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Abstract

This paper focuses on the contribution of fluvial geomorphology to flood management. We define what fluvial geomorphologists understand by 'fluvial risk' and examine the relationship between fluvial geomorphology and fluvial hazards. The paper details how fluvial geomorphology can present innovative approaches to flood prevention, river maintainance and floodplain restoration. Management of soil erosion and floodwaters is the key question in the plateaus and plains of northern France. In mountainous terrain, strong connectivity between the slopes and high order streams induces permanent risk for local people living near the river, on alluvial fans or on the lower river terraces as demonstrated in the French Alps and in Nepal Himalayas. Management of debris flows resulting from interaction of erosion processes on the slopes and valley bottom is of fundamental importance. The paper highlights the diversity of concepts and methods, such as hydrogeomorphological mapping, sediment budget and functional flood areas, developed by fluvial geomorphologists in order to understand spatio-temporal variability of flood hazard and induced flood risk in temperate, Mediterranean and mountainous areas. The discussion places the existing research in the context of the main ecological issues, future climate change and the constraints imposed by the land-use conflicts, political and social choices and the need to preserve natural heritage.

Key words: applied hydrogeomorphology, flood hazard, fluvial risk, river-basin management.

Résumé

Cet article fait le bilan des compétences des hydrogéomorphologues en matière d'analyse des risques fluviaux. Après avoir précisé ce que les hydrogéomorphologues entendent par « risque fluvial » et les connexions existant entre l'hydrogéomorphologie et les aléas de crue, l'article fait état des connaissances produites par les hydrogéomorphologues et décrit comment leur production scientifique peut être mise à profit afin de proposer des actions innovantes en matière de prévention contre les crues, d'entretien des lits de rivière et de restauration des plaines alluviales. L'érosion des sols et la gestion des eaux fluviales sont les éléments clés de la gestion des risques dans les plateaux et les plaines du nord de la France. En régions de montagne, la connexion très forte entre les versants et le lit torrentiel, démontrée ici à travers les cas des Alpes françaises et de l'Himalaya du Népal, induit un risque permanent pour les populations locales vivant près de la rivière, sur les cônes torrentiels ou sur les basses terrasses. Ainsi, la gestion des flux de débris, résultant de l'interaction des processus d'érosion sur les versants et le fond de vallée, est fondamentale dans les montagnes. L'article met en évidence la diversité des concepts et des méthodes, comme la cartographie hydrogéomorphologique, les budgets sédimentaires et l'espace de liberté, développés par les hydrogéomorphologues dans le but de comprendre la variabilité spatio-temporelle des aléas de crue et des risques induits dans les zones tempérées, méditerranéennes et montagneuses. L'apport des recherches actuelles est replacé dans le cadre des grands enjeux écologiques de demain, des changements climatiques et des limites imposées par les conflits d'usage, les choix politiques et sociaux et la préservation du patrimoine.

Mots clés : *hydrogéomorphologie appliquée, aléa de crue, risque fluvial, gestion des bassins versants.*

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L'hydrogéomorphologie fluviale occupe aujourd'hui une place de choix pour mesurer l'impact des aléas hydro-climatiques. Cette position est le fruit de l'évolution récente des recherches sur les hydrosystèmes fluviaux, de plus en plus en lien avec les gestionnaires et dans un contexte de forte demande sociétale, économique et environnementale. Les objectifs de l'article sont de faire le bilan des compétences des hydrogéomorphologues, utiles à l'analyse des risques fluviaux, et de montrer, à partir d'exemples de rivières françaises, suisses et népalaises, comment leur production scientifique peut être mise à profit pour proposer des actions innovantes en matière de prévention contre les crues, d'entretien des lits de rivière et de restauration des plaines alluviales.

Les recherches actuelles en hydrogéomorphologie fluviale font l'objet d'approches globales visant à améliorer les actions de gestion et de prévention de ces risques, en mettant l'accent sur l'aléa et l'impact des modifications d'usages des sols de la plaine, mais aussi du bassin et des aménagements fluviaux (fig. 1). Les risques fluviaux ne sont pas de même nature ni de même ampleur selon que l'on se situe en régions de montagne, de plateau et de plaine ou dans de grandes vallées. Dans les bassins montagnards, l'importance de la dynamique hydrosédimentaire est contrôlée par des types particuliers d'aléa : les coulées de débris et les écoulements hyperconcentrés. Dans les montagnes gagnées par le tourisme, les plaines alluviales et les cônes torrentiels sont de plus en plus aménagés et de grandes zones habitées peuvent alors se trouver dans les zones de débordement ou dans la trajectoire de chenaux de crue. Dans les régions de plateau et de plaine, l'aléa a deux origines, les crues lentes et les crues rapides. L'occupation dense des lits de rivière à crues lentes (fig. 2) induit une forte vulnérabilité mais le risque reste faible, aboutissant à des crises hydrosédimentaires de courte durée. Dans les régions de plateau du nord-ouest de la France, les crues rapides sont la manifestation exacerbée du ruissellement érosif (fig. 3). Ces écoulements torrentiels, qui surviennent dans des vallons secs urbanisés, font peser des risques importants sur les populations. Enfin, le risque fluvial dans les grandes vallées (à l'échelle européenne) est détaillé à travers les cas de la Loire et du Rhône. Ces deux fleuves sont soumis aux crues lentes et rapides, qui rendent la gestion du risque relativement difficile. L'étude hydrologique et morphodynamique de l'événement de décembre 2003 sur le Rhône (fig. 4) et sur la Loire met en lumière le rôle des ouvrages, mais aussi celui de l'évolution récente du lit fluvial sur les dysfonctionnements hydrologiques et le risque qui en résulte.

La production de connaissances par les hydrogéomorphologues pour mieux comprendre l'aléa porte sur sa dimension spatiale et sa mise en perspective historique. Les méthodes de spatialisation reposent sur la cartographie hydrogéomorphologique à l'échelle des tronçons et des bassins versants. L'adaptation de la méthode de cartographie hydrogéomorphologique à la vallée du Rhône (Bravard et al.*, 2008) a permis de rendre compte de la complexité du fonctionnement fluvial dans chacun des principaux tronçons de la vallée entre la frontière suisse et la Méditerranée (fig. 5). Des alternatives à la cartographie hydrogéomorphologique peuvent être proposées avec le développement d'autres concepts tels que l'espace de liberté (fig. 6), de rétention et de bon fonctionnement, mais aussi par les budgets sédimentaires (fig. 7).*

Dans le cas de la mise en perspective historique de l'aléa, le caractère aléatoire des crues est montré par l'analyse des fluctuations de l'activité hydrologique au cours du temps, de la dilatation et la rétraction des bandes actives au gré des fluctuations du transport solide et de la propagation des masses sédimentaires dans les bassins-versants. La variabilité historique de l'aléa doit être davantage prise en compte par la paléohydraulique et la paléohydrologie pour définir les crues de référence et notamment l'estimation des débits anciens et de leur fréquence. Des actions innovantes (restauration-réhabilitation-« renaturation », prévention, entretien) sont proposées quant à la gestion des corridors fluviaux afin de minimiser l'impact des crues. Par la connaissance du terrain, les géomorphologues précisent là où il faut intervenir dans la plaine alluviale, tout en ménageant certains secteurs. Ainsi, des actions de restauration des bandes actives ont été proposées dans le sud de la France, utilisant le concept d'espace de liberté couplé à celui de la gestion douce (fig. 8 et fig. 9). Le recreusement des lits majeurs est également considéré comme une des actions favorisant à la fois la restauration écologique et le laminage des crues. La cartographie des fonds alluviaux permet de reconstituer les paléoenvironnements que les aménagements importants ont fait disparaître, en particulier les tracés sinueux effacés par les rectifications et les bras secondaires comblés. Ainsi, il est possible de réaliser des actions de « renaturation » durable des lits fluviaux. La diversification des faciès d'écoulement favorise également la restauration des écosystèmes aquatiques. Par ailleurs, la modélisation des écoulements de crue constitue une aide indéniable à la prévention des inondations. Des approches fondées sur la simulation numérique offrent la possibilité d'étendre la réflexion à l'ensemble des cours d'eau, qu'ils soient jaugés ou non.

Quelques pistes de réflexion sont également avancées quant à la gestion de l'érosion des berges et la notion de fuseau de mobilité dans le corridor fluvial. Comme dans le cas du bois mort, les avancées scientifiques récentes soulignent que l'érosion latérale n'est pas un fléau contre lequel il convient de lutter systématiquement. La préservation de l'érosion peut être un enjeu fort sur certains cours d'eau où elle constitue véritablement le moteur écologique des milieux rivulaires. Dans ce contexte, anticiper le risque en identifiant les secteurs soumis à cet aléa et en réglementant l'exercice des usages est apparu comme une stratégie bénéfique pour la collectivité. Enfin, des solutions efficaces sont envisagées en matière d'entretien des lits fluviaux en lien avec la production de bois mort. En particulier, plusieurs actions sont proposées pour gérer les risques associés aux embâcles.

Plusieurs questions restent ouvertes et constituent les enjeux de la recherche en hydrogéomorphologie pour la décennie à venir. La modélisation et la minimisation des crues *constituent le premier de ces enjeux, qui passera par une meilleure intégration de l'évolution de l'occupation du sol et de la dynamique fluviale. La gestion durable des bassins versants est le deuxième enjeu identifié, qui devra répondre à la législation nationale (Plan de Prévention des Risques d'Inondation ; Loi sur l'Eau et les Milieux Aquatiques) mais aussi à celle de l'Union européenne (Directive Cadre Européenne). Des approches intermédiaires entre celles dites ascendantes et analytiques permettront certainement de mieux résoudre les problèmes inhérents aux conflits d'usage, aux choix politiques ou sociaux et à la conservation du patrimoine. Enfin, la nécessité de pérenniser les recherches fondamentales de terrain apparaît comme le troisième enjeu, en particulier celle de développer la connaissance des processus d'ajustement des cours d'eau.*

Introduction

Fluvial geomorphology is a science of synthesis at the interface between geosciences, geography and applied engineering (Kondolf and Piégay, 2003). It provides additional knowledge beyond that attainable from other fields (ecology, chemistry, hydrology, human and environmental sciences), and allows the river system to be studied in all temporal dimensions, from the channel to the floodplain, from the mountainous reaches to estuarine or deltaic river mouths (Brierley and Fryirs, 2005). Fluvial geomorphology has become essential to our ability to quantify the impact of hydro-climatic hazards.

Until the late 1980s studies on rivers in France were carried out at regional scales and based mostly on monographic approaches. Apart from a few studies (Tricart, 1958; Bravard, 1987), research on hydrology and on fluvial forms was developed independently. In the last twenty years, assessment of historical geomorphological changes, of flood impacts upon societies living along rivers, and the analysis of both the structures and physical functioning of the rivers in relation to fauna and flora have become more frequent and increasingly based upon a systemic approach to fluvial hydrosystems (Amoros and Petts, 1993; Bravard and Petit, 2000). The evolution of the scientific approach is linked to: (i) the need to manage fluvial systems differently as an adaptation to new social needs, (ii) increasing interest in landscapes and a healthy environment, (iii) the need to reconcile multiple floodplain use, (iv) sustainable management of river flows and sediment movement and deposition, and (v) fluvial systems as natural infrastructures along which conservation and restoration of zones of flood expansion, autopurge function of the water in the wet zones and new technologies developed by ecological engineering ensure sustainable development for society (Piégay *et al.*, 2008). Thus, floodplains are being increasingly studied in relation with administrators and environmental managers within the French regulatory and legal framework (Piégay *et al.*, 2002) or, more generally, of the European Water Framework Directive, which seeks to achieve sustainable ecological status in all modified water bodies by 2015. Fluvial geomorphology has become integrated into the environmental sciences, and the work of geomorphologists is now included in multi-disciplinary environmental teams. The emergence of thematic workshops, called "Zones Ateliers" in France, which are similar to the American Long Term Ecological Research, reflects these recent scientific advances (Lévêque and Mounolou, 2004).

The objectives of this paper are to summarize the recent contributions of some French geomorphologists in the fluvial risk management, and to show how they can contribute innovative approaches to flood prevention, riverbed maintenance and floodplain restoration (Piégay and Roy, 2006). After defining what geomorphologists mean by 'fluvial risk', the paper details their scientific inputs leading to theoretical and practical approaches to restoration, prevention and maintenance. We then evaluate the current research in the context of the main ecological issues, future climatic change and constraints imposed by land-use conflicts, political and social choices and the preservation of the natural heritage.

