"Data gathered just after the floods of October 1994 in the Besòs river basin. Implications on flood management"

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Abstract. In October 9-10th of 1994, heavy rains badly affected the coastal ranges of Catalonia, Eastern Spain. Rainfall exceeded 200 mm in 48 hr in most of the region while highest precipitation records reached 424 mm. Data gathered few days after the event allowed not only the reconstruction of the flood but also a better understanding of the flood process. In the Tenes River, calculated discharges at different sections ranged from 480 to 950 m^3/s. Most of the rivers behave like torrents. In upper reaches, the steep bed slope allowed bed scouring and the mobilisation of large boulder (over 1 m^3) while on lower reaches, aggradation made the former bed floor to rise. Scouring and bed load transport caused severe damage on river defences and public works, which showed an inadequate design. The flood plain has revealed as a basic element for flood control of lower reaches.

1. INTRODUCTION

On October 9-10 of 1994 an intense rainfall event hit the coastal ranges of Catalonia region, eastern Spain, causing extensive flooding. Eight people died and damage to buildings and infrastructures was evaluated in more than 22,000 millions of spanish pesetas (around 175 million US $). Many villages and facilities were affected by flooding. For example, the Francolí River overflowed by the industrial area of Tarragona and forced the evacuation of 900 neighbours in the Serrallo district. Flooding of buildings near the streams was the main cause of damage. Erosion of river banks and road embankments located on the floodplain, collapse of bridges by pier scouring (12 road bridges were destroyed), and landsliding of residential areas (L'Estartit, La Riba) were additional causes of damage. Geomorphic effects of floods included shifting of river channels, bed scouring, bank undermining and enlargement.

2. THE MEDITERRANEAN CONTEXT

Autumn is traditionally the season of intense rains in the western Mediterranean region. Historical archives show that intense rains resulting in flash floods occur periodically in all mediterranean rivers. For instance, huge floods of the Ter River occurred in 1552, 1617, 1678, 1763, 1802 and 1843. In the present century the 1907, 1937, 1940 and 1982 rainy events must be specially mentioned affecting the Pyrenean range (Corominas, 1985). These rains are a common occurrence in the late summer and fall seasons when moist and warm air masses coming from south Mediterranean sea are forced to flow upwards through the coastal ranges. If a cold air front is located beyond the ranges, the collision between both warm and cold air masses provoke a sudden condensation and a subsequent precipitation. Rainfall records over 300 mm per day are usual in such circumstances and precipitation over 700 mm per day was recorded during the 1940 event (Novoa, 1984). In these events is not unusual to collect more than 50% of the mean annual rainfall in 24 or 36 hr.

Relief exerts a strong influence in flood development in two ways. First of all forcing the upward movement moist air masses and their consequent condensation. Maximums of precipitation are related to the presence of obstacles. (coastal ranges and eastern Pyrenees). Secondly, the steep slopes make superficial waters to concentrate rapidly generating sharp peak discharges that last only for few hours (flash floods). Villages located at the mountain fronts are the most affected by the arrival of the peak discharge shortly after the maximum rainfall intensity has been reached.

3. THE EVENT OF 9-10 OCTOBER 1994

Rainfall distribution followed the orientation of coastal ranges with a predominance of rains on the eastern side (**figure 1**). Maximum rainfall in 48 hr was recorded west and south of Tarragona. Records reached up to 424 mm in Alforja, and 406 mm in Cornudella. Another maximum was located close to Roses gulf where rains attained 381 mm at Torroella de Montgrí and 325 mm at l'Estartit. Between both maximums precipitation recorded ranged between 100 and 200 mm.

Peak river discharges during the October 9-10 event are shown in **figure 2** (Corominas et al. 1995). Most of rivers overflowed their banks and spread over the alluvial plain. Largest peak discharges were reached by Llobregat river (1800 m^3/s) and Francolí river (1400 m^3/s). These discharges were lower than previously recorded floods. Discharge of Llobregat river was 40% lower than that of September 1971 (3080 m^3/s). Peak discharge of the Francolí River was overcome in October 18-19 of 1930 (1976 m^3/s) and in September 1874 (2200 m^3/s). Besòs river reached 1100 m^3/s at its mouth, only slightly lower than its recorded maximum of 1234 m^3/s of September 25, 1962. Minor damage occurred in the lower reach of Besòs river in 1994 thanks to defence works built after 1962 floods. Instead, Besòs tributaries (Caldes, Tenes, and Congost rivers) destroyed bank defences and overflowed.

