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# HYDROMETEOROLOGICAL AND HYDRAULIC FACTORS AND PROBLEMS RELATED TO FLOODS IN ARID REGIONS OF SPAIN

***Juan B. Marco***
*Universidad Politecnica de Valencia*
*Departamento de Ingenieria Hidraulica y Medio Ambiente*
*46071 Valencia*
*SPAIN*

**Abstract**. Meteorological and hydrological aspects and hydraulic problems related to extreme floods, which occur in arid regions of Spain, are reviewed. Small coastal basins with steep slopes and little vegetation cover are characteristics of these regions in which "flash floods" develop. They are produced by large convective rainfall, resulting in very intense soil erosion and deposition. The flow in alluvial cones is basically two-dimensional, unsteady, and often supercritical. Using mathematical models that incorporate these features are typically prohibited because of the cost associated with topographical precision requirements. Since a large number of dams has been constructed and are operational in Spain, management of reservoirs considering the potential of flood events has become an important problem.

## 1. GEOGRAPHIC INTRODUCTION

Spain is a large (505,000 km$^2$) and high country with an average altitude of 540 m.a.s.l., crossed by important orographic systems running East to West. The Iberian system and some of the eastern mountains complete the division of the Peninsula into two unequal portions. Basically, the Iberian Peninsula can be thought of as a large plateau, encircled by mountains on three sides and gently tilting toward Portugal.

Due to this orography, most large Iberian watersheds (the Rivers Duero, Tagus, Guadiana and Guadalquivir) flow to the Atlantic Ocean, while the River Ebro (86,000 km$^2$) forms the only large Mediterranean basin. Along the eastern and southern coasts of Spain, a series of small basins are located between the mountains and the Mediterranean Sea. These are steep, fast-response watersheds. Among them, the Jucar (18,757 km$^2$) and the Segura (14,432 km$^2$) are important, not only for their medium size but mostly for their intensive water resources exploitation. Possessing the mildest climate, southeastern Spain has almost completely exhausted its water resources as a result of highly intensive irrigated agriculture, in addition to population and domestic consumption.

Located between the Atlantic Ocean and the Mediterranean Sea, the climate of Spain is controlled by Atlantic frontal rains, crossing over Europe from South-West to North-East. Only one out of three fronts, however, affects the Spanish plateau. Only the North-West and the North Coast (the so-called "wet" Spain) have a mean rainfall close to or over the European average

(1,473 mm/yr, on 54,000 km$^2$). Most of the national territory belongs to the so-called "dry" Spain with rainfall ranging from 400 to 600 mm/yr; that is, a semi-arid climate. The Mediterranean Coast leeward from the mountains, however, is very rarely affected by frontal rains, to the point that southeastern Spain receives less than 350 mm/yr average precipitation. Almeria (229 mm/yr) is the most arid, heavily desertized region of Europe.

However, as in most arid countries, convective storms are extremely severe in summer all over dry Spain and heavy, convective mega-scale phenomena are present all along the Mediterranean coast from Gibraltar to Catalonia, with huge recorded precipitations (greater than 600 mm/day). Due to being land-locked between the Sahara and Europe, the Mediterranean Sea is overheated by the end of the summer. The energy and moisture supply is guaranteed to fuel this type of large-scale convective phenomenon.

The Spanish population (39 million), which is sparse by European standards, is heavily concentrated along the coast. On the other hand, the four regions occupying the plateau and central Spain comprise 70% of the nation's extension but they are occupied by only 10% of the total population. This process has occurred during this century due to the concentration of industry, cash-crop agriculture and tourism (9.6% of the Spanish GDP) along the coast. The narrow coastal plains, especially in the Mediterranean area, are overcrowded by the development of linear urban settlements and transportation corridors along the coast.

Needless to say, after this introduction, flash floods along the Mediterranean coast are the main flood problems. Flood problems in the plateau are definitely secondary, since towns have neither developed nor encroached on the flood plains. The major rivers cut deep canyons before entering Portugal. Flood problems in these rivers are all related to management of the large hydropower developments located on the border with Portugal.