What is fluvial risk?

Fluvial risk is the integration of direct or indirect risks linked to the action of superficial water flows: flood, lateral and/or vertical erosion and sedimentation in the channel and the riverbanks, channel avulsion in the floodplain, pollution and severe low flows. Current research in fluvial geomorphology consists of global approaches that aim at improving management of these risks. The risk approach not only concerns the management of hydrological crises. It is more complex because it results from a large number of physical and human factors, and requires the knowledge of both hazard and vulnerability of various components. Therefore, societal vulnerability can only be reduced by integrating (i) the hazards and consequences, (ii) risk management through public policies and collective actions including crisis assessment, disaster relief and prevention, and (iii) the perception and understanding of the risk by the users (Alexander, 2000). Fluvial geomorphologists contribute to fluvial-risk analysis by emphasizing the hydro-climatic hazards and the impact of land-use and hydraulic management changes in the floodplains and hillslopes at the catchment scale. Figure 1 details the systemic approach of flood risk developed on left-bank tributaries of the Aude River, southern France, following the catastrophic flood event of 12-13 December 1999. Systemic analysis of the event highlights two types of triggering and aggravating factors, natural and anthropogenic. Generally, their fluvial-risk analysis is conducted as follows: characterisation and cartography, analysis of the predisposing-triggering-aggravating factors, evolution across different timescales (from short to long term), frequency and magnitude variability. The long-term (500-10,000 years) nature of fluvial hazards must be taken into account by current management, as well as the definition and the integration of 100-yr recurrence interval floods (Bravard *et al.*, 2008) and the palaeohydrological crises such as those occurred during Iron Age, the Antiquity and the Little Ice Age (Arnaud-Fassetta, 2007). The nature and dimension of fluvial risks are

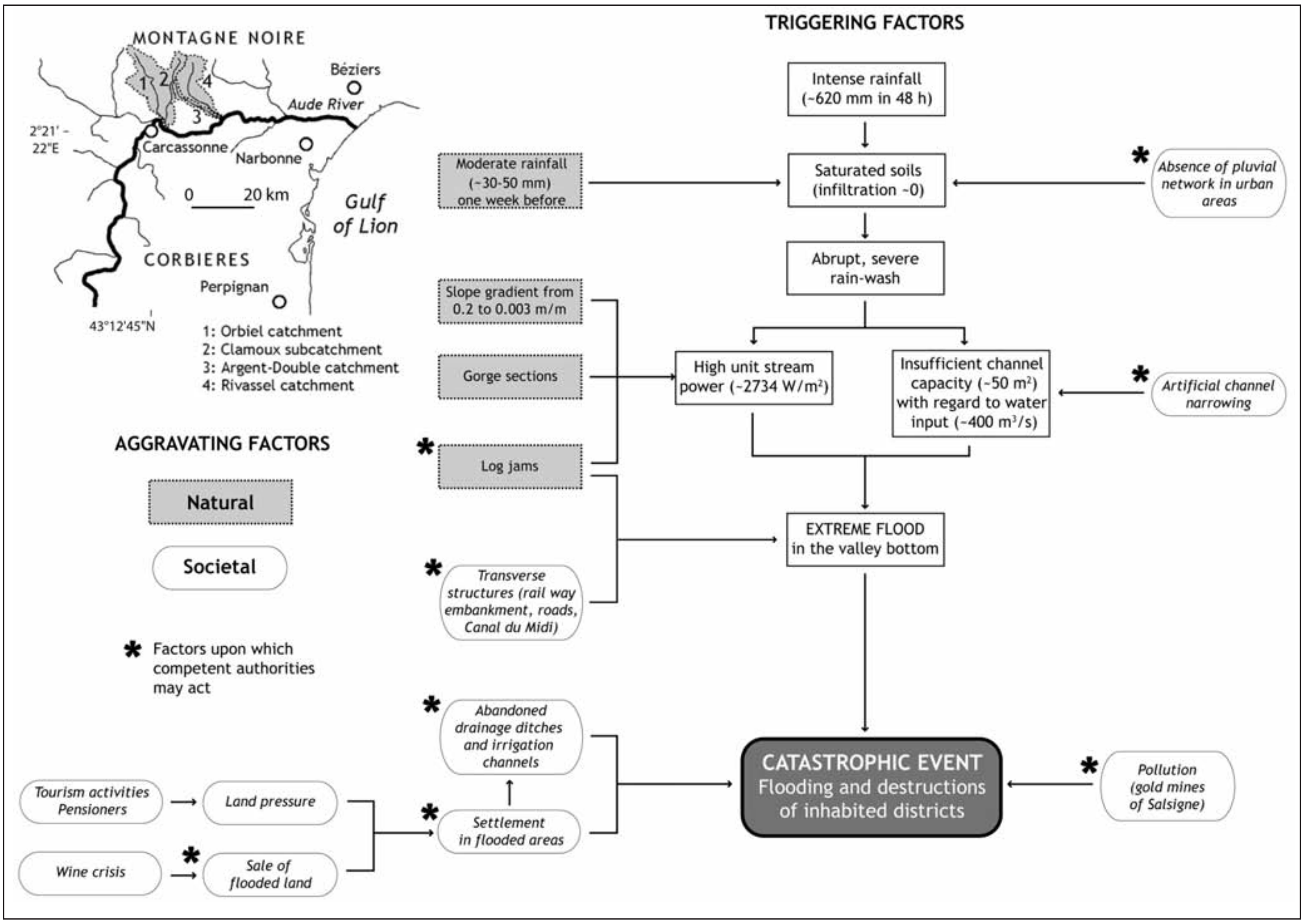


Fig. 1 – **Systemic approach of flood risk, left-bank tributaries of the Aude River, southern France**. Values correspond to the 12-13 December 1999 in the Argent-Double River, which is characterised by a 80-yr recurrence interval (data from G. Arnaud-Fassetta and M. Fort).

*Fig. 1 – **Approche systémique du risque de crue sur les affluents de rive gauche de l'Aude, sud de la France. Les chiffres indiqués** correspondent à la crue des 12-13 décembre 1999 (période de retour de 80 ans) sur l'Argent-Double (données G. Arnaud-Fassetta et M. Fort).*

different in mountain regions, plateaus, plains and large valleys. Nevertheless, whatever the area considered, the study of continental hydrosystems is based on a systemic analysis of environmental dynamics in relation to human activities, and geomorphologists prioritize hazard analysis.

Mountain torrent risk

Mountain torrent risk is considered a common phenomenon in mountainous areas, in the same way as snow avalanches and landslides. An increasing number of dwellings are being built on floodplains, alluvial fans, or along the trajectory of avulsed channels, particularly in areas of touristic value. The human and economic impacts of floods may be more severe in the lower reaches and associated floodplains of large river, but torrential floods, being sudden, are also responsible for significant human losses (~350 deaths/year in Himalayas; ~5-10 deaths/year in the European Alps; Dahal and Hasegawa, 2008). However, this number pales in comparison to the touristic accidents (*i.e.*, there are over 300 mountaineers by year dying in mountaineering accidents). In mountainous catchments, the relief energy is responsible for a high degree of geomorphic activity. Geological structure, earthquake activity and legacy of Quaternary glaciations, in extensively glaciated terrain, influence the geomorphology of valleys considerably and, in particular, the geography of floodplains and gorges. Usually narrow and confined, floodplains are drained by gravel-bed rivers characterised by high values of specific stream power (up to 1130 W/m^2 at Q_{30} stage in the Guil River, southern French Alps; Arnaud-Fassetta *et al.*, 2005). In the gorge sections, specific stream power can often exceed 1000 W/m^2 (19,820 W/m^2 in the Kali Gandaki River during monsoonal high flows, Nepal Himalayas; Fort *et al.*, 2009). The proximity of sediment sources derived from erosion of geological substrate and reworking of active and inherited sedimentary formations leads to large sediment fluxes from mountain slopes to the river channels. Torrential floods are linked to predisposing factors such as geological structure, slope, sediment yield, drainage density, shape of the hydrographic basin, and triggering factors such as rainfall in the catchment, associated with a series of aggravating factors including intensity and duration of rains, snow cover, landslides along the torrents and land use on the slopes and in the floodplains (Bardou *et al*., 2003). These factors all control the connectivity between slope, flood plain and channel, and the efficiency of sediment-water transfers along the longitudinal profile. The importance of sediment dynamics implies a time-scale analysis of phenomena such as debris flow, hyperconcentrated flow or bedload transport. While there is still no universal physical model allowing us to simulate these events, field investigations and geomorphological analysis of levees, terraces, and so on, allow hydraulic geometry to be adequately reconstructed.

Fluvial risk in plateaus and plains of northern and centre-eastern France

Hazards increasing the risk in these regions are of two types, *i.e.* long-period floods and flash floods. Risk linked to long-period floods generally occurs on plateaus and plains where the rivers (Strahler stream order > 4) drain valleys that widen rapidly downstream. Thalweg slopes are low (generally < 0.001 m/m) and result in low flow velocities and low erosion rates in the floodplain. However, these fluvial corridors are also characterised by extensive human activities, and while the fluvial hazard is considered to be low, dense human populations imply high societal vulnerability (but only if flood defenses are insufficient). As a consequence, flood-related crises are mounting in these valleys during exceptional flood events during the last three decades. Numerous workers have analysed floodplain adjustments during floods (Astrade, 2005; Corbonnois, 2005). The scientific approach is based on the determination of conditions in the flood plain. In northern France where total annual rainfall is 800-900 mm, the inundation of the floodplain at specific discharge of 8-10 $l.s^{-1}.km^{-2}$ begins through the inundation of ancient abandoned fluviatile channels, before the complete inundation of the floodplain. Palaeochannels are more visible in the wide floodplain and clearly show the juxtaposition of several fluvial forms (fig. 2). In central eastern France, the Saône River is characterised by a low energy slope (0.00001 m/m), wide flooding areas (mean width: 2.5 km; max. width: 5 km), slow water velocity (0.4 m/s for Q_{10}) and very low suspended sediment loads. In both cases, the main flood risk is determined by flood duration, which can often last several weeks, and the flood height. These two parameters were used to map the flood hazard in the valleys of the rivers Somme, Escaut, Lys and Canche to establish an atlas of potential flood zones (Laganier *et al*., 2000). Conversely, the flood regime of the Saône River has been modified since the 1980s, due to the impact of both anthropogenic actions and changes in rainfall conditions in the catchment. These impacts have increased the frequency of floodplain inundation and contributed to floods occurring later than usual in the year, which in turn affect societal vulnerability and question the pertinence of current human activities in the floodplain.

Risk is also linked to flash floods which occur in rivers draining small catchments across the plateaus of northwestern France. They mostly affect urbanised areas located in the downstream part of dry valleys, and present significant risks to societies living in the floodplains. The Seine-Maritime, a region of northwestern France, has experienced an increase in the number of catastrophic flash floods, particularly since 1990 (fig. 3). The processes and dynamics of these flash floods, inducing debris flows and hyperconcentrated flows, are analysed in detail by D. Delahaye (2005). Flood events are linked to erosion by runoff processes. In agricultural lands, erosion may often supply the whole sediment load carried by floodwaters. However, recent studies show that the relationship between runoff processes and flash floods is more complex. While some catchments may be widely cultivated (more than 80% of the surface), in most cases, potential runoff surfaces are more limited: only 22% of lands are cultivated in the catchment of Saint-Martin-de-Boscheville (16 June 1997 flood, Seine-Maritime), 60% of grasslands and forests in the catchtments upstream to Trouville-Deauville (1st June 2003 flood, Calvados), and 19% of cultivated land in the catchtment of Petit-Appeville (25 June 2005 flood, Seine-Maritime; Douvinet *et al*., 2006). Therefore, the occurence of a catastrophic event is not simply due to the impact of runoff on extensively cultivated catchments. It is linked to threshold effects resulting from spatial interactions between numerous variables such as rainfall, seasonality, hydrographical features, slope and land use. It also depends on types of flash floods, which are subdivided in winter floods generated by long, low intensity rainfall affecting large catchments (10^2 to 10^3 km^2), and spring floods associated with rainstorms affecting small catchments (10^{-1} to 10^2 km^2).

