, independently of the land use of the flood plain. That is to say that the same flow will flood the same area with the same physical parameters, whatever should be the real land use.

The vulnerability that describes the sensitivity or the susceptibility of the land use to floods; this component is classically expressed in monetary units, as FF, £ or US$. It depends only on the type of land use and the social perception of risk. It can be different from an area to another, even for the same type of land use (local perception of risk), and can also evolve in time.

According to these two basic factors, a situation of risk is due to the incompatibility between hazard and vulnerability levels. And this comparison is possible because, instead of having a description of the vulnerability in monetary units, we propose to have a description of the objective of protection in hydrological units (T: return period, d: duration, p: water depth). This is possible by using synthetic hydrological models called flow-duration-frequency (QdF).

2.2 Risk mapping

As a result of the hazard modelling using Flow-duration-Frequency (QdF), hydraulic and topographical models, we obtain a map of the area flooded by each hydrographic of each return period.

Similarly we define the vulnerability, expressed in terms of return period, duration, depth, and transformed into an equivalent variable using the same QdF model.

Once we dispose of such a map of both hazard and vulnerability, we are able to spatially compare these two values putting in a prominent position.

Some places where hazard is greater than vulnerability: such plots will be colored in red to emphasize the problem.

Other places where hazard is lower than vulnerability: such plots will be colored in green showing that they are flooded but in a compatible way with their objectives or with their acceptable levels.

There are still some plots out of the largest flooded area, which are not flooded by the maximum known flow: such plots will be colored in yellow.

Such risk maps sum up the knowledge we have about the risk: summary of the hydrology of the catchment, summary of the hydraulic behavior of the river, and summary of the socio-economy of the area.

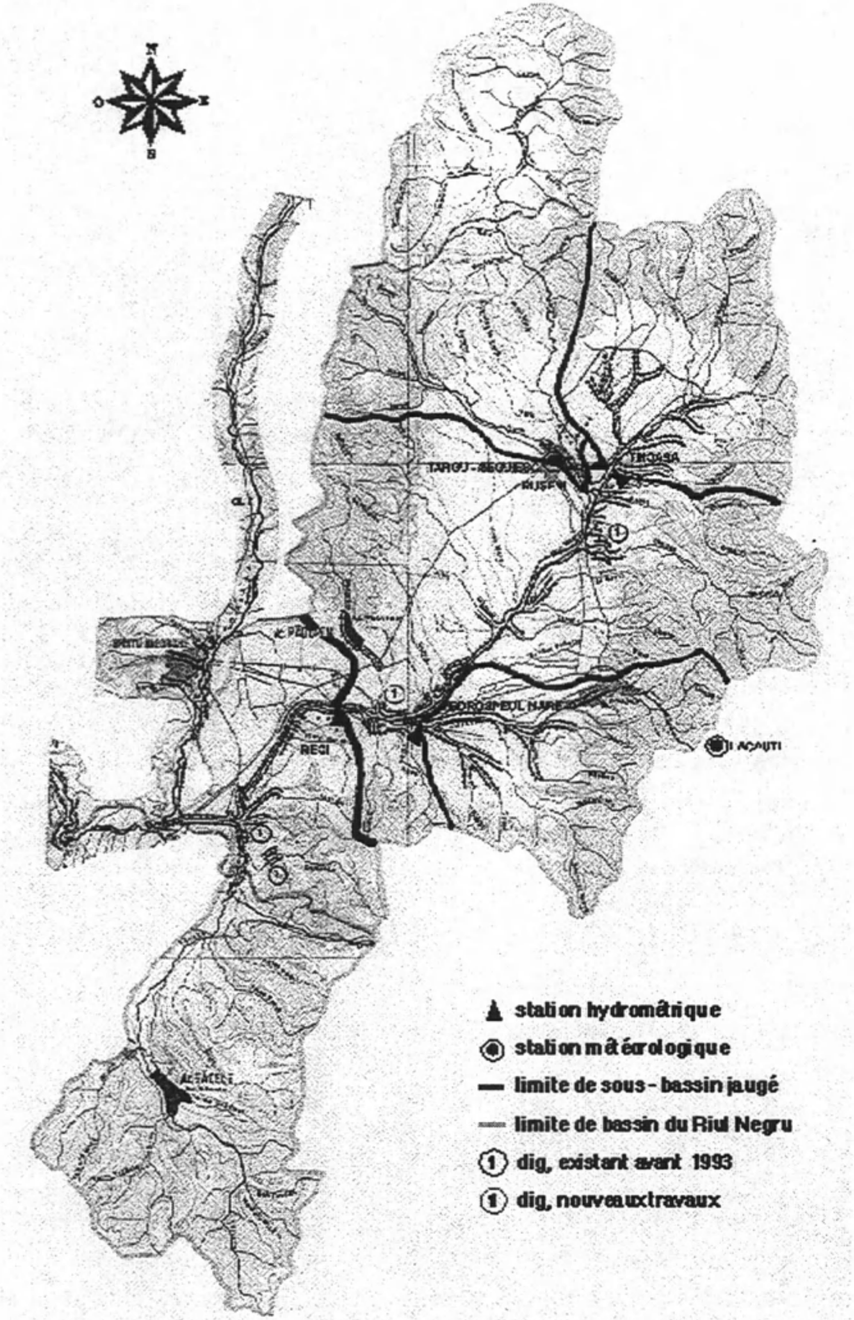
3. Presentation of the Riul Negru Basin

3.1 The Riul Negru catchment

The river Riul Negru is a tributary of the river Olt, itself a tributary of the river Danube. The Riul Negru catchement is located in the center of Romania and has a total area of 2320 km^2. Its elevation varies from 1280 m at its source to 500 m at its confluence, with a total length of 80 km. The river Riul Negru has five main tributaries on its left bank: Ojdula, Ghelnita, Zabala, Covasna and Tarlung and three on its right bank: Casin, Marcusa and Padureni.

The forest is mainly present on the upstream of the catchment (55%) and the land use is mainly rural at the downstream. There are few towns.

Fig. 2 - Riul Negru catchment



3.2 The main hydrological characteristic

The average yearly rainfall on the Riul Negru catchment is around 500 mm with some maxima in summer (June to August with 80 mm/month) and some minima from October to March (20 mm/month). The spring floods are generated by snowmelt and rainfalls. The summer floods are generated by intense and usually short rainfalls. The main floods since 1955 are given in table 1.

Table 1 - Main floods on the Riul Negru basin

Date / Station	Tinoasa	Ruseni	Borosneul Mare	Reci
May 1970	32.5	76.2	64	201
July 1975	82.2	**136**	**124**	206
August 1979	**110**	73.7	40.7	201
May 1981	100	100	110	**342**
May 1984	**104**	**102**	**128**	**387**
June 1988	39.1	47	122	312
May 1991	53.9	37.4	110	192

3.3 The available data

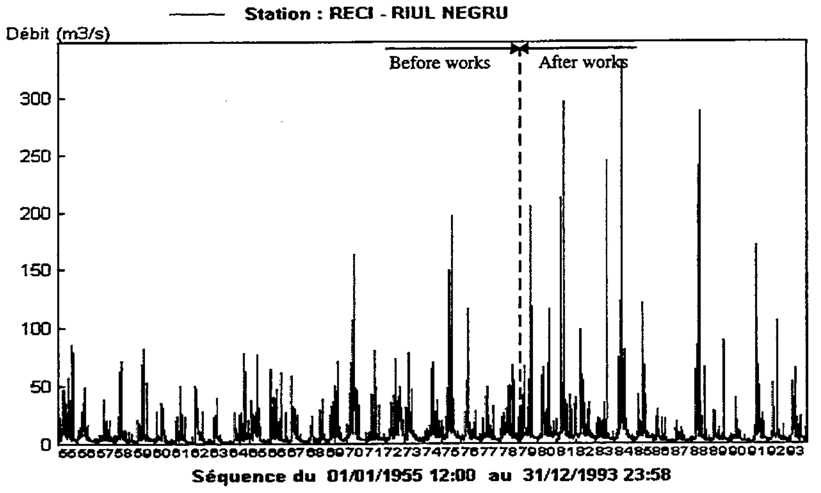
There is one meteorological station on the catchment at Targu-Secuiesc (568 m) with data for the period 1961-1995. Moreover, we have one more station just near the Riul Negru catchment, at Lacauti (1776 m), with data for the period 1956-1995. The recorded data are daily rainfalls.

We have also four hydrometric stations: two on the river Riul Negru (Tinoasa, Reci) and two on its tributary (Ruseni on the river Casin and Borosneul Mare on the river Covasna). The recorded data are the mean daily discharge completed with the maximum discharge in case of flood.

Table 2 - Hydrometric stations

River	Station	Period	S (km^2)	H (m)
Riul Negru	*Tinoasa*	1954-1993	293	825
Casin	*Ruseni*	1955-1993	476	830
Covasna	*Borosneul Mare*	1954-1993	239	739
Riul Negru	*Reci*	1955-1993	1672	760

Fig. 3 - Recorded data at Reci



3.4 The hydraulic works

Hydraulic works all along the river Riul Negru have been mainly done between 1975 and 1977. During this period, 64 km of dikes have been built to protect around 8000 ha of agricultural land. 53 km of dikes had been previously built since 1968 along the river. Now, we have 125 km of dikes on the river Riul Negru and 88 km on its tributaries.

The very short time during when the more influent hydraulic works have been done allows us to divide the period of the following hydrological analysis in two parts:

- 1955-1978: before hydraulic works (24 years);
- 1979-1993: after hydraulic works (25 years).

