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Research Article

Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: The case of the Drôme River basin (S.E. France)

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Abstract. Geomorphic responses to changes in bedload transport in gravel-bed rivers are complex. Such responses occur over long time scales and vary as a function of distance from sediment sources and local channel characteristics. As a result, different types of cascading ecological and social consequences are observed in different parts of a drainage network. This paper presents the results of an interdisciplinary research project, conducted by geomorphologists, ecologists, social scientists, and river managers that focused on changes in bedload transport in the Drôme River catchment in south-eastern France. Our objective was to document a general conceptual framework of the historical and current physical, ecological, and social implications of human-caused bedload transport changes in the Drôme River watershed that could be used to develop sediment management plans for similar gravel-bed river catchments. First, we synthesized the historical trajectory of the Drôme River over the past two centuries from a geomorphic perspective in relation to the evolution of socio-economic activities. Then, we summarized typical ecological responses to gravel-bed channel adjustment. Third, we reviewed how the problems of water and sediment management in the Drôme have been addressed over the past 20 years. We identified the best technical solutions for the replenishment of incised reaches by considering practical interdisciplinary questions including each technique's juridical feasibility, ecological impacts, and its degree of acceptance by managers and the public. Finally, we integrated geomorphic processes, ecological dynamics, and socio-economic values into a functional river reach typology that was used to map target restoration reaches and potential sediment sources throughout the Drôme River catchment.

Key words. Channel incision; ecological impact; sediment reintroduction; water policy; interdisciplinarity.

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Introduction

River channel geometry is shaped by a flux of sediments and water moving from watersheds to the sea (Schumm, 1977). This is especially evident in piedmont gravel-bed rivers characterised by high sediment supply, where bedload dynamics dictate the morphology of the river channel and the aquatic and riparian biocenoses that interact with the fluvial system (Petts and Amoros, 1993). An increase or decrease in bedload transport will tend to favour the aggradation or incision of the river channel, respectively, but the intensity of the channel response will be also a function of its initial geometry (e.g. river width). In watersheds where human activities are widespread, land uses such as agriculture and timber harvesting can radically modify the flux of sediments to downstream channel reaches (Gregory and Madew, 1982; Burton, 1997; Liébault et al., 2005), thereby changing floodplain and channel geometry (Owens and Walling, 2002). Land use changes can narrow, widen, incise, or aggrade river channels (Grant, 1986; Liébault and Piégay, 2002; Kondolf et al., 2002), begetting multiple social, economic and ecological consequences (Bravard et al., 1999).

Geomorphic responses to changes in bedload transport have often been addressed through retrospective analyses in relation to climate change, river development, land use changes, or other past uses (Eschner et al., 1983; Petts et al., 1989; Jacobson and Primm, 1997). Conceptual geomorphic models have been used to describe successional stages of incised channels (Schumm et al., 1984) and to illustrate gravel-bed river changes over space and time, considering the whole catchment rather than local sites and the temporal lags between human impacts and downstream effects (Piégay and Schumm, 2003; Brierley and Fryirs, 2005).

Nevertheless, while a management plan based strictly on a geomorphic perspective may provide a good way to preserve gravel resources, it may not meet ecological and social objectives. To maximise the benefits of watershed management, there is a clear need to promote interdisciplinary approaches that integrate multiple perspectives on complex system adjustment in order to identify best practices and management actions (Habersack and Piégay, 2008).

In 2000, we developed an interdisciplinary research project on the Drôme River involving geomorphologists, riparian, fish, and macroinvertebrate ecologists, specialists in water chemistry, researchers in law and political sciences, and local river managers, following the integrative scientific approach promoted by Brierley and Fryirs (2008). A similar integrated river management project has been conducted in the Willamette River basin, Oregon, U.S.A. (Dole and Niemi, 2004), although such an approach was lacking for gravel-bed river catchments. For such interdisciplinary efforts to successfully solve practical problems such as river incision, a common conceptual and historical context for prospective analysis is required (Innes, 2005; Benda et al., 2002; Boulton et al., 2008).

As a starting point, we identified the internal and external forces acting on the Drôme River (Fig. 1). Our first goal was to produce an overview of the past and present situation in the catchment by examining i) the social and geomorphological trajectory of the river over the past two centuries, ii) the general ecological consequences of bedload transport change in gravel-bed rivers, iii) how the problems of water and sediment management have been addressed in the Drôme basin, and iv) potential replenishment techniques and their legal feasibility.

Based on this synthesis and field study results, we established an integrative, spatially-based, functional typology of river reaches including geomorphic, ecological, and human use criteria. Using this tool, we mapped the Drôme River catchment and identified target incised reaches as potential sediment sources for their replenishment. Together, we propose practical technical solutions for the replenishment of incised reaches from interdisciplinary perspectives.

The past and present situation of the Drôme River

A synthetic historical trajectory

Located in the Southern French Alps, the Drôme River is a 106 km long, medium-sized tributary of the Rhône River that drains 1640 km^2 of steep, mountainous terrain, ranging in elevation from 800 to 2000 m (Fig. 2). The annual discharge is 19 m^{3}s^{-1}, with an average 10-year flood discharge of 381 m^{3}s^{-1}. Most of the Drôme's northern tributaries originate in karstic ridge formations (limestone), whereas the southern tributaries are Mediterranean regime torrents. These torrents are typified by severe summer low flows, intense flash floods, and high sediment transport rates due to a marly landscape sensitive to erosion.

The geography and chronology of geomorphic changes over the last two centuries in the Drôme River (Fig. 3) have principally been caused by three natural and anthropic factors (Fig. 4). The first factor was climate, which controls the intensity and frequency of major floods and their associated bedload transport. The second was land use change within the catchment, especially within riparian areas. Third,