Fluvial risk in large valleys

On European scale, the Loire (catchment: 117,000 km^2; length: 1020 km; mean discharge at Saint-Nazaire: 931 m^3/s) and the Rhône (catchment: 97,800 km^2; length: 812 km; mean discharge at Beaucaire: 1700 m^3/s) are considered large rivers. Collectively, both catchments drain 31.8% of France. They are subjected to two different types of flood, which complicates fluvial-risk management: (i) floods linked to western disturbances correspond to slow, winter flood events associated to west atmospheric circulation, leading to gradual water-table elevation and relatively long flood duration whereas (ii) Mediterranean-type floods typically correspond to flash floods generated by stormy, Mediterranean depressions occurring from the end of summer to the beginning of winter. The floods of 30 November-4 December 2003, which affected the catchments of the Rhône River with a peak discharge at Beaucaire-Tarascon of 11,500 m^3/s, and the Loire River with a peak discharge upstream to Villerest dam of 2800 m^3/s, were the latest Mediterranean-type flood events. Hydromorphological studies of these events in both catchments allow us to characterise the present fluvial hazard and risk in floodplains.

In the Loire valley, initial studies of the December 2003 flood event have been used to update the spatial limits of the flooding area. Indeed, the present atlas of the potential flood

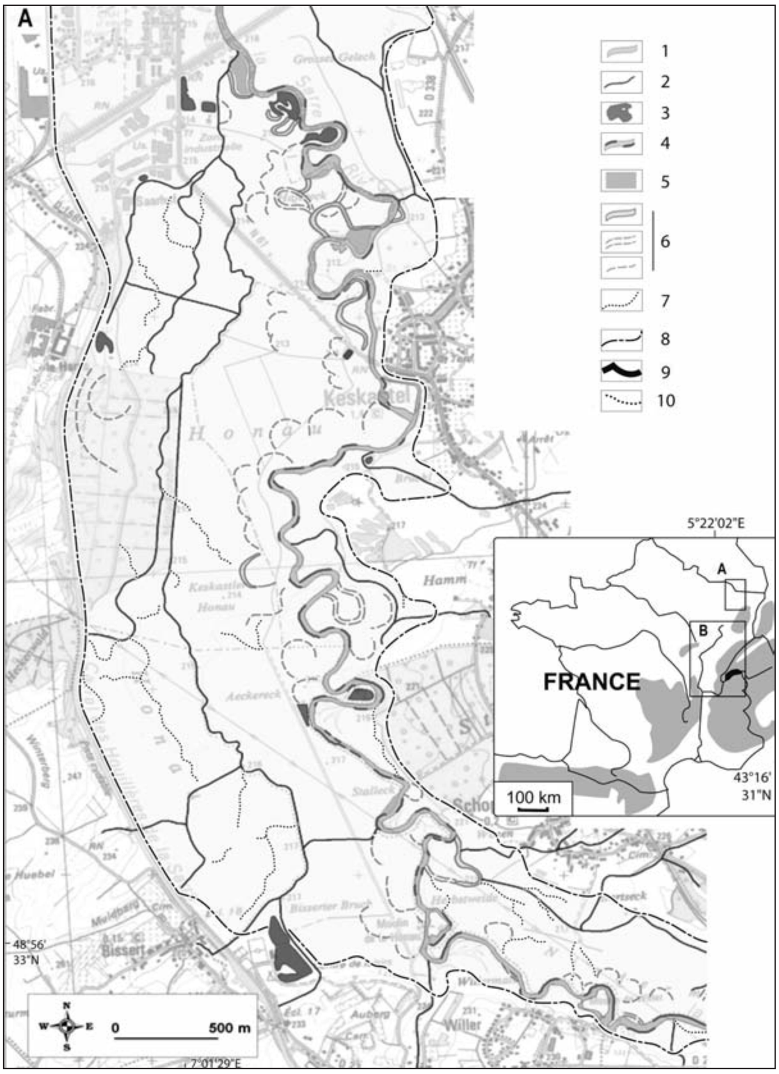
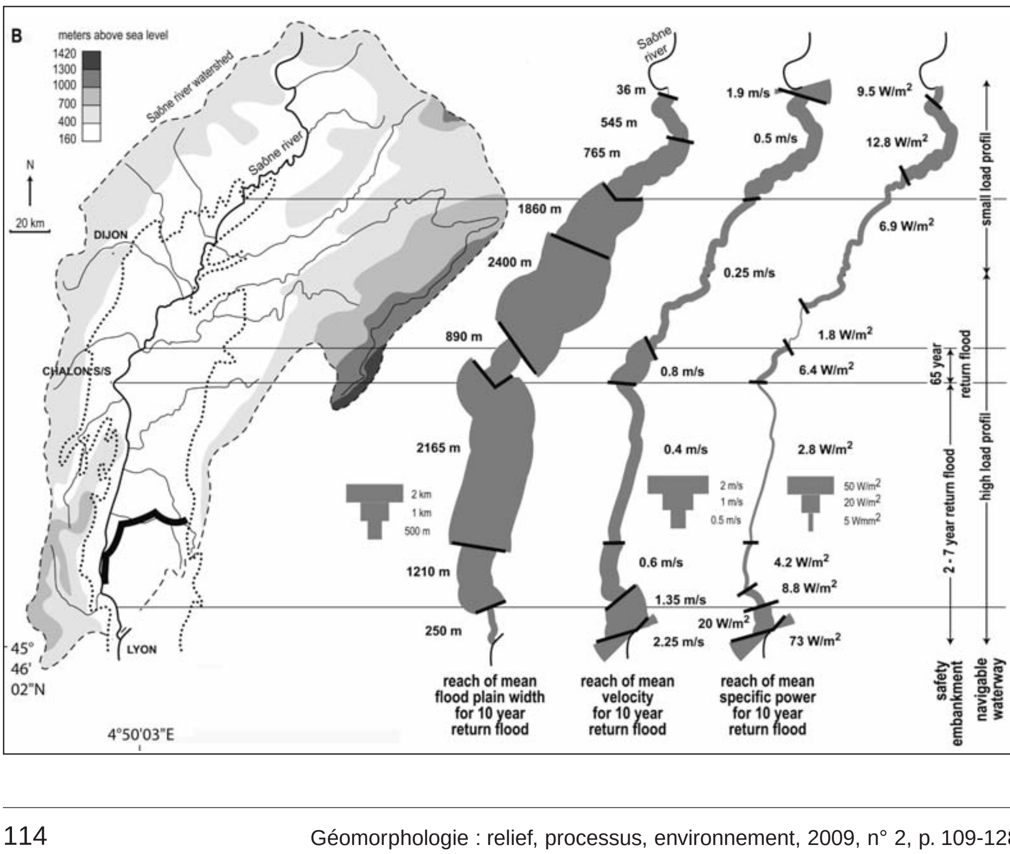


Fig. 2 – **Characteristics of riverbeds and floods of the rivers (A) Sarre and (B) Saône** (data from L. Astrade and J. Corbonnois). 1: stream bed; 2: perennial stream/drain; 3: waterlogged borrow pit; 4: bank undercutting; 5: swampy zone; 6: old stream beds; 7: flood channel; 8: flood plain limit; 9: limit of outer Würm moraines; 10: maximum extent of Würmian lake.

*Fig. 2 – **Caractéristiques des lits et des crues (A) de la Sarre et (B) de la Saône** (données L. Astrade et J. Corbonnois). 1 : chenal ; 2 : chenal/drain pérenne ; 3 : nappe phréatique sub-affleurante ; 4 : sapement de berge ; 5 : zone marécageuse ; 6 : paléochenaux ; 7 : chenal de crue ; 8 : limite de la plaine d'inondation ; 9 : limite des moraines frontales würmiennes ; 10 : extension maximale du lac würmien.*

zone is based on hydrological surveys of the 19th century, but substantial morphological changes in the channel and the floodplain have since occurred. Hydrological and Differential Global Positioning System surveys associated with aerial photo interpretation have been used to define the maximum flooded area on 6 December (Grivel and Gautier, 2007). Results show the presence of unsubmerged surfaces during this flood, which was nevertheless the largest event (3400 m³/s) in this part of the Loire valley since 1907. The hydrological impact of hydraulic structures has also been evaluated. In the middle part of the valley, the Loire River is lined on its left bank by dykes built between the 18th and the 19th centuries. These hydraulic structures were constructed, not to protect against floodwaters, but to improve conditions for navigation (Gautier *et al.*, 2007). After the large floods of the 19th century, which caused numerous dyke breaches, overflow spillways were built to reduce the hydrostatic pressure on the dykes and to facilate the gradual inundation of the floodplain, with the objective to protect urbanised zones downstream. However, most of these overflow spillways were designed for higher discharges. Therefore, the peak discharge in December 2003 propagated relatively quickly downstream and the floodwater volume was reduced only of 5-10%. Effects of river channelization by dykes have been aggravated by the recent evolution of the riverbed. In the



