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Christophe Esposito, Sylvain Chave, Jean-Louis Ballais, Virginie Delorme-Laurent. Hydrogeomorphological Mapping and Recent Floods in France. 9th International Conference on the Mediterranean Coastal Environment (MEDCOAST 09), Nov 2009, Sotchi, Russia. pp.1053-1064. hal-01570817

HAL Id: hal-01570817

<https://amu.hal.science/hal-01570817>

Submitted on 31 Jul 2017

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Hydrogeomorphological Mapping and Recent Floods in France

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Abstract

On November 12th and 13th, 1999, and September 8th and 9th, 2002 two uncommon rainfall events occurred in the Mediterranean part of France (400 mm and more in 24 hours). These generated extensive damage (2 billion Euros) and loss of human lives (58 dead). These events offered a rare opportunity for comparing the observed flood areas with the boundaries of the floodplain. The hydrogeomorphological approach is rising up in the engineering field relative to the natural hazards forecast.

If we superimpose the boundaries, we can measure an excess length and a non-excess length. We can also proceed to a research on the origins and the process that originate an excess. Thanks to graphical and numerical processing, the results obtained widely show the floods' extent within the floodplain of the twenty-seven rivers studied. Besides, there were no incoherent situations thanks to the principles of the hydrogeomorphological mapping. The contradictions with these principles remain very limited (about 10%) and clearly delimited. So, this study demonstrates the efficiency and the importance of using this field approach.

Introduction

The aim of this paper is to show the results of research carried out when two recent rainfall events took place in the south of France in November 1999 and September 2002. They created major floods whose spatial limits often revealed to be more spread out than the forecast limits. The purpose of this research is to compare the limits of the areas liable to flooding and obtained by applying the hydrogeomorphological mapping method with that of the observed flooded areas during the two events.

Hydrogeomorphological mapping is a recent field approach (Masson *et al*, 1996). It enables one, from the recognition of the river channel and floodplain of a river, to identify areas liable to flooding during rare to exceptional floods. This approach is based on the concepts of fluvial geomorphology proposed by Schumm (1977).

When applied to the spatial prevention of flood risks, the hydrogeomorphological mapping enables the hazard to be determined qualitatively. Indeed, a hazard level can be given to a river channel and floodplain beds if the identification of rivers as well as the hydrodynamics (observed via topography and study of landforms of river channel and floodplain) are considered -or also thanks to the sedimentological study of forms (Garry *et al*, 2002, Ballais *et al*, 2005).

Two hydrogeomorphological events chosen to carry out this research took place in November 1999 and September 2002. Indeed, from 12th to 14th November 1999, the Aude, Pyrénées Orientales, Tarn and Hérault departments were affected by cumulative rainfalls greater than 600 mm (e.g. 621 mm in 48 hours in Lézignan-Corbières, Aude). However, the events were particularly remarkable because of the size of the areas where the rain fell : in fact, successive rainfalls of more than 300 mm in 48 hours fell onto an area of about 2 500 km² and more than 600 mm onto an area of about 80 km². Floods of a rare flow spread out along the whole of the hydrographical network causing 35 people to die and 50 million Euros damages. Two hundred and twenty six communes declared a state of natural disaster.

On the 8th and 9th September 2002 a similar event took place, affecting this time the Gard, Vaucluse and Hérault departments. It was a comparable event to that of November 1999, for example 687 mm of rainfall in 24 hours was measured in Anduze, Gard. The spatial extension of the rainfall was exceptional: more than 650 mm fell on an area of more than 150 km² and more than 300 mm fell over a surface of more than 3 200 km². 22 people died and 1.2 billion Euros damage was caused. Nevertheless, if each of these events now takes a historical dimension, there were some precedents along the rivers concerned and it meant historical comparison was possible in terms of flooded spaces, surfaces and limits.

The floods caused by the events of 1999 and 2002 are rare. Due to the regional dimension, we have checked if the limits of the river floodplain agreed with that of the flooded zones.

Following this methodology, we showed the results obtained along the twenty-seven rivers studied, first using the lengths' measurement (river lengths) exceeded or

not by the floodwaters, then by looking at the causes of isolated excess in the floodplain and flooded area.