4. Hydrology

The hydrological analysis is based on several steps:

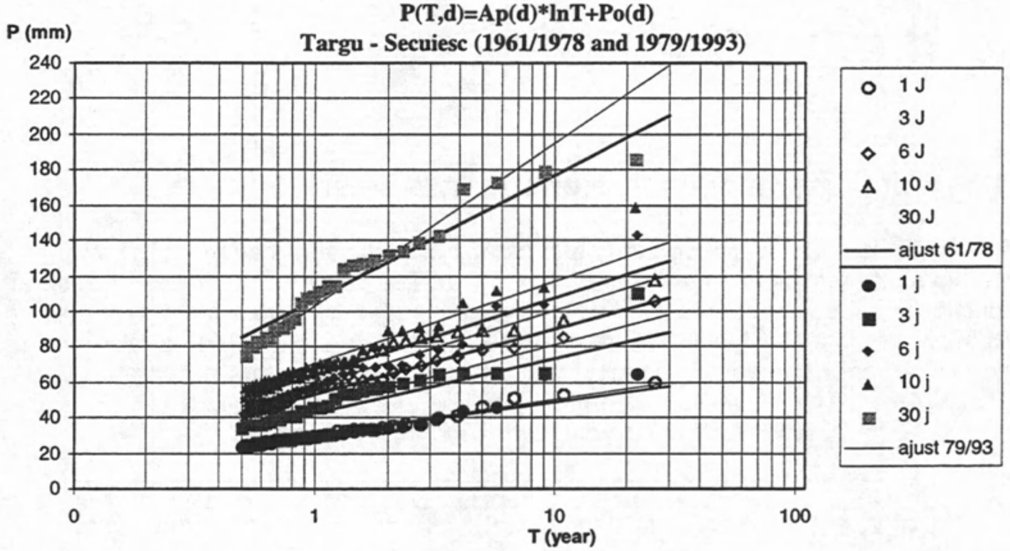
- Sampling of the variables VCXd, QCXd, PXd and the study of the stationary of the process;
- Adjustment and extrapolation of the different variables for different return period;
- Determination of the QIXA10 and the characteristic duration of floods;
- Choice of a reference model for the transfer of parameters all along the river.

4.1 Sampling

The method for sampling consists of the extraction of maximal values over a certain threshold, satisfying hypotheses of stationary-homogeneity, of independence of the events and of the Poisson law. We then use the method of renewal for the determination of the probability law of the yearly maxima. This analysis has been done before and after hydraulic works.

Concerning the rainfall process, we have analysed the monthly mean rainfall during the two periods for the Lacauti and Tergu-Secuiesc meteorological stations. It appears that we have little change but we can consider that we do not have a climatic change. The rainfall GRADEX for different durations are quite the same before and after works.

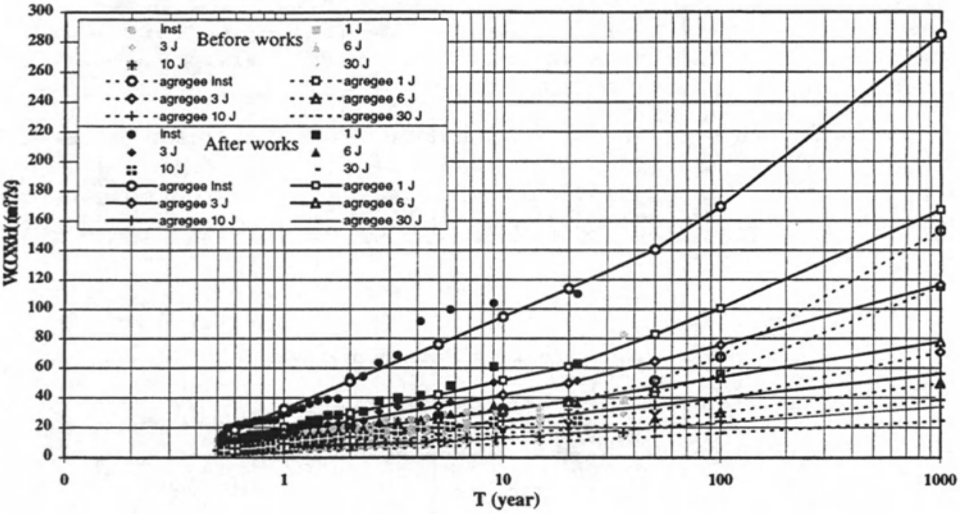
Fig. 4 - Adjustement with an exponentiel law



4.2 Adjustment and extrapolation

The adjustment and the extrapolation have been done using the AGREGEE method. We obtain a coherent and homogeneous curve faisceau of the distribution of the observed data and the extrapolated data with a law of two mixed exponential. These conclusions are true for the VCX, QIX and QCX variables. But for the discharge variables, there are main differences between the flow regime before works and the one after works.

Fig. 5 - Observations and extrapolations at TINOASA in VCX



4.3 Estimation of characteristic parameters

The analysis of the 4 hydrometric stations on the Riul Negru catchment shows that we have different values before and after works. The QIXA10, which expresses the function of production of the catchment, increases after the hydraulic works, essentially on the river Riul Negru where the works had been the most important. The D decreases after the works, expressing the fact that the transfers are faster due to chenalization. The results are summed up on the following table.

Table 3: QIXA10 and D before and after hydraulic works

River	Station	Period	QIXA10 (m3/s)	D (h)
Riul Negru	TINOASA	1954/1978	32.4	39
		1979/1993	94.9	22
Casin	RUSENI	1955/1978	70.2	30
		1979/1993	82.9	30
Covasna	BOROSNEUL	1954/1978	76.4	20
	MARE	1979/1993	121.3	18
Riul Negru	RECI	1955/1978	147.3	60
		1979/1993	338.6	50

4.4 Choice of models

To translate the description of the hydrological regime obtained on the hydrometric stations in other points of the river Riul Negru, we need to have a calibrated QdF model. We have different models function of the period. We have a majority of Soyans model before the hydraulic work (the floods are rather slow) and a majority of Florac models for the period 1979-1993 (the floods are faster).

Table 4 - Hydrological models

	Before hydraulic works			After hydraulic works		
STATION	*D (h)*	*QIXA10 (m^3/s)*	*Model*	*D (h)*	*QIXA10 (m^3/s)*	*Model*
TINOASA	39	32.4	**SOYANS**	22	94.9	**FLORAC**
RUSENI	30	70.2	**SOYANS**	30	82.9	**SOYANS**
BOROSNEUL MARE	20	76.4	**FLORAC**	18	121.3	**FLORAC**
RECI	60	147.3	**SOYANS**	50	338.6	**FLORAC**

4.5 Discussion

The hydrological analysis shows two essential elements:

- We have a good modelling of the hydrological regime using the QdF models (Soyans, Florac and Vandenesse). Even if they have been calibrated in France, it appears that they can be successfully used in other countries as Romania.
- We can put in evidence the influence of hydraulic works on the river regime. The modification of the riverbed has consequences on the characteristic parameters of the river Riul Negru (QIXA10 and D) but also, and it is essential, on the hydrological regime. After the hydraulic works, we do not have a description with the Soyans model but with the Florac one.

5. Hydraulics

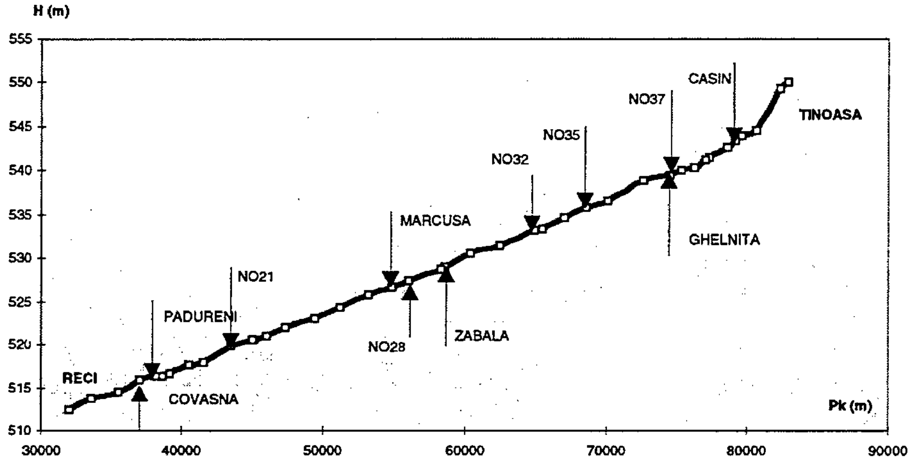
A hydraulic modelling has been done to calculate and map the spread of the different floods. The calculation has been done for 8 return periods: 2, 5, 10, 25, 50, 100, 500 and 1000 years. We choose to modelize the river before the works for two reasons:

- We do not have the nowadays topography. We only have cross-sections established on the river before 1968.
- With a modelling before the hydraulic works, we can evaluate if the decisions taken in the 70's were the good ones.

5.1 The hydraulic data

To modelize the river Negru, the first step is the definition of the different nodes and reachs. The river is divided into 12 reachs with six main tributaries and five specific points modelised as compartments. The next figure shows the long profile of the river Riul Negru with its decomposition.

Fig. 6 - Long profile of the river Riul Negru



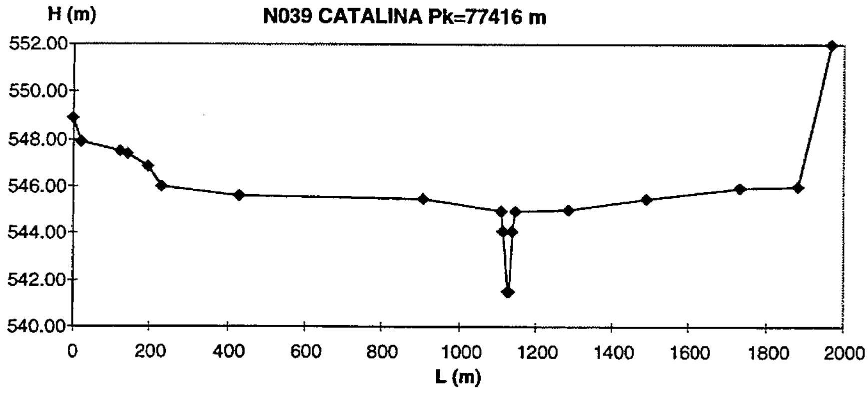
5.1.1 Hydrological input

For the hydraulic modelling, we need to have inputs for the tributaries and lateral input between these tributaries. These data are calculated from the previous hydrological description. We have, for each return period, specific hydrographs.