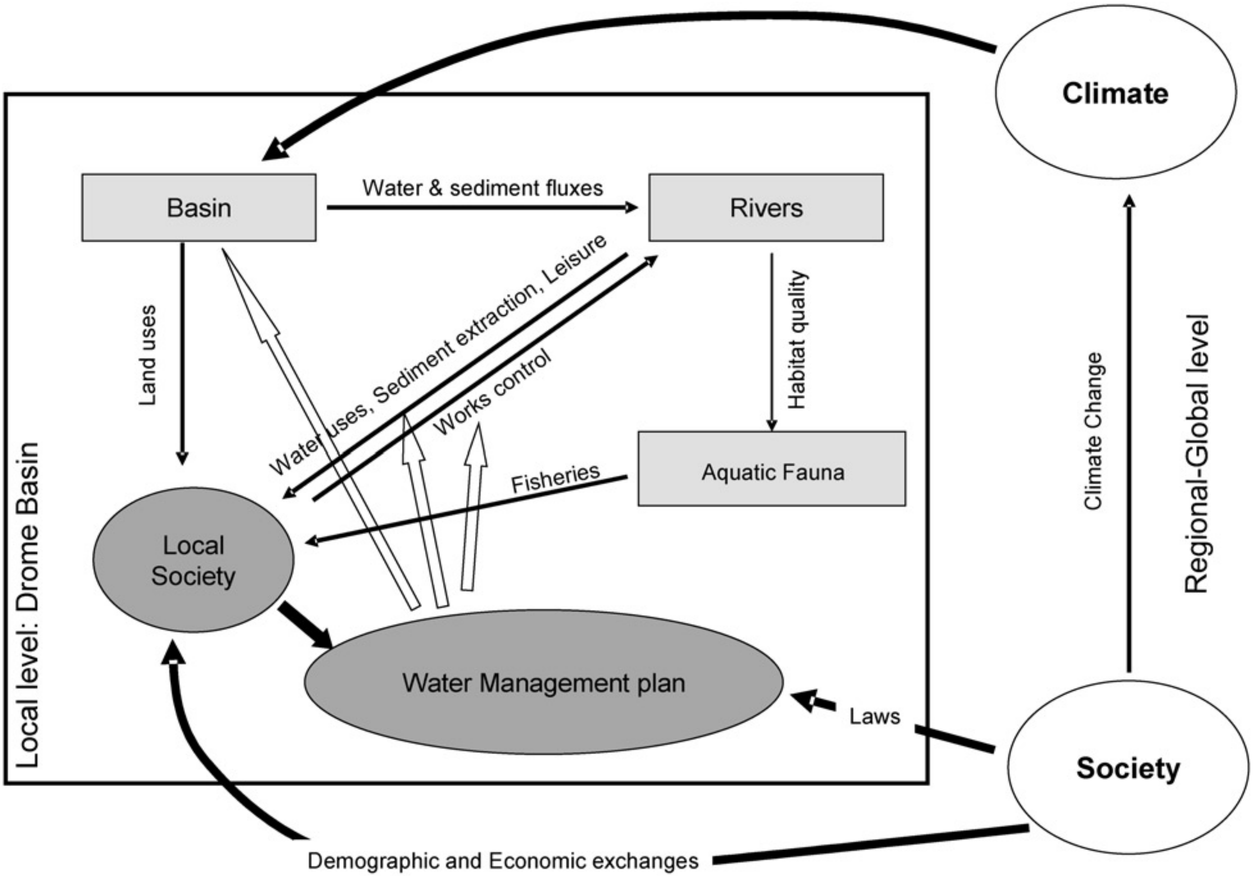

Figure 1. Conceptual framework of natural and anthropic factors and effects on the fluvial dynamics of the Drôme River. Fluvial dynamics, determined by sediment and water fluxes, are a key driver of aquatic and riparian habitat diversity. Catchment residents interact with natural factors through land uses and modification of vegetative cover, economic activities directly linked to the river (e.g. water use, sediment extraction, fisheries, and leisure activities), management strategies, and cultural heritage. In the long term, the main driving forces affecting the evolution of both the natural and the human components of the system are climate variability, demographic and economic exchanges, and French and European legislation.

direct human interventions and infrastructure in and along the river channel modified lateral and longitudinal sediment transfer (Landon and Piégay, 1999).

The 19 century was a period of both intense human pressure and heavy rainfall and flooding, especially during the summers (Landon and Piégay, 1999). The population reached a maximum of 55,700 inhabitants in 1851, and the basin was subject to overgrazing, deforestation and intense farming. Overgrazing was frequent in floodplains, reducing the banks' resistance to erosion and forest cover was reduced to a low of 49,246 ha in 1835. Hillslopes were largely connected to channels with high levels of sediment delivery, and the channels widened and aggraded.

Because of intensive soil erosion and associated flooding problems in the valleys, the French State implemented an extensive soil conservation programme called the "Restauration des Terrains en Montagne" (RTM) in the 1860s. Some 10,500 small weirs or check-dams were built. A total of 338 km of channels were cleared to reduce sediment transfer, and 13,000 ha of former farmlands were reforested. Throughout the 19 century, 56 km of dikes and embankments were built along 94 km of the Drôme River to protect settlements and agriculture (Landon and Piégay, 1999).

But after the turn of the century, the human population began to decrease, reaching a low of 31,555 inhabitants in 1975. After the 1930s, the steepest and most remote lands were abandoned and quickly afforested, thereby increasing forest cover to 82,265 ha in 1988 (Taillefumier and Piégay, 2002). Today, more than half of the human population is concentrated in three towns located in the alluvial valleys downstream (total watershed population was 39,100 in 1990). The valley bottoms are intensely cultivated with orchards, vineyards, and ploughed lands, whereas the upstream areas are sparsely settled and mainly covered by forest, with only one town of 4500 residents. Rural tourism has developed considerably, with 2.6 million overnight stays a year. A significant portion of leisure activities are now

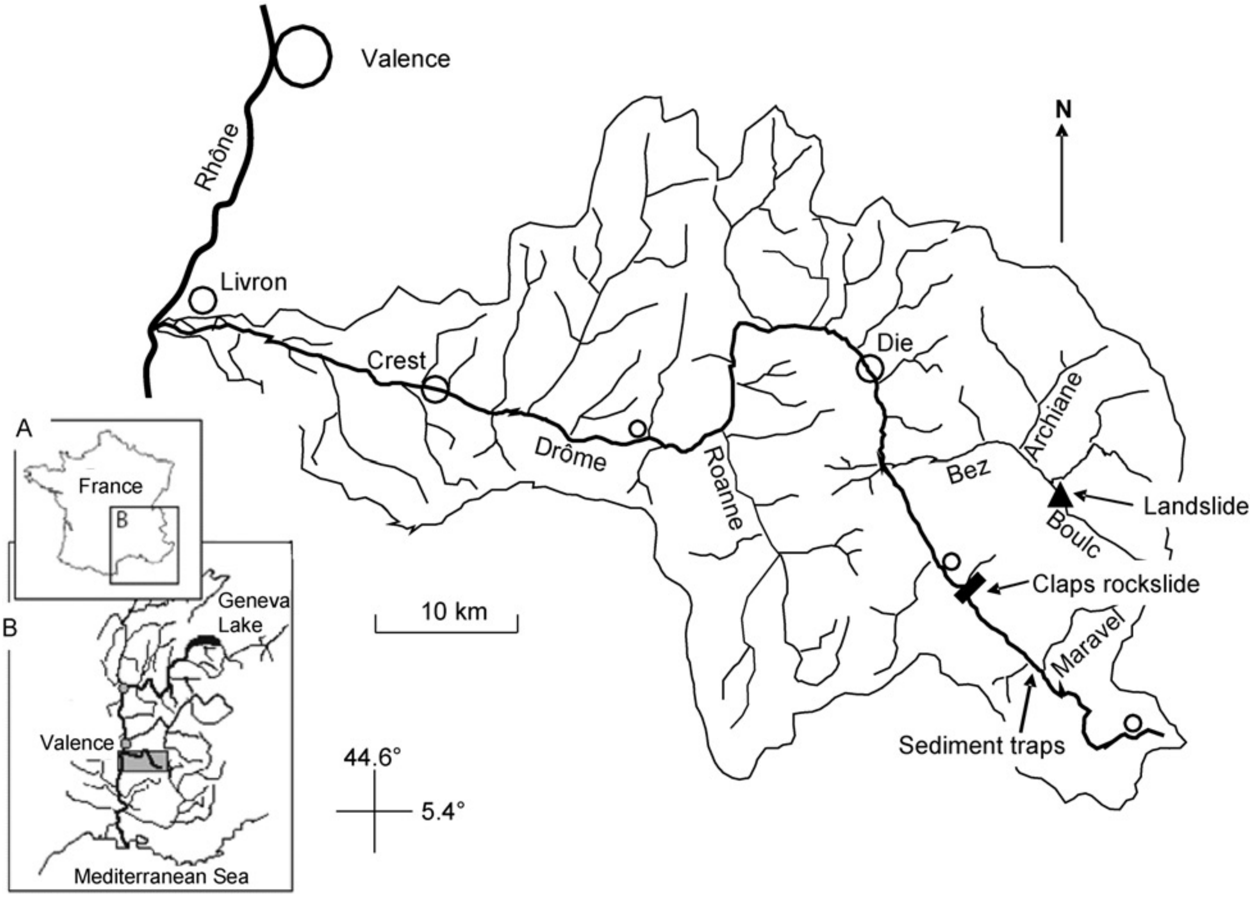

Figure 2. Location of the Drôme River and the drainage network of its catchment. Recent landslides and sediment traps are also shown.