Methodology

Two successive analyses were carried out using a digital method conceived to determine, first: the excess length value - that is the river floodplain which remained within the flooded zone - and second: to record the areas where some floods happened over the outside the floodplain limit (excess polygon).

Rivers studied

The study was carried out on a 492 km long strip, the total length of 27 rivers situated in the Aude and Gard departments (Table 1). They were selected to establish a representative database for the set of stream channels that make a hydrographical network. Rivers ranging from 1 to 6 (Strahler, 1952) are represented. They drain catchment-areas between 3 and 2 000 km².

One study (Chave, 2002) was carried out after the floods of November 1999. It includes the survey of seven rivers in the catchment area of Aude River, which represents a strip of about 154 km (Table 1). Another study (Esposito, 2003) was carried out after the floods of September 2002. It included the analysis of twenty rivers 338 km long in total (Table 1). All the rivers studied are tributaries of the Gardon River: 139 km long, draining a watershed of 2 014 km².

Methodology

In the two catchments, the flooded areas were mapped. The hydrogeomorphological mapping of the Aude department rivers was carried out quickly after the floods. The mapping of the Gard department rivers were carried out during the summer 2002, just before the floods.

The comparison between floodplain limit and observed flooded area limit was done in two major stages, using GIS software (Mapinfo). The superimposition allowed the graphic treatment: the methodological progression being in two stages. The first is the identification of the areas flooded by the rainfalls in 1999 and 2002. The second stage is for verifying all the cases in which the geomorphologic limit was not respected.

First stage: excess and non-excess length measurement

The first stage of the approach consists in superimposing two limits to be compared to determine, along a river, the limit of the flooded zone compared to that of the floodplain. The longitudinal evolution of the two limits allows classification into three types:

- Excess length: the flood extent is much greater than the floodplain;
- Coincident length: the flooded area is essentially the same as the floodplain;
- Non excess length: the flood is contained within the floodplain.

Table 1: General data relating to the 7 rivers of the catchment area of Aude and of Berre and relating to 20 rivers of the catchment of Gardon

Rivers	Watershed area	Ranging	Maximum altitude	Junction altitude	Length (km)	Studied length (km)	Streams total (km)	Drainage density (km.km ⁻²)	Estimated discharge (m ³ .s)	Specific discharge (m ³ .s ⁻¹ .km ⁻²)
AUDE / BERRE										
Clamoux	87,0	4	1211	89	32,4	19,0	119,5	1,37	375 à 400	4,5
Nielle	127,8	4	530	57	13,5	8,0	162,0	1,27	800 à 1000	7,8
Argent Double	110,0	4	1013	38	37,3	22,0	148,7	1,35	400 à 500	3
Berre	248,5	5	707	0	38,4	32,0	376,6	1,52	1100	12,7
Orbiel	251,8	5	1031	84	39,2	14,0	354,0	1,41	260 à 380	1,3
Cesse	269,0	5	1013	12	50,8	9,0	353,3	1,31	?	?
Orbiel	754,5	5	950	18	86,0	50,0	890,0	1,18	2000	2,65
GARD										
Rieu	3,3	1	75	67	5,1	1,6	5,1	1,57	?	?
Bruèges	7,2	2	162	138	3,1	2,1	7,3	1,02	?	?
Amous	20,3	3	266	126	7,9	5,3	29,7	1,46	400	19,7
Arrière	20,6	3	151	59	8,1	5,4	34,8	1,69	?	?
Esquielle	27,4	2	118	64	8,5	7,4	37,8	1,38	188	6,9
Crabieux	35,2	4	160	136	3,0	3,0	53,6	1,52	700 à 800	19,9 à 22,7
Avène	57,1	3	510	107	29,7	18,9	74,0	1,30	1000	17,5
Candouillère	57,3	3	132	95	9,4	9,4	72,8	1,27	1000	17,5
Galeizon	85,5	4	800	150	28,7	9,8	154,0	1,80	1500	17,6
Gardon de Saint Martin	87,4	4	364	224	12,3	2,3	131,8	1,51	?	?
Seynes	89,3	3	330	44	26,7	14,8	104,6	1,17	?	?
Bourdic	93,1	4	200	53	24,0	12,2	134,6	1,45	1000	10,7
Droude	129,6	4	156	72	21,4	21,4	163,7	1,26	1500	11,6
Braune	140,1	4	111	57	14,2	14,2	148,2	1,06	1500 à 2000	10,7 à 14,3
Alzon	195,2	4	195	24	23,6	20,5	202,6	1,04	?	?
Gardon de Mialet	241,7	5	224	130	20,4	20,4	373,7	1,55	600	2,5
Gardon de Saint Jean	264,4	5	1060	130	49,3	30,5	402,3	1,52	1500	5,7
Gardon d'Alès	443,1	5	823	94	62,5	48,0	652,0	1,47	3000 max	6,8 max
Gardon d'Anduze	626,2	6	130	94	17,2	17,2	950,7	1,52	2500	4,0
Gardon	2014,0	6	94	17	74,4	74,4	2615,5	1,30	7000	3,5