On the other hand, along the Mediterranean coast, the following three factors converge:

- high intensity convective rainfall;
- small, steep basins which are heavily differentiated and have very short response times; and
- heavy population and economy encroachment on the coastal alluvial plains.

## 2. FLOODS IN SPAIN 1955-1995

Between 1957 and 1972, Spain had 15 years of accelerated economic growth, largely fuelled by the tourist boom. Large population migrations took place from rural central regions to coastal towns and to Madrid. Urban growth was fast, uncontrolled, and, largely, unplanned, without any prior development of the necessary infrastructure. On occasions, it even meant the disappearance of the local drainage network, which consisted of a system of ephemeral streams.

The flooding of Valencia in October 1957 anticipated the problems that later became generalised. A 2,500 m$^3$/s flow of the River Turia (6,395 km$^2$) flooded the entire downtown area of Valencia, Spain's third largest city in terms of population, and resulted in the deaths of 86 people. The new urban developments with the worst urban conditions were the most affected. However, the flooding of the Vallés area in 1962, the industrial suburban belt of Barcelona, was symbolic of the situation created by the rural exodus that was taking place. The Riera de Rubí dry bed on the outskirts of Barcelona, with a drainage basin of only 400 km$^2$, carried/transported 1,200 m$^3$/s and killed 973 people. Most of them were living in the dry bed of the Riera in pitiful buildings. All the encroaching factories were washed away. Without reaching such large disaster proportions, the Catalonian rieras have produced flash floods from the Ter (1970) to the Francolí (1994) dry beds.

The 1963 flooding in southeastern Spain, without involving such a large economic and death toll highlighted a different aspect of the Mediterranean floods. The Rambla de Nogalte carried as much as 28% of sediment by volume. The River Almanzora and other ephemeral streams carried similar mudflows in this heavily deserted region.

For almost 15 years, however, flooding spared the large population centers. It can be said that in 1982 the flooding problem had been neglected and virtually forgotten, totally unlike other aspects of Spanish economy and politics where frantic changes had been taking place.

After October 1982, nothing was ever the same. On October 20, two large mega-scale convective storms hit the Jucar basin and the southeastern watersheds, including the River Segura. Rainfall on the middle Jucar basin was extensive, involving an area of around 5,000 $km^2$ that received over 300 mm precipitation in a single day. The only recording gauge located at the Cofuentes Nuclear Power Plant registered 600 mm, most of which fell in just six hours. On the mountains, unofficial records of around 1,000 mm were estimated. As a result, a flood with an estimated peak of 9,800 $m^3/s$ was produced. Most of the rainfall event took place during the night. By dawn, the flood wave had already reached the Tous Dam, which was still under construction but already in service. The Tous Dam was a 60 m high rockfill dam, completed in its first phase to hold 50 $Hm^3$ to feed the intake of a canal. When the flood occurred it was full. The dam had no provisions for any type of night vigilance. When the engineers arrived, there was no electricity to open the gates. The emergency generators were stacked by the roadside and the flood started to spill over the closed gates and the embankments, cutting an access to the spillway and, hence, preventing the gates from being blown open by explosives. At 19.12 hours, a breach opened up and the top part of the dam collapsed. A flood peak of 15,200 $m^3/s$ was produced. The valley downstream was already flooded to a depth of 2 m on the extensive flood plain, due to high tributary flows and water overflowing the dam. By nighttime, the water had reached a depth of 4.5 m on the plain and was entering the second story of buildings. The 8-km wide flood plain was fully inundated. It should be noted that due to its heavy, solid load, the main channel of the River Jucar, capable of holding only 200 $m^3/s$, stands above the plain. Downstream from Alzira, where the valley narrows again to 1 km, a system of levees protected the lowest alluvial plain, mostly an area of rice paddies and lagoons. The flood broke the levees and two diverging streams branched until the flood reached the sea over a coastal stretch more than 40 km wide.