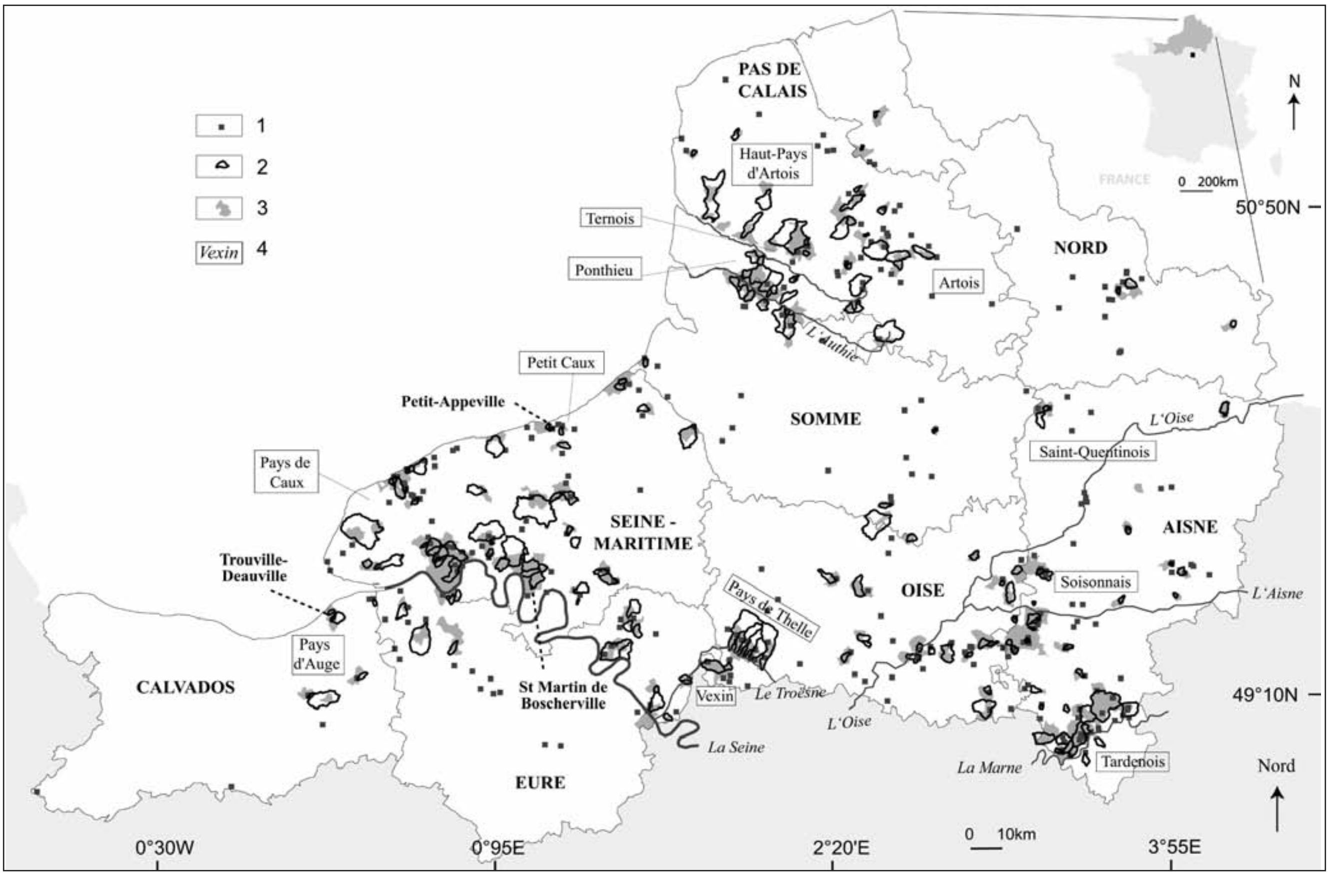
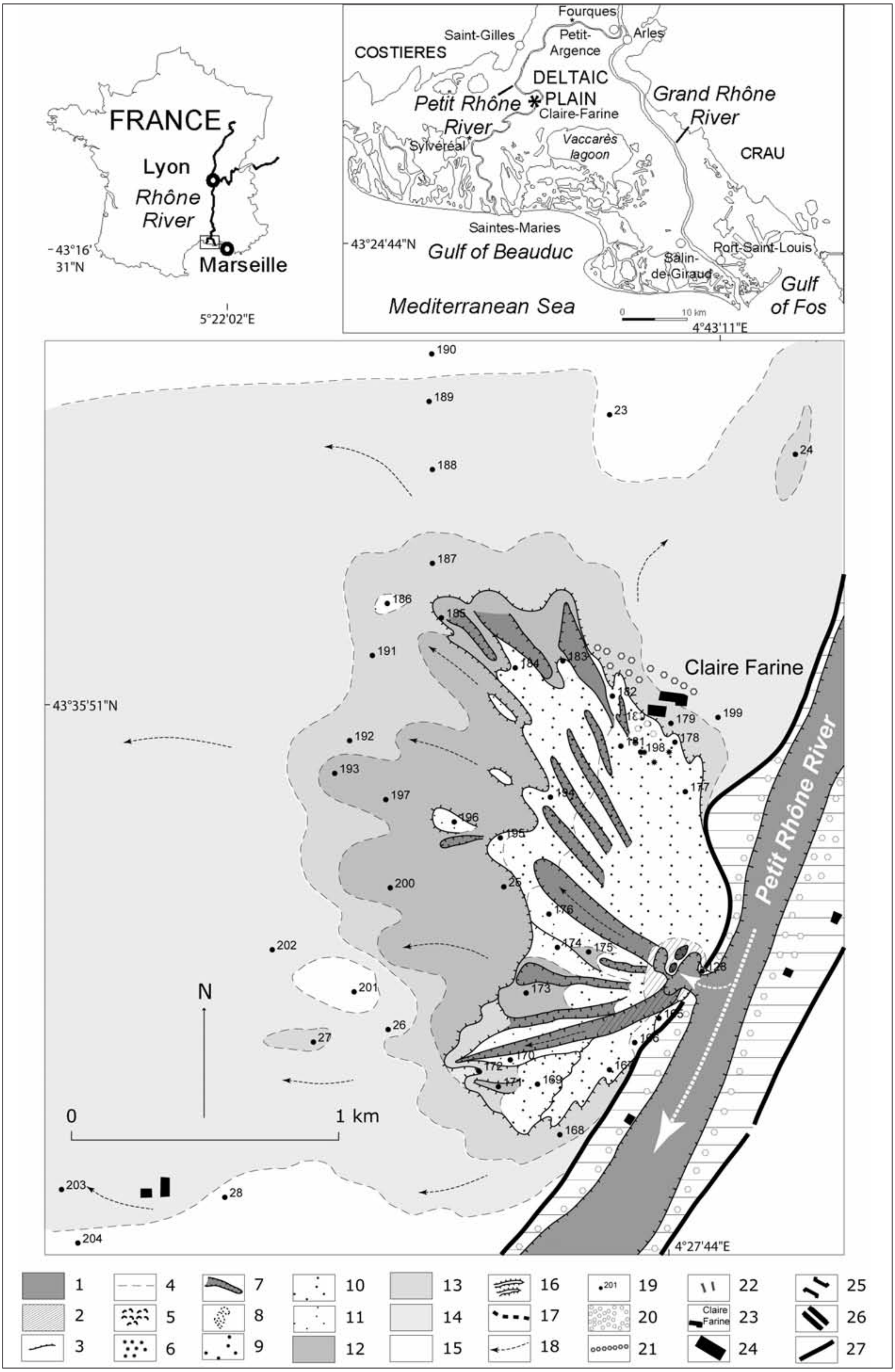


Fig. 3 – **Inventory of inundations (flash floods linked to violent, stormy rainfall) in the plateaus of Parisian basin deduced from 'Cat-Nat' documents (1983-2005) analysis.** 1: phenomenon of localised runoff (n = 346); 2: catchment affected by flash floods; 3: municipalities affected by flash floods linked to stormy rainfall (n = 292); 4: regional areas sensitive to flash floods (small agricultural areas; data from J. Douvinet).

*Fig. 3 – **Inventaire des inondations (crues rapides liées à de fortes pluies orageuses) sur les plateaux du Bassin parisien à partir des dossiers « CatNat » (1983-2005).** 1 : phénomène de ruissellement très localisé (n = 346) ; 2 : bassin-versant affecté par des crues rapides ; 3 : communes touchées par une crue rapide liée à de violents orages (n = 292) ; 4 : régions sensibles aux crues rapides (petites régions agricoles ; données J. Douvinet).*

middle part of the Loire River, active-channel width has decreased since the 19th century. In the mid-19th century, the active channel occupied 75% of the floodplain between the valley slope and the riverbank. At present, the active channel occupies only 40% of the floodplain, leading to a significant increase in the extent of islands and vegetation on the channel margins. Morphological and biological evolution has also led to a more rapid propagation of floodwaters downstream. Today, both former and current protective measures against flood risk including flood maps are used to limit or even prohibit urban development in some areas most prone to flooding.

In the Rhône valley, hydromorphological analysis of the December 2003 flood event has been used to characterise the present fluvial risk in the lower Rhône valley and to quantify fluvial processes during dyke breaching in the lower Rhône floodplain (fig. 4). In the alluvial plain downstream of Beaucaire-Tarascon and in the delta, the floodwaters of the Rhône River deposited a sediment volume of 810,429 m^3 (67% of which was sand) outside the dykes. The sediment balance was estimated at 674,227 m^3, taking into account eroded reaches, which represented a volume of 136,202 m^3 (Arnaud-Fassetta, 2007). This hydrological disaster was only one of six large floods that have occurred since 1993 during which peak discharges exceeded 8500 m^3/s at Beaucaire (9800 m^3/s in October 1993, 10,980 m^3/s in January 1994, 9750 m^3/s in November 1994, 8980 m^3/s in November 1996, 10 500 m^3/s in September 2002, 10,200 m^3/s in November 2002, 11,500 m^3/s in December 2003). These floods occurred in a floodplain modified by dykes and channel embankments during the second part of the 19th century. Hydraulic structures were calibrated on water levels and hydromorphological impacts of the 1856 flood (11,640 m^3/s). Active-channel contraction, incision of the channel bed and reduction of the flooding area have occurred in response to river management in the delta and the catchment, in part, in association with hydroclimatic changes following the Little Ice Age at the end of the 19th century (Arnaud-Fassetta, 2003). Land-use has significantly changed since the mid-19th century: dwellings have been built in the interfluves, in the sub-catchments and in the Rhône floodplain where flood risk is very high in case of dyke breaches. In the Rhône catchment, the concentration time of runoff and floodwaters


FRANCE
Lyon
Rhône River
Marseille
43°16'31"N
5°22'02"E
COSTIERES
Saint-Gilles
Fourques
Petit-Argence
Arles
DELTAIC PLAIN
Petit Rhône River
Claire-Farine
Grand Rhône River
CRAU
Sylvéréal
Vaccarès lagoon
Saintes-Maries
Gulf of Beauduc
43°24'44"N
Port-Saint-Louis
Salin-de-Giraud
Gulf of Fos
Mediterranean Sea
0
10 km
4°43'11"E
Claire Farine
Petit Rhône River
43°35'51"N
N
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4°27'44"E
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Fig. 4 – **High-resolution map of the December 2003 crevasse splay of Claire Farine (western part of the Rhône Delta, right bank of the Petit Rhône River).** 1: Petit Rhône channel and head of the main crevasse channel; 2: floodplain stripping; 3: scarp; 4: gradual boundary; 5: peat blocks; 6: fluviatile shells (Corbicula fluminea) deposited upstream of the breach axis; 7: crevasse channel; 8: erosion cavity; 9: lobe of crevasse splay (coarse sand and gravel near the breach); 10: lobe of crevasse splay (medium sand); 11: lobe of crevasse splay (fine sand); 12: lobe of crevasse splay (silty sand); 13: proximal flood basin (sandy silt); 14: distal flood basin (coarse silt); 15: distal flood basin (fine silt); 16: hydraulic dune; 17: flooding-area boundary; 18: direction of flood flows; 19: sampler number; 20: riparian forest and grove; 21: hedge (cypress, poplar); 22: hedge breached by flood flows; 23: permanent settlement ('mas') and outbuilding; 24: raised road; 25: tunnel; 26: bridge; 27: Rhône dyke (data from G. Arnaud-Fassetta).

*Fig. 4 – **Cartographie haute résolution du delta de rupture de levée (DRL) de Claire Farine (partie occidentale de la plaine deltaïque rhodanienne, rive droite du Petit Rhône) lors de la crue de décembre 2003**. 1 : chenal du Petit Rhône et racine du chenal principal de DRL ; 2 : zone de décapage superficiel de la plaine d'inondation ; 3 : talus ; 4 : contact graduel ; 5 : blocs de tourbe ; 6 : coquilles de faune fluviatile (Corbicula fluminea) déposées en amont de l'axe de la brèche ; 7 : chenaux de DRL ; 8 : cuvette d'érosion ; 9 : lobe de DRL constitué de sables grossiers associés à des graviers abondants surtout à proximité de la brèche) ; 10 : lobe de DRL constitué de sables moyens ; 11 : lobe de DRL constitué de sables fins à très fins ; 12 : lobe de DRL limono-sableux ; 13 : épandage sablo-limoneux dans bassin d'inondation proximal ; 14 : épandage de limons grossiers dans bassin d'inondation distal ; 15 : épandage de limons fins dans bassin d'inondation distal ; 16 : dune hydraulique isolée ; 17 : limite de l'inondation ; 18 : direction des écoulements de crue ; 19 : numéro d'échantillon ; 20 : ripisylve et bosquet ; 21 : haie d'arbres (cyprès, peuplier) ; 22 : trouée dans les haies d'arbres par les flux de crue ; 23 : habitat permanent (mas) et dépendances ; 24 : remblai autoroutier ; 25 : tunnel ; 26 : pont ; 27 : digue du Rhône (données G. Arnaud-Fassetta).*

has shortened: during the flood of December 2003 the Rhône discharge at Beaucaire increased from 2400 m^3/s to 10,000 m^3/s in ~30 hours. The maximum channel capacity of the present Rhône River, which was calibrated on the 1856 flood, was reached or even exceeded in some sections during the most recent large floods due to localised channel aggradation. Furthermore, the maximum hydrostatic pressures of the dykes are exceeded when discharge exceeds 10,000 m^3/s (HYDRATEC, 2003). In the Rhône Delta, the floodplain dykes currently protect 80,000 people, more than 2500 firms and about 70,000 hectares of agricultural lands. The financial costs of the damage caused by the flood of December 2003 (some 1.092 billion euros) demand that greater attention be given to the development of effective adaptive management strategies to reduce the impact of fluvial hazards. New forms of floodplain management such as recalibration of channel cross-sections, construction of dykes adapted to present floodwater heights and specific stream powers, harmonization of dyke systems to the sea, flood expansion areas in the lower Rhône floodplains, hydraulic restoration of Rhône palaeochannels and reduction of peak discharges upstream of Beaucaire are now encouraged more than 150 years after the first engineering works were undertaken. These questions are currently being debated between researchers, decision makers and administrators such as Regional Direction of the Environment, Rhône National Company and catchment agencies.

