Mediterranean Extreme Floods and Flood Risk : The Hydrogeomorphological Method

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CHAPTER EIGHT

MEDITERRANEAN EXTREME FLOODS AND FLOOD RISK: THE HYDROGEOMORPHOLOGICAL METHOD

JEAN-LOUIS BALLAIS

Abstract

Nowadays, in the valleys surrounding rivers, the problematic of flood hazard leads to observe familiar functional floodplain objects from a point of view slightly different from those generally admitted in fluvial dynamics. Interest in microtopography and its variations thus allows us to distinguish up to four beds in a Mediterranean watercourse valley. Currently under development, the hydrogeomorphological method already has produced new results with the description of exceptional high waterbeds in some watercourses in Mediterranean France and Tunisia.

Building up of numerous Mediterranean functional flood plains began during Classical Antiquity. The high water bed finegrained formations which have accumulated during the Middle Ages and the Modern and Contemporary periods. Using isotopic dating, we were able to show that this trend goes on during the second part of the 20th century and should continue in the future. Those formations are mainly produced by soil erosion due to cultural practices.

1. Introduction

Inside the watercourses' functional alluvial plain, two forms of fluvial beds have been precociously recognized in temperate environments (Leopold *et al.*, 1964; Derruau, 1962): the channel and the floodplain. The channel concept has rapidly appeared very fruitful due to the modelling possibilities it allowed (Birot, 1981) and in this way it has given a basis for several hundreds of fluvial activity researches (Bravard, Petit, 1997)

But the floodplain has remained, for a long time, a neglected one because of the complexity to have it modelized; this has been shown in 1978 by Lewin, then by Gupta (1983) and then by Nanson and Croke (1992). In France, a new interest for fluvial valleys forms prone to be flooded has been provoked by the natural hazards problematic introduced by the Tazieff law (1982, July 13th) (Masson *et al.*, 1996; Garry *et al.*, 2002; Ballais *et al.*, 2005b). The needed precision of the request studies (scales from 1/20,000 to 1/5,000) has shown two new forms of geomorphologic objects: the intermediate flow channel (Masson *et al.*, 1996; Ballais *et al.*, 2009), then the exceptional high water bed (Chave, 2003; Chave, Ballais, 2006).

Those beds present more or less important risks for people and goods, varying from maximum risk in the intermediate flow bed, up to the weaker risk in the exceptional high water bed. Historical low flow bed and high water bed evolution allows foreseeing those risks evolution in future decades.

The hydrogeomorphological method and mapping have been invented in Mediterranean France (Masson, 1983; Masson *et al.*, 1996; Garry *et al.*, 2002; Ballais *et al.*, 2005b; Ballais, 2006; Ballais *et al.*, 2011a) probably because of the very precise relations between the different beds which are due to the much contrasted regime of the rivers. This new method has become necessary because the traditional statistics hydrological-hydraulic methods, used worldwide have shown their limits in the case of catastrophic floods in Nîmes (1988) and Vaison-la-Romaine (1992). Indeed, the result of models and the accuracy of calculated water lines were not always satisfactory, because of the lack of measuring on some watersheds and also sometimes the insufficient quality and number of data (rainfall, heights of water) with the exception of well known big rivers. As soon as in the 1930s, those same limits have made the United States decide to abandon the probability method and to define a flood hierarchy: Intermediate Regional Flood, Standard Project Flood and Maximum Probable Flood (Ward, 1978), without reference to the morphology of the functional alluvial plain.

2. Hydrogeomorphology and inundability

Only watercourses of an order greater than 2 (according to Strahler, 1952) will be generally examined here because the smaller ones present specific problems (Ballais *et al.*, 2009; Mascareñas, 2012).

On this type of watercourses, the main dynamic is the longitudinal one because it allows setting up the functional alluvial plain different units. In

the transfer zones (Schumm, 1977), the logical series of different beds is observed: low flow bed, intermediate flow channel, ordinary high water bed and exceptional high water bed. They constitute the functional alluvial plain or the prone to be flooded zone. Several alluvial terraces (glacial or post-glacial) are as well observed (Fig. 8-1).
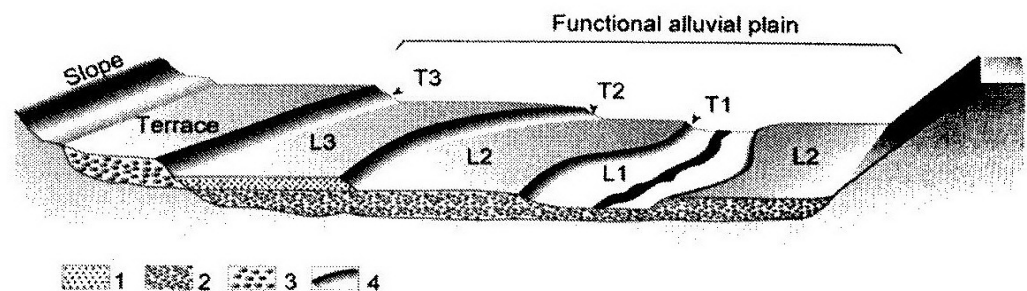
1: flood silts, 2: sandy-gravelly alluviums of the functional alluvial plain, 3: sandy-gravelly alluviums of the alluvial terrace, 4: slope
L1: low flow bed, L2: intermediate flow bed, L3: high water bed
T1: limit of the non flooding swellings, T2: limit of the frequent floods, T3: limit of the rare to exceptional floods

Fig. 8-1. Topographic relations between the different beds (Ballais *et al.*, 2005b, modified)

2.1. Low flow bed or low flow channel

The low flow bed must be distinguished from the "bande active" (braided rivers) (Bravard, Petit, 2000), mainly characterized by the lack of vegetation, and from the "channel" that more often gathers at once low flow bed and intermediate flow bed. In much contrasted fluvial regime zones as in the Mediterranean basin, it can include a low water channel during dry season.

