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Théo Bulteau

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Dynamique et discontinuité hydro-morpho-sédimentaire d'un continuum fluvial, le cas de la Garonne Amont

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SUMMARY

Since the beginning of the 20th century, numerous natural and human disturbances have profoundly affected the Upper Garonne (Central Pyrenees) hydro-sedimentary regime, resulting in multiple ecosystem services losses. Prior to potential actions that would tend at past degradation resorption and current pressures impacts limitation, the work conducted in this PhD aims at achieving a robust diagnosis of the Upper Garonne hydro-sedimentary functioning at multiple spatial and temporal imbricated scales. To conduct this diagnosis, historical data were collected and re-interpreted, afterwards coupled with an experimental geomorphology approach in order to better understand current river functioning, and notably the interactions between sediment transport, flood regime, and dams.

The historical approach allowed for a detailed characterisation of river morphological trajectory, consisting mainly in channel planform simplification, bed incision, and coarsening. This response, very common in European mountainous hydrosystems, is nevertheless very contrasted depending on given sub-reaches. Each sub-reach adjusted differently, according to (1) its initial conditions, and (2) the nature, magnitude, and temporality of anthropisation factors which overlapped with natural evolution.

The experimental approach has notably shed light on the role of the Plan d'Arem dam in overall observed degradations. From one side, we show its contribution in disturbing hydro-sedimentary dynamics since its construction in 1970, but from the other, we state on the real efficiency of the current management in restoring natural flood hydrology and preserving minimal sediment transport, resulting in good functionality of the downstream reach despite the presence of the dam.

The structural sediment deficit of the uppermost catchment, associated with a relatively natural flood hydrology downstream from the set of dams, are likely to induce inevitable degradation of current state and return to conditions similar to the ones before the 100-yr flood occurred in June 2013, if no actions are taken in favour of sustainable sediment management. Therefore, a first management scenario relies on the preservation of all sediment inputs from the upper catchment, the optimisation of Plan d'Arem dam management to parsimoniously route the sediments stored within the reservoir, and the re-injection of sediments stored within check-dams of the Upper Pique catchment. Once these levers exhausted, new sediment sources will have to be identified and quantified to assess their potential for buffering sediment deficit of the whole catchment.

RÉSUMÉ

Au cours du 20^{ème} siècle, de nombreux changements d'origine naturelle et anthropique ont profondément modifié le régime hydro-sédimentaire de la Garonne amont (Pyrénées Centrales), et engendré de multiples pertes de services écosystémiques. Afin de proposer d'éventuelles mesures visant à résorber les dégâts déjà causés et à limiter l'impact des pressions actuelles, ce travail de thèse a pour objectif d'établir un diagnostic du fonctionnement hydro-sédimentaire de la Garonne amont, à plusieurs échelles spatio-temporelles imbriquées. Pour conduire ce diagnostic, des données historiques ont été collectées et ré-interprétées, puis couplées à une approche de géomorphologie expérimentale visant à mieux comprendre le fonctionnement actuel du cours d'eau et notamment les interactions entre flux solides, flux liquides, et barrages, à partir notamment de techniques RFID et de suivi du remplissage interstitiel couplé à une acquisition thermographique aéroportée.

L'approche historique a permis de mettre en évidence la simplification du tracé en plan du cours d'eau, son incision, et le développement d'un pavage de surface sur les secteurs en aval immédiat des barrages. Cette réponse morphologique classiquement observée dans les hydrosystèmes intra-montagnards en Europe est cependant très contrastée selon les secteurs. Chaque sous-tronçon a connu une trajectoire spécifique, fonction de (1) son potentiel initial d'ajustement, (2) la nature, l'intensité, et la temporalité des pressions anthropiques qui sont venus se superposer aux changements naturels.

L'approche expérimentale a notamment permis de lever le voile sur le rôle du barrage du Plan d'Arem dans les dégradations observées. Nous avons ainsi pu mettre en évidence son rôle de perturbateur des flux hydro-sédimentaires entre sa construction en 1970, mais également l'efficacité de son mode de gestion actuelle pour restaurer une hydrologie de crue naturelle et préserver un transit sédimentaire fonctionnel, avec *in fine* un secteur aval aujourd'hui très fonctionnel malgré la présence du barrage.

Le déficit sédimentaire structurel du bassin amont, couplé à une hydrologie de crue préservée en aval des différents barrages espagnols et français, tendent aujourd'hui à induire une inéluctable dégradation et un retour à des conditions dégradées similaires aux conditions antérieures à la crue centennale du juin 2013 si aucune action n'est entreprise en faveur d'une gestion patrimoniale des apports sédimentaires. Un premier scénario de gestion pointe donc vers l'arrêt de toute forme d'extractions de matériaux en amont du Plan d'Arem, l'optimisation de la gestion du Plan d'Arem afin que les sédiments stockés dans la retenue tamponnent le déficit amont le plus longtemps possible, et la ré-injection des matériaux stockés dans les ouvrages de correction torrentiels de la Pique amont. Une fois ces leviers épuisés, il s'agira d'identifier de nouvelles sources de sédiments et de quantifier leur pouvoir tampon vis-à-vis du déficit.

RESUM

Des de principi del segle XX, el règim hidrosedimentari de l'Alta Garona (Pirineu Central) s'ha vist alterat per diverses pertorbacions naturals i antròpiques, donant lloc a la pèrdua de nombrosos serveis ecosistèmics. Com a pas previ a la implementació d'accions per revertir la degradació passada del medi fluvial i limitar les pressions actuals, el treball realitzat en aquest doctorat té com a objectiu realitzar un diagnòstic sòlid del funcionament hidrosedimentari de l'Alta Garona a múltiples escales espacials i temporals. Per a dur a terme aquest diagnòstic, s'han obtingut i reinterpretat dades històriques, que després s'han combinat amb un enfocament de geomorfologia experimental per tal d'entendre millor el funcionament actual del riu, i sobretot de les interaccions entre el transport de sediments, el règim fluvial (riuades) i les preses.

L'enfocament històric ha permès una caracterització detallada de la trajectòria morfològica del riu, que ha consistit principalment en la simplificació de la forma de la llera, combinat amb incisió i cuirassament. Aquesta resposta, molt freqüent en conques de drenatge de muntanya europees, és tanmateix diversa segons els sectors fluvials estudiats. Cada sector s'ha anat ajustant de manera diferent, segons (1) les seves condicions inicials i (2) la naturalesa, la magnitud i la temporalitat dels impactes antròpics, que s'han anat solapant amb l'evolució natural del riu.

L'enfocament experimental ha aportat nou coneixement sobre el paper de la presa de Plan d'Arem en el conjunt d'impactes observats. D'una banda, el treball mostra el paper de la presa en la degradació de la dinàmica hidrosedimentària del riu des de la seva construcció el 1970; però per altra banda, és important remarcar l'eficàcia de la gestió actual a l'hora de preservar la hidrologia natural de les riuades i assegurar una mínima transferència de sediments, que es tradueix en una bona funcionalitat del tram aigües avall malgrat la presència de la presa.

El dèficit estructural de sediments de la capçalera de la conca, associat a un règim de riuades relativament natural aigües avall, és probable que porti a una degradació continuada de l'estat actual del riu i el torni a condicions similars a les anteriors a la inundació de 100 anys de juny de 2013, si no es porten a terme accions destinades a una gestió més sostenible dels sediments. Per tant, un primer escenari de gestió es basa en la preservació de totes les aportacions de sediments des de la capçalera de la conca, l'optimització de la gestió de la presa del Plan d'Arem per transferir progressivament els sediments emmagatzemats dins de l'embassament, i la re-injecció de sediments retinguts als dies de la capçalera de l'Alt Pique. Un cop exhaurides aquestes fonts, caldrà identificar i quantificar noves fonts de materials per avaluar el seu potencial d'esmoreir el dèficit de sediments del conjunt de la conca.

RESUMEN

Desde principios del siglo XX, el régimen hidrosedimentario del Alto Garona (Pirineo Central) se ha visto alterado por diversas perturbaciones naturales y antrópicas, dando lugar a la pérdida de numerosos servicios ecosistémicos. Como paso previo a la implementación de acciones para revertir la degradación pasada del medio fluvial y limitar las presiones actuales, el trabajo realizado en este doctorado tiene como objetivo realizar un diagnóstico sólido del funcionamiento hidrosedimentario del Alto Garona a múltiples escalas espaciales y temporales. Para llevar a cabo este diagnóstico, se han obtenido y reinterpretado datos históricos, que después se han combinado con un enfoque de geomorfología experimental para entender mejor el funcionamiento actual del río, y sobre todo de las interacciones entre el transporte de sedimentos, el régimen fluvial (crecidas) y las presas.

El enfoque histórico ha permitido una caracterización detallada de la trayectoria morfológica del río, que ha consistido principalmente en la simplificación de la forma del cauce, combinado con incisión y acorazamiento. Esta respuesta, muy frecuente en cuencas de drenaje de montaña europeas, es sin embargo diversa según el sector fluvial estudiado. Cada sector se ha ido ajustando de forma diferente, según (1) sus condiciones iniciales y (2) la naturaleza, magnitud y temporalidad de los impactos antrópicos, que se han ido solapando con la evolución natural del río.

El enfoque experimental ha aportado nuevo conocimiento sobre el papel de la presa de Plan de Arem en el conjunto de impactos observados. Por un lado, el trabajo muestra el papel de la presa en la degradación de la dinámica hidrosedimentaria del río desde su construcción en 1970; pero, por otro, es importante remarcar la eficacia de la gestión actual a la hora de preservar la hidrología natural de las riadas y asegurar una mínima transferencia de sedimentos, que se traduce en una buena funcionalidad del tramo aguas abajo, pese a la presencia de la presa.

El déficit estructural de sedimentos de la cabecera de la cuenca, asociado a un régimen de crecidas relativamente natural aguas abajo, es probable que lleve a una degradación continuada del estado actual del río y lo vuelva a condiciones similares a las anteriores a la inundación de 100 años de 2013, si no se llevan a cabo acciones destinadas a una gestión más sostenible de los sedimentos. Por tanto, un primer escenario de gestión se basa en la preservación de todas las aportaciones de sedimentos desde la cabecera de la cuenca, la optimización de la gestión de la presa del Plan de Arem para transferir progresivamente los sedimentos almacenados dentro del embalse, y la reinyección de sedimentos retenidos en los diques de la cabecera del Alto Pique. Una vez agotadas estas fuentes, será necesario identificar y cuantificar nuevas fuentes de materiales para evaluar su potencial de reducir el déficit de sedimentos del conjunto de la cuenca.

GENERAL INTRODUCTION

Since the second half of the 20th century, the Upper Garonne (Central Pyrenees, Spain – France) has been subjected to growing watershed and river network anthropisation, largely affecting river ecology (Bosc *et al.*, 2012; Coll *et al.*, 2016). Catchment-scale land use changes occurred, consisting mainly in hillslopes afforestation, while economic activities drifted from traditional, extensive, grazing-based agriculture to industry and tourism. During the same period, the need to prevent natural hazards led to the construction of in-stream torrential control structures in the upper basin, and channelisation of natural channel within the valley bottom. The Spanish part of the catchment has been marked by important hydroelectricity production activities relying on a series of dams (1955 – 1965), penstock pipes and hydropower plants, generating frequent discharge fluctuations, called ‘hydropeaks’. In order to laminate those hydropeaks and warrant sufficient water supply to feed downstream hydropower plants, the construction of the Plan d’Arem run-of-river dam (RoR, France) was decided and achieved in 1970. Regrettably, the water storage capacity of this dam decreased rapidly after construction due to important sediment inputs from its catchment, drastically decreasing its lamination potential. After the extreme flood of June 18th 2013, that achieved to fill the reservoir with sediments, an emergency dredging was carried out to rapidly restore a sufficient capacity, which remains only half the initial capacity. Since then, systematic drawdown flushing actions are operated during floods, with the aim of, at least maintaining its current capacity and potentially restoring its initial water storage capacity.

Consequently to the flood, which severely damaged habitations and infrastructures, a regional project of integrated management was launched, in order to conciliate ecosystem functioning, hydropower generation and security of assets and people. Despite the large number of technical reports commissioned or produced by different actors implied in this project, dealing with some specific aspects of the Upper Garonne hydro-sedimentary dynamics, those reports are marked by strong heterogeneity, both in terms of methods and spatio-temporal resolution. Furthermore, the complexity of the local context, in relation with the multiplicity of human pressures and transboundary river management, confused previous diagnoses and thwarted the possibility to design restoration actions that aligned with actors that were effectively responsible for river degradation. Crucial needs for quantified and spatialised catchment-scale knowledge on hydro-sedimentary dynamics then emerged to further value this information from an operational perspective.

The project was first initiated in 2018 by the post-doctoral work of Mélodie David (David, 2018) who conducted a synthesis of existing literature on the Upper Garonne hydro-sedimentary dynamics and highlighted the following knowledge requirements.

(1) In the Spanish part of the catchment, sediment supply and its potential alterations by hydropower generation remain unquantified. As this area theoretically produces most of sediments supplied to the downstream system, a better characterisation of spatio-temporal patterns of river evolution and current sediment dynamics has to be achieved to relate upstream supply and Plan d'Arem reservoir sediment infilling, and to identify continuity disruptions.

(2) Bathymetric measurements conducted on the Plan d'Arem reservoir since 1997 shed some light on the general kinetic of sediment infilling. However, some more investigations are needed, to more finely understand the sediment response to drawdown flushing actions, both in terms of suspended load potentially at the source of riverbed clogging downstream, and bedload, notably spawning gravel size-classes.

(3) Downstream from the dam, local stakeholders have highlighted significant improvements of fish habitats after the 2013 flood, and generally agreed to consider this flood as a significant reset from previously degraded, sediment-starved, and rather clogged fluvial environment. Nevertheless, the heterogeneity of measurement protocol for riverbed clogging assessment that were deployed consecutive to the flood prevents a finer understanding of the incidence of systematic drawdown flushing actions on the hyporheic compartment. A more general question also arises regarding the progressive attenuation of post-flood benefits and the future evolution of the system.

Therefore, achieving a good understanding of the current position of the Upper Garonne river system within a broader spatial and temporal context, and how it responds to natural events, dam management and potential improvement in management procedures which may be implemented in the future, is the cornerstone for further discussions on sediment management practices that is least impacting, and potentially bringing benefits, for aquatic ecosystems and human activities.

From the applied question of sediment management on the Upper Garonne arises a set of more general **scientific challenges**. On the one hand, scientific method in fluvial geomorphology has often implied fairly inductive approaches which do not always allow to establish causal connections, because the parameters potentially conducting to a given situation are numerous within a given reach. For this reason, a shift from inductive to more hypothetico-deductive approaches is a major issue in fluvial geomorphology (Downs & Piégay, 2019), both scientifically (i.e. to better characterise the respective roles of spatially and temporally concomitant factors) and operationally (i.e. to better assess the recovery potential of a degraded river reach and design actions that comply with this objective). On the other hand, the Upper Garonne reach offers a unique opportunity to study the effects of RoR dams within a multi-driver context. Indeed, if the effects of large dams and reservoirs on hydrology, sediment disruptions and downstream biogeomorphic changes has been subjected to a number of studies, much less is known on the effects RoR dams. Furthermore, and to the best of my knowledge, their effects were mostly evaluated remotely (Ibáñez *et al.*, 2013), and through computational approaches (Dépret *et al.*, 2019; Vázquez-Tarrío *et al.*, 2019), but no attempt was made to link those results with field-based approaches. Even less studied is the assessment of the effects on downstream sediment dynamics of any type of flushing actions operated on RoR dams, taking into account all sediment grain sizes (i.e. fines/suspended load and coarse/bedload) as well as the processes that are potentially implied (i.e. transport, deposition, infiltration within the bed matrix and clogging of this matrix): this represents a very recent field of investigation, necessary to improve their management (Loire *et al.*, 2019a, 2019b, 2021).

The **general objective** of the research conducted in this PhD was to assess the hydrological, morphological and sedimentary dynamics of the Upper Garonne over a wide range of spatial and temporal scales, and hierarch the respective role of multiple anthropisation factors in influencing such dynamics. To that end, the study relies on a combination of historical and experimental geomorphology approaches, and frames along the following chapters (Figure 1).

Chapter 1 presents the thematic and geographic framework within which the work is carried out, and comprises, in sequence, (1) a general state-of-the-art on the effects of main river anthropisation factors on river morphology and arising issues in regards with river restoration, (2) a presentation of the Upper Garonne catchment under geomorphic, hydro-climatic, and anthropic descriptors, and (3) a formulation of research questions and hypotheses, as well as an overview of the methods implemented to answer those questions.

Chapter 2 addresses the evolutionary pathways of the Upper Garonne since the middle of the 20th century, with a special attention paid to the effects of Plan d’Arem RoR dam on river morphology. This historical geomorphology analysis is the initial stepping-stone, on which subsequent chapters rely, and has been published in *Geomorphology* (402) in July 2022.

Chapter 3 focusses on the role of multiple factors in affecting bedload transport regime. After the characterisation of bedload transport, and in line with the geomorphic diagnosis presented in Chapter 2, we propose some practical recommendations on sediment management. This work will be submitted to the *International Journal of Sediment Research* by March 2023.

Chapter 4 deals with the characterisation of the effects of the Plan d’Arem dam on interstitial fine sediment dynamics. This chapter has been submitted to *Anthropocene* in December 2022 and is still under revision at the time of manuscript submission.

Chapter 5 synthesises the main outcomes of the preceding chapters and proposes practical recommendations for future river and dam management.

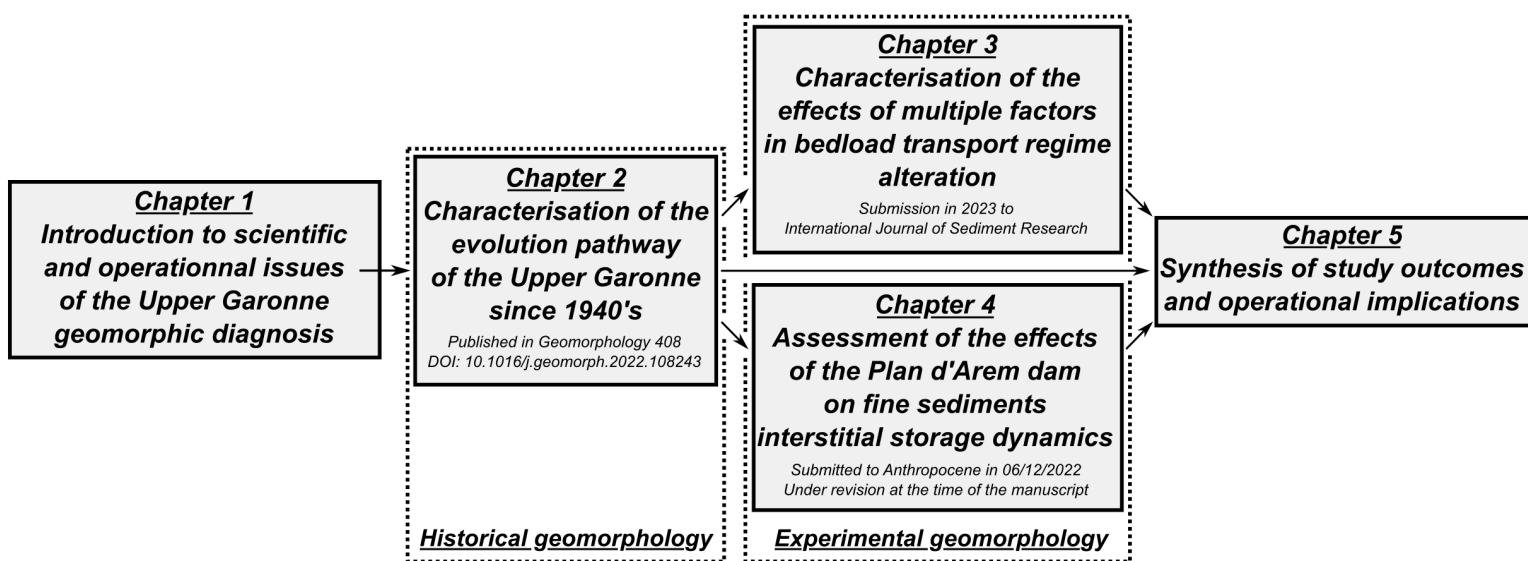


Figure 1. General structure of the thesis.

CHAPTER 1. Thematic and geographic framework

1.1. Thematic framework

River bio-geomorphic structure and functioning rely on a set of complex interactions between physical, biological, and more recently human factors. On physical aspects, *fluvial systems* can be conceptualised as continuous and complex process-response systems involving multi-scale imbricated variables that shape river channels (Schumm, 1977). Geology, topography, climate and land cover, known as **dominant variables**, correspond to external constraints imposed onto the system (Knighton, 1998). The variety of possible combinations for these variables (i.e. igneous vs calcareous bedrock, steep vs gentle slopes, narrow vs wide valley, humid vs dry climate, bare vs forested hillslopes, etc) control the dynamics of water (Q_L) and sediment (Q_S) fluxes (labelled as **driving variables**) received and conveyed by the system and thus shape the main features characterising fluvial type (Fig. 1.1; Lane, 1955, Schumm & Winkley, 1994). Although **dominant variables** are relatively stable through time, **driving variable** magnitudes may change even on very small timescale (minutes, hours, days), from a single hydrological event to decadal variations. These changes in turn control river channel characters (width, depth, planform pattern, grain size) known as **adjustment variables**. In other terms, current river geometry reflects its capacity to convey hydro-sedimentary fluxes, but also archives past- or ongoing-changes in **driving variables**. Enduring the complexity of hydrological and geomorphological interactions, biotic communities constantly adapt to such dynamic conditions that change all along the river continuum (Vannote *et al.*, 1980).

Within *fluvial systems*, the nature and structure of energy, material and biota exchanges organise across the various spatial dimensions and vary through time (Fig. 1.1; Petts & Amoros, 1996). In the longitudinal dimension (upstream – downstream), three distinct zones are classically used to describe the structure of bio-geomorphological patterns, generally found in rivers flowing in temperate regions, i.e. perennial or quasi-perennial systems. (1) The headwater, or **production zone**, is characterised by a large number of small and steep single-thread streams hosting biological communities typically composed of cold-water rheophilic species tied to oligotrophic areas. This zone provides most of water, sediments and solutes to the system. (2) Within the **transfer zone**, material is routed through a less dense drainage system with channels showing lower slopes and variable grain sizes. According to biotypological classifications, bryophytes are slowly replaced by the emergence and development of macrophytes, along with grazing invertebrates (Vannote *et al.*, 1980) and transition from Salmonids- to Cyprinids-dominated fish communities (Huet, 1954;

Verneaux, 1981) although some permeability still persists between both assemblages. (3) The **storage zone** presents the highest water discharge for a given river and low to very low slopes, resulting in deposition-dominated sedimentary processes within a fine-sediment cohesive floodplain. Fish communities living within the storage zone are warm-water Cyprinids-dominated, with diadromous migratory species sometimes representing a substantial part of fish biomass (Jones, 2006). In the lateral dimension (river – margins), abiotic interactions consist mainly of river – groundwater exchanges, on which depend important functionalities (e.g. water quality, thermal refuges, support during low flow conditions), and sediment exchanges (e.g. fine sediment deposition within the floodplain, sediment input from floodplain erosion). Riparian vegetation is also structured along a lateral gradient (Fig. 1.1), with pioneer vegetation (e.g. *Salix* and *Poplar sp.*) close to the river channel and progressive transition towards softwood (e.g. *Salix*, *Poplar* and *Alnus sp.*) and hardwood tree species (e.g. *Fraxinus sp.*, *Quercus sp.*) as distance from the channel increases. Natural and anthropogenic disruptions of hydro-sedimentary processes may cause a re-assemblage of those communities (Janssen *et al.*, 2020), as in the case of active meandering rivers which provide rich examples of the biological importance of lateral connectivity. Indeed, the mobility of meanders frequently leaves abandoned side channels, which progressively terrestrialise and substantially contribute to the diversification of the fluvial landscapes mosaic (Piégay *et al.*, 2000). Finally, in the vertical dimension, water exchanges between the surface and the hyporheic zone, as well as sediment grain size distribution, govern physical and chemical characteristics of the sediment matrix (e.g. temperature, dissolved oxygen, hydraulic conductivity, etc.), which in turn controls the diversity and the abundance of biological communities, mostly made of bacteria and invertebrates (Brunke & Gonser, 1997). As for lateral connectivity, functional hyporheic exchanges play an important role for stream ecology as they control thermal refuges distribution (Ward, 1992), water self-purification, nutrients supply (Ward, 1989), or intra-gravel siltation and potential clogging (Brunke & Gonser, 1997).

In summary, the temporality and magnitude of hydro-sedimentary processes are the key parameters in the evolution of fluvial systems, ensuring the continuity of functions and services brought to biological communities and human societies. However, the anthropisation of rivers and their catchments has greatly modified these processes, and hence the ecosystem services they offer. Since pioneer works of Gregory & Park (1974), Graf (1975), or Gregory (1977), a dominant branch of fluvial geomorphology has taken to address issues related to human-to-river relationship, with a special focus on (1) the alteration of hydro-sedimentary fluxes by human activities, (2) the effects of these alterations on fluvial systems, and, by extension and benefiting from other scientific disciplines, (3) on their ecological, sociological and economical impacts. Half a century later, many

facets of the problem have become clearer. Individual contributions of the main anthropisation factors responsible for the degradation of river functioning have been globally identified, quantified, and reported in scientific literature (see Section 1.2.). Nevertheless, the variety of climatic, geological and morphological contexts, together with the local specificity in the set of human pressures that affect a given reach, turn each river into a unique case study. Indeed, the morphological response to changes in *driving variables* that are caused by river anthropisation depends, from one side, on the magnitude of those fluctuations, and from the other side, on the potential of a given river reach to adjust. Although the latter has been conceptualised in the early time of fluvial geomorphology (Graf, 1975), awareness of its importance for river restoration remains scarce, thus justifying the need for more studies and methodological development to fill the gap between river sciences theoretical knowledge and applied management strategies (Downs & Piégay, 2019).

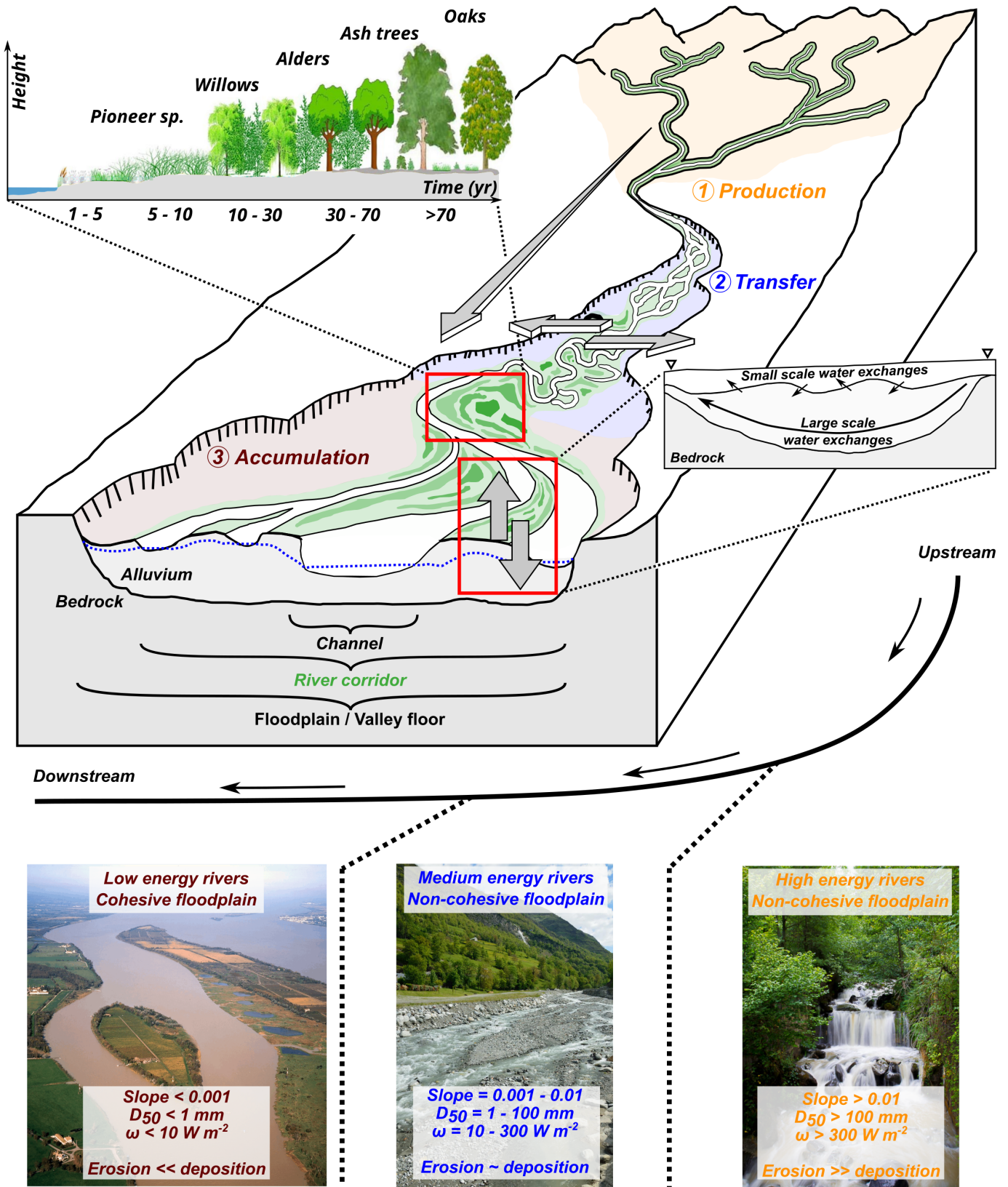


Figure 1.1. Schematic representation of the fluvial system (modified after Petts & Amoros, 1996) with distinction of production, transfer and accumulation zone characteristics (Downs and Gregory, 2004). Examples are given for three-dimensional interactions, notably lateral ecological succession (modified after Girel *et al.*, 1997) and vertical groundwater pathways (modified after Brunke & Gonser, 1997 and Kondolf, 2000).

1.2. River degradation: actors, processes, consequences

Among all pressures exerted by human-activities on river systems, damming, in-stream gravel mining, channelisation and land use changes are the most frequently encountered. Hereafter is a summarised description of these activities in their nature, aims and effects on hydro-sedimentary dynamics.

1.2.1. Land-use changes

For centuries, mountain areas have been subject to forest exploitation and intensive grazing of floodplains. Such activities have progressively reduced forest cover, increased the erosive activity of those catchments, and thus, sediment inputs to river systems (Liébault & Piégay, 2002). The paroxysmal phase of the Little Ice Age (1850 – 1890; Paasche & Bakke, 2010), characterized by an important hydrodynamism with frequent and intense flood events within very responsive and sensitive catchments, corresponds to a major erosive crisis during which torrential processes occurred and caused major damages. In response, ambitious masterplans to control torrentiality were undertaken from the end of the 19th century. Attempts to reduce the overall sediment inputs from hillslopes relied on planned afforestation and the construction of check-dams on torrential channels to protect downstream population (Fig. 1.2.A; Piton *et al.*, 2019). In addition with land planning for torrential risk control, a large number of mountain areas in Europe have experienced spontaneous afforestation allowed by post-LIA climate warming. In the Pyrenees, such afforestation have been especially intense since the second half of the 20th century, as on the Noguera Pallaresa catchment (Buendia *et al.*, 2016b), and more generally in most headwaters of the Ebro catchment (Gallart & Llorens, 2004). As a consequence, sediment supply to river system was greatly reduced (Fig. 1.2.B; Boix-Fayos *et al.*, 2008), and so was annual runoff (Buendia *et al.*, 2015), with morphological changes consisting mostly in active channel narrowing and bed incision (Beguería *et al.*, 2006; Boix-Fayos *et al.*, 2007).

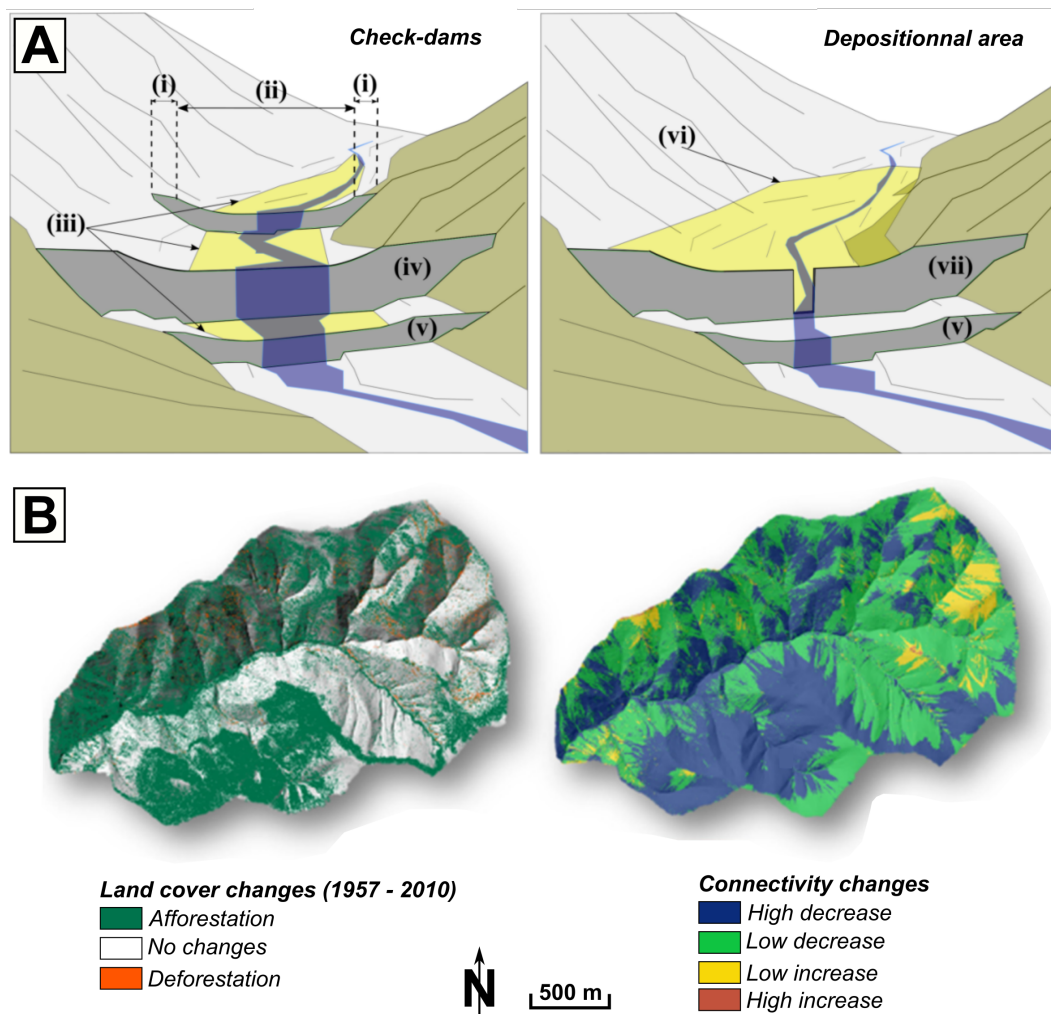


Figure 1.2. A. Torrential control structures (modified after Piton *et al.*, 2019). Check-dams exploitation relies on successive construction of transversal structures after complete filling of the upstream one. Depositional areas are equipped with spillways to avoid water retention, and need frequent dredging to maintain sufficient storage capacity. B. Land cover changes between 1957 and 2010 on the Cinca River catchment (Spanish Pyrenees) and decreased sediment connectivity after afforestation. Modified after Llana *et al.*, 2019.

1.2.2. River damming

Aiming at controlling the important natural variability in water availability (Hjorth, 2012), water retention behind dams has emerged very early in Human history – as early as 4900 yrs BP in Egypt and 3800 yrs BP in Irak –, but has developed very intensively since 1950 to support increasing needs to manage floods, supply water for irrigation and domestic uses, develop industries and provide electricity. All those functions rely on different types of dams that can be classified into two categories according to the International Commission on Large Dams (ICOLD):

(1) **Large dams** correspond to structures above 15 m in height, or between 10 and 15 m and meeting at least one following conditions: a crest length longer than 500 m, a spillway discharge potential above $2000 \text{ m}^3 \text{ s}^{-1}$, or a reservoir volume larger than 15 hm^3 (McCully, 1996).

(2) Even there is no official definition for **small dams**, they are often described as dams lower than 10 – 20 m. When built for hydroelectricity production without reservoir retention and sometimes with a by-pass, small dams are also named **run-of-the-river (RoR) dams**. They are often located in middle and lower river courses, where wide valley and low slopes, combined with dense human activities, do not allow for a large transversal structure inundating the upstream valley, RoR dams have little to no storage, typically less than one day of average discharge, making their exploitation very dependent on inflow and suitable mostly for base load electricity supply. Water is diverted by the dam and conveyed to hydropower plants through penstock pipes or aerial canal, bypassing the natural channel. Census of the total number of small dams gives an approximate value of 800.000 worldwide (Vörösmarty *et al.*, 2003).