All the discrepancies (Fig. 1) are isolated. Each case constitutes a digital object referred to as an “excess polygon”. Once all the polygons are identified, the treatments consist in transforming polylinear objects so that the “excess lengths” can be measured. This length corresponds to the distance separating two intersections of layers at the origin of the creation of the polygon (Fig. 1). Its value is measured with the software. For each river, the sum of these unitary lengths, classified among three types of situations, compared to the surface of the floodplain leads to the estimation of the percentage of its “excess length”, of its “coincident length” and its “non excess length”. The perimeter of the floodplain for each river is called “the geomorphologic envelope”; the sum of the envelope of all the rivers is named “the whole geomorphologic envelope” (E.g.-Fig. 1 and Table 2).

Second stage: significance threshold and average width

Once the three categories of length have been isolated, interest is in the one that represents the excess. Some supplementary analyses were carried out on the excess polygons to determine the reasons for this situation. To concentrate on the most significant cases, excess polygons were sorted out to eliminate residual information. In order to do so, a “significance threshold” was used. The value retained for this threshold is 25 m.

What remains to be defined is the transversal value of the excess which is referred to as “the average width” (noted A_m –Fig. 1). It is estimated from the ratio of the area of the polygon and its “excess length” (Fig. 1) via an equivalent rectangle.

Table 2: Table of synthesis for excess and non-excess length related to the excess and non-excess polygons

	Aude / Berre watershed		Gard watershed	
	Total geomorphological envelope (E.g. - km)			
	349,1		746,2	
	Linear	Rate	Linear	Rate
Non-excess total linear	232,7	66,7%	473,9	63,5%
< 25 m	106,7	30,6%	283,5	38,0%
> 25 m	126,0	36,1%	190,4	25,5%
Total excess linear	116,4	33,3%	272,3	36,5%
< 25 m	72,7	20,8%	205,2	27,5%
> 25 m	43,7	12,5%	67,1	9,0%
	Number	Rate	Number	Rate
Non-excess total polygons	625	100,0%	2212	100,0%
< 25 m	541	86,6%	2090	94,5%
> 25 m	84	13,4%	121	5,5%
Total excess polygons	632	100,0%	2272	100,0%
< 25 m	581	91,9%	2200	96,8%
> 25 m	51	8,1%	72	3,2%