Numerous river work arrangements (reprofiling, corrections) modify the low flow bed and, when it exists, a part or all of the intermediate flow bed. They have been employed since a long time to protect cultivated high water beds from the more frequent floods. Then, they have been progressively generalized to a great part of the fluvial network. So, the low flow bed morphology has been radically modified from reprofiling with cleaning out or earthworks without changing the course up to this line complete correction on some kilometres or more. More localized works have been also frequently performed to protect threatened towns such as at

Arles (France) (Allard, 1992), Sidi Bel Abbès (Algerie) (Hallouche *et al*, 2010) or Sfax (Tunisia) (A. Daoud, 2013).

2.2. Intermediate flow channel

In studying intermediate flow channel, the main difficulties are that it has a discontinuous form along the fluvial continuum and it does not exist along all the watercourses. Indeed, it has been proved that the intermediate flow channel is present along numerous Mediterranean zone watercourses (Masson *et al.*, 1996).

Intermediate flow channel (Delorme-Laurent, 2007; Delorme *et al*, 2013) is a horizontal or sub-horizontal surface whose detailed topography is very irregular. This irregularity is due to the presence of flood channels shaped by currents coming from the low flow bed. Those channels sometimes have either, active downcutting erosion forms or forms that are in the process of being built up. Thus, possible alluvial dynamics on this surface are numerous. Intermediate flow channels can equally have a more or less wide bench form so that they then look very similar to the high water bed. This is the case of the Nile River (Middle Egypt) or of the Asse River (Provence, France) (own observations).

The riverine forest that grows on those surface conditions flows as well because it increases roughness: bushes and herbaceous comb out and considerably slow down those flows. It sometimes influences the intermediate flow channel topography because the flow is abruptly slowed down and part of its load is deposited when clearing the banks. This process allows the formation and the development of alluvial levees or bank rolls, mainly in concave bank (Schumm, 1968; Nanson, Beach, 1977).

The different dynamics that allow the formation of this unit act upon its grain size distribution. Generally, the channels' base is formed by very coarse material deposited at the flood maximum. Those coarse deposits are sometimes covered by end of flood deposits (silts and clays). On the Argent-Double River at Peyriac-Minervois (France), for example, the range of coarse elements (coarser than 2 mm) at the surface of the intermediate flow channel, can be higher than 72 %, something that proves a very strong hydrodynamism (Delorme-Laurent, 2007). Nevertheless, it must be noted that this unit size grading is mainly controlled by the substratum.

Next to flooding, the slope that separates the intermediate flow channel from the high water bed is particularly significant. It is the result of recently spaced out floods and is very little evolutive at human life scale

When low flow channel bursts its banks, successive downcuttings of the high water bed sediments, alluviums deposits and channels evolution shape the slope. Its linear is often constituted by secant arcs of a circle succession. At the beginning, those arcs of a circle have a steep slope; this form often softens with times, in particular because of ploughings when the intermediate flow channel is partly cultivated (Masson et al., 1996).

In the Mediterranean basin, intermediate flow channels can be eroded during the more important floods (that occur generally in Autumn or in Winter) and building up can occur during less important floods that more often occur in Autumn or in Winter but as well in Spring. The frequency of swellings that flood the intermediate flow channel is still poorly known because it requires long and homogeneous series of hydrologic data and topographic studies. For information only, the Ouvèze River intermediate flow channel has been flooded 12 times in 70 years at Vaison-la-Romaine and the Orbieu River some 52 times in 45 years at Luc-sur-Orbieu (France) (Delorme-Laurent, 2007).

Generally, the downstream extremity of a water course is in relation with the oceanic base level. It is mainly controlled by the longitudinal slope decrease due to the rising of this level during the last millenaries. So, the decrease of the current velocity provokes the sedimentation of the clayey-silty suspended load. This load covers first the high water bed, then the intermediate flow channel and sometimes it can be accumulated even in the low flow channel. In this way, the functional alluvial plain is only made of the low flow channel and the high water bed. The geomorphological evolution can as well continue up to the change of the intermediate flow channel into a bank roll or an alluvial levee. Then, the so-called "lit en toit" (levees) is realized. It is characteristic of some coastal alluvial plains such as the Roussillon plains and the lower Aude Valley in France and the Pô Valley in Italy, for example. This situation is eminently dangerous, as far as flooding over the roll can provoke an avulsion (Ballais et al., 2011a).

Otherwise, intermediate flow channels have been very often modified by material extractions, hydraulic work buildings as well as clearings. The result of those human interventions is a very diversified morphological transformation that can affect the whole surface of this unit as well as its external erosion slope. Survey and delimitation of the intermediate flow channel are thus, sometimes, difficult (Ballais et al., 2011a).

