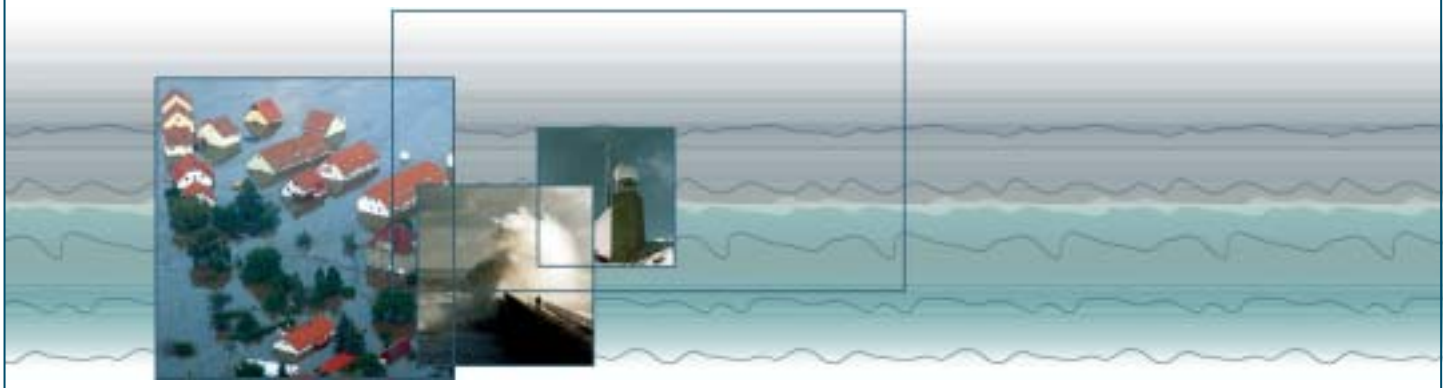
Integrated Flood Risk Analysis and Management Methodologies



Requirements for Flash Flood Hydrometeorological Monitoring

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SUMMARY

The aim of this report is to describe the requirements for the coherent monitoring of rainfall and discharge data for flash-flood events. First, the meteorological and hydrological characteristics of flash floods are presented. Response times of urban and natural watersheds will be specified. Such response times actually control the rainfall and discharge observation timesteps, while the size of the catchments of interest controls the required spatial resolution. Typical values suggest that the resulting observation constraints can only be satisfied over a reduced number of pilot sites, already well instrumented with operational observation systems. Three hydrometeorological observatories are described:

(a) representative of a large urban area (Barcelona, Spain),

(b) a medium-elevation mountainous region (Cévennes-Vivarais, France) and

(c) a high-elevation mountainous region (Adige valley, Italy).

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1. Meteorological and hydrological aspects of flash flood

Flash floods are phenomena in which the important hydrologic processes occur at the spatial and temporal scales of stormy precipitations. Flash flood understanding is therefore at the interaction of the atmospheric and hydrologic sciences, namely hydrometeorological science.
Flash flood research focuses on diagnosing and forecasting excessive precipitation accumulation in terms of spatial and temporal distribution at very fine scales. Nevertheless, flash flood forecasting is also linked to the understanding of the hydrology of the phenomena. Thus, observation (geomorphologic data, active soil processes) as well as modeling needs to be better documented. Forecasting potentiality is limited by both the fast response of the catchment area and the uncertainty in the temporal and spatial variability of the soil properties and the rainfall.
This part, divided in 2 sections, proposes a state of the understanding of the meteorological and hydrological processes leading to flash floods events. Proposals and recommendations aim at highlighting the needs in each field in order to better understand their interaction.

1.1 The flash flood producing storms

1.1.1 The mesoscale convective system

Heavy precipitation is the result of either convective or non convective processes, or combination of both. Over southern France, large amount of precipitation might be cumulated during several day-periods when one or several frontal perturbations are slowed down and enhanced by the Massif Central and the Alps relief. But in most cases, large amount of precipitation is cumulated in less than one day when a mesoscale convective system (MCS) stays over the area during several hours (Rivrain, 1997). Riosalido (1990) has also shown that most of the flash-flood events in the Eastern Spain can be attributed to quasi-stationary MCSs. Frequently, these quasi-stationary MCSs are backward regenerative systems that take a V-shape in the infrared satellite imagery (Scofield, 1985) and in some cases in the radar reflectivity images. Backward regeneration is obtained by a continuous generation of new cells at the tip of the V, whereas the mature and old cells are advected toward the V branches (Rivrain, 1997, Benech *et al*, 1993, Ducrocq *et al*, 2003). The V-shape results from the interaction of the divergent convective motions at the top of the anvil with the upper south to south-westerly diffluent environmental flow that prevails generally during these heavy precipitation episodes.

Needs and proposals:
- By the use of long term meteorological data base (NCEP/NCAR, ERA40), determine the percentage of heavy precipitating events that can be attributed to quasi-stationary MCSs?
- To document the characteristics of the MCS during its life cycle from satellite and radar data. How frequent the V-shape in the infrared satellite imagery is associated with quasi-stationary MCSs?
- Using high resolution mesoscale modelling, identify the factors that favour the stationarity of MCSs (stationary large-scale systems, orography, evaporative cooling, density currents)

1.1.2 Heavy orographic rainfall climatology

On a climatic point of view, Frei and Schär (1998) have gathered high resolution rain gauge observations of daily surface rainfall to produce a precipitation climatology covering a large part of the Mediterranean arc. This climatology shows the enhancement of precipitation along the Alpine foothills, with dryer conditions in the mountain range. It also reveals clearly that the Cévennes-Vivarais region, the southern part of the Massif Central, is one of the five rainiest areas of the region. This region is particularly prone to heavy rainfall (*i.e.* more than 100 mm in 24 hours) as shown by the climatology of precipitation over the southern France established by METEO-FRANCE and MATE[1] for the 1958-2000 period.

[1] MATE: French government Department of town and country Planning and of the Environment

Figure 1 shows the number of days for which the daily surface rainfall were above 200 mm between 1958 and 2000 over the southern France: the Southern Alps, the Eastern Pyrenees, the Eastern Corsica and the Cévennes-Vivarais region are the areas the most frequently concerned by heavy precipitation; the Cévennes-Vivarais region being the area where the highest number of heavy precipitation events have been recorded. From Figure 1, it is clear that the heavy precipitation events occur mainly over the south-eastern flank of the mountainous areas, facing the moist low-level south to south-easterly flows over the Mediterranean Sea which generally prevails during these flash-flooding episodes.

Figure 2 presents the monthly distribution of number of days with precipitation above 200 mm for the four rainiest departments of the Cévennes-Vivarais region. It shows clearly that heavy precipitation climatology is characterized by an autumn maximum. This is a common feature of the heavy rainfalls in the western Mediterranean regions. At that period of year, the Mediterranean Sea is still quite warm after the long sunshine periods of the summer, whereas upper cold air, advected from northern Europe, begins to concern the area, thereby producing propitious conditions to lower static stability and to ensure a sustained moisture supply.

Need and proposal:

- Using long term data base and mesoscale meteorological models, establish a climatology, for the Mediterranean region, of the location where convective cells initiate repeatedly, in particular with respect to the underlying orography and to the low-level incident flow.

1.1.3 Synoptic and mesoscale environments conductive to flash flood producing thunderstorms

Lin et al. (2001) have synthesized some common synoptic and mesoscale environments conductive to heavy orographic rainfall, based on US, Alpine and East Asian cases. The common environmental ingredients of theses cases have been identified as follows:

i. a conditionally or potentially unstable air stream impinging on the mountain;
ii. a very moist low-level jet;
iii. a steep mountain to help release the conditional instability ;
iv. a quasi-stationary synoptic system to slow the convective system over the flash-flood area.

For some cases, a deep short wave trough or positive potential vorticity (PV) anomaly is found to approach the threat areas. The approaching trough tends

i. to induce a low-level jet perpendicular to the mountain range,
ii. to reduce the static stability beneath the upper-level PV filament, and
iii. to provide upper-level divergence for additional upward motion over the upslopping topography to enhance convection (Massacand et al, 1998).

The PV streamer, considered as a dynamical precursor of heavy precipitation over the southern flank of the Alps (Doswell et al, 1998), may be absent as for example for the East Asian cases studied by Lin et al (2001). For these cases, a high convective available potential energy (CAPE) value is observed and seems to compensate the increase of instability beneath the PV streamer for the other dynamically forced cases.

One of the projects of MAP, the P2 project[2], focused on the impact of upper-tropospheric potential-vorticity streamers approaching the Alps on the generation of heavy precipitation. It appears

[2] The MAP Design Proposal identified 8 projects (Binder and Schär, 1996) :
P1 : " Orographic precipitation mechanisms"
P2 : " Incident upper-tropospheric PV anomalies "
P3 : "Hydrological measurements for flood forecasting"
P4 : "Dynamics of gap flow"
P5 : "Unstationnary aspects of Föhn in the Rhine valley"
P6 : "Three-dimensional gravity waves"
P7 : "Potential –vorticity banners"

that the approach of considering PV streamer as a precursor of heavy precipitating events has to be modulated by:

i. the precipitation fields are rather sensitive to the fine scale features of the upper-level PV filament (Fehlman et al , 2000);
ii. the orography, as well as diabatic processes associated with convection, can altered the streamer's PV evolution (Morgenstern and Davies, 1999; Hoinka et al, 2003);
iii. a precursor upper-level trough and an associated moist southerly flow at low-levels do not necessary induce an heavy rainfall event (Rotunno and Ferreti, 2001).