Scientific inputs in order to better understand the flood hazard

In floodplains, integrated methods are necessary to quantify the spatial impact of flood hazards and better manage fluvial risks. The present research emphasises this point, through the development of hydrogeomorphological methods, the integration of functional space and erodible corridor concepts, and the quantification of sediment budgets at the catchment scale. When implemented and managed in a GIS, the data enable environmental dynamics to be characterised at multiscales to produce maps of the flood hazards and economic, human and/or ecological risks, as well as the natural heritage. These data should be made available for information and consultation by the managers in charge of regional development, economic stakeholders and users for an integrated approach of river-basin management.

Spatial, multidimensional analysis of flood hazard

Hydrogeomorphological mapping leads to develop a set of maps integrating several temporal scales. Working on fluvial-risk projects requires an understanding of floodplain dynamics and the way the river can react to environmental changes (Hooke and Mant, 2000; De Moel *et al.*, 2009). In the absence of the historical data and a robust set of field data, it is not possible to practice applied fluvial geomorphology. Thus, it is not possible to study the risks without having understood the flood hazard. In 2001, experts appointed by the French Ministry of Regional Development and the Environment established hydrogeomorphological guidelines. The first official map legend was published by J.-L. Ballais (2006) and raised the issue of which 'reference floods' should be considered (Q_{30}, Q_{100}?) and of the possible and necessary revision of these maps with respect to the future morphological evolution of the channel over the long term (Bravard, 1998; Meschinet de Richemond *et al.*, 2006). Of particular importance is the need to determine the periodicity at which flood maps should be revised. In fact, flood hazard maps can be produced, as demonstrated by J.-P. Bravard *et al.* (2008), for the whole Rhône valley where the complexity of fluvial forms is much greater than the simple recognition of the three minor, medium, and major riverbeds (fig. 5). The guidelines of the hydrogeomorphological map of the Rhône floodplain established between the Swiss border and the Mediterranean Sea reiterate the complexity of the fluvial functioning for each of the main reaches of the valley. It is now required to define floodplain dynamics before and during the phases of hydraulic work in the second half of the 19th century. From a risk-management perspective, it can be used to mitigate present hydrodynamic malfunctioning by taking into account the hydraulic structures and human

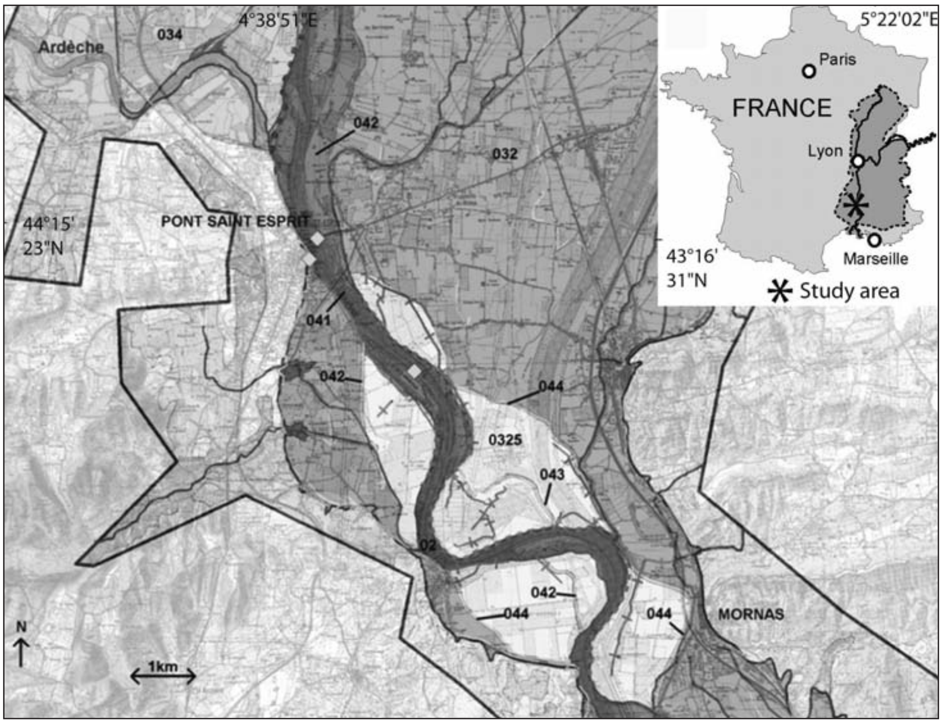

Fig. 5 – **Extract of hydrogeomorphological mapping of the lower Rhône River between Pont-Saint-Esprit and Mornas** (after Bravard *et al.*, 2008). Floodplain (02: low-flow riverbed with single channel). Holocene floodplain overflowing by large or small floods; construction by mineral-sediment deposition [032: zone built by channel migration (0325: from 500 BP to present); 034: aggradation and migration characterising large confluence]. Braided active channel (041: active channel in 1860; 042: active channel at the beginning of the 19th century, isolated by dykes in 1860; 043: active channel ante-19th century, isolated by dykes; 044: active channel of the Little Ice Age, abandoned by channel migration).

*Fig. 5 – **Extrait de la cartographie hydrogéomorphologique du Bas-Rhône entre Pont-Saint-Esprit et Mornas** (d'après Bravard* et al.*, 2008). Plaine alluviale (02 : lit mineur à chenal unique). Plaine alluviale holocène inondée par des crues fortes à faibles ; construction par dépôts de sédiments minéraux [032 : zone construite par migration du chenal (0325 : de 500 BP à l'actuel) ; 034 : aggradation et migration de type grande confluence]. Bande active à tresses fluviales (041 : bande active en 1860 ; 042 : bande active au début du XIXe siècle, isolée par des digues en 1860 ; 043 : bande active pré-XIe siècle, isolée par des digues ; 044 : bande active du petit âge glaciaire, abandonnée par migration).*

stakes in the Rhône floodplain. In particular, hydraulic planning aims to restore the full function of both the hydraulic channel capacity and retention, expansion and power reduction of waterflows in the floodplain.

Alternative methods can improve hydrogeomorphological mapping. This latter is considered as an additional method to the development of concepts such as the erodible corridor, water retention and functional space concepts, and the sedimentary-budget concept. The first three concepts have led to the development of floodplain-management policies, which have evolved over about twenty years from reach-based management to integrated, catchment scale management. The nature and the applicability of these concepts were discussed within the framework of a scientific seminar of the Rhône-basin workshop held in Prieuré-Blyes in April 2005 (ZABR, 2005). The concept of the erodible corridor or 'freedom space' appeared in the 1980s from the work of the Multidisciplinary Environmental Research Programme in the Rhône valley. Researchers advocated the need to preserve sufficient space of reversibility so that the river can assume its natural function of water drainage and sediment transfer. At the same time, the active channel margins must support well-developed aquatic and terrestrial ecosystems. The scientific purpose is sustainable management based on a relative equilibrium between environment and users. The fluvial risk can be anticipated by identifying reaches characterised by active channel shifting and define relevant policy implements to restrict use and urbanization and, as such, prevent crisis situations. In similarity to flood zoning, an erodible corridor is defined to prevent hazardous situations created by bank erosion. The method of mapping the extent of active channel mobility was detailed in a technical guide published by the Water Agency Rhône-Mediterranean-Corse (Malavoi *et al.*, 1998) and a critical review of the available tools can be found in H. Piégay *et al.* (2005). The water retention concept is highly connected to floodplain function and, in particular, the extension of overflowing floods. Different approaches to flood management such as reduction of peak discharges and retarding reservoirs can be adopted to minimise flood-hazard impacts downstream. The definition of functional mobility zones derives from the synthesis and the outcome of the previous concepts. Its application should assure the continuity of five major floodplain functions such as flooding, hydrobiology, fluvial dynamics, autopurge and landscapes within the framework of the catchment. The work undertaken in the Aude catchment in southern France has aimed to integrate the concepts of functional space and water retention. A survey headed by the Mixed Syndicate of the Aquatic Environments and Rivers (called 'SMMAR') in 2004 recommended the implementation of functional mobility zones in the Argent-Double River and identified several potential flooding zones in the Argent-Double and Rivassel catchments (Arnaud-Fassetta and Fort, 2009). The concept of functional flooding area was tested upstream of Peyriac-Minervois in the first catchment. Results show that functional floodplain width varies from 22 m to 186 m (mean 124 m; fig. 6). Hence the duration and hydromorphological impacts of large floods such as the event of November 1999 could be significantly reduced in the downstream part of the flood plains.

The use of sediment budgets has found renewed interest in fundamental and applied studies of torrential risk manage-

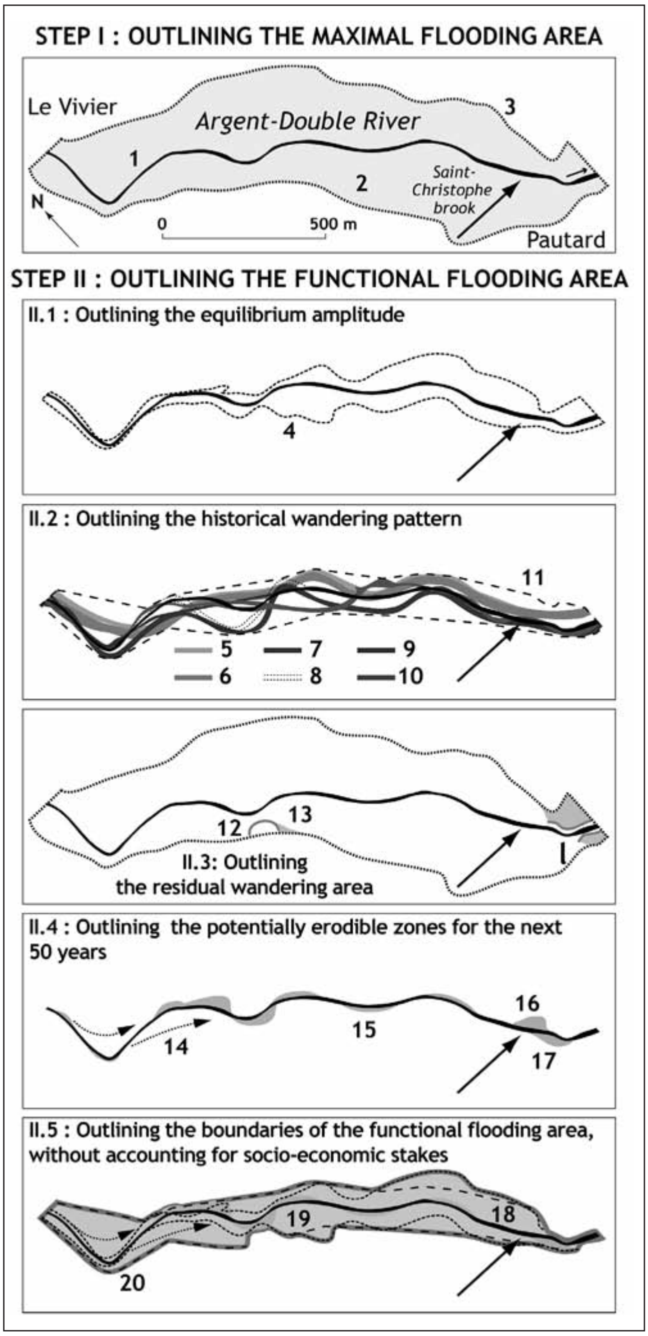

Fig. 6 – **The concept of 'functional flooding area' [Malavoi *et al.*, 1998] applied to the Argent-Double River, left-bank tributary of Aude River, Mediterranean France** (see location in fig. 1; data from G. Arnaud-Fassetta and M. Fort). 1: present channel (2003); 2: modern floodplain; 3: boundaries of maximum flooding area; 4: boundaries of the theorical amplitude = active channel of the >80-year flood (1999); 5: 1864 channel; 6: 1889-1900 channel; 7: 1937-44 channel; 8: 1948 channel; 9: 1958 channel; 10: 1999 channel; 11: boundaries of the historical wandering pattern; 12: bank protection (levees and gabions); 13: unauthorized rubbish dump; 14: artificially managed reaches where flooding and avulsion are prevented; 15: potential chute cut-off; 16: concave bank undermining; 17: erosion on the bank opposite to the confluence; 18: potential exacerbated erosion caused by meander cloging downstream; 19: zone of present ecological interest; 20: zone of potential ecological interest; 21: boundaries of the functional flooding area without accounting for socio-economical stakes.