Hydrological alteration by dams show more diversity than other pressures as it depends on the considered type of dam (Fig. 1.3.A). On the one hand, large dams affect flood regime through a reduction in the intensity, duration and frequency of peak flows, while base flows are often increased. Numerous examples are provided in the literature, as for the Ebro and Guadalupe (Batalla *et al.*, 2004), the Missouri (Skalak *et al.*, 2013) or the Dordogne Rivers (Boutault *et al.*, in prep). On the other hand, hydrological effects of RoR dams are often directly linked to design flows, and circumscribed to the by-passed reach (BPR). During low flows, a minimum ecological discharge spills over the dam into the by-passed reach, whereas the rest of the discharge goes to the turbines. During floods, the discharge going into the by-passed reach progressively increases, as design flow is overpassed. Contrary to large dams, RoR dams tend to decrease base flows whereas they have relatively limited effects on peak discharges (Ibiate *et al.*, 2013).

Effects of dams on sediment dynamics are also variable and conditional to the possibility of routing sediments within the reservoir and through the dam itself. Again, large dams are commonly more impacting. Because of large retention volume and longer section of river influenced by the impoundment, it is virtually impossible or impracticable to fully empty a reservoir during a flood event, which would help maximising energy slope and sediment transport within the former channel. Moreover, many large dams are not equipped with low level gates or sediment by-passing infrastructures. As a result, they trap a major part of incoming sediment, almost 100% in some extreme cases (Vericat & Batalla, 2006). Somehow, the effects of small dams on the sediment cascade are similar to those of large dams during the period following their construction. However, small dam reservoirs often experience silting, impelling managers to implement methods to control sediment accumulation, with the twofold interest of extending the lifespan of the reservoir and of preserving downstream channels when removed sediments are delivered downstream from the dam (Kondolf *et al.*, 2014).

The morphological effects to river damming thus depend on the degree and relative preponderance of hydrological and sedimentary processes alteration. Classically, “hungry water” released from large dams (Kondolf, 1997) recovers sediments from bed erosion, inducing bed coarsening (Fig. 1.3.B) and incision (Fig. 1.3.C). As the channel deepens, channel margins and sediment bars emerge more frequently, providing room for vegetation encroachment, reducing active channel width and exacerbating bed incision (Rodrigues *et al.*, 2007). Lamination of peak flows then plays a modulatory role in the propagation of sediment deficit, as infrequent bedload mobility slows down this propagation, but promotes side-channels colonisation by pioneer vegetation, inducing channel narrowing (Liébault & Piégay, 2002). The intensity of morphological adjustments to damming decreases in the downward direction with water and sediment input from tributaries (Schmidt & Wilcock, 2008), in the case those tributaries do not also experience to flow regulation and sediment starvation (Batalla & Vericat, 2011).

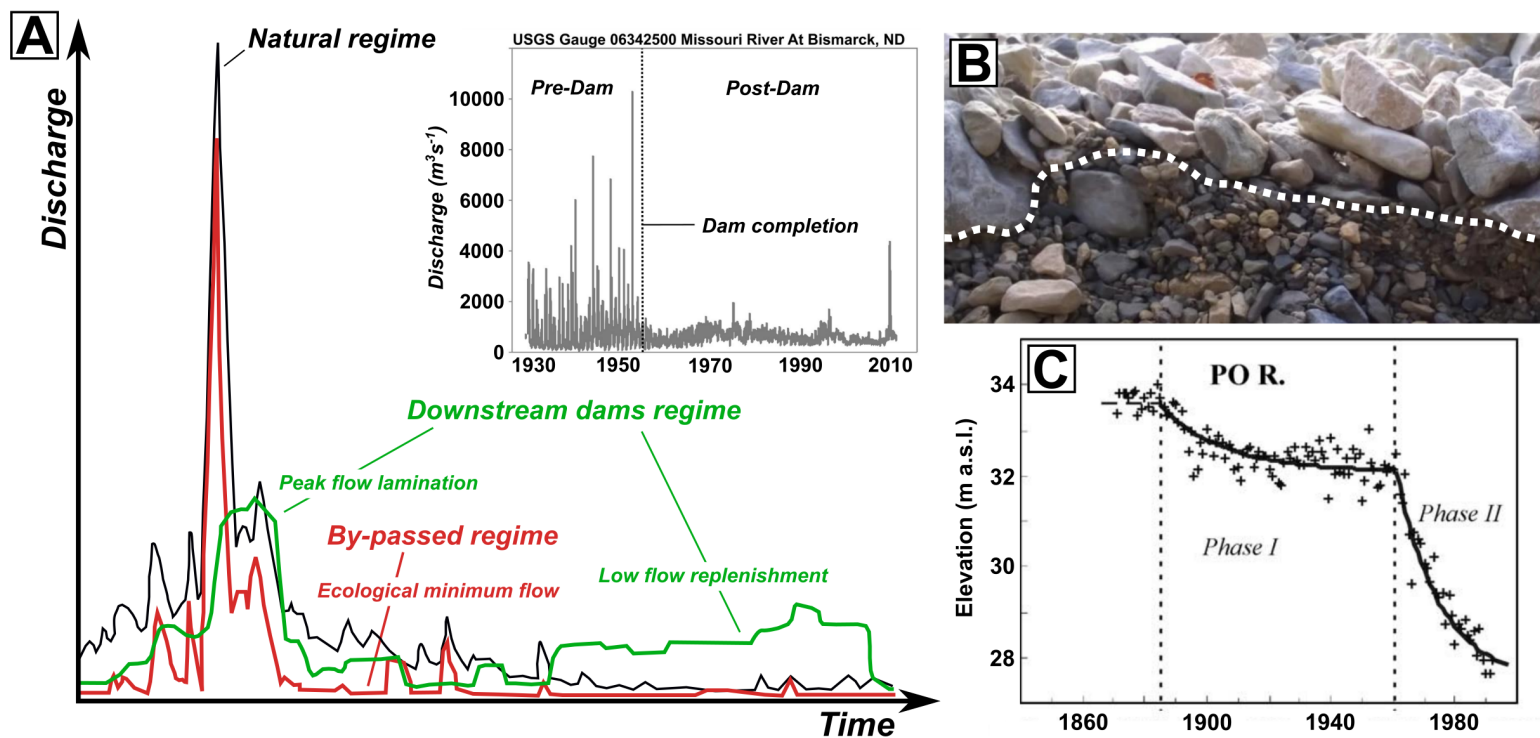


Figure 1.3. **A.** Schematic representation of natural hydrology alteration by large dams (green line) and diversion dams (red line), modified after Baran & Leroy-Gravet, 2007. An outstanding example from the Missouri river is provided, where discharge frequency and magnitude at Bismarck peak have experienced extreme reduction after completion of the Garrison dam (Skalak *et al.*, 2013). **B.** Typical bed armoring, which can be observed downstream from dams due to the release of “hungry-waters” (modified after Recking *et al.*, 2022). **C.** Exponential function describing the two-staged bed incision after land use changes (phase 1), and after gravel mining and dam construction (phase 2) on the Po River (North Italy, modified after Surian & Rinaldi, 2003).

In parallel of hydro-sedimentary regime perturbations by dams and reservoirs themselves, hydroelectricity production can also largely impact downstream processes through frequent, rapid and sometimes intense fluctuations in sub-daily flow conditions, called ‘hydropeaks’ (Batalla *et al.*, 2021). Typical physical degradations observed within reaches affected by hydropeaking concern size-selective sediment transport during flow releases, which despite being of lower magnitude than natural floods usually occur in such a high frequency that they may profoundly alter bed structure at the reach scale (Vericat *et al.*, 2020).

1.2.3. In-stream gravel mining

Mainly used for construction, the provision of sands and gravels has long relied on in-stream mining, now being one of the main cause of sediment deficit in rivers. In most cases, the intensity of gravel mining largely exceeded annual bedload fluxes, leaving long over-deepened pits that could last for decades after the end of extractive activities depending on the capacity of the river to adjust (Kondolf, 1994; Petit *et al.*, 1996; Latapie *et al.*, 2014). The so-created local bed incision further can propagate downstream (progressive erosion), because those pits trap a large proportion of bedload, but also upstream, due to local increase in energy slope (regressive erosion), until achieving a new equilibrium profile (Fig. 1.4; Kondolf, 1994).

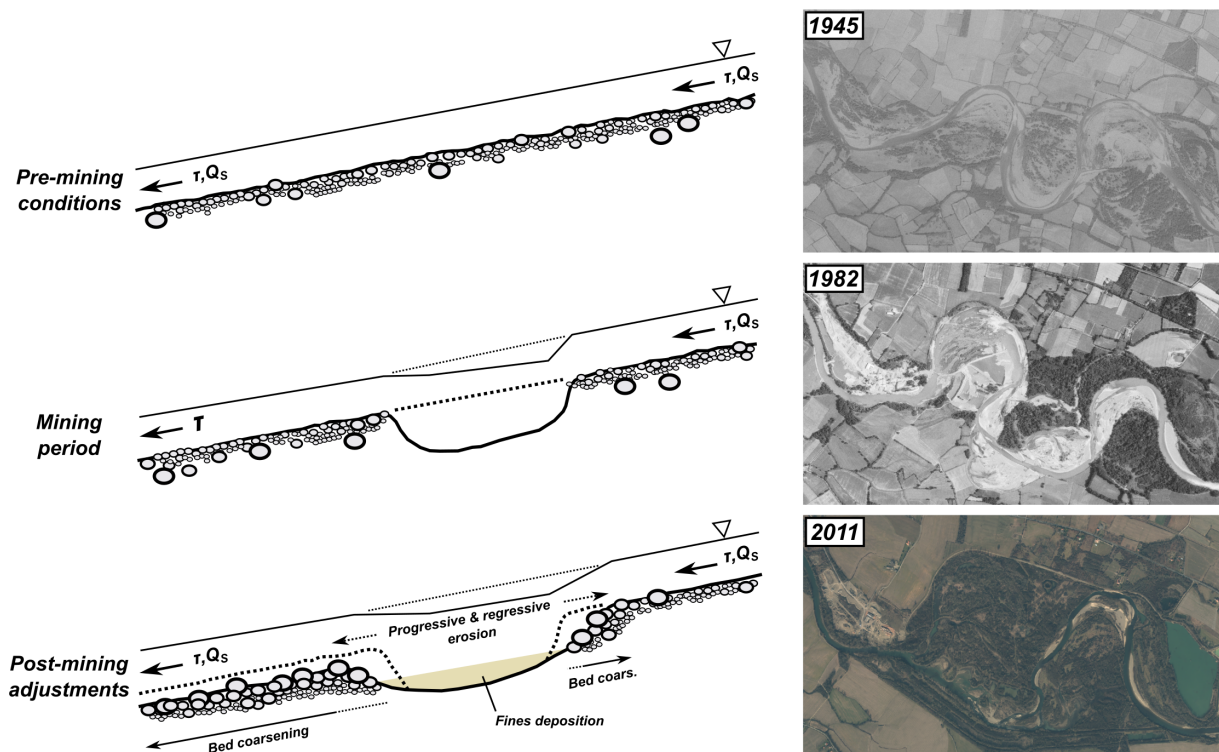


Figure 1.4. Channel adjustments after gravel mining activities (modified after Kondolf, 1994). An example of gravel mining area and channel adjustments is given on aerial photographs (Adour River, SW France). The former active channel, showing meandering pattern in 1945, has experienced intense narrowing due to channel incision and vegetation development, resulting in a sinuous single-bed channel pattern in 2011.

In most gravel-bed rivers impacted by mining activities, size selective transport induces progressive bed armouring, which may stop the propagation of channel incision. Gravel pits may then last until complete filling by upstream supply leading to long-term adjustments. For instance, Rovira *et al.* (2005) estimated that sand and gravel mining rates equalled to 14 times the replenishment rate on the Lower Tordera River (NE Spain), leading extensive recovery time to pre-mining conditions of around 420 years. In some cases, catchment lithology has been pointed as an important factor controlling recovery rates. Dépret *et al.* (2021) highlighted that although former pits on the Cher River (France) did not fully recover from mining activities almost half a century later, filling rates were surprisingly high considering the low energy of this river, due to sand-rich sediment production from the catchment.

1.2.4. Embankments

Embankments are built to control floods, to ensure navigation, and/or to limit channel migration in order to protect adjacent fields, habitations or industries. The channelisation consists in the modification/fixation of channel planforms and transverse profile, to increase the hydraulic capacity of the channel. After embankment works, channel width and sinuosity generally decrease, while channel slope increases (Fig. 1.5). As a result, sediment transport capacity increases within a shorter constrained channel, promoting bed incision, coarsening, and potentially inducing bank instability. To counteract this instability, banks are often protected with rip-raps or bioengineering techniques, reducing sediment inputs from bank erosion processes thus exacerbating bed incision (Brooks, 1987; Arnaud *et al.*, 2015).

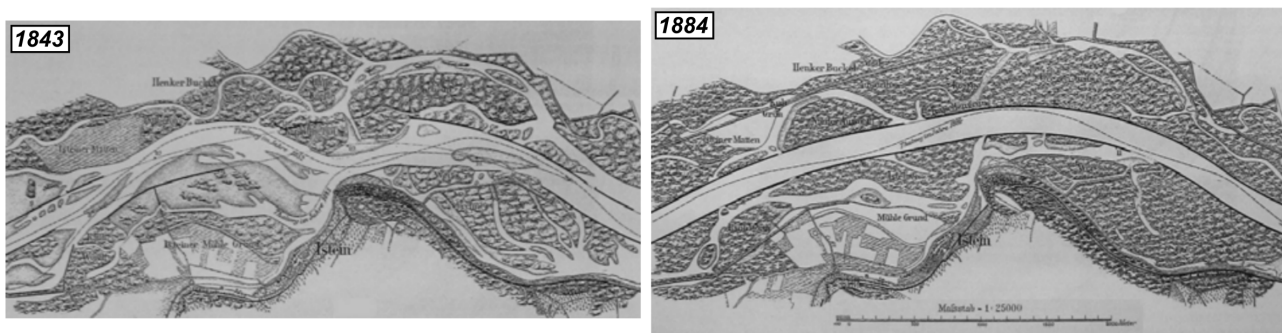


Figure 1.5. Channelisation of the Rhine river in the Istein area. Modified after Honsell (1885) and Arnaud (2012).

1.2.5. Ecological, sociological and economic impacts of river anthropisation

Issues related to river anthropisation concern all biological processes and human activities relying on good hydro-sedimentary functioning of fluvial system (Bravard *et al.*, 1999). From an ecological perspective, the scientific consensus on the role of fluvial dynamics in shaping functional aquatic and riparian habitats is supported by numerous studies. Modifications of natural hydro-

sedimentary regimes by anthropisation thus have unavoidable consequences on ecological processes. Sediment deficits classically observed downstream from dams and within gravel mining areas lead to channel incision, narrowing and bed armouring. In response, in-stream biological communities experience intense modifications, due to (1) a simplification of channel planforms resulting in the disappearance of habitats tied to gravel bars and riffle-pool sequences, losses in thermal refuges, reduction of adequate size spawning gravels, or flow velocity fields homogenisation within cross-sections (Kondolf & Wolman, 1993; Kondolf, 1997), and (2) the disconnection between surface and groundwater affecting water temperature, hyporheic habitats or low flow replenishment (Brunke & Gonser, 1997; Poole & Berman, 2001; Caissie, 2006). Riparian vegetation also suffers from a decreased lateral connectivity following bed incision (e.g. reduction of floodplain inundation frequency and duration, water stress), whereas terrestrialisation of secondary channels after the settlement of perennial woody and less adapted vegetation reduces the diversity of river corridor habitats (Bravard *et al.*, 1997; Francis *et al.*, 2005, Comiti *et al.*, 2011). Within reaches affected by hydropeaks, the main ecological impacts concern invertebrates drift during the rising limb of the hydrograph (Gibbins *et al.*, 2007), and the trapping of fishes within secondary channels and submerged gravel bars during the falling limb, i.e. when water level drops rapidly (Bosc *et al.*, 2012; Coll *et al.*, 2016).

However, river anthropisation can also largely impact human activities and cause important socio-economic losses. Because of incision, the groundwater table drops, affecting water abstraction for irrigation and domestic water supply, and structures such as bridges or dykes can be critically undermined, sometimes until complete destabilisation and destruction (e.g. Wilson Bridge, Tours, France, destroyed in 1978 – Kondolf, 1997; Batalla, 2003, Rovira *et al.*, 2005). In-channel vegetation development can also increase flood risk by increasing roughness.

1.3. Geomorphic diagnosis & process-based restoration downstream from dams

Facing with the magnitude of multiple degradations, river restoration programs and modifications in management methods have spread worldwide where socio-economic conditions allow to undertake actions (Costanza *et al.*, 2002; Costanza, 2012). Although river restoration has long relied on the re-creation of a particular river structure or form, e.g. floodplain channel reshaping (Riquier *et al.*, 2015), remeandering (Kondolf, 2006), vegetation removal on alluvial bars (Bankhead *et al.*, 2017), on the basis a past static state perceived as “good” as reference (Wohl *et al.*, 2005), recent advances in conceptualisation and paradigm rather point towards the achievement of a new (and often different) dynamic state. Such a state is characterised by spatial and temporal changes in channel geometry due to flow and sediment supply variability, and variations in biotic

abundance and diversity in response to these changes (Dufour & Piégay, 2009; Wohl, 2015). Achieving a good understanding of river geomorphic functioning, considering spatio-temporal variability of hydro-sedimentary processes and morphological changes, as well as their alteration by anthropisation factors, are then the only way to correctly assess the evolutionary trajectory of a given river reach, in order to guide future actions and tactics within a process-based perspective. In that respect, a geomorphic diagnosis must (1) identify and quantify the relative contribution of anthropisation factors in the alteration of hydro-sedimentary processes and the associated river response, (2) define restoration goals in cooperation with the relevant stakeholders, and (3) assess which levers of actions are the most likely to efficiently counter the observed degradations, while ensuring their sustainability.

Process-based restoration consists in restoring functions that are normally supported by natural processes, correcting anthropogenic disruptions of these processes with the aim of reaching a functional, resilient, self-sustaining system with minimal human intervention (Beechie *et al.*, 2010). Application of process-based restoration principles in reaches downstream of dams then focusses on (1) restoring peak flows when they are laminated (Loire *et al.*, 2019b, 2021) and (2) restoring bedload supply and transport (Kuhl, 1992; Kondolf *et al.*, 2005; Arnaud *et al.*, 2015). For instance, when a dam totally disrupts bedload supply without possibility to route sediment downstream, the available options are often limited to the implementation of gravel augmentation, in order to mitigate effects of sediment deficit on aquatic organisms (Kondolf *et al.*, 2014). However, such actions present limits in their application and expected outcomes. Extraction and transport of significant amounts of allochthonous sediments require to find source of material nearby to limit economic and ecological costs (Pulg *et al.*, 2022). The mobilisation of augmented gravel during floods without upstream supply decreases the life-span of those actions (Merz *et al.*, 2006) and their benefits (Harvey *et al.*, 2005), which must then be frequently repeated. Finally, key parameters such as the volume of material, augmentation frequency and peak flow restoration actions need to be carefully designed in the light of the river transport capacity to avoid any worsening of the situation (e.g. restoring peak flows within a supply-limited reach can further propagate sediment deficit), or the induction of other new and sometimes unexpected consequences (e.g. riverbed clogging following non-mobile augmented gravels). Therefore, allowing sediments to be routed within the reservoir and through the dam during high flows, when it is possible, is advocated as a more sustainable option (Kondolf *et al.*, 2014). This way, issues related to sediment sources availability, continuity of action benefits, and accordance with natural hydro-sedimentary regime are avoided. If drawdown flushing, sluicing or (eco)morphogenic flow releases may lead to economic losses to the hydroelectricity producers (Loire *et al.*, 2021), those costs have to be put in perspective with long-

term losses due to reservoir siltation or ecological compensation. Although the literature richly documents the effects of large dams on downstream reaches (Kondolf & Curry, 1986; Stevaux *et al.*, 2009; Ma *et al.*, 2012), as well as the effects of gravel augmentation (Bunte, 2004; Staentzel *et al.*, 2020; Marteau *et al.*, 2022), few studies focussed on smaller dam effects (Csiki & Rhoades, 2010, 2014) and management (Loire *et al.*, 2019a, 2019b).

Furthermore, implementation of dams' management strategies involves the manipulation of fluvial processes which then has to be done with careful considerations of the related risks. Such risks may be (1) socio-economic, as flood levels can rise following increased sediment supply (Arnaud *et al.*, 2015) and damage downstream infrastructures (Gaeuman, 2012), but also (2) biological as sediment released from reservoirs may be contaminated (Krein & Symader, 2000; Watts *et al.*, 2009) or may induce substrate clogging (Loire *et al.*, 2019b). Therefore, it is crucial to estimate the benefit-risk ratio of those strategies before implementation, or their effects if they are already implemented, as a part of the diagnosis phase, even though it often implies to collect complementary data.

1.4. The Upper Garonne System

The Garonne river basin is located in SW France and extends over 56 000 km² (Fig. 1.6). Headwaters first drain two main mountain massifs – the Pyrenees at the south and the Massif Central at the east – with middle and lower courses flowing within the substantially large Aquitaine sedimentary basin. The catchment is often acceptably divided into three distinct zone. The Mountain Garonne (170 km), extending from the source at the Pla de Beret (1830 m a.s.l. ; Spain) to the confluence with the Ariège, its main tributary, in Toulouse. This reach, characterised by steep slopes (> 0.001) and a relatively narrow channel (10 – 150 m), can further be divided into two subreaches. The Upper Garonne (see Section 1.4.1., 78 km), upstream the confluence with the Neste River in Montréjeau, and the Piedmont Garonne (92 km) from this confluence to Toulouse. The Middle Garonne, from Toulouse to the confluence with the Dropt at Castets-en-Dorthe, presents lower slopes and a wider channel (100 – 300 m) and receives water and sediment from relatively important right bank tributaries that drain the Massif Central (the Tarn, the Aveyron, the Lot Rivers). The Lower Garonne, downstream from Castets-en-Dorthe, where the river is influenced by tides of the Atlantic Ocean, and mixes its waters with the Dordogne river to form the Gironde estuary (75 km).

1.4.1. Geological settings

The study reach is located in the central part of the Pyrenees, characterised by high peaks (Aneto, 3404 m a.s.l.) and steep slopes due to the low spatial extent of the chain to the north (50 km). The Pyrenean range is orientated WE (430 km) and extends over France and Spain. The current lithology of the Pyrenees is the complex end-product of two orogenic events: the Hercynian (-360 to -290 Ma) and the Alpine (-85 to -20 Ma) orogenesis (Monod, 2014 cited by Blanpied, 2019). As a result, the chain nowadays organises, from the centre to the north, as a succession of magmatic and metamorphic rocks originating from the deformation of Primary old series in the high axial zone, to importantly folded and faulted calcareous Secondary series, and finally to Tertiary and Quaternary deposits in the piedmont zone. As a consequence of this metamorphic-dominated lithology, sediment primary production of the catchment is naturally sand-rich. The morphology of the Upper Garonne valley results from this complex orogeny, but has also been more recently shaped by the Garonne glacier, an Alpine-type glacier which reached its maximal extent ca. 35 ka BP (Andrieu-Ponel *et al.*, 1988; Stange *et al.*, 2014; Fernandes *et al.*, 2017) as attested by a terminal moraine complex in the Comminges region (Fig. 1.6, RK70). Post-Würmian deglaciation left an incised valley of variable width which controlled hydro-sedimentary processes over succeeding millennia. From the source of the Garonne to St Béat, the narrow valley (100 m – 1 km) has filled with fluvio-glacial deposits frequently fed by colluvial processes at times remobilised by fluvial dynamics during extreme events and which now constitutes the main source of sediments available to the river (Blanpied, 2019). From St Béat down to Montréjeau and the confluence with the Neste River, the valley enlarges significantly (1 – 4 km). As the Garonne glacier overdeepened the substratum, its retreat left a 12 km-long and 100 – 300 m-deep lake (Arricau & Chapron, 2021) closed downstream by Late Glacial Maximum terminal moraines. The paleolake progressively filled up with glacial, fluvio-glacial, fluvial and lacustrine sediment, leaving behind a wide and flat valley, which experienced frequent submersion over the last centuries (Sturma *et al.*, 2017).

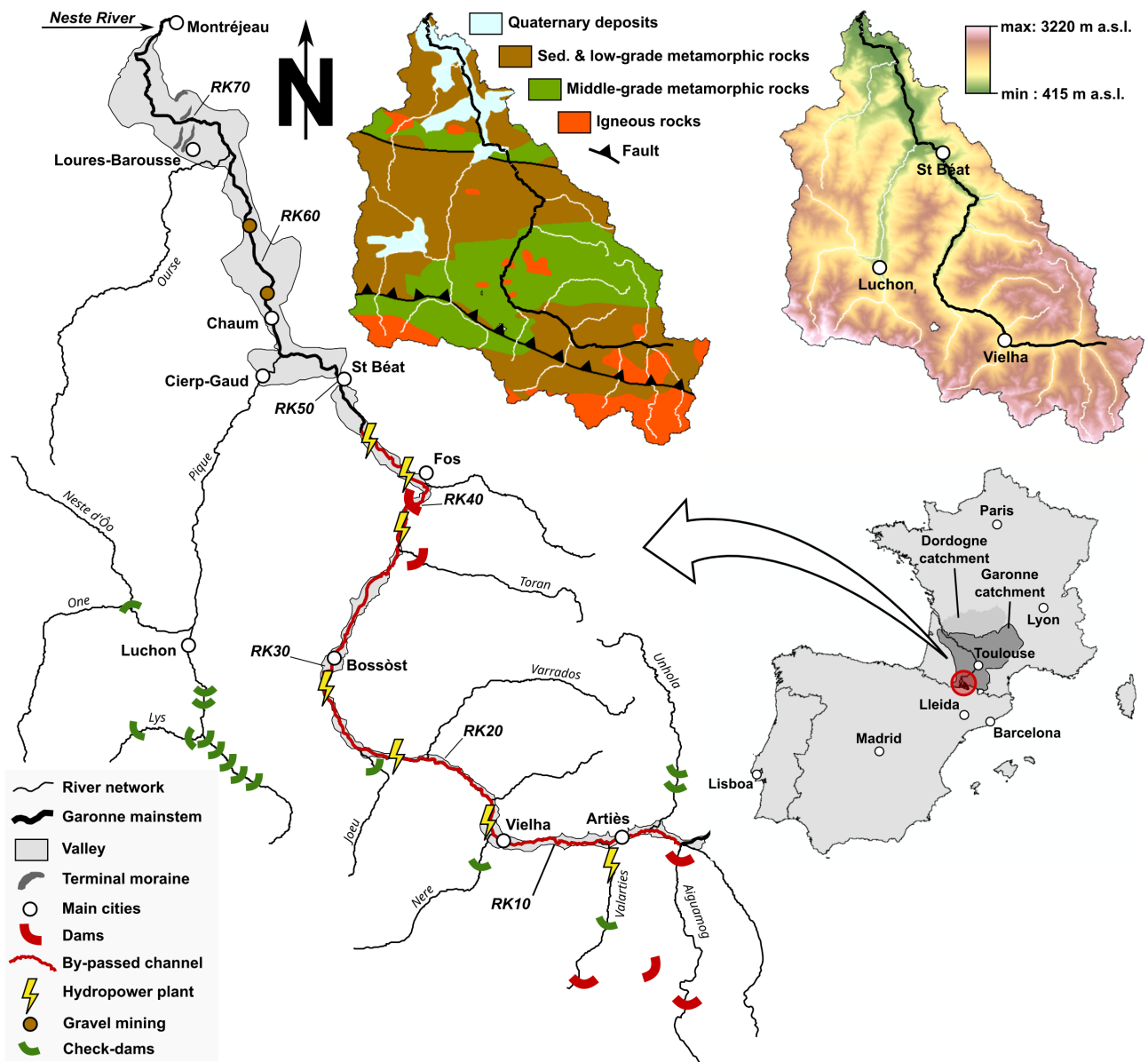


Figure 1.6. Study site location and characteristics (simplified geology, river network and main anthropisation factors). For graphical purposes, only some of the check dams on the Upper Pique catchment are represented, to provide the reader a general overview of their location.

1.4.2. Longitudinal pattern of channel characteristics

The Upper Garonne basin is the production zone to the Garonne fluvial system. Along the 78-km long reach, the Garonne mainstem receives water from 12 main tributaries draining steep hillslopes (Fig. 1.6). Channel features largely evolve downward, transitioning from torrential to alluvial patterns in relation with strong reduction in slope gradient (Fig. 1.7). Channel patterns can be described after segmentation of the longitudinal profile into 5 homogeneous reaches. The sector A, going from the source to Arti es corresponds to the transition between the Beret Plateau and the valley bottom. The Garonne channel is a few meters wide with slope exceeding 0.3 m m^{-1} . Within

sector B, from Artiès to Vielha, the Garonne flows within a 200 to 500 m wide valley and receives water from 4 tributaries which also contribute greatly to sediment furniture. Channel slope and width are approximately 0.03 m m^{-1} and 15 m, with channel morphology showing step-pool patterns. The sector C, from Vielha to Bossòst, collects water from last headwaters tributaries. Channel slope decreases (to approximately 0.02 m m^{-1}) together with bed surface grain size, and its morphology changes to plane-bed. From Bossòst to the confluence with the Pique (sector D), main tributary within the study reach, valley widens significantly (400 – 1000 m) and channel slope decreases below 0.01 m m^{-1} . Within this reach, the river shows higher lateral dynamism with the development of bedforms, typical of wandering fluvial type. River margins are also characterised by riparian forest development. Finally, the sector E, downstream from the confluence with the Pique, displays channel widening (40 m), slope decrease (0.002 m m^{-1}) and absence of large cobbles from surface grain size distribution. The valley also enlarges to reach about 4 km within the paleolake, allowing lateral mobility and further development of a riffle-pool morphology.

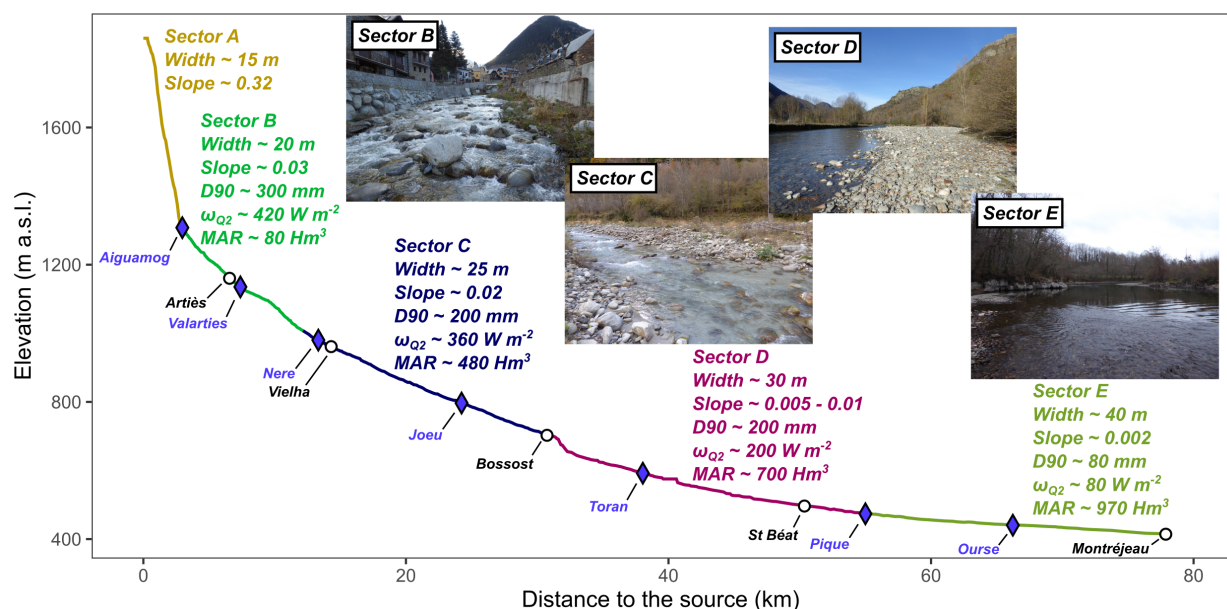


Figure 1.7. Longitudinal profile of water surface elevation. White circles show main cities. Blue diamonds represent main tributaries.

1.4.3. Hydro-climatic context

Precipitations in the Upper Garonne basin are characterised by high overall volumes during spring rains (April-May) and winter snowfall (November-January), and annual precipitation at Vielha averages 983 mm (1950 – 2019, Fig. 1.8.A). Flow regime is snow-melt dominated with high-flows occurring from April to July (Fig. 1.8.B). Along the study reach, annual runoff increases from 77.25 hm^3 at Artiès (1950 – 1991 ; 2011 – 2022), to 468.46 hm^3 at Bossòst (1966 – 1974 ;

1977 – 1991 ; 2006 – 2022), 710.17 hm³ at St B at (1921 – 1928 ; 1948 – 2022) and 968.98 hm³ at Chaum (1993 – 2022). The important increase observed between Arti s and Boss st (~ 25 km) results from the large contribution of torrential headwater tributaries (Aiguamog, Valarti s, Nere, Varrados, Joeu). Annual runoff rises more progressively downwards, with supply from the Pique basin significantly contributing for around 30 % of total runoff at the most downstream gauging station of Chaum.

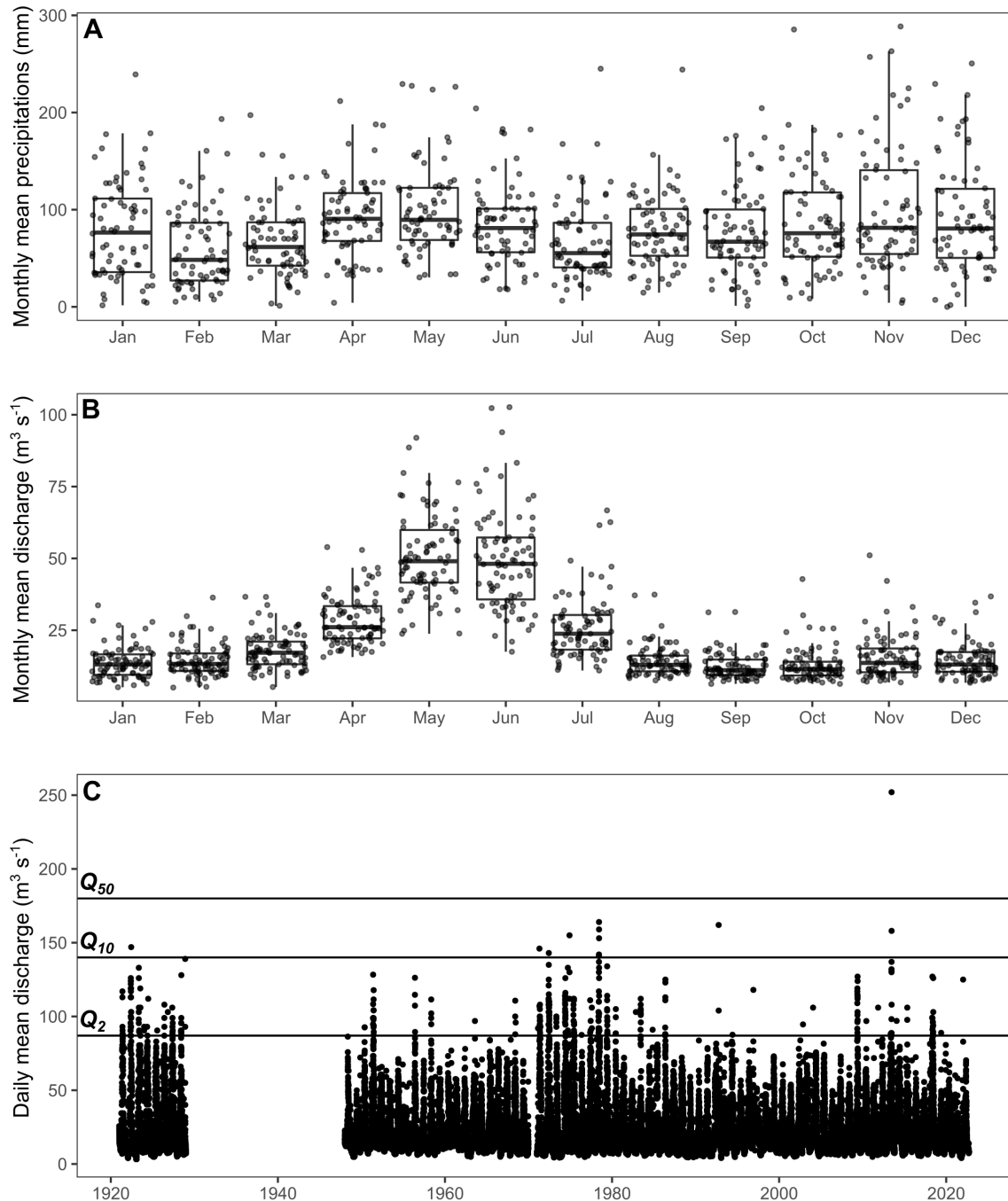


Figure 1.8. A. Monthly mean precipitations at Vielha (1950 – 2019). B. Monthly mean discharge at St B at (1921 – 1928 ; 1948 – 2022). C. Flow discharge at St B at since 1922.

Over the last century, floods in the Upper Garonne originated mostly from rainfall during snow-melt period, with 88 % of floods occurring during May and June, and 92 % when including early (April) and late (July) snow-melt events. The remaining 8 % is shared quite evenly over summer to winter periods, although autumn rainfalls result in 5 % of observed flood. Over the last 30 years, the proportion of floods induced by autumn rainfall increased to 16 %, as a likely consequence of recent climate change and decreased snow cover. Discharge for 2-years return-period floods are $13 \text{ m}^3\text{s}^{-1}$, $70 \text{ m}^3\text{s}^{-1}$, $88 \text{ m}^3\text{s}^{-1}$ and $113 \text{ m}^3\text{s}^{-1}$ at Artières, Bossòst, St Béat and Chaum, respectively (Fig. 1.8.C).