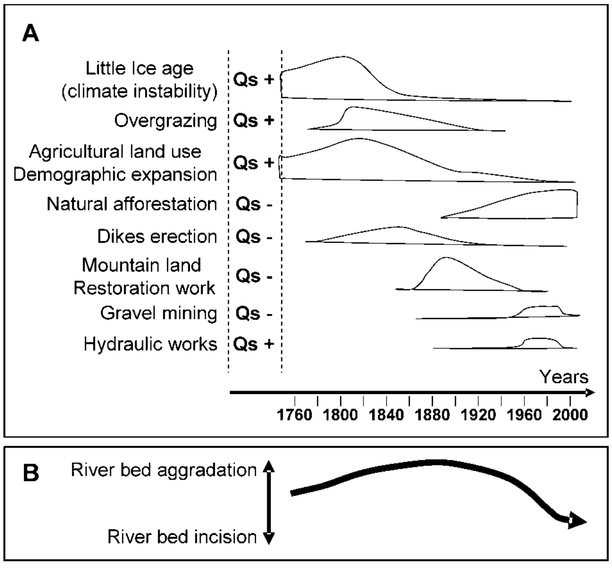

Figure 3. A. Historical model with potential causal factors of the contemporary geomorphic changes in the Drôme River catchment. Qs+: positive effect on coarse sediment transport. Qs-: negative effect on coarse sediment transport. B: River bed responses to the control factors listed in figure 3A. Magnitudes of impacts are qualitative but illustrate the main factors acting on the fluvial dynamics of the Drôme River.

centred on the river, which is used for camping, hiking, bathing and canoeing (Piégay et al., 2002).

In contrast to the 19 century, the river channels have narrowed and incised over the past 100 years. The mainstem Drôme River channel narrowed between 1930 and 1970 due to higher floodplain resistance (riparian afforestation) in conjunction with a decrease in peak flows (catchment afforestation) (Liébault and Piégay, 2002). Upstream, the narrowing of small torrents was induced by a downstream progression of incision resulting from the stabilisation of sediment sources.

Between 1970 and 1990, considerable gravel mining occurred on the lower Drôme, with up to 250,000 m^3 of gravel extracted annually. As a result, the channel incised and the groundwater table dropped (Landon et al., 1995). Due to this water deficit (around 6 hm^3) and to local development of irrigated agriculture (up to 30,000 ha), the volume of water abstracted from the river exceeded the volume available three years out of four by at least two million cubic metres during the low flow period. The river went completely dry in summer.

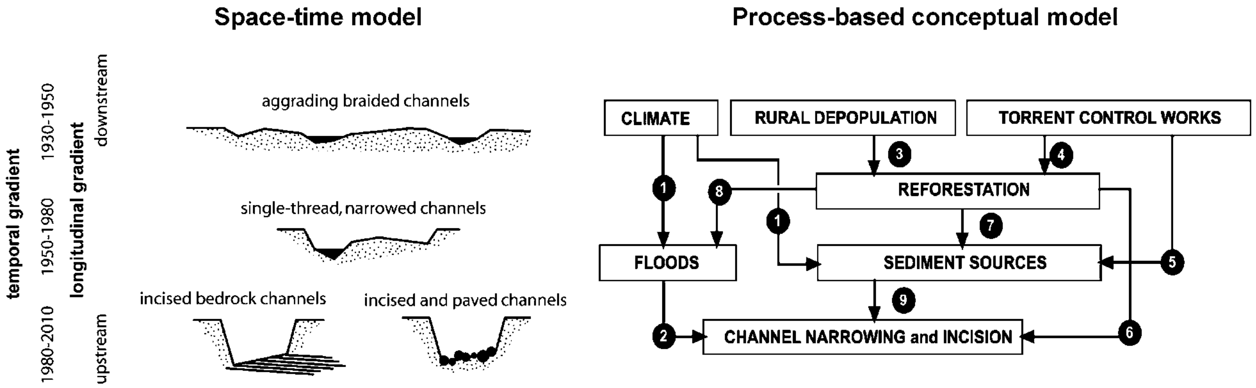

Figure 4. Space-time and causal, process-based models of adjustments between geomorphic channel stages observed in the catchment. The process-based model shows cascading responses among different factors explaining the observed adjustments. 1: Decreasing frequency and/or intensity of extreme rainfall events; 2: Decreasing frequency and/or intensity of channel-forming floods; 3: Spontaneous afforestation of hillslopes and valley floors due to the abandonment of agricultural uses; 4: Reforestation for soil conservation and construction of check-dams in steep headwater reaches; 6: Increasing the bank roughness and stability by riparian vegetation and decreasing peak flows; 9: Decreasing the sediment supply.

In addition, the water was seriously polluted by wastewater, garbage dumps, agricultural fertilizers, livestock manure, fish farming, three slaughterhouses located close to the rivers, plus seasonal activities from 40 wine cellars, which contributed sulphates, phosphates and potassium to the rivers (District d'Aménagement du Val de Drôme, 1999). The low flow condition in the summer together with an increase in tourism exacerbated the negative effects of these organic inputs on water quality. The microbial quality of the surface waters downstream from the urban areas was so low (Anonymous, 1996) that swimming was prohibited along 80% of the river's length.

At present, the Drôme River channel is incised along 75% of its course (Landon et al., 1995). Incision attains 5 m in some reaches and 2.9 m on average (1928 to 1995). This incision has winnowed the fine gravels from the river bed, forming a coarsely paved substrate in some areas. Along 6.5 % of its length, water flows directly over outcropped bedrock, where gravel has been washed away. In the upstream river network, most gravel bars disappeared between 1948 to 2001 (Fig. 5).

In the Drôme River catchment, sediment propagation has been estimated to be 500 m per year (Liébault, 2003), and the bedload transport is estimated to be 35,000 m^3 yr^{-1} on average (21 m^3 km^2 yr^{-1}). This is in contrast to most Mediterranean regime torrents flowing through marly landscapes, which usually have high sediment transport rates with many braided reaches. Still, the Drôme remains one of the last French alpine rivers without any large dams, with a largely natural hydrologic regime (except for downstream sections), and which is still capable of active fluvial dynamics.