In this way, the intermediate flow channel of a Mediterranean torrential regime watercourse must be considered as exposed to the maximal risk because it is a priori affected by all the flooding swellings, from the more frequent to the more exceptional, with the highest water

heights and flow velocities of the functional alluvial plain (Ballais *et al*, 2011a).

2.3. High water bed and super floodplain

The high water bed is a horizontal or sub horizontal surface that is separated from the intermediate flow channel by a slope. Its morphology is generally a great deal simple as this of an intermediate flow channel (Fig 8-2). It is only submerged by the less frequent floods and the currents that go through this surface are generally slow.
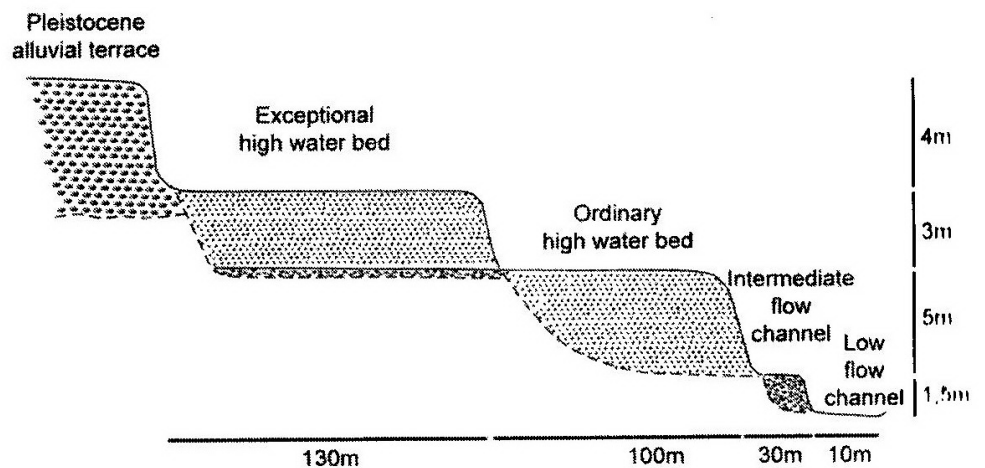

Fig. 8-2. Section of the Orbieu River alluvial plain at « La Mourède », Ferrals les Corbières, France (Delorme-Laurent, 2007, modified)

The water strip is thus much thinner than the one on the low flow bed and the intermediate flow channel, in a way that coarse elements cannot be transported. Generally speaking, the high water bed is made of fine elements coming from the deposit of suspended load at the end of the flood. Due to those deposits, this surface is a very fertile unit. In natural conditions, it is colonized by riverine forest. Nevertheless, due to this fertility, the high water bed has been systematically cultivated since a long time so that the spontaneous vegetation has been nearly almost cleared (Ballais *et al.*, 2011a).

Some small depressions can be found in the high water bed; they correspond to channels. In those channels dynamic is stronger and can be proved by accumulation of coarser deposits.

The high water bed external limit allows the definition of the most important past floods envelope curve which is the floods maximal

extension limit we have defined as the liable to flooding zone limit. The high water bed external limit is then the limit that must be known with the maximal precision. Thus, the high water bed is the geomorphologic high water bed (Nanson, Croke, 1992; Beltrando, 2004; Cosandey, 2003) that must be clearly distinguished from the hydrologic high water bed (Bravard, Petit, 2000) which is only the surface covered by the centennial flood.

As for the intermediate flow channel, frequency of high water beds flooding in the Mediterranean basin is poorly known. It seems as well very variable: the Ouvèze River high water bed has been flooded 4 times in 70 years at Vaison-la-Romaine and the Orbieu River high water bed has been flooded 9 times in 45 years at Luc-sur-Orbieu (Delorme-Laurent, 2007).

About flood hazard, particular geomorphological situations are often present in the Mediterranean basin. They must prompt to be extra careful and consequently to qualify the high water bed with a high risk, even to classify it as a potential intermediate flow channel (Montagné, 2003).

2.4. Distinction between ordinary high water bed and exceptional high water bed

In some cases, an exceptional high water bed intervened between the ordinary high water bed and the lower Upper Pleistocene or Holocene alluvial terrace. They have been described in France on the Gardon d'Anduze River (Aimon, 2003), on the Orbieu River (Chave, 2003), on the Tech River (Mussot, 1992), on the Cèze River (Delorme-Laurent, 2007), on the Cavu River (Lavigne, Lecoeur, in press) and probably on the Bayon River (Touabi, 2004). An exceptional high water bed has been recently observed on the Wadi Mekera (Sidi Bel Abbès, Algeria; Direction de l'Hydraulique, 2006, Hallouche, 2008, Hallouche *et al.*, 2010). But the widest and most continuous exceptional high water beds have been observed in Tunisia where they have been well dated mainly from the 1969 exceptional floods (Ballais, 1973; Fehri, 2003) and partly from the 1973 floods. The two types of high water beds have very similar localisation and characteristics (Fig. 8-2), but at the same time, are very distinct because they are separated by a 1 to 2 m marked sub vertical slope.

When the high water bed is flooded, the whole floodplain is submerged, therefore it would be possible to establish an equivalence between those two terms. Nevertheless, the Nanson and Croke (1992) "genetic floodplain" seems to include the intermediate flow channel as well as the high water bed and Beltrando (2004) includes those two beds

in the flood plain. Consequently, it is necessary to prefer "high water bed". Otherwise, the exceptional high water bed could correspond to the Gupta (1983) "super floodplain".