A study of heavy precipitation over the Cévennes - Vivarais region has shown that the environment of this case exhibits the common ingredients to heavy orographic rainfall as those previously mentioned (Ricard, 2002). A short-wave trough associated to a southerly flow over the Massif Central was also identified. For convection over this area, the low-level south to southeasterly flows from the Mediterranean sea provide the moisture for the heavy precipitation events, and convection may be triggered over the Massif Central crests. In addition, Alps or Pyrenees round-over low-level flows can generate low-level convergence over the near Mediterranean Sea which help to trigger convection. Moreover, for some heavy precipitation events, as for example the Gard disaster in September 2002, the maximum of precipitation was not located over the mountainous areas but in the upwind lower mountainous areas. Therefore, upslope triggering is not the only process involved in the conditional instability release in this region. Romero et al (2000), by studying two cases of extreme precipitation over eastern Spain, have also pointed out the role of the Atlas ridge to enhance the low-level easterly flow toward eastern Spain and the horizontal convergence over the Mediterranean sea.

Need and proposal:

- Try to identify some precursors in order to better predict the events leading to flash-flooding. Using long term data base and ANALOG method to extract specific meteorological situations, a climatology of the key parameters (PV anomaly, CAPE, Precipitable Water, intensity and direction of low-level flow) has to be established in order to better understand why a heavy precipitation event becomes an extreme precipitation event. Mesoscale meteorological modeling can also be used to highlight the small scale processes in such events. These constitute one of the major objectives.

1.1.4 Topographic factors acting in the genesis and evolution of the quasi-stationary MCS

In the western Mediterranean region, the Mediterranean Sea and the orography form a strong topographic component acting on the genesis and evolution of the quasi-stationary convective systems. Mediterranean Sea provides the moisture supply to the strong low-level southerly flow that feeds up the heavy precipitating events. The role of the Mediterranean Sea, through sensible and latent heat fluxes, have been studied by Buzzi et al (1998) for one case of heavy precipitating event. They have found that the Mediterranean Sea acts essentially on the intensity of the convective precipitation and not on the location for their studied case.

For both synoptic-scale forced and unforced cases, recent numerical studies (Buzzi et al, 1998; Ferreti et al, 2002; Ricard, 2002) have shown that suppression of orography significantly reduces total simulated rainfall, clearly indicating a major role of the orography in producing flooding rain.
Inside the P1 project of MAP, "Orographic precipitation mechanisms", the basic mechanisms of production or enhancement of precipitation by topography have been addressed.

- Based on a climatology of radar data for the 1998 and 1999 autumns, Houze *et al* (2001) have shown that most of the precipitation growth in the Mediterranean side of the Alps occurs below the Alpine crest height.
- They showed also that the nature of the precipitation was a strong function of the Froude Number (Fr) of the flow (Durran, 1990): for high Fr (i.e., un-blocked or flow-over regime),

P8 : " Structure of the planetary boundary layer over steep orography"

the low-level flow rose up over the terrain and most of the precipitation enhancement occurred directly over the lower slopes, whereas for low Fr (i.e., blocked or flow-around regime), the low-level flow turned cyclonically as it approached the Alpine barrier, instead of rising over the terrain.

- Medina and Houze (2003) has extended the work of Houze *et al* (2001), by exploring the microphysical processes conductive to an orographic enhancement of the precipitation associated with baroclinic systems for these two flow regimes.
  i. For the blocked and stable case, the rain was mainly produced by a simple stratiform process over the windward slopes. Precipitation amounts may be large as a result of the persistence, although rainfall intensity is limited as the lower layer of air is blocked and do not contribute to the lifting of moist air and also as convective cells are infrequent under these stable conditions.
  ii. For the unblocked and unstable case, the general background of precipitation was also stratiform. But for this high Fr case, the low-level air rose together with the upper level air, so that a larger amount of moisture was transported compared with the blocked case. Also, as the air was slightly unstable, embedded convective cells formed and enhanced the formation of precipitation on the windward slopes.

  The two combined effects add significantly to the precipitation production in the unblocked case. Rotunno and Ferretti (2001) have shown that the two types of flow (blocked and unblocked) can cohabit within the same situation, so that the variations along the mountain barrier in the orographic-flow response can also induce convergence that enhances precipitation in an area that may not be collocated with the steepest mountain slopes.

The shape and fine-scale structure of the mountain range play also a role in modulating the precipitation. Scheidereit and Schär (2000) have shown that the specific arc-shape of the Alpine topography may intensify the Coriolis-induced asymmetry of the flow and concentrate precipitation in some small areas. Miniscloux *et al* (2001), Cosma *et al* (2002) and Anquetin *et al*. (2003), for shallow convection organized in bands, and Ricard (2002), for a quasi-stationary convective system over the Cévennes-Vivarais, have shown that the small-scale orographic features of the Massif Central, focus and intensify the precipitation due to the convergence of low level air masses within the succession of oriented east-west ridges and penetrating valleys.

There is also evidence of precipitation feedbacks which interact with orography to contribute to the rainfall enhancement. During persistent rainy periods, the subsidence caused by evaporation and melting of precipitation particles may induce the formation of downslope and down-valley flows (Steiner et al, 2003). The subsiding air concentrates in river valleys which act as air drainage channels. This drainage flow is similar to the nocturnal drainage flow that occurs during clear sky and weak synoptic conditions. This down-valley flow can develop underneath an opposite-directed moist southerly flow aloft that is forced to lift over the mountain and in which precipitation forms. However, atmospheric instability, through vertical overturning of air, may prohibit such development of down-valley flow. Besides, for convective systems, the density current produced by the evaporation of falling precipitation in the sub cloud layer may serve as a formation mechanism for convective cells and both the combined effects of cold-air outflows and orography forcing has to be taken into account in the generation and evolution of quasi-stationary convective systems (Chu and Lin, 2000). In particular, evaporative cooling may trigger new cells far upstream of the mountain.

Soil moisture has been found to have an impact on the development and evolution of convection over continental areas (Clark and Arrit, 1995; Pan et al, 1996; Gallus and Segal, 2000). It is not certain that the quasi-stationary convection over the western Mediterranean region is sensitive to soil moisture, as the low-level flows that feed up the convective systems do not cover a long distance over the continent.

Needs and proposals:

- Using high resolution mesoscale meteorological models, study the role of the underlying orography at different scales as well as the role of the proxy mountain ridges.

- Based on long term data base (radar, rain gauge) and simulated rain fields, identify the contribution of the shallow convection enhanced by the topography within the general pluviometric system of a region prone to regular flash-flood events.

1.1.5 Extremes and climate change

Precipitation is the main contributor to the variability in the water balance and changes in surface rainfall have large implications for hydrology. Flood frequency is altered by changes in the year-to-year variability in precipitation and by changes in short-term rainfall properties, such as for example thunderstorm rainfall intensity. Extreme climate events receive increased attention. The main focus, motivated by the increase in deaths and in economic losses associated with the extreme events, is to identify if extreme weather events, including heavy precipitation events, are increasing in frequency. One of the major problems to answer to this question is the lack of long-term, high-quality data. Most of the countries have only reliable data since World War II. Moreover, potential changes in heavy rainfall frequency are difficult to infer from global climate models (GCM), as such models have still some difficulties in reproducing the observed patterns of variability and especially in simulating precipitation at small scales.

First and foremost, trends in heavy precipitation events must be examined in the context of trends in average annual precipitation. Nicholls et al (1996) concluded from the observed available record that global mean precipitation has increased since the start of the twentieth century. However, there are different trends in different parts of the world, as reported by the Third Assessment Report (TAR) of the IPCC[3] which had summarized studies into trends in precipitation from long series of data. These studies show that there is a general increase of annual land precipitation in the middle and high latitudes of the Northern Hemisphere (estimated between 0.5 to 1% by decade), while land-surface rainfall has decreased on average over the tropics and subtropics in both hemispheres (Houghton *et al*, 2001). Moisselin *et al* (2002), by analyzing long series of homogenized monthly precipitation at 40 sites over France, tends to confirm such an increase trend of precipitation, even though a large part of the precipitation rises are not statistically significant. It is not possible to infer any tendency to an increase or decrease of the precipitation over southern France during fall. Climate models tend also to simulate an increase of precipitation in winter over northern Europe and a decrease of surface rainfall in summer over Southern Europe.

Considering the increase/decrease in global precipitation, one would expect an increase/decrease in extreme events (Mearns et al., 1984). There is effectively some evidence that the increase in precipitation is reflected in the increase of extreme precipitation events over the United States (Karl and Knight, 1998). In the United Kingdom, there has been also an increased frequency of heavy precipitation events in winter (Osborn *et al*, 2000). Easterling *et al* (2000) showed that in most cases when a country experienced a significant increase or decrease in seasonal precipitation, the change in the amount of precipitation falling during the heavy precipitation events is of the same sign (increasing or decreasing), but the variations in frequency of heavy precipitation events are not so directly linked to the variations in seasonal precipitation. Climate model results tend also to indicate an increase in the relative variability of seasonal and annual precipitation as well as an increase of frequency of heavy precipitation events with global warming. Confidence on these results must however be considered with respect to the current limitations of the climate models. So that, it is still beyond our reach to conclude to an increase or decrease of extreme precipitation events due to global warming for the western Mediterranean regions.

Need and proposal:

- To increase confidence in climate model results for the rainfall over the western Mediterranean regions, through the use of climate regional models or of a precursor-base approach.

1.2 Hydrology of flash floods

As seen before, flash-floods can occur in urban and rural settings. Over small natural river basins of typically 25 to 2500 km^2, rain accumulations of typically more than 200mm in 6 hours

[3] IPCC : Intergovernmental Panel on Climate Change

produce flash-floods within a few hours. Over built-up areas of typically 1 to 100 km^2, urban flash-floods are produced even faster by shorter storms (over 50mm in less than 1 hour). The time and space scales of these floods as well as their intensity make their study very different from the study of classical large river floods (basins of 2500 km² and over) that forged the hydrology science during the last century. The classical strategy in hydrology is to identify target points like cities or dams where a flood prediction must be established. The upstream watersheds are equipped with rain gages and the outflow is routinely measured at the target point. Provided a long series of rainfall-runoff data is taken, models of prediction can be fitted to predict runoff from rainfall measurements. In the case of flash-floods, this strategy fails at least for two reasons – these phenomena are difficult to observe and, consequently, it is difficult to identify the dominant generating processes and to model them.