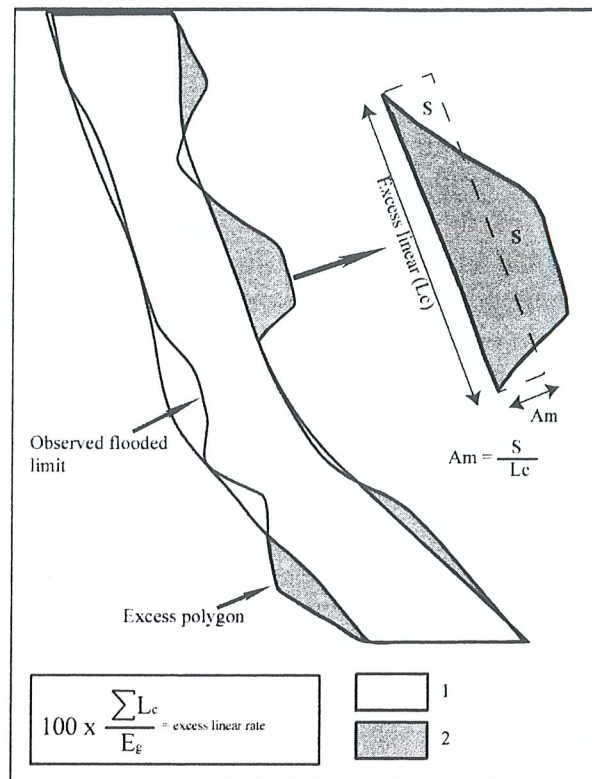


Fig. 1: Superimposition of limits and scheme of excess polygons. 1: river floodplain; 2: observed flooded area beyond the floodplain (excess polygon)

Results

Measuring the lengths

Graphic treatments (cf. 1.2.1), applied to the twenty-seven rivers studied enable us to gather evidence of the very large spread that occurred during these two rare floods inside the limits of their alluvial plain.

Excess lengths represent 12.5% of the geomorphologic envelope in the Aude department and less than 9% of that of the geomorphologic envelope in the Gard department (Table 2). Only 5% of this length shows an average width greater than 60 m (Fig. 2).

When the limit of the flooded zone is situated at less than 25 m of that of the floodplain of the river, the length is classified as coincident. It is the situation mainly observed along the 27 rivers studied: more than 51% of the alluvial plain of Aude department rivers, and 66% of Gard department rivers (Table 2).

Finally, the cases when the alluvial plain of the rivers was not completely flooded remain on the whole the minority: one third and on fourth of the geomorphologic envelope respectively in Aude and Gard departments.

The reasons for this variability observed on the level of the watersheds are puzzling. They reveal different situations when five main factors lead to the coincident of the floodplain of rivers: spatial and temporal characteristics of rainfalls, lithological and topographic characteristics of watersheds, man-made modifications to the natural river morphology.

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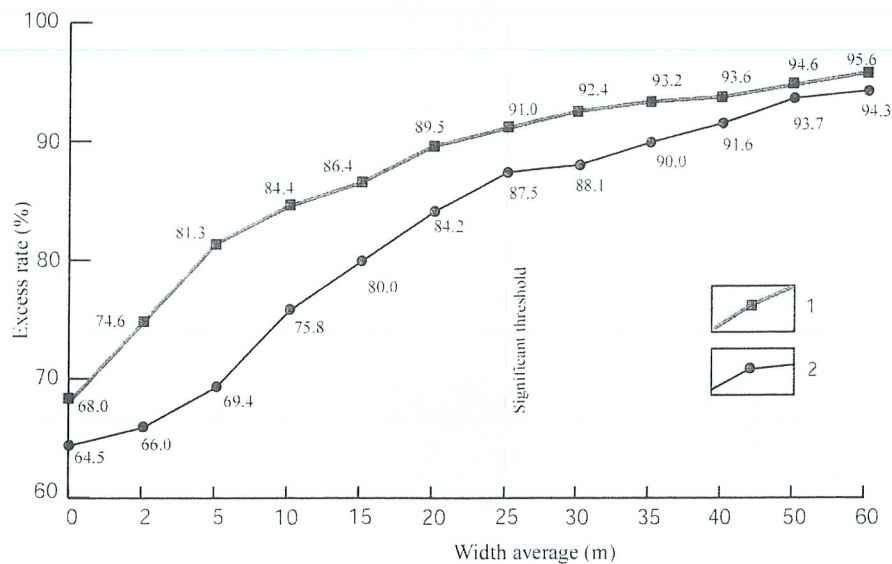


Fig. 2: Superimposition of limits and scheme of excess polygons. 1: river floodplain; 2: observed flooded area beyond the floodplain (excess polygon).

Indeed, when the rivers studied show high coincident rates, it means in general that the rivers are localised near the most important rainfalls. This is the case for the Nielle (Aude) which shows a coincident rate of 93%. In the Gard department, several rivers are in this situation: the Candouillère, the Esquille and the Amous have filling-up rates greater than 84% (Table 3). Yet, although the Gardon of Mialet is characterised by similar coincident rates (84%), the reason is due to its geographic situation. Indeed, this river is in the Cévennes part of the watershed of the Gardon, where all the pluviometric accumulations were the smallest and also where the rivers reach the downstream plains through gorges lines.