The recent hydrology of the study reach has been marked by the exceptional flood of 18th June 2013 where daily discharge and peak discharge reached $250 \text{ m}^3\text{s}^{-1}$ and $350 \text{ m}^3\text{s}^{-1}$ respectively at St Béat, making this flood the largest event observed on the Upper Garonne since 1875. This episode, which affected most rivers within the Central Pyrenees, originated from the combination of intense and late snowfalls resulting in $> 10 \text{ m}$ -thick snow cover in altitude until early June, with rapid temperature rising and important rainfalls ($\sim 80 \text{ mm}$ in the Val d'Aran between 17th and 19th June, Fig. 1.9.A). After a preliminary destabilisation of most erodible morphostructural units during an intense rainfall event in October 2012, the June 2013 flood largely re-activated fluvial and torrential dynamics (Blanpied, 2019; Yassine, 2020). Sediment inputs from hillslopes and quaternary deposit erosion contributed to the accentuation of the morphological response of the river to the flood, especially over the upstream part of the study reach where channel locally widened to 10-times pre-flood width, destroying habitations, roads and bridges (Fig. 1.9.B). The flood also killed 2 people in a neighbouring catchment. The financial costs of post-flood recovery works has been estimated to above 35 million euros for the only study reach, and up to 100 million euros taking into account all damaged regions (Sturma *et al.*, 2017). Moreover, the flood of 18th June 2013 highlighted the weakness of the knowledge base dealing with hydro-sedimentary processes in this area of Central Pyrenees, justifying for multiple ambitious study projects (Blanpied, 2019; Yassine, 2020). Results from those projects pointed toward the increased sensitivity of those mountain territories to natural hazards in relation with prior land and river channel degradation, hence confirmed the need for further basin-scale diagnosis.

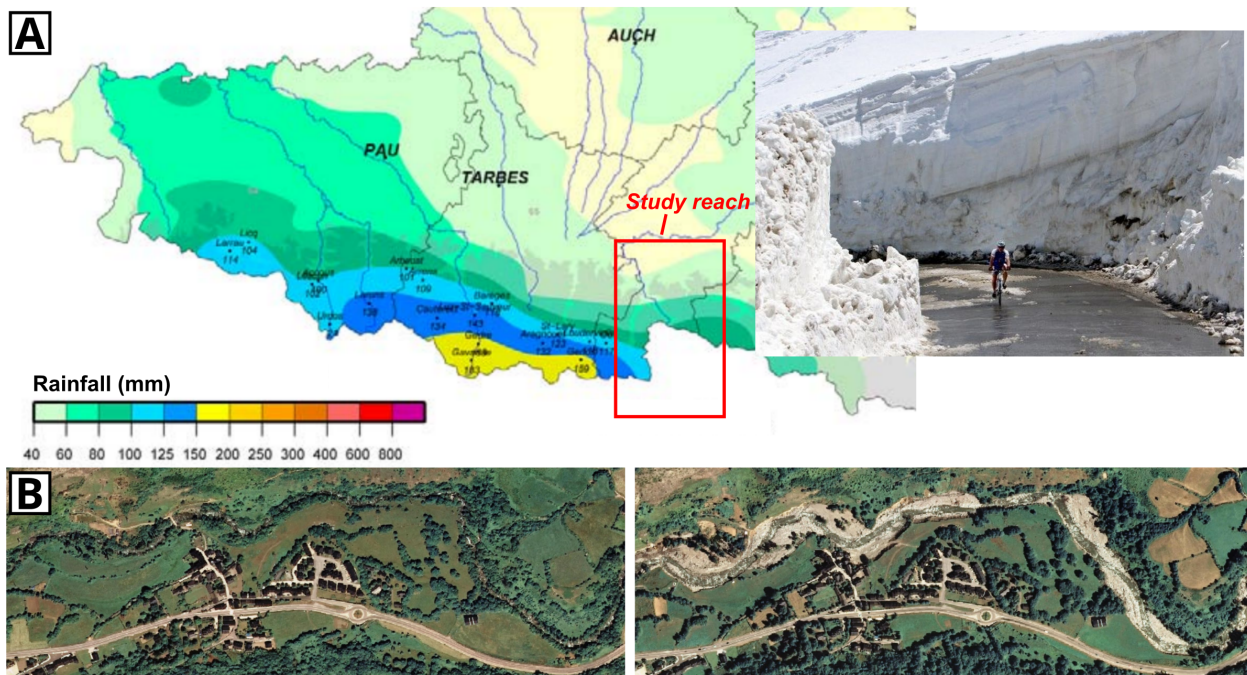


Figure 1.9. The 18th June 2013 flood. **A.** Cumulated rainfall over North Pyrenees between 17th and 19th June 2013 (source: MétéoFrance). Right photograph: cyclist passing the Tourmalet early June (source: La Dépêche). Road is both sides surrounded by > 5 m-high snow cliffs. **B.** Channel planforms changes before (2012, left) and after the flood (2013, right) in the area of Trédos (Val d’Aran, Spain).

1.4.4. Anthropisation factors and associated issues

Over the 20th century, multiple factors may have affected the Upper Garonne hydro-sedimentary regime. At the catchment scale, important land use changes have occurred with noticeable afforestation affecting most catchments in Central Pyrenees but still unquantified in the Garonne basin (Fig. 1.10.A). In the headwaters, a network of dams and water abstraction features from high-altitude lakes was built between 1955 and 1965 to feed 5 successive hydroelectric plants, thus completely by-passing the natural channel from Artiès to the Pont de Rei (RK 39). With a storage capacity of 4.2 hm³ and a diversion capacity of 14 m³s⁻¹ to 28 m³s⁻¹, this diversion network may had the potential to exert significant flow reduction over this reach. In addition, hydropeaks released by those hydropower plants have affected downstream hydrology (Fig. 1.10.B), conducting French authorities to build the Plan d’Arem dam (1970) to mitigate hydropeaks and ensure water supply to the hydropower plants of Fos and Arlos. However, the Plan d’Arem reservoir has experienced siltation since its construction, waning its storage capacity from approximately 0.35 hm³ in 1970 to 0.116 hm³ in February 2013 (Fig. 1.10.C) and critically reducing its ability to laminate hydropeaks (Fig. 1.10.B). Little information on in-stream gravel mining on the Upper Garonne exist. Spanish authorities have sensed that around 61 000 m³ were extracted since the 1990’s for safety purposes. Aerial photographs attest that at least two mining sites operated during

1970's in the area of Galié (RK60), although extracted volumes remain undeclared. Finally, intense torrential history on the Upper Pique basin lead to the construction of torrential control structures to protect the Luchon urban area (late 19th century to 1960). Latest quantification of stored volumes gives an estimate of 180 000 m³ of sediments trapped upstream of these structures (Artelia, 2015), equally depleting downstream reaches. As a consequence of those multiple pressures, local stakeholders have listed important ecological dysfunctions, especially in terms of fish habitat distribution (i.e. spawning gravels depletion), quality (i.e. riverbed clogging) and sustainability (i.e. emergence due to hydropeaks) (Bosc *et al.*, 2012; Coll *et al.*, 2016). Nevertheless, and despite numerous studies already engaged aiming at quantifying these degradations, driving factors and their relative contribution have not been clearly identified.

Sediment inputs during the June 2013 flood completed Plan d'Arem reservoir sediment filling, reducing its storage capacity to 0.053 hm³, and forcing dam managers to implement drawdown flushing actions after 2014. In parallel, this flood seems to have rehabilitated some ecological functions in the downstream channel. First, important sediment inputs from catchment and bank erosion have restored spawning gravels where the bed was previously armoured. Moreover, trout redds census conducted in 2018 showed that flood benefits were maintained over time, with an increase in potential spawning area of 43 % when compared with the 2015 census (Duclos, 2018). If drawdown flushing actions seem efficient in controlling siltation (Fig. 1.10.C), their effects downstream are not clearly assessed, notably on the hyporheic zone. In theory, one main operational issue is now to achieve a balance between sediment inputs and outputs into and from the Plan d'Arem reservoir capable to preserve, or maybe even increase, the storage capacity of the reservoir, and to ensure the sustainability of post-floods habitats improvement.

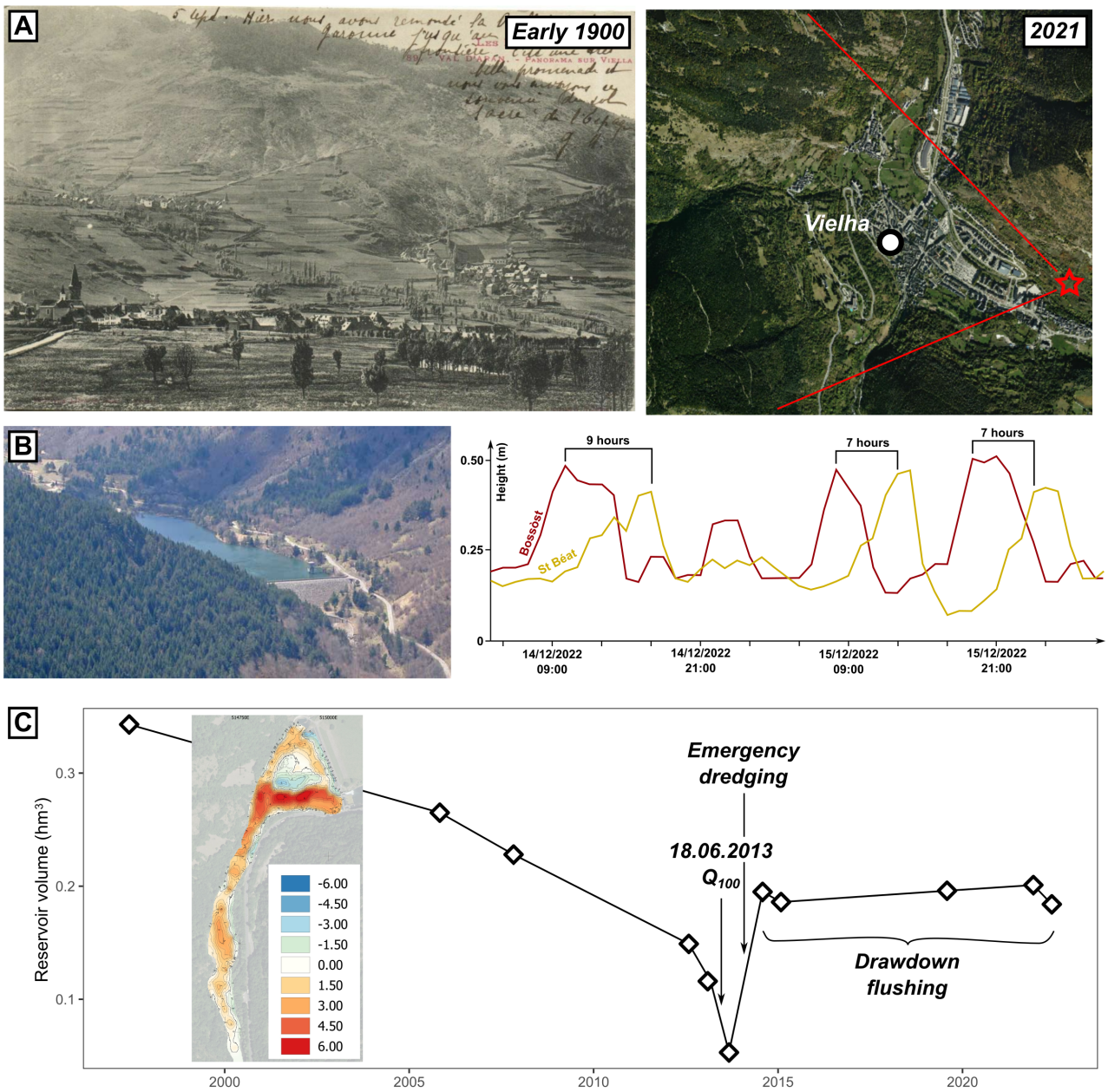


Figure 1.10. Main anthropisation factors affecting the Upper Garonne. **A.** Changes in land use over the last century in Vielha. **B.** Examples of the Aiguamog dam (left) and hydropeaks propagation between Boss ost and St B at (right). **C.** Evolution of Plan d’Arem reservoir volume since 1997. The map represents the 2007 - 1997 bathymetric DoD.

1.5. Research Problem & Methodological Framework

1.5.1. From inductive ‘expert-based’ to deductive ‘hypothesis-driven’ approaches

As river managers and institutions progressively recognised the importance of functional physical (i.e. hydro-sedimentary) processes in ecosystem services ensured by rivers (Wohl, 2019), restoration programs increasingly involved some elements of fluvial geomorphology (Wohl *et al.*, 2015). One major challenge in geomorphic diagnosis is then to provide comprehensive informations

about anthropisation impacts on fluvial systems. Methodologically, such informations have frequently been obtained from fairly inductive approaches, broadly linking a general morphological response with a set of drivers (Downs & Piégay, 2019). If such approach has provided key elements for our overall understanding of fluvial systems, and is rather reliable for river reaches impacted by a very limited number of anthropisation factors, it presents a number of limitations when more drivers concurrently affect hydro-sedimentary dynamics over a range of varying temporality and magnitude, as in most Anthropocene rivers. From a river restoration perspective, attributing one impact to one single factor, or disentangling the respective role of multiple factors in a given river response, is a critically important issue to consider when designing restoration actions that align with actors and feed river response models.

To do so, concepts in river diagnosis have recently advanced and point towards the consistency of hypothesis-driven approaches supported by comparative ‘*Control-Impact*’ sampling strategies to achieve robust analysis of causal connections between a given driver and its geomorphic effects, whether for restoration success appraisal (Marteau *et al.*, 2022) or diagnosis purposes (Vázquez-Tarrió *et al.*, 2022). On the basis of a preliminary geomorphic description, which can be rather qualitative when a reach has not already been studied, otherwise based on previous researches, one or more hypotheses are explicitly formulated, together with a set of criteria allowing for hypotheses validation or falsification. Such criteria can be defined statistically (i.e. p-value, Liébault & Piégay, 2002; Rollet *et al.*, 2014) when the sample size is sufficiently large. In a number of fluvial geomorphology studies, however, sample size is limited (1) spatially, for instance because of time-consuming field data collection (Liébault *et al.*, 2011), and/or (2) temporally, due to the lack of pre-existing long-term data (Marteau *et al.*, 2022) or the duration of field monitoring programs, only rarely exceeding 10 years (Bradley, 2017). In such cases, site-specific discriminatory criteria can be defined and tested empirically on the basis of spatio-temporal comparison between a *Control* and an *Impacted* situation. Finally, each situation has to be evaluated and compared in a dynamic perspective (i.e. in terms of trajectorial changes), in order to lessens the bias inherent to the comparison of two static states potentially being the end-product of a combination of factors, and thus not necessarily reflecting the single effect of a given driver (Dufour & Piégay, 2009).

It is within this scope that the analyses presented in this manuscript were conducted. In the following sections (1.5.2 – 1.5.4), I provide an initial chapter-by-chapter description of the study objectives, research hypotheses and operational questions, as well as an overview of fieldwork

design and methods. A more detailed description of those elements is given in each of the following result chapters.

1.5.2. Multi-decadal geomorphic response of the Upper Garonne to river and catchment anthropisation

In this chapter, we aim at evaluating morphological changes caused by the Plan d'Arem dam, and disentangling its morphological effects from other drivers (post-Little Ice Age climate change, changes in agricultural practice, catchment afforestation, upstream damming, and by-passing). The main operational issue addressed within this chapter is the achievement of a robust knowledge basis on the long-term evolutionary pathways at the reach-scale to further identify potential action levers that effectively align with involved actors and current river morphodynamics.

To do so, the work is based on a *Before-After-Control-Impact* (BACI) approach, a space-time and hypothesis-driven strategy that should allow for such discrimination. After a preliminary assessment of the drivers of change, we explicitly formulated the following hypotheses:

(H2.1) Due to the reduction in hydrological activity and hillslopes afforestation post-Little Ice Age, the study reach has experienced a first phase of hydro-sedimentary dynamics reduction which resulted in the simplification of channel planforms (before 1955).

(H2.2) Cumulative effects of headwater dams on flood hydrology and sediment continuity increased the rate of on-going change (1955 – 1970).

(H2.3) After its construction, the Plan d'Arem dam has reduced flood hydrology and disrupted sediment continuity, and induced channel narrowing, incision and bed coarsening downstream (1970 – 2014).

(H2.4) After 2014, flushing actions operated on the dam have preserved natural-like flood hydrology and restored sediment conveyance, resulting in the preservation of post-2013 flood planforms.

To address these hypotheses, we distinguished three sub-reaches (upstream Plan d'Arem – by-passed reach – downstream the restitution) and four sub-periods (before headwaters damming, after headwaters damming, after the construction of the Plan d'Arem dam, and after the 2013-flood), and characterised reach-specific morphological changes by coupling historical (aerial photographs, discharge series, water surface elevation longprofiles, reservoir bathymetry) and original (bed grain size distribution) data.

1.5.3. Bedload transport regime along the Upper Garonne continuum

The main objectives addressed in this chapter are: (1) according to the catchment-scale diagnosis presented in Chapter 2, to identify the key factors controlling differences in bedload transport regime, (2) to provide estimates of bedload transport at different stations distributed along the study reach and potentially experiencing such differences, and (3) to propose reach-specific practical recommendations on bedload management along the continuum based on the restoration of sediment transport processes, in line with the alterations observed.

After an initial assessment of factors that may lead to sediment transport alterations, we formulated a set of hypotheses on the varying transport regime we expect:

(H3.1) As sediment supply probably presents large variability due to local variations in anthropisation and configuration of the river network, we expect transport regime to differ along the study reach according to such difference: the higher the supply the more efficient the transport is.

(H3.2) Similarly to sediment supply, multiple dams being managed differently should induce varying levels of hydrological alterations, which we expect to be “recorded” by bedload transport: the lower the flood hydraulics the smaller the transport is.

(H3.3) Independently from the supply and the flood hydrology, in-stream conditions, namely slope, bed surface grain size distribution, and channel morphology, induce differences in transport regime.

To address these hypotheses, four sites were selected along the study reach according to their differences in hydro-morpho-sedimentary features, and sediment transport characteristics were assessed over a 36 months sediment tracking program.

1.5.4. Effects of the Plan d’Arem dam in fine sediments interstitial storage dynamics

In this chapter, we investigated the effects of flow diversion and drawdown flushing actions on fine sediments interstitial storage dynamics downstream from the Plan d’Arem dam. Because such dynamics may not only be related to the dam itself, we first assessed its proper role in inducing fine sediment enrichment within the bed matrix, relying on a high-frequency sediment sampling programme. We then questioned whether fine sediment storage always means clogging from a functional perspective on the basis of airborne thermal infrared (TIR) mapping that allow for the detection of hyporheic water exchanges.

1.6. References

Andrieu-Ponel, V., Hubschman, J., Jalut, G., Hérail, G., 1988. Chronologie de la dégladation des Pyrénées françaises. Dynamique de sédimentation et contenu pollinique des paléolacs; application à l'interprétation du retrait glaciaire. *Bulletin de l'Association française pour l'étude du quaternaire* 25, 55–67. DOI: 10.3406/quate.1988.1866.

Arnaud, F., 2012. Approches géomorphologiques historique et expérimentale pour la restauration de la dynamique sédimentaire d'un tronçon fluvial aménagé: le cas du Vieux Rhin entre Kembs et Breisach (France, Allemagne). PhD Dissertation. University Lyon 2. 280 p.

Arnaud, F., Piégay, H., Schmitt, L., Rollet, A.J., Ferrier, V., Béal, D., 2015. Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: the Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology* 236, 163–177. <https://doi.org/10.1016/j.geomorph.2015.02.009>.

Arricau, V., Chapron, E., 2021. Archives historiques et sédimentaires des paysages lacustres du piedmont de Pyrénées (Lacs de Barbazan et de Loures-Barousses en Haute-Garonne, France). *Collection EDYTEM*, 21.

Artelia, 2015. Localisation et gestion possible des sédiments des cours d'eau de la Garonne amont et de la Pique. Study report.

Baran P., Leroyer-Gravet F., 2007. Le débit, élément-clé de la vie des cours d'eau. Bilan des altérations et des possibilités de restauration. Editions Onema, Focus, 20 p.

Batalla, R. J., 2003. Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Cuaternalario y Geomorfologia*, 17(3).

Batalla, R.J., Gibbins, C.N., Alcazar, J., Brasington, J., Buendia, C., Garcia, C., Llana, M., Lopez, R., Palau, A., Rennie, C., Wheaton, J.M., Vericat, D., 2021. Hydropeaked rivers need attention. *Environ. Res. Lett*, 16: 021001. DOI: 10.1088/1748-9326/abce26

Batalla, R. J., Gómez, C. M., Kondolf, G. M., 2004. Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290: 117 – 136. DOI: 10.1016/j.jhydrol.2003.12.002

Batalla, R. J., Vericat, D., 2011. A review of sediment quantity issues: Examples from the River Ebro and adjacent basins (Northeastern Spain). *Integrated Environmental Assessment and Management*, 7(2): 256 – 268. DOI: 10.1002/ieam.126

Bankhead, N.L., Thomas, R.E., Simon, A., 2017. A combined field, laboratory and numerical study of the forces applied to, and the potential for removal of, bar top vegetation in a braided river. *Earth Surface Processes and Landforms*, 42(3): 439-459. DOI: 10.1002/esp.3997

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. *Bioscience* 60(3): 209–222. DOI: 10.1525/bio.2010.60.3.7

Beguiría, S., López-Moreno, J., Gómez-Villar, A., Rubio, V., Lana-Renault, N., García-Ruiz, J., 2006. Fluvial adjustments to soil erosion and plant cover changes in the Central Spanish Pyrenees. *Geografiska Annaler* 88A (3), 177–186. DOI: 10.1111/j.1468-0459.2006.00293.x

Blanpied, J., 2019. La torrentialité dans les Pyrénées centrales : évolution depuis la fin du Petit Âge Glaciaire, spécificités et dynamiques géomorphologiques actuelles. PhD Dissertation. University of Toulouse Jean Jaurès.

Boix-Fayos, C., Barberá, G.G., López-Bermúdez, F., Castillo, V.M., 2007. The impact of land use change and check-dams on catchment sediment yield. *Hydrol. Process.* 22 (25): 4922–4935. DOI : 10.1016/j.geomorph.2007.02.003

Boix-Fayos, C., de Vente, J., Martínez-Mena, M., Barberá, G.G., Castillo, V., 2008. The impact of land use change and check-dams on catchment sediment yield. *Hydrol. Process.* 22 (25), 4922–4935. DOI: 10.1002/hyp.7115.

Bosc, S., Nars, A., Menchi, O., 2012. Etude de l'impact des éclusées hydroélectriques sur les peuplements piscicoles du haut bassin de la Garonne. Action MPIEG 11. MIGADO. Study report.

Boutault, F., Piégay, H., Bulteau, T., Lascaux, J.-M., in prep. Understanding drivers of change, a preliminary step to assess anthropised river responsiveness and recovery. The Middle Dordogne River, France. *Geomorphology*.

Bradley, D.N., 2017. Direct observation of heavy-tailed storage times of bed load tracer particles causing anomalous superdiffusion. *Geophysical Research Letters* 44: 12227-12235. DOI: 10.1002/2017GL075045

Bravard, J.-P., Amoros, C., Pautou, G., Bornette, G., Bournaud, M., Creuzé des Châtelliers, M., Gibert, J., Peiry, J.-L., Perrin, J.-F., Tachet, H., 1997. River Incision in South-East France: Morphological Phenomena and Ecological Effects. *Regul. Rivers: Res. Manag.* 13: 75–90. DOI: 10.1002/(SICI)1099-1646(199701)13:1<75::AID-RRR444>3.0.CO;2-6.

Bravard J.P., Kondolf G.M., Piégay H., 1999. Environmental and societal effects of channel incision and remedial strategies. In: Darby S.E. & Simon A. [eds], *Incised Rivers Channels*, John Wiley & Sons, Chichester, 303-342.

Brooks, A., 1987. River channel adjustments downstream from channelization works in England and Wales. *Earth Surface Processes & Landforms*, 12: 337–351. DOI: 10.1002/esp.3290120402

Brunke, M., Gonsler, T., 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* 37:1-33. DOI : 10.1046/j.1365-2427.1997.00143.x

Buendia, C., Batalla, R.J., Sabater, S., Palau, A., Marcé, R., 2016a. Runoff trends driven by climate and afforestation in a Pyrenean basin. *Land Degrad. Dev.*, 27, 823–838. DOI: 10.1002/ldr.2384

Buendia, C., Bussi, G., Tusset, J., Vericat, D., Sabater, S., Palau, A., Batalla, R.J., 2016b. Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment. *Sci. Tot Env.*, 540: 144-157. DOI: 10.1016/j.scitotenv.2015.07.005

Bunte, K., 2004. State of the Science Review Gravel Mitigation and Augmentation Below Hydroelectric Dams: A Geomorphological Perspective. Stream Systems Technology Center. USDA Forest Service. 145 p.

Caissie, D., 2006. The thermal regime of rivers: a review. *Freshwater Biology*, 51: 1389 – 1406. DOI: 10.1111/j.1365-2427.2006.01597.x

Coll, M., Durbe, G., Bosc, S., Menchi, O., 2016. Evaluation du colmatage du substrat des frayères à salmonidés sur le bassin de la Garonne amont. Study report.

Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., Lenzi, M.A., 2001. Channel Adjustments and Vegetation Cover Dynamics in a Large Gravel Bed River over the Last 200 years. *Geomorphology*, 125: 147–159. DOI: 10.1016/j.geomorph.2010.09.011.

Costanza, R., Voinov, A., Boumans, R., Maxwell, T., Villa, F., Wainger, L., Voinov, H., 2002. Integrated ecological economic modeling of the Patuxent River watershed, Maryland. *Ecol. Monogr.*, 72(2): 203–231. DOI: 10.1890/0012-9615(2002)072[0203:IEEMOT]2.0.CO;2

Csiki, S., Rhoads, B.L., 2010. Hydraulic and geomorphological effects of run-of-river dams. *Prog. Phys. Geogr.* 34 (6), 755–780. DOI: 10.1016/j.geomorph.2013.10.009.

Csiki, S., Rhoads, B.L., 2014. Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology* 206, 215–229. DOI: 10.1177/0309133310369435.

Costanza, R., Voinov, A., Boumans, R., Maxwell, T., Villa, F., Wainger, L., Voinov, H., 2002. Integrated ecological economic modelling of the Patuxent River watershed, Maryland. *Ecol. Monogr.*, 72: 203–231. DOI: 10.1890/0012-9615(2002)072[0203:IEEMOT]2.0.CO;2

David, M., 2018. Dynamique sédimentaire dans le bassin de la Garonne Amont. CNRS UMR 5602 GEODE. Study report. 171 p.

Dépret, T., Piégay, H., Dugué, V., Vaudor, L., Faure, J.-B., Le Coz, J., Camenen, B., 2019. Estimating and restoring bedload transport through a run-of-river reservoir. *Sci. Tot. Env.* 654: 1146 – 1157. DOI: 10.1016/j.scitotenv.2018.11.177.

Dépret, T., Vermoux, C., Gautier, E., Piégay, H., Doncheva, M., *et al.*, 2021. Lowland gravel-bed river recovery through former mining reaches, the key role of sand. *Geomorphology*, 373: 107493. DOI: 10.1016/j.geomorph.2020.107493.

Downs, P.W., Gregory, K.J., 2004. *River Channel Management. Towards Sustainable Catchment Hydrosystems*. Arnold, London, UK, ISBN 978-1-4441-1907-7, 395 pp.

Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late "Anthropocene": implications, limitations, prospect. *Geomorphology* 338, 88–104. <https://doi.org/10.1016/j.geomorph.2019.03.021>.

Duclos, G., 2018. Mise à jour de l'inventaire des zones potentielles de frayères de Salmonidés sur la Garonne amont – Etat des lieux sur le transport solide et la recharge sédimentaire post crue 2018. FDAAPPMA31. MS thesis.

Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration : forget natural references and focus on human benefits. *River Research and Applications*, 25 : 568-581. DOI : 10.1002/rra.1239

Fernandes, M., Oliva, M., Palma, P., Ruiz-Fernandez, J., Lopes, L., 2017. Glacial stages and post-glacial environmental evolution in the Upper Garonne valley, Central Pyrenees. *Sci. Total Environ.* 584-585, 1282–1299. DOI: 10.1016/j.scitotenv.2017.01.209.

Francis, R.A., Gurnell, A.M., Petts, G.E., Edwards, P.J., 2005. Survival and Growth Responses of *Populus Nigra*, *Salix Elaeagnos* and *Alnus Incana* Cuttings to Varying Levels of Hydric Stress. *For. Ecol. Manag.*, 210: 291–301. DOI: 10.1016/j.foreco.2005.02.045

Gallart, F., Llorens, P., 2004. Observations on land cover changes and water resources in the headwaters of the Ebro Catchment, Iberian Peninsula. *Physics and Chemistry of the Earth, Parts A/B/C* 29 (11): 769-773. DOI: 10.1016/j.pce.2004.05.004.

Gaeuman, D., 2012. Mitigating downstream effects of dams. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), *Gravel-bed Rivers. Processes, Tools, Environments*. John Wiley and Sons, Chichester, UK, pp. 182–189.

Girel, J., Garguet-Duport, B., Pautou, G., 1997. Present structure and construction processes of landscapes in Alpine floodplains. A case study: the Arc-Isère confluence (Savoie, France). *Environmental Management*, 21(6), 891-907. DOI: 10.1007/s002679900075

Graf, W. L. 1975. The impact of suburbanisation on fluvial geomorphology. *Wat. Resour. Res.* 11: 690 – 692. DOI: 10.1029/WR011i005p00690

Gregory, K.J. 1977. The context of river channel changes. In Gregory, K. J. (Ed.), *River Channel Changes*. Wiley, Chichester. pp. 1-12

Gregory, K.J., Park, C.C., 1974. Adjustment of river channel capacity downstream from a reservoir. *War. Resour. Res.*, 10 : 870 – 873. DOI: 10.1029/WR010i004p00870

Gibbins, C., Vericat, D., Batalla, R.J., 2007. When is stream invertebrate drift catastrophic ? The role of hydraulics and sediment transport in initiating drift during flood events. *Freshwater Biology*, 52(12): 2369-2384. DOI: 10.1111/j.1365-2427.2007.01858.x

Harvey, B., McBain, S., Reiser, D., Rempel, L., Sklar, L., 2005. Key Uncertainties in Gravel Augmentation: Geomorphological and Biological Research Needs for Effective River Restoration. *Gravel Augmentation Report (April)*: 99.

Hjorth, P., 2012. Large dams and environment. In Bengtsson, L., Herschy, R. W., Fairbridge R. W., 2012. *Encyclopedia of Lakes and Reservoirs*. Springer. ISBN: 978-1-4020-5616-1

Honsell M., 1885. Atlas zum dritten heft: Die Korrektion des Oberrheines von der Schweizer bis zur Gr. Hessischen Grenze. *Beitrage zur hydrologie des Grossherzogthums Baden*. Enthaltend: Eine Karte des Oberrheines in fünf Blättern und acht figurentaffeln. Karlsruhe.

Huet, M., 1954. Biologie, profils en long et en travers des eaux courantes. *Bulletin Français de Pisciculture*, 175: 41-53.

Ibiate, A., Diaz, E., Ollero, A., Acin, V., Granado, D., 2013. Channel response to multiple damming in a meandering river, middle and lower Aragon River (Spain). *Hydrobiologia* 712, 5–23. DOI: 10.1007/s10750-013-1490-0.

Janssen, P., Stella, J. C., Piégay, H., Räßle, B., Pont, B., Faton, J.-M., Cornelissen, J. H. C., Evette, A., 2020. Divergence of riparian forest composition and functional traits from natural succession along a degraded river with multiple stressor legacies. *Science of the Total Environment*, 721: 137730. DOI: 10.1016/j.scitotenv.2020.137730

Jones, C.M., 2006. Chapter 4. Estuarine and diadromous fish metapopulations. In *Marine Metapopulations*. Eds. Kritzer, J.P., Sale, P.F., Academic Press. DOI: 10.1016/B978-012088781-1/50007-8.

Knighton D., 1998. *Fluvial Forms and Processes. A New Perspective*. Routledge. 400 p. DOI: 10.4324/9780203784662

Kondolf, G.M., 1994. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning*, 28 : 225-243. DOI: 10.1016/0169-2046(94)90010-8

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. *Environ. Manag.* 21 (4), 533–551. DOI: 10.1007/s002679900048.

Kondolf, G.M., 2000. Assessing Salmonid Spawning Gravel Quality. *Transactions of the American Fisheries Society*, 129(1): 262-281. DOI: 10.1577/1548-8659(2000)129<0262:ASSGQ>2.0.CO;2

Kondolf, G.M., 2006. River restoration and meanders. *Ecology and Society* 11(2): 42.

Kondolf, G.M., Curry, R.R., 1986. Channel erosion along the Carmel River, Monterey County, California. *Earth Surf. Process. Landf.* 11, 307–319. DOI: 10.1002/esp.3290110308.

Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2 : 256–280. DOI : 10.1002/2013EF000184.

Kondolf, G.M., Minear, J.T., McBain, S., Krause, A., Falzone, A., Lutrick, E., 2005. *Gravel Augmentation to Improve Salmonid Habitat in Rivers: General Geomorphic Considerations and Experiences from Northern California*. California Bay-delta Authority Ecosystem Restoration Program White Paper. San Francisco Estuary and Watershed Science, USA.

Kondolf, G. M., Wolman, M. G., 1993. The sizes of salmonid spawning gravels. *Water Resources Research*, 29(7): 2275-2285. DOI: 10.1029/93WR00402

Krein, A., Symader, W., 2000. Pollutant sources and transport patterns during natural and artificial flood events in the Olewiger Bach and Kartelbornsbach basins, Germany, in: *Proceedings of a Symposium Held at Waterloo*. IAHS, Waterloo, pp. 167–173.

Kuhl, D., 1992. 14 years artificial grain feeding in the Rhine downstream the barrage Iffezheim. *Proc. 5th Int. Symposium River Sedimentation*, Karlsruhe, Germany, pp. 1121–1129.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering. *Journal of the Hydraulics Division*, 81: 1–17.

Latapie, A., Camenen, B., Rodrigues, S., Paquier, A., Bouchard, J.P., Moatar, F., 2014. Assessing channel response of a long river influenced by human disturbance. *Catena*, 121: 1 – 12. DOI: 10.1016/j.catena.2014.04.017

Liébault, F., Bellot, H., Chapuis, M., Koltz, S., Deschâtres, M., 2012. Bedload tracing in high-sediment-load mountain stream. *Earth Surface Processes and Landforms*, 37: 385-399. DOI: 10.1002/esp.2245

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and Piedmont Rivers and streams of Southeastern France. *Earth Surf. Process. Landf.* 27, 425–444. DOI: 10.1002/esp.328.

Llena, M., Vericat, D., Cavalli, M., Crema, S., Smith, M.W., 2019. The effects of land use and topographic changes on sediment connectivity in mountain catchments. *Sci. Total Environ.* 660, 899–912. DOI: 10.1016/j.scitotenv.2018.12.479

Loire, R., Grosprêtre, L., Malavoi, J.-R., Ortiz, O., Piégay, H., 2019a. What discharge is required to remove silt and sand downstream from a dam? An adaptive approach on the Selves River, France ». *Water* 2019, 11, 392 ; DOI :10.3390/w11020392.

Loire, R., Piégay, H., Malavoi, J.-R., Beche, L. A., Dumoutier, Q., Mosseri, J., Kerjean, C., 2019b. Unclogging improvement based on interdate and interreach comparison of water release monitoring (Durance, France). *River Res Appl* 35(8) :1107-1118. DOI: 10.1002/rra.3489.

Loire, R., Piégay, H., Malavoi, J.-R., Kondolf, G. M, Bèche, L. A., 2021. From flushing flows to (eco)morphogenic releases: evolving terminology, practice, and integration into river management. *Earth-Science Reviews* 213: 103475. DOI: 10.1016/j.earscirev.2020.103475.

Ma, Y., Huang, H.Q., Nanson, G.C., Li, Y., Yao, W., 2012. Channel adjustments in response to the operation of large dams: the upper reach of the lower Yellow River. *Geomorphology* 147–148, 35-48. DOI: 10.1016/j.geomorph.2011.07.032.

Marteau, B., Michel, K., Piégay, H., 2022. Can gravel augmentation restore thermal functions in gravel-bed rivers? A need to assess success within a trajectory-based before–after control–impact framework. *Hydrol. Process.* 36(2). DOI :10.1002/hyp.14480.

McCully, P., 1996. *Silenced Rivers: The Ecology and Politics of Large Dams*. London: Zed Books. 1996.

Merz, J.E., Pasternack, G.B., Wheaton, J.M., 2006. Sediment budget for salmonid spawning habitat rehabilitation in a regulated river. *Geomorphology* 76(1–2): 207–228. DOI: 10.1016/j.geomorph.2005.11.004

Monod, B., 2014. Carte géologique numérique à 1/250 000 de la région Midi-Pyrénées. Notice technique, BRGM, 160p.