The main obstacle to study flash flood is clearly the lack of reliable measurements. The difficulty of building a scientific argumentation on inaccurate data probably explains why the papers reporting on extreme hydrological events are sparse and generally published in reviews of limited audience (Gilard et al., 1995; Gutknecht et al., 1994; Cosandey, 1993; Hemain et al., 1989; Dacharry et al., 1988, Kolla et al., 1987). Moreover, most of the publications in international reviews are focused on specific and limited issues: peak discharge and return period estimation methods (Rico et al., 2001; Alcoverro et al., 1999; House et al., 1995, Costa et al., 1987), and sometimes on the flash floods geomorphic consequences (Alcoverro et al., 1999). An analysis of the rainfall-runoff relationship is seldom proposed (Ogden et al., 2000, Belmonte et al., 2001; Gaume et al., 2002).

In conclusion the main need regarding the study of flash-floods is certainly to develop reliable high resolution observation strategies covering regions large enough to be exposed to extreme storms with a reasonable frequency. In other words flash-floods are at the very heart of the fashionable question of ungauged basins.

The lacks in the understanding of flash-floods are summarized by two main questions:

- What are the dominant processes that produce runoff under extreme rainfall?
- Is there a commonality of behaviour of the watersheds under these extreme conditions?

1.2.1 Dominant processes

There is still no unique and simple theory about the runoff production on watersheds during flood events. The main reason is that a variety of processes can be involved which are usually grouped in two categories - saturation excess (Dunne process) or infiltration excess (Horton runoff). Due to the high space and time variability of the watershed's characteristics (land use, soil type and depth and wetness, subsoil, local slope, usptream contributing area), these processes can be active at the same time in various combinations (Ambroise, 1998). Dealing with extreme rainfall accumulations (i.e. typically more than 200mm in a few hours), the question is then to understand what dominant processes govern the triggering of the fast horizontal flows and how they develop into a flash-flood.

Needs and proposals:

To identify the processes triggering the runoff at the agricultural surface unit the following aspects must be investigated:

- To determine the relationship between the soil and subsoil conditions with the formation of runoff and preferential flow in macro pores (non-destructive geophysical techniques must be developed and applied).
- To analyze the impact of vegetation and more generally soil occupation on the above mentioned relationship.

To understand how fast horizontal flows develop the following aspects must be investigated:

- To determine the structure of the intermittent hydrographic network.
- To understand the role of man made networks like roads or drains.

1.2.2 Disparity of behaviours

The disparity of the watershed hydrological behaviours especially during extreme flood events is an important research issue. What are the important watershed characteristics (land use, soil properties, geology, morphology, initial wetness conditions) which have a real influence and should be particularly measured and well taken into account in the models?
To tackle this question of disparity, available measurements on gauged watersheds are not sufficient. Being very localized in space, flash-flood seldom occur on gauged watersheds, and being very violent in intensity they frequently damage the equipments along the rivers. The surest way to turn around this difficulty is to conduct post-flood investigations able to collect data like flood marks, witness accounts, films and photos). Post-flood investigation is an arid and time consuming activity. It is nevertheless an absolute necessity, firstly because the scientific questions can only raise from a detailed observation of the studied phenomenon and secondly because it is the only way to multiply the case studies and to show evidence of an eventual impact of the watershed characteristics (land use, soil properties, geology, morphology) on its hydrological behaviour during flash flood events. Some first investigations were conducted during the past years by the research teams contributing to the OHM-CV, especially on the 1999 Aude event (Gaume et al. 2003) and the 2002 Gard event (Gaume et al. 2004, Delrieu et al. 2004).
Based on this strategy, it is possible to identify the hydrological processes dominant during the event. For instance, the Gard case study confirmed the close link existing between the spatial-temporal structure of the rain event and the subsequent flash-floods on the head tributaries both in terms of timing and amplitude. The surface and sub-surface flows were also shown to explain the hydrological response over most of the tributaries with the exception of karstic watersheds for which both an important storage capacity during the rain event and a delayed response during the days following the event were evidenced. In-depths analyses are being performed to confirm the links between the hydrological response and the geologic characteristics of the watersheds.

Needs and proposals:

- To study series of extreme rainfall runoff data in order to identify eventual commonalities of behaviour.
- To define the effect of the initial distribution of soil moisture on the development of surface runoff.
- To develop a new model concept for extreme flood response that can be parameterized for ungauged basins (i.e. without local calibration).

2. Observation strategy

Understanding the genesis and dynamics of storm-driven floods needs observation resources over a wide range of resolutions (time scales ranging from a few minutes up to a few hours, and space scales from one to few hundreds of km^2). Countries planning issues, as well as climate studies, impose to work at the regional scale over periods as long as centuries in order to observe a statistically significant number of extreme events. There is undoubtedly a scientific challenge to develop observation strategies and tools able to deal with such a variety of space and time scales. Working with heterogeneous spatial and time series is certainly an inherent feature of the problem of interest, if we consider the following points:

a) observation in the mountainous and maritime environments is both essential and difficult;
b) the development of operational weather and hydrological networks is recent (networks developed essentially after World War II and telemetry appeared during the 70s) and strongly evolves, not always in the good direction for in situ instrumentation.

It is obvious that research observation systems must take advantage of the existing operational observation systems and, in return, that research must contribute to improve operational observation systems. In the last decades, space-borne and ground-based remote sensing techniques represent a major advent in terms of space-time resolution for observation of both hydro-meteorological (cloud

height and thickness, water vapor, cloud water content, rainfall rate, sea surface temperature, etc) and surface (topography, land use, etc) variables. Finding a complementary, rather than a concurrent, use of remote sensing and in situ observation techniques is certainly an important objective in order to take the best benefit of both measurement principles (high space-time resolution versus accuracy). The river discharge measurement is of primary importance for the considered thematic and still poses very difficult problems, especially during floods.

Based on these preliminary remarks, a three fold observation strategy is needed and proposed within research platforms, detailed in the next sections:

- Develop a number of **research hydro-meteorological observatories** where detailed observation is performed over a significant period (the current decade, at least) and a significant spatial domain.
- Develop a methodology and organize the research/operational communities in order to perform, under a common format, hydro-meteorological **post-flood investigations** for the extreme storm-driven floods occurring all over the Mediterranean region.
- Increase for some selected sites the length of flood records using **historical archives and field evidence of past floods** (historical data, paleo-hydrological indicators).

In this part, we propose to highlight how operational observation practices in the Mediterranean and new research possibilities could be used in synergy to improve the hydrometeorological observation.

2.1 Hydrometeorological observation: operational practice in the Mediterranean region.

2.1.1 Environment data base

Digital terrain models (DTM), geographical information systems (GIS) and in particular urban data banks (UDB) are becoming largely available for the description of the surface topography (with a typical horizontal resolution of 100 m), land use (agriculture, transport infrastructures, urbanization) and drainage networks (river and channel networks, urban drainage systems, etc). The time evolution of the environmental data is difficult to handle and to maintain up to date. Furthemore, for some specific applications (e.g. hydraulic modeling), the accuracy of the standard topographical data is not sufficient. The geometrical and hydraulic description of rivers and urban hydroworks (dams, storage reservoirs…) and their operating rules are sometimes difficult to obtain from operational bodies. In some mountainous areas, the flow regulation may be dominant for the low hydrological regime, the hydroworks becoming "transparent" only during floods. Finally, there is a lack of knowledge concerning the description of macro heterogeneities of the ground which act in the storage and transport capacities of the soil, and are therefore important on the hydrological regime, in particular during the floods.

Needs and proposals:

- Perform if required topographical campaigns to collect environment data (land use, river beds morphology) at adequate accuracy.
- Improve and develop a centralized access strategy of an environment data base (geological and pedological maps (thickness and type of the soils), maps of the macro-heterogeneities (e.g., the karstic networks)) and keep it open to the research community (at least, be aware of an updated catalogue of collected data and where to find it).

2.1.2 Meteorological observations

Surface measurements

In the particular case of France, the project RADOME is currently running at Météo France. It aims at renewing its network of automated weather stations. The project will be completed in 2005 resulting in a network of 550 high-quality stations deployed over the entire country. This will lead to an average resolution of 1 station every 1000 km², which will be quite unique in Europe. For obvious meteorological reasons, some regions such as the south-east of France have a higher density. Each station provides real-time measurements of wind, temperature, precipitation, humidity and for one

station out of three, pressure. Among these parameters, only the temperature, the pressure and the humidity are assimilated by the current French operational prediction model (ARPEGE). The expected resolution of one station every 1000 km ² will however not be sufficient for all parameters and all geographical environments. For instance the humidity and precipitation fields over hilly regions have a much higher spatial (3D) variability than the pressure field over the plains. Therefore, additional efforts are currently done at Météo France to concentrate and make an optimal use of other existing networks that have been deployed in the past for hydrology (e.g. flood warning) and security (e.g. forest fires) purposes.
Surface measurements over the Mediterranean Sea are provided by a very limited number of ships and buoys. This is recognized as an important weakness of the current observing network as the wind and humidity (surface) fields are essential to account for (and predict) the occurrence of flash-floods in the coastal mountains bordering the Mediterranean Sea. The recent MAP experiment has shown that the exact location and intensity of precipitating systems in the Southern Alps depend upon the stability conditions well upstream of the mountain range (Bousquet and Smull, 2003; Medina and Houze, 2003; Steiner et al., 2003).