The factors mentioned previously also apply to the non-excess situations. The case of the Cesse is a good example of this situation with a non-coincident rate of its alluvial plain of 90% (Table 3). In the watershed of the Gardon, the rivers draining the Cévennes part (Gardon d'Alès, Grabieux, Galeizon) are similar to the Cesse case since it is the zone with the smallest rainfall (Table 3). Indeed, there are numerous long rivers which are characterised by a part of their watershed where smaller amounts of rain than on the other part fell. Consequently, we obtain a contrast between the non-filled-up upstream part followed downstream by a progressive coincidence of the floodplains (Orbiel in the Aude department, Avène or The Seynes in the Gard department). Some river parts show non-excess situations when the greatest cumulative rainfalls occur. For example, on the Gardon d'Alès flowing across Alès town, the superimposition of several series of man-made works (embankments, dikes, watercourse recalibration) account for certain parts of the floodplain not having been inundated despite their flood-prone character.

After this first series of results, the figures obtained show the large spreading of the November 1999 and September 2002 floods in the alluvial plain of the rivers studied. This means therefore that it is feasible to forecast for these vulnerable areas via this method at relatively modest cost (Masson *et al.*, 1996).

Table 3: Table of synthesis for the results obtained after the first stage of verification with the coincident, non- excess and excess rates

Rivers	Geomorphological envelope (m)	Excess linear rate (%)	Rate of coincident (%)	Non-excess rate (%)
AUDE / BERRE				
Nielle	16708	0%	93%	7%
Orbiel	30120	6%	66%	28%
Cesse	30580	0%	10%	90%
Clamoux	39120	3%	68%	28%
Argent-Double	39630	11%	63%	27%
Berre	86586	10%	58%	32%
Orbieu	106400	26%	30%	44%
GARD				
Rieu	3380	13%	31%	57%
Gardon de Saint Martin	4543	0%	55%	45%
Bruèges	5151	0%	75%	25%
Arrière	6260	26%	60%	14%
Grabieux	7357	0%	41%	59%
Esquielle	9436	7%	85%	8%
Amous	11268	11%	84%	5%
Galeizon	21824	0%	42%	58%
Bourdic	23056	33%	45%	22%
Braune	27422	37%	54%	9%
Candouillère	27880	8%	91%	2%
Seynes	32445	0%	57%	43%
Avène	39575	3%	54%	43%
Gardon de Mialet	44043	0%	84%	16%
Alzon	45722	8%	57%	35%
Gardon d'Anduze	49614	20%	54%	25%
Droude	57650	7%	76%	17%
Gardon de Saint Jean	63370	2%	75%	23%
Gardon d'Alès	96664	1%	47%	52%
Gardon	169540	13%	77%	10%

Typology of excess cases

The measurement of floodplain lengths (cf. 2.1) provided evidence of the existence of several sectors where the limit of the flooded zone was beyond that of the floodplain. These polygons, 51 for the Aude department rivers and 72 for the Gard department rivers, represent many situations which could contradict the principles of hydrogeomorphological mapping. So, supplementary analyses were carried out on each of the 123 polygons, by means of aerial photos and field observations. At the end of this second analysis, excess is explained by four main processes.

Type 1: Flooding of alluvial terraces near man-made works

This first type of excess gathers the sectors for which the flooding of alluvial terraces was identified. This was caused by the presence of modifications changing

quite the spreading of floodwaters inside the floodplain. These works, whether they concerned the crossing (bridge, railway or road embankment, Canal du Midi in the watershed of Aude) or protection (dikes mainly), provoked two distinct excess situations. The first (type 1a) is linked to the breaking of a work. Hence, the released waters could spread to the forms surrounding the floodplain of the river. The second type (type 1b) is due to works on the alluvial plain of the river making a screen which modifies the water line at its immediate upstream. Consequently, the waters are forced to spread beyond the alluvial plain.

The results show noticeable disparities between the two zones studied. Indeed, if about one third of the significant “excess length” (13 748 m – Table 4) is explained by the presence of works (specially the Canal du Midi) in the Aude department plains, it accounts for only 3% of this same length in the Gard department plains (2 166 m – Table 4). Furthermore, in the case of Aude department rivers, this excess shows a great amplitude - on average greater than 242 m (Fig. 3). This means that in such cases, the forms built by the river lose their hydrologic influence.

