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# ASSESSMENT OF CONSEQUENCES OF SEDIMENT DEFICIT ON A GRAVEL RIVER BED DOWNSTREAM OF DAMS IN RESTORATION PERSPECTIVES: APPLICATION OF A MULTICRITERIA, HIERARCHICAL AND SPATIALLY EXPLICIT DIAGNOSIS

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## ABSTRACT

As regards river restoration, it is fundamental to better link human pressures and environmental responses and to take into consideration not only target species or habitat but diverse ecological elements. This permits to assess sustainable restoration plan, especially concerning sediment augmentation below dams. The use of a hierarchical multicriteria approach on the Ain River permits us to assess a diagnosis of sediment deficit impact integrating several morphological (channel shifting, river bed degradation and river bed coarsening) and ecological components (Riparian and floodplain lake and fish communities). Our diagnosis also integrates a temporal and spatial approach better to link human pressures and environmental responses and to identify the dam effects amongst other drivers (e.g. grazing decline and channel regulation). The results confirm causality links between sediment deficit and slight channel bed degradation (0.01 m.year$^{-1}$) or channel bed paving and thus highlight the impact of the dam on the drying of the riparian forest and on former channel community. However, the relationship between incision and reduction in active channel lateral mobility is more difficult to establish. The role of sediment deficit in the current variability of the riparian regeneration capacity and, thereby, landscape diversity along the lower valley remains unclear. This study also confirms the relevance of using different ecological indicators, notably because all components present different adjustment time scales, whereas some of them are more sensitive to other impacts. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: river restoration; river ecology; sediment deficit; floodplain lake; dam impact

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## INTRODUCTION

During the 20th century, a wide range of human activities (dam construction, gravel mining and land-use changes) affected most European rivers, limiting both water and sediment supply (Bravard, 1986; Petts *et al*., 1989). Among these activities, damming has been widely studied, and most of the dammed rivers observed in Western countries currently show a sediment deficit and therefore serious loss of lateral mobility, bed degradation (incision) and the development of pavement (e.g. Williams and Wolman, 1984; Collier *et al*., 1996; Topping *et al*., 2000; Grant *et al*., 2003; Vörösmarty *et al*., 2003; Petts and Gurnell, 2005; Renwick *et al*., 2005; Yang *et al*., 2007; Walter and Merritts, 2008; Kummu *et al*., 2010; Draut *et al*., 2011). The amplitude of these adjustments does not necessarily result from the distance downstream of the dam but depends on the degree of hydrological disturbance (i.e. amplitude of peak flow decrease), the volume of any remaining sediment supplied to the channel and on local geomorphic constraints (Sherrard and Erskine, 1991; Grams and Schmidt, 2005). Bed degradation and the development of pavement can occur at a considerable distance downstream of dams (Andrews, 1986, Erskine *et al*., 1999) and for long periods, depending on changes made to the hydrological regime (Church, 1995) and stream type (Williams and Wolman, 1984). Morphological adjustments have substantial ecological and economic consequences affecting all components of the river system (Ligon *et al*., 1995; Kondolf, 1997). Qualitative and quantitative impacts of dams on sediment transport can adversely affect in-stream biota by sediment coarsening of the channel bed, thus reducing available habitat or modifying reproduction conditions for fish, notably lithophilous species (Sear, 1995; Milhous, 1998; Grams and Schmidt, 2002). This results in biotic diversity reduction and alteration of the food chain (Power *et al*., 1996). In-stream biotas are affected by changes in the main

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channel/floodplain interactions, owing to the alteration of surface and interstitial connectivity (Bravard *et al*., 1997; Poff *et al*., 1997; Surian and Rinaldi, 2003).

At river corridor level, whereas the hydrological modifications due to the dam can significantly affect floodplain ecosystems integrity (Johnson, 1994; Rood *et al*., 1994; Thomas, 1996; Merritt and Cooper, 2000; Nilsson and Berggren, 2000), the loss of lateral mobility and bed degradation generated by sediment deficit both potentially play an important role, too. For example, forested stands located along degraded reaches are associated with less frequent overbank flows and drier conditions, hence a lower rate of tree growth and regeneration (Dufour and Piégay, 2008; Dufour and Piégay, 2010). Moreover, lateral mobility is a crucial process for riparian landscape diversity and pioneer species conservation (Salo *et al*., 1986; Kalliola and Puhakka, 1988; Florsheim *et al*., 2008); thus, the mobility loss decreases the relative abundance of pioneer habitats and species whose regeneration is associated to the morphological disturbance regime (Karrenberg *et al*., 2003).

Floodplain lakes are also affected by these morphological adjustments. Numerous studies have outlined several key factors involved in such situations (Bornette and Heiler, 1994; Bornette *et al*., 1996; Bravard *et al*., 1997; Bornette *et al*., 1998). These are the following: (i) the intensity of river channel incision, which governs connectivity between the active channel and its former channels (Bravard *et al*., 1997); (ii) the geomorphological pattern of the lake, which controls the rate and pattern of the ecological successions that develop in former channels by influencing erosion and/or siltation rates (Bornette *et al*., 1998); and (iii) the quality and quantity of groundwater supplied to the cut-off channels, which determines lakes piezometric and trophic levels and contributes as well to the rate and pattern of ecological successions (Bornette and Heiler, 1994; Bornette *et al*., 1996).

Finally, processes of bed degradation contribute to alter infrastructures by weakening dikes and bridges (Collins and Dunne, 1990; Kondolf 1994, 1997) while exhuming and damaging pipes (Kondolf and Larson, 1995) and reducing groundwater storage capacity (Tagliavini, 1978).

Sediment deficit and its consequences are now well known, but only a few studies have examined the links between river morphological adjustments and their joint impacts on multiple landscape elements, although such a multicriteria approach has demonstrated how relevant it actually is concerning bed degradation impacts (Bravard *et al*., 1997) or restoration monitoring (Woosley *et al*., 2007). Moreover, few studies (Kondolf and Matthews, 1993; Bunte, 2004; Reckendorfer *et al*., 2005) have focused on sustainable sediment management or on restoration plans aiming to mitigate the effects of the resulting sediment deficit. As regards restoration, it is essential to take into consideration not only target species or habitat but diverse ecological elements, as this permits to assess sustainable restoration plan. First, it limits the risk that the restoration might negatively impact other ecological components following negative feedbacks (Schmidt *et al*., 1998, Kondolf *et al*., 2006). Second, it reduces the relative cost of restoration drives, as their objectives are multiple and can concern several components at once. The aim is then for a greater part of the river ecosystem to benefit from one particularly successful restoration drive. Finally, conducting integrative restoration potentially improves civil society's support of the action and limits the risk of conflict between different river stakeholders.