Moreover it has been confirmed that, contrarily to some hasty generalizations (Bravard, Petit, 2000), the wadis can have a low flow bed, an intermediate flow channel, an ordinary high water bed and an exceptional high water bed. The presence of perennial flow is not a necessary criterion.

2.5. Alluvial terraces

Alluvial terraces are topographic levels, more or less ancient, that are the testimony of passed hydrodynamism (Figs. 8-1 and 8-2). Therefore, those surfaces are no more liable to flooding (Coque, 1993; Campy, Macaire, 1989). In the Mediterranean basin, the younger generalized alluvial terraces have been accumulating during the last glacial period (Upper Pleistocene). Nevertheless, later alluvial terraces have accumulated along some watercourses, all around the Mediterranean Sea (Vita-Finzi, 1969).

In Tunisia, in Algeria, in Libya (Ballais, 1995), in Morocco (Gartet et al., 2001), in France (Delorme-Laurent, 2007), along some Spanish watercourses (Uribelarrea, Benito, 2005) for example, an important historical downcutting has occurred in soft rocks and superficial formations and has produced one or two alluvial terraces (Ballais, 1991).

Nevertheless, submersion of Pleistocene alluvial terraces has been seldom observed (Chave, 2003; Esposito et al., 2009). It has been proved this submersion was due to very specific situations. The first one is when the Pleistocene alluvial terrace went under the functional alluvial plain (Cèze River at Bagnols-sur-Cèze, Gardon River at Remoulins) (Ballais et al., 2009)). The second one is when downstream river work arrangements provoked a raising of the water line (Aude River at Villedaigne) (Esposito et al., 2009). The third one was due to floods deposits that have built up in the high water bed (cf. below) like on the Gardon River at Remoulins (Esposito et al. 2009) or on the Ouvèze River at Roaix downstream of Vaison-la-Romaine (Delorme, 2004).

2.6. Functional alluvial plain inundability

Following floods that have harshly affected the Aude department (France) and the border departments (35 dead, damages: 500 million Euros) in November 1999 then those that took place in the Gard

department (France) (28 dead, damages: 1.1 milliard Euros) in September 2002, the limits reached by the swellings have been compared to those first ones determined by hydrogeomorphological mapping.

The goal was to test the aptness of this field methodology method (Chave, 2003; Esposito *et al.*, 2009). Analyses revealed a good correspondence for those two limits for each of those two events. The comparison has been carried out on about 500 km long watercourses linear in French Languedoc, in watersheds the surface of which varies from some ten square kilometres to some hundred square kilometres. Limits are superposed on more than 80 % of this studied linear (Fig. 8-3).

Consequently, those studies once more show the importance of knowing the functional alluvial plain external limit that corresponds to the limit of a November 1999 or September 2002 type flood. Therefore, when planning or setting up statutory documents it's necessary to take this fact into account.
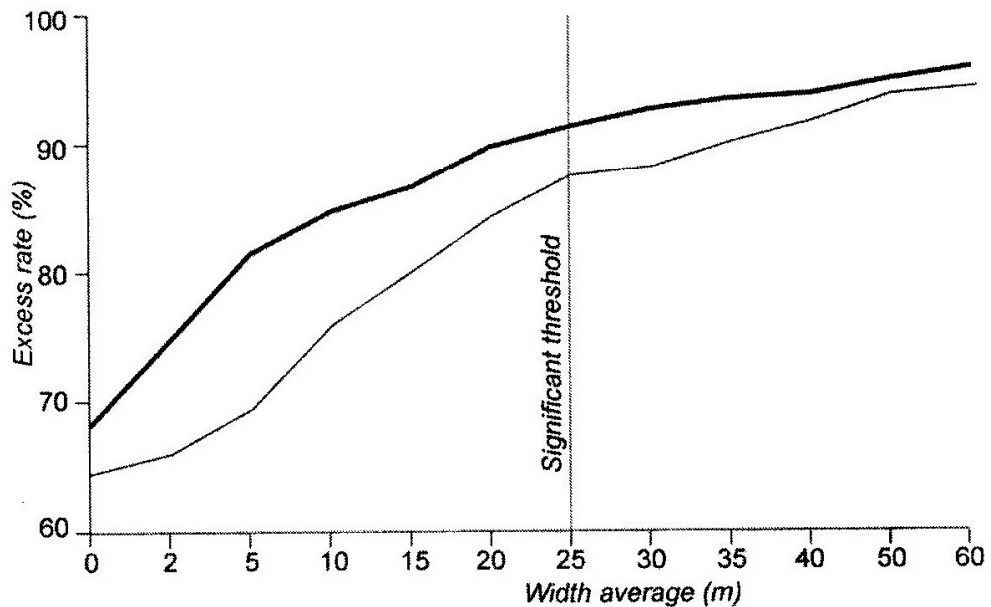
1: river floodplain
2: observed flooded areas beyond the flood plain

Fig. 8-3. Superimposition of limits of river floodplain and flooded areas

2.7. Functional alluvial plain mapping in the Mediterranean basin

Hydrogeomorphological mapping has been invented in Mediterranean France (Masson, 1983; Masson *et al.*, 1996; Garry *et al.*, 2002; Ballais *et*

al., 2005b; Ballais, 2006) (Fig. 8-4). Since, the Mediterranean basin remained at the tip of the prone to flooding areas (hydro) geomorphological mapping.