The population affected by the flood was about 300,000. Thirty-eight people were killed, nine of them in the flood plain and the rest on roads mostly in the upper basin. Economic damage was evaluated at 800 million U.S. dollars. It must be noted that the flooding that occurred at Alzira, where almost 5 m of water covered the entire city, lasted less than 48 hours.

At the same time, a more heterogeneous mega-scale rainfall produced a flood in the Segura basin and adjoining small basins. The flood plain in the Segura basin, is similar to that of the Jucar, with its tiny ordinary channel, is capable of carrying 80 $m^3/s$ high over the plain by natural levees. Here too the entire valley was flooded with a complex two-dimensional pattern that affected about 80,000 people. In the neighboring basin of the Barranco de las Ovejas (196 $km^2$), an always dry ephemeral stream, flows peaked at 900 $m^3/s$ in only 20 minutes, killing two people.

In 1987, the River Jucar again flooded its entire alluvial plain, this time without the additional effect of any dam and reaching a flood peak of 6,500 $m^3/s$. A similar pattern was observed here, a convective storm at night, flash flooding, and the complex hydraulic behavior of the plain. Damage again was over 800 million U.S. dollars. The estimated economic damage for the Valencia region alone stands at 3 billion U.S. dollars for the decade. Close to the Jucar basin in 1989, a convective storm hit the small watersheds of La Safor. Rainfall in Gandía totalled over 1,000 mm in one day. The Barranco de Beniopa (2,500 $km^2$), an ephemeral, ever-dry stream, peaked at 1,000 $m^3$/s, flooded Gandía and 60,000 inhabitants were affected.

This colossal convective phenomenon repeats itself time after time all over the Mediterranean coast: Malaga, Murcia, Valencia and Barcelona, to name only the major cities, are all too aware of its impact. It is like a Fall lottery: a relatively small area, generally under 1,000 $km^2$, is pounded with incredible rainfall intensity of over 300 mm in less than six hours. Damage depends mostly on the spatial extent and localization with respect to the basin. Hence, for the Spanish Mediterranean rivers, there is no such thing as the 5-, 10- or even 25-year flood event. Essentially, low return-period floods cannot be distinguished from the average flow (Jucar: 40 $m^3$/s, Turia 12 $m^3$/s), which for many basins is zero. The floods display more of "rare event" behaviour following no-mode distributions.

Other regions of Spain, however, are also subject to this type of event. In 1983, a "cold drop" event, â mesoscale, convective type of storm deposited 200 mm over the Basque Country. This heavily industrialised region has almost no flood plain and the population and industry are crammed along the narrow valleys running between the mountains and the sea. The damage caused was over 3 billion U.S. dollars when these rivers peaked in less than six hours, and Bilbao, the major economic city of the region, was hardest hit. Entire factories on the riverbanks were washed away.

By the end of the summer, even Spain's central plateau is subject to minor-scale thunderstorms, pounding small basins locally. In Valdepeñas, 27 people were killed by a flash flood after a heavy one-hour thunderstorm occurred. As recently as August 10, 1995, a storm-produced flash flood killed 10 people in Yebra in the Tagus basin.

It may be appreciated from this short account how the large Spanish basins come way down the ranking for catastrophic events. Nevertheless, some problems do exist: the River Ebro, although mostly used for agricultural purposes, can inflict a lot of damage to its valley, particularly if a strong frontal rainfall coincides with thawing in the Pyrenees. Badajoz, Seville, and Talavera also suffer from flooding problems, but predictability and, hence, control by dams or evacuations, reduces its potential damage.