The purpose of this contribution is to present the multicriteria diagnosis carried out on the Ain River in France—a dammed water stream—prior to a restoration project. To integrate the impact of dams on sediment dynamics and on different ecological components, we have used a process-based hierarchy that is particularly suited to assessing the processes linking successive levels of dam impacts (Petts 1984; Jorde *et al*., 2008; Burke *et al*., 2009). First, we have highlighted the sediment deficit and the location of already affected reaches. Second, we have identified the current and the future consequences these processes will have on the river morphology; and finally, we have tested whether this deficit has had consequences on the ecological integrity of the floodplain ecosystems through the study of riparian, floodplain lakes vegetation and fish communities. Our diagnosis will also be spatially explicit, with a progressive downstream analysis (Braatne *et al*., 2008). This approach permits to distinguish the relative effect of sediment starvation that spreads from the dam to downstream areas, due to the hydrological alteration effects that have rapidly and simultaneously occurred all along the main channel (Liébault and Piégay, 2002; Piégay and Schumm, 2003). Moreover, it makes it possible to focus on future restoration drives on the most relevant sites and to integrate the longitudinal dimension (Kail *et al*., 2009), notably regarding sediment transfer (Piégay *et al*., 2006; Liébault and Laronne, 2008)

## STUDY AREA

The Ain River is one of the greatest tributaries of the Rhône River in Eastern France, and it drains a 3630-km$^2$ watershed (Figure 1). The study reach is located in the downstream part of the river (the last 40 km of the channel, before its confluence with the Rhône River). The channel is bordered with a riparian forest and flows through an agricultural floodplain. Active channel widths range between 80 and 100 m, on average. The mean annual discharge and the



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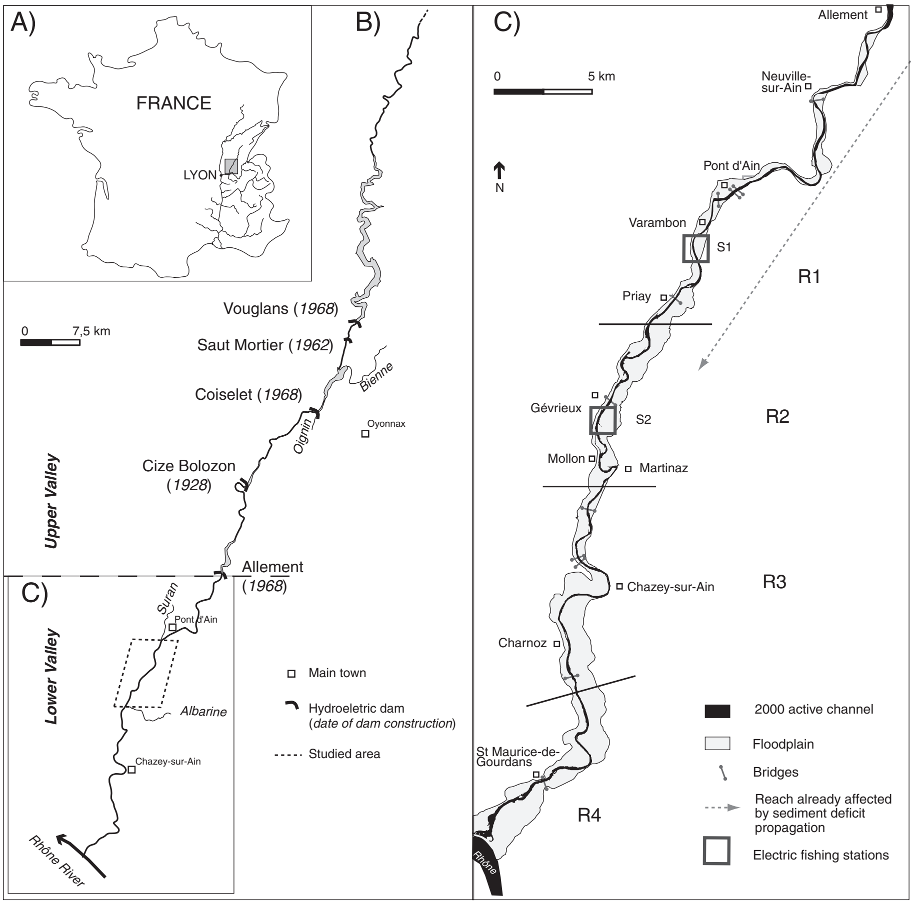


Figure 1. (A) Location of the Ain River in the Rhône basin. (B) Position and date of construction of dams located in the middle reach, studied lower alluvial reach. (C) Reaches R1 to R4 come from hydromorphic sectorization performed by Rollet (2007)

annual flood approximate 120 and 780 $m^3s^{-1}$, respectively. In a European context, the Ain is an unusually natural and freely meandering river. It has been largely unaffected by in-stream gravel mining and uninhibited, as very few embankments can be found along its length. However, the upper valley is impacted by five hydroelectricity dams, built between 1931 and 1968, which act as sediment traps. Since 1968, maximum annual peak flows have been regulated, following the construction of the Vouglans Dam, the biggest one in the chain of dams along the Ain River, which governs only 1/3 of the watershed. The lower valley still registers, annually, 4 to 6-day discharges exceeding the bankfull discharge, estimated at 530 $m^3.s^{-1}$ (Rollet, 2007). The Ain River lower valley is of high ecological interest, due to its diverse mosaic, composed of a gravel bed channel, post-pioneer woodlands (dominated by *Fraxinus excelsior* and *Populus nigra*), pioneer units (*P. nigra and Salix spp.*), sparse dry grasslands and numerous former channels, complete with a set of emblematic species such as *Thymallus thymallus, Luronium natans*, *Zingel asper*, *Charadrius dubius*, *Lutra lutra*, *Salix* spp.

## MATERIAL AND METHOD

### *Sediment deficit characterization*

Two indicators have been analysed because they are particularly sensitive to sediment deficit, namely, the multidate evolution of gravel bar areas and the longitudinal grain size pattern along the lower valley (Rice and Church, 1998; Surian, 2002).

Gravel bar area is a parameter that is particularly sensitive to water discharge variations. Therefore, only aerial photographs corresponding to low flow conditions were taken into account (1945, 1963, 1980 and 2000 at a scale between 1 : 14 500 and 1 : 25 000). Because of the high variability of photograph quality (e.g. resolution, scratches, etc.), gravel bars were manually digitalized in a geographic information system environment (ArcGis software, Esri, Redlands, CA, USA). The information was extracted at every 250-m reaches (Alber and Piégay, 2011). The longitudinal grain size pattern was assessed through systematic grain size measurements on bar heads by means of ground photographs (covering areas from 0.95 to 1.25 $m^2$), which



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were analysed using the semiautomatic process (see methodological details in Graham *et al*., 2010). In only 2 days, 109 gravel bars were sampled, to ensure sampling was conducted in similar conditions (e.g. discharge in the main channel). This first approach was reinforced by determining a pavement index (D50 surface/D50 subsurface) comparing surface and subsurface grain size on 13 different gravel bars along the lower valley to assess the degree of the bed pavement we observed. On seven sites, we used grid measurements to sample both the surface and subsurface, following the aforementioned previous recommendations (Buffington, 1996). On six other sites, we benefited from volumetric samplings to obtain grid measurements of the surface and volumetric samples for the subsurface. In these cases, volumetric data were converted to grid measurements (Kellerhals and Bray, 1971).

*Bed degradation and channel shifting*

The channel incision was tackled using three historical water level long profiles (from 1920 to 1999) covering a section stretching from Pont d'Ain (upstream) to the Rhône River collected at low flow. Their use was limited by three main restrictions: (i) surveys were made for discharges ranging from 7.5 to 50 $m^3.s^{-1}$; (ii) channel length varies from one survey to the next because channel shifts and measurements only partly overlap in space; and (iii) sampling pressure is different from one profile to another, ranging from 0.86 to 6.48 points/km. We tested the impact of variations in discharges between surveys at fixed gauging stations, using the discharge/depth relationship. These variations result in a difference in water levels ranging from 0.03 to 0.5 m, which could thus be considered as a margin of error. The data overlap was assessed using steady points in time (mostly bridges). We only retained points belonging to common comparable reaches. As a result, the data could be considered as offering different degrees of 'reliability' from 'good' (for reaches where multidate data are reliably comparable) to 'uncertain' (where the river was too mobile in space to ensure the validity of interdate comparisons).