Although both, stress tolerant, species resistant to drought are not always the same with those adapted to fire. At the same time, the number of species per functional group is reduced by each disturbance. In such a way that, when both disturbances are combined, some functional groups may completely disappear because of the lack of redundancies, or their population may be at very low levels to be effective.

Practically, four successive years of drought proved to be a critical threshold for the resilience of the forest ecosystem to fire, as well as four fires in 50 years a limit for the resilience to droughts.
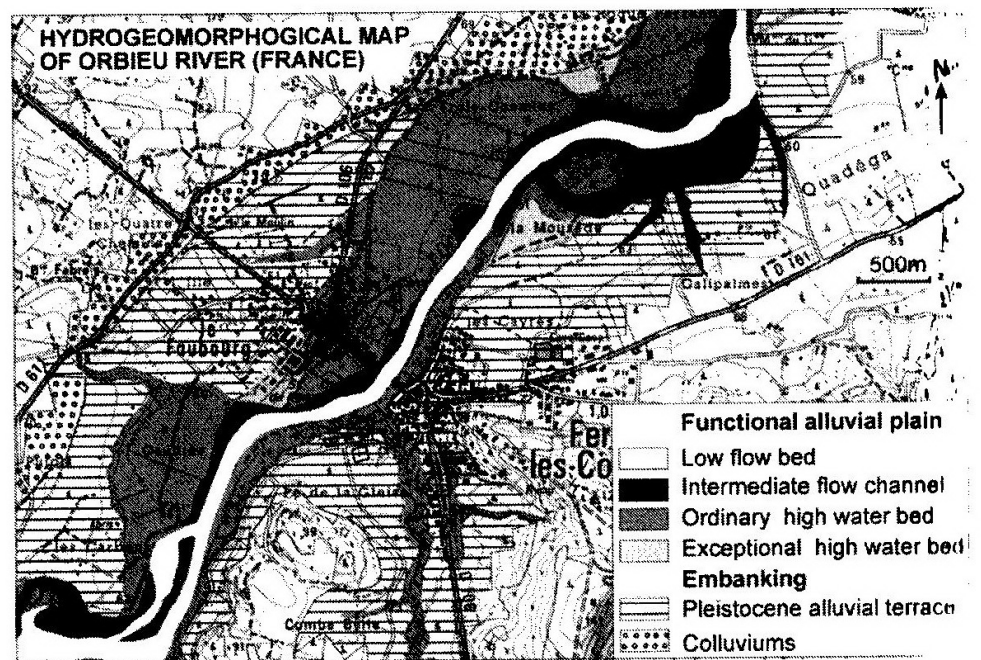
Fig. 8-4. Hydrogeomorphological map of the Orbieu valley (Ferrals-les-Corbières, France) (Delorme-Laurent, Ballais, 2006, modified).

In Northern Italy, Luino had proposed a first black and white map (1998) that was limited to the delimitation of the alluvial plain that experiences strong floods. Then, with two colleagues (2002), it has carried out a geomorphological analysis to mapping the Oglio River prone to flooding areas by reconstructing the river evolution since 50 years with thorough study of different aerial photography missions coupled together with field work along the river which defines the prone to the flooding area and compares it to the September 1960 flooded area.

In Algeria, a systematic mapping has been carried out at a 1/10 000 scale along the wadi Mekeraa by a French research consultancy and published by the Sidi Bel Abbès Wilaya (Direction de l'Hydraulique, 2006; Hallouche, 2007; Hallouche et al., 2010). This mapping legend follows very closely the French one (MEDD, 2002).

In Spain, a group of geomorphologists (Lastra et al., 2008) has realized an unpublished map integrated in a "geomorphological method". It distinguishes four "prone to flood terraces": low, middle, high and very high. The Geological Survey of Spain has published a handbook of flood hazard mapping methodologies (Díez-Herrero et al., 2009).

Finally, the first hydrogeomorphological map realized in Tunisia has just been presented in a recent thesis (Chouari, 2009).

This general presentation of the Mediterranean watercourses functional alluvial plain must be now replaced in the context of the two main beds (low flow bed and high water bed) historical evolution in order to allow the inundability evolution prediction for the next decades.

3. Low flow bed and high water bed recent evolution

3.1. Low flow bed evolution

3.1.1. Recent low flow bed downcutting

On some more or less important Mediterranean hydrographical network reaches, a longitudinal profile change is observed in soft rocks: generally, a pulling down of the low flow bed bottom occurs. It is well brought to the fore by the bridges observation.

This tendency is particularly marked in Algeria and in Tunisia (Ballais, 1984, 1991, 1995), on the Rhône tributaries and sub tributaries in France (Ballais et al., 2004) and on several Spanish watercourses such as the Guadalquivir River (Uribelarrea, Benito, 2005).

Downcutting is more important during floods as the great 1969 Southern Tunisia floods example has shown: scours have then varied from 20 cm up to 3 m, according to wadis and watersheds characteristics (Ballais, 1973).