In a context of flash flood mitigation, real-time monitoring of rainfall at the regional scale is essential to provide information for heavy precipitation warnings and the assessment of the hydrologic impact of such rain events using rainfall-runoff models.

Rain gauge represents the reference sensor for measuring rainfall at ground level. Nevertheless, their use for the spatial estimation of rainfall in mountainous regions is not straightforward. First, the rain gauge network density needs to be adapted to the required time resolution. Based on a series of rain events observed over urban Mediterranean watersheds, Berne et al. (2004) show that the required time resolution of the rain measurement should be a fraction of ¼ to 1/3 of the average lag time of the catchment. For natural Mediterranean catchments, Lebel et al. (1987) estimated the spatial structure of the rain fields for different time steps ranging from 1 to 24 hours. For watersheds of 100, 500, 1000 km^2, the temporal resolution is typically of about 25, 60 and 100 min, respectively, and the spatial resolution of 6.4, 8.5 and 10 km, respectively. Except in some urban areas, actual rain gauge network densities are in the best cases of 10 km for the daily time step and drop to about 15 km for the infra-daily time steps. Therefore, the rain gauge network spatial resolution is not adequate for real-time monitoring of watersheds smaller than 1000 km^2. Moreover, there is generally a lower density of the network in altitude since the installation and maintenance of the gauges are easier in the valleys. A further difficulty is related to the evaluation of the respective contributions of liquid and solid precipitation.
In summary, rain gauge networks provide valuable point references for checking the quality of radar estimates or precipitation forecasts based on numerical model. The density of the networks is more appropriate to the event time scale than to capture the dynamics of the storms variability leading to flash floods at fine rural and urban scales.
Daily rain gauge networks are essential for post flood investigation.

Weather radar systems offer a number of advantages in the real-time monitoring context with spatial and temporal resolutions of typically 1 km^2 and 5 min, a large spatial coverage and an immediate availability. However, in mountainous regions, the measurement of rainfall is complex and the quality of radar estimates varies strongly, depending on the location.
The interactions of the electro-magnetic waves with the relief (ground clutter and screening effects) and the vertical structure of the atmosphere (reflectivity enhancement or decrease below the sampled volume, bright band effects, partial beam filling at cloud tops, etc) explain a large part of this range-dependent spatial variability (Joss and Waldvogel 1990; Andrieu et al. 1997; Berne et al. 2004). Other error sources can be evoked, such as calibration defaults, attenuation (a wavelength dependent effect), uncertainty in the Z-R relationship(s), anomalous propagation. During the last two decades, research efforts were devoted to develop identification methods and correction algorithms for the various error sources (e.g., Andrieu et al. 1995; Delrieu et al. 1997; Vignal et al. 1999; Nicol et al. 2004) and procedures for optimizing the radar sitting and the operating protocols (Pellarin et al. 2002). Radar hydrology case studies (e.g. Andrieu et al. 1997; Creutin et al. 1997) and more comprehensive radar

rain gauge evaluations (e.g. Joss and Lee 1995; Joss et al. 1998; Young et al. 1999; Vignal and Krajewski 2001) have allowed to better quantify the potential of weather radar for the quantitative estimation of rainfall.
In parallel of such developments, an important operational effort has been dedicated to the development of weather radar networks in the Mediterranean region. For example, this is the case in France with the deployment of four S-band radar systems at Bollène, Oppoul, Collobrières and Aléria within the "Arc Méditerranéen" project of the ARAMIS network (Météo France) funded by the Ministry of Ecology and Sustainable Development. These radar systems complement the existing systems in Nîmes (S-band) and Sembadel (C-band).
In regions of very low visibility and high vulnerability (e.g. cities located in mountainous settings), the use of radar systems working at attenuated frequencies (X- band) has been proposed (Delrieu and Creutin, 1991) to locally complement the conventional radar networks. The required attenuation corrections could be based on the use of mountain returns (mountain reference technique; Delrieu et al 1997; Serrar et al. 1999) and/or on polarization and phase diversity techniques (Testud et al. 1999).

There are unfortunately very few **operational microphysical measurements**: a number of ceilometers and telemeters have been deployed in some airports (e.g. Nice) allowing the estimation of the visibility, the cloud base height only for aircraft safety purposes. Accurate knowledge of the drop size distribution and/or discrimination between snow, rain and hail is crucial for QPE with radars but there are no disdrometers or such instruments operated in real-time by Météo France and the conversion of radar reflectivity into rain rates is performed with a standard Z-R relationship (Marshall-Palmer). Dual-polarization radars (at X, C or S-band) appear as very promising tools to improve the microphysical description of precipitating systems. Over the years, their potential has been illustrated in many research campaigns. During MAP experiment for instance, real-time particle-typing algorithms were applied to the NCAR S-band S-POL radar (Bougeault et al., 2001). The diagnostics turned out to be qualitatively very consistent with the 3D kinematical information provided by co-located dual-Doppler system but validation is always a difficult task as aircraft measurements are too scarce with respect to the volume of radar data. Polarimetric radars have been used for now 20 years in the field of research and need now to be introduced within operational networks.

Apart from geo-stationary satellite measurements (Meteosat and MSG - Meteosat Second Generation – that has been declared on January, the 29th 2004) that only provide an integrated view on the vertical structure of the atmosphere and cloud winds, there are actually very few **altitude measurements** in the Mediterranean region. The operational radio-sounding stations in the French-Spanish-Italian Mediterranean region are Nîmes, Ajaccio, Palma de Mallorca, Cuneo (Italy), Geneva. Aircraft observations (AMDAR) of wind and temperature during the take-off and landing phases are now also assimilated by operational GCMs but most of them are concentrated in Northern Europe (Paris, London, Frankfort). A number of UHF / VHF wind profilers are operated by National Weather Services and some of them are assimilated by GCMs with a slightly positive impact. In the French Mediterranean region, the Nice airport is equipped with a UHF profiler. All in all, not to mention the spatial resolution, the upper-air meteorological conditions are clearly not well documented in the Mediterranean region. Modellers hope that this gap will be filled in the near future with the MSG products, GPS technology and an increase of ASAP (Automated Shipboard Aerologic Program) measurements – radiosondes launched from ships – as a consequence of EUCOS (EUMETNET Composite Observing System) recommendations.

Needs and proposals:
- Establish a community infrastructure for collecting and making available large datasets of remote and in situ hydro meteorological observations and products,
- Increase the quality of the radar estimation of rainfall at the regional scale in mountainous regions:
  1) characterize the “hydrologic visibility” of the existing networks,
  2) improve algorithms for the radar-based estimation of quantitative precipitation and quantify uncertainties,
  3) develop algorithms for the optimal combination of multi-radar data,
  4) Reinforce the radar network densities,

5) Develop and introduce within the operational services the concept of dual-polarization radars (at X-band, C-band or S-band) to improve the microphysical description of precipitating systems.

- Intensify the transfer of specific radar data processing techniques proposed by the research communities towards the operational radar services (e.g. the use of volume scanning strategies for identifying radar waves - relief interactions and the vertical structure of precipitation).
- Develop disdrometer network that might be used in two ways: i) to calibrate accurately weather radars at the time scale of the episode; ii) based on long-term statistics of disdrometer data, it can be used to refine locally the Z-R relationship used for hydrological purposes.
- Follow and be linked to the Global Precipitation Mission (NASA website: http://gpm.gsfc.nasa.gov/) that would be of special interest for monitoring and understanding the flood-producing storms along the Mediterranean coasts, and to improve the skills of global and regional weather prediction models through assimilation of such precipitation measurements. The first workshop on the ground validation of GPM took place in Abington (UK) in 2003 (http://www.rcru.rl.ac.uk/GPMGV/).

2.1.3 Hydrological observations

Soil moisture monitoring can help to understand flood triggering. The reaction of a watershed to rain depends on the initial soil moisture conditions. Antecedent precipitation indexes and base flow conditions are indicators of the hydric state of the watershed that are commonly used for runoff prediction. A more assessment of soil moisture would improve our understanding of flood triggering in complementing the above indicators. Very few soil water content measurements are available from operational practice. Some punctual measurements of soil humidity are available in the world (Soil humidity data bank) for climate studies. Western Europe is not included at all in this project. The only techniques that provide such information over long periods is global coverage satellite program involving microwave radiometer. Nevertheless, several attempts have been made to use the Special Sensor Microwave Imager data (SSM/I sensor board of several DMSP satellite platforms, 19,4 GHz, lowest available frequency) in soil moisture studies with limited success (Choudhury and Golus, 1988; Jackson, 1997; Kerr and Njoku, 1990; Owe et al, 1992). To our knowledge, no specific studies have been realized in the Mediterranean region on this subject.

In 2007, a new sensor called Surface Moisture Ocean Salinity (SMOS) will be launched. This sensor will provide a global coverage at 1,4 GHz with about 50 km and 3 days resolution. This frequency is well adapted for soil moisture studies because the measured brightness temperature provides access to the soil emissivity, which explicitly depends on soil moisture. Other means (higher frequency radiometry, optical domain, active remote sensing) suffer strong deficiencies, due to vulnerability to cloud cover and/or various perturbing factors, such as soil surface roughness or vegetation cover, as well as poor sensitivity.

From multispectral satellite measurements, attempts have been made to estimate evaporative fraction (ET, i.e. the ratio of evapotranspiration to the fraction of available energy (net radiation + soil heat flux)) (Choudhurry et al., 1997). Providing remote sensing data sets and local atmospheric measurements, process-based models simulate a series of physical and plant physiological process controlling ET such as radiation absorption. The spatial resolution depends on the resolution of the available data sets (Liu et al. 2003).