5.1.2 The topography

The description of the topography of the river Riul Negru, and specifically its minor bed, is realized with cross-sections. We have 38 cross-sections for the 51 km of the modelised river.

Fig. 7 - cross section pk=77416 m

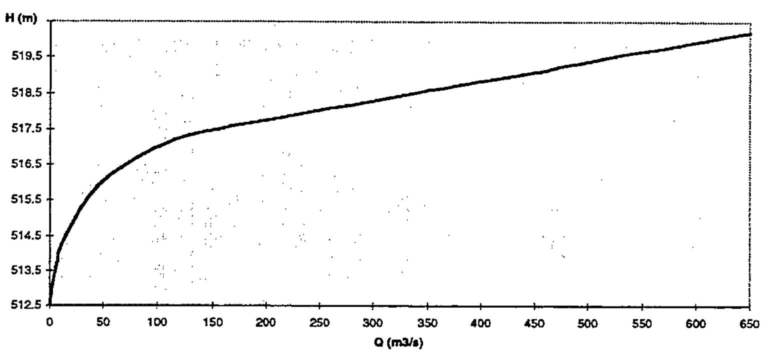


This description is completed with 8 bridges that have an influence on the flows during the floods. These bridges are modelised with orifice-weir laws.
We dispose of a water depth-volume law for the description of the 6 compartments.

5.1.3 The downstream condition

We use the hydrometric station of Reci for the downstream condition. We have at this cross-section a rating curve to complete the data.

Fig. 8 - Rating curve at Reci



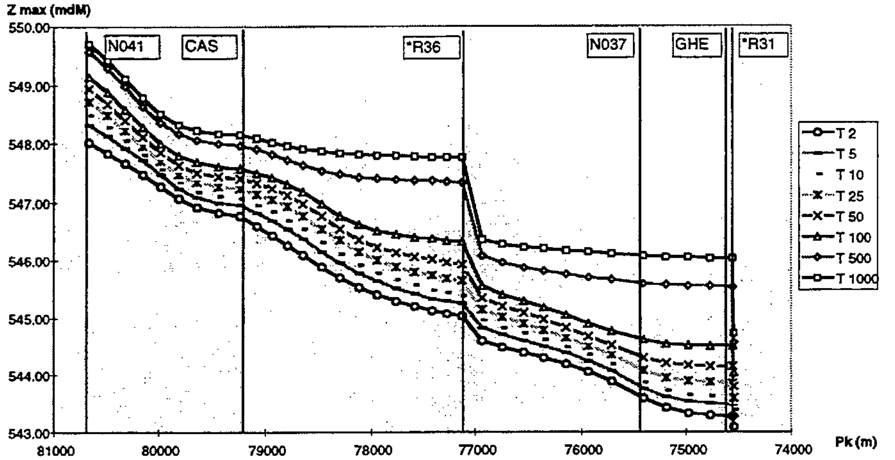
5.1.4 Calibration

The calibration of the model has been done with the knowledge of the Strickler parameter. A previous model had been done in the 80's and we use the same K parameter because we do not have the measured levels of different inundations.

5.2 The results

It appears that the topographical description is not as good as we could think because the river Riul Negru overflows on its main course from the return period of 2 years. More over, the bridges are in charge from the return period of 2 years that is not credible.

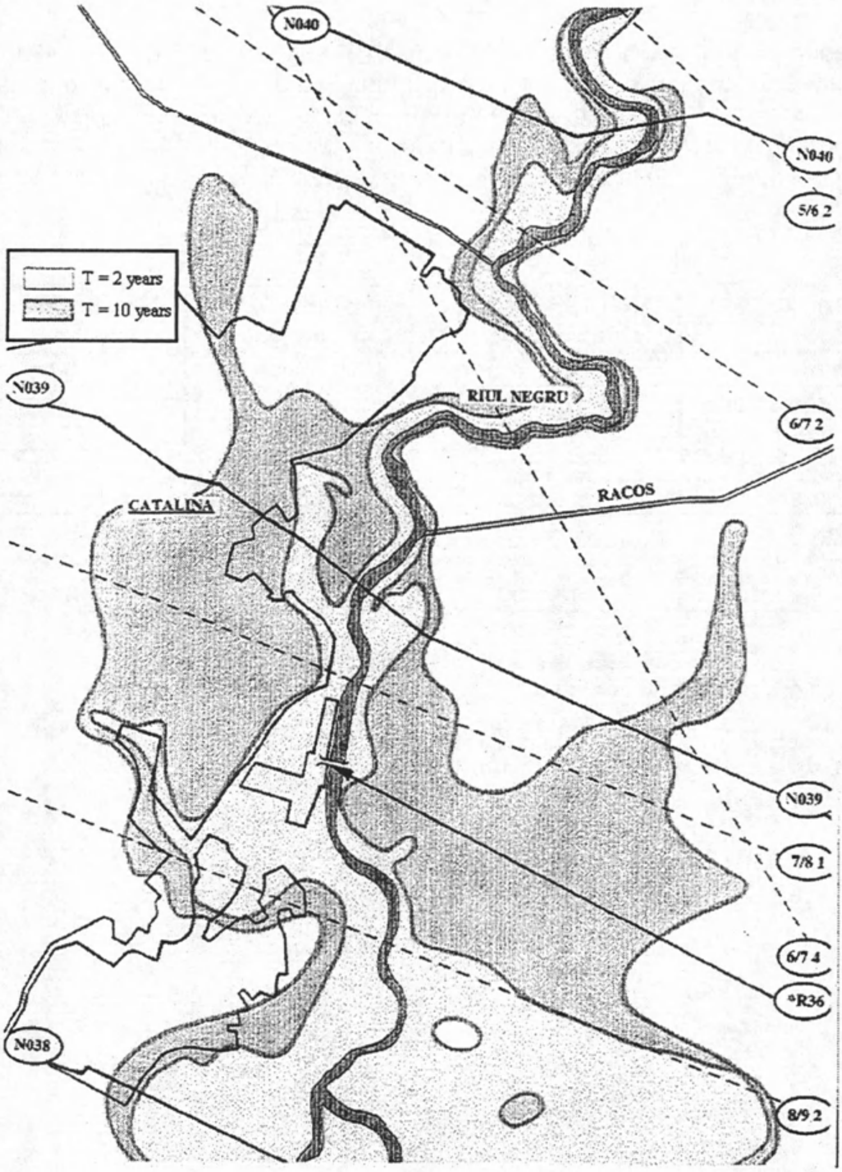
*Fig. 9 - water levels (Zmax) between N041 (downstream Odjula) and *R31 (Bridge SNCFR Ghelnita)*



Nevertheless, despite this lack of relevant data, we have a coherent modelling all along the river Riul Negru. We obtain at the last cross-section a final hydrogramme that is not far from the one calculated from hydrological data.

For the following risk analysis, we have limited the studied area between the river Casin and the river Ghelnita.

Fig. 10 - Map of the hazard



6. Risk

6.1 The vulnerability

The description of the land use is done with Romanian maps. We distinguished seven specific land uses. And for each land use, we give an objective of protection. Because of the distance of the basin (the modelling has been done in France), we could not have local reviews. So, we use for the description of the maximal risk acceptance some French standards. These are given in the following table:

Table 5 - Objectives of protection

Land use	Return period of submersion	Duration of the submersion	Water depth of the submersion
Urban zone	100 years	instantaneous	0 cm
Scattered settle-ment	10 years	instantaneous	0 cm
Field	5 years	1 day	0 cm
Forest	5 years	2 day	20 cm
Meadow	2 years	2 days	20 cm
Fallow	1 year	1 day	20 cm
wetland	1 year	5 days	40 cm

Using the QdF local curves, we determine the vulnerability. It appears that we are limited with 3 different values:

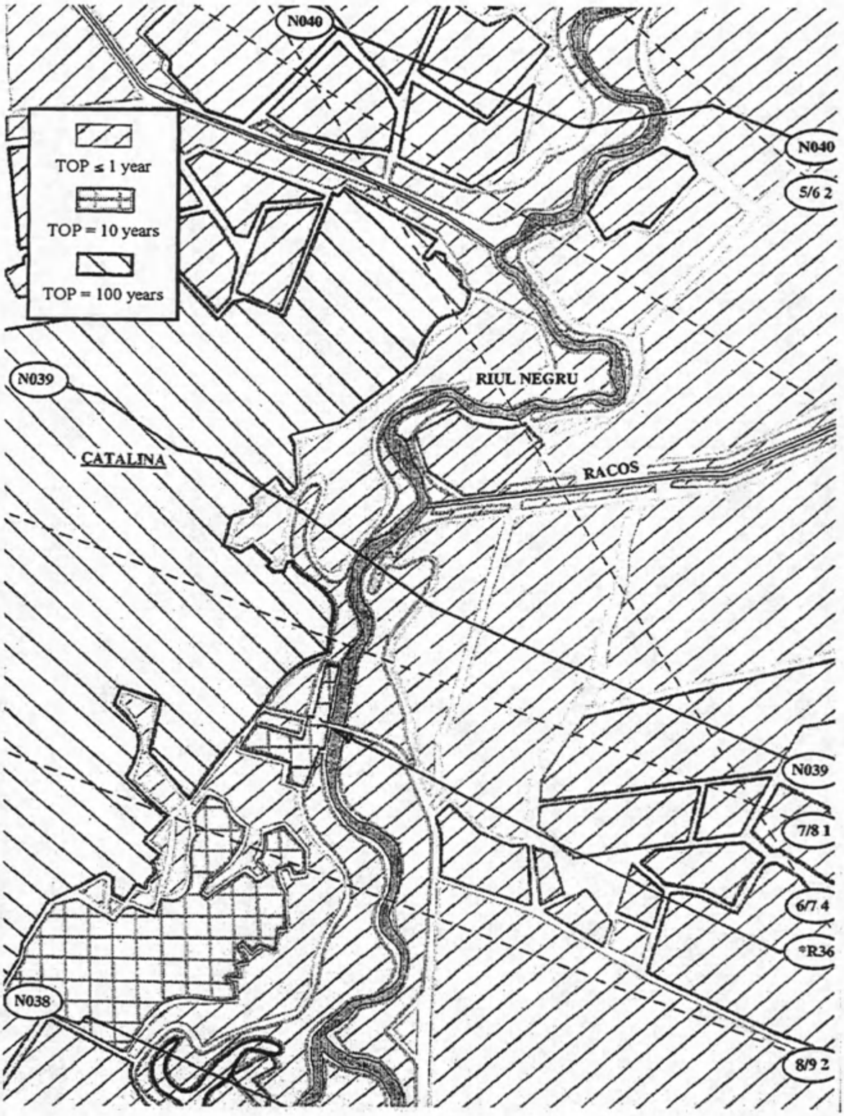
TOP ≤ 1 for field, forest, meadow, fallow and wetland

TOP = 10 for scattered settlement

TOP = 100 for urban zone

The final result is the following vulnerability map.