Channel shifting has been studied on a set of eight aerial photo series to obtain a complete data set over the whole floodplain at least every 10 years, from 1945 to 2000 (Figure 2). Such data are especially useful to highlight the major geomorphic changes (e.g. from short to long time scale) and then to underline the temporal and spatial pattern of the channel adjustment (Piégay *et al*., 1997; Gilvear *et al*., 2000; Winterbottom, 2000; Burge and Lapointe, 2005; Wallik *et al*., 2007; Cadol *et al*., 2010). Contrary to gravel bar surfaces, active channel and floodplain areas are less sensitive to water discharge variations. This is why we hold photos for which no overflowing discharge (530 $m^3.s^{-1}$) has occurred. All photos were scanned at 600 dpi and rectified (RMS $< 5$ m). On each photo, active channel and floodplain were mapped and then overlaid to identify, on one hand, areas corresponding to floodplain destruction following lateral erosion and on the other hand floodplain construction following gravel bar accretion and vegetation encroachment. The results were then used to build a sectorization of the lower valley distinguishing two contexts: mobile or stable channels. The reaches were visually defined (Rollet, 2007) depending on lateral erosion intensity.

*Riparian and floodplain lake ecological characters*

We used the vegetation map drawn up by the Office National des Forêts (ONF, National Forestry Office) in 2003 on behalf of an EU LIFE programme. Following the Corine land cover European typology, 27 different habitats were identified and mapped by photo interpretation and field surveys (Dumas, 2004; European Environmental Agency: www.eea.europa.eu). The 27 habitats correspond to two lentic aquatic habitats (22.1 and 22.43 in Corine typology), three lotic aquatic habitats (24.2, 24.43 and 24.52), one shrub habitat (31.81), six grassland habitats (34.32, 34.33, 37.1, 37.2, 37.71 and 38), nine forest habitats (41.26, 44.11, 44.12, 44.13, 44.31, 44.33, 44.41, 44.91 and 44.92) and six wetland habitats (53.11, 53.14, 53.16, 53.21, 53.3 and 53.33). The lateral extension of the map was limited

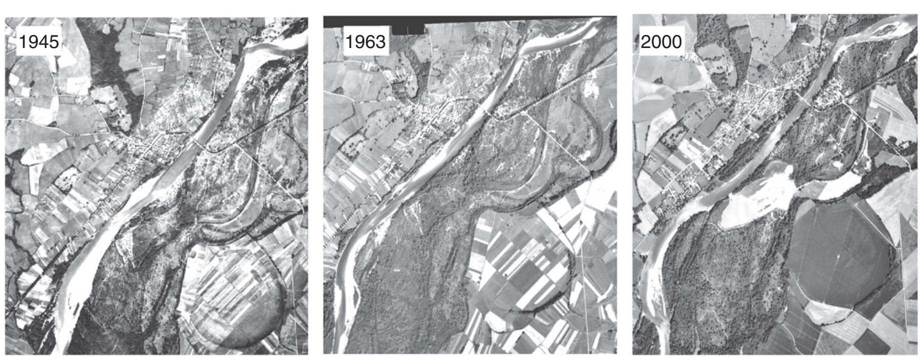


Figure 2. Extracts of aerial photographs (1945, 1963 and 2000) used to assess channel shifting between 1945 and 2000



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to the area actually eroded over the last 55 years. These limits were identified by overlaying the channel planform drawn up at all eight dates taken into consideration between 1945 and 2000. Data were disaggregated every 250-m elementary subreaches. For each subreach, the characterization of landscape structure is based upon Shannon's Diversity index, number of different habitats and proportion of pioneer habitats (i.e. stands dominated by willow species). All are computed by V-LATE plug-in, which is an extension devised for the ArcGIS environment (available at http://www.geo.sbg.ac.at/larg/vlate.htm) and based on metrics included in the FragStat software (available at http://www.umass.edu/landeco/research/fragstats/fragstats.html).

Floodplain lakes and their aquatic vegetation have been inventoried from 1995 to 1996 along the lower Ain River through field survey and map analysis as well as through complementary observations made in 2003. Indeed, aquatic vegetation has been largely used to assess river quality (Haury *et al*., 2006) and notably as regards hydrogeomorphic drivers (Hupp and Bornette, 2003).

Each floodplain lake was characterized in terms of trophic level (oligotrophic, mesotrophic and eutrophic) and flood disturbance regimes (from undisturbed to very frequently disturbed lakes submitted to siltation processes) on the basis of the ecological requirements of the freshwater plants that colonize them (for more details about the method, see Amoros *et al*., 2000, Bornette *et al*., 2008).

### *Fish communities*

Electric fish surveys, based on the Abundance Punctual Sampling method (Nelva *et al*., 1979; Persat and Copp, 1990; Persat and Olivier, 1991), were carried out in 1996, 1997, 2002 and 2005 on two stations over a length of 2 km, an upstream station (S1) affected by sediment deficit (downstream of Varambon) and a station (S2) in an equilibrium state (Gévrieux) (Figure 1). The survey period included the exceptional drought event occurring in 2003, during which the water discharge reached 10 to 15 $m^3s^{-1}$ (20% of the mean monthly low discharge calculated over a 53-year period) over 3 months (from June to August). Particular attention was paid to the evolution of three rheophilous marker species: the Rainbow Trout (*Oncorhynchus mykiss*), the European Grayling (*T. thymallus)* and the Apron (*Z. asper*), because these species are closely associated with changes in channel morphology and sediment deficit. The electrofishing technique that was used provides both spatial and temporal data for comparison between sites and sampling periods. Changes in the abundance of the selected fish species and the relative contribution of fishing dates and reach types (incised or in equilibrium) were tested using the correspondence analysis (CA).

## RESULTS

### *Spatial extent of sediment deficit*

From the analysis of aerial photographs, we observed a reduction in gravel bar surface area along the 30-km downstream of the river from the Allement Dam since 1945 (Figure 3A). This reduction was more substantial and generalized from 1945 to 1963 (P1) than during later periods. The following periods registered continuous gravel bar reduction, but the process of colonization by vegetation slowed down and it stopped in 1980 (Figure 3B). Furthermore, this reduction mainly occurred along a longitudinal gradient from upstream to downstream (P2 and then P3) (Figure 3A).

Ground photo analysis shows that longitudinal bar heads underwent a downstream fining along the lower valley (Figure 4A). However, the upstream reach (Priay–Gévrieux) is significantly coarser than the intermediate (Priay–Gévrieux) ($p = 0.048$) and downstream reaches (downstream of Gévrieux) (Figure 4B) except where bars have been influenced by local infrastructures (weirs or bridges) that, locally, artificially retain fine residual sediment (Figure 3A). Furthermore, the pavement index on this reach is particularly high whatever the applied method of calculation (Figure 4A). The grain size differences between the upstream (Pont d'Ain–Priay) and downstream (Priay–Rhône River) reaches are too high to be explained away by a ‘natural' downstream fining process with regard to channel slope, which is not significantly different ($p = 0.350$) between these two reaches. On the Priay–Gévrieux reach, the median grain size is also coarse, but the pavement index indicates that the paving process is still in progress (Figure 4). This reach may correspond to the current location of the sediment deficit front, 26-km downstream from the Allement Dam (built in 1960). This hypothesis of a sediment deficit propagation of 500 m/year$^{-1}$ seems to be consistent with observations made using passive transponder tracing (Rollet *et al*., 2008) or with estimates on similar systems in southeastern France (Liébault, 2003).