Paasche, O., Bakke, J., 2010. Defining the Little Ice Age. *Climate of the Past Discussions*, 6, 2159-2175. DOI: 10.5194/cpd-6-2159-2010

Petit, F., Poinart, D., Bravard, J.-P., 1996. Channel incision, gravel mining and bedload transport in the Rhône river upstream of Lyon, France ("canal de Miribel"). *Catena*, 26: 209 – 226. DOI: 10.1016/0341-8162(95)00047-X

Petts, G.E., Amoros, C., 1996. *Fluvial Systems*. Chapman et Hall. 332 p.

Piégay, H., Bornette, G., Citterio, A., Hérouin, E., Moulin, B., Statiotis, C., 2000. Channel instability as control factor of silting dynamics and vegetation pattern within perifluvial aquatic zones. *Hydrological Processes*, 14: 3011–3029. DOI: 10.1002/1099-1085(200011/12)14:16/17<3011::AID-HYP132>3.0.CO;2-B

Piton, G., Carladou, S., Recking, A., Tacnet, J.-M., Liébault, F., Kuss, D., Queffelec, Y., Marco, O., 2019. Functions of check-dams in steep creeks. *Cybergeo : European Journal of Geography*.

Poole, G.C., Berman, C.H., 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation. *Environ. Manag.*, 27, 787–802. DOI: 10.1007/s002670010188.

Pulg, U., Lennox, R.J., Stranzl, S., Espedal, S.O., Gabrielsen, S.E., Wiers, T., Velle, G., Hauer, C., Dønnum, B.O., Barlaup, B.T., 2022. Long-term effects and cost-benefit analysis of eight spawning gravel augmentations for Atlantic salmon and Brown trout in Norway. *Hydrobiologia*, 849: 485–507. DOI: 10.1007/s10750-021-04646-2.

Recking, A., Vázquez Tarrío, D., Piton, G., 2022. The contribution of grain size sorting to the dynamics of the bedload active layer. *Earth Surface Processes and Landforms*. DOI: 10.1002/esp.5530.

Riquier, J., Piégay, H., Michalkova, M. S., 2015. Hydromorphological conditions in eighteen restored floodplain channels of a large river: linking patterns to processes. *Freshwater Biology*, 60 (6): 1085-1103. DOI:10.1111/fwb.12411.

Rodrigues, S., Bréhéret, J.-G., Macaire, J.-J., Greulich, S., Villar, M., 2007. In-channel woody vegetation controls on sedimentary processes and the sedimentary record within alluvial environments: a modern example of an anabranch of the River Loire, France. *Sedimentology*, 54(1): 223 – 242. DOI: 10.1111/j.1365-3091.2006.00832.x

Rollet, A.J., Piégay, H., Dufour, S., Bornette, G., Persat, H., 2014. 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. *River Research and Applications*, 30: 939-953. DOI: 10.21002/rra.2689.

Rovira, A., Batalla, R.J., Sala, M., 2005. Response of a river sediment budget after historical gravel mining (The Lower Tordera, NE Spain). *River Research and Applications*, 21: 829-847. DOI: 10.1002/rra.885.

Schmidt J.C., Wilcock P.R., 2008. Metrics for assessing the downstream effects of dams. *Water Resources Research*, 44, W04404, DOI:10.1029/2006WR005092.

Schumm, S.A., 1977. *The fluvial system*. John Wiley & Sons, New-York, 338 p. DOI: 10.1002/esp.3290040121

Schumm, S.A., Winkley, B.R., 1994. *The Variability of Large Alluvial Rivers*. New York: American Society of Civil Engineers Press. DOI: 10.1029/95EO00262

Skalak, J., Benthem, A.J., Schenk, E.R., Hupp, C.R., Galloway, J.M., Nustad, R.A., Wicke, G.J., 2013. Large dams and alluvial rivers in Anthropocene: The impacts of the Garrison and Oahe Dams on the Upper Missouri River. *Anthropocene*, 2 : 51 – 64. DOI : 10.1016/j.ancene.2013.10.002

- Staentzel, C., Kondolf, G.M., Schmidt, L., Combroux, I., Bariller, A., Beisel, J.-N., 2020. Restoring fluvial forms and processes by gravel augmentation or bank erosion below dams: A systematic review of ecological responses. *Sci. Tot. Env.* 706: 135743. DOI: 10.1016/j.scitotenv.2019.135743
- Stange, K.M., van Balen, R.T., Kasse, C., Vandenberghe, J., Carcaillet, J., 2014. Linking morphology across the glaciofluvial interface: a ¹⁰Be supported chronology of glacier advances and terrace formation in the Garonne River, northern Pyrenees, France. *Geomorphology* 207, 71–95. DOI: 10.1016/j.geomorph.2013.10.028.
- Stevaux, J., Martins, D., Meurer, M., 2009. Changes in a large regulated tropical river: the Parana River downstream from the Porto Primavera Dam, Brazil. *Geomorphology* 113, 230–238. DOI: 10.1016/j.geomorph.2009.03.015.
- Sturma, A., Antoine, J.-M., Becerra, S., Peletier, A., 2017. The Flood of June 2013 in the Garonne Pyrenees: From the Hydrological Crisis to the Territory in Crisis. *Sud-Ouest Européen*, 44: 117-135. DOI: 10.4000/soe.3521.
- Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, 50: 307-326. DOI: 10.1016/S0169-555X(02)00219-2
- Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The River Continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37: 130-137. DOI: 10.1139/f80-017
- Vázquez-Tarrío, D., Tal, M., Parrot, E., Camenen, B., 2022. Effects of continuous embankments and successive run-of-the-river dams on bedload transport capacities along the Rhône River, France. *Sci Total Environ.*, 658: 1375-1389. DOI: 10.1016/j.scitotenv.2018.12.109.
- Vázquez-Tarrío, D., Tal, M., Parrot, E., Piégay, H., 2022. Can we incorrectly link armouring to damming? A need to promote hypothesis-driven rather than expert-based approaches in fluvial geomorphology. *Geomorphology*, 413: 108364. DOI: 10.1016/j.geomorph.2022.108364.
- Vericat, D., Batalla, R.J., 2006. Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology*, 79 : 72 – 92. DOI : 10.1016/j.geomorph.2005.09.017
- Vericat, D., Ville, F., Palau-Ibars, A., Batalla, R.J., 2020. Effects of Hydropeaking on Bed Mobility: Evidence from a Pyrenean River. *Water*, 12 : 178. DOI : 10.3390/w12010178.
- Verneaux J., 1981. Les poissons et la qualité des cours d'eau. *Annales scientifiques de l'Université de Franche-Comté, Besançon*: 33 - 41.
- Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J. P.M., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, 39: 169 – 190. DOI: 10.1016/S0921-8181(03)00023-7
- Ward, J. V., 1989. The four dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society*, 8: 2-8. DOI: 10.2307/1467397.
- Ward, J. V., 1992. *Aquatic Insect Ecology. Vol.1. Biology and Habitats.* Wiley, New York. DOI: 10.2307/1467653

Watts, R.J., Allan, C., Bowmer, K.H., Page, K.J., Ryder, D.S., Wilson, A.L., 2009. Pulsed flows: a review of environmental costs and benefits and best practice. National Water Commission. ISBN: 978-1-921107-77-1

Wohl, E., 2019. Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors. *Water Resources Research*, 55: 5181-5201. DOI: 10.1029/2018WR024433

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D. M., Palmer, M. A., Poff, N. L., Tarboton, D., 2005. River restoration. *Water Resources Research* 41: W10301. DOI: 10.1029/2005WR003985

Wohl, E., Lane, S. N., Wilcox, A. C., 2015. The science and practice of river restoration, *Water Resour. Res.*, 51, 5974–5997. DOI: 10.1002/2014WR016874

Yassine, R., 2020. Evaluation de l'efficacité probable d'un projet de restauration fonctionnelle et durable d'un cours d'eau. PhD Dissertation. National Polytechnique Institute of Toulouse.

CHAPTER 2. Multi-decadal geomorphic response of the Upper Garonne to river and catchment anthropisation

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Abstract

In this paper, we evaluate morphological changes related to the Plan d'Arem dam (1970), a run-of-the-river (RoR) dam located on the Upper Garonne (central Pyrenees), and disentangle its morphological effects from other drivers (post-Little Ice Age [LIA] climate change, changes in agricultural practice, catchment afforestation, upstream damming, and bypassing). The work is based on a before-after-control-impact approach, a space-time framework that allowed the stating of four hypotheses distinguishing the effects of the considered dam from other pressures. We first examined the potential reduction to the flow regime (Q_L) and bedload transport (Q_S) from these pressures, then assessed planimetric changes (1942–2019), vertical evolution (1922–2014), and sediment size within the channel. The results show the river completed adjustments related to post-LIA climate change and catchment afforestation at the beginning of the study period, with channel narrowing affecting the whole study reach and ranging from 0.6 % to 1.2 % yr⁻¹. Upstream dams and catchment afforestation reduced both the frequency and magnitude of peak flows and sediment supply, resulting in an increase in the channel narrowing rate on the upstream sub-reach (–1.2 % yr⁻¹). However, downstream tributaries buffered these changes, and no downstream propagation was found. The effects of the Plan d'Arem started around 15 years after its construction, with channel narrowing at a rate of 0.9 % yr⁻¹ until the 2010's. The exceptional flood of June 2013 resulted in important channel widening followed by a new period of narrowing upstream of the Plan d'Arem dam, combined with channel stability downstream due to a new dam management regime (flushing actions). We conclude that the before-after-control-impact approach is effective for isolating the effects of an RoR dam from those of other pressures, and that flushing actions mitigated the effects of the dam.

Keywords: *By-passed reach; RoR dam; Dam management; Channel adjustments; BACI approach; Upper Garonne River*

2.1. Introduction

River channel morphological changes observed over recent centuries are attributable to a set of pressures related to human activities that are known to influence physical and biological processes in a rapid and intense way. But fluvial systems also respond to a combination of environmental factors – climate and catchment characteristics – unsteady through time and unequally distributed in space (Downs & Gregory, 2004). Altogether, these different factors influence two main processes in the channel that are the flow regime (Q_L), particularly flood magnitude and frequency, and sediment transport (Q_S). Understanding river evolution in time and space, in response to potential changes in catchment and channel processes is both a research and practical issue. Case studies are strongly needed to (1) position the current conditions in temporal trajectories, (2) identify main factors having an effect on a specific system, (3) feed meta-analysis to better assess responsiveness and hierarchical control factors according to their effect on channel change, and (4) target the main contributors to river changes and actions that have to be carried out to meet the requirements of riverine ecosystems as well as expectations of stakeholders and overall river users.

Over the twentieth century, a significant amount of work has been done aimed at quantifying effects of human activities on river morphology, and specific contributions of each of these activities are fairly well characterised (e.g., Downs & Gregory, 2004). Within this context, the great majority of river morphology changes that occurred in European mountain rivers over the last two centuries can be related to a combination of factors (Downs & Piégay, 2019), including reduction in peak flow frequency and magnitude and associated sediment delivery following the post-Little Ice Age (LIA) climate change, hillslopes afforestation (spontaneous/man-made), river damming, channel training, and in-stream gravel mining. The trend towards stabilisation is characterised by bar encroachment and increased bank resistance (Williams & Wolman, 1984) related to changes in floodplain land-use practices (grazing decline) and river adjustments following upstream control changes such as those indicated above. The nature, spatial distribution, temporality, and intensity of drivers of changes may differ greatly from one catchment to another, often resulting in different river responses. Thus, the conclusions of previous studies cannot be directly applied elsewhere, and more case studies are needed to improve our understanding of cause-effect relationships in multi-driver contexts (Downs & Piégay, 2019).

Dams, which are one of the most widespread causes of fluvial system alterations, can be dichotomised into two types of infrastructure. In one type, a dam is built on the main course of a river impounding a large quantity of water within a reservoir. The ability of large dams to disrupt

sediment transfer (Collier *et al.*, 1996; Kondolf, 1997; Vericat & Batalla, 2006) and lower high flows (Petts, 1979; Eschner *et al.*, 1983) with significant effects on channel morphology and riverine ecosystems downstream (Rollet *et al.*, 2014) has been widely studied, and is now well documented in Europe (see Table 2.1), the U.S. (Kondolf & Curry, 1986; Jenkins *et al.*, 1988; Kondolf, 1997), Asia (Haddeland *et al.*, 2007; Ma *et al.*, 2012), South America (Agostinho *et al.*, 2004; *et al.*, 2009), and Oceania (Jellyman & Harding, 2012). In the other type, weirs or run-of-river (RoR) dams divert part of the discharge towards a canal or buried penstock pipe, and these structures can have rather different effects on the river downstream. RoR dams usually modify the hydrological regime of the by-passed reach (BPR), conveying a minimum flow most of the time, and only slightly affect peak flows and the sedimentary regime. Less effort has been made to assess river responses to bypassing activities (Csiki & Rhoads, 2010). Ryan (1997) observed that a long-term reduction in total annual discharge of 20 % to 60 % resulted in a narrowing of the active channel because of decreased base flow, which created space for recruitment during growing periods and facilitated vegetation encroachment along channel margins. Ryan (1997) highlighted a significant geomorphic control, and found that wide riffle-pool channels with gravel bars were more impacted than steep step-pool channels. Caskey *et al.* (2014) also came to similar conclusions: in mountain streams, low gradient reaches respond more actively to flow diversion by channel width reduction than do steep channels. In the case of the River Rhine (Arnaud *et al.*, 2015), previous navigation improvement works accentuated channel narrowing and bed degradation. Depret *et al.* (2018) and Vázquez-Tarrío *et al.* (2019) showed that by-passing reduced the bedload transport capacity of the Rhône River because of a slight lowering of peak flow and a flood water slope decrease. Ibisate *et al.* (2013) and Csiki & Rhoads (2014) stated that channel responses to RoR dams are not systematically observed, but are reach-specific, and other drivers may be more important. If the magnitude of peak flows is generally preserved or only slightly decreased, pioneer vegetation removal is more frequent. Among the previously cited studies, those that highlighted a significant bypassing effect all focused on relatively large rivers and infrastructures. Conversely, the effects become less evident when water is diverted by a weir, with less alteration to sediment transfer and peak flows. The by-passing modality, i.e., the nature of the water intake infrastructure, may then also exert certain downstream effects through bypassing.

Study	Time period	Study area	Drivers						
			Climate Change	Large Dams	RoR Dams	Torrent Control Works	Channelisation	Gravel Mining	Land Use Changes
Liébault <i>et al.</i> , 2005	1800 - 2000	North Island (NZ) South Alps (FR)	X			X			X
Marchese <i>et al.</i> , 2017	1850 - 1950	South Tyrol (IT)	X						
Provansal <i>et al.</i> , 2014	1860 - 1990	Rhône River (FR)	X	X	X		X	X	
Preciso <i>et al.</i> , 2012	1930 - 2000	Reno River (IT)	X			X		X	X
Ibiate <i>et al.</i> , 2013	1930 - 2010	Aragón River (SP)		X	X				X
Liébault and Piégay, 2002	1945 - 2000	SE France	X	X		X			X
Boix-Fayos <i>et al.</i> , 2007; 2008	1950 - 2000	Rogativa River (SP)				X			X
Kiss and Blanka, 2012	1950 - 2010	Hernád River (HU)	X	X					
Batalla, 2003	review	NE Spain		X				X	

Table 2.1. Literature covering multi-driver studies in Europe. RoR dams appear less studied in multi-driver context, and most studies focus on the combined effects of large dams, climate change, in-stream mining and land use changes. NZ: New-Zealand. FR: France. IT: Italy. SP: Spain. HU: Hungary.

To better understand the geomorphic effects of RoR dams within a multi-pressure context, we focus on an upland region with the objective of disentangling reach-scale from basin-scale controls, a crucial task that has partly been explored in previous studies (Rollet *et al.*, 2013; Provansal *et al.*, 2014) and requires additional case studies. For this work, we studied the Upper Garonne River in the north central Pyrenees, which is impounded by the Plan d’Arem Dam downstream of the Spain/France border. This dam feeds a diversion canal that conveys a large

proportion of annual flows to downstream HPPs, e.g., 63 % over the period 2017 – 2019; the channel may then respond intensively to such dewatering. The Garonne offers a very interesting case study as its small-sized upland catchment is generally known to show high responsiveness to drivers of change (Brown *et al.*, 2017). In this work, we assessed changes in the Garonne over the past 80 yr, and analysed the hierarchy of geomorphic controls to validate our working hypotheses (stated below).

2.2. Study area

The River Garonne (Garona) is located in the central Pyrenees, flowing through Spain and France. The study reach is 78 km in length from the source of the Garonne (1830 m a.s.l.) to the confluence with the Neste River. This mountain catchment has an area of 1265 km² at the confluence with the Neste, and encompasses a wide range of elevation from 415 to 3220 m a.s.l. (Fig. 2.1). The study reach corresponds to the largest north Pyrenean glacial valley (~80 km in length), which contained a glacier that extended from the Ruda valley to the Barbazan glacial landforms (Andrieu-Ponel *et al.*, 1988; Fernandes *et al.*, 2017; Arricau & Chapron, 2021), and reached its maximal extent ca. 35 ka BP (Andrieu-Ponel *et al.*, 1988; Stange *et al.*, 2014, Fernandes *et al.*, 2017). From its source on the Pla de Beret to the Spain-France border, the river flows successively westward and northward within the Pyrenean axial zone (Fernandes *et al.*, 2017). The valley width is less than 1 km and narrows to 100 m at the Fos glacial lock, corresponding to the Spain-France border. The reach shows an important reduction in slope gradient, from 20 % to 0.8 %, and a fluvial style that alternates between sinuous and straight patterns when the valley is sufficiently large, and strictly straight patterns in narrow gorge reaches. The valley enlarges between Fos and the St B at glacial lock, where the slope decreases to 0.7 % and the channel shows sinuous and wandering patterns. Downstream of St B at, the valley enlarges significantly, reaching 2, 4, and 3 km, in the Marignac, Fronsac, and Barbazan basins, respectively. This area corresponds to the Garonne paleolake that formed after the glacier retreated, and was progressively filled by glacial, glacio-lacustrine, lacustrine, and fluvial deposits (Fernandes *et al.*, 2017, Arricau and Chapron, 2021). In this area, the river flows northward and the slope progressively decreases from 0.5 % at St B at to 0.3% at the confluence with the Neste River, the downstream limit of this study reach. The fluvial style of this section alternates between straight and sinuous patterns. The Garonne meets the Pique, its main tributary, at river kilometer (RK) 55 from the source, which increases the catchment area by around 50% (Fig. 2.1.C). The study reach is marked by an important increase in flow discharge from upstream to downstream. The mean annual water yield at Arties (1950–1991 and 2011–2015) is 91 hm³. The Valarties, Nere, Varrados, and Jœu tributaries are then major

contributors, increasing the water yield to 538 hm³ at the Bossòst gauging station (1964–1991 and 2010–2018). The contribution from the River Toran further increases this value to as much as 613 hm³ at the Spanish catchment outlet (1931–1935 and 1948–1969). At St Béat gauging station, the annual water yield increases to 715 hm³ (1921–1929 and 1948–2018). Finally, the Pique makes another important contribution and increases the water yield to 984 hm³ at the Chaum gauging station (1993–2019).

At the catchment headwaters, a network of small dams (D1–D4, Fig. 2.1.B) constructed between 1955 and 1965 impound 4.2 hm³ of water, corresponding to 4.6 % of the annual runoff at the Arties gauging station (1950–1991). These dams divert water to the downstream hydropower plant (HPP) of Arties (H1). Buried penstock pipes then subsequently convey this water to downstream HPPs (H2–H6), while weirs and water intakes progressively increase the total discharge delivered to successive HPPs. The maximum operating discharge is 14 m³s⁻¹ at H1 and H2, 23 m³s⁻¹ at H3 and H4, and 48 m³s⁻¹ at H6 (see Fig. 2.1 for HPP locations; Daumas, 1962). Although the effect of this by-passing on sediment continuity is probably negligible (Q_s), it may affect the hydrology (Q_L) by reducing both base and peak flows. The Plan d’Arem RoR dam is located at RK40. It is the only one that directly impounds the mainstem of the Garonne River. Water travels to H7 through penstock pipes, then to H8 through an aerial canal, after which it is returned to the Garonne. The main channel is by-passed for 6 km, with a minimum ecological discharge of 4 m³s⁻¹. Because of its size and position on the Garonne mainstem, the Plan d’Arem dam disrupts sediment conveyance, thus affecting Q_s . Moreover, the discharge diversion for electricity production also affects the river’s hydrology (as for upstream by-passing, by decreasing base and peak flows (Q_L) by a maximum of 34 m³s⁻¹, the maximum operating discharge at the Fos-Arlos hydroelectric complex (H7 and H8). When the construction of the dam and the diversion canal was achieved in 1970, the water storage capacity was 0.35 hm³. After 40 yr of operation, the capacity has been reduced to a critical value of 0.10 hm³, requiring stakeholders to dredge sediment and to implement drawdown flushing actions to control sediment accumulation. When the discharge overpasses 70 m³s⁻¹ (~1-yr flood), operators stop electricity production and open the bottom gate to lower the lake level and maximise sediment transfer by restoring critical slope conditions. Therefore, drawdown flushing may minimise the effect of the dam on the downstream reach because it has no impact on peak flows and a relatively lower impact on sediment transfer. A significant portion of the river banks are protected from erosion by rip-rap – 26.9 % of the upstream catchment, 39 % of the Plan d’Arem BPR, and 41.3 % of the downstream reach – potentially reducing sediment inputs (Q_s) from this sediment reservoir and leading to channel incision where

the system experiences a sediment deficit. In-stream gravel mining has not been an official industrial activity on the Upper Garonne, where bed material extractions were generally relatively sporadic and related to flood risk mitigation and the maintenance of engineering structures. On the reach upstream of the Plan d'Arem dam, legal extractions reached 61 000 m³ over the period 1993–2012, with 40 000 m³ on the Arriu Joeu. Therefore, we can reasonably assume that gravel extractions did not exceed 100 000 m³ (taking into account declared works and estimating non-declared works), although the actual volume extracted remains unknown.

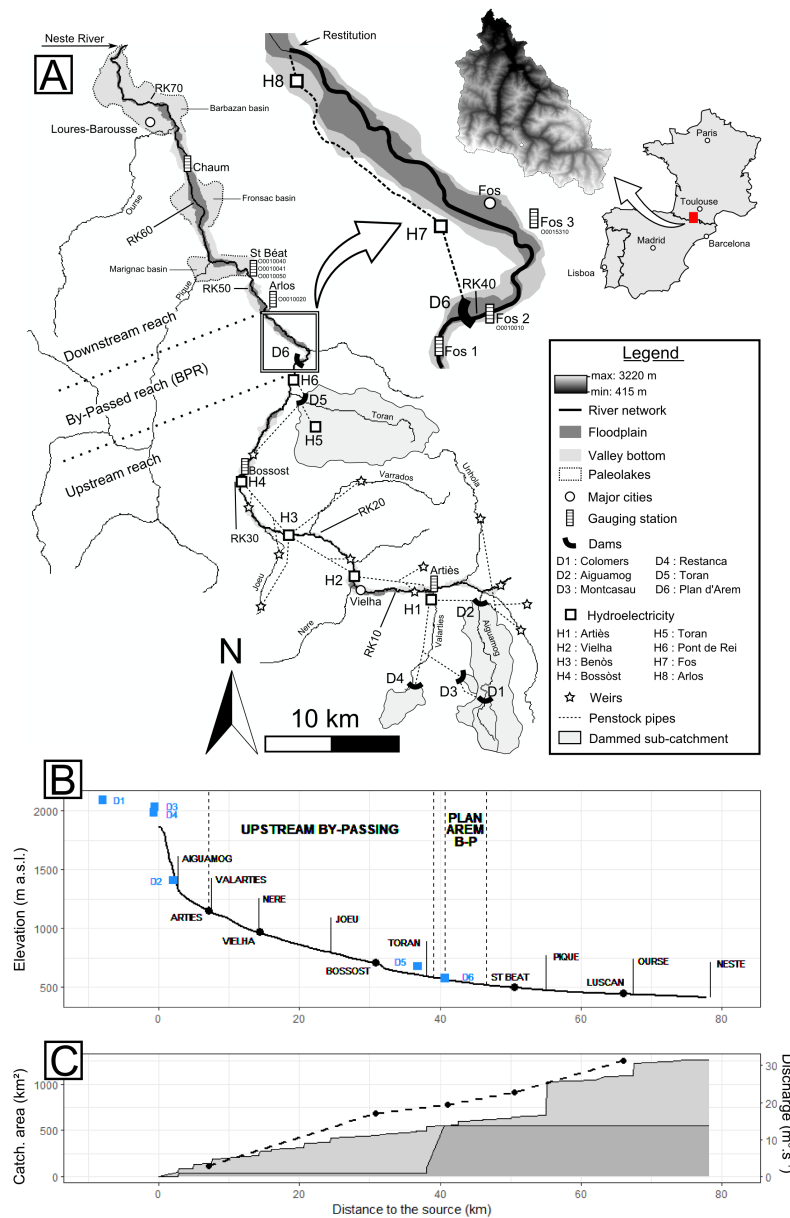


Figure 2.1. A. Location of the study site and spatial distribution of hydroelectricity production infrastructures. B. Length profile in 2014. Blue squares: dams. Black dots: main villages. Vertical lines: main tributaries. C. Cumulative catchment area (light-grey shading), cumulative disconnected area (dark-grey shading), and evolution of the mean discharge (dashed line).

2.3. Material & Methods

2.3.1. A trajectorial Before-After-Control-Impact (BACI) approach to disentangle cause-effect relationships

A BACI (Before-After-Control-Impact) approach is classically used to assess the effects of river restoration actions (Marteau *et al.*, 2022) but can be appropriate to assess the unit-effect of any driver of change. It relies on the comparison with a “pre-” state (*Before*), (e.g., before the construction of the Plan d’Arem dam), and with a reach out of the zone of influence of the considered pressure (*Control*), (e.g., upstream the Plan d’Arem dam). Those states are considered as non-impacted by the pressure for which we assess its potential effects, and we are then likely to attribute post-dam channel changes (*After - Impacted*) to the dam itself. Arguably, these are strong initial postulates that potentially introduce some bias in the methodological hypothetico-deductive framework. Even under natural conditions, i.e., without any human disturbances, river channels continuously adjust to climatic and catchment-scale forcing (Batalla *et al.*, 2018), and the multiplicity of human pressures affecting Northern Hemisphere river systems (Table 2.1) may lead to making a mistake in attributing observed changes (partially or totally) to one single factor. The Control reaches may be also impacted by other pressures and could not reflect the most representative functional conditions we observe in this geographical context without any human pressures. To avoid these bias, the choice of the reference has to be carried in a dynamic perspective, and comparison with this reference must be done in terms of changes in the temporal trajectory of studied reaches, rather than differences between two static states. By applying such approach to assess the unit effects of a RoR dam, we can distinguish them from other driver effects and therefore address issues related to nature, temporality, magnitude, and downstream propagation of change.

To distinguish effects specifically related to the Plan d’Arem dam, we divided the reach into three sub-reaches, separately considering the by-passed reach, upstream reach considered as the control, and downstream sub-reaches considered as the impacted reaches. Table 2.2 summarises the main characteristics of each of these sub-reaches.

Sub-reaches		Upstream	BPR	Downstream
Characteristics	RK	2.7 – 39.6	40.7 – 46.6	46.6 – 78.2
	Length (km)	36.9	5.9	31.6
	Mean slope	2 %	0.7 %	0.3 %
	Style in 1940’s	Wandering/Sinuuous	Wandering/Sinuuous	Sinuuous/Straight

Table 2.2. Main characteristics of the three sub-reaches studied for the BACI approach

The before-after design was used to state four hypotheses considering three distinct periods. This design allowed assessment of cause-effects in a trajectorial perspective, with consideration of RoR effects as well as other potential driver effects described in the literature (e.g., post-LIA climate change, mountain depopulation, grazing decline, and afforestation), and the study site conditions (e.g., upstream hydroelectric activity, mining, and channel regulation for flood and erosion control). Conceptually, changes in flow regime and sediment supply over a given time period induce a river morphology response. This is the logical basis to consecutively state the following hypotheses:

Before-Control: A period of pre-dam construction (before 1955)

Hypothesis H1: Following climate change, rural depopulation, grazing area abandonment, and afforestation, the catchment experienced a reduction-effect on sediment supply (Q_s1). We also hypothesise that human activities on the Pique catchment also reduced sediment supply, with these including torrent control works upstream of the Luchon plain (1870–1950) and river damming for electricity production on the Pique and its tributaries (1920–1930). The Garonne probably responded with a decrease in channel width and bed incision, and all reaches would have been affected (**UPI, BPR1, DOI**).

Before-Impact: A period of channel adjustment following dam construction in Spain (1955–1970)

Hypothesis H2: Construction of the upstream chain of dams (D1–D4) may have resulted in a reduction in peak flows (Q_L1), and especially a disruption to sediment transfer (Q_s2). Bypassing on the rest of the upstream reach may have affected the hydrology, which would also result in channel width reduction (**UP2**) by reducing peak and base flows (Q_L1). Considering that the dammed tributaries are located far upstream and that four important tributaries (Valarties, Nere, Varrados, and Joeu) reach the main course of the Garonne downstream of the chain of dams, hypothesis H2 states that dam effects are important at the catchment head and become less intense downstream (**BPR2, DO2**), with discharge and sediment supply from tributaries potentially buffering dam effects.

After-Impact: A period showing contrasting effects of the Plan d’Arem RoR dam resulting from two distinct strategies of dam management (1970–2020)

Hypothesis H3: Because of its position on the main course of the Garonne, the Plan d’Arem dam has disrupted river sediment continuity (Q_s3) and reduced the magnitude of peak flows (Q_L2). Between 1970–1984 and 1997–2014, the dam was managed without flushing actions, potentially resulting in a reduction of peak flows and coarse sediment supply. However, between 1984–1997,

flushing actions were operated, although they targeted mid-flows. We therefore hypothesise that during this period sediment continuity was partially restored, but that the removed material was mostly composed of fine sediments, with less shaping of channel morphology. As a result, H3 states that the BPR experienced channel width reduction (**BPR3**) after the dam construction, and that flushing actions performed from 1984–1997 were not efficient at buffering channel narrowing. The downstream reach (**DO2**) may not see the same pattern of channel width reduction in response to the restoration of transport capacity as soon as the operated discharge returns to the main stem of the river (see Fig. 2.1.A, “restitution”). If morphological adjustments on the downstream reach are observed during this period, they may have been attributable to the potential sediment starvation induced by the Plan d’Arem.

Hypothesis H4: Between 2014–2020, flushing actions targeting peak flows were performed. H4 therefore states that peak flows and sediment continuity were maintained, with no effect on channel morphology (**BPR3** and **DO2**). As stated in Hypothesis H3, if channel changes are first observed in the BPR and do not propagate downstream, they are related to by-passing and its potential effects on hydrology. Conversely, if these effects propagate downstream, they are related to the dam and its potential effects on sediment conveyance. If the sequence of changes scales with dam management periods, we will conclude that dam management has an effect on channel morphology.

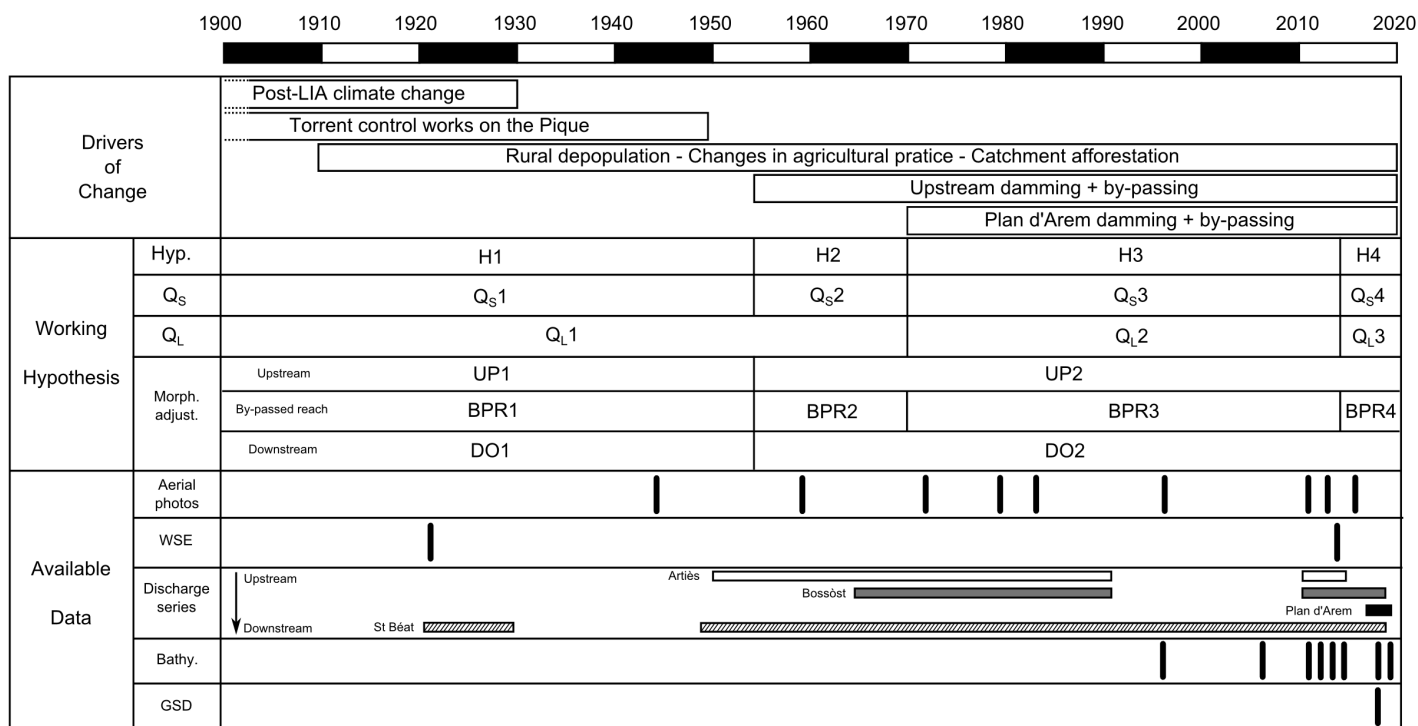


Figure 2.2. Chronology of drivers, expected changes in Q_s , Q_L , and river morphology, and available datasets (Boutault, 2020). WSE: Water surface elevation. Bathy.: Bathymetry of the Plan d’Arem lake. GSD: Grain size distribution.

2.3.2. Assessment of drivers of change

2.3.2.1. Modification of flood frequency and magnitude

Precipitation

To appreciate potential changes in precipitation over the study period, we used the daily precipitation series of Arties (see Fig. 2.1 for location). This series suffers from discontinuities, obliging us to consider three distinct periods of 1925–1943, 1964–1987, and 2006–2019. A Kruskal-Wallis test was performed to assess the significance of any hydrological changes between the periods.

Upstream damming and by-passing

Over the time that river discharge has been monitored, eight gauging stations have registered daily discharges (Fig. 2.1). To assess potential hydrological changes over the longest period possible at a point downstream of the study reach, a discharge series for St Béat was reconstructed by combining various gauging stations (see Fig. 2.1 for location details), as follows:

(1) Original data from St Béat station (Banque Hydro-stations O0010040, O0010041, O0010050) were used without any modification for the periods 1921–1929 and 1992–2019;

(2) For the period 1948–1960, we found a robust relationship ($R^2 = 0.99$) between the discharge at Fos 2 (Banque Hydro-station O0010010) and Arlos (Banque Hydro-station O0010020). The reconstructed Arlos series was then used without any transformation to reconstruct the long-series at St Béat considering the close proximity (4 km) between the stations and the absence of a major tributary in between them;

(3) For the period 1960–1970, we added the discharge at the Fos 2 (Banque Hydro-station O0010010) corresponding to the Garonne at Plan d’Arem to the discharge at Fos 3 (Banque Hydro-station O0015310) corresponding to the Maudan torrent (gauged since 1960, and the only tributary between Plan d’Arem and St Béat), a significant contributor with an average discharge of around $1 \text{ m}^3\text{s}^{-1}$ and up to $10 \text{ m}^3\text{s}^{-1}$ during floods;

(4) For the period 1971–1991, we used the discharge series of the Arlos station (Banque Hydro-station O0010020), as used for 1948–1960.

To assess the effect of upstream dams on hydrology, the discharge series at Arties was analysed, considering 1950–1965 as the pre-dam period, and 1966–1991 and 2011–2015 as the post-dam period. The magnitude and frequency of peak flows were extracted and compared for both periods. The downstream effects of upstream dams were evaluated using the reconstructed

discharge for St Béat, considering 1921–1928 and 1948–1965 as the pre-dam period, and 1966–2019 as the post-dam period. We used a Gumbel type 1 distribution to determine discharge associated with 1-yr, 2-yr, 5-yr, 10-yr, and 20-yr floods before and after damming. We used the ratio of the post-dam to pre-dam discharge to assess the dam’s impact over previously cited return periods (Batalla *et al.*, 2004). To assess the effects of upstream bypassing, with there being no discharge series available before bypassing, we used the discharge series at Bossòst over the period 2017–2019, for which “electricity productive” discharge is available. The reduction in the peak discharge by bypassing was then back-calculated for the periods 1964–1991 and 2010–2018.