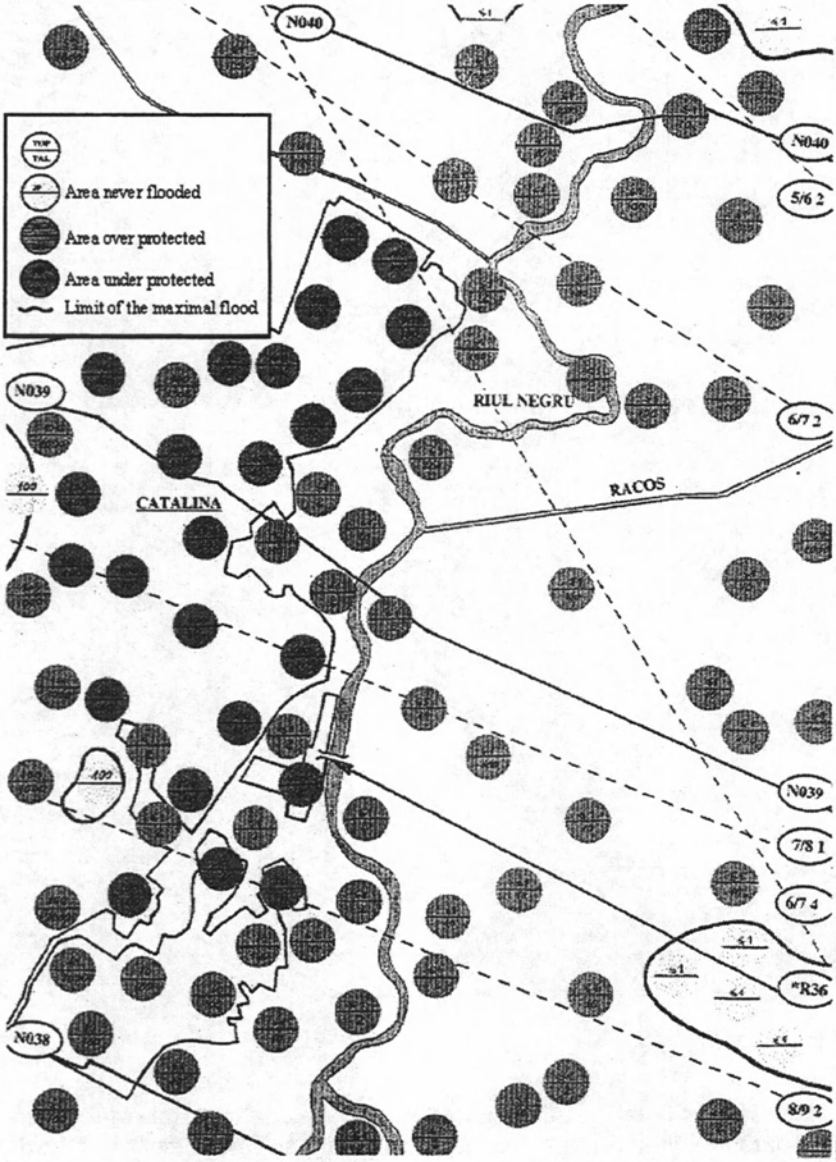
Fig. 11 - Vulnerability map



6.2 The risk map

To estimate the risk level, we then compare the hazard map and the vulnerability map. It appears that we do not have many risky areas. The ones concerned are the urban zones. But they can be easily protected with dikes, built only on the side of the town. The floods can then spreads on the other side. By this way, we limit the consequences downstream, we reduce the costs of the construction and we preserve the groundwater layer. Unfortunately, an another solution had been retained a few years ago and they built the dikes on the two sides of the river Riul Negru.

Fig. 12 - Risk map



7. Conclusion

To quantify the flood risk, we have to estimate the hazard and the vulnerability.

The hazard is classically computed with hydraulic models.

The needs of protection result from compromises between various factors such as flood damages, flood tolerance, flood benefits, environmental and economic values...

The Inondabilité method is based on this concept and has essentially been applied in France. The study of the Riul Negru basin shows that it can be used in other countries. As we have done the modelling in France, there were no negotiations about the objective of protection with the local concerned people. But we easily imagine that it will just modify the TOP parameters but it would not throw the method back into question.

Moreover, the specificity of the river Riul Negru with important hydraulic works realised in a short time put into evidence the influence of river management on the river hydrological regime. We do not have only a modification of some characteristic parameters, but the whole regime change on the river. And we have quantified it.

Thanks to that point, we learn a great deal from this example and it will be very useful for further research.

Perception of flood danger dependency on the site of living

Perception du risque d'inondation : influence du lieu d'habitation

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Abstract
The Slovenian contribution on FLOODAWARE is report about our recent research on inhabitants perception of flood danger and behavior concerning floods. Only a part of the data is presented here. We were interested how site of living (flooded vs. non-flooded) influences people's opinion. Therefore inhabitants from flooded and non-flooded parts of small Slovenian town Celje were questioned about the danger of floods and relevant behavior concerning prevention or mitigation of flood consequences.

Résumé
Ce rapport présente nos recherches sur la perception du risque d'inondation et le comportement des habitants face aux inondations. Seule une partie du travail est présentée ici. Nous avons cherché à comprendre comment le lieu d'habitation (inondable vs. non-inondable) influençait l'opinion des populations. Ainsi, les habitants de zones inondables et non-inondables de la petite ville slovène de Celje ont été interrogés sur le risque d'inondation et le comportement approprié en matière de prévention et réduction des conséquences des inondations.

1. Method

1.1 Subjects

Altogether 150 subjects participated in the research. Fifty were from the Center of the town, which was not threatened by the floods in the past, while two groups of fifty persons were taken from the often flooded parts of the town, Glazija and Lisce, located on the west and north-west of the town center, closer to the river. In average subjects were aged 43,03 years (from 17 to 77 years), 71 were males and 79 females. They were of all educational levels, though secondary school education prevailed (52%). There were 62% married, 27.33 % single, 8.67 % widowed and 2% divorced subjects. In average there were 3,10 members of the housekeeping (from 1 to 7 members).

1.2 Material

The questionnaire consisted of the 18, mainly closed type questions. Subjects were questioned about the frequency and possibility of floods, how much they are concerned because of this, about the floods' characteristics, about counter measures, about responsibility for taking measures, about insurance and reimbursement, and about warning. On the town map they had to circle all those parts of the town they thought that are threatened because of floods. Also some questions concerning demographic variables were included.

1.3 Procedure

Inquiry was carried out individually in the homes of subjects in the first part of December. Though the weather was rainy during the part of the inquiry, there was no flood in that time in this place.

2. Area description

Investigations were going on areas presented on figure 1. Center is in medieval part of town and out of flooded area. The inhabitants suffered because surrounding parts are flooded but they and their property are out of dangerous.

Glazija, area on north-west from Center have been settled in past hundred years. Urban area is half kilometers far from river bed and embankment. Inhabitants suffered from flood in 1990, but area is not frequently threaten by floods.

Lisce, area on west from Center is in inundation of river protected by levees. The areas have been settled in past thirty years on frequently flooded surface. The inhabitants are very familiar with water regime in river, which they could survey through window in living room.

3. Results and discussion

Subjects experienced different number of floods, what was clearly dependent on the region of the town where they used to live. Also some of the inhabitants of the floods safe area in the town center experienced floods, though in much lesser degree. It is evident that experience with floods influences estimation of the future floods only to a certain degree. The estimation of the subjects from the safe area was between the estimation of the subjects from the flood prone areas of the town. The range of this estimation was between zero and 40. It must be mention that the estimation of the number of future floods was for the whole town and not only for subjects neighborhoods.

Subjects from the flood prone areas of town were more concerned because of possible floods than the people from the safe areas. Differences were statistically significant, though not so great. In principle all subjects were concerned because of the future floods.