This recent incision has negative consequences for river users. Many engineered structures built during the 19 century have been undermined. Some 7.5 km of dikes are damaged, which raises severe funding problems for the municipalities faced with new flooding problems. Among the 43 bridges along the Drôme River, three were destabilised in the late 1980s, and two others collapsed (Mirabel-et-Blacons in 1995 and Die in 2003). Many of the bridges crossing the tributaries near their confluences are protected from the regressive erosion by weirs, some of which continue to be undermined, whereas many others have been rebuilt at least once.

Although most river reaches are incising and narrowing, a few particular areas associated with landslides are still aggrading. Twelve landslides occurred during the 20 century in lithologically sensitive areas, with the last major slump in 1994 (Bez River). In the Upper Drôme, the formation of a natural dam by the Claps rockslide event in 1442 enabled the formation of a floodplain (Fig. 2) and continues to contribute to the aggradation of the upstream reaches near the Maravel confluence (1 cm yr^{-1} during 1928-1996) (Piégay et al., 2004).

Ecological consequences of bedload transport changes

From an ecological perspective, several conceptual models have described variations in biodiversity along fluvial corridors in relation to geomorphic processes and channel geometry (Petts and Amoros, 1993; Montgomery, 1999; Rice et al., 2001; Frothingham et al., 2002; Tockner et al., 2002; Woolsey et al., 2007). In general, structural diversity is considered critical to support biodiversity (Angermeier and Schlosser, 1989). However, few authors have described ecological responses to a bedload transport gradient within a catchment context.

In the Drôme catchment, channel types range from extremely incised with paved and bedrock substrates, to rapidly aggrading, braided gravel-beds. For each of these channel types, we evaluated biological diversity in response to geomorphic changes at two different scales. Alpha diversity is measured for the smaller habitat unit scale, and beta diversity is measured at the morphological, or reach scale (Fig. 6).

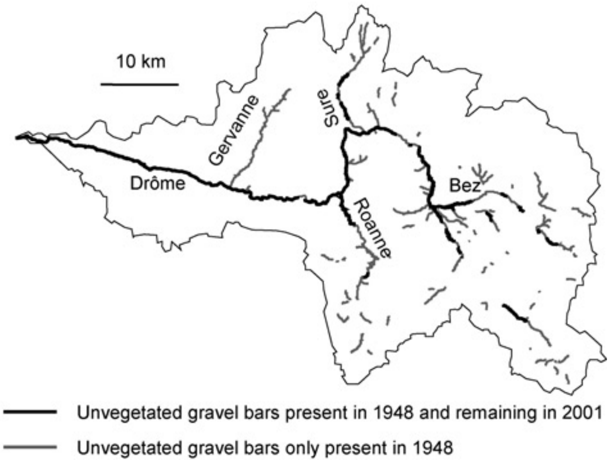

Figure 5. Comparison of the drainage network of the Drôme catchment characterised by a >20 m active channel width (e.g. unvegetated gravel bars and low flow channels) observed on 1:20,000 scale aerial photos of the *Institut Géographique National* in 1948 and 2001. The Gervanne, on the lower right side was a gravel contributor in 1948, but has completely disappeared in 2001. The Roanne, the Sure, as well as the Bez tributaries now only form wide gravel-bed rivers on their main channels, whereas in 1948 they formed an extensive network of active gravel-bed patterned streams.

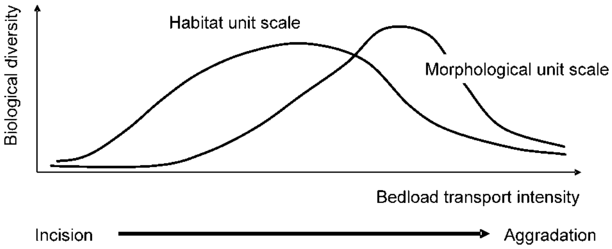

Figure 6. Conceptual ecological responses to change in bedload delivery at two scales: the morphological unit, or reach scale, which is related to beta diversity, and each habitat unit itself, which is related to alpha diversity. An optimal bedload transport for beta diversity would be higher than for alpha diversity. At both scales, extreme high and low bedload transport levels (i.e. extreme incision or aggradation) would have a negative effect on biodiversity.

At the scale of the habitat unit, species richness defines the alpha diversity. An active bedload transport leads to a relatively low aquatic biodiversity, compared to more stable channels. In braided channels, the limited water depth increases the risk of dry periods and leads to under-representation of pelagic species and adults of larger species (e.g. trout). The absence of ligneous vegetation along braided channels enables enormous daily temperature variations, eliminating the most sensitive stenothermic species.

In contrast, a moderate river incision favours local aquatic biodiversity. Water depth increases, deeper pools appear and mature riparian forests develop along channel banks, reducing diurnal temperature variation. As incision increases and fine sediments are winnowed from the substrate, large cobbles and boulders form a coarser, paved stream bed. Some hydraulic refuges are maintained, but the disappearance of sand and gravel substrate will tend to reduce invertebrate densities and spawning substrates for most fish species. A complete removal of bed material from the channel will clearly disadvantage all benthic species by eliminating porous substratum.

Within a given river reach, the diversity of aquatic and riparian habitats and the turnover of species between habitats determines beta diversity (Petts and Amoros, 1993; Ricklefs and Schluter, 1993). At larger scales, whole bed incision has negative impacts on biological communities (Bravard et al., 1999). Habitat diversity is reduced by the loss of secondary channels and sand and gravel bars, the disconnection of the aquatic floodplain, and a reduction in longitudinal and lateral connectivity within the river network, such as the excavation of bedrock steps and sills. Particularly strong impacts concern alluvial forests, hyporheic organisms, and fish species that spawn in gravels.

On the other hand, intense aggradation associated with morphodynamic instability also severely limits biodiversity. Surface flow often dries out during low flow periods and is only maintained within the bed sediment. A good example is the rivers of Northern New Zealand, where intense erosion of soft sandstones has led to extremely rapid aggradation, to the point that alluvial forests have been literally buried in sediments and permanent aquatic habitats have become rare (Page et al., 2000).

In summary, an increase in bedload transport would have a more pronounced positive effect on beta diversity than on alpha diversity (Fig. 6). From an ecological perspective, continuous but modest bedload transport intensity appears to be the optimal situation. In the Drôme, riparian tree species and bullhead fish demonstrate the need for balance between extreme aggradation and incision.

The Ash tree (*Fraxinus excelsior*) is the dominant riparian species in this area. When channels are incised, Ash is progressively replaced by *Pinus sylvestris*, a typical hillslope pine tree species, which is able to colonize the drier margins of the river. When channels incise to marl bedrock, the water table drops too low to support Ashes, resulting in high tree mortality. Inversely, in the rare reaches that are aggrading with an associated increase in floodplain inundation, Ash trees are greatly affected (Fig. 7), as demonstrated by the reduction in annual tree ring growth (Piégay et al., 2003).

A four year survey of bullhead populations, a benthic species dominating the fish assemblage in upstream reaches of the Drôme (Fig. 8), along a 12 km stretch in the Bez catchment shows that mean densities significantly decrease downstream from the confluence of the Boulc River where an active landslide considerably increases the sediment fluxes in the narrow valley. The bullhead has higher densities downstream following an increase of water flow and of the sediment layer stability. At the most downstream location, low bullhead density is related to local bed outcropping (Abdoli, 2005).