The evaluation of land-atmosphere processes (evapotranspiration) at the watershed scale is a crucial point to follow and evaluate the hydrological state of a basin before an important rain event. The usual techniques available to observe turbulent fluxes at the surface are point measurement techniques like aero-dynamical, variance or eddy correlation methods. They provide a poor spatial representative measurement at the watershed scale. To improve the resolution proposed by sensors board on satellites and to provide an integrated measurement of turbulent fluxes, scintillometry technique is of great promise. Large aperture infra red scintillometer provides an average sensible heat flux measurement over the optical path of the instrument (from 500 m to 5000 m). Developed over flat terrain the

method has been also validated in various conditions including smooth relief variation (De Wekker, 1996; Hartogensis, 1997; Chehbouni et al., 2000; Meijninger et De Bruin, 2000). This technique needs now to be applied to hilly landscapes over little watersheds (typical size: 25 km^2).

River discharge observation and quantification remain a difficult task to handle.
The most classical technique for discharge measurement is based on the water stage measurement in a river section not prone to backwater effects, coupled with a calibration of the stage-discharge relation. The rating curve is established point by point by means of a gauging (i.e. a flow velocity sampling over the river section). The limits of this technique are the cost and the difficulty to gauge rivers during highflows for opportunity and safety reasons. This results in a poor accuracy of river discharges at highflows which are extrapolated through hydraulic formulas.
Hydroworks sometimes offer more satisfactory discharge estimation methods based on the hydraulics laws of the regulating works (weirs, sills, sluice gates, etc). Other specific difficulties for measuring high discharges are linked to the characterization of overflows in the major beds, solid transport that modifies the water viscosity, the possible modification of the river beds and the often-observed destruction of the stage equipment during floods.

There is an important lack of information, particularly for rivers prone to flash floods.
New efforts are, therefore, devoted to the development of remote sensing techniques for discharge measurement (Creutin et al. 2003). Such techniques are already employed for height measurements (e.g. ultra-sonic probes fixed on bridges, video camera for a global surveillance of the river) and should complement and/or replace in-situ sensors often based on pressure measurement principles. Complementary information is then possible to be derived from these observations and would be important to assimilate in hydraulic models (e.g. surface velocity, bathymetry of the changing river beds).

Needs and proposals:
- Develop remote sensing techniques for discharge measurement relying on river surface velocity measurements (PIV technique based on video imagery and Doppler radar/Lidar techniques) and estimation of river bathymetry (use of ground penetrating radar (GPR) or Lidar).
- Develop airborne and/or satellite photogrammetric surveys to characterize flooded areas and evaluate the geomorphological changes in the river beds and their re-balancing in the months following the event.
- Develop remote sensing of soil moisture (local, air and space borne radiometry, indirect measurement using scintillometry detector of latent heat flux) for hilly landscapes over small watersheds.

2.2 Natural laboratories – Proposition of Pilot sites

The scientific objectives are:
- the development of modern observation techniques that could be generalized in a next step to the whole Mediterranean region,
- the validation of the available or newly proposed meteorological and hydrological models in the perspective of their further coupling.

These sites must rely on existing operational systems to be reinforced by means of concerted instrumental actions associating the operational and the research communities. The creation and maintenance of research databases is an important goal to achieve for such observatories.
Such hydrometeorological observatories are also promoted by the US weather research program (Droegemeier et al., 2000).

In this document, we present three complementary existing sites prone to flash-floods within the Mediterranean region:
- The ***Cévennes-Vivarais area in France*** corresponding to a medium-elevation mountainous area.
- The ***region of Barcelona in Spain*** representative of a big urbanized area crossed by fast reacting coastal rivers.

- The ***watershed of the Adige river in Italy*** representative of an Alpine high-mountainous area.

2.2.1 The Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory (OHM-CV), France

The OHM-CV initiative (http://www.lthe.hmg.inpg.fr/OHM-CV/index.html) started in 2000 and has received the label of "Environment Research Observatory" (ORE is the French acronym) from the Ministry of Research in 2002.
One of the OHM-CV objectives is to develop a hydrometeorological laboratory in the Cévennes-Vivarais region, described hereafter.
Figure 3 presents the general view of the OHM-CV (radar, rain gauges) and a short description of the region (topography, geology) that is regularly prone to flash floods especially in autumn.
Several historical major floods (Jacq 1994; Deblaere et Fabry 1997) can be mentioned: 1858, 1933, September 1958 (Cévennes region), October 1988 (Nîmes), September 1992 (Ardèche area), September 2002 (Gard region), and December 2003 for all the right bank tributaries of the Rhône River.
The punctual 10 year return period rainfall is greater or equal to 50 mm and 200 mm for the hourly and daily time steps, respectively, over most of the region (Bois et al 1997). Two Cévennes hydrological watersheds (Gardon d'Anduze river at Anduze 550 km^2 and the Ardèche river at Vogüé 635 km^2) were especially studied in the last three decades and may continue to be used as reference basins for detailed research projects. The problem of prediction on un-gauged (or poorly gauged) basins is particularly acute in this region and should be addressed specifically.

This region is already well instrumented with operational observation systems. Nevertheless, the operational instrumentation is managed by several weakly connected meteorological and hydrological services having their own metrological objectives and practices.
A first on-going action of the OHM-CV concerns the creation of a research data base by gathering, normalizing, examining and archiving the operational data. This effort started in 2000 and is planned to last for at least ten years in order to document a broad sample of rain events with a rich and rather stable observation system. The rain gauge and water level networks belong to no less than five services specialized in weather and environmental surveying and flood alerts. During the period 2000-2002, 22 rain events, with rain amounts greater than 50 mm per day at some locations in the region of interest, were processed and archived. Obviously, besides the rainfall and hydrological datasets, the OHM-CV also benefits from the Météo-France meteorological datasets (radio-soundings, analyses of the operational NWP model, etc).

Ongoing actions, needs and proposals:
The OHM-CV operational observation system is being progressively upgraded and complemented by means of concerted operational and research actions:

- ***GPS meteorology***: The objective is to assess the potential of the Global Positioning System for measuring the atmospheric water vapor content. Four permanent GPS are located within the OHM-CV window.
  - Perform specific campaigns with additional GPS sensors to :
    - Estimate the 3D water vapor field and its evolution above the network (30 x 30 km^2) through a tomographic inversion techniques,
    - Characterize the entering water vapor fluxes from the Mediterranean sea shore and to start establishing a climatology.
- ***Improve the quantitative use of the ARAMIS weather radar network for meteorological and hydrological applications in mountainous regions.*** The case of the two S-band radars (Nîmes and Bollène) separated by only 60 km is especially suited
  - to assess the value of a radar volume scanning strategy to cope with radar waves - relief interactions and to identify and account for the vertical structure of precipitation,
  - to develop the radar networking techniques to estimate rain fields at the regional scale.
  - Install a permanent DSD (Drop Size Distribution) instrumentation to improve the inversion of the radar measurements.

- ***Development of light-configuration weather radar*** (X-band polarimetric radar systems) to locally complement the weather radar network.
- ***Development of a scintillometry technique within hilly landscape over small watershed*** (25 km^2) to provide an estimation of latent heat flux. Implementation of the BLS 900 scintillometer acquired by OSUG (Observatoire des Sciences de l'Univers de Grenoble) in the OHMCV region.
- ***Test new discharge measurement techniques***: compare a video-camera based prototype for measuring both the river stage and surface velocities to classical measurement techniques at the EDF/INPG discharge station on the Isère river at Grenoble, France (Fourquet and Saulnier, 2004).

2.2.2 The Barcelona region, Spain

The region of Catalunya (Spain) (Figure 4) is known to be prone to severe storm-floods, especially during the autumn period, when primary or secondary cyclonic perturbations advect moist and unstable air masses coming from the Mediterranean sea. This region is drained by a set of coastal rivers. Many of them cross densely urbanised and industrialised zones. Among them, the Besòs River and the Llobregat River pass north and south through the conurbation of Barcelona (more than 3 millions of inhabitants). Of special interest is the Besòs watershed (1020 km^2, Figure 5) which was affected in 1962 by a catastrophic flood event that caused about 800 casualties and exceptional economical damages. During last decades, the river bed has been degraded and canalised by means of big concrete protection structures. Considerable EU and Spanish investments have been devoted in recent years to rehabilitate this area into a modern urban sector and create a fluvial park. The city of Barcelona organizes in 2004 an International Forum of the Cultures in a newly urbanised area precisely built in the Besòs river delta.

The radar observation network (Figure 4) allows a remarkable coverage of the Barcelona area and its main coastal rivers. The 1962 event made the Besòs watershed to be extensively instrumented and studied in recent years with exceptional hydrological time series compared to the Spanish standards (Figure 5).
The creation of the fluvial park has motivated the development of a flood forecasting centre operated by CLABSA (the Sewer Management Company of Barcelona City). CLABSA has implemented new instruments (stage record stations) and control structures (inflated dams) along the park. Up to now this system relies on very simple hydrometeorological models, and the warning thresholds are based on conservative assumptions, but research efforts are made to improve this system. An on-line alert system based on hydro-meteorological data and hydrological models is being developed to monitor and forecast the combination of the flows coming from the semi-urbanised Besòs basin and the flows produced by the urban drainage network of the City.

The Hydrometeorological Observatory of Catalunya, and more specifically the Besòs River Project, is supported by CLABSA (Clavegueram de Barcelona, S.A.), the SMC (Servei de Meteorologia de Catalunya) and the ACA (Agència Catalana de l'Aigua).

Ongoing actions, needs and proposals:

- Improve the rainfall observation network
    - Increase the rain gauge network density (especially over Barcelona city) and install several disdrometers.
    - Install a vertically-pointing Doppler precipitation and cloud profiling radar.
    - Install a complete meteorological tower
- Improve the derived rainfall products
    - Develop rainfall algorithms based on C-band radar data and rain gauge data
    - Improve the accuracy of the rainfall measurement to later validate the satellite rain products.
    - Improve ground radar correction procedures by the satellite measurement

- Hydrological qualification of the radar images at Besòs catchment scale
    - Validation of the derived rainfall products in terms of discharges at different points within the Besòs catchment.
    - Hydrological evaluation of the improvement of the ground radar corrections
    - Participation to the development of a flood forecasting warning system (SAHBE) operated by CLABSA.