Fig. 1 - Celje - map of flooded area

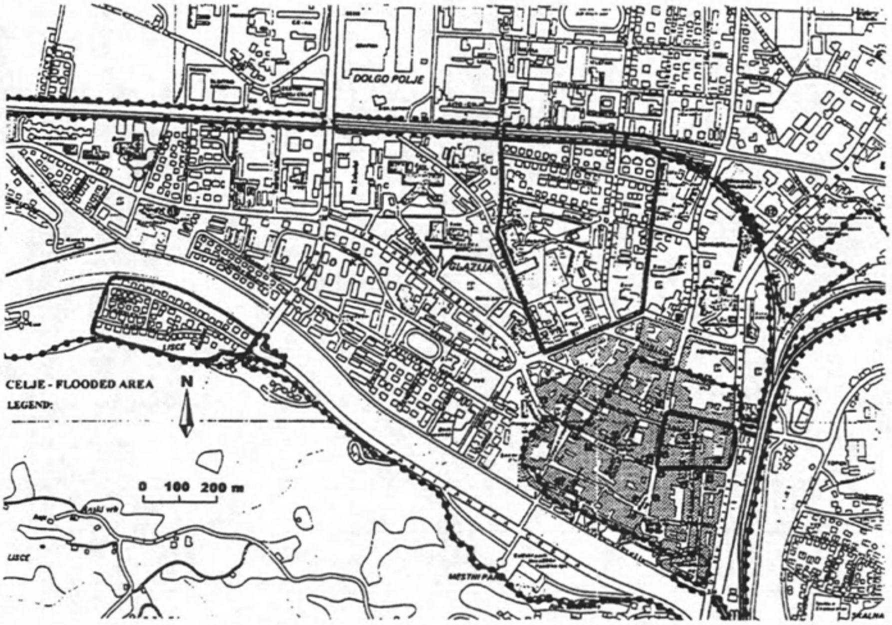


Fig. 2

Freguency of floods of home, work place and frequency of possible floods in Celje in future ten years

Rao R (6,288)=3,17; p<,0050

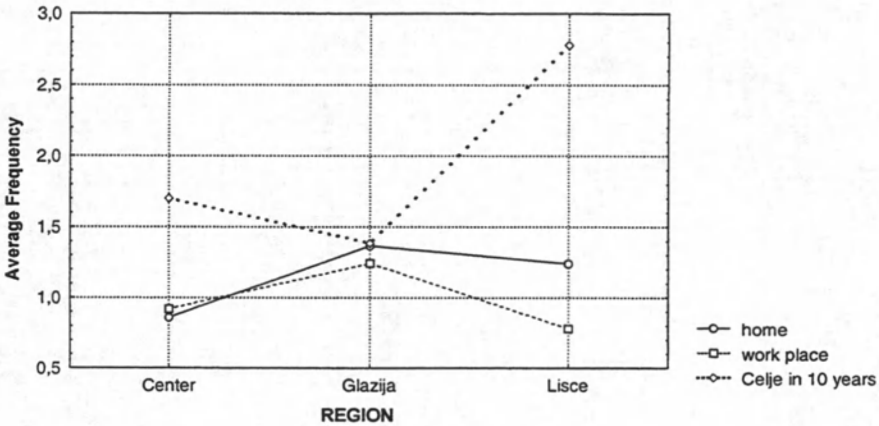
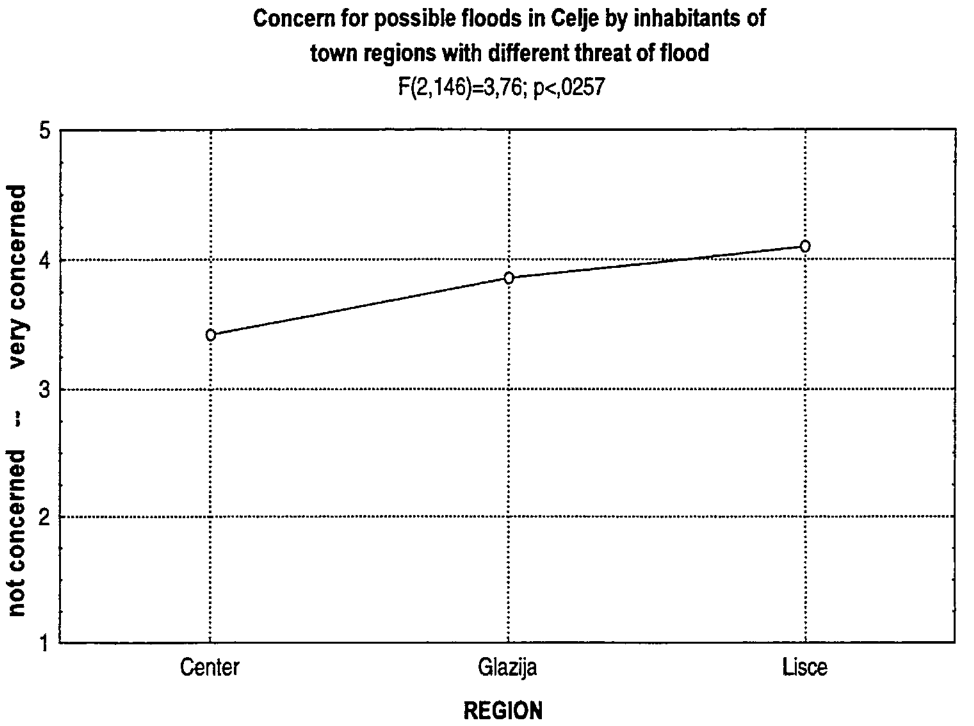
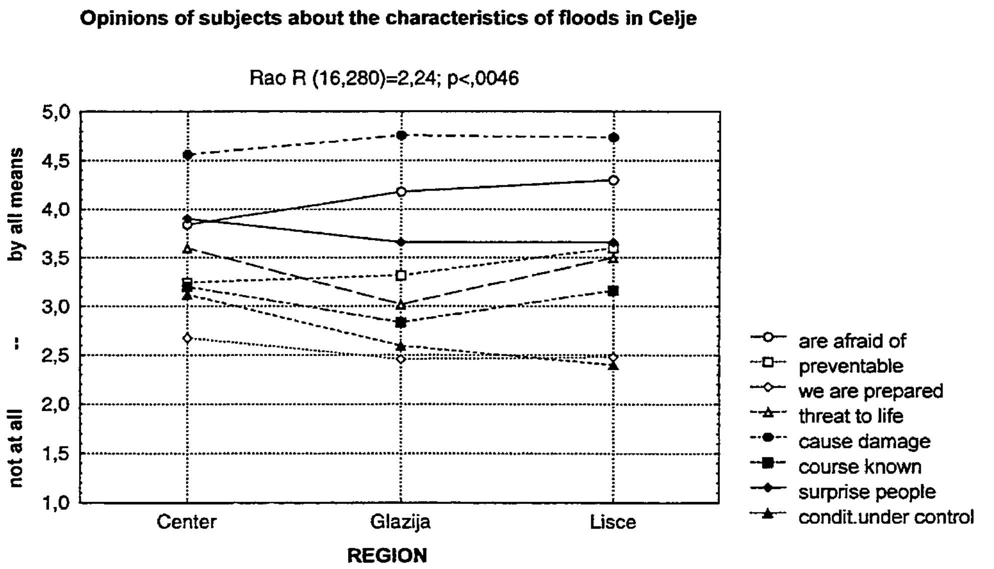


Fig. 3



Concern for possible floods in Celje by inhabitants of
town regions with different threat of flood
F(2,146)=3,76; p<,0257
5
4
3
2
1
not concerned -- very concerned
Center
Glazija
Lisce
REGION

Fig. 4



Opinions of subjects about the characteristics of floods in Celje
Rao R (16,280)=2,24; p<,0046
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
not at all -- by all means
Center
Glazija
Lisce
REGION
are afraid of
preventable
we are prepared
threat to life
cause damage
course known
surprise people
condit.under control

Subjects did not differ a lot concerning flood characteristics. Interesting difference is, that subjects from the safe area thought that during floods situation is more under control, than other two groups. Floods certainly brought damage and people are afraid of them, more so the people from flood prone areas.

Fig. 5

Readiness for different countermeasures

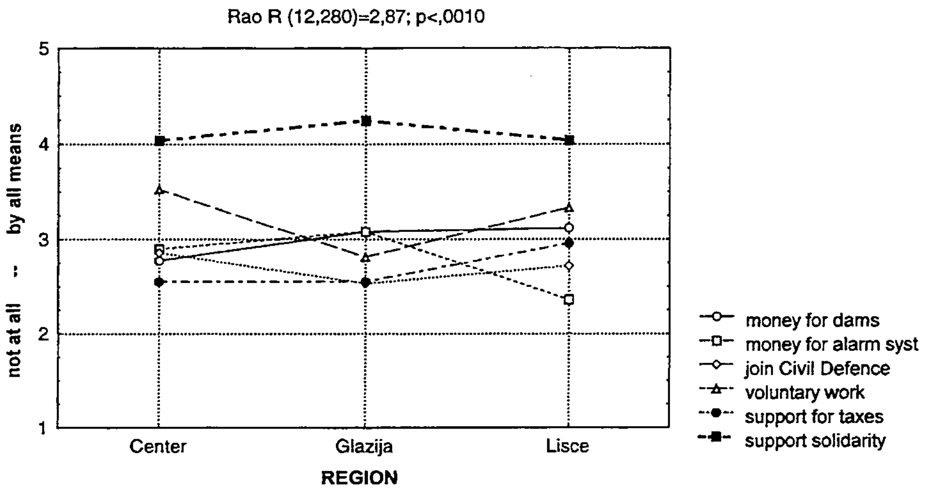


Fig. 6

Measures to prevent or mitigate flood consequences

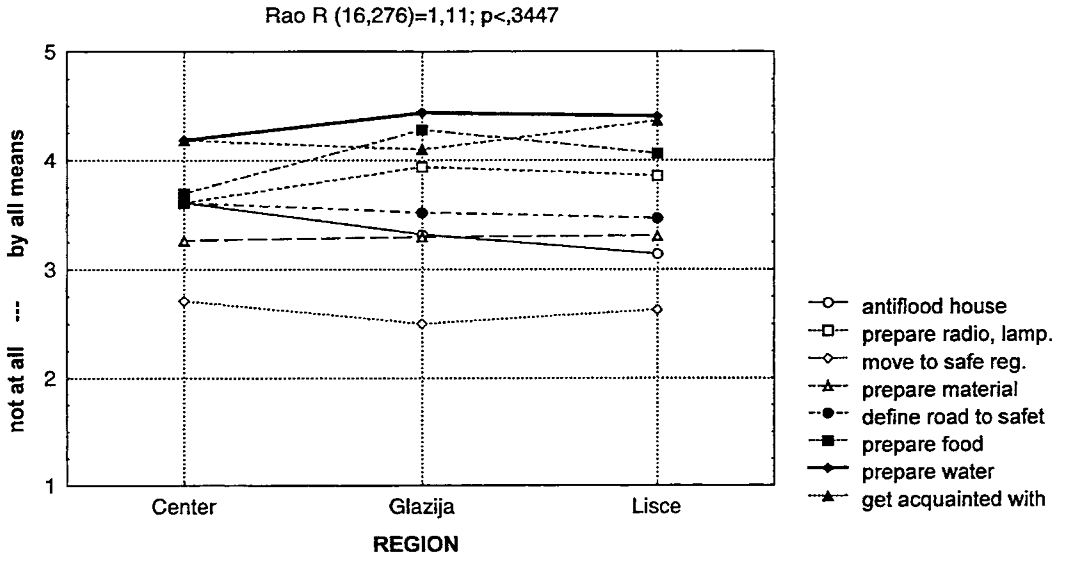
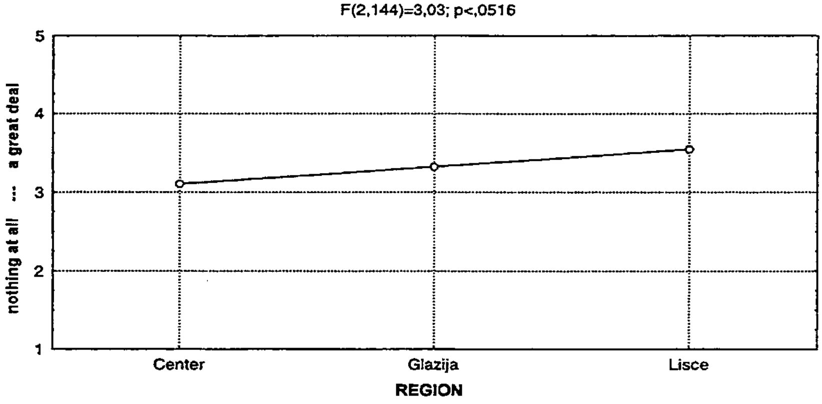