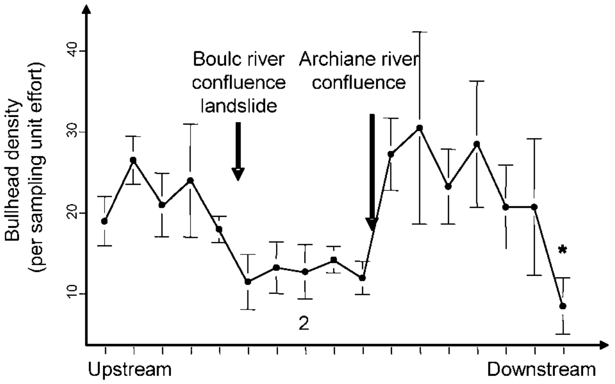

Figure 8. Density of bullhead *Cottus gobio* along a 12 km stretch in the Bez catchment upstream and downstream from the landslide of "Ravel et Ferrier" and the confluence of the Archiane River. Mean density values per sampling unit effort and confidence intervals are for the period 2002 to 2005. Each unit on the x-axis corresponds to a distance of 750 m. "*": local bed outcropping. The observed longitudinal pattern is not significantly correlated with changes in physical and thermal characteristics of the river.

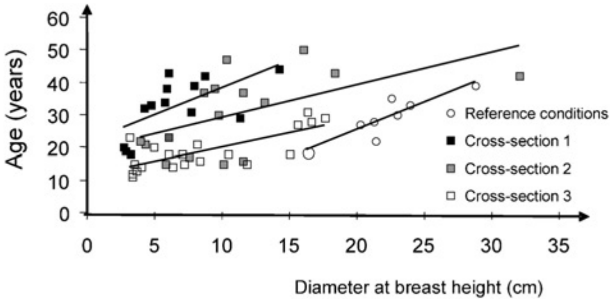

Figure 7. Variation of Ash tree (*Fraxinus excelsior*) growth. Ash tree ring survey done along three cross-sections along a gradient of aggradation intensity from cross-section 3 (mild) to cross-section 1 (severe). The Ash tree growth is compared with a reference reach where conditions did not change during the study period. The graph shows that the Ash growth is clearly influenced by changes in habitat conditions as compared to the reference site (modified from Piégay et al., 2003).

Local river management, protection of water resources, and the river incision problem

To improve the situation and implement a water policy at the basin scale, a partnership between local communities and the regional administration was established in the 1980s. This "River Contract," signed in 1990, provided state funding to local authorities to reduce water pollution and to restore and maintain the river banks and surrounding areas (District d'Aménagement du Val de Drôme, 1999).

To reduce water pollution, water treatment plants were built and slaughterhouses closed or brought up to standards and connected to wastewater treatment facilities (Anonymous, 1996). All the existing garbage dumps were closed and the sites rehabilitated. Recycling for household refuse was provided. Once a forsaken and polluted river, the water quality of the Drôme is today quite high, and residual concentrations of toxic substances are low (Richard-Mazet, 2005). Some problems of microbial pollution remain downstream from the towns of Chatillon and Luc-en-Diois (Anonymous, 2003). But generally, improvements to water quality and river landscapes have had a direct positive impact on tourism and leisure activities.

Unfortunately, the problem of river channel incision was not considered at that time. During the 1990s, despite increased concern and numerous complaints from both private landowners and municipalities regarding the effects of incision, only a handful of piecemeal local initiatives were implemented. At the catchment scale, there was no general consensus about how to handle the problem. Similarly, problems related to the drying of the downstream part of the Drôme River during summer also remained unsolved.

In 1992, the French Water Law introduced a procedure of participatory river-basin planning called the *Local Water Management Plan* (SAGE), which defines rules for the use, development and protection of water resources within medium sized catchments. SAGE plans are developed by a Local Water Commission (CLE), composed of local elected officials (half of the members), river users and non-profit associations (one fourth of the members), and governmental resource managers. In 1997, the Drome Water Management Plan was officially approved, giving priority to the two main remaining problems: river incision and summer water shortages (Allain, 2001; Piégay et al., 2002). This opportunity to bring together different stakeholders with conflicting views to debate these problems collectively gave hope that a common agreement could be reached.

During this period, the ministerial order of September 22, 1994 forbid any further sediment extraction from active river channels. Authorization for dredging could henceforth only be obtained to alleviate new flood risks caused by major floods in mountain river reaches or by landowners to regulate water courses and maintain the stability of the river banks.

To resolve downstream summer water shortages, several guidelines were created to manage water stocks. River water abstraction for irrigation was restricted to its 1995 level. A minimum flow rate of 1 to 10% of the mean annual discharge of the Drôme River was established for the reaches downstream of the irrigated zone. Water abstraction from aquifers was reduced by 800,000 m^3y^{-1}, and a downstream weir was constructed to raise the aquifer water level. Most of these recommendations have been put into practice, but there are still conflicts during the summers when water availability is limited.

Concerning the incision problem, CLE members viewed sediment issues from different perspectives (Allain et al., 2005). Several downstream authorities were troubled by the risk of further incision, while upstream authorities were anxious about increased flood risks in places where river beds were actively aggrading. The CLE Executive Board decided to implement several mid-term projects in order to convince reluctant stakeholders of the importance of a catchment-scale sediment management plan (Allain, 2004). Instead of simply requesting scientific proposals of technical solutions (Landon et al., 1995), this process allowed for the development of locally-relevant measures such as the preservation of in-channel sediment storage areas, the creation of a catchment-scale monitoring system to track the evolution of the river beds, and experiments to evaluate the efficiency of various techniques.

Nevertheless, most of the measures remained local and it was not possible to find a general agreement between CLE members regarding a long-term, watershed-scale solution to the replenishment of incised river reaches. Our interdisciplinary project aimed to further this stakeholder-based, consensus-building process by describing technical solutions and their legal feasibility, and by providing an objective functional typology and map of incised reaches and potential sediment sources that could be used to holistically manage these issues.

Technical options for the replenishment of degraded reaches

Since the 1990s, several experimental techniques have been applied to replenish sediment to identified target reaches in the Drôme catchment (Landon, 2000). The goal of these activities has been to stop and, when possible, reverse the incision process by increasing the sediment supply at a rate that exceeds the transport capacity of a reach. On principle, channel incision might be stopped or slowed down not only by increasing the bed material supply, but also by reducing the channel's transport capacity by widening it. However, in practice, channel widening is only possible in reaches not constrained by natural hillslopes or man-made infrastructure close to the channel.

One project transferred gravels extracted from an artificial sediment trap in the lower Drôme River, near its confluence with the Rhône River, to protect undermined embankments and replenish sediments in upstream target reaches. Two gravel traps were constructed near the Maravel confluence as overflow channels during flood events. Every one to two years, gravels are excavated from these traps, generally after high spring floods. The main advantage of this solution was its immediate geomorphic effect on the river channel, while the main disadvantage was the immediate negative ecological impact of large volumes of gravels dumped into the river. Additional drawbacks were the associated truck traffic on small rural roads, the high cost, and a preference by local authorities to use the gravels collected by the sediment trap for road maintenance and construction needs.