Unit discharges of some rivers were high. Tributaries of the Francolí river, Brugent and Glorieta rivers, reached >7.2 $m^3/s/km^2$ and 3.3 $m^3/s/km^2$ respectively. Besòs tributaries such as Caldes river flowed 5.9 $m^3/s/km^2$, Congost river 4.7 $m^3/s/km^2$ and Tenes river 3.2 $m^3/s/km^2$. These values are among the highest recorded in this century. Unit discharges were much lower on northern rivers (Ter, Fluvià and Muga rivers), less than 1 $m^3/s/km^2$. This is because most of the rain fell on thexoastal ranges and not in the Pyrenees.

4. A CASE STUDY: FLOOD EFFECTS IN THE TENES RIVER

The Besòs River basin was one of the most affected by the October 1994 floods. Three of its main tributaries, Riera de Caldes, Tenes and Congost rivers, crested significantly. Peak flood took place around 1 pm and lasted for less than one hour.

Besòs tributaries showed a torrential behaviour. In the upper reaches, they displayed a powerful erosive capability. Partly weathered granite and limestone pieces of 0.3m^3 and almost 1m length were detached from jointed bedrock ledges and entrained by the flow. In the lower reaches, the alluvial bed was scoured at the passage of the peak flood and then refilled. Scouring did not occur at the farthest reaches, instead a thin layer of sand and gravel was deposited.

Few days after the event we started an intensive reconnaissance campaign in this basin, especially in the Tenes River. The Junta d'Aigües (Catalonian Water Authority) helped us by surveying high-water marks and providing machinery for digging trenches. Most of the data were gathered before the river restoration works started. The reconnaissance basically consisted in the identification of high-water marks, surveying of selected sections at different reaches, and both identification and measurement of transported bedload. Erosion in alluvial bed was determined by digging trenches. Peak flood discharges were calculated at six transverse sections: Riells, Bigues, Santa Eulàlia, Lliçà de Vall, Parets del Vallès and

Montmeló (**figure 3**). Aerial photographs taken few days after the event were also available and allowed the delineation of the flood limits.

4.1. River erosion: consequences on river bank protection

In the upper reaches of the Tenes river, waters flowed over fixed and steep bedrock. Boulders transported in previous floods or fallen from neighbouring slopes were present at the thalweg when the 1994 flood occurred. Some boulders were so big that they could not be mobilised, giving thus the opportunity to check the transport capability of this flood. Identification of mobilised boulders was based on the presence of several indicators: imbricated patterns; percussion marks in boulder edges and downstream sides; and pieces of wood, plastic bags, and brick fragments trapped beneath the boulders. Huge boulders of limestone and conglomerate were transported due to the steep gradient. At Riells, elongate or prismatic boulders as long as 1.5 to 2.5m were arranged with major axis transverse to the flow. Volumes of largest boulders measured attained 1.4 to 1.6m^3 in river sections having longitudinal gradients ranging from 1.5 to 4.8×10^{-2}. The size of transported boulders decreased with the reduction of river gradient and velocity. In lower reaches only boulders up to 0.5 m in length were found (see table 1).

River section	Gradient (m/m)	Size of transported boulders (m^3)
Riells	0.031	1380
Bigues	0,008	806
Santa Eulàlia	0.0055	470
Lliçà de Vall	0,01-0,006	690
Parets	0,006	332
Montmeló	0,007	276

Table 1. Size of boulders trasported by the 1994 flood at different reaches of the Tenes river.

One of the consequences of this transport capability was the dismantling of riverbank defences at Lliçà de Vall and in the neighbouring basin of Riera de Caldes. Channelized banks protected with large blocks of rocks (rip-rap) of 0.8m length and a volume of 0.3m^3 were damaged by detachment of the rock blocks which were transported some hundreds metres downstream. Interlocking of rip-rap was overcome by both bank undermining and by overtopping and scouring at the extrados. Trenches dug in the Riera de Caldes found boulders from the bank defences buried at a depth of 1.75m.

This event shows that it is necessary a careful design of bank defences in accordance to the river transport capability. The critical velocity required for the mobilisation of protective blocks used in the banks must be higher than velocities expected in largest floods.

4.2 Mobility of the alluvial bed: scouring and sedimentation

The mobility of the alluvial bed during the 1994 flood was analysed by means of several trenches dug with a backhoe. These trenches gave a direct insight of the mobilised sediments and allowed a first estimation of the erosion produced in the alluvial bed.