Nevertheless, some exceptions can be observed on some Lana River tributaries in Tirana (Albania), on the Maritsa River at Erdine (Turkey) and the Pivka River at Postojna (Slovenia) where stability has been predominant, and on others, more rare, like Wadi Himmer, close to Fès (Morocco), where the low flow bed bottom has been recently raised up 40 to 60 cm (Gartet, 2007). In the case of calcareous watersheds, this stability

can be due to travertine building up dams, frequent in the Mediterranean basin, and spectacularly developed on the Krona River at Plivitce (Croatia).

Similarly to low flow beds cut down, they sometimes widen due to banks undermining, for example in Tunisia (Ballais, 1973), in Algeria (Ballais, 1984) and in Morocco (wadi Fès, wadi Sebou (up to 1.50 m/year from 1997 to 2007) (Gartet, 2007)).

3.1.2. Causes of low flow bed downcutting

Natural causes

When low flow bed downcutting occurs in the ablation or transfer zones, geomorphologists (Bravard, Petit, 2000) explain it as a consequence of an alluvial material supply deficit. This deficit is due to decreasing ablation on the slopes.

Anthropogenic causes

Two anthropogenic causes can, at least, be pointed out. The first one is the silting compartments that are being built on braided rivers. Even if, at the beginning, the accumulation of coarse then fine alluviums was natural, the silting compartments have amplified this accumulation. Therefore, low flow beds have heavily shrunken and high water beds have been consequently extended. This metamorphosis has accelerated a very slower natural process that concerns a lot of Mediterranean watercourses in France like the Gardon River, the Var River, the Groseau River or the Buech River (Gautier, 1992), as well as in Northern Italy (Luino et al, 2002).

The second cause of anthropogenic low flow bed downcutting on numerous watercourses is due to material extraction either in gravel and sand quarries or in reprofiling works. On numerous French Mediterranean rivers (Gardon River, Ouvèze River, Durance River) this deepening can locally reach 1 m (Branka, 2002; Durin, 2001). Systematic studies carried out on the Orb River watershed have allowed appraising the extractions impact on this river low flow bed (Malavoi, 2003): in the Thézan to Béziers area, the deepening can reach up to 3 to 4 m since the 1930-1940 years.

3.1.3 Downcutting consequences

Because of its obvious and even spectacular character, downcutting is currently integrated in hydraulic studies. Its consequences are conse-

changes. Those changes are fast in the watercourses ablation or transfer zones and more progressive downstream. In each case, the recent historic evolution can be at least partially reconstituted using aerial photographs and topographic maps. Nevertheless, it is sometimes difficult to distinguish the evolution part due to own river morphodynamism from the anthropogenic one.

Low flow bed downcutting frequently matches well with narrowing as shown by numerous bridges : Roman bridges on the Caudarhisar River (Turkey), Guadiana River at Mérida and Douro River at Salamanca (Spain), medieval bridges on the Arga River at Puente la Reina (Spain) and at Allos (Turkey), modern bridges on the Lana River in Tirana (Albania), and at several cases, in France: the Arre River at Le Vigan, the Hérault River at Saint-Julien-de-la-Nef, the Orb River at Béziers, the Durance River at Pertuis, the Luech River at Chamborigaud, the Recordier River and the Rieutord River at Sumène, the Lay River at Mane (own observations).

Under those conditions, the ancient low flow bed can become the new high water bed and its often lenticular coarse deposits are covered by finely bedded sands, silts and even clays, like for the Rio Cuadros at Bedmar, Andalucia, Spain (Ballais *et al.*, 2012).

If low flow bed downcutting is very important, it can potentially contain all the floods, even the most important. So, the high water bed is hunging out above the low flow bed and becomes an alluvial terrace. This situation is observed in two cases. The first one is represented by small rivers where reprofilings have been very important compared to the discharges, as on a lot of 1 to 2 order watercourses in France (Gardon and Arc Rivers subtributaries) and in Morocco, for example. The second one is due to regressive downcutting on 2 to 4 order watercourses combined with present day cultivated land extension (Andalucia (Spain), Morocco, Algeria, Tunisia (Ballais, 1991; Ballais *et al.*, 2003; Ballais *et al.*, 2012)). This evolution can favour dangerous works like in Amman (Jordan) where the Roman forum restoration in 1947 has removed the bridge and totally covered the river in such a way that flood risk has increased.

3.2. High water bed evolution

3.2.1. Historical building up

A historical silt building up tendency has been indicated in many Mediterranean watercourses. It often began during Classical Antiquity or even before on wadis in Libya (Vita-Finzi, 1969), Tunisia (wadi

Medjerda), Algeria (wadi Biskra), Jordan (wadi Mussa in Petra (Besançon, 2010)) and on rivers in France (Ouvèze River (Ballais, 2009), Rhône, Aigues, Gardon, Durance, Hérault, Buèges, Laye, Eze, Riaille and Escoutay Rivers) and in Turkey (Turca River at Edirne). It went on during the XXth century, at least on some of them (Bonté et al., 2001).

At Vaison-la-Romaine, Pomerol and Baye brooks, tributaries of the Ouvèze River, have accumulated about 3 m of clayey-silty deposits with small pebbles after the 1st century AD; the Merovingian chapel paving is 1.5 m under the Ouvèze River high water bed topographic surface, an indication which shows that the mean aggradation rate is about 10 cm/century (Ballais, 2009).