Plan d’Arem by-passing

Providing information on dam management, the 1-hr discharge series at Plan d’Arem operating station (Electricité De France, personal comm.) was analysed for the period 2017–2019. Low flows, high flows, and peak flows were considered separately to quantify the effect of the Plan d’Arem Dam on each. Low flows were defined as those from July to March, high flows from April to June, and peak flows as discharge exceeding $70 \text{ m}^3\text{s}^{-1}$, which is the threshold used to trigger sediment flushing. The effect of the Plan d’Arem dam on peak flows was quantified for both management methods, namely with and without drawdown flushing actions, considering the dam to reduce the discharge by its maximum operating capacity, $\sim 34 \text{ m}^3\text{s}^{-1}$, when managed without flushing.

2.3.2.2. *Change in sediment delivery*

Rural depopulation and grazing decline

Considering the lack of available and robust datasets, retrospective quantification of the effects of changes in economic and agricultural practices on sediment delivery is difficult, especially for early periods. Nevertheless, some authors (Scorpio & Piégay, 2020; Boutault, 2020) have successfully employed population density as a proxy for global trends in catchment occupation. In the case of the Garonne upstream catchment, population census campaigns were carried out on a 10-yr basis since the beginning of twentieth century up to 1970, and on a 5-yr basis from then on. With the aim of assessing changes in sediment delivery related to the evolution of agricultural practices, we investigated changes in the proportion of the population living in rural areas. This task was achieved by splitting the datasets into two subsets, one corresponding to the two main urban areas of Vielha and Naut Aran, and the other corresponding to the rest of the catchment. In parallel, we reviewed the existing literature on livestock breeding and exchange in this area of the Pyrenees.

Catchment afforestation

Afforestation of the Plan d’Arem catchment was assessed for 3 dates: 1957, 1987, and 2017 (Table 2.3). Orthophotographs from 1957 were resampled at a resolution of 30 m. The main land uses were then extracted using a nine-class unsupervised classification. A majority filter was applied to delineate larger areas with a similar land use and reduce the bias related to inaccurate classification. Land use maps from 1987 and 2017 were reclassified to extract all areas covered by forest. The catchment was then divided into three land use units: ‘bare areas’ that correspond typically to highest and non-vegetated area, ‘meadows’ which mostly corresponds to pasture grasslands, and ‘forests’ as tree-dominated areas.

Year	1957	1987	2017
Source	Spanish National Geographic Institute	Institute of Cartography and Geology of Catalunya	Research Center of Ecology and Forest Application
Type	Orthophotographs	Land use maps	Land use maps
Resolution (m)	0.5	30	30

Table 2.3. Available data for characterisation of land-use changes

Plan d’Arem RoR dam

During the first period following the Plan d’Arem construction (1970–1984), no actions were taken to control sediment storage, allowing the dam reservoir to trap all or part of the upstream sediment supply, and potentially equally depleting the downstream reach. Although no data is available on the sediment accumulation during this period, the dam owner implemented drawdown flushing actions in 1984, performing these at mid-flows, but then returned to the previous management strategy without flushing flows in 1994, and started repeated bathymetric surveys (Table 2.4). The compiled dataset, together with grain size measurements (see Section 2.3.3.3.) constitutes the most relevant proxy for assessing the efficiency of sediment transfer through the dam. Over the period of bathymetric surveys, 10 campaigns were completed, covering from 47% to 100% of the reservoir. For each survey, a Digital Elevation Model was created by interpolating point clouds using the Triangulated Irregular Network tool in ArcMap10.6.1 (advanced license). The storage capacity was then defined as the volume between the lake bottom Digital Elevation Model and the maximum operating water level of 577.5 m a.s.l., using the Surface – Volume tool (3D-Analyst). These volumes were then extrapolated to the entire lake surface using simple linear regression, with the 1997 bathymetric survey being used as a reference for the largest extent (see Table 2.4).

Date	1997– 05	2007– 10	2012– 07	2013– 02	2013– 08	2014– 07	2015– 01	2015– 12	2018– 07	2019– 07
Type	Multi	Mono	Multi	Mono	Multi	Multi	Multi	Multi	Multi	Multi
Extent (%)	100	96	73	68	47	63	63	86	86	73

Table 2.4. Available bathymetric datasets for the Plan d’Arem reservoir

2.3.3. Assessment of channel geomorphic responses in space and time

2.3.3.1. Planform evolution

Analysis of the planform evolution of river channels is one of the most common strategies for assessing and ranking the cumulative effects of various factors affecting changing river morphology. It provides key information about the magnitude and temporality of the changes, as well as a good understanding of the sensitivity of river reaches through the whole continuum, sensitivity being an especially important parameter to evaluate in our case because the study reach encompasses very different conditions of slope, grain size distributions, vicinity with hillslope sediment sources, thus may adjust very differently according to initial conditions. Analysis of planform evolution is also well-adapted to a trajectorial BACI approach. For this purpose (Table 2.5), the active channel width (active gravel bars and wetted channel), wetted channel, and islands were digitised for each date. Bars were then extracted by subtracting the wetted channel from the active channel area. As the available photographs extended over two countries, the results are presented using a mean date for graphical purposes. Real dates were kept for narrowing the calculation of rates and statistical analysis. To better characterise the morphological adjustments following the Plan d’Arem dam construction, the active channel was digitised for 1972, 1983, and 2019 in the by-pass reach only. For each sub-reach, a Mann-Whitney U test was performed to assess the significance of differences in active channel width between consecutive dates and sub-reaches.

Common date	Real date	Discharge (m ³ s ⁻¹)	Type	Pixel size (m)	RMSE (m)
1944	09/1945 07–09/1946	-	OP	4	-
	23/06– 07/08/1942	-	AP	0.5	-
1959	1956	-	OP	0.5	-
	11/08/1962	12	AP	0.5	-
1972	03/1972	9–29	AP	0.12	
1979	1979	-	AP	0.67	3.69
	08/07/1979	30	AP	0.5	-
1983	05/08/1983	12	AP	0.65	
1997	07/1997	16–30	OP	2	-
	17/06– 19/07/1996	46–27	AP IR	0.48	2.75
2011	06/2012	19–60	OP	0.5	-
	07/08/2010	15	AP	0.5	-
2013	01-10/08/2013	22–27	OP	1	-
	21/08/2013	21	AP	0.35	1.35
2016	20-26/08/2015	12	OP	0.5	-
	2016	-	OP	0.5	-
2019	15/09/2019	10	OP	0.1	

Table 2.5. Available data for characterisation of the Upper Garonne River planform evolution

2.3.3.2. Grain size distribution over the channel continuum

Study of the longitudinal distribution of grain size facilitates a time substitution strategy permitting reflections of past adjustments in sediment transport and informing on potential discontinuities in transport conditions (e.g., armoring following sediment starvation, sediment supply and propagation from a specific source, change in transport capacity). A total of 28 bar heads

were sampled in winter 2019, picking 100 particles and following a grid-by-number protocol (Wolman, 1954; Rice and Church, 1998; Bunte and Abt, 2001) on both surface and subsurface layers (Buffington, 1996). The armouring ratio was calculated as the ratio between the surface median grain size ($D50_{SURF}$) and the subsurface median grain size ($D50_{SUB}$).

2.4. Results

2.4.1. Temporality and intensity of changes of potential drivers

2.4.1.1. Rainfall changes

Analysis of the precipitation series shows that annual precipitation decreased from a median 1048 mm yr⁻¹ for 1925–1943, to 835 mm yr⁻¹ for 1964–1987 and to 780 mm yr⁻¹ for 2006–2019 (Fig. 2.3), indicating a climatic fluctuation during the Q_{LI} period. A Kruskal-Wallis test indicated that these changes are statistically significant (p-value = 0.012).

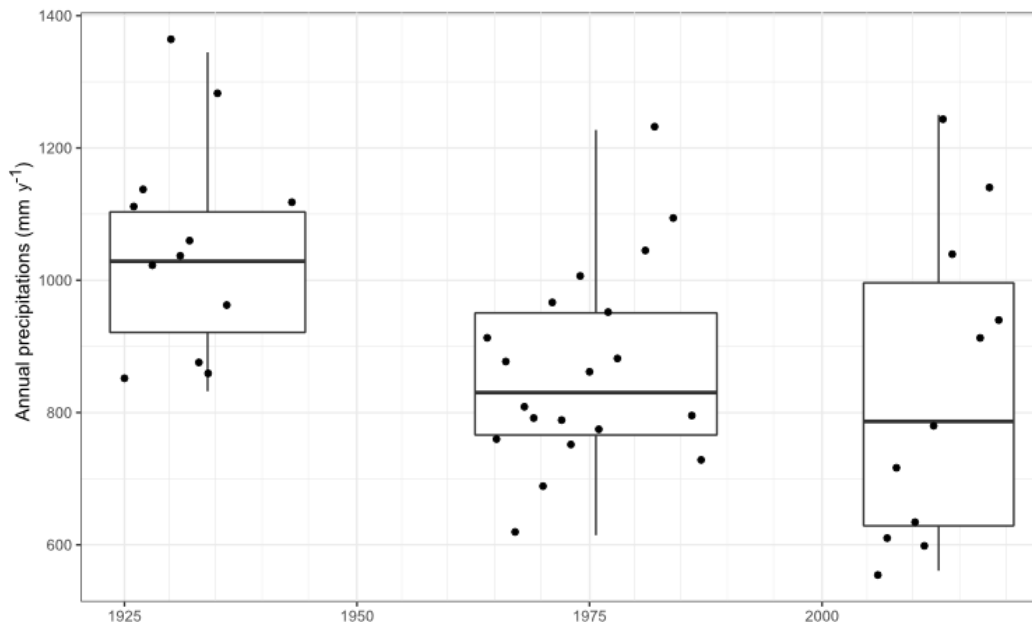


Figure 2.3. Annual precipitation at Arties over 1925 – 2019

2.4.1.2. Changes in peak flows

Upstream dams

Analysis of annual maximum peak discharges at the Arties station shows that upstream damming drastically decreased both the magnitude and frequency of flood events (Fig. 2.4, Table 2.6, Q_{LI}). A major reduction in the frequency of floods was observed, with a decrease of 58 % and 34 % in 2-yr and 5-yr floods, respectively. Larger events, typically with a return period over 10 yr, also showed a strong reduction in frequency, with 23 % lower 10-yr floods and 16 % lower 20-yr

floods. Interestingly, this reduction in peak flows is restricted to the reach immediately downstream from the chain of dams. Non-dammed tributaries, namely the Nere, Varrados, and Jœu rivers, provide important contributions to the supply of water to the Garonne main course, mitigating the effects of upstream dams on hydrology. At St B at gauging station, the peak discharges remained relatively unchanged after closure of the dams, and even increased somewhat in relation to the heavy runoff conditions during the 1970's. We observed Q₂, Q₅, Q₁₀, and Q₂₀ increases of 2 %, 8 %, 11 %, and 13 %, respectively.

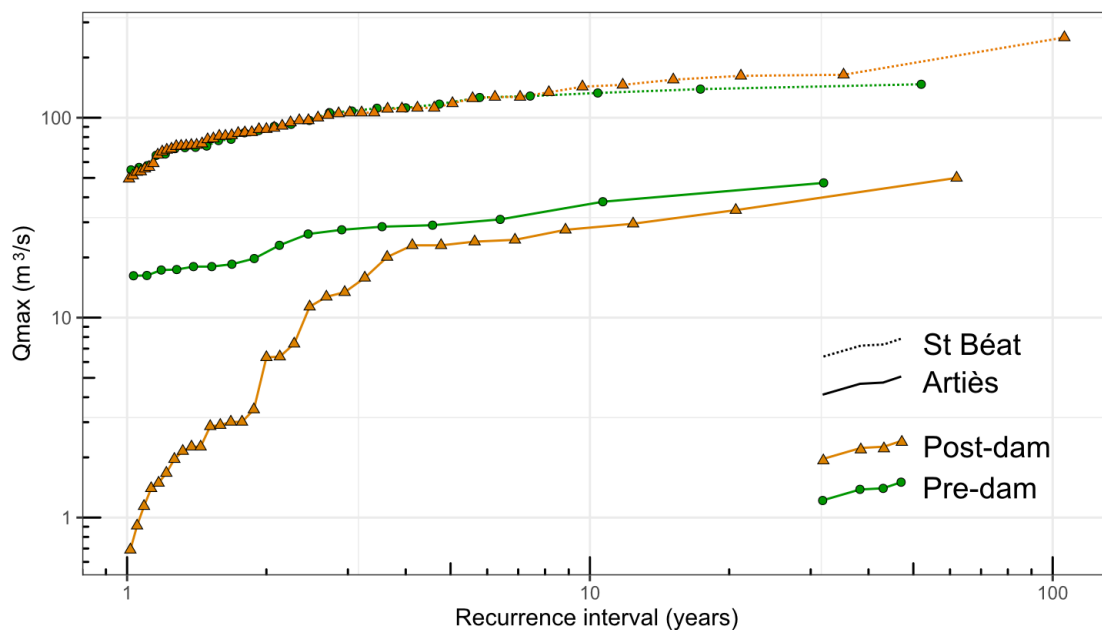


Figure 2.4. Changes in flood magnitude and frequency downstream from the headwater dams

		Q₂ (m³s⁻¹)	Q₅ (m³s⁻¹)	Q₁₀ (m³s⁻¹)	Q₂₀ (m³s⁻¹)
Art�es	Pre-dam	23	31	36	41
	Post-dam	10	21	28	35
	�	0.42	0.66	0.77	0.84
St B�at	Pre-dam	89	113	129	144
	Post-dam	91	123	144	164
	�	1.02	1.08	1.11	1.13

Table 2.6. Changes in flood magnitude and frequency downstream from the headwater dams

Upstream by-passing

At Bossòst, an average discharge of $8 \text{ m}^3\text{s}^{-1}$ (ranging from 7 to $10 \text{ m}^3\text{s}^{-1}$) was permanently diverted to feed downstream HPPs over the period 2017–2019. The hydrological reduction related to this by-passing was therefore constant, affecting both low and peak flows. For the same period, the bypassing resulted in an average reduction of 36 % in the total annual discharge. Back-calculation of the effect of the diversion shows Q1 ($70\text{--}77.5 \text{ m}^3\text{s}^{-1}$), Q2 ($77.5\text{--}85 \text{ m}^3\text{s}^{-1}$), Q5 ($85\text{--}90 \text{ m}^3\text{s}^{-1}$), and Q10 ($90\text{--}95 \text{ m}^3\text{s}^{-1}$) were lowered by 8% to 10% (Q_{L1}).

Plan d’Arem RoR dam

Over the period 2017–2019, for which the “electricity producing” discharge is available at Plan d’Arem, bypassing resulted in an average reduction in the total annual discharge of 63 % within the by-passed reach. Base and high flows were reduced by 66 % and 59 %, respectively. This dam, without regard to its management, had considerable effects on the hydrology of both low and high flow periods. Conversely, for the same period, peak flows ($> 70 \text{ m}^3\text{s}^{-1}$) remained unaltered by the Plan d’Arem because of the drawdown flushing actions. In the case that the Plan d’Arem dam is managed without flushing actions targeting peak flows, as was the situation over 1970–2014, peak flow is reduced by $34 \text{ m}^3\text{s}^{-1}$, corresponding to 37 % of Q2, 28 % of Q5, and 24 % of Q10. These results confirm that the Plan d’Arem dam can profoundly affect hydrology by lowering base and peak flows (Q_{L2}), but that its management can considerably mitigate the effects on hydrology (Q_{L3}).

2.4.1.3. Potential changes in sediment delivery due to changes in human pressures

Rural depopulation and grazing abandonment

Although there is little literature available on grazing in this part of the Pyrenees, some authors state that the area corresponding to the Plan d’Arem upstream catchment, named Val d’Aran, was a key frontier zone for livestock exchange between France and Spain for quite a long period. Sanllehy (1981) found that in 1787, 2000 donkeys and mules were bought in French markets, raised in the Val d’Aran, and afterwards sold in Catalunya and Aragón in Spain. Soler i Santaló (1988) found the same number of 2000 mules per year at the beginning of the twentieth century. Even though no quantification of other livestock species has been made, the literature mentions their presence, indicating that livestock grazing was intense and extended over several centuries in this region. The total human population of the upstream catchment decreased between 1910 and 1970, decreasing from 7850 to 5500 inhabitants (Fig. 2.5; CHE, 2008), after which it showed a continuous increase until 2005 (9650 inhabitants, mostly in relation to tourism and other

activities related to the service sector). Interestingly, the rural population shows a similar decreasing trend (Fig 5) from 4800 inhabitants in 1910 to 2150 inhabitants in 1975, with the number of inhabitants then stabilising or only slightly increasing to a value of 2950 in 2005. The proportion of rural inhabitants also decreased over the twentieth century, especially between 1950 and 1980 (Fig. 2.5). Altogether, reduction in the rural population and grazing activities led to afforestation of slopes and grazing areas, as elsewhere in the Pyrenean Range, a dynamic that is responsible for reducing Q_s .

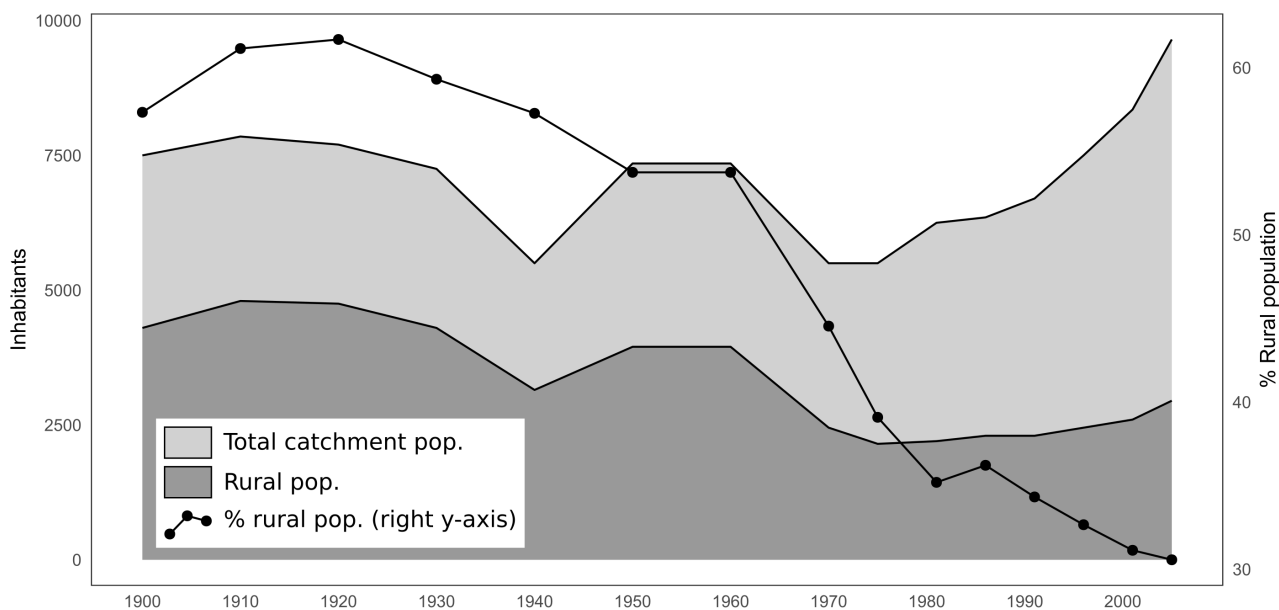


Figure 2.5. Evolution of the population on the upstream catchment. Dark-grey area: Rural population. Light-grey area: Total population. Dotted line: Percent of population considered rural.

Catchment afforestation

Currently, forest is predominant lower than 1600 m a.s.l. (Fig. 2.6), occupying 87.4 % of the catchment surface, followed by meadows that account for 9.1 %. From 1600 to 2600 m a.s.l., the surface covered by forest decreases considerably to 22.7 %, and meadows become the main land use, with 69.3 % coverage. Above 2600 m a.s.l., most of the surface corresponds to high mountain areas, and is completely bare (74.3 %) or sparsely covered by dry meadows (24 %).

Focusing on the lower areas, which were predominantly covered by forest in 2017, afforestation appears as a major process characterising the upstream catchment, potentially having a great influence on sediment transfer. Indeed, in 1957, forest only accounted for 33.1 %, and the catchment was mostly covered by meadows (59.3 %) corresponding to grazing areas. From 1957 to 1987, forest cover became increasingly present (63.6 %), especially on slopes between 700 and

1600 m a.s.l. This stabilised the ground and reduced the efficiency of detachment and transport processes through the sediment cascade. The 1960–1980 period shows the most important decrease in the rural population (Fig. 2.5). In 2017, forest also extended to the valley bottom, which was previously dominated by meadows. Forest covered the majority of surfaces below 1600 m a.s.l. (87.4 %), with a general increase in proportion over the basin. Consequently, afforestation was a major dynamic in the Garonne basin over the study period (Q_{s1}), and was related to changes in agricultural practice and planned/spontaneous slope afforestation. Even though no land use data are available before this period, this dynamic probably started a few decades earlier when grazing activities became less intense.

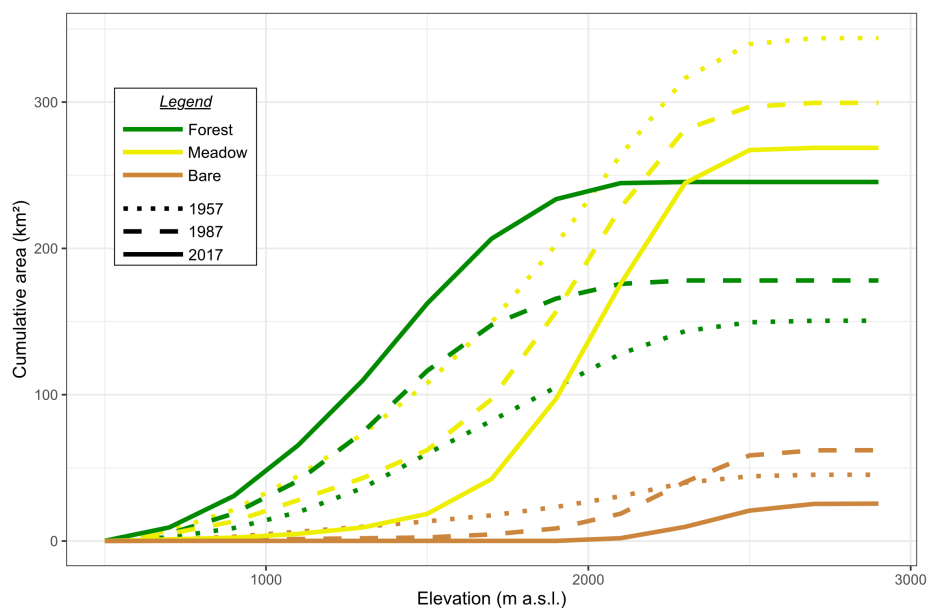


Figure 2.6. Altitudinal distributions of land use in 1957, 1987, and 2017.

Plan d’Arem RoR dam

In 1997, when dam stakeholders started bathymetric surveys, the reservoir capacity was close to the initial capacity at its construction, $\sim 0.369 \text{ hm}^3$. Between May 1997 and February 2013, a period over which no flushing actions occurred, this capacity was reduced by 51 %, reaching 0.181 hm^3 (Fig. 2.7.B). Over this period, the daily mean discharge exceeded Q_2 on 17 occasions allowing us to back-calculate that a Q_2 -event delivered $11\,000 \text{ m}^3$ of sediment (total load) to the reservoir. The downstream reach was then equally depleted (Q_{s2}). The extreme event of June 2013 contributed to this reduction by delivering $80\,000 \text{ m}^3$ of sediment to the reservoir, and in the same year, the discharge exceeded Q_2 on 14 occasions. Back-estimation of the sediment delivery gives a value of 5700 m^3 for each Q_2 -day, indicating that extreme events can transfer a large part of incoming sediments to downstream reaches, probably because the water residence time in the dam

reservoir is too short to allow the suspended load to settle. The emergency dredging performed in 2014 following the 2013 flood resulted in extraction of 50 000 m³ of fine material, which has been stored in the alluvial plain downstream of the dam. Since 2014, the dam has operated with drawdown-flushing actions, which have a positive influence on the downstream routing of sediment during flooding. During this period, the sediment balance was almost stable – the reservoir capacity was 0.257 and 0.259 hm³ in 2014 and 2019, respectively – although the discharge exceeded Q₂ on 10 occasions.

The bathymetric dataset shows that dam management was efficient at allowing sediment to be transferred downstream and controlling sediment accumulation within the dam reservoir. The 1997–2013 period is therefore characterised by important sediment depletion downstream of the dam, with sediment transfer being re-established since 2014 and the water capacity of the reservoir being generally stable (*Q_{s4}*).

The longitudinal pattern of grain size distribution (GSD) gives particularly interesting information on past-sediment architecture within the by-pass reach (BPR). This information corroborates previous observations. Indeed, all the highest (> 3), and most of the lowest (< 1.5) values of the armouring ratio ($D_{50_{SURF}}/D_{50_{SUB}}$) are found within the BPR or in its extreme vicinity (Fig. 2.7.C). The highest values can be interpreted as a legacy of the 1997–2014 period (*Q_{s3}*), and conversely, the lowest values seem to be related to the input of finer fresh material stored within the reservoir during the no-drawdown flushing period, and then subsequently released during flushing actions.

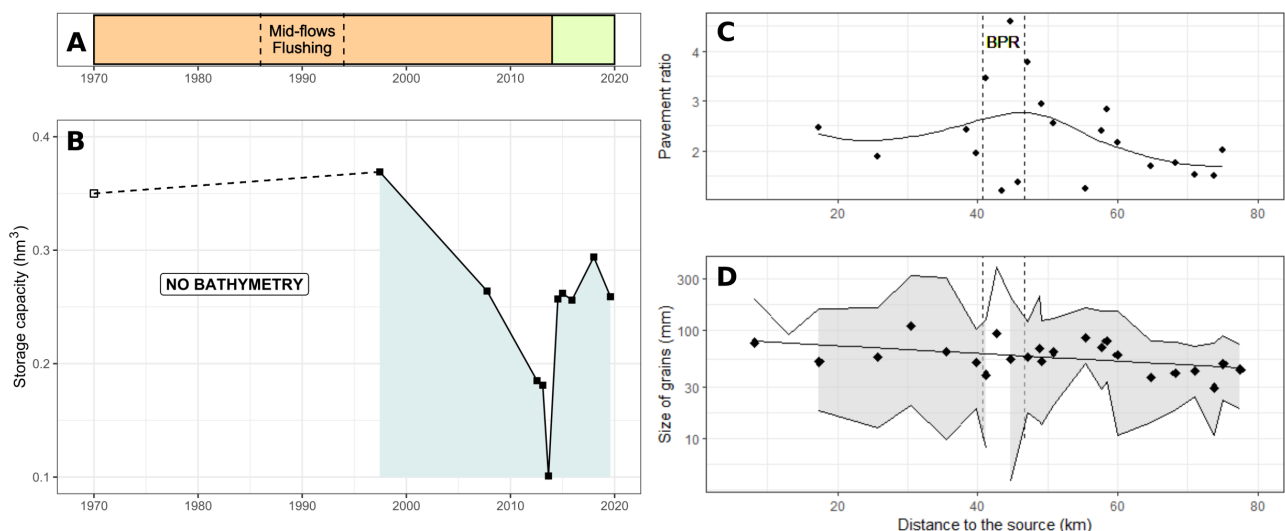


Figure 2.7. A. Plan d’Arem dam management. Orange: no drawdown flushing. Green: Drawdown flushing. B. Water storage capacity. C. Longitudinal pattern of armouring ratio. D. Longitudinal pattern of grain size distribution. Black dots: D50. Grey area: D10–D90 range.

2.4.2. Geomorphic channel response

2.4.2.1. Long-profile adjustments

Evaluation of low-flow water surface elevations between 1922 and 2014 reveals that channel incision reached 0.65 m on average below Plan d'Arem, with significant heterogeneity between reaches (Fig. 2.8). Within the BPR, slight bed aggradation (+ 0.08 m) occurred between 1922 and 2014, with a longitudinal variability ranging from -1 m and +1.1 m. Conversely, the reach downstream of the Plan d'Arem restitution shows mainly bed incision (-0.84 m on average), with significantly incised reaches (with a maximum value of -2.7 m) alternating with fixed sections caused by weirs and bridges.

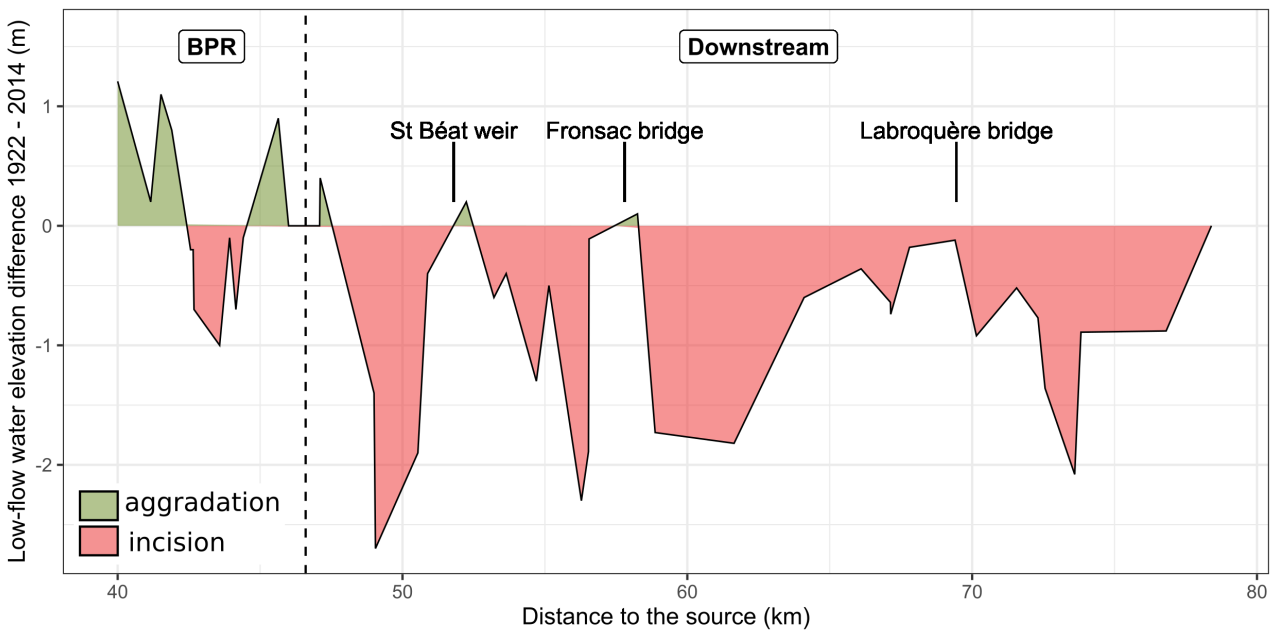


Figure 2.8. Water surface elevation differences between 1922 and 2014 in BPR and DS reaches. Green: aggradation. Red: incision.

2.4.2.2. Channel planform

Upstream from Plan d'Arem

In 1944, the upstream reach had a wandering pattern and around 35 % of the active channel was occupied by gravel bars that provided a surface for vegetation encroachment, thereby increasing the sensitivity of this reach to adjustments. From 1944 to 1997, the channel narrowed significantly, with an overall reduction in the active channel area of 39.9 % (Table 2.7), although this trend was not continuous in time and space. Indeed, channel narrowing became increasingly important over this period. A first phase of adjustments can be observed between 1944 and 1979, with a loss of active channel area of 0.8 % yr⁻¹ and 0.7% yr⁻¹ over 1944–1959 and 1959–1979, respectively, and then a second phase with a loss of active channel area of 1.2% yr⁻¹ over 1979–

1997. This long-term narrowing involved the colonisation of gravel bars by pioneer trees, reducing the part of the active channel occupied by gravel bars to around 19 % in 1997. This narrowing started around three main narrowing areas located at RK7, RK14, and RK25, corresponding to confluences with the Valarties, Nere, and Joeu, respectively, and indicated a reduction in the sediment and/or water supply that was already on-going at the beginning of the study period. After 1956, the channel narrowing was not restricted to specific reaches, but was generalised all along the channel continuum (**UP2**). The channel appears to have become newly adjusted to hydro-sedimentary conditions by 1997, as no narrowing occurred during the period 1997–2011, and the channel even widened by 11.4 % between RK25 and RK30, potentially highlighting an increase in sediment supply coming from the Joeu (Fig. 2.1). The proportion of bars reduced from 19 % to 3 % over the same period. This value, which is inconsistent with the observation of a slight channel widening, needs to be carefully interpreted because the aerial photographs of July 1997 were taken with a discharge of 16–30 m³s⁻¹, whereas the discharge was 19–60 m³s⁻¹ when the June 2012 photographs were taken. The flood of June 18, 2013, resulted in the re-establishment of 1945-like conditions, with a strong channel widening of 68.2 % and a large proportion of gravel bars (33 %). The post-flood period (2013–2016) was also marked by significant channel narrowing, with a loss of 18.1 % of the active area.

Conditions in the By-Pass Reach

In comparison with the upstream reach, the by-pass reach (BPR) in 1944 was less responsive because the proportion of gravel bars was lower at 21 %. The channel narrowed significantly between 1944 and 1959, losing 23.4 % of its active area, especially around two short reaches located at RK43.2–43.6 and RK45.2–45.8 (**BPR1**). Between 1959 and 1972, the channel width increased by 21.5% in relation to artificial modification of the channel during construction of the Plan d'Arem dam. The channel width was stable during the following decade, a period during which the dam was managed without flushing actions, and all changes observed between 1972 and 1983 were statistically non-significant (p-values = 0.1802 over 1972-1979 and p-value = 0.5647 over 1979-1983; **BPR2**). During the 1980s, channel adjustments related to the Plan d'Arem dam started, extending until 2010. Channel narrowing of 12.3 % over 1983–1997 (flushing actions) and 10.6 % over 1997–2010 (no flushing actions) was then observed. This leads us to a preliminary conclusion that the river response after the dam construction is representative of post-dam channel adjustments. We estimate a reaction time of around 15 yr, although we have not been able to estimate the following relaxation time because of the effects of the 2013 flood. These effects, although not as important as those observed upstream, remain significant over this reach, producing

an increase in the active channel area of 36.4 %. Interestingly, the post-flood response contrasts with the upstream reach, with the new channel morphology being maintained (p-value = 0.7961) over the 3 yr following the flood event. Between 2016 and 2019, the channel area increased by 6.2 %. This information indicates that: (1) the 2013 flood reactivated the morphological activity in this reach, especially with bank erosion, and (2) the new Plan d'Arem dam management, with flushing actions targeting peak flows, is efficient at restoring river processes because of the conservation of peak flows and sediment continuity.

Downstream reach

Finally, the downstream reach presents a simpler trend of channel evolution (Fig. 2.9), with channel narrowing between 1944 and 1959 (-11.7 %; **DO1**) because of secondary channel abandonment at RK62 and RK64, followed by a long period of channel stability (**DO2**; p-values = 0.3348, 0.995, and 0.0528 between 1959–1979, 1979–1997, and 1997–2011, respectively). The Plan d'Arem dam did not affect this reach. Once the discharge is returned to the main river course, we observe a restoration of the river's capacity to maintain its morphology, indicating that bypassing is the main cause of fluvial alteration through modification of the hydrological regime. In 1944, the sensitivity of the channel to change was already very low, with only 6 % of the active channel occupied by gravel bars. The effect of the 2013 flood is less important than it was upstream, although still significant (p-value < 0.0001), with a gain of 3.2 % in the active channel area. The post-flood response was almost negligible and non-significant, with a reduction in the active channel area of 1 %.