Several problems were encountered during the excavation of trenches:

- Trenches could not be dug until the flow had decreased significantly.
- The recently deposited alluvial deposits are very pervious. River water infiltrated through the sediments caused the rapid inundation of the trenches. Although a pump was used, the large inflow and instability of the trench walls difficulted the reconnaissance works.

The identification of the mobilised sediments during the flood was made using the following criteria:

- Presence of vegetal remnants. Fragments of fresh grass leaves mixed with the sediments, indicate their recent deposition. As trenches were dug just few weeks after the floods, organic matter did not decay.
- Cohesion of sediments. Sediments left by the flood were clean sand and gravels. They showed no compaction and crumbled immediately when touched with the fingers.
- Colour. Recent deposited sediment showed light colours (brown, yellowish) while older deposits were darker.
- Pollution. Old alluvium had been polluted with industry spills. Black coatings around cobbles and pebbles were indicative of non-mobilised alluvial sediments.
- Standing plants. Plants in living position and roots were indicative of lack of erosion and of the presence of the former ground surface.
- Other criteria. Presence of asphalt fragments, metal or brick pieces, boulders and cobbles with impact signs, were

indicative of recent deposition. Hydraulic conductivity was much higher in recently deposited sediments.

Trenches shown that the alluvial deposits were mobilised to a depth of 1.75m in non-influenced reaches. In most of the trenches, erosion attained more than 1m depth in the upper reaches. In **figure 4**, several cross-sections of trenches dug at the Tenes River alluvium are shown. However, the erosive effects increased around bridge piers. At the Lliçà de Vall bridge which was undermined, footings were at more than 2.5m underneath the ground surface while trenches located 200m upstream showed a maximum erosion of 1.35 m.

Lower alluvial reaches, exhibited only slight erosion or aggradation. In these reaches bed load (sands and gravels) was deposited on top of the former alluvial surface. The former alluvial plain raised few decimetres in the lower reach of Tenes river (**figure 4**). Even thicker sedimentation was observed in rivers located south of Tarragona, such as Alforja and Maspujols creeks. These rivers built real alluvial fans. In the Maspujols creek, 2.5 m of sediments were deposited above the former ground surface and buried former river banks and rip-rap protection.

Sedimentation on lower reaches had important consequences on flood management. Sediments deposited rose former riverbeds and waters overflowed the channels. In road crossings, sediments reduced the effective section of bridges causing additional overflowing.

5. FLOOD DISCHARGE ESTIMATION

High-water marks of the inundated areas were identified directly in the field. Six reaches along the Tenes River have been used to estimate de peak flood discharge. At each reach, four transverse sections were surveyed, providing the area inundated. Estimation of discharge at each section took into account the area overflowed. The river was channelised from Lliçà de Vall until the junction with the Besòs River. Downstream Parets waters did not overtop the banks and rested within the channelled section.

Bedrock outcropped at the three selected reaches. There, peak discharge was calculated using the area of the cross-sections and the high-water marks which provided the gradient. The riverbed was composed of alluvium at four reaches. The estimation of flood discharge is discouraged in mobile riverbeds because the uncertainty of the erosion. However, we undertook the calculation of the peak flood discharge using the information provided by the trenches. As a working hypothesis, we assumed that the effective area of a section during the peak flood included that of the mobilised sediments. Then, we corrected the measured sections accordingly.

The reconstruction of the flood gave the following discharges estimations (Buxó, 1997):

Location	Distance from Riells (km)	Peak discharge (m^3/s)
Riells	0	950
Bigues	4	690
Sta. Eulàlia	10	510
Lliça de Vall	14.1	550
Parets	16.2	485
Montmeló	17.9	478

Table 2. Calculated peak discharges at different reaches of the Tenes River during the October 9-10, 1994 flood.

Table 2, shows that peak flood discharge has been reduced significantly in the downstream direction. The only exception is the discharge at Lliçà de Vall, which increases with respect to Santa Eulàlia. This can be explained by the obstruction produced to the flow by the Lliça de Vall bridge which caused an upstream rise of the flood stage until its collapse. The maximum discharge at this point was estimated from the highest watermarks observed in the section.