*Fig. 6 – **Le concept d'espace de liberté [Malavoi** et al.**, 1998] appliqué à l'Argent-Double, affluent de rive gauche de l'Aude, France méditerranéenne** (voir localisation sur fig. 1; données G. Arnaud-Fassetta et M. Fort). 1 : chenal actuel (2003) ; 2 : plaine alluviale moderne ; 3 : limites de la surface d'inondation maximale ; 4 : limites de l'amplitude théorique de la bande active = bande active de la crue de 1999 (type > Q80) ; 5 : chenal de 1864 ; 6 : chenal de 1889-1900 ; 7 : chenal de 1937-44 ; 8 : chenal de 1948 ; 9 : chenal de 1958 ; 10 : chenal de 1999 ; 11 : limite de l'espace historique de divagation ; 12 : protections de berge (digues et gabions) ; 13 : décharge sauvage ; 14 : secteurs protégés des inondations et des défluviations ; 15 : zone potentielle de recoupement de méandre ; 16 : sapement de berge concave ; 17 : érosion de berge en rive opposée à une confluence ; 18 : érosion de berge exacerbée par le blocage de méandres en aval ; 19 : zone actuellement d'intérêt écologique ; 20 : zone future d'intérêt écologique ; 21 : limites de l'espace de liberté sans intégration des enjeux socio-économiques.*

ment (Schrott *et al.*, 2003). It has been used to develop methods for quantifying sediment storage based on the principle that mapping water and sediment volumes transported by floods is the key element to minimise flood-hazard impacts. The sediment budget concept associates description, understanding and spatialization of hydrosedimentary dynamics with quantification and modelling at the catchment scale (Slaymaker, 2006; Fort *et al.*, 2009). The nature of sediment fluxes and potentially mobile sediment stores is dependent on their connectivity within the catchment: coupling and decoupling processes determine which areas contribute to the sediment flux and the morphological behaviour during hydrosystem disturbance. In the mid-valley of the Kali Gandaki River in Nepal Himalayas (fig. 7), a preliminary sediment budget was established in the framework of a research programme supervised by M. Fort (Fort *et al.*, in press). Objectives of the study were to quantify erosion and hydrological processes in the different parts of the valley (slopes, bottom valley). Specific goals were to identify causative and triggering factors leading to the formation of catastrophic landslides and resulted inundation in the inhabited bottom valley. The study focuses here on Tatopani site, situated downstream of Annapurna and Nilgiri massifs. Geomorphological surveys and mapping lead to reconstruct the volumes of the last large landlide dam, the induced lake and the debris eroded by the river after the event. Hydrosedimentary surveys and hydraulic calculations allow an estimation of paleodischarges during and after the landslide. Results lead to reconstruct the evolution as follows (Fort *et al.*, 2009): (i) after three months of abundant precipitation, on September 28, 1998, a large collapse (1.1 10^6 m^3) in the quartzites and chloritoschists of the Lesser Himalaya started at 7 a.m and blocked the river. (ii) The Kali Gandaki, with a discharge estimated to be 54 m^3/s rapidly rose upstream the landslide dam, leading to the extent of a large lake (1.5 10^6 m^3) that flooded the lower settlement of the Tatopani village situated upon a gravel terrace, at +25 m above the present alluvial valley floor. (iii) Progressive erosion of the front of dam slide by spill over process lead to an eroded entrenchment volume estimated to be 0.2 10^6 m^3. (iv) At 4 p.m, the lake drained naturally and the peak discharge reconstructed downtream the landlide dam was 389 m^3/s. Hence the

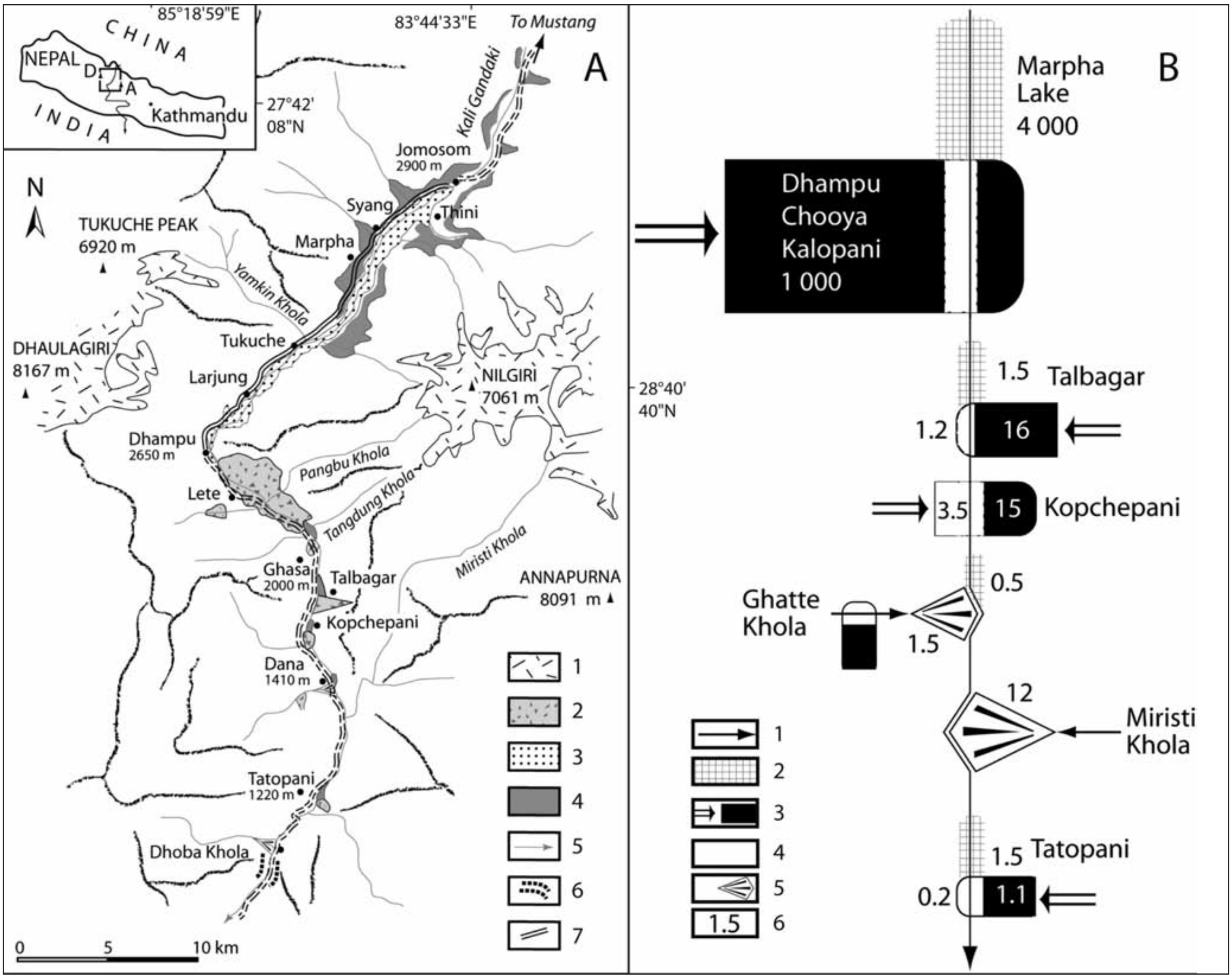

Fig. 7 – **Preliminary sediment budget in the Kali Gandaki valley, Nepal Himalayas** (after Fort *et al.*, 2009). A: Geomorphological features of the Kali Gandaki valley. 1: glaciers; 2: landslides; 3: floodplain; 4: lacustrine deposits; 5: river; 6: gorge; 7: road. B: Preliminary sediment budget in the middle Kali Gandaki valley. 1: stream; 2: lake; 3: landslide; 4: entrenchment; 5: alluvial cone; 6: volume (in 10^6 m^3).

*Fig. 7 – **Budget sédimentaire préliminaire dans la vallée de la Kali Gandaki, Himalaya du Népal** (d'après Fort et al., 2009). A : Contexte géomorphologique de la vallée de la Kali Gandaki. 1 : glaciers ; 2 : glissements de terrain ; 3 : plaine alluviale ; 4 : dépôts lacustres ; 5 : rivière ; 6 : gorge ; 7 : route. B : Budget sédimentaire préliminaire dans la moyenne vallée de la Kali Gandaki. 1 : chenal ; 2 : lac ; 3 : glissement de terrain ; 4 : érosion ; 5 : cône alluvial ; 6 : volume (en 10^6 m^3).*

ability to quantify and map effective and potentially mobile sediment stores can lead to a better understanding of the impacts of landslide and induced-flood hazards for improved risk management.

In-channel wood and logjams constitute aggravating factors of floods and large-scale efforts to manage transfer of woody debris in rivers have begun in French catchments (Piégay, 2003). A demographic peak was reached in France around 1830. In the middle of the 19th century, the country was mainly rural and people exploited local natural resources. During this period, human pressure on fluvial systems was high; alluvial forests were cut down and the riparian margins were used for arable crops and grazing pasture. Following the industrial revolution, the population became increasingly urbanized. Furthermore, in the aftermath of the Second World War, agricultural practices were transformed and this precipitated a decline in agriculture in the riparian margins and has led to *renaturalisation* and, in particular, shrub and forest encroachment (this has been especially pronounced in mountain areas between 1945 and 1970). As a consequence, many catchments and alluvial corridors as well have been characterised by a spontaneous afforestation (Liébault and Piégay, 2002). This evolution has had clear implications for flood hazards over the last few decades: (i) the bedload delivery from the catchments was decreasing which has led to a change in channel geometry and degradation downstream from the disconnected sediment sources. In addition, the ability of the floodplains to protect downstream reaches from flooding has been compromised as the floodplains are now disconnected from the main channel, reducing their flood retention capacity and increasing peak discharges. (ii) Trees, which had been a valuable natural resource for the local population over past centuries, are now increasingly frequent along the river margins and within the channels. The transfer of woody debris is becoming a problem for flood risk management in these catchments because large logs can block infrastructures such as bridges. The old bridges were built during a period in which wood transfer was infrequent and are consequently not designed to allow the easy passage of woody debris. The central piles of bridges are now frequently trapping wood, acting as a plug that increases water pressure on the bridge and causes damage to the infrastructure and flooding of riparian margins upstream.

Historical perspective of flood hazard

The variability of flood events in space and time has been addressed by fluvial geomorphologists who are interested in hydrological variability at multidecadal scale, adjustment of active channel and sediment transport at the reach and cross-section scales, and sediment transfer at the catchment scale along the longitudinal profile. French hydrogeomorphological research (Bravard, 1989; Miramont and Guilbert, 1997; Antoine *et al.*, 2001; Taillefumier and Piégay, 2002; Jacob, 2003) has highlighted periods of intense hydrological activity at multidecadal scale (e.g., the end of the 18th century; the mid-19th century; the decade 1950-1960; the decade 2000-2010). Hydrological variability of French rivers correlates well with period of high flood frequencies in Spain, Germany and Central Europe (Llasat, 2004; Starkel *et al.*, 2006). At finer timescales, the analysis of seasonality (for example in the Saône River and in the Diois; Bravard, 2000; Astrade, 2005) confirms the monthly variabilility of flood frequencies. On the other hand, on the Mediterranean border, the intra-annual distribution of floods does not seem to have changed during the last 250 years but both the ten-year frequencies and the intensity of flood events have varied (Jacob *et al.*, 2006).