2.2.3 The north-eastern Italy Hydrometeorological Observatory (LINE)

The "north-eastern Italy Hydrometeorological Observatory" (LINE) started in 2000 with focus on the Adige river basin. During 2004, an agreement was reached with the OSMER of the Friuli-Venezia Giulia region to extend the research to the region covered by the Fossalon di Grado weather radar center (with main focus on the Tagliamento river basin). The main objective of LINE is to develop a framework aimed at the effective utilization of radar rainfall estimates for the identification and prediction of flash flood events in a region characterized by rugged topography.

Two study regions are considered in this Observatory: the Adige river watershed (Figure 6), and the Tagliamento river watershed (Figure 7), both in north-eastern Italy.
Most floods in the Adige basin are widespread phenomena generated by frontal precipitation systems. This is the case for the most important floods in 1882, 1965, 1966, and for the floods that occurred from 1998 to 2002. The city of Trento, as well as a large number of towns in the basin, was flooded and heavily hit during the 1966 event. The region, and especially the upper Adige river basin, is frequently hit by flash flood events (Fortezza, July 1999), which trigger important debris flow phenomena.

A number of different agencies are responsible for the operation of the hydrometeorological data gathering and analysis: Ufficio Idrologico in Provincia of Bolzano, METEOTRENTINO in Provincia of Trento, CSIM in the Veneto Region. The Spino d'Adda radar system is managed and maintened by Nuova Telespazio (TELECOM group).

Ongoing actions, needs and proposals:
The main focus of the LINE Observatory activity is on observational and modelling studies of extreme floods in humid mountainous basins. The core science issues which are examined are (Creutin and Borga, 2003):

- ***Identification of the critical controlling processes*** (related to soil properties, topography and precipitation variability) for extreme flood response in humid, mountainous basins;
- ***Identification of dependencies between control processes*** and 1) space-time scales, and 2) rainfall and flood frequency.

Diagnostic and modelling studies are combined to address the following hypothesis: the dominant runoff production mechanism for flood response changes from subsurface stormflow to infiltration excess as the return period of the event increases and that the change in runoff mechanism can be characterized by systematic changes in runoff ratio and response time of flood response.

On-going investigations are focused on:

- ***Characterization of the extreme rainfall regime***, by means of both rain gauge data statistical analysis (Borga et al., 2004) and of radar / rain gauge case studies investigations (Tonelli et al., 2004);
- ***Development of a radar rainfall estimation algorithm adapted to the characteristics of the high alpine terrain.*** The algorithm is based on the procedures already developed (Borga et al., 2002c; Dinku et al., 2002);
- ***Integration of radar rainfall estimates into flood forecasting models*** used in the region (Da Ros and Borga, 1997; Borga et al., 2000; Borga, 2002; Hossain et al., 2004);

- ***Coupled monitoring and modelling studies*** of runoff generation and shallow landsliding during extreme rainfall events (Borga et al., 1998, 2002a, 2002b, 2004).
- ***Installation and monitoring of hydrological sensors within Vizza, Cordon and Moscardo catchments***
    - Network of crest piezometers to characterize the water table depth and depth of near surface saturated layers ("perched water tables").
    - Soil hydraulic measurements (using a Guelph permeameter) to determine the vertical profile of saturated hydraulic conductivity for the modelling studies of runoff generation.
    - Soil moisture mapping (TDR measurements) to identify patterns of space-time variability of soil moisture.
- ***Analysis of the intermittency of the channel network***.

2.3 Post-event flood investigation

The scientific objectives are:

- To document and keep the memory of the extreme events,
- To identify the hydrological processes dominant during flash floods.

Such post-event investigations must also concern socio-economical variables, to identify victims and exposed persons and goods, to analyze differential vulnerability, psycho-social impacts, preparatory and response behavior, and to assess the social and economical cost of floods.

Due to the rarity of extreme events, it is important to develop a strategy for observing them wherever they occur and not only in places where refined observation systems actually exist. This observation strategy, classical in other geo-sciences (e.g., seismic events, volcanic irruptions), was initiated and applied in France for recent flash floods (Gaume et al. 2003a, 2003b; Gaume et al. 2004; Delrieu et al. 2004).

Basically, the procedure aims at estimating maximum discharges for the head watersheds (sizes in the range of 10 to 200 km^2) in the affected areas. The methodology is based on two steps:

- ***The field observation***
    - Geometrical estimates of the maximum wetted sections and perimeters, of the topographical and energy slopes, are performed using water level marks for river streams not subject to back-water effects.The visualization of video-camera records taken during floods shows the important differences in terms of surface flow velocities between the minor and major river beds, a fact which can be accounted for in the discharge estimation by considering specific roughness coefficients in these different parts of the river. Roughness coefficients are empirically estimated using for instance the recommendations of Barnes (1967). For a given catchment, the sampled sections are multiplied in order to check the discharge estimates consistency and accuracy.
    - The post-event investigation procedure also consists of interviewing witnesses to document the chronology (time and duration of the flooding for various particular levels, number of peaks, etc) and the dynamics of the flood (duration of the raising and decaying phases…). The interviews also bring a lot of information concerning the way such dramatic events are lived by the exposed populations.
    - The field observations are complemented by the collection of all the available data concerning rainfall (professional and amateur rain gauge estimates, radar data sets). The confrontation of the rain gauge and radar estimates at point and spatial scales, and the application of merging methods, are important tasks to reduce the uncertainty on rainfall estimation.

- Airborne and/or satellite photogrammetric surveys should also be realized and exploited for major events to characterize the extent of the flooded areas and evaluate the geomorphological changes in the river beds and their re-balancing in the months following the event.

- ***The hydrological data analysis***
  - Use a robust hydrological model, based on the SCS production function coupled with the kinematic wave model to route the discharges through the watersheds.
  - Post-event discharge estimates and operational stage-discharge measurements must be critically used to characterize the hydrological response of the watersheds. This allows the consistency between the estimated rainfall and discharge over the affected areas to be checked and various hypotheses to be tested concerning the hydrological processes dominant during flash floods.
  - A 2D hydraulic model, using the estimated discharge time series as boundary conditions, should be implemented in a final step for simulating the flood propagation and the overflows in the hydrographic network.

Needs and proposals:
- To normalise and extend the post-flood investigation procedures to the major events that are foreseen to occur in the Mediterranean region.
- Note that such post-event investigations require a very heavy organisation and should then involve both the research and operational communities.

2.4 Use of systematic, historical and paleo-flood data for flood risk estimation

The first two observation strategies rely on data recently collected or to be collected in the future. Based on the analysis of available data on flash floods that occurred in the Mediterranean region in the past, the scientific objective, here, is to improve rain and flood frequency analysis. This is crucial information for both town and country planning issues and climate studies.

Numerous works were devoted to analyze rainfall and discharge time series obtained during the recent systematic observing period (the last 30-50 years) with the objective of mapping statistical rainfall and discharge parameters (Neppel 1997, for the Languedoc-Roussillon region; Bois et al. 1997, for the Cévennes-Vivarais region; Kieffer and Bois 1997, for the French and Italian Alps). However, such time series are certainly too short for a reliable quantification of extremes and it is desirable to increase, at least for some specific sites, the record periods.
Past flood information can be obtained from historical documents that allow the extension of the observation period up to about the 17th century. Paleo-flood hydrology, based on stage geological indicators sampled in different geomorphological settings, may help to document the magnitudes of the largest floods over much longer periods (100 to 10 000 years).
Promising multi-disciplinary studies, associating geologists, historians, hydraulicians and hydrologists, are devoted:
- to “detect” the paleo and historical floods,
- to convert the stage information into discharge estimations using hydraulic modelling and
- to perform refined statistical analyses of these heterogeneous time series (Benito et al. 2004).

Interesting examples on the use of historical and paleo-flood data sets for flood frequency analysis are provided by Naulet al. (2004) and Sheffer et al. (2004) for the Ardèche river, located in the Cévennes-Vivarais region.

Proposal:

- Perform a regional analysis of extreme rainfall and flood events in the Languedoc-Roussillon region which overlaps the Cévennes-Vivarais area. Historical data on two large watersheds (Hérault and Gard rivers) and five sub-catchments of the Aude river will be collected over a period of about two centuries to complement the Ardèche case study at the regional scale.