Fig. 7

Knowledge about behavior during the flood



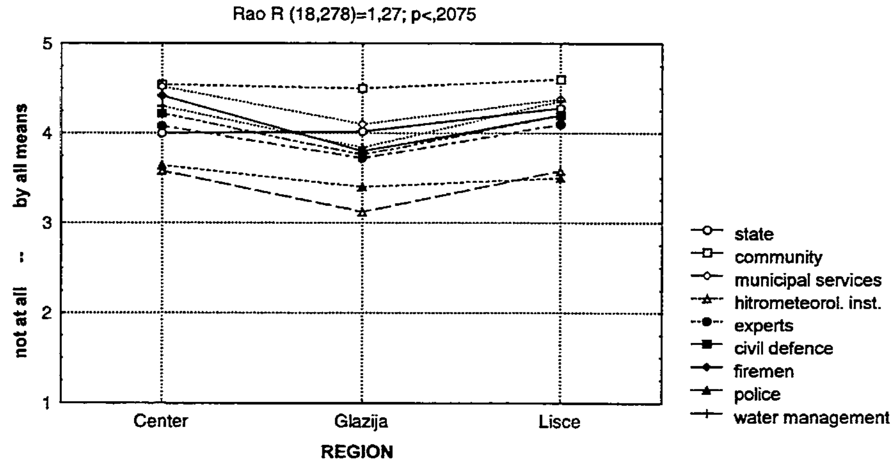
Subjects from all areas would support collecting of solidarity help, and in a lesser degree all other measures. There were not great differences between people from flood prone and flood safe areas.

Regarding flood consequences prevention and mitigation subject would mainly prefer to get acquainted with possible course of the flood, prepare food and water etc. They are not very prone to move to a flood safe area.

Subjects from the flood prone areas estimated their own knowledge about behavior during the flood as greater than subjects from the safe area, though the differences were not so great and were at the limit of significance.

Fig. 8

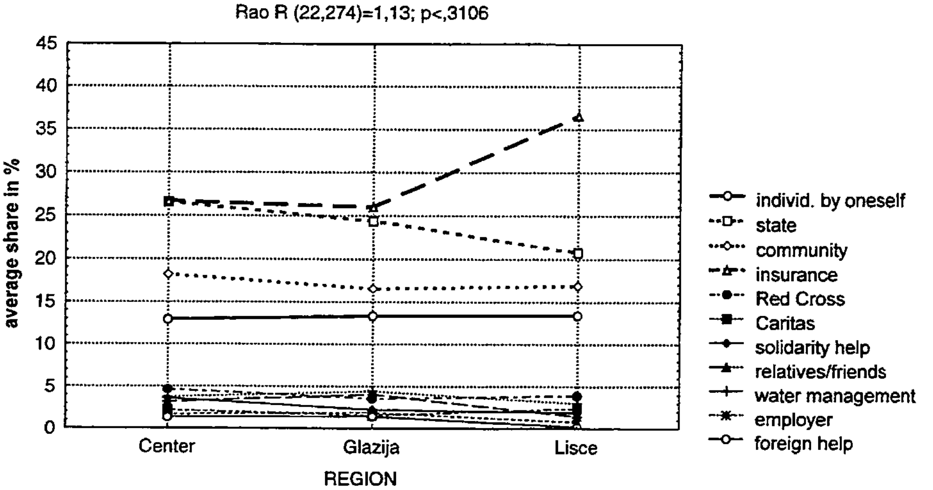
Responsibility for the flood management



Respondents thought that a number of institutions had the responsibility for taking measures during the floods, but the greater is for local community, and the least for institute of hidrometeorology and police. Region of living did not significantly affects these opinions.

Fig. 9

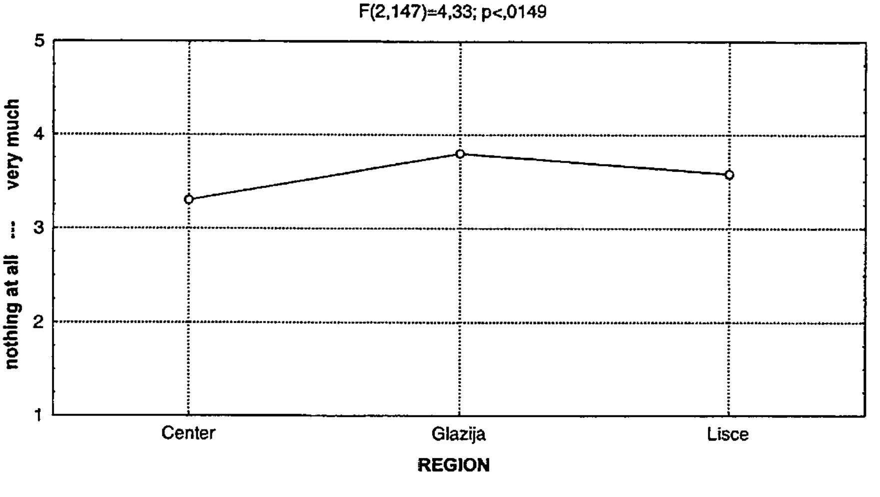
Sources of flood damage reimbursement



Insurance, state, community, and individual himself (in that order) were perceived as the main sources of flood damage reimbursement.

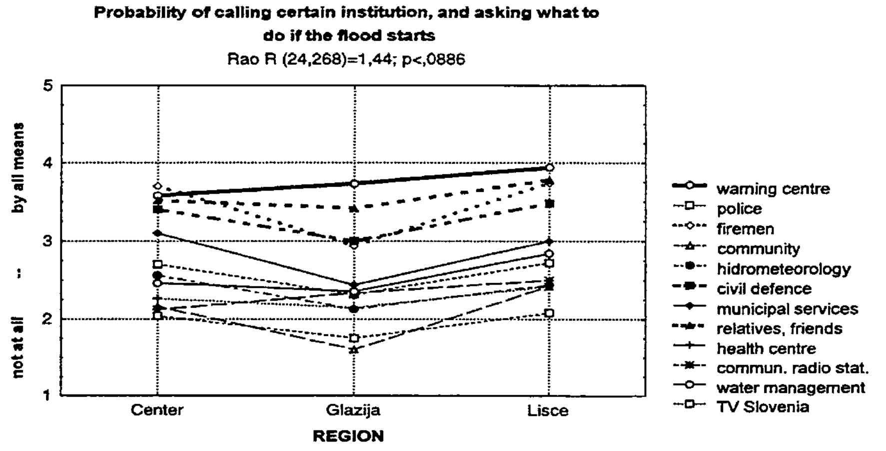
Fig. 10

Confidence in weather and floods forecast in mass media



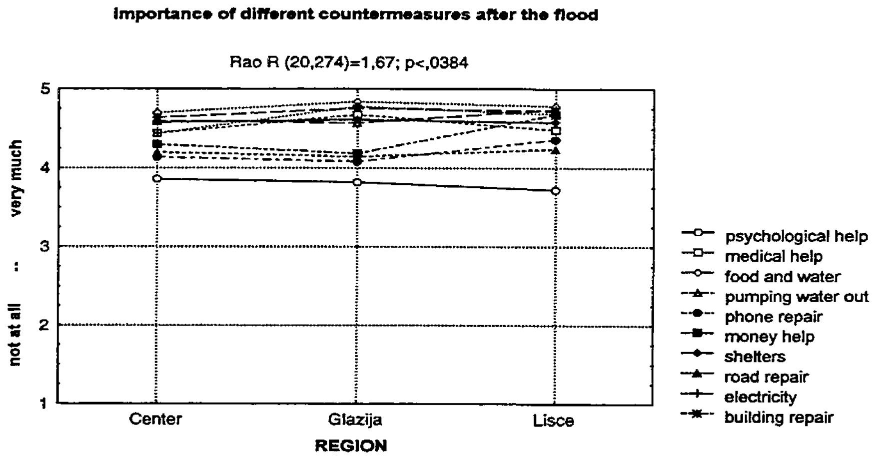
Subjects from the flood prone areas had greater confidence to weather and floods forecast than people from the flood safe area. Differences were statistically significant, though not so great. The difference is perhaps caused by the simple reason that people from the flood prone areas are more dependent on these forecasts.

Fig. 11



After the start of the flood subjects would mainly call warning centers (institution established in the last years), firemen, relatives and civil defense.

Fig. 12



All mentioned measures carried out after the flood was evaluated as highly important. the least so psychological help.

Acknowledgements: the authors wish to acknowledge the contribution of the Ministry of Science and Technology of Slovenia in funding much of this research and the Mayor of Celje who support us.