Two other projects used the river to transport the sediment, instead of a truck. In the first, hard rock materials were placed directly in the Boulc Torrent in the Bez River sub-catchment, to replenish recently eroded areas. This operation provided temporary protection of agricultural lands threatened by bank erosion and an increased sediment supply to the degraded reaches of the torrent. The second project increased the sediment mobility in aggraded reaches by excavating remobilisation trenches and cutting vegetation established on gravel bars. This increased the shear stress and decreased the gravel bars' resistance to erosion. This kind of action, easy to implement, has been largely used by local river managers because it satisfies two different management issues: the dredging of aggrading reaches and the replenishment of incised reaches. Nevertheless, the efficiency of this technique is variable and highly dependent on local river geometry.

A fourth potential strategy could be the removal or lowering of old check dams built in the 19 century along small high-gradient tributaries, as most of the lands they protect are no longer of any agricultural value. But this option has never been tested because most of these old check-dams have been destabilised by successive floods and are located too far from incised reaches to be efficient as a sediment source for target reaches.

A fifth much more attractive option would be to reactivate wooded sediment stores located in the vicinity of target reaches by cutting forests established on hillslopes, gullies, or alluvial terraces along river channels. An experiment was begun in 2005 to measure the potential sediment contribution of forest removal near target reaches in the Drôme basin. Two experimental sites were established to gather baseline data on sediment contributions from forested gullies and alluvial terraces. After a calibration period, a part of each experimental site was deforested and the increase of sediment supply will be evaluated using coarse sediment traps located downstream. An analysis of the geomorphic effect of deforestation will be possible after substantial flood events.

The legal feasibility of the technical options

Until recently, the aim of the French legislation related to sediment management was only to provide a basis for land restoration by promoting the reduction of soil erosion, channel aggradation and its associated flooding risk. Today, it is recognized that the lack of land erosion appears to have negative impacts on rivers (i.e. incision). Fifteen years ago, new laws were passed that promoted the maintenance of a moderate level of erosion to counteract river bed incision and to preserve free laterally shifting water courses (Piégay et al., 2005). Nevertheless, it is obvious that contradictory tendencies now exist in French law regarding sediment management.

From a legal point of view, some of the proposed technical options for replenishment of target reaches are more feasible than others. For example, reactivating sediment stocks located near or within the fluvial corridor by increasing the mobility of a river channel is now legal (decree of 30 February 2002 and act of 30 July 2003). This legislation makes it possible to maintain or recreate fluvial dynamics in particular reaches of general public interest. In these designated areas, nothing can be done or built that could interfere with the watercourse shifting, and the owners of the areas must be indemnified for damages caused by these dynamics (e.g. a local increase in flooding and related land loss).

The feasibility of mobilisation of sediment stocks by hillslope deforestation is a function of the juridical status of the forest lands, in particular for private forests. However, the act of 30 July 2003, related to natural risk prevention, could be used to force private owners to clear their forests. This act could also support the destruction of check-dams.

On the other hand, solutions involving the artificial transfer of sediments from reaches with excess sediment to incising river reaches could be problematic. In general, the law forbids the extraction of sediment from the active channel or any modification of the water course, with the exception of mitigating high flood risks. Moreover, each injection of sediment into an incised river reach must be authorized by the government. Furthermore, local biodiversity must not be affected when the reach is classified of great ecological interest. In all cases, the fish fauna and its relevant habitat must not be altered.

Proposed framework for a sediment management plan

An integrative, spatially based functional typology

In order to create a map of target restoration reaches and potential sediment sources, the preceeding geomorphic and ecological reviews were combined to establish a functional typology for the Drôme River network. In this typology, we categorized two catchment types: three reach types in high gradient headwaters, and four reach types in alluvial floodplains farther downstream (Fig. 9).

The two catchment types reflect the ability of slopes to deliver sediment to the stream as a function of geological conditions, geomorphic heritage, and current land uses. The active landslide catchment type contains actively eroding landscapes, which contribute substantial sediment fluxes to the river. The afforested landscape catchment type contains more stable, tree-covered landscapes.

In the headwaters, three reach types were distinguished, all with narrow floodplains due to the river slope and valley morphology. The first is associated with the active landslide catchment type, and the second and third result from catchments with afforested landscapes. The channels of aggrading, type A or gravel bar reaches flow through mobile and unstable gravel-beds. In incised type B reaches, the slope lithology and grain size of the pre-existing sediment deposits allow for the maintenance of a paved bed channel. In incised reach type C, pre-existing valley bottom deposits are thin, and the underlying limestone bedrock has been completely excavated creating an outcropped substrate, which allows groundwater to drain directly into the river. In upstream gorges, the river often flows directly on bedrock,

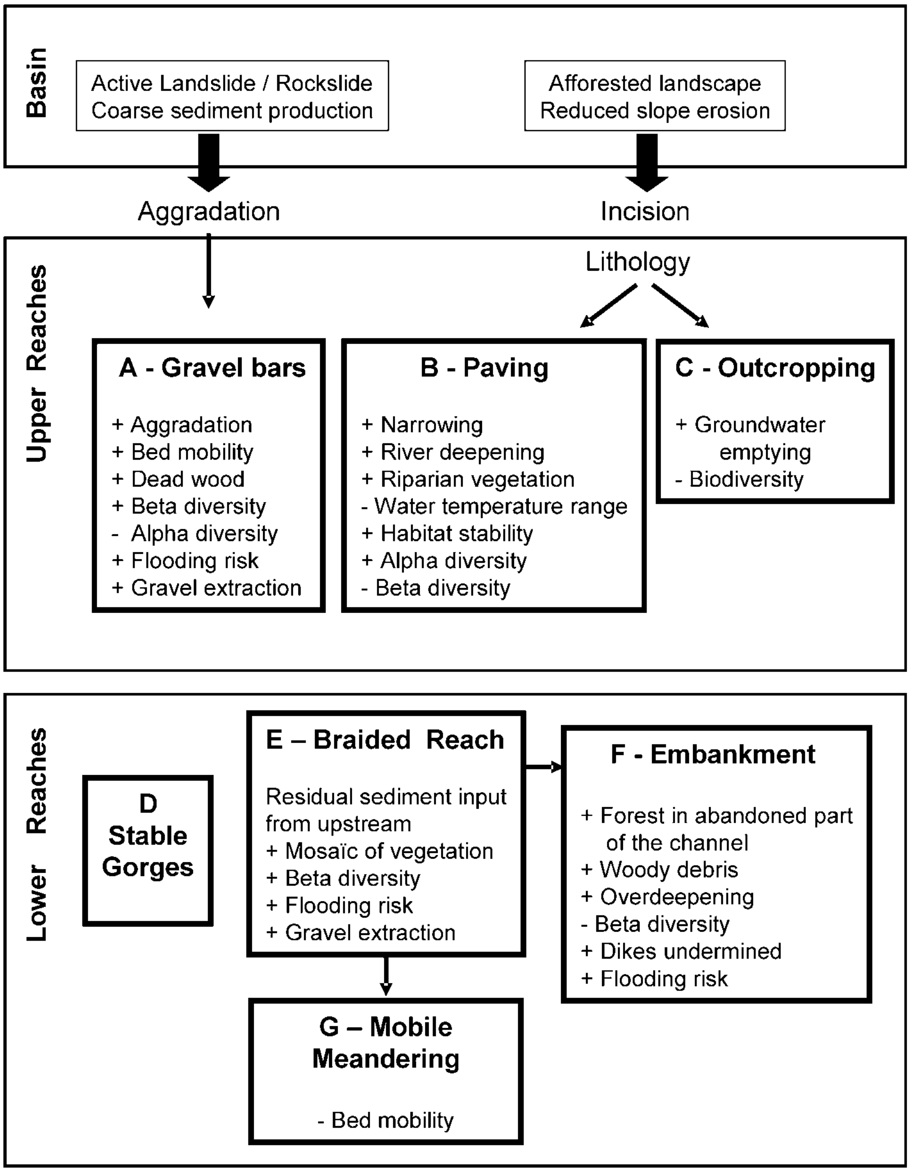

Figure 9. Conceptual model of the river system's geomorphic and ecological responses to local changes in bedload delivery in upstream and downstream reaches. +: increase; -: decrease.