### *Morphological adjustments*

As shown in Figure 5, bed degradation had already been observed between 1920 and 1976 (0.01 m.year$^{-1}$). It especially affected the upstream and the lower parts of the lower valley. Local maximum is observed at confluence: −6 m.

Upstream incision extended slightly downstream during the following period (1976–1999), thus accounting for the downstream propagation of starvation. This observation is consistent with the decline of tree growth observed in the floodplain by Dufour and Piégay (2008). Thus, the river has been undergoing bed degradation probably since the middle of the 20th century because of the dams that were



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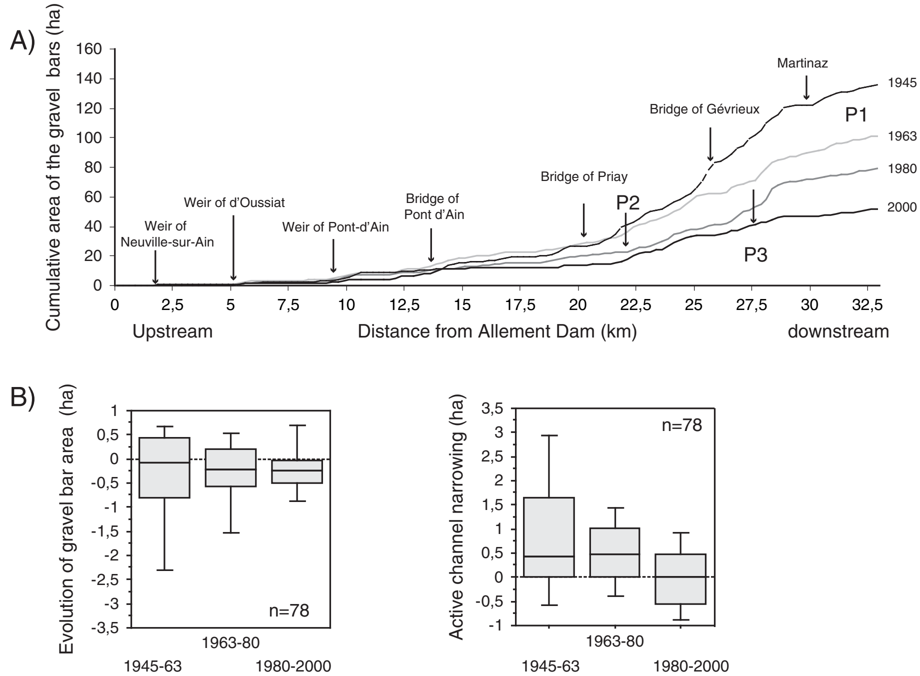


Figure 3. (A) Cumulative gravel bar areas in the active channel in 1945, 1963, 1980 and 2000 from Allement Dam to Chazey (measured per unit reach of 250 m long) and (B) evolution of gravel bars areas and active channel narrowing from 1945 and 2000. Box plot provide a set of centiles values, the 10th, 25th, 50th, 75th and 90th

erected along the upstream tributaries for local hydroelectric production. After the construction of dams on the main channel (1930–1960), this process spread from upstream to downstream, along with the progressive extension of the sediment deficit. 45-km incision was again observed between 1976 and 1999, whereas aggradation occurred at confluence. That incision can be explained here by artificial cut-offs and straightening imposed by human pressures to ward off bank erosion in floodplain mining areas and to prevent bridges from being damaged.

The channel has also registered a narrowing process since 1945 and a 35% reduction of the active channel area between 1945 and 2000 (Figure 6A). Two distinct periods are to be distinguished. From 1945 to 1971, this process was the most significant (median value of 2 m/year$^{-1}$), especially during the first decade (1945–1954) before the construction of the Vouglans dam, which is the only one likely to affect peak flows. Then, the active channel width levelled off during the second period (1980–2000) and locally underwent slight enlargement after the 1991 flood. Moreover, the spatial pattern of the narrowing remains constant over time, always occurring in two reaches: at Villette–Martinaz and at downstream Pont de Blyes, synchronously.

Lateral erosion is not so variable in time. Average annual bank retreat commonly reaches 2 m over 25% of the elementary subreaches (250 m) during the whole study period (1945–2000) (Figure 6B), and no significant variation could be observed before and after the dam was built. Nevertheless, two periods, 1954 to 1963 and 1980 to 1991, underwent more extensive lateral activity caused by the very serious 1957 and 1991 floods. However, the evolution of the bank erosion process is very different from one reach to another, and two different cases can be distinguished (Figure 6C). Since 1945, reaches R1 and R3 have both presented very low lateral mobility. On the other hand, reaches R2 and R4 on the Rhône River are particularly dynamic and register concomitant lateral erosion. All did not present significant changes over time, except during periods 1954 to 1963 and 1991 to 1996, when exceptional floods occurred.

### *Ecological consequences of geomorphic changes*

Spatial differences in channel mobility due to gravel bar erosion have generated contrasting ecological conditions and patterns along the Ain River. The stable reaches, such as incised reaches (R1) or reaches controlled by morainic deposits (R3), show a landscape diversity measured using the Shannon index of 1 (median value), which is significantly lower than other reaches, where that index is 1.2 and 1.5 (Figure 7A). Habitat richness is also lower in stable reaches, where the median value is 4 habitats per subreach versus 8 habitats in dynamic reaches (Figure 7B).



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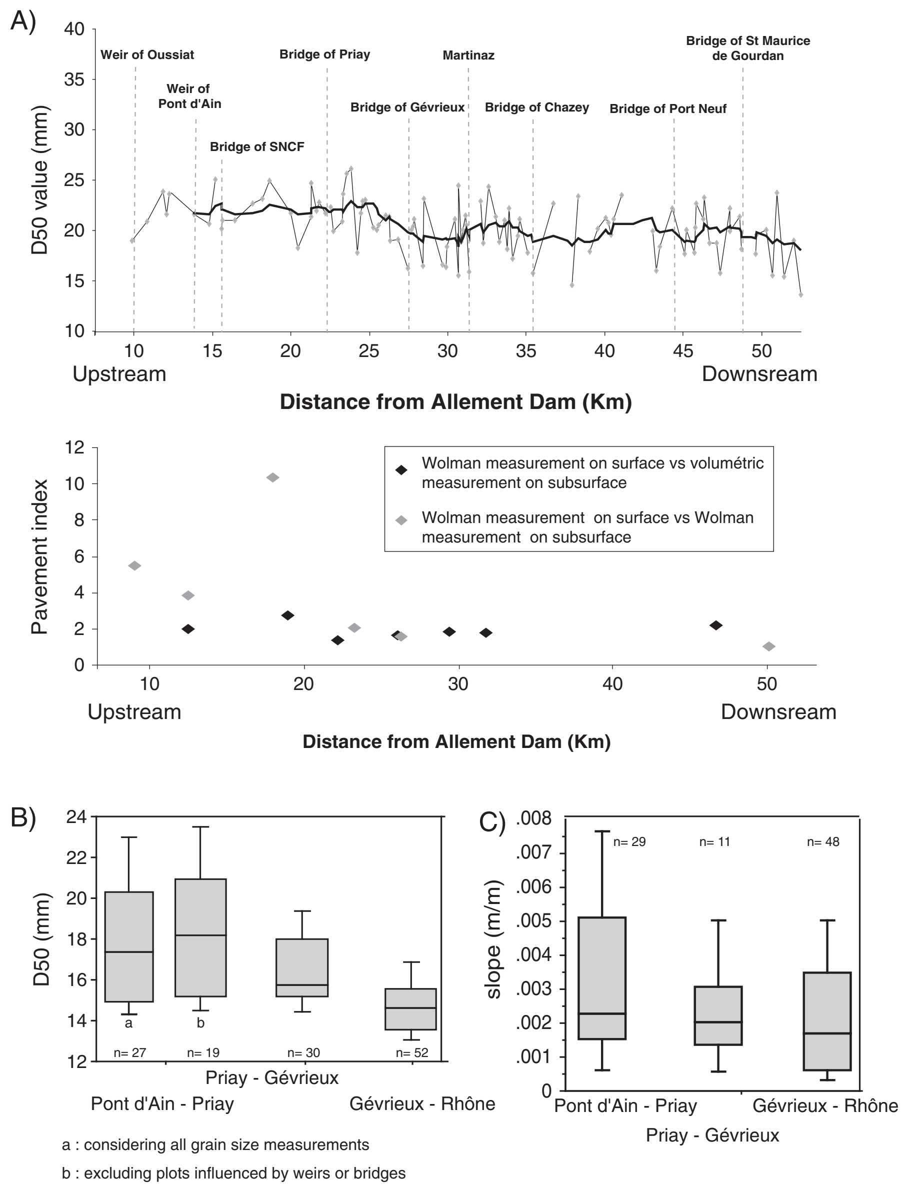