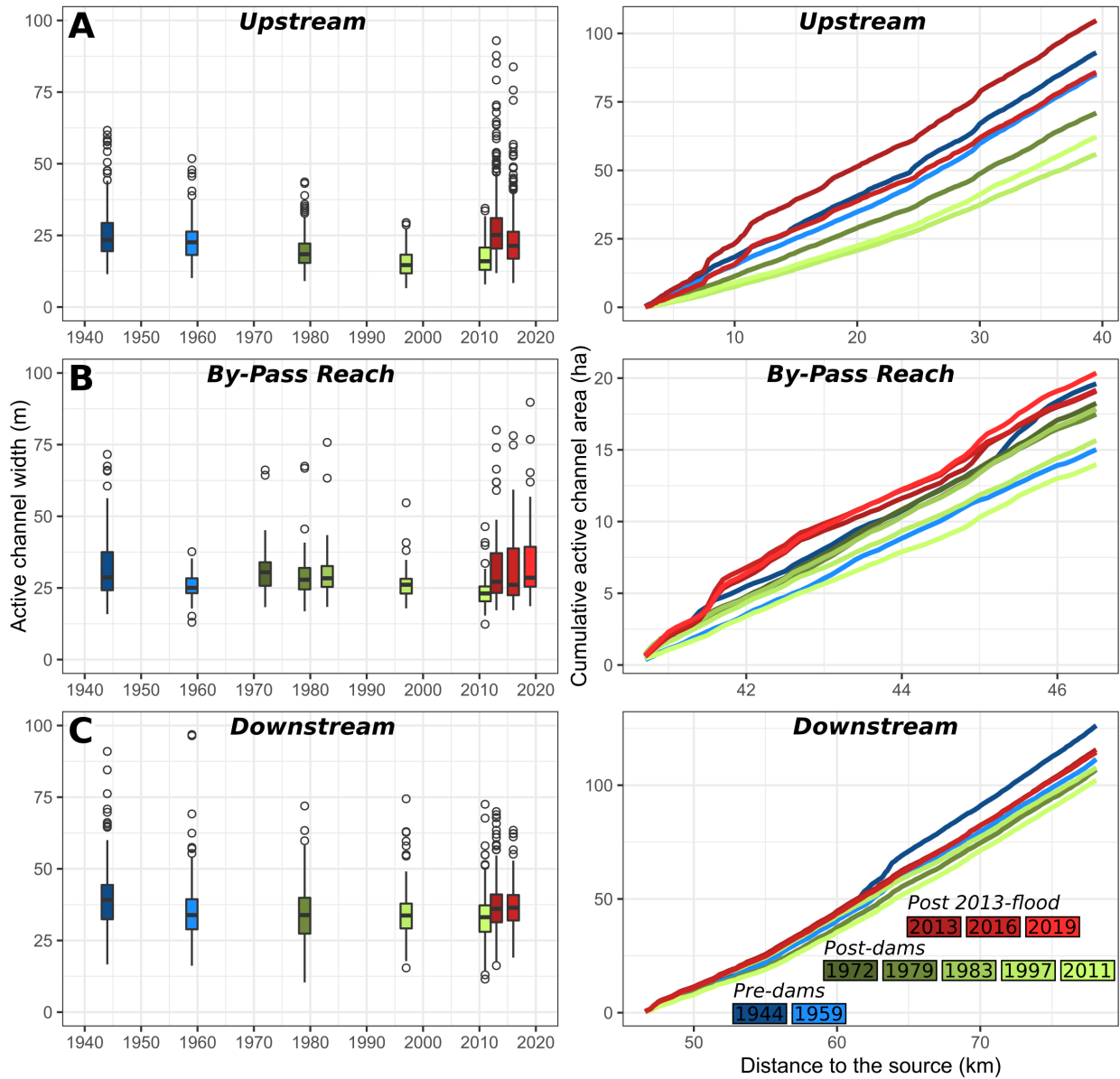


Figure 2.9. Changes in the active channel width (left) and cumulated channel area (right) for the upstream reach (A), by-passed reach (B), and downstream reach (C).

Period	Reach	Change in active channel area (%)	Mann-Whitney-Wilcoxon <i>p</i> -value	Significance	Change rate	
					cm yr ⁻¹	% yr ⁻¹
1944–1959	US	-8.5	0.0011	S	-20	-0.8
	BPR	-23.4	0.0016	S	-39	-1.2
	DS	-11.7	<0.0001	S	-23	-0.6
1959–1979	US	-16.5	<0.0001	S	-17	-0.7
	DS	-4.2	0.3348	NS	-9	-0.2
1959–1972	BPR	+21.5	<0.0001	S	+54	+2.2
1972–1979	BPR	-4.2	0.1802	NS	-4	-0.6
1979–1983	BPR	+2.1	0.5647	NS	+8	+0.5
1983–1997	BPR	-12.3	0.0034	S	-28	-0.9
1979–1997	US	-21.2	<0.0001	S	-23	-1.2
	DS	+ 0.9	0.995	NS	+2	+0.1
1997–2011	US	+ 11.4	<0.0001	S	12	+0.8
	BPR	-10.6	0.0009	S	-20	-0.8
	DS	-5.2	0.0528	NS	-13	-0.3
2011–2013	US	+ 68.2	<0.0001	S	-	-
	BPR	+36.4	<0.0001	S	-	-
	DS	+ 13.2	<0.0001	S	-	-
2013–2016	US	-18.1	<0.0001	S	-256	-9.1
	BPR	+ 0.4	0.7961	NS	4	+0.1
	DS	-1	0.9873	NS	-12	-0.3
2016–2019	BPR	+6.2	0.0665	NS	+67	+2.1

Table 2.7. Summary of channel planform changes over the 1944–2016 period for the three subreaches (US: Upstream, BPR: By-Passed Reach, DS: Downstream)

2.5. Discussion

2.5.1. Synthesis of the results and validation of the hypotheses

Hypothesis H1 stated that channel adjustments observed between 1940 and 1955 were already ongoing as a cumulative effect of grazing decline, post-LIA climate change, and catchment afforestation. Grazing decline affected the sediment supply from the upstream catchment, which decreased over the period 1944–1959 (Q_sI). The rural population also decreased from 4800 inhabitants in 1910 to 3150 inhabitants in 1940, and cattle exchange activities dropped over the same period. Blanpied *et al.* (2020) showed that the rural population decline in the Pyrenees started around 1860 and lasted until WWII, after which the development of thermal cure activities led to a new increase in the Pyrenean population. A decreasing trend in precipitation was observed between 1925–1923 and 1964–1987, with a reduction in annual precipitation of 20 % between the two periods, suggesting that post-LIA climate change affected precipitation. Although the available data did not allow us to estimate the potential reduction in peak flows related to climate change, nor make a quantitative assessment of afforestation before 1957, we may nevertheless consider these drivers as working in the same direction, towards a reduction in Q_s and Q_L . Although the effects of torrent control works on the Pique Upper catchment have not been assessed, we must mention that this driver could have affected the Garonne channel downstream of the confluence (D_sI) through the propagation of the induced sediment deficit downstream, but the initially low sensitivity of this reach to planimetric adjustments could have resulted in bed coarsening and incision. Even though bed coarsening has not been observed, probably because of important sediment inputs during the 2013-flood event and relaxation, torrent control works could explain the significant incision measured over this reach that is not observed upstream. Balasch *et al.* (2019) made similar observations in the Ebro basin (southern Pyrenees, Spain), highlighting the predominance of large catastrophic floods at the end of the nineteenth century. David *et al.* (2016), working on the Garonne around 150 km downstream of our study site (i.e., downstream of the piedmont area), also demonstrated that the first morphological adjustments were related to post-LIA reductions in peak flow magnitude and frequency prior to dam construction. As climatic fluctuations and changes in economic activities are catchment-scale dynamics, the whole study reach responded through active channel width reduction, by 0.8, 1.2 and 0.6 % yr⁻¹ for upstream, BP, and downstream reaches (UPI , $BPRI$, DSI), respectively. Altogether, these results allow us to validate hypothesis H1 (Fig. 2.10).

Hypothesis H2 stated that upstream damming resulted in decreased peak flow frequency (Q_L1) and sediment transfer efficiency (Q_S2). The system responded through channel narrowing. We also stated that downstream tributaries should buffer this trend. The results show that upstream dams (D1–D4) drastically decreased both the magnitude and frequency of peak flows at the Arties gauging station (Q_L1). The frequency of peak discharge corresponding to 1-yr, 5-yr, and > 10-yr return periods was reduced by 83 %, 77 %, and 43 %, respectively, between pre-dam and post-dam periods. Interestingly, this reduction occurred after 1970, five years after construction of the last dam. Over the upstream reach, the period 1959–1979 shows a narrowing rate similar to 1944–1959 (0.7 % yr⁻¹). This indicates that the hydrological reduction effect of the dams was already acting (Q_L1), and that combined with sediment trapping by the dam itself and by-passing all along the upstream reach (Q_S2), the river system was still responding to pre-dam pressures (H1). The following period (1979–1997) showed an increase of this narrowing rate to 1.2 % yr⁻¹. This result can be interpreted as the combined effect of pre-dam pressures supplemented with those from upstream dams and bypassing ($UP2$). The river channel then adjusted to new hydrosedimentary conditions around 2000. We estimated that in the absence of upstream damming and assuming a “no-dam” narrowing rate of 0.7 % yr⁻¹, the system would have adjusted one decade later, around 2010 (Fig. 2.10). Tributaries located downstream of the chain of dams buffer their effects on hydrology and sediment supply. BPR and downstream sub-reaches therefore did not experience active channel width reduction over the period 1959–1979 ($BPR2$, $DO2$).

Although we stated in hypothesis H1 that catchment afforestation was also responsible for decreasing sediment supply before the construction of upstream dams, we have not been able to assess this dynamic for times before 1957. Our results show that forest cover first increased between 1000 and 1500 m a.s.l. (1957–1987), corresponding to hillslopes, which then reduced the efficiency of sediment transfer from upland production areas to the river system. The following years saw a generalisation of plant and tree colonisation on lower areas, typically lower than 1000 m a.s.l. and corresponding to valley bottoms, thereby stabilising banks, limiting channel lateral migration, and reducing sediment input from bank erosion. These results corroborate the recent work of Blanpied (2019) on neighboring catchments to the west, which stated that sources of sediment on high altitude areas and slopes have progressively been disconnected from the river system, resulting in an important decrease in sediment supply over the second half of the twentieth century. Similarly, Llana *et al.* (2019) working on small central-southern Pyrenean catchments concluded that afforestation is a major cause of reduced sediment supply to the main channel network. Buendia *et al.* (2015) demonstrated that the neighboring catchment of Noguera Pallaresa

to the east experienced similar afforestation, with an increase in forest cover ranging from 19 % to 57 % between 1987 and 2009. Additionally, Ibisate *et al.* (2013) concluded that afforestation was the main cause for the reduction in the Aragon River dynamism between 1927 and 1957.

In combination, climate change, changes in economic activities, catchment afforestation, and upstream damming and by-passing reduced both peak flow magnitude and frequency, and induced a generalised sediment deficit. This deficit affected channel morphology through channel width reduction, incision and armouring, vegetation encroachment, and secondary channel abandonment. As the initial potential of channel adjustments differed between sub-reaches, the relaxation time and magnitude of changes also differed. The upstream reach, which had a high potential for adjustment with around 35% of the active channel being occupied by gravel bars, reached a new equilibrium in the 1990s (**UP2**). The BPR and downstream sub-reaches, which were less sensitive to adjustments in 1944 with 21 % and 6 % gravel bars, respectively, within the active channel, showed a lower degree of anthropisation, having already reached a new state of equilibrium in 1959 (**BPR2, DO2**). When managed without flushing actions (1970–1984 and 1997–2014) or with flushing actions that did not target peak flows (1984–1997), the Plan d’Arem RoR dam resulted in a reduction of peak flows of 20 % to 40 % in magnitude (Q_{L2}), and trapped around 11 000 m³ of sediment per day of discharge above Q2 (Q_{S3}). The BPR did not respond to this alteration between 1972 and 1983, a period during which active channel width remained roughly stable (**BPR3**). During the 1980s, the first morphological adjustments related to the disruption of sediment transfer and hydrological regulation by the Plan d’Arem started. During 1983–2010, the channel width decreased by -0.8 \% yr^{-1} (**BPR3**). Conversely, the active channel width on the downstream reach remained stable over the period 1979–2011 (**DO2**). Nevertheless, the channel has adjusted over this period through bed coarsening, with armouring ratio reaching up to 3. Those results indicate that a thin alluvial mattress of fresh sediments delivered from Plan d’Arem circulates over an armoured sub-layer of legacy sediments. Fresh mobile material is temporarily stored in deposition areas, especially where the channel enlarges significantly, and this material is exported downstream during the next flood event. This functioning implies a high sensitivity of the BPR to sediment starvation with a deleterious effect on salmonid reproduction. Moreover, this also underlines a low sensitivity to bed incision because the armoured sub-layer requires major flood events to be broken and exported. Very few vertical changes in the BPR were observed over the 1922 – 2014 period, which indicate that bed coarsening may have been established prior to the Plan d’Arem dam and related to other upstream drivers of sediment supply reduction. Changes observed in the BPR did not propagate downstream, thereby indicating that the Plan d’Arem dam changed channel morphology mostly

through flow alterations (Q_{L2}), or that the period without flushing actions has not been sufficiently long to allow the sediment deficit to propagate downstream. Downstream of Arlos, the operated discharge is returned to the main course of the Garonne, restoring the river's capacity to maintain its morphology. The morphological response of the BPR to the Plan d'Arem dam is not correlated with dam management before the 2013 flood. Indeed, the channel started to adjust during the 1980's, allowing us to estimate a reaction time of around 15 yr. These results allow us to conclude that hypothesis H3 is valid (Fig. 2.10).

The 2013 flood resulted in significant channel widening on all reaches, ranging from 13 % to 68 %. The upstream reach narrowed immediately after the flood (-9.1 \% yr^{-1}) because of intense river training works and the continuation of dams and bypassing effects. Since 2014, flushing actions are performed at peak flows (above $70 \text{ m}^3\text{s}^{-1}$) at the Plan d'Arem dam, and these are efficient at controlling sediment accumulation by routing incoming sediments through the dam towards the downstream reach (Q_{S4}) and preserving peak flow magnitude (Q_{L3}). Consequently, the BPR and downstream reaches did not experience statistically significant channel changes over the three years after the flood. Bank erosion initiated by the flood in the BPR is still active, and the active channel widened between 2016 and 2019. The flood then restored morphological activity within the BPR, with the new dam management allowing this to be maintained. These results allow us to conclude that hypothesis H4 is valid (Fig. 2.10).

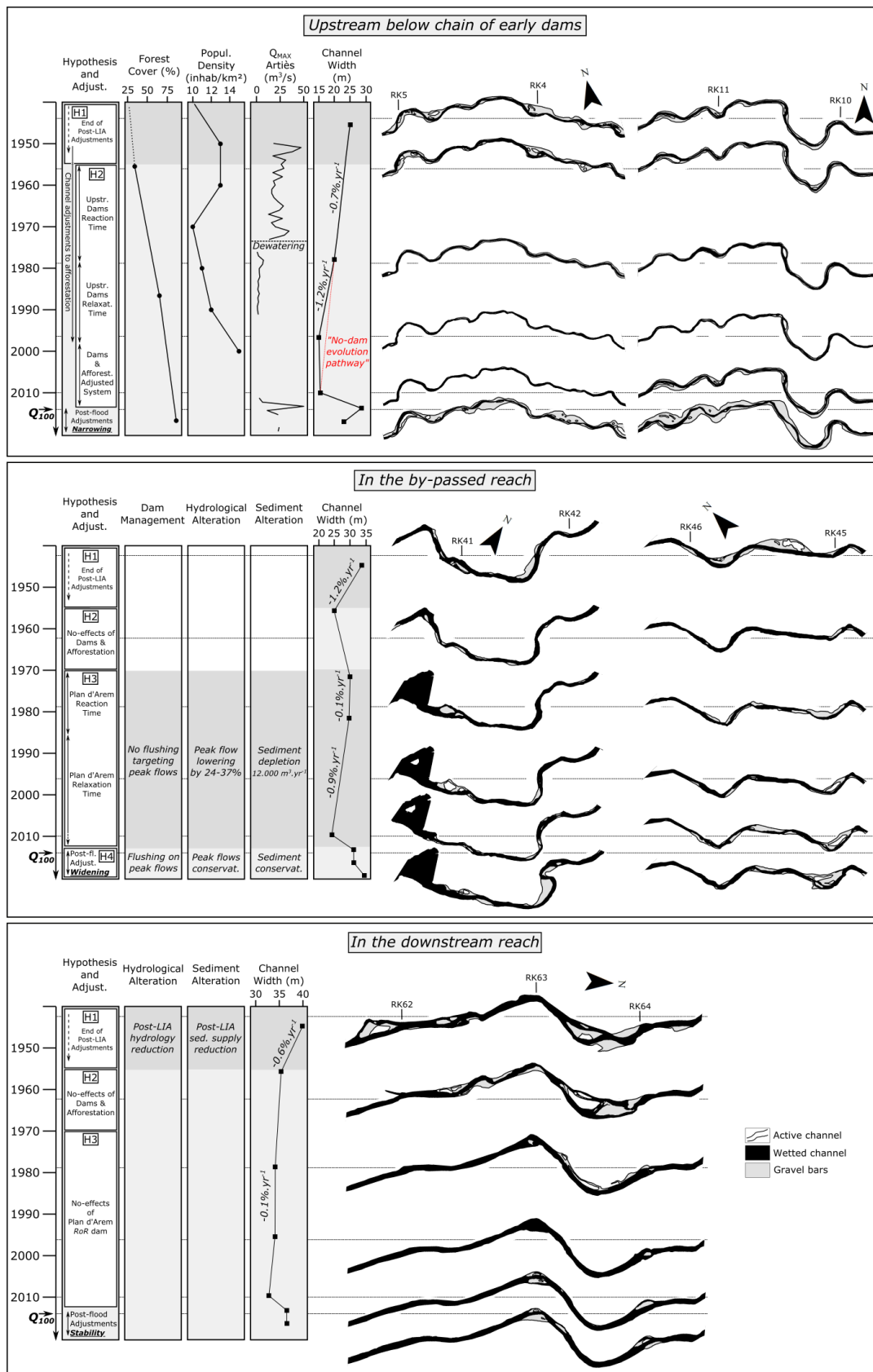


Figure 2.10. Synthesis of a working hypothesis and changes in drivers and associated morphological responses in upstream, by-passed, and downstream reaches. Morphological maps highlight the role of the catastrophic 2013 flood on refurbishing the channel planform, mostly in the upstream reach.

2.5.2. Effects of the RoR

Channel morphology in the BPR was stable for over 15 yr following the Plan d'Arem dam construction in 1970. The first effects are observed between 1983 and 1997, consisting of active channel width reduction and changes in grain size distribution, with higher values for the armouring ratio (> 3). These changes are consequences of the effects of the dam on both sediment supply and hydrology. A sediment deficit was induced by the dam itself, with an increase in sediment storage (both suspended load and bedload) within the dam reservoir of $12\,000\text{ m}^3\text{ yr}^{-1}$. Even if most of this volume consisted of fine suspended sediment, this trapping effect primarily affected coarser particles that control channel morphology.

Water diversion for hydroelectricity production resulted in reduced flow conditions on the BPR, by 63 % on average. As a minimum ecological discharge of $4\text{ m}^3\text{ s}^{-1}$ was maintained during low- and mid-flows (a value corresponding to the natural discharge under severe low-flow conditions), new emerged spaces became available for pioneer vegetation encroachment. In parallel, the available energy for potential vegetation removal during floods was reduced in comparison with the natural hydrology, and a constricted morphology was then maintained. Our study on the Garonne River gives similar conclusions to the study of Ibisate *et al.* (2013) on the Aragon River (southern Pyrenees), where hydrological reduction related to by-passing ranged from 34 % to 62 %, but changes in high flows are not as evident, with the upstream Yesa reservoir (operating since 1959) exerting the main flood-control effect. The authors concluded that low-dam effects on sediment transfer were short-lived and become negligible as soon as the dam filled with sediments, a conclusion also shared by Csiki and Rhoads (2010). Ibisate *et al.* (2013) also stated that evidence for unit- and cumulative-effects of RoR dams is difficult to disentangle from other factors causing change, as they seem to accentuate a long trend of river simplification initiated by changes in land cover and upstream damming. Working on the Old Rhine, Arnaud *et al.* (2015) also concluded that river adjustments related to by-passing were less intense than those during previous periods during which river training works resulted in a reduction of the active channel area by 45 % between 1828 and 1872.

After the Plan d'Arem construction in 1970, no significant changes were observed until 1997. Dam management over 1970–1997 was organised as follows: no-flushing actions during 1970–1986 and 1994–1997, and flushing actions under mid-flow conditions during 1986–1994. Channel changes during 1983–1997 could be associated with the end of flushing actions or to the dam itself, allowing us to estimate the reaction time as being in the order of 20 yr. Examination of aerial photographs from 1993 shows that vegetation developed on bars before and during 1983–

1993, prior to the end of flushing actions, thereby indicating that flushing actions performed on mid-flows had no effects on buffering dam-related morphological adjustments. Morphological changes related to the extreme flood event of June 2013 thwarted the possibility to precisely estimate the post-dam relaxation time. Nevertheless, we can still state that the channel had adjusted to new conditions in 2011, despite the low potential of this reach to adjust (with less than 20% of the active channel occupied by gravel bars), thereby giving a relaxation time of around 25 yr. This observation is consistent with results obtained by Curtis *et al.* (2010) in Vermont, which indicated a 20-yr reaction time and a 30-yr relaxation time, as well as with those of Arnaud *et al.* (2015), who estimated a 20-yr relaxation time on the Old Rhine.

Comparison of the effects of the Plan d'Arem dam with other upstream dams is difficult because the unit effects of these dams are not clearly defined. Indeed, changes observed over the upstream reach are the results of a combination of factors that include dams, land-use changes, and post-LIA climate changes. The river was already responding to previous pressures when the chain of dams was built, but we nevertheless observed that the river reached a new equilibrium state around 1995, 30 yr after the construction of the last dam, a value that includes the total response time and is also consistent with values from the literature. The main difference between upstream dams and the Plan d'Arem dam rests on the dam management and its effects on channel morphology. Indeed, after the 2013 flood that resulted in an important channel widening over the whole study reach, upstream dams still had the same hydro-sedimentary reduction effect they had before the flood, resulting in narrowing of the active channel. Conversely, the new management of the Plan d'Arem dam allows the rejuvenated morphology resulting from the 2013 flood to be maintained.

2.5.3. Uncertainties in disentangling multi-driver effects

The BACI approach allowed us to disentangle the unit-effects of a RoR dam in a multi-driver context. This approach relied on the parallel characterisation of: (1) changing factors and their effects on control variables (Q_S and Q_L), and (2) temporality and magnitude of river morphological adjustments within a space-time framework that considered before–after and upstream–downstream aspects of the dam. Nevertheless, such an approach presents several limitations, which we now describe.

The first of these limitations is related to data availability. For the Plan d'Arem dam, the discharge series is only available since 2017, precluding the direct assessment of its effects on hydrology between 1970 and 2017. Similarly, the discharge series of Bossòst is the only proxy for

hydrological alterations related to by-passing, although the whole upstream reach is affected by water diversion. A complete hydrological budget would be highly valuable for better assessing and understanding the correlation between hydrological changes and local morphological adjustments. Bathymetrical measurements on the Plan d'Arem started in 1997, and we were therefore unable to estimate the effect of the dam on sediment transfer over the first period (1970–1984) when sediment flushing was not performed, nor over the following period (1984–1994) when flushing actions targeted mid-flows. Assessment of the difference between the effects of mid-flow and high-flow (since 2014) flushing actions on sediment storage would have been of great interest. Assessment of channel planimetric changes in upstream and downstream reaches over 1944 – 2011 has been achieved using five sets of aerial photographs, giving a temporal resolution of approximately 13 yr and potentially introducing uncertainties in correctly evaluating the temporal dynamics of planforms changes. Nevertheless, and considering the moderate dynamism of the Garonne River over the twentieth century, we found this resolution acceptable to draw the general trajectory of the river. Considering the objectives of the study and the focus on the Plan d'Arem dam, we increased this temporal resolution in the by-passed reach. The post-dam period (1972 – 2019) is covered by eight sets of aerial photographs, giving a temporal resolution of approximately six years.

Another limit to disentangling the individual effects of various factors in a multi-driver study is related to the spatial and temporal co-occurrence of changing factors. In our case, land-use changes and upstream damming induced the first morphological responses. Afforestation is a catchment-scale dynamic, and can therefore be considered as a diffuse pressure that affects both hydrology and sediment supply over the whole catchment. These alterations are dependent on afforestation dynamics such as the afforestation rate and potential responses of the catchment. For example, we can hypothesise that the channel morphological response to afforestation would be greater if the afforestation rate is high and the catchment rapidly afforested, and if slope colonisation by trees affects areas of high sediment production and/or high drainage density. Reaction and relaxation times are then variable and highly complex to estimate. Moreover, the same reach is affected by both damming and by-passing. The spatial extent of these pressures is well defined, but here again, the reaction and relaxation times can vary. The morphological effects of damming are superimposed on those related to slope afforestation, and we have finally been able to disentangle the effects of the Plan d'Arem dam from the effects of the whole set of upstream pressures. Moreover, channel adjustments propagate from upstream to downstream. We found that upstream adjustments started around the 1950's and lasted until the 1990's, whereas within the BPR, channel adjustments started during the 1980's. We can therefore legitimately wonder whether

they are a specific response to the construction and operation of the Plan d'Arem dam, or a combined effect of both damming and by-passing on one hand, and propagation of upstream changes on the other hand. Moreover, no data are available on gravel mining on this reach, and even though it has never been an important economic activity, sporadic extractions for private individual uses may also have locally affected sediment supply.

2.6. Conclusions

The objective of this paper was to disentangle the separate effects of a RoR dam on river responses within a multi-driver context. We fulfilled this objective using a space-time framework that considers upstream–downstream and before–after aspects of the dam construction and operation. The main conclusions of the study based on the four working hypotheses can be drawn as follows:

1) Hypothesis H1 and H2 were related to the pre-dam period, stating that the channel was already responding to land-use changes and upstream damming. We validated those hypotheses by highlighting the important afforestation of the upstream catchment, the hydrological reduction through upstream damming and by-passing, and the channel narrowing.

2) Hypothesis H3 stated that the Plan d'Arem dam, through its sediment depletion and hydrological reduction effects, induced channel narrowing on the BPR. This hypothesis was validated, but we showed that hydrological reduction was the main driver because channel changes did not propagate downstream of the HPP water return.

3) Finally, hypothesis H4 stated that dam management can buffer the effect of the dam on Q_s and Q_L . We showed that drawdown flushing actions allowed the post-flood morphological activity to be maintained, whereas the upstream reach shows a new phase of channel narrowing after the catastrophic 2013 flood that completely refurbished the channel planform, especially in the upstream reaches.

In disentangling the unit-effects of a set of pressures we met two main difficulties. The first is related to the temporal resolution of existing data (e.g., vertical changes): large time gaps must be taken into account in the analysis, requiring that caution is exercised on the results obtained. The second lies in the co-occurrence of the pressures, as well as in their similar impacts, which are likely to all contribute to a reduction in liquid and solid fluxes. Within this perspective, we focused on the channel narrowing rate in terms of % yr⁻¹. Indeed, changes in the narrowing rate over a certain period may reflect: (1) a change in the potential of a reach to adjust, and (2) a change in control variables that can be related to changes in pressure settings. In our case, the channel

response to land-use changes was 0.7 % yr⁻¹, which increased to 1.2 % yr⁻¹ after damming, allowing the individual contributions of afforestation and dams to channel narrowing to be estimated as 60 % and 40 %, respectively.

2.7. References

Agostinho, A.A., Gomes, L.C., Veríssimo, S., Okada, E.K., 2004. Flood regime, dam regulation and fish in the Upper Paraná River: effects on assemblage attributes, reproduction and recruitment. *Reviews in Fish Biology and Fisheries* 14: 11–19. DOI: 10.1007/s11160-004-3551-y

Andrieu-Ponel, V., Hubschman, J., Jalut, G., Héraïl, G., 1988. Chronologie de la dégladation des Pyrénées françaises. Dynamique de sédimentation et contenu pollinique des paléolacs ; application à l'interprétation du retrait glaciaire. *Bulletin de l'Association française pour l'étude du quaternaire*, 25(2-3): 55-67. DOI: 10.3406/quate.1988.1866

Arnaud, F., Piégay, H., Schmitt, L., Rollet, A.J., Ferrier, V., Béal, D., 2015. Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology* 236: 163-177. DOI: 10.1016/j.geomorph.2015.02.009

Arricau, V., Chapron, E., 2021. Archives historiques et sédimentaires des paysages lacustres du piedmont de Pyrénées (Lacs de Barbazan et de Loures-Baroussesn Haute-Garonne, France). *Collection EDYTEM*, 21.

Balash, J.C., Pino, D., Ruiz-Bellet, J.L., Tuset, J., Barriendos, M., Castellort, X., Peña, J.C., 2019. The extreme floods in the Ebro River basin since 1600 CE. *Sci. Total Environ.* 646: 645-660. DOI: 10.1016/j.scitotenv.2018.07.325

Batalla, R.J., 2003. Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Cuaternario y Geomorfología* 17: 79–91.

Batalla, R.J., Iroumé, A., Hernández, M., Llena, M., Mazzorana, B., Vericat, D. 2018. Recent geomorphological evolution of a natural river channel in a Mediterranean Chilean basin. *Geomorphology* 303: 322-337. DOI: 10.1016/j.geomorph.2017.12.006.

Blanpied, J., 2019. La torrentialité dans les Pyrénées centrales: évolution depuis la fin du Petit Âge Glaciaire, spécificités et dynamiques géomorphologiques actuelles. University of Toulouse. (Ph. D. Dissertation).

Blanpied, J., Antoine, J.M., Carozza, J.M., Valette, P., 2020. Approche géohistorique de l'évolution de la dynamique torrentielle du torrent du Bastan. *Sud-Ouest Européen*, 49: 29-46.

Boix-Fayos, C., Barberá, G.G., López-Bermúdez, F., Castillo, V.M., 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: Case study of the Rogativa catchment (Murcia, Spain). *Geomorphology* 91: 103-123. DOI: 10.1016/j.geomorph.2007.02.003

Boix-Fayos, C., de Vente, J., Martínez-Mena, M., Barberá, G. G., Castillo, V., 2008. The impact of land use change and check-dams on catchment sediment yield. *Hydrological Processes*, 22(25): 4922–4935. DOI : 10.1002/hyp.7115

Boutault, F., 2020. Etude de l'impact cumulé des facteurs d'anthropisation sur la Dordogne moyenne et préconisations en vue de la restauration écologique du cours d'eau. University of Lyon, France. (Ph.D. Dissertation). DOI : 10.13140/RG.2.2.10836.32643

Brown, A.G., Tooth, S., Bullard, J.E., Thomas, D.S.G., Chiverrell, R.C., Plater, A.J., Murton, J., Thorndycraft, V., Tarolli, P., Rose, J., Wainwright, J., Downs, P.W., Aalto, R., 2017. The Geomorphology of the «Anthropocene»: emergence, status and implications. *Earth Surf. Process. Landf.* 42: 71–90. DOI : 10.1002/esp.3943

Buendia, C., Batalla, R.J., Sabater, S., Palau, A., Marcé, R., 2015. Runoff trends driven by climate and afforestation in a Pyrenean basin. *Land Degrad. Dev.* 27: 823–838. DOI: 10.1002/ldr.2384

Buffington, J.M., 1996. An alternative method for determining subsurface grain size distributions of gravel-bedded river. American Geophysical Union 1996 Fall Meeting, supplement to EOS, AGU transactions, 77(46).

Bunte, K., Abt, S., 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics and streambed monitoring. General Technical Report RMRS-GTR-74. Fort Collins, CO: U.S. Department of agriculture, Forest service, Rocky mountain research station, 428 p.

Caskey, S.T., Blaschak, T.S., Wohl, E., Schnackenberg, E., Merritt, D.M., Dwire, K.A., 2014. Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA. *Earth Surf. Process. Landf.* 40: 586-598. DOI: 10.1002/esp.3651

CHE, 2008. Plan hidrológico de la cabecera del río Garona. Gobierno de España. Ministerio de Medio Ambiente y Medio Rural y Marino. 141 p.

Collier, M., Webb, R.H., Schmidt, J.C., 1996. Dams and Rivers: A Primer on the Downstream Effects of Dams, vol. 1126. US Dept. of the Interior, US Geological Survey, Tucson, AZ.

Csiki, S., Rhoads, B. L., 2010. Hydraulic and geomorphological effects of run-of-river dams. *Progress in Physical Geography* 34(6): 755–780. DOI: 10.1016/j.geomorph.2013.10.009

Csiki, S., Rhoads, B. L., 2014. Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology* 206: 215-229. DOI: 10.1177/0309133310369435

Curtis, K.E., Renshaw, C.E., Magilligan, F.J., Dade, W.B., 2010. Temporal and spatial scales of geomorphic adjustments to reduced competency following flow regulation in bedload-dominated systems. *Geomorphology* 118: 105–117. DOI : 10.1016/j.geomorph.2009.12.012

Daumas, M., 1962. L'équipement hydro-électrique des Pyrénées espagnoles. *Revue géographique des Pyrénées et du Sud-Ouest. Sud-Ouest Européen* 33: 73-106.

David, M., 2016. Dynamique fluviale de la Garonne à l'anthropocène : trajectoire d'évolution du tronçon fluvial compris entre les confluences de l'Ariège et du Tarn (Garonne toulousaine, 90 km). University of Toulouse. (Ph. D. Dissertation).

Dépret, T., Piégay, H., Dugué, V., Vaudor L., Faure J-B., Le Coz, J., Camenen, B., 2018. Estimating and restoring bedload transport through a run-of-river reservoir. *Sci. Total Environ.* 654: 1146-1157. DOI: 10.1016/j.scitotenv.2018.11.177

Downs, P.W., Gregory, K.J., 2004. River Channel Management. Towards Sustainable Catchment Hydrosystems. Arnold, London, UK (395 pp.). ISBN: 978-1-4441-1907-7

Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late «Anthropocene»: implications, limitations, prospect. *Geomorphology* 338: 88-104. DOI: 10.1016/j.geomorph.2019.03.021

Eschner, T., Hadley, R.R., Crowley, K.D., 1983. Hydrologic and Morphologic Changes in Channels of the Platte River Basin in Colorado, Wyoming, and Nebraska: A Historical Perspective. US Dept. of the Interior, US Geological Survey, Tucson, AZ.

Fernandes, M., Oliva, M., Palma, P., Ruiz-Fernández, J., Lopes, L., 2017. Glacial stages and post-glacial environmental evolution in the Upper Garonne valley, Central Pyrenees. *Sci. Total Environ.* 584-585: 1282-1299. DOI : 10.1016/j.scitotenv.2017.01.209

Galop, D., 1998. La forêt, l'homme et le troupeau. 6000 ans d'histoire de l'environnement entre Garonne et Méditerranée, 285 p.

Galop, D., 2000. La croissance médiévale sur le versant nord des Pyrénées à partir des données palynologiques in Berthe, M., Cursente, B., Villages Pyrénéens Morphogenèse d'un habitat de montagne. p. 45-54.

Haddeland, I., Skaugen, T., Lettenmaier, D.P., 2007. Hydrologic effects of land and water management in North America and Asia: 1700–1992. *Hydrol. Earth Syst. Sci.*, 11: 1035–1045.

Ibáñez, A., Diaz, E., Ollero, A., Acin, V., Granado, D., 2013. Channel response to multiple damming in a meandering river, middle and lower Aragon River (Spain). *Hydrobiologia* 712: 5–23. DOI: 10.1007/s10750-013-1490-0

Jellyman, P.G., Harding, J.S., 2012. The role of dams in altering freshwater fish communities in New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 46(4): 475-489. DOI: 10.1080/00288330.2012.708664

Jenkins, S. A., Inman, D. L., Skelly, D.W., 1988. Impact of dam building on the California coastal zone. *California Waterfront Age* September.

Kiss, T., Blanka, V., 2012. River channel response to climate- and human-induced hydrological changes: Case study on the meandering Hernád River, Hungary. *Geomorphology* 175-176: 115–125. DOI: 10.1016/j.geomorph.2012.07.003

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. *Environ. Manag.* 21(4): 533–551. DOI: 10.1007/s002679900048

Kondolf, G. M., Curry, R. R., 1986. Channel erosion along the Carmel River, Monterey County, California. *Earth Surf. Process. Landf.* 11: 307–319. DOI: 10.1002/esp.3290110308

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and Piedmont Rivers and streams of Southeastern France. *Earth Surface Processes and Landforms* 27: 425-444. DOI: <https://doi.org/10.1002/esp.328>

Liébault, F., Gomez, B., Page, M., Marden, M., Peacock, D., Richard, D., Trotter, C.M., 2005. Land-use change, sediment production and channel response in upland regions. *River Res. Appl.*, 21: 739-756. DOI: 10.1002/rra.880

Llena, M., Vericat, D., Cavalli, M., Crema, S., Smith, M.W., 2019. The effects of land use and topographic changes on sediment connectivity in mountain catchments. *Sci. Total Environ.* 660: 899-912. DOI: 10.1016/j.scitotenv.2018.12.479

Ma, Y., Huang, H. Q., Nanson, G. C., Li, Y., Yao, W., 2012. Channel adjustments in response to the operation of large dams: The upper reach of the lower Yellow River, *Geomorphology*, 147-148: 35-48. DOI: 10.1016/j.geomorph.2011.07.032

Marchese, E., Scorpio, V., Fuller, I., McColl, S., Comiti, F., 2017. Morphological changes in Alpine rivers following the end of the Little Ice Age. *Geomorphology*, 295: 811-826. DOI: 10.1016/j.geomorph.2017.07.018

Marteau, B., Michel, K., Piégay, H., 2022. Can gravel augmentation restore thermal functions in gravel-bed rivers? A need to assess success within a trajectory-based before-after control-impact framework. *Hydrological Processes* 36(2). DOI: 10.1002/hyp.14480.

Petts G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography* 3: 329-362. DOI: 10.1177/030913337900300302

Preciso, E., Salemi, E., Billi, P., 2012. Land use changes, torrent control works and sediment mining: effects on channel morphology and sediment flux, case study of the Reno River (Northern Italy). *Hydrological processes* 26: 1134-1148. DOI: 10.1002/hyp.8202

Provansal, M., Dufour, S., Sabatier, F., Anthony E.J., Raccasi, G., Robresco, S., 2014. The geomorphic evolution and sediment balance of the lower Rhône River (southern France) over the last 130 years: Hydropower dams versus other control factors. *Geomorphology* 219: 27-41. DOI: 10.1016/j.geomorph.2014.04.033

Rice, S., Church, M., 1998. Grain-size along two gravel bed river: statistical variations, spatial patterns and sedimentary links. *Earth Surf. Process. Landf.* 23: 345-363. DOI: 10.1002/(SICI)1096-9837(199804)23:4<345::AID-ESP850>3.0.CO;2-B

Rollet, A.J., Piégay, H., Dufour, S., Bornette, G., Persat, H., 2013. Assessment of consequences sediment deficit on a gravel river bed downstream of dams in restoration perspectives: applications of multicriteria, hierarchical and spatially explicit diagnosis. *River Research and Applications*, 30(8): 939-953. DOI: 10.1002/rra.2689

Ryan, S., 1997. Morphologic response of subalpine streams to transbasin flow diversion. *J. Am. Water Resour. Assoc.* 33(4): 839-854. DOI: 10.1111/j.1752-1688.1997.tb04109.x

Sanllehy, M.A., 1981. *Era Val d'Aran*. University of Barcelona. p. 88

Scorpio, V., Piégay, H., 2020. Is afforestation a driver of change in Italian rivers within the «Anthropocene» era? *CATENA*, Elsevier, pp.105031. DOI: 10.1016/j.catena.2020.105031

Soler i Santaló, J., 1988. *Era Val d'Aran*. University of Lleida, IEI, p. 69-70.