At Petra (Jordan), the Wadi Moussa high water bed was accumulated after the Roman city building.

At Toledo (Spain), the Tajo River was accumulated 9 m of alluviums above an old medieval gate, the "Puerta del Vado" (Diez-Herrero et al., 2005).

During more recent periods, the best example is the Argent-Double River one. At La Redorte, this Aude River tributary was accumulated more than 3 m of alluviums upstream the Canal du Midi built in 1681 (Chave, 2003; Delorme et al., 2009).

This tendency partially coincides with a major colluvial phase on the slopes due to maximal extension of cultivated soils during the modern period and the beginning of the contemporary period (17[h]-19th centuries).

Regarding the contemporary period, Benito et al. (2005) have shown the Guadalentin River (Spain) has experienced nine swellings over 20% years; each of them has accumulated some alluviums above the previous ones. The more recent swelling, probably the 1973 one, was the strongest.

The use of artificial (^{137}Cs and ^{134}Cs) or natural (^{210}Pb) radioisotopes has allowed to show that this tendency persists during the 20th century, at least on the Gardon d'Anduze River (1958 flood), the Ouvèze River (1992 flood) (Bonté et al., 2001; Ballais et al. 2004) and the Argent-Double River (Delorme, 2004; Delorme et al., 2009) (Fig. 8-5). These radioisotopes measures (Bonté et al., 2001) have allowed to evaluate the alluvium thickness deposited in one flood: about 30 cm by the Gardon d'Anduze River at Attuech in 1958 and at least as much by the Ouvèze River at Vaison-la-Romaine in 1992.

The tendency can be as well observed in other Mediterranean countries. For example, in the North of Morocco, 1.5 m of fine deposits have been accumulated in the wadi Ouerrah high water bed above an old plastic bottle (Ballais et al., 2005a).
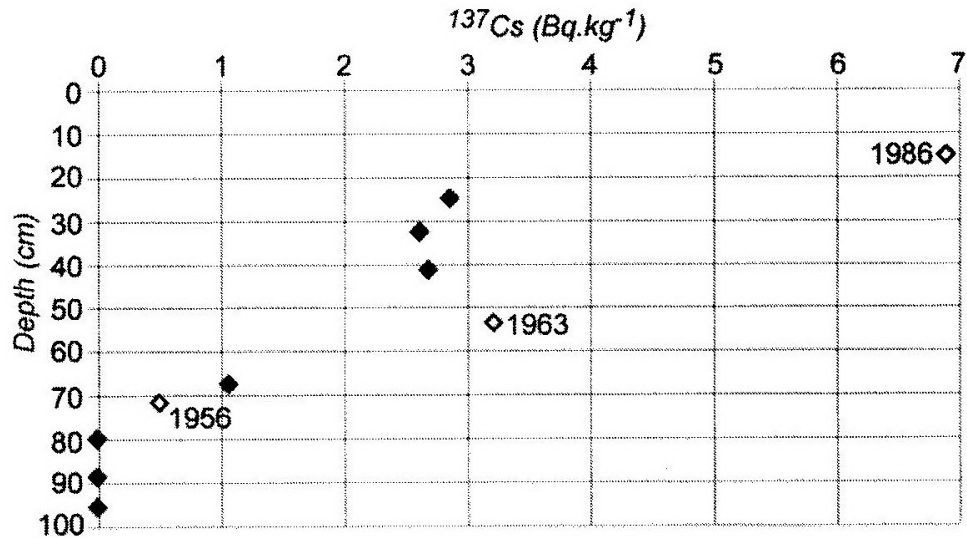
Radioactivity is measured on horizontal axis

Fig. 8-5. Building up of the Argent-Double River high water bed at La Redorte (France) during the 20th century (Delorme, 2004, modified).

Here as well, as was the case for the low flow bed, some exceptions can be noticed: building up in the high water bed was not always systematic. For example, at Qusayr Amra (Jordan), bathes that have been built in 705-710 in a prone to flood area, have not been covered by later alluviums (own observations).

3.2.2. Causes

It is a quite common that in the rivers, bed load is diminishing for two reasons. The first one is the slope vegetal recolonization and the second one is material extraction (cf. above). Nevertheless, building up of high water beds is going on because some colluviums are still conveyed to the rivers.

Colluviums are particularly plentiful in the Mediterranean basin when a sporadic overland flow can take away the soils during intense rains when vegetal cover is open. In fact, in natural condition, this is seldom the case: it seems colluviums appeared with the first impacts of farmers occupation on slopes. In Provence (France), in particular, the first colluviums generation could be protohistorical and the second one historical (Ballais, Crambes, 1992). Thus, in the Mediterranean basin, the very important anthropization (pasture, massive clearings and ploughings) has favoured or even created the conditions for a massive colluviation. It is the case, for example, in the Aurès Mountains in Algeria (Ballais, 1984) or at Jerash in

Jordan where the Hellenistic-Roman-Byzantine-Omayyad site is still partly buried under an enormous mass of colluviums (Sartre, 2001).

Indeed, present day rock weathering processes efficacy remains very weak or even nil in hard rocks (Gabert et al., 1981). Nevertheless, wetting and drying, thermoclasty and salt weathering, either individually or combined, can be efficient: they produce numerous clasts according to observations in France (Southern Alps, Provence (Abdel Moeti, 2002) and in Spain.