Type 2: Flooding of terraces, glacis and fans in natural conditions

When in natural conditions of flood propagation, surrounding forms were flooded, a contradiction regarding the hydrogeomorphological mapping principles was noticed. By natural conditions it is understated that flow is not influenced by hydraulic structures- either upstream or downstream. Landforms can be classified in three main types. First and most common are terraces (type 2a). This sub-type includes alluvial terraces as well as rocky terraces. When they are absent, the floodplain joins with downslope forms. In some cases, it is a glacis following transversally the floodplain (type 2b). In other cases, the resulting form is an alluvial-colluvial fan (type 2c).

Ten polygons were identified and classified in this type 2. Among the Aude department rivers, only one showed this type of excess (the Orbieu – Table 4). The concerned lengths only represented a small part of the geomorphologic envelope (680 m, that is 1.6%). However, it is not the case for 9 polygons recorded alongside Gard

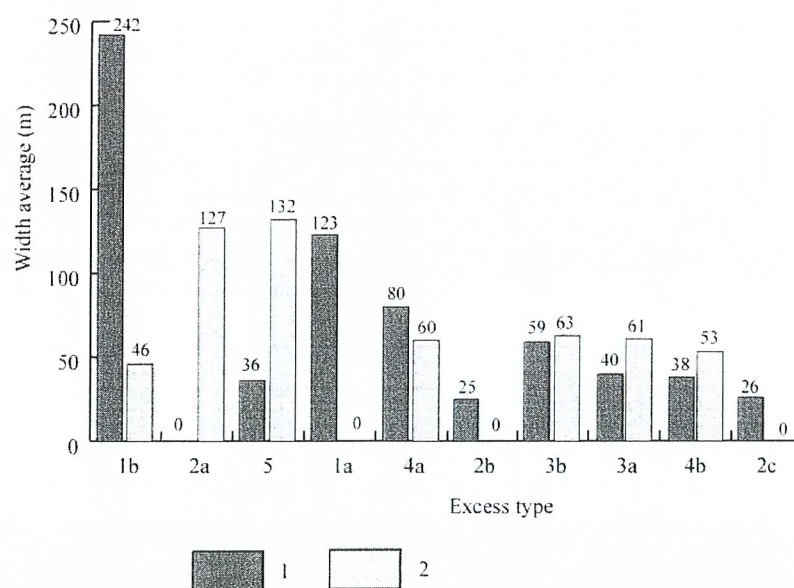


Fig. 3: Average curve of non-excess ratio of the floodplain limits by those of flooded areas. 1: Gardon catchment area; 2: Aude and Berre catchments areas

department rivers: each site is either alluvial or rocky terraces. All the polygons are situated near the local (confluence with the Rhône) and general (the Mediterranean sea) base levels. These terraces were set up during the Würm period when the Mediterranean sea was 120 m below its present level. Consequently, the longitudinal profile of these forms is steeper than that of the floodplain of the Gardon, suggesting that these polygons are located in the zone where the Würmian terraces move progressively under the present high water bed.

Type 3: Excess on the connecting slope between low terrace and floodplain

In some situations, the contact is progressive, characterised by a long convexo-concave form stretched on a strip of 10s of metres. When the waters reach beyond the external part of the floodplain, the limit of flooding is then situated between the lower concavity and the upper convexity. Considering type 3 is contrary to situations referenced in type 2, the forms considered out of floods' reach were not flowed over. This configuration was seen as much in the case of a contact between floodplain and alluvial terrace (type 3a) as in a contact between floodplain and substratum forms (type 3b).

The excess situations explained above represent up to one third of the excess length significant for the geomorphologic Gard department envelope- so about 24 000 m (Table 4). These situations are twice as scarce as in Aude department catchment. They occur when the lithology is favourable to a progressive contact between the alluvial plain and the substratum, that is to say when the latter is constituted of marly formations.