whereas further downstream bed outcrops are less frequent as the sedimentary stocks increase. Reaches in gorges downstream (reach type D) are less sensitive to changes in channel geometry and cause geomorphic pattern discontinuity.

In the downstream alluvial floodplains, high levels of sediment transport in the past caused river bed aggradation, forming a braided pattern with several active channels migrating laterally and side-channels and oxbows along the margins of the floodplain (reach type E). Where embankments have been constructed along downstream reaches in the lowest section of the Drôme River, early signs of response to reduced bedload transport are manifested by channel deepening (type F), but the channels remain relatively mobile. With channel incision, dikes and other engineering structures are undermined and there is greater risk of dike breakage during high flow conditions. In a more advanced stage of adjustment, channels will become more stable and less mobile, constrained to the deepened central part of the streamway. Forests will develop on the lateral margins of the formerly active floodplains within the diked area. The greatest flood risks are then associated with flows that overtop the dikes.

The reduction of coarse sediment delivery over the past century has resulted in a channel metamorphosis (Marston et al., 1995); i.e. a progressive shift from a braided pattern towards a mobile meandering pattern (reach type G) wherein the mobility of the river is maintained across the streambed but with only one main channel. Responses in the headwaters to the reduction of the bedload input are already apparent, whereas the lower reaches are still adjusting and we can expect that most of the reaches of type E will shift to reach type G in the next decades. Exceptions will occur where type E reaches are located just downstream of type A reaches and thus still receive substantial sediment inputs.

A general ecological response to bedload transport change can be described for each reach type (Fig. 9). In upstream aggrading reach type A, alpha diversity is reduced due to instability but beta diversity is relatively high when the valley form allows the presence of secondary channels. In incised, but paved type B reaches, a reduction in bedload transport reduces beta diversity but can favour alpha diversity in association with a stable narrow channel. In the case of the outcropped reach type C, ecological conditions for aquatic fauna are poor. In the lower reaches, beta diversity is high in reach type E (floodplain). Reducing the river mobility (types F and G) will reduce the biodiversity at the floodplain scale (beta diversity), but can increase the channel stability and thus alpha diversity.

This functional typology allows human uses to be related to each reach type (District d'Aménagement du Val de Drôme, 1999; Landon and Piégay, 1999; Piégay et al., 2002). The transformation of the previously agricultural open mountain meadows to a more homogenous, forested landscape may be responsible for the Drôme catchment's increased attractiveness for tourists. In the upstream areas when the water depth is sufficient, reach type B is attractive for fishing, hiking, and canoeing, and reach type C is popular for swimming in water that flows directly over limestone bedrock. Downstream, reach type G is often more attractive for bathing and canoeing than reach type E, as summer water flow is concentrated in a single channel. Agriculture remains important in floodplains associated with stabilized past rockslides (type G). Type F is associated with irrigated agriculture in drained lowlands, urbanization, and a significant flooding risk. Areas with high sediment delivery rates (types A and E) are the highest flood risk zones. Reach type E is also associated with previously important economic activities such as grazing, wicker production, and gravel extraction.

The spatial distribution of the reach types is complex as shown in the examples of the Bez and the Upper Drôme catchments (Fig. 10). After mapping the river reach types for each catchment, target reaches were identified as those containing severely undermined in-channel infrastructure or channel incision greater than 2 m. Next, the potential for bedload supply to the target incised reaches from nearby or upstream sediment sources, such as actively eroding hillslopes, was evaluated. The "bedload supply potential" of each sediment source in relation to a given target reach was calculated using GIS (Liébault et al., 2008) by considering i) the lithological characteristics of the rocks and of the superficial deposits affected by the erosion processes, ii) the distance to the target reach as a proxy to roughly evaluate the capacity of the source to deliver sediment to the target reach in less than 50 years, and iii) precautions to prevent increased flood risks or geomorphic hazards to existing infrastructure. Such maps (Fig. 11) can now serve as tools to help managers to identify the areas where erosion should be preserved or exacerbated for the replenishment of sediments to incised downstream reaches.

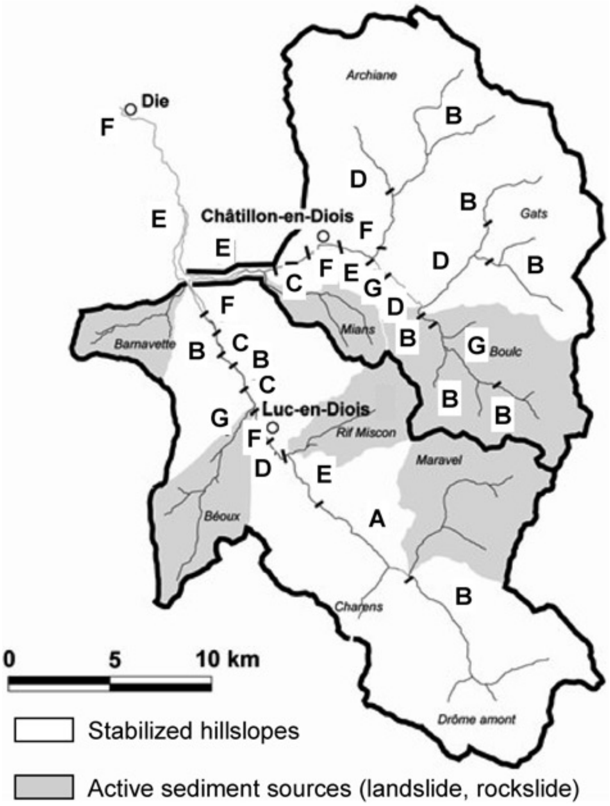

Figure 10. Distribution of channel reaches in the upper Drôme catchment. Afforested catchments are the most frequent, whereas sediment source areas are less numerous and smaller in size. Almost all of the channel types with a well-developed reach type E at the confluence of the Bez and the Drôme are moving to a reach type G downstream. Some type D and F reaches are also observed locally. A few type A reaches occur slightly upstream, connected to landslide areas, but there are mostly type B reaches with more occasional and short type C reaches.