6. THE ROLE OF THE ALLUVIAL PLAIN IN REDUCING THE FLOOD MAGNITUDE

High-water marks determined during the fieldwork along with mapping of the flooded area based on the interpretation of the aerial photographs, provided a precise estimation of the volume of water that was stored in the alluvial plain. This volume was segregated from the peak discharge as the waters overflowed the riverbanks.

The peak discharge in October 1994 lasted for less than one hour. Thus, the volume of water stored in the alluvial plain may represent a significant fraction of the volume of water transported during the peak flood. This can be seen in **table 3** in which both volume of water transported by the peak flood and stored in the alluvial plain are presented.

Reach	Peak discharge (m^3/s)	Volume transported (m^3)	Volume stored (m^3)
Riells			
Bigues	690	2.484.000	
			958.250
Sta. Eulàlia	510	1.836.000	
			462.000
Lliçà de Vall	550	1.980.000	
			92.500
Parets	485	1.746.000	
			0
Montmeló	478	1.720.800	

Table 3. Volume of water transported by the peak flood of 1994 at different sections of the Tenes River and volume of water stored in the alluvial plain between consecutive sections. Transported volume has been calculated considering 1-hr lasting peak discharges. Volume of water stored in the alluvial plain has been calculated using aerial photographs and high-water marks.

The results of **table 3** show the effect of the alluvial plain in reducing the peak flood discharge. Consequently, a proper flood management policy should consider the whole river basin. Flood control in the Tenes river basin based simply on structural measures such as channeling of the riverbanks in the upstream reaches will aggravate the effects of future floods in downstream direction. In fact, channeling at Riells, Bigues and Santa Eulàlia in a situation like that of October 1994 would have transferred peak discharges of 600-900 m^3/s to the lower reaches that would be thus overflowed.

A similar effect can be expected from the invasion of the floodplains by facilities such as road or railway embankments acting as artificial levees.

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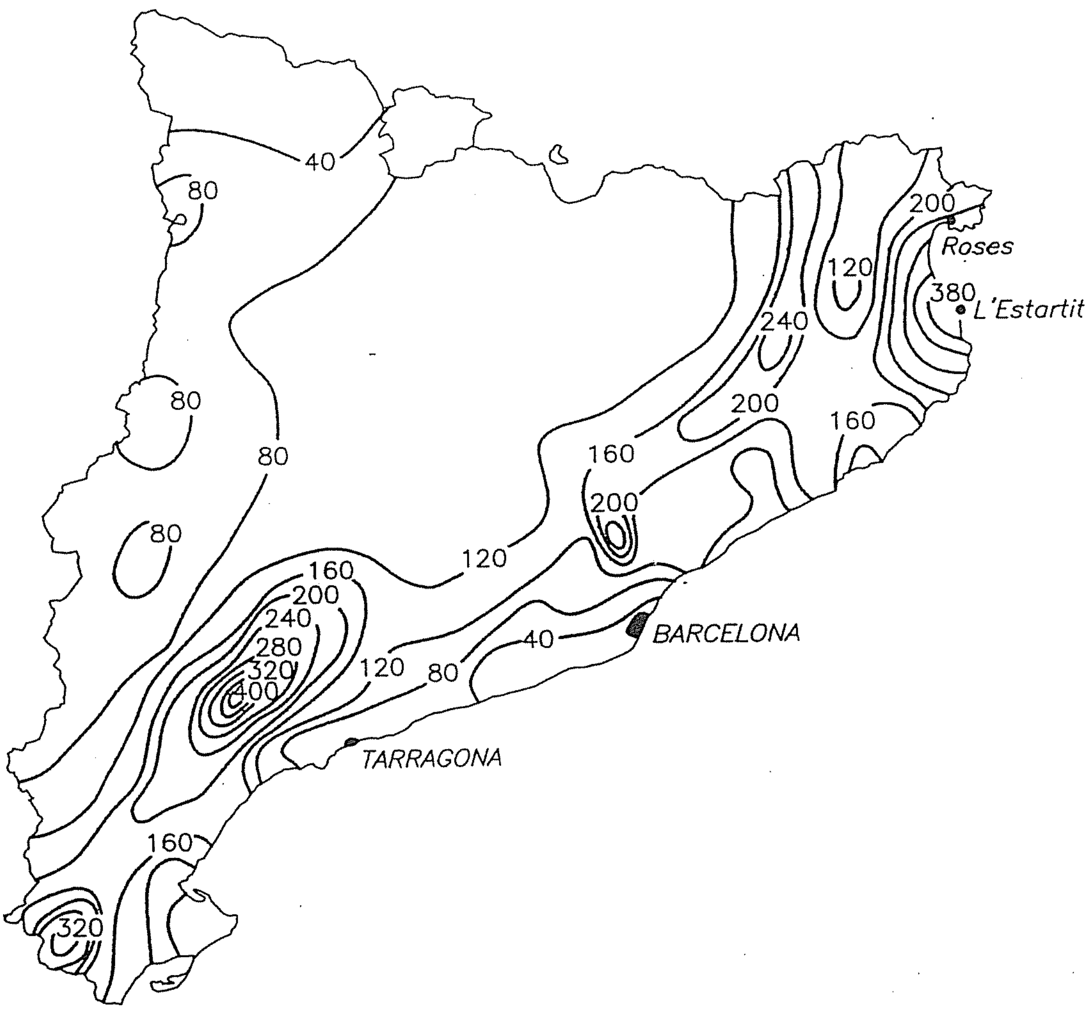