## 3. METEOROLOGICAL ASPECTS

The flood-producing rainfall in Spain is convective in nature. As in every arid country, heavy thunderstorms are a common possibility in summer, particularly if a cold front crosses over the upper atmospheric layers. Squall lines can then develop. Large-scale catastrophic events, however, are produced by large, convective â mesoscale storms. At summer's end along the Mediterranean coast, a "cold drop" or cold shield under -50 ?C can become detached from the upper latitudes at high altitude by oscillations of the jet-stream. A low-level depression can form in the Gulf of Cadiz, entering the Mediterranean via Gibraltar. The combination of these two synoptic features results in the development of this so-called "supercell". At the beginning, a cluster of convective cells develops. If conditions are right, the cells collapse into a considerable mesoscale convective storm. The shear from the northeast wind in the upper atmosphere helps develop this "anvil cloud," as it is called by Houze et al. (1982). Orographic effects play a crucial part, since these storms always become stalled over specific locations for hours. Distinct favorite spots occur, as pointed out by Albero (1989), with location probabilities increasing as much as five times for certain valleys. The cell characteristics, in terms of peak, intensity and duration, also differ distinctly from location to location (Camarasa, 1992).

The energy and moisture supply for this huge convection effect is guaranteed by low-level winds from the Mediterranean, which at this time of year can have temperatures of well over 25 ?C. Moisture whipped off the hot Mediterranean surface is funnelled to the standing supercell. In October 1992, infrared satellite imagery showed moisture being adverted from the entire western Mediterranean basin.

A time pattern definitely can be set. Development takes place at night, with the supercell phase occurring mostly after midnight and lasting until dawn, with activity gradually waning throughout the following day. The overall event does not last more than 24 hours. Eighty per cent of these events occur in the period between 25 September and 10 November. It is worthwhile to note that these events usually release more rain in a single day than the average annual rainfall. This is the scourge of aridity!

The spatial concentration out of the large mesoscale supercells follows the classical patterns of arid regions, as described by Osborn & Laursen (1973) or Jacobs, et al. (1988) and verified by Lázaro and García-Bartual (1991). With ordinary floods, the whole catchment area is seldom covered. Camarasa (1992) shows the evolution of a rainfall event. He describes how a cell was generated and lingered over a sub-basin of the Barranco de Caraixet, near Valencia. This event resulted in a 400 $m^3/s$ discharge out of the sub-basin. In contrast, the Upper Caraixet, as recorded by the only stream gauge in the basin, only showed a reading of 5 $m^3/s$. The resulting flood washed away a bridge near the confluence, lifting concrete slabs of more than a ton, while the flood was not even capable of moving the bottom sediments only 4 km downstream. This flood peaked in less than 20 minutes. Also shown is a pluviograph of a 250 mm rain event with a five-minute time resolution. The same abrupt changes in rainfall intensity of as much as two orders of magnitude can be observed in minutes.

## 4. HYDROLOGICAL ASPECTS

The reported space and time example of a typical flash flood event suggest the special character of the hydrological cycle in arid regions such as Spain. The soil tends to be absolutely parched after the long, dry and hot Spanish summer. The infiltration capacity is expected to be very high at the beginning. Moreover, the geological formations along the Spanish Mediterranean overwhelmingly consist of limestone, which is either fractured or karstified. Heavy desertification has exposed the cracks and the soil cover in the mountains is very thin. Although a hydrological theory of hill-slope behavior is lacking for this type of formation, it is understandable that most of the rainfall does infiltrate. A study of 70 years of daily readings in the Rambla de la Viuda (Segura, 1989) concluded that daily rainfall of under 60 mm produced no runoff at all. The pluviograph reported (250 mm) over the Albaida River basin only yielded a 15% runoff. Considering that average yearly rainfall is around 500 mm in this region, it can be understood that surface runoff takes place once per year at most. In many years, all river flows come from groundwater discharge if a permanent stream is involved. These, however, are very few. Most basins under 300 $km^2$ are ephemeral. It stems from this situation that ordinary flood regimes are generally suppressed. More than five floods per century rarely can be seen for any given basin.

When the rainfall occurs over the infiltration threshold, the runoff produced is Hortonian or can best be described as a Betson (1964) partial area Hortonian mechanism. The Dunne (1970) exfiltration saturation excess mechanism is rarely observed, since the soil cover is very thin and the soil is frequently underlain by more pervious formations. Consequently, the preceding moisture scenario is unimportant since the soil is always dry and the rainfall needed to produce runoff is so high.