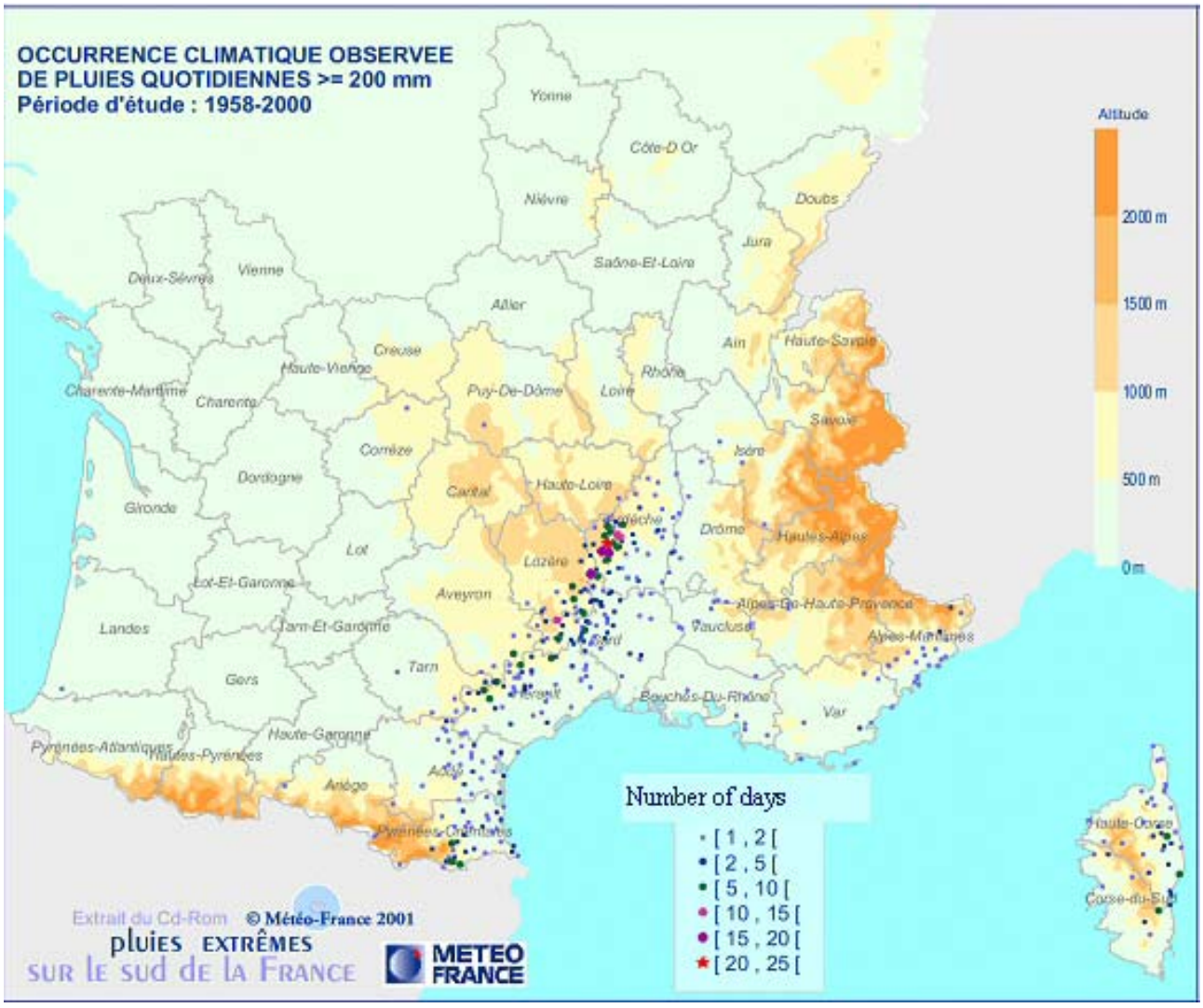

Figure 1: Number of days with daily precipitation greater than 200 mm over southern France

(from CDROM-pluies extrêmes sur le sud de la FRANCE, METEO-FRANCE and MATE, 2002).

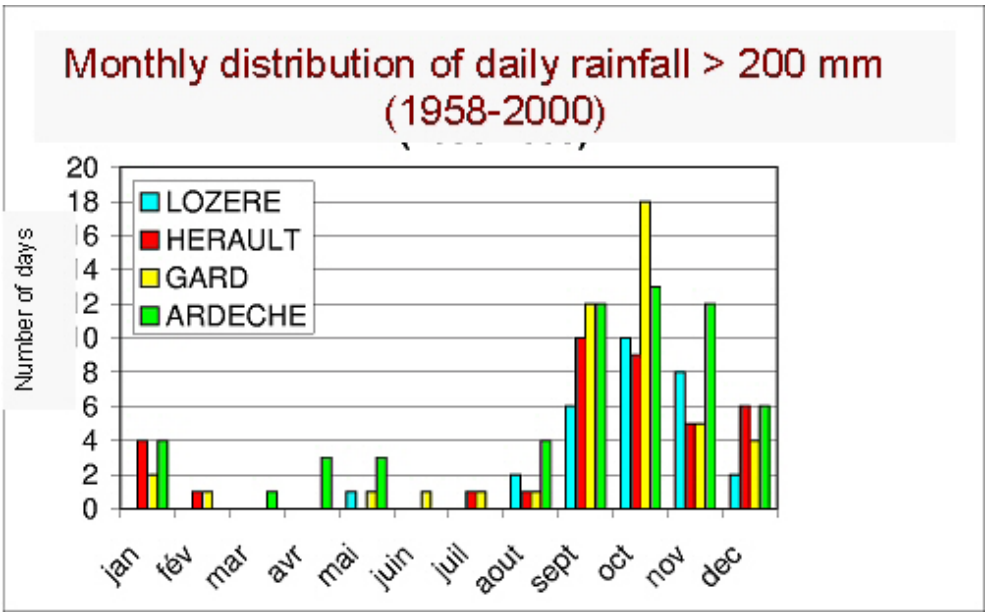

*Figure **2**: monthly distribution of the number of days with raingauge precipitation above 200 mm from 1958 to 2000 for the Lozère, Hérault, Gard and Ardèche departments.*

(from CDROM-pluies extrêmes sur le sud de la FRANCE, METEO-FRANCE and MATE, 2002).

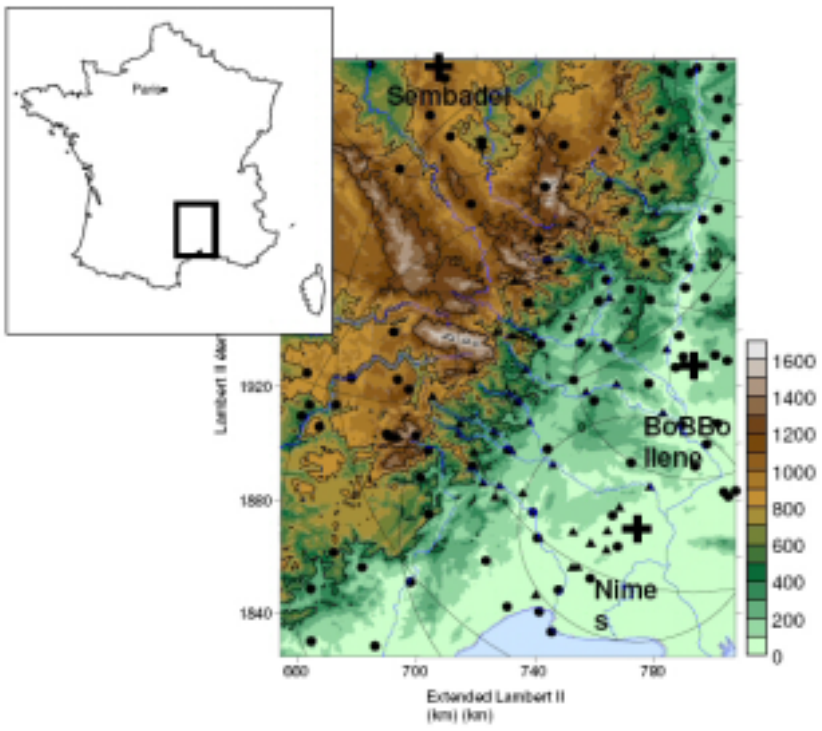

Figure 3 The Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory window.

The coloured map represents the topography (m asl) which culminates at the Mount Lozère site (1699 m). The main Cévennes rivers (Cance, Doux, Eyrieux, Ardèche, Cèze, Gard and Vidourle) are right bank tributaries of the Rhône river with a typical Mediterranean hydrological regime (very low waters during summer, floods occurring mainly during the autumn). They are characterized by steep slopes in the head tributaries of the Cévennes Mountains. In terms of geology, the mountainous part of the region (north-west of the map) corresponds to the Primary era formations of the Massif Central (granite, schists) while sedimentary and detrital formations dominate in the Rhone valley region (south-eastern part of the map) with, in places, karstified limestones. Many villages and several small to medium-sized cities exist in the region (the main city, Nîmes, counts 200 000 inhabitants).

The three weather radar sites are indicated by the crosses and the 40 km range indicators. The black circles and triangles give the locations of the hourly rain gauge network.
Within the 160 x 200 km2 Cévennes-Vivarais window, the observation system is comprised at the moment of: (i) three weather radars of the Météo-France ARAMIS network located at Nîmes (S-band), Bollène (S-band) and Sembadel (C-band), (ii) two networks of about 400 daily rain gauges and 160 hourly rain gauges and (iii) a network of about 45 water level stations.

The "green tourism" is very developed, with in particular the famous Ardèche gorges site, leading to a spatially diffuse vulnerability to flash-floods.

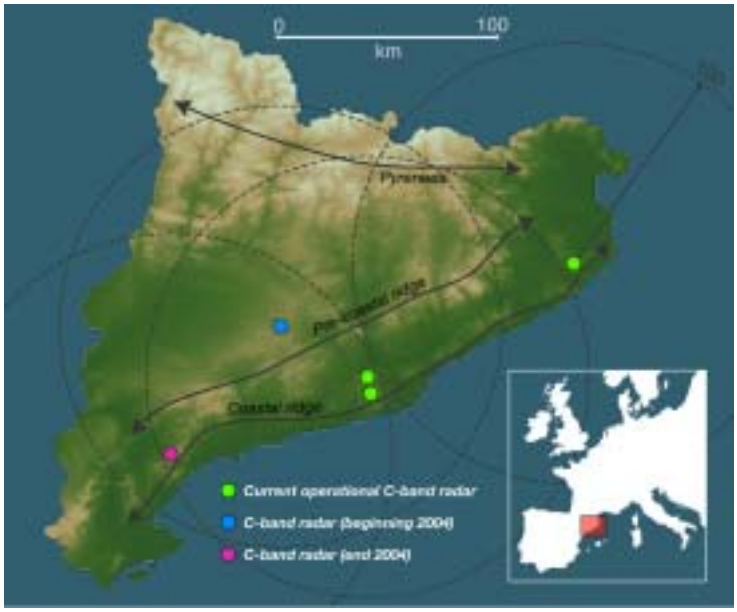

Figure 4: Map of the Region of Catalunya showing the deployment of the C-band radar network.