Figure 1. Rainfall distribution map of the October 9-10 event (Corominas et al. 1995)

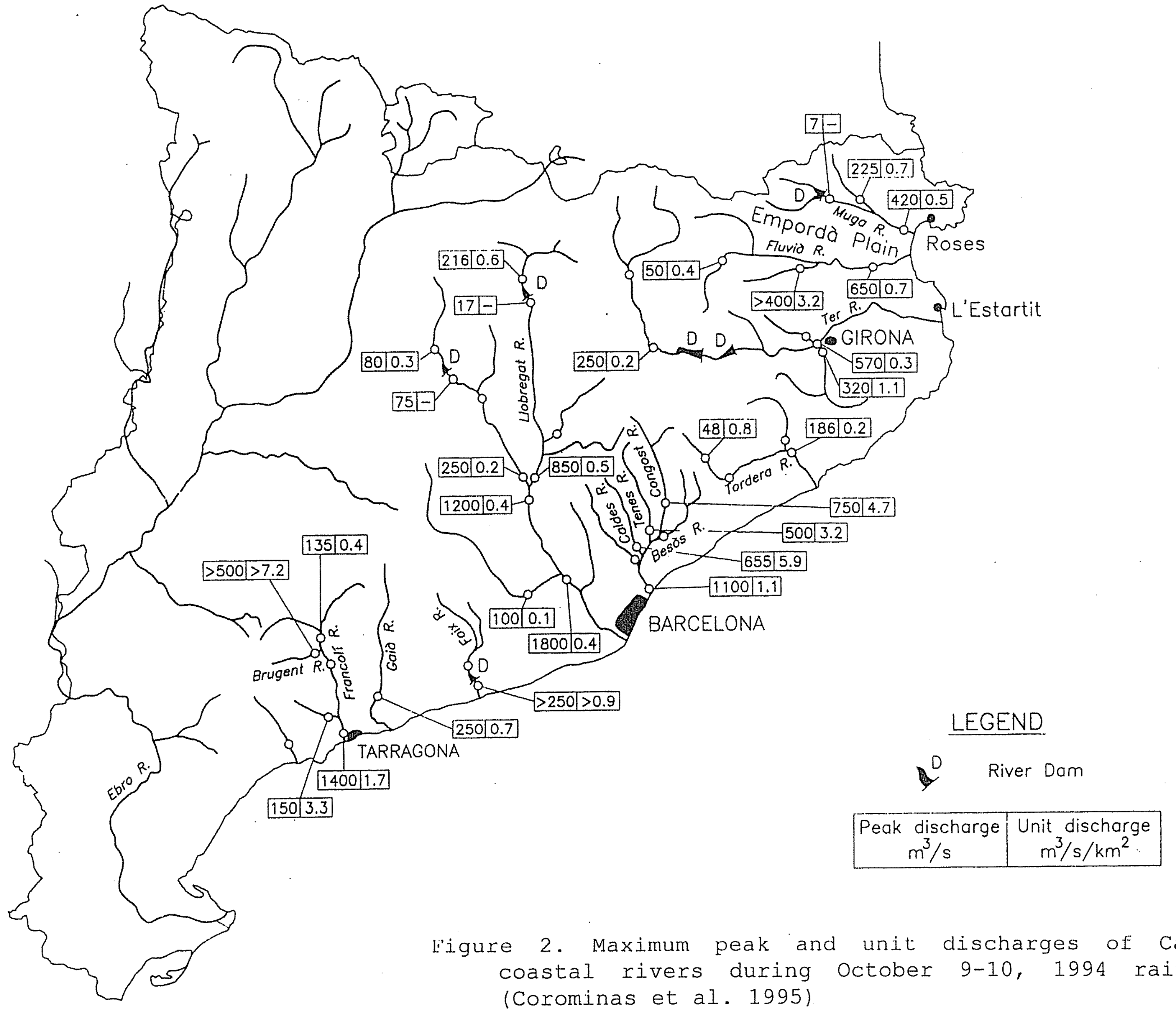

Figure 2. Maximum peak and unit discharges of Catalonian coastal rivers during