Runoff duration, if we assume a very high infiltration level, is very short and very intense. It generally lasts much less than the average hill-slope travel time. As a consequence, post-infiltration downhill of the rainfall produced is very significant. Only for extremely intense and long-lasting rainfall events will the entire hill-slope contribute to the stream network and, therefore, to the flood. It stems from this that spectacular increases in flow quantities can be expected for very low frequency events. These extreme events behave in an essentially different way.

The Smith & Parlange (1978) model of hill-slope hydrology seems to be the most adequate for the description of these processes. It has been included in the Kineros model (Woolhiser, et al., 1990) and despite its many shortcomings, (Michaud & Sorooshian, 1994 a, b), it appears to be the best modeling option.

In areas with small slopes, endorheicisms can develop and the stream network is so sparse that hill-slope lengths of over 2 km are usual. In many large basins, like the Jucar, these semi-endorheic areas never contribute to the flood. Effective areas very seldom coincide with the geographical watershed.

The overall infiltration behavior described here triggers a hydrological methodology problem for rainfall evaluation over an area. Unless distributed modeling is performed, any kind of area-related averaging prior to infiltration computations is likely to distort the real infiltration process. A net rainfall area-related evaluation consistently performs better than the best possible total rainfall averaging. Similar caution is needed in using any type of lumped spatial approaches such as unit hydrographs or black-box models. Since radar data are generally not available, the use of Larrieu unit hydrographs or multiple input ARMAX models consistently improve results in simulation or forecasting.

The reasons for this are the important differences in rainfall intensity occurring at different rain gauges in the basin. Averaged pluviographs bear little resemblance to what is actually happening. It may be raining heavily over the gauge nearest the basin outlet, while almost no rain is falling over the other rain gauges. Averaging will grossly underestimate peak flow and, what is worse, the time to peak. This is a common problem for arid regions (Michaud & Sorooshian, 1994b).

Infiltration processes do not end at the foot of hill-slopes. Since most of the network is made up of ephemeral streams, over deep aquifers, transmission losses are considerable. Losses over 10 $m^3$/s/km are very common. Considering the Barranco de Caraixet event described above, transmission losses only depend to a small extent on flow rates. They reduce an important part of the hydrograph, most notoriously during the rising limb, and also during the recession. Hydrographs are somehow truncated and, most crucially, the rising limb is sharpened to the point that a surge can develop. In other words, the peak occurs almost immediately after the appearance of the flood. A front wave can develop on dry, alluvial infiltrating channels. Its erosive power is much greater than the corresponding similar flow depths. The surge, therefore, carries an important debris load.

Since the most flood-prone areas of eastern Spain coincide with the most heavily deserted areas, soil erosion and sediment problems are of primary concern. Erosion takes place on hill-slopes as a consequence of the Betson-Horton runoff mechanism. Since runoff duration usually does not exceed hill-slope equilibrium time, sediment transport takes place in an intermittent fashion, running downslope with any flood event. In general, less than 15% of eroded soil reaches the fluvial network. In large floods, even in medium-sized basins like the Jucar or the Segura, sediment concentration and depositional patterns become important for hydraulic flood plain analysis. The sediment concentration during the 1982 flood in the Jucar basin was over 5% by volume, almost 15% by weight on average, and varied in time and space. Mud deposits averaged 25 cm over more than 100 $km^2$, thus changing the topography. The valley floor has risen 4 m in 10 centuries as a result of flooding and each flood substantially changes the topography.

Another important desertified-related hydrological element on both the quantity and the quality of water is the impact of forest fires.

## 5. FLOOD HYDRAULICS

Although flood plains develop along the valleys of the most important rivers, nothing special happens there from a hydraulic point of view since the slopes are gentle, floods are moderate and encroachment is much reduced. Conventional routing techniques and models are sufficient for flood risk evaluation and forecasting.