At the reach and cross-section scales, extensive research concerning floodplain-channel connectivity has led to a clarification of key factors inducing flood hazard variability. In intramontanous basins or in the catchments located on piedmonts, numerous workers have observed significant active-channel variability characterised by alternating phases of contraction and widening of active channels (Bardou and Jaboyedoff, 2008). In the upper Guil catchment, the grading of the active channel width remains very much dependant upon the hydro-climatic variability, because of the magnitude of the flood hazards and because of the difficulties to control their hydro-geomorphic impacts all along the various segments of the rivers (Arnaud-Fassetta and Fort, 2004). In the French Prealps, variability of active-channel width was more importantly linked to changes in land use and decrease in sediment delivery (Liébault and Piégay, 2002). These phases of sediment starvation, and the abandonment of the river margins by rural societies following changes in agricultural and pastoral practices, have led to the colonisation of the banks by riparian vegetation and to an increase in channel incision. The effects of historic sediment aggradation in the floodplains play an important role in determining the vulnerability of the inhabited areas. In the Mediterranean floodplains, alluvial processes since Antiquity have led to an increasingly critical state in inhabited areas, which have been gradually covered by sediment and are now dominated by a perched channel (Calvet *et al.*, 2002). The height of floodwaters has increased consistently over the last century and several sites, which were outside of the flooding areas in the past, are now very vulnerable to flooding. Various techniques such as embankments, flood dams and channel rectification were used since the Modern times to reduce the impacts of floods. Effects of hydraulic changes on flood hazard are complex. Human impacts on channel cross-sections have had a significant effect on sediment transport and deposition (Arnaud-Fassetta, 2003). In additional, runoff and waterflow conditions have also been modified, making it difficult to identify the 'reference flood-hazard' because the system is in a state of perpetual evolution (Bravard, 2004). The understanding of what occurs at the reach scale requires an analysis at the catchment scale so that longitudinal relations can be reconciled across the hydrosystem (Piégay *et al.*, 2006).

At the catchment scale, hydrological fluctuations interact with the sediment yield and transport capacity of rivers, leading to substantial changes in channel geometry downvalley (Piégay *et al.*, 2004). Channel-geometry changes at the reach scale do not operate with the same intensity or the same periodicity in all catchments. Recent research has allowed us to identify two types of hydrosedimentary and morphological changes. In French intramontanous basins characterised by high sediment supply (southern and northern Alps, Massif Central, Pyrenées), several 'sediment waves' were recorded during the last four centuries (Peiry, 1997; Salvador, 2005). In the Alps in particular, aggradation of riverbeds and channel braiding date from the 16th-19th centuries and continue until the beginning of the 20th century (Peiry, 1997). Therefore, impact of flood hazards was strong during this period, as demonstrated by D. Cœur (2002) in the study case of Isère River at Grenoble. The sediment volumes eroded from inherited periglacial cones and terraces during the Little Ice Age, and the period of maximum demographic pressure on hillslopes, propagated downvalley, causing significant riverbed widening (Astrade *et al.*, 2007; Liébault *et al.*, 2008). At the present time, channel incision and the low sediment supply minimise the flood-hazard. However, flood risk remains high because the magnitude of the most exceptional flood events is comparable to that of the floods of the 18th, 19th and the first part of the 20th centuries (Arnaud-Fassetta *et al.*, 2005). In the lower valleys or in the piedmont regions, fluvial changes have occurred only over the long term (10^2 to 10^4 years) because here geomorphic processes operate more slowly, there is great relaxation time (10^1 to 10^2 years) and the specific stream powers are significantly low (Arnaud-Fassetta *et al.*, 2009).

To conclude, in river studies, 'geomorphological time' is doubtless the most relevant temporal scale at which to analyse fluvial dynamics. Indeed, in comparison to geological time, it leads to a better connection between inherited fluviatile forms and the recent fluvial dynamics, and hydromorphological changes and the climatic and/or human factors. Furthermore, the geomorphological timescale study permits sustainable river management, which can be readily reconciled with societal time scale.

Current innovative strategies and actions for mitigating fluvial-hazard impacts

Modern river management requires sustainable policies and methods to resolve the conflicts in human use and natural adjustment capacity of rivers. Substantial changes have occurred over the past two decades in the way that rivers are managed following increased public awareness and appreciation of the ecological value of the river corridor (Knight and Shamseldin, 2006). The current developments in fluvial geomorphology consist of the restoration, rehabilitation or *renaturalisation* of over-engineered rivers, in flood prevention, and in riverbed maintenance (Bravard *et al*., 1999a; Habersack and Piégay, 2007).

Restoration, rehabilitation and *renaturalisation* of rivers

The sustainable management of river hydrosystems based on river restoration assumes that hydraulic engineering works in the floodplain are effective and that the flood risk is very low. Some approaches to river restoration were pioneered in French Mediterranean river systems. Using their field knowledge, fluvial geomorphologists target specific floodplain areas where restoration, rehabilitation and/or *renaturalisation* are necessary. They have often demonstrated the necessity of soft engineering measures oriented towards a 'living river' perspective, particularly in some upper, high-energy river basins, such as the upper Guil River, a left-tributary of the Durance River in the southern French Alps (Arnaud-Fassetta *et al*., 2005), or in some floodplains of the Mediterranean France characterised by low vulnerability and few elements at stakes (fig. 8). Indeed, some 'environmentally friendly', low cost structures were encouraged where the rivers are still 'natural' and freely flowing such as the left tributaries of the Aude River in the southern France (Arnaud-Fassetta and Fort, 2009). In the Argent-Double River, the erodible corridor concept was applied in order to calibrate the active-channel width (fig. 9). In the Clamoux River, a left tributary of the Orbiel River, the use of erodible corridor concept was combined with the use of the riparian trees as natural sediment traps, which were locally reinforced by low cost structures. Figure 9 shows how the breach opened during the flood of November 1999 was artificially increased to force the river temporally to cut-off the meander during the next floods. Furthermore, restoration projects will be implemented along the rivers Ain (Rollet *et al*., 2009), Rhône and Rhine. Floodplains will be excavated in the sites that were either drained due to channel incision or infilled due to the static position of the channel over several decades. These actions are intended to feed the channel with sediment, restore the connection between riparian ecosystems and surficial and groundwaters, and improve flood retention to mitigate high peak discharges downstream. The alluvial corridors are being mapped to reconstruct conditions prior to the introduction of engineered infrastructure, notably the former sinuous and multi thread channel that were lost during the straightening of the main branch and the infilling of secondary channels. It will then be possible to promote *renaturalisation* and sustainable use of the floodplains. The diversity of in-channel features will also be enhanced to improve the quality of aquatic habitats for fish communities. On the Rhine, along a 45 km by-passed reach

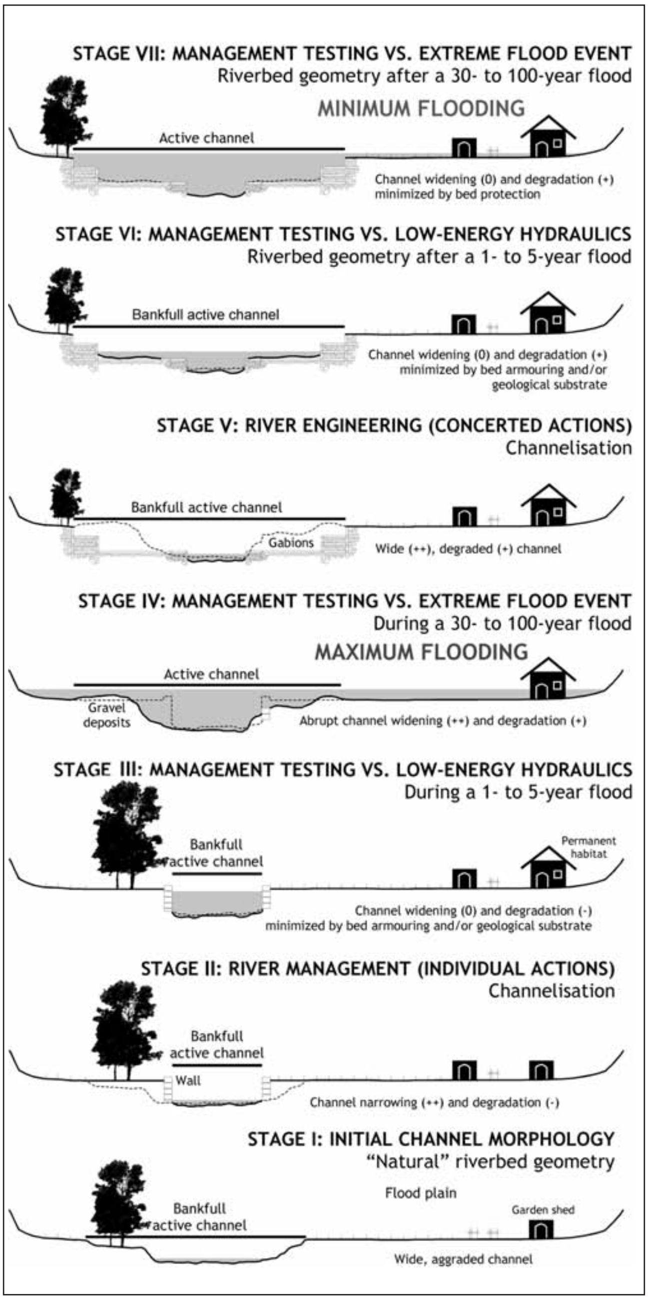

Fig. 8 – **Two conceptions (inefficient, expensive, on the left handside; efficient, sustainable, on the right handside) of floodplain dynamics and channel restoration, left bank of the Aude's tributaries, Mediterranean France** (see location in fig. 1; data from G. Arnaud-Fassetta and M. Fort).

Fig. 8 – ***Deux conceptions (mesures inefficaces et coûteuses, à gauche ; mesures efficaces et durables, à droite) de la gestion de la dynamique fluviale et de la restauration de la bande active des affluents de rive gauche de l'Aude, France méditerranéenne*** *(voir localisation sur fig. 1 ; données G. Arnaud-Fassetta et M. Fort).*

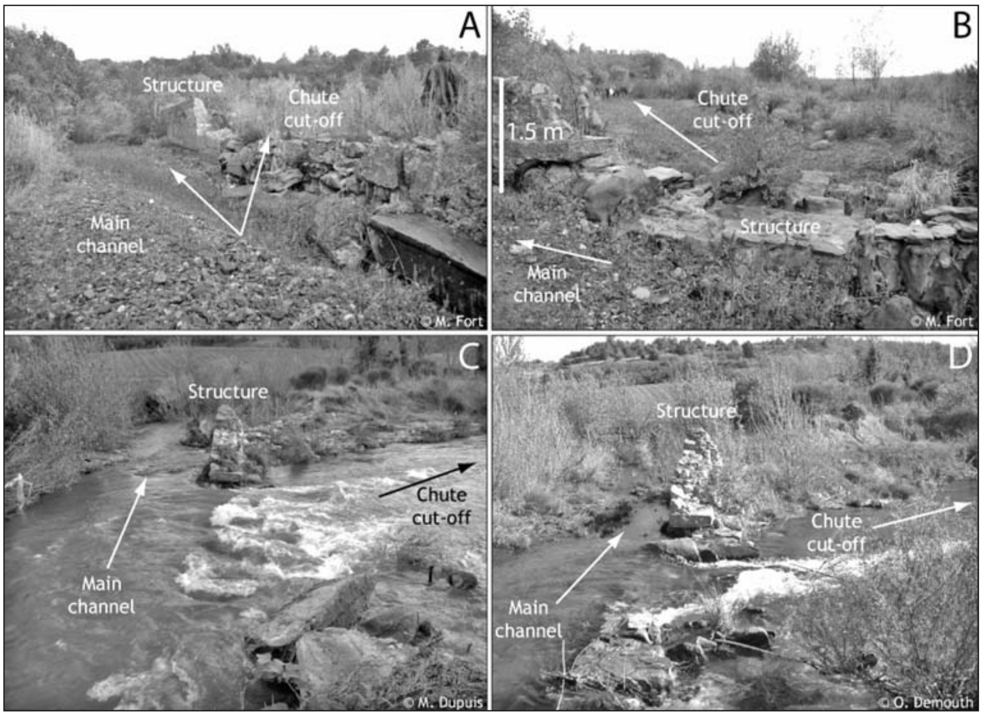

Fig. 9 – **Example of management for naturalness along the Clamoux River, Aude catchment, Mediterranean France** (see location in fig. 1). A: 2007/10; B: 2007/11; C and D: 2008/4 (data from G. Arnaud-Fassetta, O. Demouth, M. Dupuis, M. Fort and P. Vandemeulebrouck).