Figure 4. (A) Longitudinal distribution of grain size (dark line corresponds to the moving average of rank 5) and pavement index, (B) grain size distribution within the three studied subreaches (distinction is justified in the text) and (C) channel slope from Pont d'Ain to the Rhône River. Box plots provide a set of centile values, the 10th, 25th, 50th, 75th and 90th

Moreover, in a mobile meandering reach, the gradual movement of the channel frequently provides freshly deposited sediments that can be colonized. This is imperative for the potential recruitment of pioneer species (Karrenberg *et al*., 2003). The conservation of these species and their associated habitats result in strong motivation to conserve or restore river mobility in river corridors. Along the Ain river, the pioneer habitats (phytosociological syntaxa: *Salicetea purpureae, Salicion elaeagni* and *S. triandro-viminalis, Salicenion angustifolii, S. salvifoliae (S. albae p.)*) take up between 10% and 60% of the corridor in the R2 reaches but usually less than 20% in other reaches (Figure 7C).

These results clearly indicate that the lateral channel mobility along the Ain River is a key component in terms of conserving riparian vegetation, by generating a diverse mosaic of habitats and by maintaining the morphological processes necessary for the regeneration of alluvial pioneer species.

Concerning floodplain lakes, we observed that they tend to be less abundant, but also more oligotrophic, in the upstream reaches (R1) than in the downstream ones



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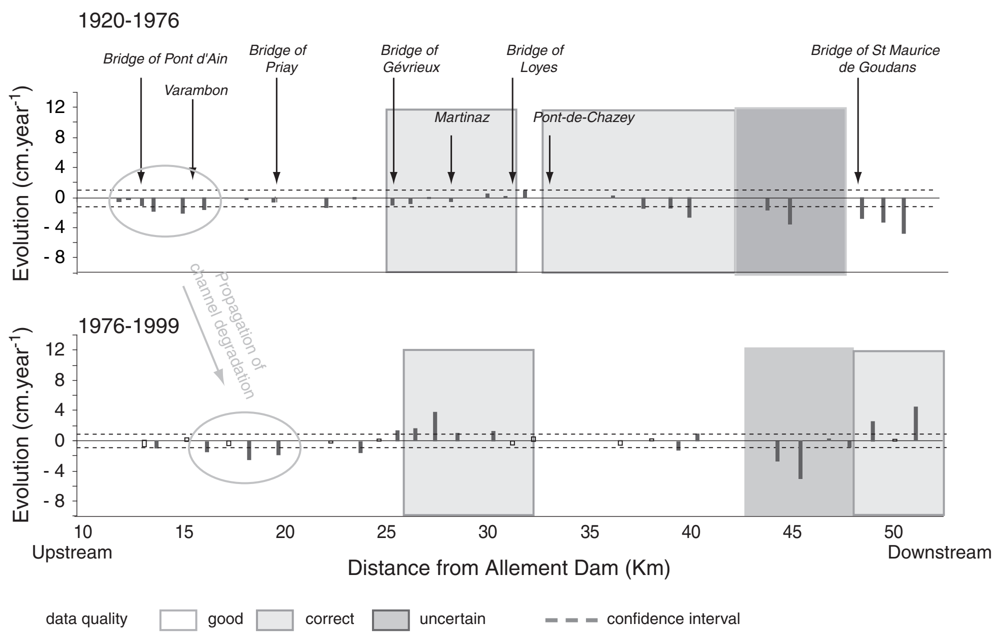


Figure 5. Longitudinal representation of the vertical evolution of the river bed between 1920 to 1976 and 1976 to 1999 (‘Good’, ‘correct’ and ‘uncertain’ refer to the data quality, see material and method for details)

(Figure 8). Moreover, lakes located in the upstream incised reaches of the Ain River (R1) tend to be less frequently disturbed by floods and colonized by tall competitive species that progressively out-compete ruderal ones (Bornette *et al*., 2008).

The fish community of the Lower Ain River is composed of about 20 species, which are regularly to be found from one sampling date to the next. The CA indicated that 55% of the variability in fish community composition is due to variability in fish catch during any given fishing operation (Figure 9). CA also showed that variability in environmental conditions between the two stations was low (e.g. 12% of the total inertia) when compared with temporal variability (before or after the 2003 drought) (e.g. 18.2% of the total inertia), which is roughly twice as high as seasonal variability (springtime or autumn). This indicated the significant effects of the scorching 2003 drought and the following warm and dry summers.

The fish community sampled between 1996 and 2002 was particularly abundant due to optimal hydroclimatic conditions, especially in terms of the salmonids there to be found (Trout and European Grayling). Nonetheless, the station (S2–Gévrieux) on the reach in geomorphic equilibrium (R2) supports greater abundances of European Grayling than the station (S1) on the degraded Varambon–Priay Reach (R1), which supports abundant stocks of Trout (Figure 10). This observation indicates a potential influence of bed morphology on these two species. Since at least 2003, the upstream reach (R1) has been sparse of stillwater fish (rudd and roach), probably because of bigger pools and the development of submerged hydrophytic stands. The relative values also show that the downstream station (R2) is more favourable to the European Grayling and Common Nose, which relish clean and clear gravel.

## DISCUSSION

From our hierarchical multicriteria approach, we are able to assess a diagnosis integrating several morphological and ecological components. All indicators concerning sediment dynamics tend to underline the existence of a sediment deficit and a slight incision in the upper part of the lower valley (from Allement to Gévrieux) due to upstream dams. Indeed, results show that, in its upstream part (R1), the lower Ain Valley underwent a sediment deficit characterized by significant and continuous incision, a reduction in gravel bar areas and gravel bed coarsening. The channel bed is winnowed and locally reaches the paving structure. In turn, this is reinforced by carbonate precipitations that increase bed stability.