October 9-10, 1994 rainy event (Corominas et al. 1995)

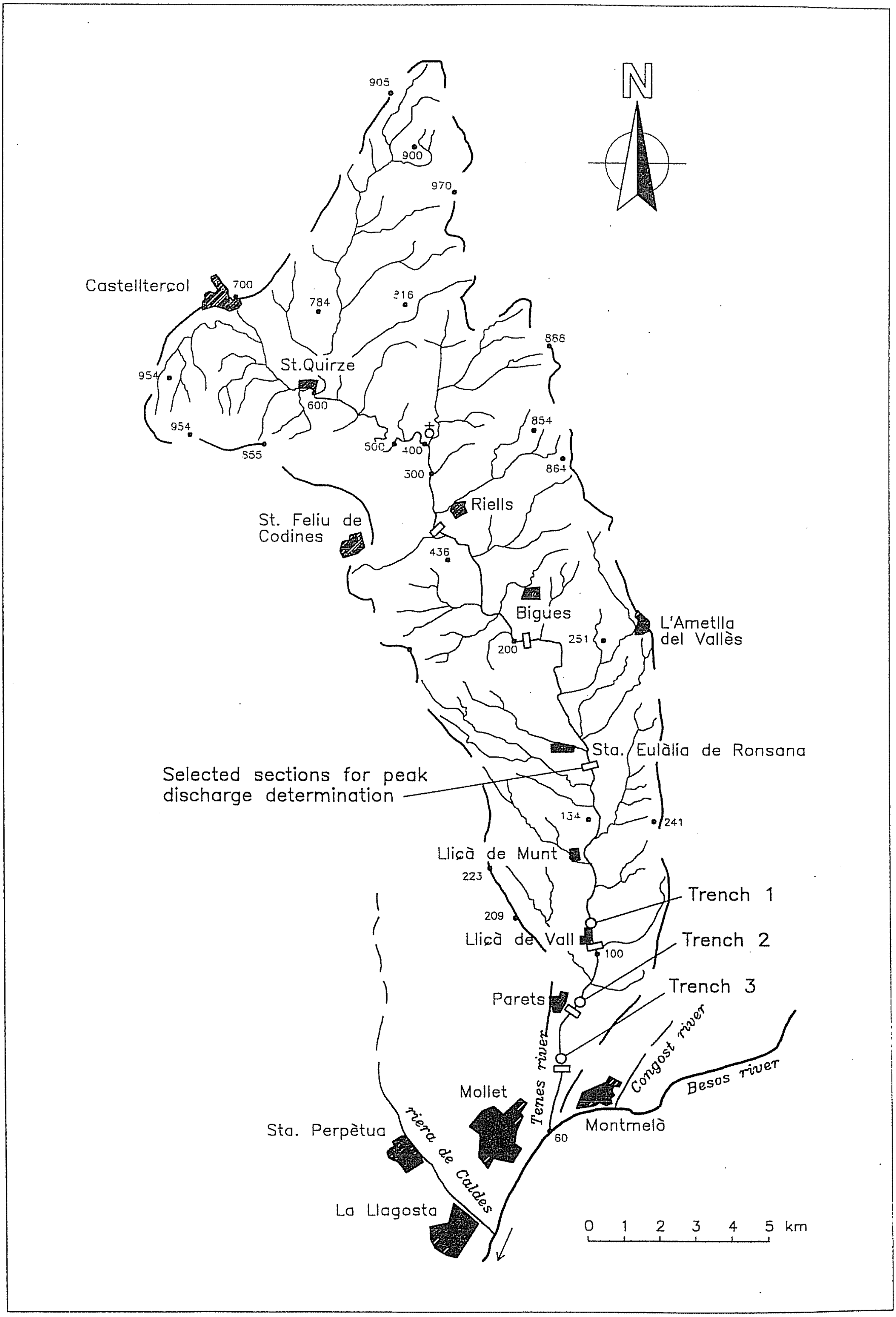

Figure 3. Sketch of the Tenes river basin: location of selected sections for peak discharge calculation and trenches