Stange, K.M., van Balen, R.T., Kasse, C., Vandenberghe, J., Carcaillet, J., 2014. Linking morphology across the glaciofluvial interface: A ¹⁰Be supported chronology of glacier advances and terrace formation in the Garonne River, northern Pyrenees, France. *Geomorphology*, 207: 71-95. DOI: 10.1016/j.geomorph.2013.10.028

Stevaux, J., Martins, D., Meurer, M., 2009. Changes in a large regulated tropical river: The Paraná River downstream from the Porto Primavera Dam, Brazil. *Geomorphology*, 113: 230-238. DOI: 10.1016/j.geomorph.2009.03.015

Vazquez-Tarrio, D., Tal, M., Camenen, B., Piégay, H., 2019. Effects of continuous embankments and successive run-of-the-river dams on bedload transport capacities along the Rhône River, France. *Sci. Total Environ.* 658: 1375-1389. DOI: 10.1016/j.scitotenv.2018.12.109

Vericat, D., Batalla, R.J., 2006. Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology* 79: 72-92. DOI: 10.1016/j.geomorph.2005.09.017

Williams, G. P., and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. US Geological Survey Professional Paper 1286.

Wolman M.G., 1954. A method of Sampling Coarse River Bed Material. *Transactions of the American Geophysical Union*, 35(6): 951-956. DOI: 10.1029/TR035i006p00951

CHAPTER 3. Characterisation of the effects of multiple factors on bedload transport regime.

Paper in preparation. Bulteau, T., Vázquez-Tarrío, D., Batalla, R.J., Piégay, H.. A multi-site and hypothesis-driven approach to identify controls on the bedload transport regime of an anthropised gravel-bed river. Submission planned for International Journal of Sediment Research.

Abstract

In anthropised rivers, morphological modifications and hydrological disturbances, as well as transverse barriers to sediment continuity have been widespread, affecting by extension the associated ecosystem services. Evaluation of the effects of those drivers is of growing interest, notably through the implementation of bedload transport measurements for river diagnosis, the design of restoration actions, and post-action monitoring. Nevertheless, such evaluations are complex, particularly in those sites where multiple factors concurrently affect the bedload transport regime, thwarting the possibility to establish robust causal connections between one factor and one effect. To overcome this challenge, classical inductive approaches attain their limits, and the need emerges for more rigorous hypotheses-driven approaches to assess unitary effects of each driver.

It is within this frame that we characterised bedload transport dynamics in the Upper Garonne (Central Pyrenees, Spain-France). This 80 km-long fluvial reach encompasses a broad range of morphological features, as well as a varying degrees of river anthropisation. In this work, we assessed the effects of (1) surface grain size distribution, (2) river morphology, (3) sediment supply, and (4) flow diversion modalities on sediment transport. Four sites were selected according to the differences they exhibit in the previously stated characteristics. After defining hypotheses on transport regime for each site, we proposed a set of discriminatory criteria that helped in the attribution on cause-effects relationships, based on intra-site temporal and inter-site spatial comparison (Control – Impact strategy). Bedload tracing experiments over ~4 yr partly allowed to evaluate unit effects of each driver.

Keywords : *bedload transport regime,*

3.1. Introduction

Sediment characteristics (i.e. size and composition) and transport dynamics (i.e. rates, volumes and transport modalities) are central components of fluvial systems. A variety of biogeomorphological processes are linked to them, as they (1) drive the evolution of fluvial landscapes (Lane, 1955; Schumm, 1977; Ashmore & Church, 1992), (2) influence the functionality of hyporheic exchanges (Wooster *et al.*, 2008; Evans & Wilcox, 2014), (3) condition the distribution and promote the availability of fish and macroinvertebrate habitats (Kondolf & Wolman, 1993; Gayraud & Philippe, 2003; Owens *et al.*, 2005), and (4) represent important issues for human activities, especially for dam management (Kondolf *et al.*, 2014), flood risk mitigation (Gaeuman, 2012), water supply, and structures stability (Batalla & Vericat, 2011). Where hydro-sedimentary regime is altered by river anthropisation, estimations of bedload dynamics are critically important to answer both scientific and operational issues (Frings *et al.*, 2014; Frings & Ten Brinke, 2017), design restoration actions (Dépret *et al.*, 2019) and evaluate their success (Arnaud *et al.*, 2017, Peeters *et al.*, 2021). Then, the measurement of bedload transport has to be considered as an integral part of river geomorphic diagnosis.

Many methods allowing for the quantification of bedload rates from field measurements are currently available, each one presenting its own strengths and weaknesses. For instance, bedload transport has been commonly measured from direct sampling using nets, samplers and traps (see pioneer works by for instance Leopold & Emmet, 1977; Emmet *et al.*, 1980; and more recently Vericat & Batalla, 2006; Claude *et al.*, 2012). This method provides good estimations of bedload grain size but often leads to large uncertainties and needs to be operated on the field during bedload-competent events, which may be dangerous and not practical in highly responsive mountain catchments where floods often last less than a day. Indirect methods have successfully been proposed for a decade or so, based on the measurement with geophones (Rickenmann *et al.*, 2014; Rickenmann, 2017) and hydrophones (Geay *et al.*, 2017; Leguern *et al.*, 2021) of sounds or vibrations emitted by bedload. Although those methods provide continuous information on bedload transport, they require field measurements for calibration (Geay *et al.*, 2020). Sediment tracing with different technologies (Hassan & Roy, 2016), recently dominated by PIT-tags, provides an interesting alternative for bedload quantification. As this method allows to follow the path of individual particles and locate buried or exposed clasts, it provides extensive information on bedload behaviour at a given site, notably on displacement lengths (Church & Hassan, 1992; Pyrce & Ashmore, 2003), particle dispersion (Hassan & Bradley, 2017; Vázquez-Tarrío *et al.*, 2019), depth of burial and active layer thickness (Hassan, 1990; Lamarre *et al.*, 2005; Tsakiris *et al.*, 2015;

Brousse *et al.*, 2018; Vázquez-Tarrió *et al.*, 2021), or bulk bedload volumes per event (Schneider *et al.*, 2014; Mao *et al.*, 2017).

Because the measurement of sediment transport rates in the field is notoriously laborious, numerous alternative attempts to approach bedload transport as a mechanistic problem, using transport formulas, were made for now more than a century (du Boys, 1879; Einstein, 1942; Meyer-Petter & Müller, 1948; Parker, 1990; Recking, 2013a). Nevertheless, and despite large efforts deployed on developing sediment transport equations, the reliability of their results has still not been up to expectations, and largely depends on the formula type (e.g. threshold vs nonthreshold, calibration) and application domain (e.g. slope, grain size) (Hinton *et al.*, 2018). Since bedload formulas implicitly assume a river bed in equilibrium with its sediment load, a condition that is mainly not satisfied in anthropised rivers, they provide reliable estimates of bedload transport rates in unconstrained alluvial rivers but fail in those rivers where sediment supply disruption (e.g. sediment deficit after damming) and hydrological regime alteration (e.g. peak flows lamination due to dams, hydropeaking) lead to different altered transport regimes (Gomez & Soar, 2022). Therefore, field-based estimations of bedload rates under different transport regimes are of central importance for scientific and operational purposes (e.g. specification of a regime-based parameter in transport formulas, characterisation of sediment deficit and hydrological modification effects on coarse sediment transport, sediment budget, restoration design and assessment). To the best of our knowledge, this topic has been rarely addressed in previous research and only recently has been the subject of specific studies (Papangelakis & MacVicar, 2020; Brenna *et al.*, 2020).

The characterisation of the drivers on the variability in the sediment regime in gravel-bed rivers is complex, due to multiple reasons. On the one hand, due to the complexities inherent in the field measure and computation of bedload volumes, stated above. On the other hand, because of the multi-scale nature of the controls on the sediment transport dynamics of a given reach, going from the grain scale (e.g. bed state, texture) to the catchment scale (e.g. hydrology, land cover), it is difficult to isolate the influence of these different drivers on the sediment regime. To achieve this kind of characterisations, a multi-site approach consisting in comparing different reaches of the same river that potentially exhibit differences in transport regime, seems an appropriate study design (Liébault *et al.*, *in press*). This experimental design should avoid the variability inherent in the comparison of contrasted river contexts, whether in terms of hydro-climatic, geologic, morphometric, as well as anthropic features. In this regard, multi-site study designs allowed to go further in the geomorphic information that can arise from particle tracking (Liébault *et al.*, *in press*), with main goals for such experiments being (1) sediment budget elaboration for river and coastal restoration (Eschbach *et al.*, 2021), (2) assessment of sediment transfer efficiency through dams or

weirs (Casserly *et al.*, 2021; Peeters *et al.*, 2020), (3) evaluation of river restoration effects (Papangelakis & MacVicar, 2020; Gilet *et al.*, 2021; Peeters *et al.*, 2021), or (4) identifying relations between bedload transport and channel components, namely confluences (Imhoff & Wilcox, 2016), and morphological features (Papangelakis & Hassan, 2016), structures (Lamarre & Roy, 2008), or geomorphic changes (McQueen *et al.*, 2021), between others.

In this contribution, we use a multi-site experimental design to explore how varying flow conditions (i.e. permanent by-passing, by-passing only during low- and mid-flow periods, full discharge), sediment availability (i.e. long-term sediment starvation, discontinuous supply downstream from a dam, ‘natural supply’ downstream the confluence of a potentially significantly contributing tributary) and channel characters (i.e. bed grain size, bed armouring, slope, morphology) influence the sediment transport regime of gravel-bed rivers. To do so, bedload transport rate is estimated by sediment tracing and topographical measurements at four different sites distributed over a ~ 30 km-long reach of a mountain river (Upper Garonne, Central Pyrenees, Spain/France), each site being selected according to a specific set of conditions. Then, we started this research by a careful descriptive analysis of each one of these sites. After sites description, we define a set of hypotheses on the relationships between bedload transport and the sites characteristics, assuming different transport regimes according to those characteristics. Finally, we test those hypotheses comparing intra-site temporal trends and inter-site spatial trends in multiple metrics such as transport rates (field-based), transport capacity (formula-based), or transport efficiency.

3.2. Study site and working hypotheses

The study was conducted on the Upper Garonne, a single-thread channel river whose headwaters are located in the Central Pyrenees (Spain, Pla de Beret, 1830 m a.s.l.) and flows to France to meet the Neste River after a 78 km path (420 m a.s.l, Fig. 3.1). The drainage basin is 1265 km² with an average discharge of 31 m³s⁻¹ at the downstream gauging station of Chaum. The hydrological regime of the Upper Garonne is snow-melt dominated with high-flows occurring from April to June. Recent hydrology of this area has been marked by the exceptional flood of 18th June 2013 (i.e. Q₁₀₀, Fig. 3.1), which resulted in complete refurbishment of channel planforms that until then were experiencing channel simplification and bed coarsening due to sediment deficit induced by multiple damming, afforestation, and gravel mining. After the flood, intensive channel works upstream of the Plan d’Arem dam (River Kilometre 40, referred as RK40 after in the text) drastically reduced morphological activity of this reach which rapidly returned to pre-flood conditions, whereas drawdown flushing actions operated on this dam have preserved post-flood

conditions downstream (i.e. must be seen as ecological improvements) with significant effects on fluvial landscape mosaic (Bulteau *et al.*, 2022), thermal exchanges (Bulteau *et al.*, under reviewing.) and fish spawning habitats (FDAAPPMA, 2015). As the flood hydrology of this reach is still relatively unaffected by damming, one main operational issue is now to ensure a sufficient sediment supply to prevent further deficit. For the present study, four sites were selected for their differences in terms of flow regulation, sediment availability and channel features (Table 3.1, see Bulteau *et al.* (2022) for more details on long term evolution of study reach).

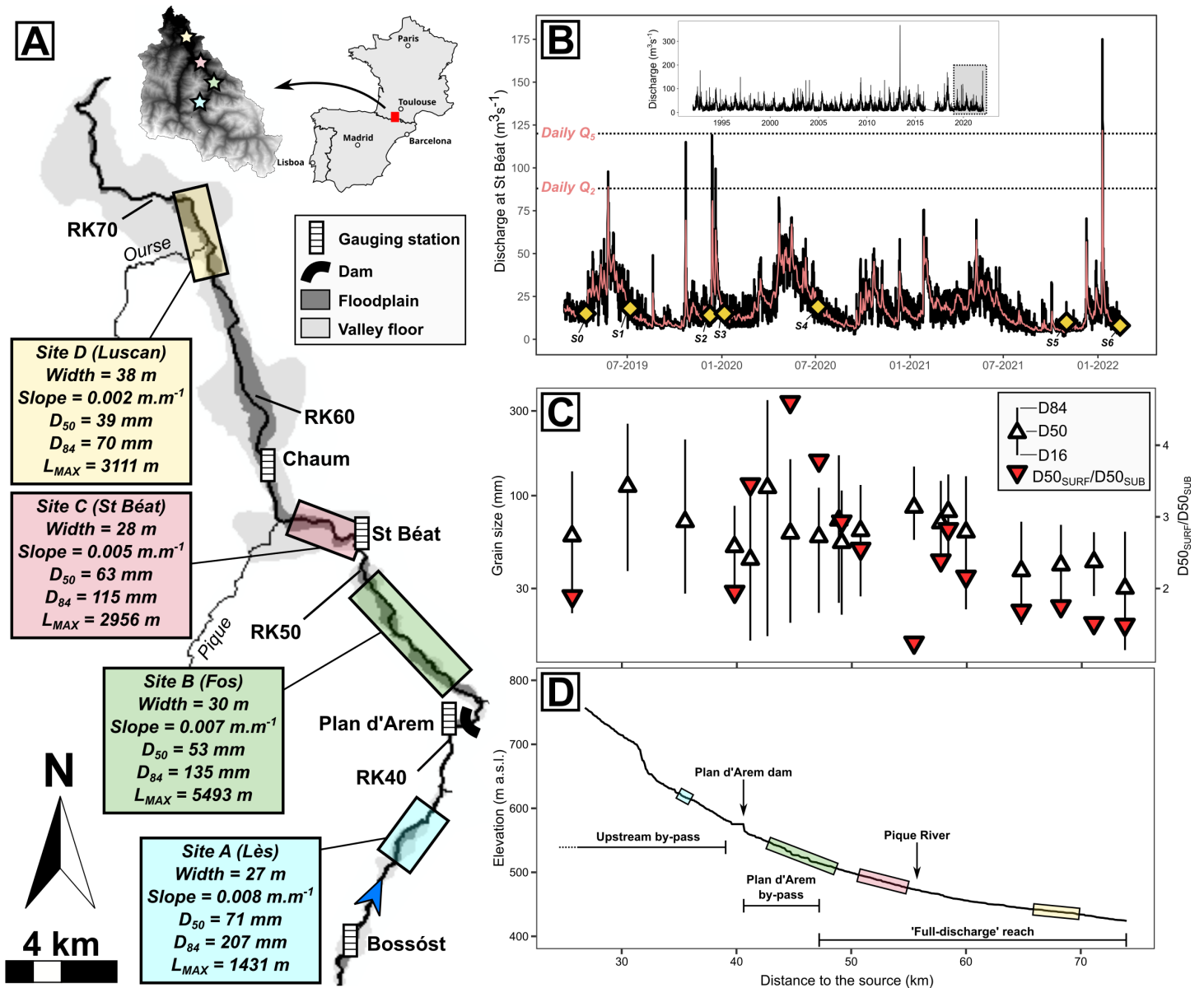


Figure 3.1. A. Study site location and characteristics. B. Hydrology at the St B at gauging station during the monitoring period and in the long-term context (inset). Black line: 1-hour discharge. Red line: mean daily discharge. Horizontal dashed line: Return period calculated on daily discharge series. Yellow dots: RFID surveys. C. Longitudinal pattern of bed surface grain size (white triangle: D_{50} , error-bars: $D_{16} - D_{84}$) and armoring (red triangle) derived from pebble counts (Wolman, 1954; Buffington, 1996). D. Longitudinal pattern of water surface elevation.

3.2.1. Lès (site A)

The site of Lès (thereinafter, site A), the uppermost reach, presents the highest channel slope (0.0081 m m^{-1} in average, locally ranging from 0.0045 to 0.0096 m m^{-1}). Bed surface grain size is marked by presence of large immobile boulders ($D_{95} = 404 \text{ mm}$) that likely exert hiding-effects on smaller particles ($D_{50} = 71 \text{ mm}$), and we visually observed in the field significant bed armouring although it has not been quantified at this site for technical reasons.

Site A hydrology is strongly affected by hydroelectricity production. It is located in a by-passed section, with multiple water abstractions reducing peak flows by 15 to $20 \text{ m}^3\text{s}^{-1}$, corresponding to $\sim 25 \%$ of a 2-year return period flood at the near upstream Bossòst gauging station (see Fig. 3.1 for exact location). Moreover, hydropower plants generate hydropeaks up to $16 \text{ m}^3\text{s}^{-1}$, twice the mean discharge ($7.9 \text{ m}^3\text{s}^{-1}$) and four times the minimum discharge ($4 \text{ m}^3\text{s}^{-1}$) for the study period).

This site is located within a severely sediment starved reach, affected by long term reduction in sediment supply due to rapid hillslope afforestation after 1960s, and decreased post-dams transport capacity of the most upper catchment. Those changes in hydro-sedimentary conditions lead to morphological adjustments which consisted in decreased channel width, vegetation encroachment of gravel bars, riffle-pool sequences disappearance, and overall fluvial pattern metamorphosis, from a former laterally active wandering channel to a stable and straight plane-bed channel, with poorly-developed bedforms, i.e. likely a sign of supply-limited sediment regime.

3.2.2. Fos (site B)

The site of Fos (site B), is located in the by-passed reach downstream the Plan d'Arem dam. Channel on this site presents some similar characteristics to site A, although slope is slightly lower (0.0068 m m^{-1} in average, locally ranging from 0.0039 to 0.0092 m m^{-1}), and bed grain size slightly smaller ($D_{50} = 53 \text{ mm}$ and $D_{95} = 341 \text{ mm}$).

Even though site B is located in a by-passed section, it has a flood hydrology that remains largely unaltered (especially in terms of competent flows), as the Plan d'Arem dam operates systematic drawdown flushing when discharge exceeds $70 \text{ m}^3\text{s}^{-1}$ (~ 1 -year return period flood), leading to discontinuous supply of size fractions typically ranging from 2 to 200 mm .

As a consequence of this intermittent supply and peak flow preservation, bed armouring of site B alternates from high values, legacy from the period between the dam construction (1970) and first flushing actions (2014), and lower values, witnessing the transfer of material stored within the reservoir. Recent morphological evolution of the channel in site B channel morphology indicates

that the reach exhibits quite high dynamism, with active lateral mobility locally creating multiple channels, well-developed bedforms (i.e. large unvegetated gravel bars, marked riffle-pool sequences), and no bed incision, features characterising functional a wandering fluvial type and probably transport-limited conditions.

3.2.3. St Béat (site C) and Luscan (site D)

Sites of St Béat (site C) and Luscan (site D, the lowermost reach) present quite similar physical characteristics. Both are located downstream of the hydroelectricity production network, the flow channel there convey the whole river discharge and flood hydrology is neither affected by upstream dams nor by water diversions. Upstream hydropeaks propagation is still observable, although with lower magnitude than in site A. Maximum hydropeak discharge ($Q_{HP} = 20 \text{ m}^3\text{s}^{-1}$) represents approximately 100% and 70% of the mean discharge for the study period at site C ($Q_{MEAN} = 18.8 \text{ m}^3\text{s}^{-1}$) and site D ($Q_{MEAN} = 27.5 \text{ m}^3\text{s}^{-1}$), respectively. Over the last century, those sites have experienced channel planform simplification, but the 18th June 2013 flood restored channel morphology to 1940-like conditions. Channel incision between 1922 and 2014 was also fairly limited, with mean values of -0.43 and -0.32 m, and maximum values of -1.3 m and -0.74 m at sites C and D, respectively. Current morphology of sites C and D typically exhibits a straight single-thread channel, laterally confined although showing local lateral mobility, and alternation of plane-bed with riffle-pool sequences. Surface grain size is significantly smaller than in sites A and B, and probably fully mobile for frequent flood ($D_{95} = 162 \text{ mm}$ and $D_{95} = 88 \text{ mm}$ at sites C and D, respectively).

Main differences potentially inducing contrasted bedload regime between sites C and D lay on (1) channel slope, significantly higher at site C (0.0053 m m^{-1} in average, locally ranging from 0.0032 to 0.0077 m m^{-1}) than at site D (0.0017 m m^{-1} in average, locally ranging from 0.0015 to 0.0034 m m^{-1}), and (2) drainage network organisation, as site D receives water and sediment from the Pique River, the main tributary over the study reach that significantly contributes to annual water yield with an increase of 32% between site C and D, and potentially also in sediment yield, as the Upper Pique River catchment is subjected to intense torrential processes.

Transport regime drivers	Hypothesised drivers effects		Site A	Site B	Site C	Site D
Channel characters	Planforms evolution	Before 2013-flood	Simplification	Simplification	Simplification	Simplification
		After 2013-flood	Simplification	Stability	Stability	Stability
	Bed grain size distribution	Coarse boulders	+	+	-	-
		Bed armouring	+	+/-	-	-
Hydrology	Hydropeaks	Relative magnitude	++	-	+	+
	Water diversion	Effects on base flows	+	+	-	-
		Effects on peak flows	+	-	-	-
Sediment supply	Upstream supply	Magnitude	-	+	+	+
	Tributary supply	Magnitude	-	-	-	+

Table 3.1. Summary of those sites characteristics that may having a potential influence on the between-site differences in the sediment transport regime.

3.2.4. Hypothesis on transport regime drivers

Based on the sites characteristics, we explicitly posed the following working hypotheses.

(H1) Sediment supply impacts overall bedload rates. In line with this hypothesis, we would expect (1) that site A, which shows the most ‘supply-limited’ morphological characteristics of the study reach, exhibits lower transport rates than other sites, (2) sites B and C show similar bedload rates as they are both located in the vicinity of the available sediment source (i.e. Plan d’Arem reservoir), and (3) site D presents higher transport rates than other sites because of the potentially significant supply from a tributary (Pique River).

(H2) Flood magnitude reduction by water diversion significantly reduces transport rates. If this hypothesis were true, we would expect that site A presents lower transport rates than sites B, C and D for most flood events, because of water diversion during floods that only affects site A permanently. For small flood events, typically not sufficiently competent to trigger flushing

management on the Plan d'Arem dam, we expect site B to show reduced transport rates, comparable with site A for the same event, whereas sites C and D should show higher transport rates.

(H3) Channel configuration modulates the effects of sediment supply and flood hydrology on bedload transport. If this hypothesis were correct: (1) site A, because of the presence of coarse immobile boulders during frequent floods, may present lower transport rates than sites C and D, for which the entire bed is probably mobile; (2) site B, which still show some boulders, also presents active wandering morphology, two opposed factors in terms of sediment transport rates (i.e. well-developed riffle-pool channels generally convey bedload more efficiently than plane-beds do), and we may then observe higher transport rates than site A for similar grain size conditions.

3.3. Material and methods

3.3.1. Flow data compilation, competence and efficiency calculation

Hydrological data were compiled at a 1-hr time-step. Discharge is given by the upstream gauging station for sites C ('St B at' station O001004003, hydro.eaufrance.fr) and D ('Chaum' station O005002001, hydro.eaufrance.fr). For site A, discharge at the gauging station of Boss st (station A019; saihebro.com) does not reflect 'real' discharge at the experimental section of L s (station 274; risqhydro.smartyplanet.com) for which discharge had to be re-routed and derived, for this a calibration exercise was carried out during the rising limb of the 23rd October 2019 flood, for which hydrology was rather *natural* ($Q = 0.0032H^{1.9}$; $R^2 = 0.89$). For site B, located within the by-passed reach of the Plan d'Arem, we recalculated discharge as the difference between discharge at site C and turbinated discharge at the hydropower plant of the Plan d'Arem (Electricit  de France, comm. pers.). For site B, located within the by-passed reach of the Plan d'Arem, we recalculated discharge as the difference between discharge at site C and turbinated discharge at the hydropower plant of the Plan d'Arem (Electricit  de France, comm. pers.).

Flow competence has been approached based on the use of unit stream power ω (in $W m^{-2}$, Eq. 3.1) since this metric (1) allows to easily integrate flow magnitude and duration, (2) has been shown more reliable to establish transport – flow relationships (Schneider *et al.*, 2014), (3) is less sensitive to the choice of a critical value than the shear stress (Parker *et al.*, 2011), and (4) only requires limited parameters for its calculation.

$$(Eq. 3.1) \quad \omega = \frac{\rho_w g Q S}{W}$$

where ρ_w is fluid density (taken as 1000 kg m⁻³), g is gravitational constant, Q is flow discharge (in m³ s⁻¹), S is channel slope (in m/m) and W is channel width (in m).

Transport efficiency, defined as the proportion of available energy effectively spent in moving sediment, was approximated through the use of the Energy Expenditure Index (Vázquez-Tarrío & Batalla, 2019), which may be considered a proxy of the amount of energy needed for moving particle a given distance (i.e. 1 m). This index can be simply calculated by dividing the time-integrated excess stream power (in J m⁻²) over a given period by the mean transport distance over the same period of time (Eq. 3.2).

$$(Eq. 3.2) \quad EEI = \frac{(\omega - \omega_c) \cdot t}{L_M}$$

where EEI is the Energy Expenditure Index (in J m⁻³), ω_c is the critical stream power (W m⁻²), t is the time between two consecutive survey (in s) and L_M is the mean transport distance (in m).

3.3.2. Sediment transport rates (field-based)

3.3.2.1. Travel distances and active layer

A total of 315 to 331 passive RFID tracers were seeded on each site in April 2019 to estimate bedload transport distances (L). Tracer size ranges from 22 to 128 mm, covering D11_{SURF}–D70_{SURF}, D20_{SURF}–D83_{SURF}, D11_{SURF}–D89_{SURF} and D18_{SURF}–D100_{SURF} ranges at sites A, B, C, and D, respectively (*b-axis*, Fig. 3.2). Tracers were marked with 23-mm PIT-tags for 22-45 mm fraction, and with 32-mm PIT-tags for 45-128 mm fraction in order to maximise detection distances (Arnaud *et al.*, 2015). Each site was surveyed 3 to 5 times from the date of tracers seeding (S0) to February 2022 (S6). Large transport distances and difficult field conditions have led to time-consuming surveys of about one week per site for the various campaigns, restricting from a more frequent field surveying. Nevertheless, data collection encompasses the entire range of peak discharges observed at each site. Thus, site A was surveyed at S1, S2 and S3, site B at S1, S3, S4 and S6, site C at S1, S3, S4, S5 and S6, and site D at S1, S3, S5 and S6. Tracer positions were recorded using a simple hiking GPS with a precision of 5 m which is acceptable considering the large transport distances we observed. After each survey, tracer recovery rates were calculated as the number of found tracers reported to the number of injected tracers (P_{TOT} , Table 3.3), and between each pair of consecutive

events, as the number of found tracers at S_{i-1} and S_i reported to number of found tracers at S_i (P_{COMMON} , Table 3.3). P_{COMMON} calculation allowed to assess consistency and representativeness of individual transport distances for characterisation of bedload transport distances, and thus bedload volumes.

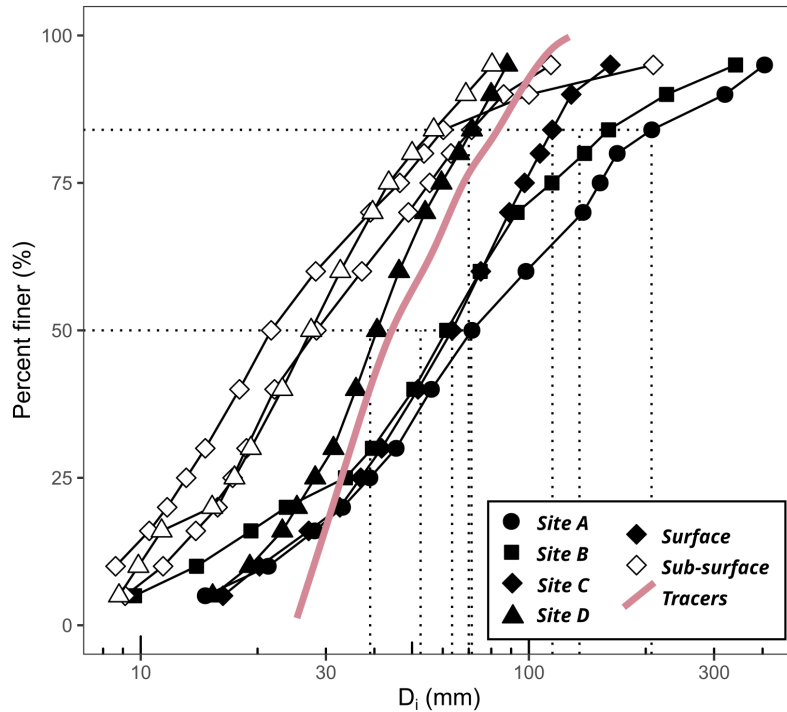


Figure 3.2. Grain size distribution of RFID sites, for surface (full dots) and subsurface (empty dots) layers and tracers (red line).

Active layer thickness has been estimated as the mean between scouring and deposition thicknesses, respectively approached using columns of active RFID which were inserted into artificial pebbles of 30 mm c-axis (Laronne *et al.*, 1992; Cassel *et al.*, 2016; Brousse *et al.*, 2018) and cross-sectional change measurements. As active RFID tags are not affected by signal collision, it is then possible to know which tracers are still in place and which have moved. Maximum scouring D_{SCOUR} (in m) is calculated as $D_{SCOUR} = n_{MOVE} \times 0.03$ where n_{MOVE} is the number of tracers that has moved; filling depth D_{FILL} (in m) is given by $D_{FILL} = Z_{S5} - Z_{S0}$ where Z_{S0} and Z_{S5} are bed elevation at survey S0 and S5, respectively. Finally, active layer thickness D_S (in m) is calculated as the mean between D_{SCOUR} and D_{FILL} . At each site, a total of 21 active RFID tags were then installed into 3 columns ($z = 0.21$ m) at S0, corresponding to D_{84} , $1.5D_{84}$, $1.8D_{84}$ and $3D_{84}$ at sites A, B, C and D, respectively. For technical reasons, columns were surveyed once at S5, integrating the maximum bed scouring over a 2.5-years period.

3.3.2.2. Virtual velocity approach

The use of tracers for bedload volume estimation relies on different techniques. Field approaches involve measuring particle displacement distances with tracers and active layer thickness with scour chains (Laronne *et al.*, 1992), measuring depth of tracer burial (Vázquez-Tarrío and Menéndez-Duarte, 2014; Papangelakis and Hassan, 2016) or active RFID columns (Brousse *et al.*, 2018). Then, bedload volumes are calculated as the simple product of mean distances and mobilised area (Liébault & Laronne, 2008). Other approaches rely on the assumption of existing relations between bedload transport, estimated using sediment traps, and particle travel distances (Schneider *et al.*, 2014; Casserly *et al.*, 2021). Finally, the virtual velocity approach has provided reasonable estimations of bedload volumes on US (Haschenburger & Church, 1998) and Italian rivers (Mao *et al.*, 2017; Brenna *et al.*, 2019).

Estimation of bedload volumes using the virtual velocity as described by Wilcock (1997) relies on the time integration of fractional mass transport rates M_i (in kg m^{-2}), distinguishing between partial bed mobility (Eq. 3.3), when only a certain proportion of grains are mobile as the armour layer has not completely disrupted, and total bed mobility (Eq. 3.4), when all grains are mobile over a given depth after armour layer breakup.

$$\text{(Eq. 3.3)} \quad M_i^{PT} = \frac{m_i F_i Y_i}{D_i^2} \quad \text{(Eq. 3.4)} \quad M_i^{FT} = \frac{m_i F_i d_s}{D_i^3}$$

where m_i is the mean mass of a single particle of fraction i (in kg) defined on the population of tracers, F_i is the proportion of fraction i in the surface grain size distribution, D_i is the mean size of fraction i grains (in m) defined on the population of tracers, Y is the percentage of mobilised streambed particles, and d_s is the active layer thickness (m).

Here, the computation of the Y parameter relied on a modified application of the Generalised Threshold Model (GTM; Recking, 2016), GTM is a two-step model that first allows estimating the size of the largest mobile clast from the observed mobility of a reference percentile from the grain size distribution (Eq. 3.5) and the mobile fraction of different size classes for given flow conditions (Eq. 3.6). Applying this model seems relevant to us as it also differentiates partial and total mobility conditions. We use the 84th percentile as the reference since total bed mobility when discharge overpasses critical discharge for D_{84} movement is commonly admitted (Recking, 2013b; MacKenzie *et al.*, 2018).

$$(Eq. 3.5) \quad M = 84 \left(\frac{Q}{Q_{c84}} \right)^\beta$$

where M is the maximum mobile percentile (%), Q is the water discharge ($m^3 s^{-1}$), Q_{c84} is the critical discharge for bed surface D_{84} mobilisation defined experimentally from tracer experiments, and β a coefficient accounting for the transition regime from partial- to full-transport as the discharge increases, e.g. β close to 1 traduces a linear dependence of bed mobility to flow whereas high β characterises an abrupt transition. β is calibrated from tracer experiments.

$$(Eq. 3.6) \quad Y_i = Y_0 + \left(1 - \left(\frac{i}{M} \right)^\gamma \right)$$

where Y_i is the proportion of mobile tracers in the i -size fraction, Y_0 the minimum proportion when i increases to M , and γ a coefficient describing the rate of decrease for Y_i ($\gamma < 0$ means low proportion of mobile particles when threshold for i -size particle motion is overpassed, $\gamma \sim 1$ traduces linear dependence between critical discharge and mobility, $\gamma > 1$ relates with near-full mobility of i -size particles as soon as threshold for entrainment is overpassed). γ is calibrated at each site and for each period to best fit the observed tracers behaviour.

Unit fractional bedload transport rate q_i^u (in $kg m^{-1} h^{-1}$) is then given by the product (Eq. 3.7) of M_i , and V_i (in $m hr^{-1}$), the virtual velocity of the considered size fraction (Eq. 3.8).

$$(Eq. 3.7) \quad q_i^u = M_i V_i \quad (Eq. 3.8) \quad V_i = \frac{L_i}{t_i}$$

where L_i is the mean distance travelled by individual tracers of i size (in m), and t_i the time during which discharge exceeds critical discharge for mobility of an i size grain (in h).

In order to overcome the loss of small tracers during the last surveys, we replaced L_i , initially defined as the mean distance travelled by i -size individual tracers, by the migration of i -size tracers centroid $C_i(X_i; Y_i)$ in the case of no common i -size tracers are found between S_{i-1} and S_i , and considering this migration as representative of the average displacement of i -size bed material. This replacement was operated three times, and concerned site C, for which we found no common tracers of 22-32 mm between S4 and S5, and of 90-128 mm between S5 and S6; and also in the case of the site D, where no common tracers of 22-32 mm were found between S5 and S6.

Decision tree for virtual velocity application proposed by Brenna *et al.* (2019) reports for the minimal data acquisition configuration depending on the river morphological features. In our case, we considered a relatively simple context as the Garonne has a single-thread channel without well-

developed bedforms. Topography and bed grain size have then been considered stable and homogenous over time and space for each site.

3.3.3. Sediment transport capacity (formula-based)

In order to estimate whether the study sites experience “transport-limited”, when actual bedload volumes overpass the transport capacity, or to the contrary “supply-limited” conditions, when for a variety of reasons not enough sediment is available on the bed to be transported, we calculated bedload transport capacities and compared predicted and observed volumes. In selecting the most appropriated transport formula, we privileged an uncalibrated equation requiring few input data since we have not sufficiently long and robust tracer dataset to perform both calibration and validation. In the light of those considerations, the Recking’s equation (Recking, 2013a, Recking *et al.*, 2016) appeared suitable since it meets previous statements, and has been developed for a range of slope (0.0002 – 0.30) and D_{50} (0.1 – 204 mm) that corresponds to the Upper Garonne conditions. Furthermore, the comparative study of bedload formulae conducted by Hinton *et al.* (2018) indicates Recking’s equation performed better than other uncalibrated equations (Parker, 1990; Wong & Parker, 2006).