The region of Catalunya is located in the North-East of the Iberian Peninsula and covers a surface of 32000 km^2 showing a marked orography characterized by the increasing altitude of the terrain from the sea to the inner regions. Three major mountain chains can be distinguished. The first two are parallel to the coast (rising up to 500 and 1700 m asl), and are located inside a strip of terrain at less than 40 km from the sea. These mountains act as a barrier that induces the convection of humid air coming from the sea, favouring the generation and growth of precipitation. The third mountain chain (the Pyrenees) is located at the North, and exhibits the highest elevations of the region (up to 3400 m).

The mean annual rainfall over the region is about 600 mm. However, one third of the annual precipitation can usually fall in less than 48 hours. In average, two events exceeding 100 mm/day are recorded every year and the return period for events over 200 mm/day somewhere in Catalunya is two years.

This region is drained by a set of coastal rivers. Many of them cross densely urbanised and industrialised zones. Among them, the Besòs River and the Llobregat River pass north and south, respectively, of the conurbation of Barcelona (more than 3 millions of inhabitants).

This area and its surroundings is the most vulnerable from the socio-economical point of view. It is also the best covered by the current radar network.

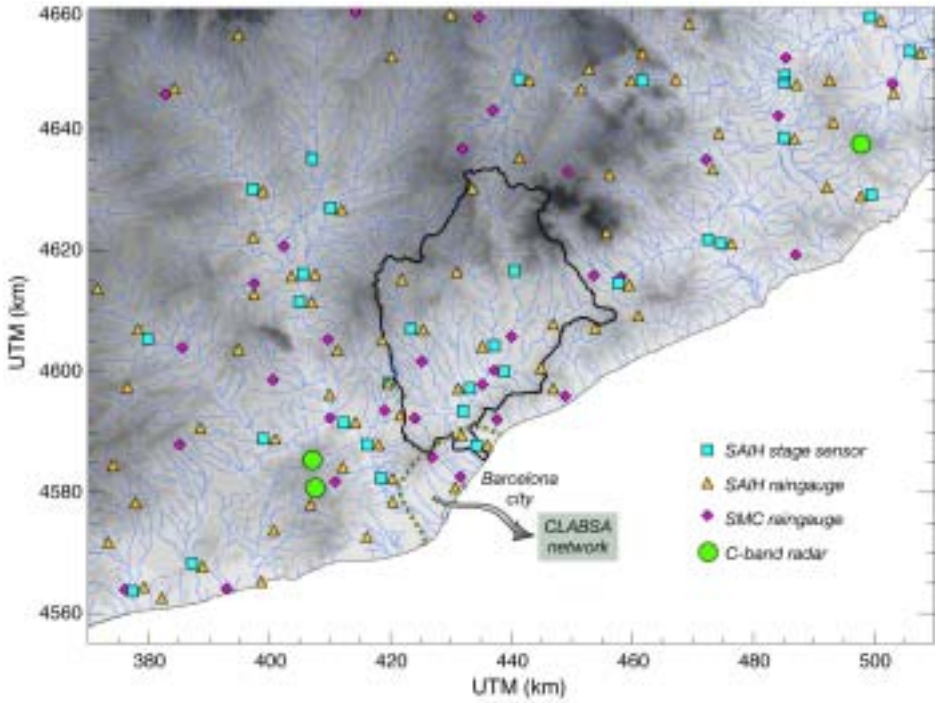

Figure 5: Topographic map of the Barcelona area showing the extension of the Besòs River and its instrumentation.

Presently, it exists a dense rain gauge telemetered network and three C-band operational radars. Two additional C-band radars are projected, one is constructed and it will be operational during the first months of 2004 and the second one at the end of 2004. They will be organized as a dense network of radars, allowing a remarkable coverage of the Barcelona area and its main coastal rivers. One of the radar systems belongs to the Spanish Meteorological Service (INM), the four others to the Catalan Meteorological Service (SMC).

The main rain gauge networks of Catalunya (one each 150 km^2 in average, tipping bucket type) are operated by the Water Agency of Catalunya (ACA) and by the Catalan Meteorological Service (SMC). Additionally there is a complementary rain gauge network around the urban area of Barcelona operated by the Sewer Management Company (CLABSA). The density on this urban area increases up to one rain gauge each 10 km^2. All these rain gauges are connected by phone or microwave links to a central office and the data is available in real time.

A good network of more then 50 stage sensors exists over the region covering the main rivers, managed by the ACA and by the Water Agency of the Ebro river (CHE). The data is available every 5 minutes in real time.

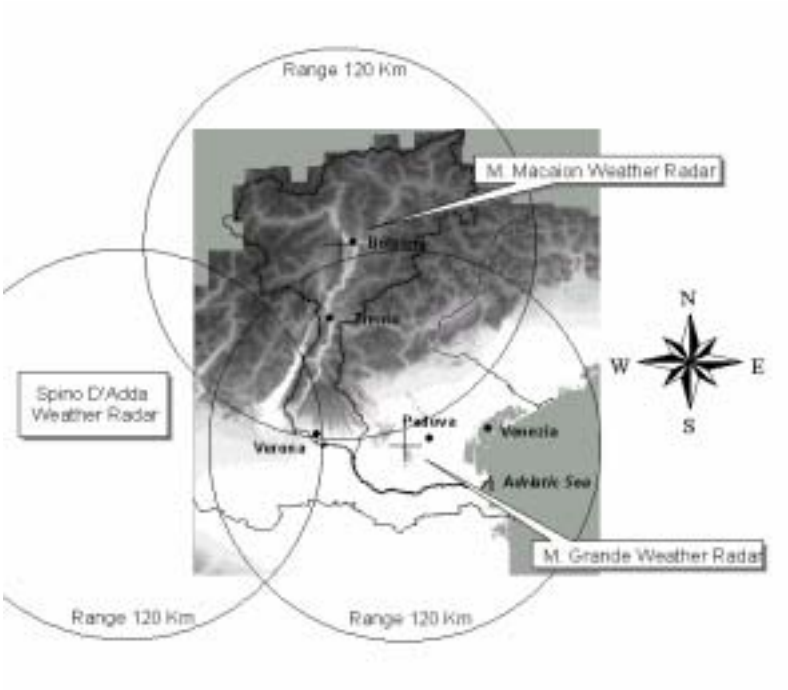

Figure 6: Radar coverage of the Adige river watershed.

The Adige river is the second longest river of Italy, 360 km long, rising in the Tyrolean Alps, Northern Italy. It flows south, past Bolzano, Trento, and Verona, to the Po valley where it turns east to flow into the Adriatic Sea. The research is focused on the mountainous part of the basin (12000 km^2), which includes two distinct administrative units: Provincia Autonoma di Bolzano (almost 7000 km^2) and Provincia Autonoma di Trento (5000 km^2). Altitudes range from 100 m a.s.l. up to 4000 m a.s.l.. The region is located south of the inner alpine province: it ranges between a dry climate (600 mm/yr, due to the dual sheltering effect of the range to both the north and the south) and a wet climate (2500 mm/yr) along the Venetian plains. The southern range experiences showery precipitation with thunderstorm and hail, particularly in summer and autumn (Bacchi et al., 1996).

The operational observation system for the Adige river basin includes:
(1) A network of three weather radar systems. Two are C-band Doppler weather radars (Mt. Macaion and Mt. Grande) and one is an S-band Doppler radar (Spino d'Adda). They are used for the hydrometeorological surveillance of the region. The Mt. Macaion weather radar (1860 m a.s.l.) has been installed in 1999. The Mt. Grande radar system (420 m a.s.l.) is in operation since 1989 and was recently improved. The S-band weather radar in Spino d'Adda, in the Po valley, has been modified in 1995, enabling coherent (Doppler) measurements. The combination of radar imagery from at least M. Macaion and M. Grande sites allows a good coverage of this region.
(2) A network of ground-based instruments, including 140 tipping bucket rain gauges and 30 hydrometric stations.

Green tourism is highly developed in the region, as well as dispersed urbanization, thus leading to high and increasing flash flood risk.



Figure 7: The Tagliamento catchment. Source: Basin Authority for the North Adriatic Rivers.

The Tagliamento River (with an area of 2871 km^2) is the dominant river system of the Friuli region in northeastern Italy (Fig. 4.3.6). From north to south, the Tagliamento traverses four major regions: (i) the Julian and Carnian Alps, (ii) prealps, (iii) the upper and lower Friulian plain, and (iv) the coast. This steep environmental gradient from north to south is associated with climatic differences, e.g., annual precipitation ranges from 3,100 to 1000 mm per year and mean annual temperature from 5 to 14 °C. The southern fringe of the Carnian and Julian Alps frequently receives very intensive rainstorms, resulting in severe erosion, especially in the alpine area.

The alpine area of Friuli mainly consists of limestone, with a spatial sequence of Silurian, Devonian, Triassic, Jurassic and Cretaceous formations north to south.

The principal tributaries of the upper catchment, the Lumiei, the Degano, the But and the Fella, converge and join the Tagliamento River forming a palmate pattern. Their basins are characterised by steep slopes and lie in one of the wettest regions of Italy, where annual precipitation can reach 3000 mm. Rainfall is concentrated mainly in heavy and erosive showers determining the torrential regime of the river. Furthermore, the mountain basin is seismically active and has a dense distribution of landslides, resulting in much bed load and a braided nature of the river downstream. At Pioverno (2400 km^2), the 10 and 100 year floods are estimated to be 2150 m^3/s and 4300 m^3/s, respectively.

The Tagliamento river basin is covered by the Fossalon di Grado weather radar, owned by ARPA Friuli Venezia Giulia (OSMER). The station is located at 25 m a.s.l.. The radar is C-band, Doppler, with dual polarization capability.

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