Stochastic structure of rainfall at a point

Modèle stochastique des précipitations en un point donné

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Abstract

A stochastic model of the rainfall process at a point should be able to describe behaviour of rainfall in time, and therefore should have the ability to statistically match the historical record, at different time levels of aggregation. In this research an application of the Bartlett-Lewis modified rectangular pulses model has been done, using historical fine-resolution rainfall data observed during period 1927-1981 in Barcelona (Spain). The reported research shows that point processes – based stochastic models are capable of reproduce the basic statistics of interest describing rainfall temporal series defined with variable time level of aggregation, for typical Mediterranean conditions.

Résumé

Un modèle stochastique du processus pluviométrique devrait permettre de décrire le comportement de la pluie au cours du temps, et devrait pouvoir être validé statistiquement à différentes échelles de temps d'agrégation. Ce papier présente une application du modèle rectangulaire de Bartlett-Lewis, utilisant des données historiques à haute résolution pendant la période 1927-1981 dans la région de Barcelona (Spain). Les conclusions montrent qu'n modèle basé sur les processus stochastiques ponctuels sont capables de reproduire des chroniques de pluies qui sont statistiquement validées, à différentes échelles temporelles d'agrégation.

1. Introduction

A stochastic model of the rainfall process at a point should be able to describe behaviour of rainfall in time, and therefore should have the ability to statistically match the historical record, at different time levels of aggregation.

If the original available series were hourly rainfall records, for instance, it would be also available the daily series, obtained by simple aggregation, and any series with level of accumulation being multiple of one hour. Although all these records are obviously related, since they come from the same continuous rainfall process, they look very different, showing important variations in their structure and statistical properties.

Therefore, a mathematical model statistically matching the historical statistics for the daily record, could be also absolutely inadequate for modelling hourly rainfall. This comes to be one more aspect of the well-known *scale-problem.*

For hydrological application purposes, and particularly flood applications, several hydrologic and geomorphologic factors determine the scale of interest in each case. This fact makes it necessary to attempt the construction of rainfall models reproducing historical records through a continuum of levels of aggregation, with a unique set of parameters, independent of the time-scale.

This approach has important practical implications, because it allows for aggregation-disaggregation in rainfall series, to obtain inferences and deductions at different time scales. When extreme rainfall events are the main objective, relations between maximum expected values for different duration (IDF curves) can be obtained via simulation. Finally, such mathematical tool can be used in order to go further in the study of the scale problem and its implications in hydrological response and flood problems.

The most successful models matching these requirements were formulated by the end of the 80's, and are still being explored as tools for applied hydrology. Their formulation is based on clustered point processes theory, incorporating a rectangular rain cell as the basic element of the process structure. [*Rodriguez-Iturbe*, 1986, 1987; *Entekhabi et al.*, 1989; *Islam*, 1990; *Burlando*, 1991; *Cowpertwait*, 1991; *Velgue et al.*, 1994].

The so called rectangular pulses models in their latest versions (mainly Neyman-Scott and Bartlett-Lewis models), exhibit some desirable properties for simulation application in rainfall time series:

a) They are able to preserve rainfall statistics (mean, variance, correlation, etc.) over a range of temporal scales of aggregation, which is strictly necessary if the model is to be used for inference at different time scales, mainly for disaggregation purposes.

b) The models, although essentially stochastic in nature, are physically realistic, in the sense that include as the basic element for model formulation rain cells, which are recognised as typical features of actual rainfall events, particularly those of convective origin.

c) The models are built according to cell's superposition procedures following point processes, and are capable of reproduce intermitency observed in real series.

d) They are mathematically tractable, since the statistics of maximum interest (mean, correlation, probability of rain=0, etc.) can be analytically obtained, and therefore the method of moments for parameter estimation can be used.

e) Finally, the models are flexible enough to satisfactory reproduce the zero depth probability for different aggregation times, a vital property if they are intended to be used as a tool for continuos simulation in time, reproducing the distribution of dry and wet periods.

Although these models are well established from a theoretical point of view, their applications so far have not been numerous, and remain far from being a common technique used in regular hydrologic problems involving simulation. Basically, this is because parameter estimation procedure yields to some numerical complexity, with high sensitivity of the procedure to the sets of moment equations used in the parameter estimation. Another inconvenient is that the required length and quality of data are not usually available.

On the other hand, the utility of this kind of models in the frame of extreme-rainfall analysis is still being explored.

Cowpertwait used in his work 10 years of hourly data in Blackpool, England. Rodriguez Iturbe, Febres de Power and Valdes (1987) used 27 years of hourly precipitation records in Denver, Colorado. The same data set was more recently used by Velgue, Troch, De Troch, and Van de Velde (1994). Burlando and Rosso (1991) used 24 years of hourly rainfall data from the Arno River, in central Italy. Recently an application using 15-min point rainfall data of Capella, in central Queensland (Australia) was presented. [Y. Gyasi-Agyei & G. R. Willgoose, 1997].

In regions along the Mediterranean coast of Spain, covering the East and South East of the Country, strong rainfall events take place typically during the months of September, October and November. At times they originate floods which can be of catastrophic consequences. Rainfall registers present in such cases some peculiarities, which question the adequacy of the Bartlett-Lewis kind of models. In this study we investigate whether or not the model is suitable in such cases. The two main characteristics of temporal rainfall series in these geographic areas are the dry-intervals dominance over the series, and the presence of high peaks associated with the occurrence of severe cells of short duration (less than 1 hour) originated by convective processes.

In this research an application of the Bartlett-Lewis modified rectangular pulses model has been done, using historical fine-resolution rainfall data observed during period 1927-1981 in Barcelona (Spain).

The results of the research concern the following points:

a) Estimation of monthly parameters of the Modified Bartlett-Lewis Rectangular Pulses Model (BL model) for the data provided by the Barcelona FLOODAWARE research group.

b) Validation of the model through indexes of goodness of fit, evaluating its capability to reproduce basic statistical properties of historical records, simultaneously at levels of aggregation ranging from ½ hour to 24 hours.

c) Evaluation of model's capability for reproducing dry-periods distribution, and external structure of the process, defined by the binary sequence dry-wet.

d) Evaluation of model's capability for reproducing extreme values distribution.

e) Testing the model as a disaggregation tool, using it for statistical inference of properties of the process in the hourly scale, with only daily rainfall available information.

2. Model description

The original Bartlett-Lewis model [*Rodriguez Iturbe et al.*, 1987, 1988; *Islam et al.*,1990] is built upon a cluster-based Poisson arrival of storms origins, with rate λ. Each storm is model in terms of cells occurring in time. The cell's time origins follow a second Poisson process at rate β, being each cell a rectangular pulse of random height and duration. This secondary process ends after a given time, exponentially distributed with parameter γ. Assuming that there is a cell associated with the storm origin, the number of cells per storm, C, follows a geometric distribution with mean $\mu_C=1+\beta/\gamma$. Finally, the cell duration is assumed to follow an exponential distribution with parameter η, and each cell depth is a random constant exponentially distributed with mean E[x]. Fig. 1 represents conceptual model building from cells in four steps.

For the application reported here, the Bartlett-Lewis rectangular pulses model is used in its extended version, or so call **modified Bartlett-Lewis rectangular pulses model** [*Rodriguez-Iturbe et al.*, 1988]. This extended version allows for different values of the cell duration parameter η from storm to storm, so that η follows a two-parameter gamma distribution with shape parameter α and scale parameter ν. As a consequence, the number of model parameters to be estimated is incremented in one. The family of parameters related to the model, and its meaning, are as follows: (two new dimensionless parameters, $\kappa=\beta/\eta$ and $\phi=\gamma/\eta$, are introduced for mathematical convenience).

■ Main parameters, to be estimated from data series

Parameter	Describes
λ	Poisson process governing storms arrivals
E[x]	Expected value of cell's depth
α	Shape parameter of η distribution
ν	Scale parameter of η distribution
$\kappa=\beta/\eta$	Dimensionless parameter
$\phi=\gamma/\eta$	Dimensionless parameter

■ Derived parameters

Parameter	Describes
β	Poisson process of cell's occurrences in a storm
γ	Cut off time of the second Poisson process
C	Number of cells per storm
μ_C	Expected number of cells per storm
η	Exponential distribution of cells duration in a storm

For the model described, [*Rodriguez-Iturbe et al.*,1987,1988; *Islam et al.*, 1990], obtained the second-order properties of the accumulated rainfall process over time intervals of variable lengh, in terms of the parameter values.

3. Parameter estimation

The *Universitat de Barcelona* partner of Floodaware Project, supplied the data used in this research project. It is a unique data set of great hydrologic value, coming from the Jardi pluviograph at the observatory of Barcelona (Spain), extending from year 1927 to year 1981. It consists on a sequence of rainfall intensity measures (mm/min), with short variable time increment (usually less than 2 minutes).

Such original series were converted to a set of different series defined with variable time levels of aggregation (intervals from ½ hour to 48 hours), and the most representative statistics (i.e. mean, varianza, covariance, correlation and probability of no-rainfall intervals) were computed for each month. A total of 432 statistics were then computed from the data series.

The parameters to be estimated for the Modified Bartlett-Lewis rectangular pulses model are λ, ν, α, E[X], ϕ, and κ. The method of moments [*Islam et al.*, 1990] is applied, by equating a combination of first and second order statistics from historical rainfall time series to their corresponding theoretical expressions derived from model formulation. As a result, a set of highly nonlinear equations with six unknowns has to be solved. Because the components have different orders of magnitude, they are first normalized, so the solution may be obtained through a simple unconstrained minimization (Powel's quadratically convergent method was used).

$$Z_{\min} = \min\left[\left(\frac{F_1(\xi)}{F_1^{'}}-1\right)^2+\left(\frac{F_2(\xi)}{F_2^{'}}-1\right)^2+.....+\left(\frac{F_n(\xi)}{F_n^{'}}-1\right)^2\right]$$

where **F'** is a vector of estimated statistics at different levels of aggregation and **F** is the vector for historical statistics at the same levels. **F** is function of the parameter vector ξ= (λ, α, E[X], ϕ, κ).