It must be remembered, however, that the most important problems in Spain occur on the coastal plains. Small and steep basins, along the Mediterranean coast and inland on the edges of the plateau, develop alluvial fans and cones of all sizes ranging from several hundred kilometres, like the Llobregat or Jucar, to less than 1 $km^2$. In many ephemeral streams the thalweg completely disappears, with the flood being dumped on the alluvial fan and sometimes forming a temporary lagoon at its end. This situation is also common for arid regions (French, 1987).

The hydraulic behavior of alluvial cones is basically two-dimensional and, in many cases, the flow is supercritical. Although important progress has been made with shallow water equation modeling, it has been mainly restricted to subcritical conditions, with supercritical conditions being admitted only locally at control points or lines, i.e., along a levee or a road. In any event, these models are extremely expensive owing to topographical precision requirements, especially along critical sections (Marco, 1994).

The analysis of small and medium-sized alluvial fans cannot afford the economic cost of these models. The flow depth is very shallow, fast, frequently supercritical and often leaves dry spots. Moreover, these alluvial fans along the coast are heavily encroached. City hydraulics under flood conditions, especially for typical European cities with their narrow streets and large closed blocks, are not being studied due to the unaffordable costs of available models.

In terms of hydrological data, it must be stressed that peak flow is clearly not enough for alluvial cone hydraulics. A complete hydrograph or flood volume and time-to-peak data are necessary and this points to the need for multivariate flood characteristics description.

In general, large flood depths and velocities are consistently different from ordinary floods. Therefore, it is doubtful that the hydraulic parameters obtained in manageable floods could apply to very large events. In other words, how can we estimate the hydraulic resistance of the Jucar canyon subject to 9,800 $m^3/s$ as in the flood of 1982, if the largest flood observed has been smaller than 300 $m^3/s$? Flood routing hydraulics for high-speed flows in alluvial channels are also far from being adequately described (Yalin, 1992). Standing waves of over 4 m in height were observed and filmed during the Barranco de las Ovejas flood in 1982. How can the water surface be assumed to be horizontal? Where is the river bottom? In this ephemeral stream, where the slope at the mouth is over 2%, a 200 $m^3/s$ flood was seen to produce bottom pools more than 0.8 m deep.

Large sediment transport even casts doubt on the fluid density, as has already been pointed out. Moreover, all these sediment transport phenomena occur in such a short time interval that steady state considerations can't be implemented.

## 6. RESERVOIR AND DAM PROBLEMS

Spain currently has 1,000 large dams, creating over 48,000 $Hm^3$ of storage capacity. Such a huge volume, larger than any other European country, is justified on the grounds of its unique water scarcity situation and irregular river regime. The rugged topography in Spain helped provide many good dam sites. Generally speaking, the dams tend to be very high. Since most of the Spanish population lives downstream of a dam, it is clear that dam safety is a major concern when flood problems arise. On the other hand, dams form a classical structural protection method. Their value in Spain is enhanced when compared with river channel intervention. It is clear that the task of training the River Jucar, with an average flow of 40 $m^3/s$, for a 6,000 or 8,000 $m^3/s$ capacity is unfeasible and environmentally damaging.

After the Tous Dam destruction, it became clear that an automated hydraulic monitoring system with forecasting capability, if possible, had to be implemented. Forecasting, however, has only been moderately successful. Its best results have been obtained in the Ebro basin, where conventional hydraulic behavior and sufficiently long forecasting lead times allowed the skilful operation of the many large Pyrenean dams. On a smaller scale, something similar occurred in the Segura basin. The SAIH works mostly as a monitoring network for the other small Mediterranean basins.

Forecasting lead times are extremely short, generally under three hours, since they have to be based on rain gauge and stream data. A radar network, where available, is not providing reliable quantitative data owing to the complex topography involved. Rainfall forecasting could dramatically extend available lead times, but nowcasting is still very much in its infancy and there are the problems with radar measurement already mentioned. For several years to come, flash flood forecasting will remain a difficult task in Spain. It is perfectly reasonable to adopt a passive, conservative dam flood management policy. Real time flood control management, with any type of optimization through dynamic programming and flow forecasting, is simply too risky to consider with such a short response time and large peak flows involved. Many dams built in the aftermath of the Tous Dam disaster ruled out the feasibility of gated spillways. PMF methods were increasingly adopted for spillway design.