However, the links between human pressures and channel adjustment, on one hand (Wallick et al., 2007), and ecological responses on the other are fairly complex and the dam effects are only one driver amongst others (e.g. grazing decline and channel regulation). In this respect, coupling temporal and spatial approaches is therefore fundamental to better link human pressures and



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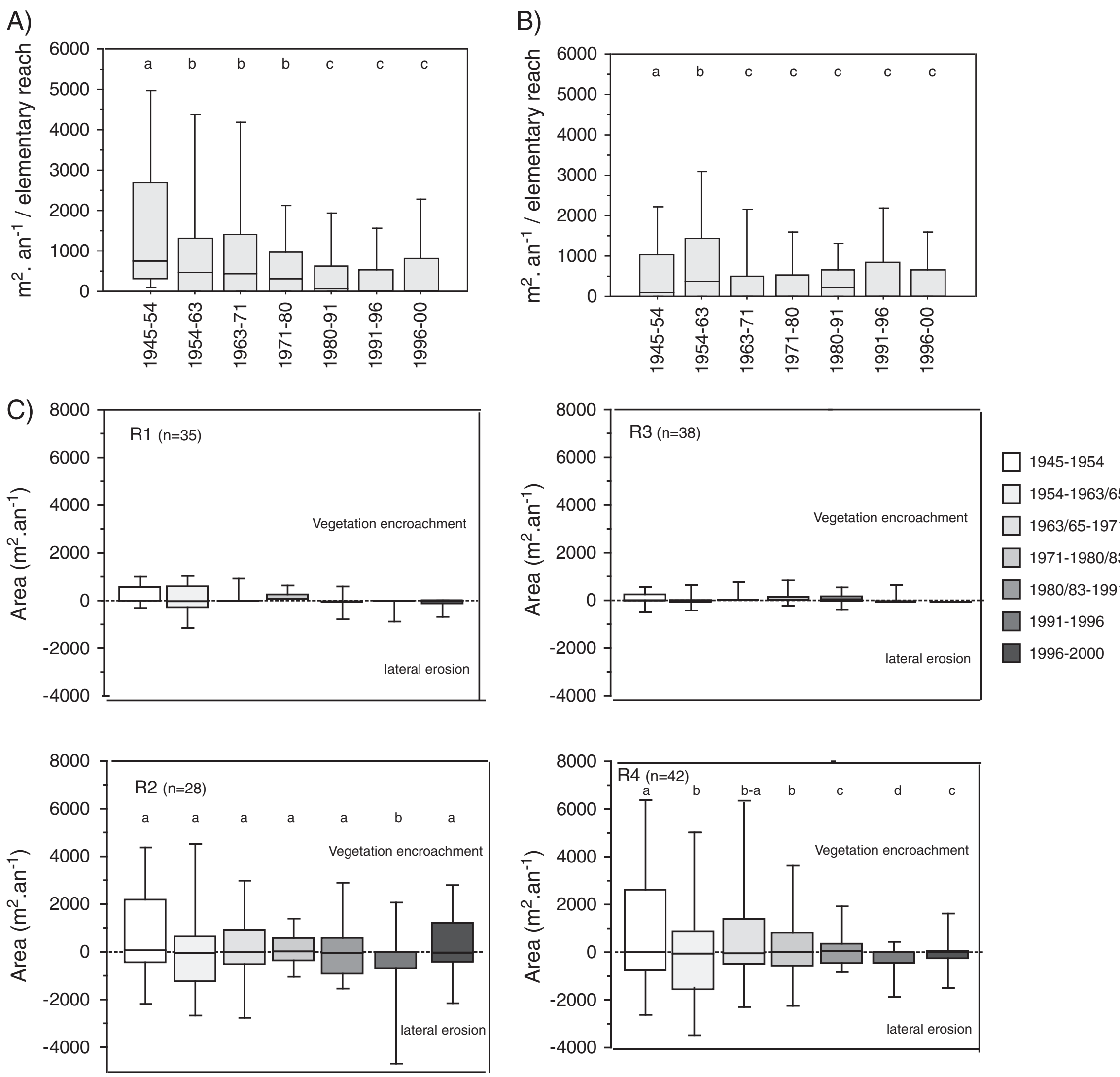


Figure 6. (A) Active channel narrowing, (B) mean floodplain area eroded between 1945 and 2000 (measured per unit reach of 250 m long. $n = 144$) and (C) mean floodplain area vegetated and eroded per reach between 1945 and 2000 (R1 to R4 are reaches located in Figure 1.). Letters (a, b, c and d) indicate homogeneous groups (Wilcoxon test)

environmental responses (Piégay and Schumm, 2003; Brierley and Fryirs, 2005 ; Braatne *et al*., 2008). We did not manage to validate all our hypotheses (Figure 11). Whereas causality links between sediment deficit and slight channel bed degradation or channel bed paving were confirmed, the relationship between incision and reduction in active channel lateral mobility is more difficult to establish. We expected the gradual disappearance of bars to cause a more obvious reduction in river lateral mobility because upstream sediment supply, gravel bar areas and bank erosion intensity are closely connected in meandering systems (Constantine, 2006). Nevertheless, the difference in gravel bar distribution due to floodplain configuration (e.g. valley width and morainic deposits) and the colonization process by vegetation make it difficult to assert there is a direct relationship between sediment deficit and planform adjustment. Channel narrowing most markedly occurred from 1945 to 1963, before the construction of the Allement Dam. Moreover, this process only concerned two reaches, Priay–Mollon (R2) and Pont de Blyes down to the Rhône River (R4), in a synchronous way, where gravel bars were particularly wide because of local floodplain configuration (slope and enlargement). Since 1963, the decrease in gravel bar area has gradually continued from upstream, even though the narrowing process stopped. Thus, channel narrowing could not be connected to effects caused by the dam because of its temporal and spatial pattern. It more likely corresponded to the development of riparian vegetation on gravel bars, due to the change in agropastoral practices after the Second World War, when



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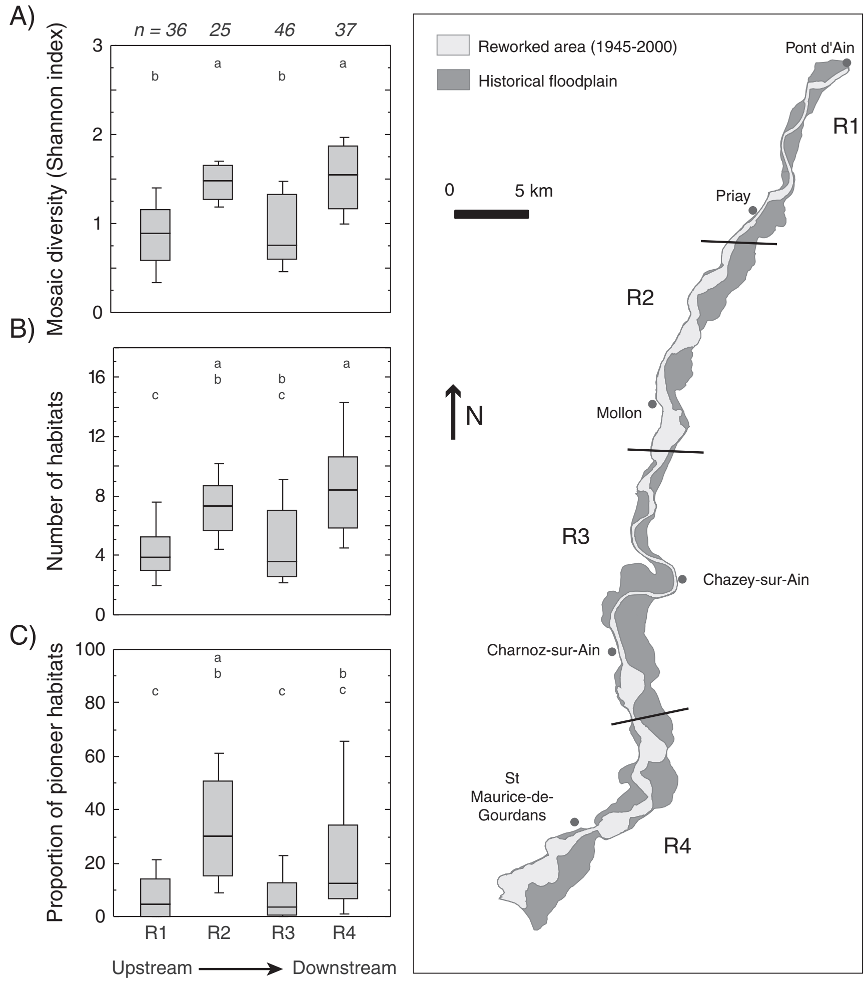