*Fig. 9 – **Exemple de gestion douce le long de la Clamoux, bassin de l'Aude, France méditerranéenne** (voir localisation sur fig. 1). A : 10/2007 ; B : 11/2007 ; C et D : 4/2008 (données G. Arnaud-Fassetta, O. Demouth, M. Dupuis, M. Fort et P. Vandemeulebrouck).*

downstream from the Kemps Dam, 55 millions of cubic meters of sediment will be extracted on the German side over the next few years. This will raise important theoretical and practical questions about the channel and the associated ecological responses expected with vegetation encroachment and sediment filling in areas where the geometry is fixed. The improvement of channel maintenance to mitigate environmental impacts downstream of dams significantly affecting peak flows is also a challenging issue. New approaches are experienced in order to prevent vegetation encroachment on gravel bars so that the channel can easily convey major floods without modifying the flood level. At the same time, introduction of wood in the active channel does not lead to damaging effects downstream. Vegetation clearing practices, including some designed to enhance the riparian ecosystem, have also been proposed along the Durance River downstream of the Serre-Ponçon dam (Boyer and Piégay, 2003). Similar issues also arise on the Isère River upstream of Grenoble, where islands encroached by vegetation following a significant reduction in bedload transport and peak flows were recently extensively cleared. This included tree felling, but also removal of stems and extraction of fine overbank material.

Flood prevention

The challenge of flood 'prevention' is to provide an acceptable degree of protection through the installation of physical infrastructure in conjunction with alternative means of risk reduction (Samuels, 2006). This demands robust modelling of water and sedimentary processes. Runoff and floodwater modelling is a helpful tool for preventing flood events. Hydrological and hydraulic modelling can be applied to all types of river basin but, no matter how complex the model may be, they always simplify morphological processes. Numerous authors have modelled geomorphological functioning at the river-basin scale using 'complexity theory'. This latter is particularly useful in physical and environmental geography with the development of cellular automata (Di Gregorio *et al*., 1998; Torrens, 2002; Coulthard *et al*., 2005; Delahaye, 2005; Douvinet, 2006; Fonstad, 2006; Van de Wiel *et al*., 2007). Currently, research is being directed towards the identification of the morphological 'abnormalities', which strongly control hydrological behavior. Priority is being given to the analysis of dynamic interactions between the morphological variables (surface area, slope, network) of the catchment with respect to spatial continuity. This approach can lead to a better understanding of the evolution of river discharge in space and time. Until recently, this question could only be approached indirectly through the analysis of discharge at the large catchment scale. However, the current approach based on numeric simulations from measurements of the physical characteristics of river basins allows the whole hydrographic network to be modelled.

With respect to bank erosion management, major changes have occurred over the last two decades with the emergence of the erodible corridor concept. Recent scientific advances have underlined the ecological benefits derived from bank erosion by shifting channels. The erosion and aggradation processes in the floodplain are important for the renewal of riverine habitats and the maintainance of high biodiversity. Thus, the mitigation of bank erosion represents a critical aspect of river corridor management. Moreover, after a few decades of fighting erosion, this policy has found to be prohibitively costly when applied to shifting rivers as the economic value of the resources being protected is much lower than the cost of flood protection, particularly where the life span of infrastructure is much shorter than expected (Piégay *et al*., 1997). Hence the geomorphological approach extends beyond the definition of the corridor and underlines a wide range of actions that promote sustainable management of bank erosion that can be applied at different spatial scales in response to different management strategies.

Riverbed maintenance

The recent recognition of the ecological importance of in-channel woody debris has created a potential conflict of interest for channel maintenance policy. A balance should be found between ecological preservation and protection of people from flooding and flood damages. Hence traditional channel maintenance policy has been progressively modified, enlarging the range of potential approaches with the development of wood trapping structures, but also integrating the new understanding of wood movement into management actions. Because in-channel wood as a tool for generating ecological improvement is a new feature for European hydrosystems, innovative solutions must be conceived to preserve woody debris without increasing the natural hazard. For several centuries, the French agencies have managed floods by promoting measures maintaining free flow. These actions of channel maintenance were applied to sediment but also to riparian vegetation and in-channel woody debris, as all reduce the wet section and slow down the flow. By law, these management actions were traditionnally supervised by landowners who took advantage of local natural resources such as tree leaves and branches, large woody pieces and gravel. After a few decades, during which landowners strongly modified their practices due to the agricultural revolution, channel maintenance practices were increasingly abandoned and the encroachment of riparian vegetation along the channel margins resulted in increased organic debris in rivers. This is why the French State has maintained its long-term policy of promoting channel clearance as one of the main solutions for reducing flood risks, while advocating that channel maintenance leads to an ecological equilibrium, which is far from being demonstrated. The official stance essentially transfers the responsibility to the angling associations or to the municipalities and departments (Barnier's Law in 1995; Recent water law of 2006). Over the last decade the scientific research has shown that woody debris fundamentally transforms riparian landscapes, and that it is a key element of natural rivers whether we maintain the channels or not. As shown by N.S. Lassettre and M. Kondolf (2000) in the Soquel basin in California, floods will continue to provide organic debris at a decadal scale, simply because the river margins are forested. Two sets of actions can help to manage the risks associated with wood transport and blockage (Piégay and Landon, 1997; Piégay *et al.*, 2002): Firstly, design a sectorized management plan for riparian vegetation and in-channel wood is based on clear objectives defined in a participative framework in order to facilitate efficient and repeated actions on reaches where the flood risk management is a priority. Such action along reaches where wood presence is valuable for aquatic habitats does not pose a flood risk. Moreover, we should expect that wood may be also reintroduced as restoration measures as it is promoted elsewhere in Europe, in order to reach the objective of good ecological status as imposed by the Water Framework Directive. The Law on Risks of July 2003 proposes to develop a slow flow strategy in order to manage floodwaters at the catchment scale. Hence the reintroduction of wood, or at least its preservation, in hydrographic networks may be an innovative solution to make the channel beds rougher, slow the rate of flow downstream, and thus reduce peak flows. Secondly, reaches and infrastructure that are sensitive to log jams must be identified in order to anticipate high risk situations. Such a policy would support the development of woody debris traps in sensitive upstream reaches or downstream reaches providing significant quantities of wood. The use of floating belts (drone) on hydro-electric reservoirs, or more traditional trapping infrastructure is actually increasing and civil engineering departments in Zurich (Switzerland) and Padova (Italy) are currently working on such approaches (Gumiero *et al.*, 2009).

Challenging issues for fluvial geomorphologists in the next decade

Fluvial geomorphologists face considerable environmental challenges in ensuring that the best use is made of available knowledge concerning the sustainable management of floodwaters, impacts of flooding, susceptibility to damage and restoration of natural resources (Knight and Shamseldin, 2006). However, integration of the major current topics such as river basin modelling and flood mitigation, river basin management and research will clearly represent a challenge for fluvial geomorphologists over the next decade (Habersack and Piégay, 2007).

River-basin modelling should be an essential tool for relearning to live with rivers and fluvial changes, accepting and understanding floodplain processes and the wider environment in which societies choose to live. Furthermore, fluvial geomorphologists should approach the mitigation of flood hazard with a better understanding of the interrelationships between land-use change in floodplains and the effects of climate change on flooding. Hence there is a need to better understand fluvial processes by encouraging multidisciplinary collaboration between geomorphologists and hydrologists, hydraulic engineers, hydrogeologists, ecologists and professionals, and to therefore develop integrated catchment models based on an 'open system' philosophy (Samuels, 2006) to better combine physical models and local needs and preferences. Thus, the challenge of delivering sustainable flood mitigation requires a 'system' approach and the understanding of several themes such as current flood risks in terms of hazard and vulnerability, ecological and environmental status of the river catchment, nature of the change in risk under future environmental and climate change scenarios, reduction of flood hazards possible from engineering interventions in the system, impact of structural and non-structural flood defence provisions on the ecology of the catchment, on economic activity and on societal expectations.

River-basin management includes the activity of mitigating and monitoring fluvial hazard and risk. A national framework for land-use planning coupled with risk mapping will contribute to limit the consequences of flooding. France is now preparing catchment flood management plans ('Plan de Prévention des Risques d'Inondation'). These

French management plans review the development of flood risks, coupled to measures of societal vulnerability and economic indicators, to provide a broad scale management framework. The management of river catchments and ecosystems is also influenced by European legislation, which has become increasingly important in national environmental policies over the last few years. The latest development is the European Union Water Framework Directive, which promotes the management of water at the catchment level by river basin autorities. At the same time in France, the new Law on Water and the Aquatic Environments emphasizes that the restoration of ecological and hydraulic continuity as the indispensable condition for obtaining good ecological status and *renaturalisation* of rivers. Considering that sustainable sediment management aims to reconcile the conservation of 'good ecological status' in floodplains and fluvial-risk management, conditions of river adjustment must be understood. In broader terms, applied research needs to be directed at 'fundamental' questions such as: Will braided rivers disappear in the next decades? Which ones? Do the modifications of bed-material grain size and fluviatile channel geometry lead to positive or negative impacts on ecological habitat? In which reach sections is the sediment balance still positive? Is it a sustainable phenomenon? Answering such 'fundamental' questions will improve the linkage between models of river flow and river geomorphology and ecology.

Restoration, rehabilitation and *renaturalisation* of floodplains will not be easy. Various infrastructures strongly affect floodplain geometries, which result in consequent topographic changes that influence the storage capacity in flood prone areas. This is the case in reach sections equipped with bank protection and submersible dykes, which should record high sedimentation rates in the vegetated margins of the floodplain. This evolution can be thwarted by lateral erosion process. Hence fluvial geomorphologists have several questions to consider, such as: will a floodplain drained by an active channel present a sustainable storage if the fluviatile active channel is fixed and does not regularly regenerate? How does sediment transfer occur between the channel and the floodplain? Can the floodplain be used as as a sustainable source of sediment for the channel? And, through which processes can this sustainability be achieved?

Sustainable river management strategies will only be achieved if the adopted procedures works are adjusted to the natural behaviour of the river system. Understanding river character, behaviour condition, and recovery potentially provides a physical platform for river rehabilitation planning. Key considerations at the catchment scale require that slopes, channels, flood plains, deltas and estuaries are considered as part of the same hydrosystem. At the same time, sustainable river management strategies must include preservation of riparian forests and fluvial landscapes, which represent major ecological components. Finally, environmental decision-making is essentially an ethical and political position rather than a scientific or technical task (Hillman, 2002). As discussed by G.J. Brierley and K.A. Fryirs (2005), current top-down or bottom-up approaches are unlikely to achieve sustainable, long-term success in flood-hazard and risk management, because of "widespread alienation from the decision-making process, and a failure to tap into local knowledge and resources". Hence emerging "middle-ground" approach between science and flood management is necessary (Carr, 2002). This scaled analysis will lead to a better integration and resolution of conflicting uses, with respect to political and social choices such as dykes conservation along the Loire River (Gautier *et al*., 2007), heritage conservation and maintenance of old hydraulic structure such as Canal du Midi in southern France (Arnaud-Fassetta *et al*., 2002), which increases flood impact in the Aude catchment.

Conclusion

This paper highlights the contribution of fluvial geomorphology to flood risk management in France and Himalayas. The various examples detailed in the article show how the inclusion of fluvial geomorphology can lead to innovative approaches to flood risk reduction, river maintainance and floodplain restoration. Management of soil erosion and floodwaters is of highest importance in northern France. In mountains, strong connectivity exists between the slopes and the torrential channel, as demonstrated in the French Alps and in Nepalese Himalayas. These induce permanent risk for local people living near the river, on alluvial fans or on the lower river terraces. Hence management of debris flows resulting from interaction of erosion processes on the slopes and valley bottom is of fundamental importance. The paper highlights the diversity of concepts and methods such as hydromorphological mapping, sediment budget, functional flood areas developed by fluvial geomorphologists in order to understand spatiotemporal variability of flood hazard and induced flood risk in temperate, Mediterranean and mountainous areas. In the near future, studies in fluvial geomorphology should continue to turn towards linking fundamental and applied research. Fundamental research will lead to a refinement of our knowledge of the spatiotemporal dynamics of hydrosedimentary processes, associated with multi-field methods based on consideration over multiple timescales. Emphasis will be placed on the systematic use of field data and modelling for the development of sediment budgets and hydraulic models. This work will require that fluvial geomorphologists further develop collaborations with the Earth and water sciences. The links between fundamental and applied research should be strengthened to achieve a better integration of academic research by environmental professionals and decision makers. These links require the adaptation of university programmes to meet professional needs. University research and the development of strong collaborative links will require that fluvial geomorphologists recognise the expectations of environmental administrators, and that environment administrators better inform fluvial geomorphologists of their specific requirements. This could be achieved by the adaptation of Undergraduate and Master programmes to include field-based training.

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