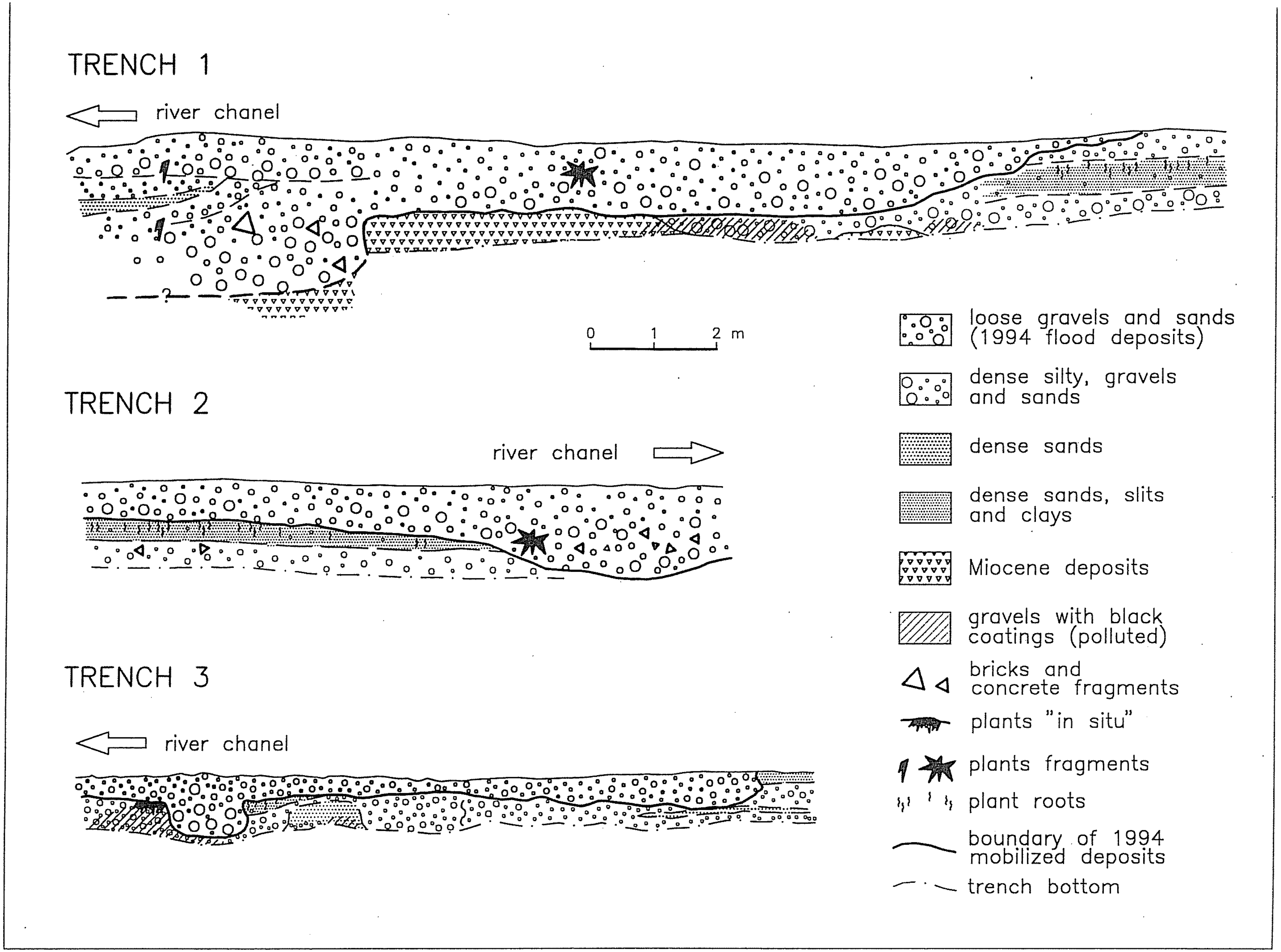

Figure 4. Geologic cross-section of trenches dug in the floodplain of the Tenes River at several localities (see location in figure 3).