Figure 7. Spatial variability of riparian landscape diversity and composition: (A) Shannon diversity Index calculated on riparian patches (H'), (B) number of different habitats and (C) the proportion of pioneer habitats within the corridor (in percentage of the reworked area). Each metrics are evaluated within 250-m length subreaches, $n$ = number of subreaches. Letters a, b and c indicate homogeneous groups defined by Kruskal–Wallis test paired comparisons. Reaches R1 to R4 come from hydromorphic sectorization performed by Rollet (2007). Box plots provide a set of centiles values, the 10th, 25th, 50th, 75th and 90th

people stopped traditional practices, such as the use of gravel bar as grazing areas, as observed on several rivers in southeastern France (Liébault and Piégay, 2002). Consequently, our study confirms the impact of the dam on the drying of the riparian forest and on former channel community, due to channel incision, for example. However, it is difficult to demonstrate the role of sediment deficit in the current variability of the riparian regeneration capacity and, thereby, landscape diversity along the lower valley.

Our results also confirm the relevance of using different ecological indicators, notably because all components present different adjustment time scales, although some of them are more sensitive to other impacts (Woolsey *et al*., 2007). The consequences of sediment starvation on the fish community structure and composition are not as clear as expected (Figure 11). Particularly, mobile fish species are less sensitive to substrate variation at the reach scale of a few kilometres and still seem little affected by this process. However, floodplain lakes' ecological integrity proves to be more sensitive to channel degradation, which, in our case, is slight, but sufficient (over 0.5 m) to induce changes, such as observed by Bornette and Heiler (1994). At the level of the entire lower Ain corridor, the first consequence of channel incision was that the river bed level deepened, leading to the lowering of the groundwater table and to partial or total dewatering of lakes. Lake dewatering was also influenced by the relative elevation of the lake compared with the level of the river and whether the lake was clogged or not. Clogging limits water infiltration to the substrate and reduces the occurrence of riffles and alluvial plugs that reduce lakes drainage capacity. Most of the water in floodplain lakes is provided by both river seepage and



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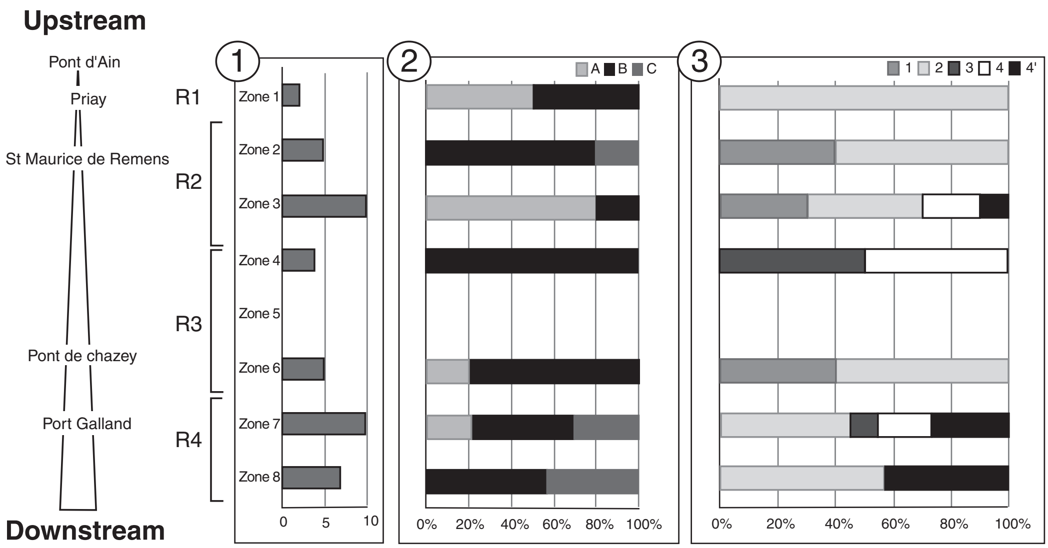


Figure 8. Abundance of floodplain lakes along the lower Ain River. The river section is divided in eight reaches of 5 km long. (1) Number of lakes censed in each floodplain reach. (2) Proportion of oligotrophic (A), mesotrophic (B) and eutrophic (C) lakes in each reach (determined on the basis of the ecological requirements of freshwater plants that colonize them, for more details about the method, see Amoros *et al*., 2000). (3) Distribution of lakes by classes of flood disturbances ( 1 undisturbed lakes, 2 rarely disturbed lakes, 3 frequently disturbed lakes, 4 very frequently disturbed lakes and 4' very frequently disturbed lakes submitted to siltation processes) (for more details about the method, see Amoros *et al*., 2000, Bornette *et al*., 2008), R1 to R4 are reaches located in Figure 1

hillslope aquifers, the relative importance of each process depending on lake elevation relative to the river channel bed. As the river channel undergoes incision, the hillslope aquifer tends to balance with the seepage piezometric level. The incision first led to decreasing the amount of water supplied to lakes by seepage, relatively to the amount contributed from the hillslopes. Because seepage was richer in nutrients than was the hillslope aquifer, such phenomenon led to a decrease in lakes water nutrient levels and to the establishment of oligotraphent aquatic vegetation. Finally, whereas the number of floodplain lakes depends on channel mobility (and thus on the gravel bar erosion process), the ecological integrity of each lake proves to be more sensitive to channel degradation.

To summarize, the morphological and the ecological impacts due to dams are still limited to gravel bed paving and a slight channel bed incision resulting in the drying

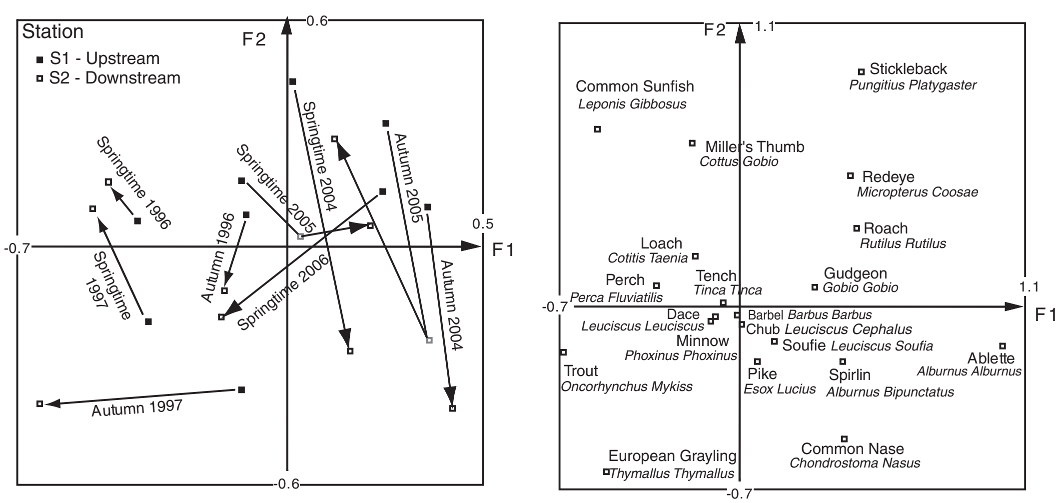


Figure 9. Results of correspondence analysis (arrows link upstream and downstream stations for a given fishing) and relative contribution of different species to this structure. S1 and S2 are stations located in Figure 1