Forest fires are one of the main colluvium sources (Sala, Rubio, 1994) all the more so since the affected surfaces increase in the Mediterranean basin. In the Maures massif (France), after the 1990 August forest fire, Martin et al. (1997) have shown that the ablation range has multiplied by 100 during the year following the fire.

Another cause of the continuation of colluviums production is the stability or even the increasing of surfaces occupied by cultivations that poorly protect the soils. It is in particular the case of traditional Mediterranean cultivations such as vine and olive tree. In Mediterranean France even if vineyards surfaces tend to diminish they have been often concentrated closer to rivers, in a way that soil erosion products transport has been facilitated (Léonard, 2003). In Andalucia (Spain), olive groves surface has locally considerably increased during the 20th century (Araque Jimenez, 2007).

European Union tries to promote a sustainable development but, in those two countries, several factors favour production of still plentiful alluviums: steep slopes characteristics of the Mediterranean basin, abundance of soft rocks and superficial formations and farming methods (in particular, mechanized ploughing) (Ballais et al., 2012).

3.2.3. Consequences

For rivers constant flood discharges, the continuation of the building up tendency in high water beds will produce an increase of the surface covered by floods followed by an increase in hazard. In this context, thus the high water bed external limit must be regarded as a minimum limit of the prone to flooding area (Ballais et al., 2004).

Consequences for planning: Statistical analyses re-examination

Those first results have a great interest for planning, especially for flood risk prevention. Indeed, studies of flood hazard that are generally based on historical floods knowledge (see above) suppose that the general formation conditions of those floods has remained invariable since 100 to

200 years and even more. Usually, this stability principle is implicit and never stated. According to this principle, when ancient swellings have not been levelled, probability calculations are carried out to determine the height of water for different return periods, with the hypothesis that the supposed constant topographic surface is the present day functional alluvial plain topographic level. Actually, the former floods have spread on an alluvial topographic level that lies lower than the present day, obliges us to re-examine all the calculations that enable us to determine those floods water lines. The potential drift is important if the above results are taken into account. So, it is possible to understand why the hydrologic studies recording those water lines heights have increased over the course of 100 or 200 years (Masson et al., 1996).

In those cases, it is necessary to revalue hydraulic calculations, especially for low frequencies (centennial to exceptional flood) in the sense of a potentially increasing risk hazard over time.

Then, this revision must lean on a sedimentation rhythm analysis during the reference period and on this future tendency projection (Ballais et al., 2011a).

A secondary consequence of this statement is to observe with care the precision of hydraulic calculations results given the fact that it is necessary to estimate the error margin. This error can be very important when the high water bed evolution is poorly known (Ballais et al., 2011a).

It must be reminded that the high water bed evolvability is highly variable from upslope to downslope and from one valley to the other. Without a doubt, it is limited in the upslope and middle sections and is maximal in the downslope part. It also varies according to watershed geology, climate and vegetation cover. Some variables, such as vegetal cover, could have been highly modified during the recent historical period. All those elements must be henceforth integrated in flood hazard forward-looking studies (Ballais et al., 2011a).

Consequences for planning: Evolution of fluvial sites inundability

In risk and planning terms, the high water bed evolution gives a new light to inundability situations to which fluvial sites and cities are subject. Then it is possible to explain why old city nucleuses (Vaison-la-Romaine and Remoulins (France), Petra (Jordan)) are prone to flooding at the present day. This situation is in all likelihood generalized to the whole cities established in the watersheds downstream part, where fine sedimentation is more active. Upstream is also foreseeable in two particular geomorphological situations. The first one is upstream gorges

that set a water line rising and the second one is sectors affected by neo-tectonic activity (Masson *et al.*, 1996).

This situation noted, it creates the necessity to finalize new protection strategies for ancient urbanized zones on those sites where geomorphological evolution has spread up and where major security problems arise because of the massive invasion of high water beds by multitude of buildings, in the whole Mediterranean basin, a situation that started in recent decades

4. Conclusion

Building up of Mediterranean high water beds generally began during Classical Antiquity. Fine grained formations have accumulated during the Middle Ages and the Modern and Contemporary periods. Using isotopic dating, we were able to show that this trend goes on during the second part of the twentieth century. Land planning must take into account this evolution.

For the future decades and in the perspective of global warming (IPCC, 2013) geomorphologic researches must be concentrated on flood hazards. In particular, understanding the exceptional high water bed genesis is essential: incipient exceptional high water beds provide evidence of the functional alluvial plain widening and thus allows us to assume there is an increasingly greater risk.

According to several climatic models, global warming could be the cause of increasingly frequent and intense rare rains (IPCC, 2013) which produced great catastrophic floods in Mediterranean (IPCC, 2012) France such as in Nîmes (1988), Vaison-la-Romaine (1992), Aude River and tributaries (1999), Vidourle, Gardon and Cèze Rivers and tributaries (2002).

Now, the hydrogeomorphological method, a field method (Masson *et al*, 1996, Garry *et al.*, 2002; Ballais *et al.*, 2005b), allows us to determine liable to flood areas. Its great reliability has been proved in the 1999 and 2002 floods. Thus, it is necessary to apply this method and to refine it by using sedimentological and isotopic methods to determine the risk for hundreds of thousands of people living or working in the Mediterranean high water beds.

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