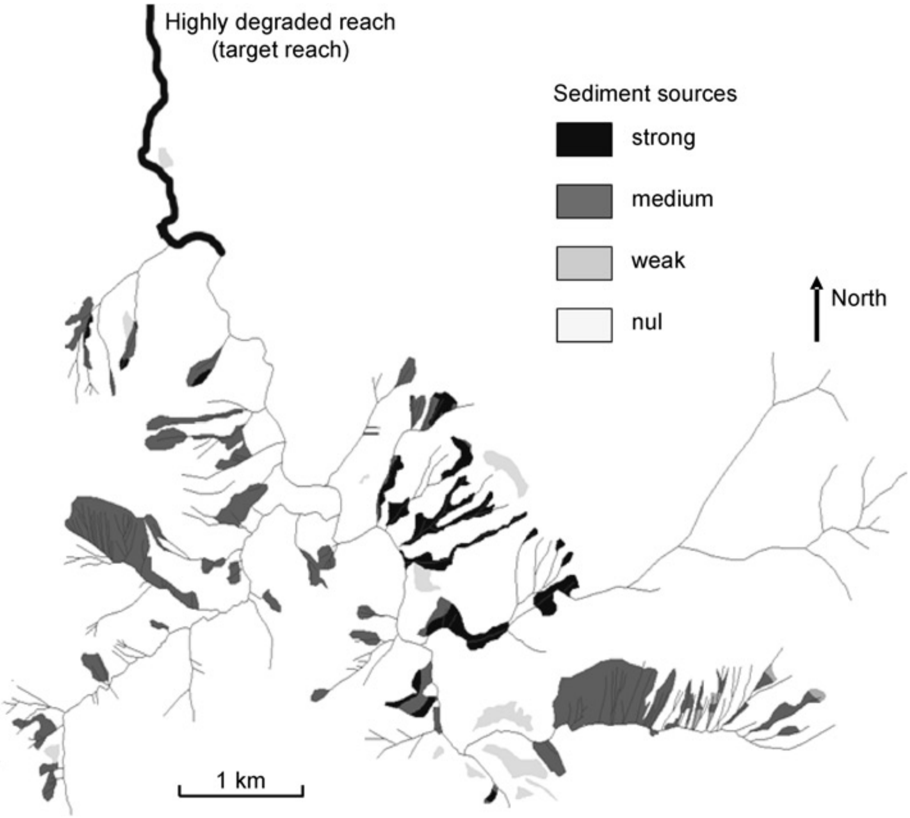

Figure 11. Excerpt from a map of the sediment sources that could be reactivated for artificial bedload re-feeding: the Roanne catchment, a tributary to the Drôme River (Modified from Liébault et al., 2008). Note the target incised reach in the downstream part of the catchment and the sources of sediment classified according to their ability to supply sediment to the target reach. The rules used to identify and characterize areas are given in the text.

Discussion

The accelerated channel incision of the Drôme River along most of its course during the 1970s and 1980s has led scientists and managers to work together to develop and promote a basin-scale sediment management strategy. Based on a comprehensive analysis of the long term geomorphic trajectory and ecological responses in the Drôme River caused by changes in bedload transport, we developed a spatially-based, functional typology of the river network. Seven main reach types were distinguished, each one characterized in term of local fluvial dynamics, stability, flooding risk, impacts on infrastructure, and general aquatic biodiversity and riparian vegetation. One of our main conclusions is that an intermediate state between incision and aggradation is a good compromise for aquatic biodiversity and riparian vegetation. Bravard et al. (1997; 1999) and Kondolf (2000) also described the ecological responses to river incision processes and underlined the importance of such an intermediate response. More generally, this conclusion concurs with the intermediate disturbance hypothesis (Connell, 1978) and the Patch Dynamic Concept (Townsend, 1989). Aggradation tends to enlarge the floodplain and to increase the habitat diversity via secondary channels and their associated beta diversity (Petts and Amoros, 1993), whereas incision increases stability at a more local, habitat unit scale and supports greater alpha diversity. Depending on the different floral or faunal elements (e.g. riparian versus terrestrial invertebrates), aggradation or incision could be more or less favourable. Thus, preserving a good mix of sediment regimes at the catchment scale, but excluding the extreme situations, would favour total (gamma) biodiversity and remain acceptable for stakeholders and managers.

Due to the complexity of bedload transport and all its consequences in space and time, it has been difficult for scientists and engineers to predict future scenarios without large uncertainties. Nevertheless, the historical and spatial analysis of the phenomena allow us to conclude that the general narrowing and incision of the Drôme River will continue in the future, propagating downstream as a function of sediment delivery decrease and disconnection between the sediment sources and the channel network. The intensity of degradation may be strongly reduced, due to the prohibition of gravel extraction from the river channel in 1992, but the channel will continue to adjust at a highly variable rate. Instead of presenting uncertain quantitative predictions, we used a functional typology to create a spatial description of the processes acting in this river network, which was used to target highly degraded reaches, identify present-day and potential bedload supplies, and to propose acceptable technical solutions.

The analysis of river management over the past 20 years demonstrates the difficulties of solving problems linked to bedload transport, as compared with those linked to water resource management. A voluntary agreement between all the stakeholders to improve water quality was easily agreed upon in the late 1980s and an additional 10 years were needed to solve some of the conflicts surrounding water use during summer droughts. It was only quite recently that the Local Water Commission began to address issues of channel incision and aggradation through the development of a sediment management plan.

Because channel geomorphology changes downstream, geomorphic and ecological responses and social consequences vary across a drainage network (Brierley and Fryirs, 2005). In addition, natural and anthropic factors continue to affect the evolution of bedload transport and the associated adjustments of the river channel, which makes it difficult to pinpoint the main causes (Liebault et al., 2005). This is why residents and river managers often do not perceive general trends in bed form changes until major problems arise and then cannot easily find consensus. Decision-makers generally focus on solving short-term problems, not on issues with long-term causes and solutions over longer time horizons.

In such a context, the idea of replenishment of incised river reaches does not receive a lot of attention from managers. Most local managers consider gravels and pebbles as a traditional resource for the maintenance of roads and construction. Similarly and regardless of recent changes in French law, local representatives from different ministries continued for years to defend quarrying interests and a traditional exploitation-based relationship with the river. Even today, French sediment management laws present contradictory counsel by supporting erosion protection for the reduction of flooding risk while promoting a moderate bedload transport to preserve free laterally shifting water courses.

Because of the complexity of the physical processes involved in technical reach replenishment techniques and their innovative character, the development of a sediment management plan involves a variety of participants and can lead to many regulatory permits that require state approval. In the Drôme, the next step is to develop relationships between forest and water managers and to encourage greater involvement by the downstream local authority in the Local Water commission. Thanks to the efforts of many, river reach replenishment is no longer considered a “theoretical” issue by the local stakeholders, but is now drawing attention from river managers.

Conclusion

The functional typology we propose in this paper is a preliminary one and can be improved in the future by quantifying the rates of aggradation and incision and analysing the ecological and land use responses to these processes in greater detail. It is also a tool that can be used by scientists and managers to improve our understanding of bedload transport issues at the catchment level. This last point is essential because the situation in each reach depends on the next reach upstream and, ultimately, on the whole upstream drainage catchment. A comprehensive view of the situation at the catchment level will promote the necessary solidarity between all partners to reach a common agreement and to approve a sediment management plan.

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