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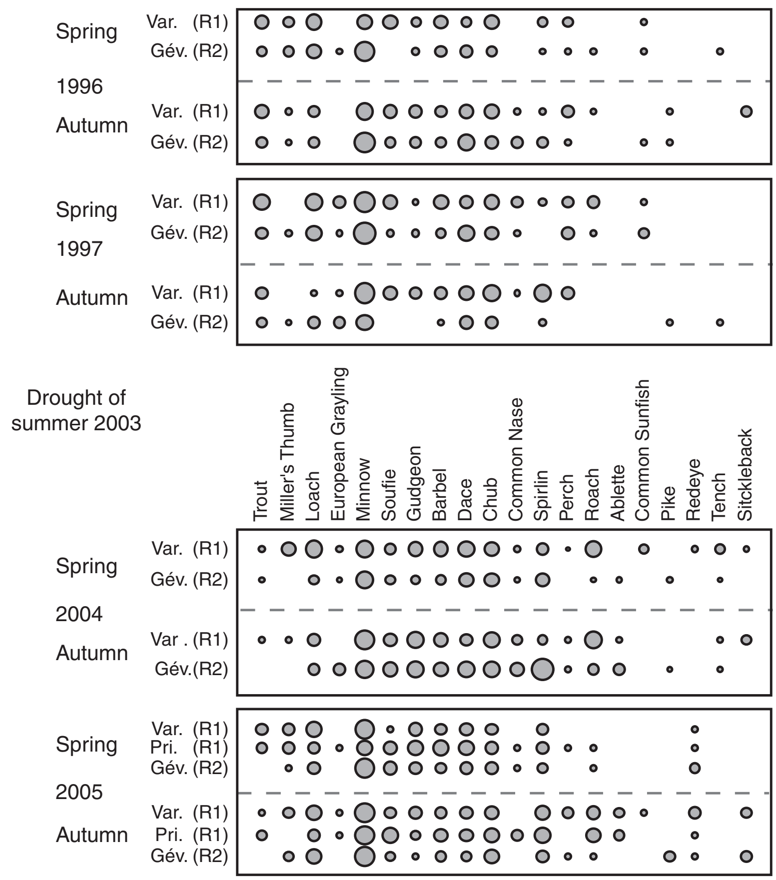


Figure 10. Interannual changes in species abundance log values and according to sampling stations (Varambon, Priay et Gévrieux, see Figure 1 for location, R1 and R2 refer to sectorization Figure 1)

of floodplain ecosystems and changes in water supply to the former channel.

Using a spatially explicit diagnosis has enabled us to distinguish an upstream affected reach (R1)—already suffering from sediment deficit—from the downstream part of the valley, which is still preserved. Since 1945, the reach already affected by sediment deficit (R1) has presented very few and small gravel bars and low lateral erosion, and it has therefore not been very sensitive to sediment depletion. Because of the low sediment supply to this area, the deficit

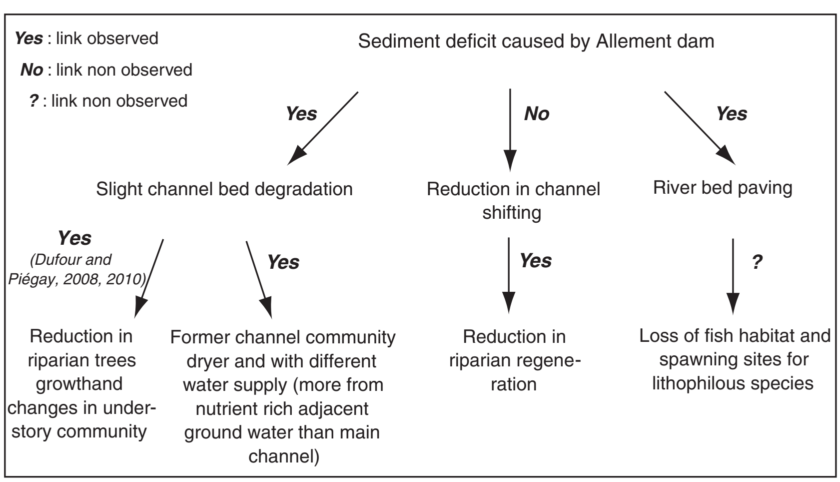


Figure 11. Synthesis of observed and non-observed links between sediment deficit, geomorphic adjustments and ecological consequences



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is propagating downstream (approximately 500 m per year) to R2 (Priay to Mollon). This downstream reach (R2) is the most interesting as it presents diverse and mobile free-meandering reaches that support valuable aquatic and riparian ecosystems, because of a lateral erosion that has been particularly active since 1945, due to huge gravel bars and a larger valley width. Yet, during the next decade, we could expect lateral mobility to have been reduced on this reach due to the progression of sediment deficits. Thus, the R2 reach is expected to be threatened within the next 20 years. This diagnosis has induced river managers to consider restoration plans to limit the sediment deficit impact. That action would not aim to restore some utopian reference state but to improve and preserve the ecological, economic and landscape functionalities in a sustainable way (Dufour and Piégay, 2009).

## CONCLUSION

The approach we developed here (multicriteria, hierarchical and spatially explicit) represents a consistent basis to assess diagnosis prior to restoration of river systems. This method is particularly adapted to a river, which has undergone strong morphological adjustments in complex systems where many drivers are likely to influence river functioning at different periods. The spatial approach permits to identify the respective contribution of the different drivers and to prioritize the reach to restore. This diagnosis that also integrates different components of the river system permits to assess the most appropriate options for restoration including multiples objectives.

On the Ain River, in view of the present diagnosis, the most appropriate solution seems to increase the amount of gravel in the upstream part of the lower valley as in the other river systems under scrutiny (Gölz, 1994; Kondolf *et al*., 2005). This would permit to respond to several objectives concerning both local and downstream issues. At local level, in the already affected upstream reach, ecological improvements are probable, whereas in downstream, it is a protection against the impacts of sediment starvation that is expected. The upstream sediment increase would restore in-stream habitat and gravel bars. Consequently, lateral mobility would ensue, and hence, riparian species would be regenerated and floodplain lakes created. Meanwhile, this sediment supply would slow down downstream propagation of the sediment deficit and decrease the morphological and ecological vulnerability of the downstream reach caused by the effects of the dam.

Finally, with a view to taking restorative action, integrating different components in diagnosis and restoration plans should increase the potential opportunities to implement restoration measures. On the Ain River, sediment enhancement operations were first carried out within the framework of restoring former channels, in the context of the European Life Natura 2000 framework. Scientists and managers decided to restore sites in the upstream degraded reach, to make use of the sediment removed while deepening and reconnecting former channels.

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