Type 4: Excess resulting from cartographic errors

Several times, the analyses concluded there was a cartographic error since the field research showed the superimposition of the two limits on the external part of the floodplain. These errors were noticed as much for the hydrogeomorphological cartography as for that of the flooded areas. These errors account for an important part of the excess length, respectively 37 % and 27 % of the geomorphologic Aude department and Gard department envelope (Table 4). They remain in a minority rating lower than 10 % of the significant excess length (Table 4) and with an amplitude limited to 50 m (Fig. 3).

Type 5: Unresolved cases due to lack of verification elements

The analyses carried out on eight polygons could not be completed due to lack of verification elements. This happened, for example, in sectors uninhabited where it was impossible to confirm the positioning of the limit of the flooded area. The sectors included in this last type will have to be investigated in the future.

Discussion

The efficiency of the hydrogeomorphological approach of flood-prone areas has just been proven via the analysis of 27 rivers. However, its application must take account of three key-points that could lead to situations that are apparently contradictory to its foundations.

Table 4: Excess polygons typology. *Numerically, 51 polygons in the catchment areas of Aude and of Berre and 72 in the catchment area of Gard were isolated. However, confronted to the conjunction of explanations of some of them, we proceeded to some intra-polygons cuttings, increasing the number by 8 units for Aude department by 3 units for Gard department

Excess types		AUDE / BERRE watersheds			GARD watershed		
		Total length		Number of polygons *	Total length		Number of polygons *
		M	%		m	%	
Hydraulic structures	1a	4196	9,6	4	0	0,0	0
	1b	9552	21,9	8	2166	3,2	6
In natural conditions	2a	0	0,0	0	10768	16,1	8
	2b	460	1,1	1	0	0,0	0
	2c	220	0,5	1	0	0,0	0
On the connecting slope	3a	3891	8,9	7	2685	4,0	3
	3b	3928	9,0	4	21630	32,2	19
Due to cartographies errors	4a	16094	36,8	23	18424	27,5	29
	4b	3878	8,9	7	4118	6,1	6
Unresolved	5	1472	3,4	4	7284	10,9	4
Total		43690	100,0	59	67075	100,0	75

First, the fact that the Pleistocene alluvial deposits have accumulated during the glacial periods means that in the downstream of rivers close to the base level, the longitudinal profiles of the terraces and of the floodplain show different slopes. Indeed, the rivers reached a sea level of minus 120 m, which is lower than the present one. This means that there is an intersection-point between these two profiles- near which the alluvial terraces could be flooded- and beyond them, these Pleistocene forms go under the present alluvial floor. This case applies to the Rissian alluvial terrace on which the city of Remoulins was built, and was flooded nearly completely by several dozen centimetres of water during the September 2002 flood. A similar case was also identified along the Cèze crossing the city of Bagnols-sur-Cèze.

The present accumulation of floodplains reveals an important determinant. Indeed, rare to exceptional floods can accumulate large volumes of alluvium on the surface of the floodplain (Bonté *et al.*, 2001; Ballais *et al.*, 2004). Regarding Remoulins, such processes are quite possible, due especially to the favourable geographic situation: the road bridge was built on a narrowing over the Gardon River. These accumulation processes appear first because of the differences in height- about 3 metres between the upstream and the downstream of the narrowing. Qualitative observations carried out in cherry orchards upstream show that their trunks were hidden by an alluvial accumulation- probably produced during the last twenty or thirty years.

Besides, these accumulation processes could have been amplified by the hydraulic works built in the river floodplain. The works, in blocking the flows, force the sediment carried away to accumulate upstream, sometimes by silting-up of the low alluvial terrace. This is the case along the downstream part of the Argent-Double when it flows across the Canal du Midi (Chave, 2003, Delorme-Laurent, 2007).

Conclusion

Despite the limitation discussed, hydrogeomorphological mapping is among the most reliable means to spatially predetermine the major floods happening frequently in the Mediterranean zone. For the last two floods in the Aude department in 1999 and in the Gard department in 2002, the external limit of the floodplain compared to that of the flooded zone shows that 87% to 91% of the length of the floodplain is beyond the limit of the flooded zone. Consequently, it means that this type of event is spatially quite predictable.

Consequently, the results confirm the necessity to apply this approach in order to make of informative or regulating maps of flooding risks. Moreover, they justify a multidisciplinary approach to address unexpected events.

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