The combination which produced better results for Barcelona data include the following six moments:

Hour	Mean	Variance	Covariance	Prob(zero rain)
0.5	❖	❖	❖	❖
24			❖	❖

Several criteria for measuring goodness of fit were applied, concluding the following:

- The mean historical mean is very well reproduced at all levels of time aggregation, because of its linear dependency with the accumulation level.
- The variance is also well reproduced through the year and through different accumulation levels, although some discrepancies in the 12hr. and 24hr. series are detected, due probably to the fact that only the historical value at 0.5hr. level was considered in the estimation process.
- The estimated value of covariance's fit fairly well to the historical ones. The worst results are obtained at 12hr. accumulation level, in September and October (the wettest months in the year).
- As far as correlation structure is concerned, the goodness of fit is satisfactory, although from 0.5hr. level to 6hr. level the estimated values are slightly lower than the historical ones in Spring and Autumn, and a bit higher in Summer months. This fact does not happen in 6, 12 and 24hr. series, where the fit is better. Finally we should also remark that no historical values of correlation were directly considered in the estimation process.
- The zero depth probability is, along with the mean, the best reproduced statistic by the model. In the Barcelona's series the number of zeros is very high, so it is very important that the model is capable of capturating the aforementioned probability.

4. External structure of the rainfall process in time

The ability of the model to reproduce the binary sequence of wet(1) – dry(0) periods has been tested. Due to the lack of a theoretical expression for transition probabilities, the study was done via simulation. The simulation consisted of a 400-year series. Transition probabilities were calculated for both the historic and synthetic series at different time intervals from 1 hour to 24 hours.

The results for the transition probability dry(0) to wet(1), in terms of a two-state single Markov chain, show that the transition probability ($0 \rightarrow 1$) is very well reproduced by the model along the year and trough the different time levels. For the small time scales this probability is very low (less than 0.02), because the number of zeros in the series is 95% aprox. This value increases as the aggregation time scale increases.

For the wet(1) to dry(0) transition probability, although the synthetic values fluctuate around the historical ones, the difference between them is in any case less than 10%. It seems that the model tends to slightly shorten the rainfall events for the larger time scales (12hr to 24hr).

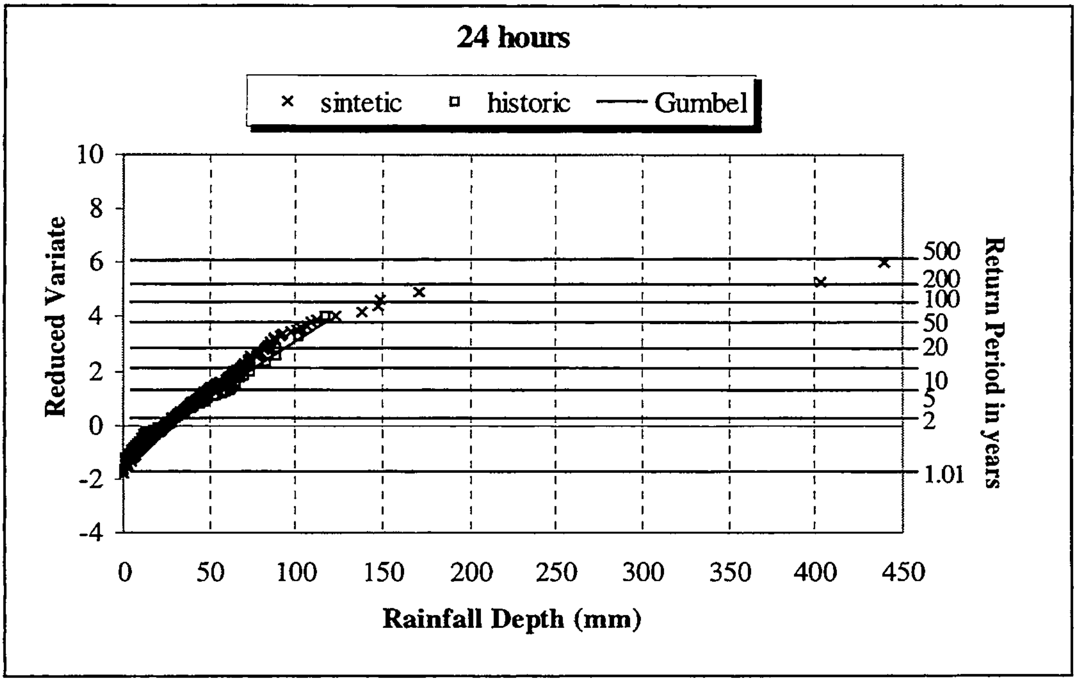
5. Analysis of maximums

Maximum historical values found in the original series (period of 57 years) were compared with the distribution of extreme values derived from the synthetic series (400 hundred years).

This aspect is not explicitly considered in model´s structure and/or formulation, and therefore no statistics concerning maximums have been used either directly or indirectly in the parameter estimation procedure.

The comparison has been made in terms of the doble-log plotting positions of extreme values, for both the historical and synthetic maximums, and also in terms of the derived intensity-duration-frequency curves.

The results indicate that the model shows a degree of sistematic underestimation of maximums associated with short rainfall durations (2 hours and lower), while maximums for larger durations are reproduced fairly well. This observed limitation is greatly due to the imposibility of describing rainfall peaks and fluctuations inside the rectangular cell employed as the basic building element of the model. This fact, inherent to model´s formulation, is clearly affecting it´s potencial capability of reproducing extreme value distribution at the shortest time scales, not being so significant the influence for durations higher than 6 hours. The following graphic shows the results of maximum distribution for a time level of aggregation of 24 hours



Another interesting point which which should be enphatized is the fact that some extraordinary maximums (outliers) are clearly detected in the long synthetic series, as it should be expected, even when the historical series contain no one. This observation is traduced in terms of a curveness of the distribution function that should fit plotting positions points on the usual reduced variate -Ln[-Ln F] graphical representation. Such behaviour of maximums distribution has been sistematically detected in the mediterranean zone of Spain, when long series are used, and particularly, some daily maximums or rainfall around 600 and even 800 mm/day have been registered in the Valencian Comunity (East and South East of the Country).

6. Disaggregation

We tried to quantify the adequacy of the B-L model in reproducing the historical statistics at different accumulation levels when using a disaggregation procedure.

This aspect of the model is really interesting because most of the rainfall data are collected on daily timescale and finer-timescale data are required for a wide variety of hydrologic applications. There are many works in the literature dealing with this problem: [*Woolhiser and Davis,* 1989; *Bo, Islam and Eltahir,* 1994; C.A. Glasbey *et all.,* 1995].

We have used the October rainfall data (24 hour and 48 hour time increments) to test the ability of the B-L model in disaggregation. The six monthly parameters were estimated following a similar strategy.

Using this parameter set, synthetic series at lower scales (from 1 hour) were generated. The results show that the main statistics are satisfactorily aproximated, proving an important potential of the model as a dissagretion tool for applied, in those cases when hourly series are not available.

7. Conclusions

The reported research shows that point processes – based stochastic models are capable of reproduce the basic statistics of interest describing rainfall temporal series defined with variable time level of aggregation, for typical mediterranean conditions (Barcelona). Several aspects that are not explicitely consider in model formulation, like maximums distribution, internal and external structure of rainfall, have been studied via simulation, with results indicating that this kind of model approaches, although costly from a computational point of view, can provide important practical benefits in hydrologic applications. One of them is the posibility of infering properties of the rainfall processes at finer temporal scales when only daily information is available.

8. Papers and comunications presented

Santiago Salsón Casado, Rafael García Bartual
Desagregación de series de lluvia para aplicaciones en simulación de sistemas de recursos hidráulicos
Revista de Obras Públicas. . ISSN: 0034-8619
Colegio de Ingenieros de Caminos, Canales y Puertos.
Asociación Española de la Prensa Técnica – Federación Internacional de la Prensa Periódica
Vol.: Juy-August 1998. Pages 25-35.

Santiago Salsón Casado, Rafael García Bartual
Inferencia en procesos estocásticos de punteo aplicada a la desagregación de series hidrológicas
Actas del XXIII Congreso Nacional de Estadística e Investigación Operativa. Pages 29.7 - 29.8. Valencia (Spain), March 1997.

Santiago Salsón Casado, Rafael García Bartual
Simulación de la intensidad de lluvia en el tiempo, con intervalo de agregación temporal definible según escala de trabajo
Primera Asamblea Hispano-Portuguesa de Geodesia y Geofísica – IX Asamblea Española de Geodesia y Geofísica. 16- 20 February 1998. Aguadulce (Almería, Spain)

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The prospect of the Floodaware project is to build a European methodology for flood management and damage mitigation with accepted standards, especially on vulnerabilities and risk maps implementations (risk = vulnerability x hazard). The objectives are to implement into models and tools new synthetic approaches developed in water sciences and management. The flood management policy must be treated with carefulness toward the water resources and ecological aspects. This knowledge has deep implications in social and economic behaviour. So, a structured effort is made to present this new knowledge under a " negotiable " form : negotiations for water volumes, and/or for land uses, between the different communities and owners living all along a river.

The Inondabilité methodology deals with synthetic models in hydrology, hydraulic modeling, hazards parameters, vulnerabilities, crossed maps... All these concepts are devoted to a dynamic slowing down producing simultaneously hazard mitigation and resources improvement with socio-economic interfaces. First results have already been obtained for a quantification of the hazard and works are done for an estimate of the objectives of protection against floods.
A synthetic Heuristic approach is developed, for prevention and forecasting. This methodology will be confronted to Inondabilité, as an alternative procedure for data management, more adapted to tumbling rivers with unstable beds. Data are collected and treated for simulations and some first results will be available soon.
Research is done in the field of Regionalization in hydrology, in the field of rainfalls, extreme rainfalls and discharges evaluations, including reservoir management rules devoted to hazard mitigation, when water resources are critical. Theoretical results will be soon available and tested on data sets.

The aim of this project is to give effective answers to help decision makers, engineers and researchers to develop solutions to their specific problems in flood risk prevention and forecasting.

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