It is mandatory to allocate flood control empty storage space. This allocated empty space is often below gate sill-level, so is only partially controllable. Since many dams can hold more than one year's river flows without any release, a sizeable empty storage space is usually available for flood control. A volume of this kind strongly modifies flood risk downstream, in accordance with its value and spilling characteristics. Risk analysis could greatly improve this type of largely passive flood control. To date, only simulation methods are used to evaluate flood management and spillway design.

## 7. RESEARCH NEEDS

Given the particular situation in Spain, research lines could be grouped together under the heading of flood hydrology in arid zones. Arid climate hydrology has been considerably less researched than that for temperate scenarios.

RAINFALL ANALYSIS TOPICS. As an example, since flash floods are dominant in Spain, rainfall forecasting and nowcasting are topics of exceptional interest in order to increase the lead-time. Convective rainfall modeling specific to arid scenarios can be used for both analysis and forecasting. Stochastic conceptual models, based on point processes, could be developed as part of a forecasting system. Deterministic physically based models are critical to ascertain the behavior of large mesoscale convective areas. Specific spatial rainfall evaluation techniques for highly irregular convection, based on the "cell" concept models, must be developed. The orographic effect on rainfall is also an important issue for mountainous countries like Spain.

- HYDROLOGICAL TOPICS. Hill-slope hydrology for arid zones must be specifically researched. In particular, the problems of Betson partial area runoff and post-infiltration downhill are crucial. Hill-slope hydrology of fractured, karstified rocks lacks an explanatory model. Distributed modeling for arid zones, as described above, is underdeveloped with respect to that of temperate climates, mainly due to a lack of understanding of the basic processes involved. Transmission losses, a distinctive feature of arid climates, are far from being understood and parameterised.

- SEDIMENT-RELATED TOPICS. Closely linked to our lack of adequate understanding of hydraulic processes in arid zones are sediment questions. Hill-slope erosion and deposition models must be developed. The effect of forest fires on hill-slope hydrology and water quality is also an important flood-related side effect for Mediterranean environments. Flood wave behavior in ephemeral streams, especially wave front propagation and erosion, on previously dry alluvial channels are also sediment-related issues specific to arid regions. Hyperconcentrated flows, such as debris and mudflows, are also characteristic and are underdeveloped research areas.

- HYDRAULIC TOPICS. Urban flooding, especially in high-density towns, is a topic worthy of research and modeling. Spain's cities pose a far different problem from the suburban environment pattern commonly analyzed. It appears that enough research has already been done on valley hydraulics, although linking results with GIS for both automatic data entering and flood mapping, is still an unsolved practical issue. On the other hand, the hydraulics of alluvial cones is not well understood. Moreover, development of approximate methods for hydraulic analysis of flood plains and alluvial cones is needed in order to avoid or reduce the cost of two-dimensional shallow water modelling.

- FLOOD FREQUENCY ANALYSIS. All the previously described problems and research lines are reflected in flood frequency analysis. For instance, frequency analysis for ephemeral streams has a number of individual features, which have not been properly tackled in hydrological practice. Censored sample analysis is related but not limited to this, since it is also used for the incorporation of the so-called *historic* data that are so abundant in European countries. Flood frequency analyses for small arid ungauged basins are, of course, interesting topics for Spain. Techniques like storm transposition, derived distributions and regional analysis are important for these topics. Lastly, multivariate analysis of flood characteristics (peak, volume, time to peak, etc.) must be developed in order to assess small basin hydrology, where correlation among these variables is low.

- RESERVOIR AND DAM SAFETY TOPICS. The great importance of dams for Spain has already been expressed. J.B. Valdés and J.B. Marco, present the research topics specifically related to dams, in the accompanying paper presented in the workshop, hence they will not be repeated here.

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