3.3.4. Deductive-scheme for hypothesis verification or falsification

Hypothesis-driven approaches rely on the definition of an explicit criterion which can be further tested to state on hypothesis validation or rejection. If statistical tests are classically performed, for which the criterion is the p-value, they can not be applied in every cases, notably when sample size is too small. In such cases, the discriminatory criterion is conditional (i.e. case-specific) and tested empirically on the basis of cause-effects relationships interpretation. For this purpose, we propose a simple deductive-scheme that should allow us to discriminate the influence of each driver in controlling sediment transport regime. We detail the role of each metric in feeding this scheme in Table 3.2.

Hypothesis (**H1**), on the role of sediment supply, is tested on the basis of inter-site comparison of both transport rates and the ratio between transport rates (field-based) and transport capacity (formula-based). The former metric informs effective bedload transport, and we hypothesised that it should be lower at site A due to long-term decreased sediment supply, higher at site B and C due to discontinuously restored supply during flushing actions, and highest at site D due to tributary supply (Table 3.2, **H1a**). With the computation of the latter parameter (ratio between rates and capacities), we aim to go further in the characterisation of the effects of sediment supply on transport regime, as the ratio between observed and predicted bedload rates may allow to state whether a given reach experiences supply-limited (i.e. ratio < 1), equilibrium (i.e. ratio ~ 1), or

transport-limited conditions (ratio > 1). We then hypothesise that this ratio should increase downward in relation with increasing supply (*H1b*). Hypothesis (*H1*) will be considered valid if the results corroborate both criteria.

Hypothesis (*H2*), on the role of flow diversion, is tested first on the basis of inter-site comparison of transport rates considering different periods. Over the entire study, we expect lower transport rates at site A than in the other sites, because of permanent flow diversion that only affects this site (*H2a*). This first criterion alone does not allow to state on the effects of flow diversion since site A may also be affected by decreased supply, as per hypothesis (*H1*). In this regard, we compared bedload transport rates more specifically during periods that only encompass small floods (i.e. not enough competent to trigger flushing actions on the Plan d'Arem dam, period S0-S1). We expect during those periods, flow diversion similarly affects sites A and B, which may then show similar and rather reduced transport rates, whereas sites C and D present higher transport rates (*H2b*). Furthermore, purely field-based approach may not allow to fully answer hypothesis (*H2*), because no 'reference' section, unaffected by water diversion, is available close to site A, i.e. we used site B as 'reference' but multiple tributaries and hydropower plants between sites induce variability and limit the reliability of such comparison. To overcome the lack of 'reference' section, we performed an intra-site comparison of transport capacity, in order to finally isolate the effect of flow diversion. Transport capacity was then estimated twice at site A, once with 'real' discharge, derived from water stage calibration and affected by upstream diversion, and once using 'natural' discharge, taken from the Bossòst gauging station (A019, see section 3.3.1). Here we expect the 'real' transport capacity is lower than the 'natural' transport capacity (*H2c*). Finally, we also expect lower tracer mobility at sites A and B than in sites C and D during small floods, due to decreased transport capacity (*H2d*). This effect may lessen for periods experiencing larger floods. Hypothesis (*H2*) will be considered valid if the results meet all of the four stated criteria.

Hypothesis (*H3*), on the role of channel configuration, is tested using other criteria than previous hypotheses, that said, it is based on bedload behaviour rather than transport rates. As coarse immobile boulders limit scouring and exert some hiding on smaller grains, we expect sites A and B to show thinner scour-depth (*H3a*), more size-selective transport (*H3b*), and lower transport efficiency (*H3c*) than sites C and D. In the case of size-selective transport, it may lessens for periods experiencing larger floods. On another hand, channel morphology may play an important role in sediment propagation, with active wandering channels conveying bedload more actively than plane-beds. We then expect transport distances at site B are higher than other sites (*H3d*). Validation of hypothesis (*H3*) relies on the achievement of the four criteria.

Hypothesis	Metric	Period	Criterion
H1	Transport rates (field-based)	Study (S0-S3 & S0-S6)	(H1a) $TR_A < TR_B ; TR_C < TR_D$
	Field-Formula ratio	Study (S0-S3 & S0-S6)	(H1b) $FF_A < FF_B ; FF_C < FF_D$
H2	Transport rates (field-based)	Study (S0-S3 & S0-S6)	(H2a) $TR_A < TR_B ; TR_C ; TR_D$
	Transport rates (field-based)	Small flood (S0 – S1)	(H2b) $TR_A ; TR_B < TR_C ; TR_D$
	Transport capacity (formula-based)	Study (S0-S3)	(H2c) $TC_{A-REAL} < TC_{A-NATURAL}$
	Mobility	Study (S0-S1 & S1-S3)	(H2d) $M_A ; M_B < M_C ; M_D$
H3	Scour depth	Study (S0 – S5)	(H3a) $D_{SCOUR-A} ; D_{SCOUR-B} < D_{SCOUR-C} ; D_{SCOUR-D}$
	Size dependence	Study (S0-S1 & S1-S3)	(H3b) $SD_A ; SD_B > SD_C ; SD_D$
	EEI	Study (S0-S3 & S0-S6)	(H3c) $EEI_A ; EEI_B > EEI_C ; EEI_D$
	Transport distance	Study (S0-S3 & S0-S6)	(H3d) $TD_B > TD_A ; TD_C ; TD_D$

Table 3.2. Summary of metrics, periods and discriminatory criteria for hypotheses validation

3.4. Results

3.4.1. Passive tracer experiments

3.4.1.1. Recovery rates

Tracer recovery rates (P_{TOT}) ranged from 12 to 50 % considering all sites and surveys, with a minimum of 38 tracers found at site D for S6 (Table 3.3). In general, recovery rates were higher for sites A and B than for sites C and D, in relation with water diversion which decreases flow level during surveys and facilitates wadability. Furthermore, at sites C and D, survey effort along long reaches, especially RK 52 – 52.3, RK 52.6 – 53 and RK 53.4 – 55 for site C, and RK 68.9 – 69.2 for site D was less important than on other sites due to harder accessibility. P_{TOT} values were overall acceptable after S3 (41 %, 51 %, 29 % and 25 % at sites A, B, C and D, respectively) but remarkably dropped afterwards reaching 33 %, 15 % and 12 % at S6 for sites B, C and D, respectively. As expected, the smallest size class (22-32 mm) presented the highest reduction in recovery rate, as for example after S6 where only 19 tracers were found at site B ($P_{22-32} = 21$ %), 12 at site C ($P_{22-32} = 13$ %) and 2 at site D ($P_{22-32} = 2$ %). If tracer burial and dispersion are the two

commonly admitted explanations for tracer loss, we found the second more convincing in the case of the Garonne as channel topographical changes were generally lower than the detection distance of the used antenna (~ 80 cm). Depending on the considered site, we also observed that transport distances were importantly size-dependant (Fig. 3.3), again indicating that ‘front-runners’ may have rapidly been transported out of the surveyed reach for each site, as it was the case of one tracer seeded at site B and found at site C during S5, some 7713 m downstream from the injection. Inter-event recovery rates (P_{COMMON}) remained rather high (> 40 %) over the entire study period, making consistent the use of individual transport distances in tracers propagation assessment.

Site	Period	Flood hydrology			Sediment tracing					
		Q_P ($m^3 s^{-1}$)	N_{FLOOD}	$T_{TRANSPORT}$ (h)	D_{MAX} (mm)	N_{TOT}	P_{TOT} (%)	N_{COMMON}	P_{COMMON} (%)	P_{MOBILE} (%)
A	S0 – S1	35	1	13	45 – 64	156	47	156	100	58
	S1 – S2	82	2	23	> 128	130	39	71	55	86
	S2 – S3	57	2	33	90 – 128	135	41	67	50	49
B	S0 – S1	68	1	15	64 – 90	133	42	133	100	62
	S1 – S3	119	3	61	> 128	160	51	79	49	91
	S3 – S4	71	5	63	64 – 90	128	41	83	65	24
	S4 – S6	175	1	38	> 128	103	33	53	51	79
C	S0 – S1	98	1	28	90 – 128	107	32	107	100	95
	S1 – S3	119	3	46	> 128	98	29	36	37	83
	S3 – S4	83	2	19	64 – 90	78	23	42	54	21
	S4 – S5	76	1	10	45 – 64	40	12	24	60	13
	S5 – S6	175	1	32	> 128	49	15	7	14	86
D	S0 – S1	139	1	46	90 – 128	117	36	117	100	91
	S1 – S3	224	3	86	> 128	80	25	38	48	97
	S3 – S5	108	5	81	45 – 64	105	33	45	43	47
	S5 – S6	230	2	75	> 128	38	12	17	45	82

Table 3.3. Flood hydrology and sediment tracing characterisation. Q_P is the maximum 1-hr discharge over the considered period. N_{FLOOD} is the number of competent event. $T_{TRANSPORT}$ is the cumulated time (in hours) with discharge above critical discharge. D_{MAX} is size class (in mm) of the largest mobile clast. N_{TOT} is the number of recovered tracers at S_i . P_{TOT} is the recovery rate (in %). N_{COMMON} is the number of recovered tracers that were also found at S_{i-1} . P_{COMMON} is the inter-survey recovery rate (in %). P_{MOBILE} is the proportion of tracers found both at S_{i-1} and S_i which travelled more than 5 m (in %), a threshold we found acceptable to define whether a given particle experienced mobility or not.

3.4.1.2. Sediment size and flood hydraulics effects on tracer mobility and travel distances

First observations of sediment tracing provided an estimate threshold for bed-material entrainment of approximately 30, 60, 70 and 80 m³s⁻¹ at sites A, B, C, and D, respectively. From tracer injection S0 to survey S6 (April 2019 – February 2022, 34 months), 8 to 11 competent events occurred depending on the considered site, with average flood duration of 20 hours and the highest discharge recorded in 10th January 2022 (175 m³s⁻¹ at St Béat (Q₅), 32 hours, Fig. 3.1).

Tracer mobility differs between sites, with site A and B showing lower proportions of mobile tracers than site C and D. After S1, tracer mobility at sites A and B was largely size-dependant (Fig. 3.3), with most of mobile tracers belonging to 22-64 mm size-class, and respectively 42 % and 38 % of tracers that have not moved. Conversely, sites C and D exhibited larger proportion of mobile grains, with only 5 % and 9 % of tracers still sitting within the seeding area after the monitoring period, and significant mobility of entire tracer size classes (22-128 mm). We then estimated that the threshold for total mobility (i.e. for D₈₄ motion) was overpassed during the study for those sites. During S1-S3 period, three floods of similar intensity (~ Q1) occurred, reducing the proportion of immobile tracers to 14 %, 9 %, 17 % and 3 % at sites A, B, C and D, respectively. During this period, all tracers size classes were mobile for all sites, a fact that shall indicate full- or near-full mobility conditions. Between S3 and S4 for site B, and S3 and S5 for sites C and D, a long period marked by relatively low floods, tracers experienced lower mobility, close to 20 % at sites B and C, and equal to 47 % at site D. Finally, for the last period of the study (S4-S6 for site B, S5-S6 for sites C and D), results show that tracers were importantly mobile due to the large flood of 10th January 2022 (Table 3.3).

As a whole, tracers experienced relatively high dispersion over the study period, with mean and maximal transport distances of 378 m and 1431 m at site A (after S3), 1850 m and 5493 m at site B, 1483 m and 2956 m at site C, 872 m and 3111 m at site D. Larger transport distances measured at site B may relate with channel morphology, supporting previous findings on the more dispersive bedload behaviour observed in wandering channels (Liébault *et al.*, in press). Furthermore, the comparison of transport distances between sites for a given flow condition indicates that transport efficiency was significantly lower at site A over S0-S3, with EEI values three times higher at this site (EEI = 31.10³ J m⁻³) than others (EEI ranging from 10.10³ J m⁻³ to 13.10³ J m⁻³, Table 3.5).

Some previous research has pointed out that the grain size of the travelling sediment, relative to that of the riverbed, may have some influence on the travel distances. To isolate this effect from the hydraulic control, we applied the transport distance and grain size scaling procedure

as described in Church & Hassan (1992) for two periods showing differences in terms of flood magnitude and duration (Table 3.3), namely S0-S1 (for which bedload behaviour is different between sites) and S1-S3 (for which all sites experienced significant mobility). First, results show that the control exerted by surface grain size decreases downward as bed material tends to be finer and more homogeneous (Fig. 3.3). For instance, when comparing sites A and D for the initial period (S0-S1) with L^*_{22-32} and L^*_{90-128} being respectively 7 times larger and 5 times smaller than L_{D50} at site A. At site D, 22-32 mm tracers were transported over the same distance than D_{50} , whereas 90-128 mm tracers travelled only 2.5 times less. In addition, we also observed that the grain size effect lessens as the flow magnitude increases, or in other terms, when peak flows are competent enough to initiate near-full bed mobility. Appreciable evidences for this can be found looking at the sites A and B (Fig. 3.3) which showed a weaker size-selective transport during the S1-S3 period than during S0-S1.

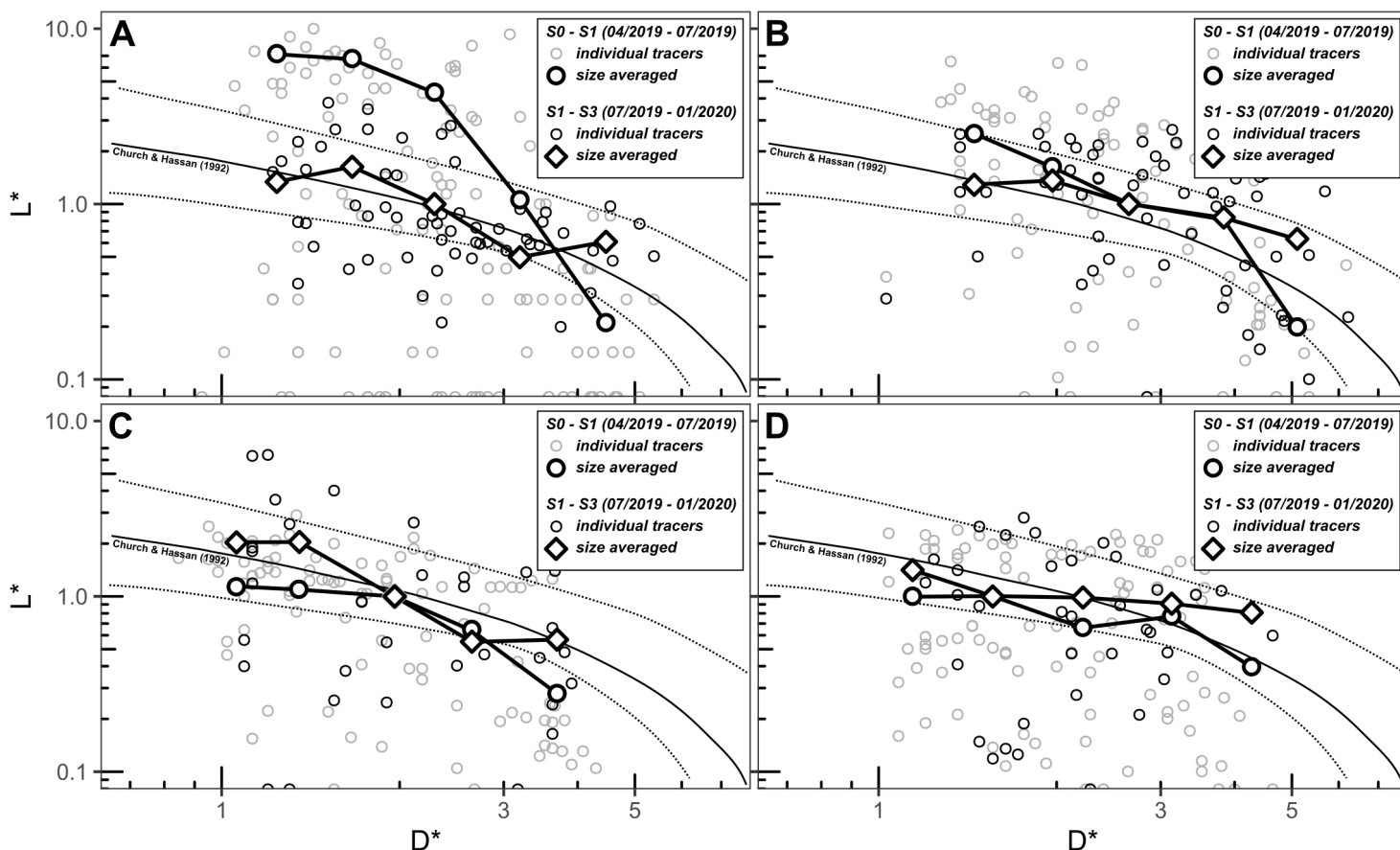


Figure 3.3. Scaled transport distances (L^*) plotted against scaled grain size (D^*) as per Church & Hassan (1992) for two periods of varying flow intensity. A, B, C, and D are the different sites.

On the Upper Garonne, mean transport distances are scaled with peak stream power with a comparable exponent to previous researches on the Erlenbach, Carnation Creek, and Ardenian Rivers, although the latter plots closer from our results, showing higher transport distances for given

unit stream power (Fig. 3.4.A; Schneider *et al.*, 2014). Similarly, transport distances scaled with cumulative stream energy with similar exponent and intercept than in Erlenbach and Carnation Creek (Fig. 3.4.B). This said, we observed large inter-site variability. We found poorer correlations at sites A and B than at sites C and D, an observation that shall indicate that flood hydraulics contributes only for a certain proportion in controlling transport distances at sites A and B (i.e. a variety of other factors control transport distances as well), whereas it explains most of the variability at sites C and D. Moreover, transport distances at sites A and B scale with a somewhat better correlation with peak stream power than cumulative stream energy. This fact indicates that transport distances show stronger dependence to peak discharge than flood duration, an observation which could be related with the more size-selective behaviour observed at sites A and B (Fig. 3.3), rather typical of partial mobility conditions.

Valuable information arises from inter-site comparison of transport distance to peak stream power and cumulative stream energy scaling exponents. Regression slope increases downward from site A to site C. Exponent values range from 0.7 to 1.3 for peak stream power, and from 0.4 to 1 for cumulative stream energy, indicating rather high dependence of transport distances to flood hydraulics at those sites. In other terms, bedload accommodates increasing available energy by being transported over larger distances. Conversely, exponent drops at site D. For this site, various transport events of significantly different magnitude and duration lead to similar distances. This seems to indicate than at site D, the armour is more easily disrupted, and then the available energy dissipates more through scouring the bed over higher depth rather than transporting sediments over larger distances.

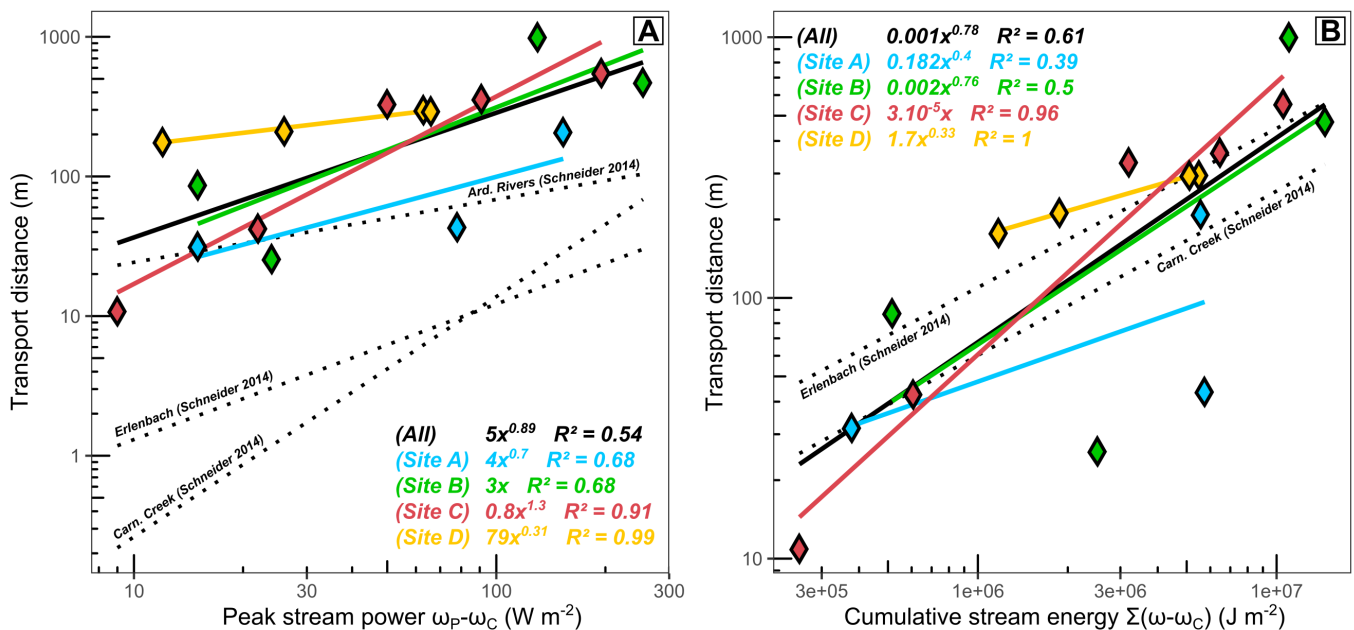


Figure 3.4. Scaling mean transport distances with peak stream power (A) and cumulative stream energy (B).

3.4.2. Estimation of the active layer thickness from the active tracer columns

Active layer thickness provides information on bedload behaviour and parameters that were further included in the virtual velocity routine for bedload volumes computation. The thinnest active layer was observed at site A ($D_S = 0.05$ m; Table 3.4), presenting the coarsest grain size and significant bed armouring. Active layer thickness showed a downstream increase, as the bed tends to be less armoured and grain size more homogeneous. In estimating scour depth at site D, we removed one of the three column because of large woody debris deposition immediately above this column, which we consider an artefact that could lead to active depth underestimation. Scour depth at this site was then estimated equal to 0.21 m (Table 3.4). Interesting elements on transport conditions arise from scaling scouring depth (D_{SCOUR}) with bed surface grain size and especially D_{84} , often considered representative for maximum mobile clast for frequent flood events. D_{SCOUR} is equal to $0.4D_{84}$, $1D_{84}$, $1.8D_{84}$ and $3D_{84}$ at site A, B, C and D, respectively. Based on this, we considered that full-mobility conditions did not occur at site A for the maximum observed discharge ($Q = 82 \text{ m}^3\text{s}^{-1}$), whereas this threshold was overpassed at sites B, C and D.

Site	Scour (D_{SCOUR} , in m)	Topographical changes (D_{FILL} , in m)	Active depth (D_S , in m)
A	0.08 (0 / 0.12 / 0.12)	0.02 (-0.01 / +0.03)	0.05
B	0.14 (0.21 / 0.12 / 0.09)	0.05 (-0.01 / +0.06)	0.10
C	0.21 (0.21 / 0.21 / 0.21)	0.10 (-0.03 / +0.13)	0.16
D	0.21* (0 / 0.21 / 0.21)	0.11 (-0.10 / +0.21)	0.16

Table 3.4. Estimation of active layer thickness. Bold values correspond to mean scouring, filling and active depth. D_{SCOUR} values in parenthesis correspond to scouring measured at each RFID column. D_{FILL} values in parenthesis correspond to mean eroded (-) and mean deposited (+) thickness.

3.4.3. Bedload rates

3.4.3.1. Calibration of the Y parameter using GTM model

From passive and active tracer experiments, we calibrated the GTM model (Recking, 2016) to better reflect streambed mobility evolution with flow discharge at each site. First step was to estimate threshold between partial and total mobility in order to circumscribe virtual velocity method application to some reference values between both transport conditions. We defined this threshold considering D_{84} mobility (Q_{c84}). Since we observed that this threshold has not been

reached at site A, we set a value above the maximum observed discharge at this site, based on observations in other sites. Q_{c84} values were then defined as equal to $90 \text{ m}^3\text{s}^{-1}$ at sites A, B and C, and $120 \text{ m}^3\text{s}^{-1}$ at site D. Second step is then to adjust β values to fit the observations of largest mobile clast for given discharge (Fig. 3.5). We found acceptable compromises defining β values equal to 1 at sites A and B, 5 at site C and 2 at site D, for partial transport conditions, and 0.25 at site A, B and C, and 1 at site D, for full transport conditions.

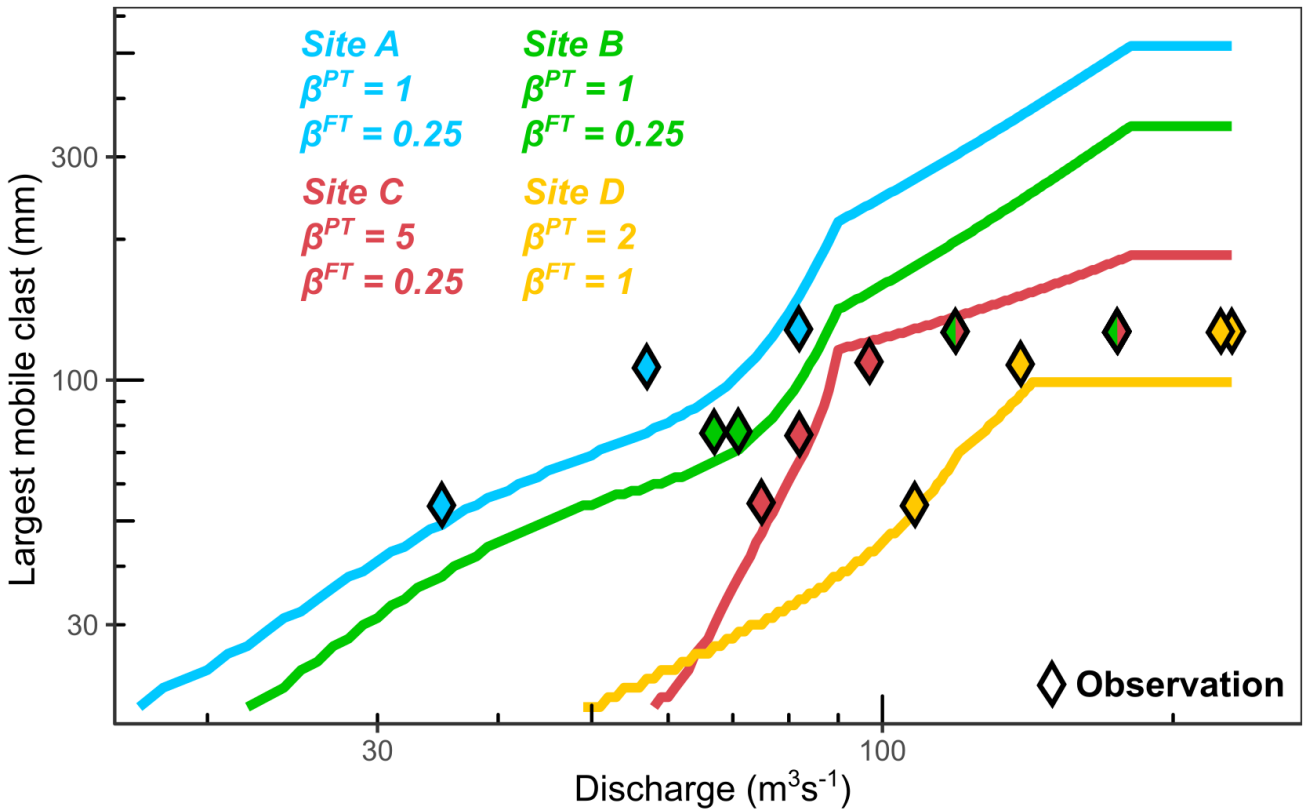


Figure 3.5. Results from the calibration of GTM model (Recking, 2016)

3.4.3.2. Transport rates and transport capacities

Estimated bedload discharge presents large heterogeneity between site A and the others (Table 3.5). Between S0 and S3, coarse transport was estimated at 81 m^3 at site A, approximately 10- to 12-times smaller than site B (842 m^3), C (975 m^3) and D (1012 m^3). We interpret this as a combined effect from (1) shorter transport distances (see section 3.4.1.2), (2) thinner active layer (Table 3.4), and (3) size-selective transport (Fig. 3.3). Even though the calibrated GTM model underestimates the Y parameter at site A for the S2 – S3 period, for which field observation showed the largest mobile clast belongs to 90-128 mm size class whereas GTM gives 64-90 mm (Fig. 3.5), it does not significantly influence our results since the inclusion of this class increases total bedload

volumes for this period by just 1.6 m³. Furthermore, the comparison between field-based transport rate and formula-based transport capacity at site A clearly points at supply-limited conditions, with field-based estimations merely representing 12 % of formula-based estimations over S0-S3. Finally, sites located downstream the Plan d'Arem dam show transport rates in the same order of magnitude over the entire study period, although we observed generally lower bedload volumes at site B over the entire study period (i.e. 1076 m³) than at sites C and D (i.e. 1952 m³ and 1730 m³).

At the event scale, transport rates exhibit strong variability between sites depending on the flood hydrology. Over S0-S1, a period marked by small flood events and no flushing actions of the Plan d'Arem dam, sites A and B presents comparable bedload volumes (i.e. 7 m³ and 15 m³, respectively), whereas sites C and D show remarkably higher values (i.e. 478 m³ and 397 m³, respectively). Conversely, during the period S1-S3, marked by three competent floods, bedload volumes remained rather low at site A while the other sites exhibited more intense transport (Table 3.5). If the difference in bedload rates observed at site B between 'derived' (i.e. without flushing actions, periods S0-S1 and S3-S4) and 'full-discharge' (i.e. with flushing actions, periods S1-S3 and S4-S6) conditions may be fundamentally explained by hydraulic forcing, sediment availability could also play a role: when flushing actions are operated, significant supply probably promote transport in the by-passed section.

Three different transport regimes emerge from the analysis of the ratio between field-based and formula-based bedload estimations (FF ratio; Table 3.3). As stated before, site A shows the lowest ratio, as a probable consequence of the supply-limited transport regime under which currently operates. Sites B and C presented similar FF ratio, respectively 0.34 and 0.33 during S0-S3, whereas at site D, formula-based and field-based estimations are in the same order of magnitude, with a FF ratio equal to 1.43 after S3 and 0.83 after S6. Furthermore, higher FF ratios were observed during sufficiently competent floods for full-transport initiation, as during S0-S3 and S5-S6 at sites C and D. Conversely, for periods experiencing only small flood events (i.e. S3-S5), the FF ratio drops at those sites. Recking's equation seems then to rather correctly reflect the observed transport in the first case, however leading to clear overestimation in the second.

Transport capacity calculation at site A using 'real' and 'natural' discharge highlights the important role of water diversion in decreasing bedload rates, with a transport capacity in the first case equal to 664 m³ over S0-S3, nearly 20 % of transport capacity under 'natural' discharge conditions (i.e. 3392 m³, Table 3.3).

Site	Period	Flood hydrology			Bedload				
		Q_P ($m^3 s^{-1}$)	ω_P ($W m^{-2}$)	$\Sigma(\omega-\omega_c)$ ($10^6 J m^{-2}$)	EEI ($10^6 J m^{-3}$)	L_M (m)	Q_{VV} (m^3)	$Q_{RECKING}$ (m^3)	FF ratio $Q_{VV}/Q_{RECKING}$ (%)
A	S0 – S1	35	103	0.38	0.012	32	7	140 / 2088	0.05 / 0
	S1 – S2	82	241	5.57	0.026	211	71	295 / 656	0.24 / 0.11
	S2 – S3	57	168	5.74	0.13	44	3	229 / 649	0.01 / 0
	S0 – S3	82	241	11.69	0.031	378	81	664 / 3392	0.12 / 0.02
B	S0 – S1	68	151	0.52	0.006	88	15	512	0.03
	S1 – S3	119	265	11.01	0.011	1008	827	1949	0.42
	S3 – S4	71	158	2.51	0.097	26	4	32	0.13
	S4 – S6	175	389	14.53	0.03	478	230	7361	0.03
	S0 – S3	119	265	11.53	0.01	1155	842	2461	0.34
	S0 – S6	175	389	28.57	0.015	1850	1076	9854	0.11
C	S0 – S1	98	189	3.2	0.01	334	478	1698	0.28
	S1 – S3	119	229	6.46	0.018	364	497	1264	0.39
	S3 – S4	83	160	0.61	0.014	43	6	270	0.02
	S4 – S5	76	146	0.25	0.023	11	1	4637	0
	S5 – S6	175	337	10.54	0.019	559	970	1251	0.78
	S0 – S3	119	229	9.66	0.012	787	975	2962	0.33
	S0 – S6	175	337	21.06	0.014	1483	1952	9120	0.21
D	S0 – S1	139	61	1.88	0.009	214	397	319	1.24
	S1 – S3	224	98	5.5	0.018	298	615	390	1.58
	S3 – S5	108	47	1.17	0.007	179	109	1029	0.11
	S5 – S6	230	101	5.11	0.017	297	609	342	1.78
	S0 – S3	224	98	7.38	0.013	558	1012	709	1.43
	S0 – S6	230	101	13.66	0.016	872	1730	2080	0.83

Table 3.5. Flood hydraulics and bedload transport rate and capacity. Q_P is the peak 1-hr discharge (in $m^3 s^{-1}$). ω_P is the peak stream power (in $W m^{-2}$). $\Sigma(\omega-\omega_c)$ is the cumulative stream energy (in $J m^{-2}$). EEI is the Energy Expenditure Index (in $J m^{-3}$). L_M is the mean tracers transport distance (in m). Q_{VV} is the bedload rate estimated from tracers virtual velocity (in m^3). $Q_{RECKING}$ is the transport capacity estimated from Recking's equation (in m^3). **FF ratio** is the ratio between field-based and formula-based estimated bedload volumes.

3.5. Discussion

3.5.1. Synthesis of the arguments and validation of the hypotheses

In the hypothesis (*H1*), we stated that sediment supply conditions overall bedload rates. We proposed to test this hypothesis on the basis of transport rates and the inter-site comparison of the ratio between transport rates and transport capacity. We hypothesised that transport rates should first increase downstream from the Plan d'Arem dam, and then again downstream from the confluence with the Pique River. On the one hand, we observed a 10-fold increase in transport rates between site A and others over S0-S3, highlighting both the role of the uppermost catchment deficit in reducing transport rates and the predominant contribution of sediments stored with the Plan d'Arem reservoir in partly restoring supply (*H1a*, Table 3.6), and this partly validated hypothesis (*H1*). On the other hand, the role of the Pique in increasing overall supply has not been observed, since we estimated similar transport rates both upstream and downstream the confluence for all periods. Considering the entire study period (S0-S6), we observed that transport rates were lower at site B than at sites C and D, and similar at site C and D. This observation suggests that the Plan d'Arem dam is only partly transparent during flushing actions. For instance, the largest event of the study period (10/01/2022, Q_5) resulted in transport rates of 970 m³ and 609 m³ at sites C and D, and only 230 m³ at site B. The FF ratio allowed to go further in the characterisation of transport regime. We hypothesise this ratio was lower at site A, higher and similar at site B and C, and the highest at site D, in relation with cumulative contribution of Plan d'Arem and Pique River sediments downward (*H1b*). Results are in good agreement with this criterion, as we observed this trend for all considered periods (i.e. S0-S3 and S0-S6). Altogether, those arguments allow to conclude on the partial validation of hypothesis (*H1*). Indeed, the first part of the hypothesis, dealing with the upstream deficit effect and the role of the Plan d'Arem in buffering this deficit is fairly well verified experimentally. Nevertheless, concerning the second part of the hypothesis, focussed on the effect of the Pique River in increasing overall supply, it is quite difficult to extract conclusions since our results do not fully comply with both criteria. If we effectively did not observed any increase in transport rate between site C and D, the FF ratio indicates more supply-limited conditions upstream the confluence, and rather equilibrium downstream. This observation may then be due to supply from the Pique River, but also to the large reduction of the slope between both sites, a parameter that has a great influence in sediment transport formula.

Regarding the effects of hydrological alteration by water diversion on sediment transport regime (*H2*), we proposed that the conditions (i.e. diversion vs full discharge), as well as the modality (i.e. permanent vs during low- and mid-flows only) of flow diversion may affect transport

rates, transport capacity, and sediment mobility, at various time-scales. First, at the study time-scale (period S0-S3), we suggested that overall transport rates may be lower at site A than others, a criterion that we verified experimentally (**H2a**). For the period S0-S6, transport rates were lower at site B than site C and D. We estimate that this reduction is related with sediment availability (as per **H1**) rather than peak discharge alteration. If peak discharge alteration had been the major factor explaining for this reduction, we may theoretically have observed larger transport rates at sites C and D than at site B during periods experiencing only small floods, typically not enough competent to trigger flushing actions (i.e. peak flow preservation), due flow competence recovery as soon as the turbine discharge returns to the Garonne mainstem. Results show otherwise, since between S3 and S5, a period marked by low hydrology and no flushing at the Plan d'Arem dam (i.e. then a period during which peak discharge at site B has been lowered by water diversion), transport rates are rather similar at sites B and C (i.e. 4 m³ and 7 m³, respectively), and only slightly higher at site D (i.e. 109 m³). Additionally, for the initial period after tracers seeding (S0-S1), transport rates were similar and rather low at sites A and B, and higher at sites C and D. By following the same reasoning as the previous sequence, we shall this time conclude on an effect of flow diversion rather than sediment availability (**H2b**). Computation of transport capacity using different input discharge series at site A (i.e. one run was performed using 'real' discharge, and the other with 'natural' discharge, see section 3.3.4 and Table 3.5) revealed that flow diversion is responsible for a reduction of river competence by 55 % to 93 % depending on the considered period, the lower the peak discharge, the higher the reduction, accordingly to our hypothesis (**H2c**). Finally, we observed that sediment mobility was also affected by varying degree of flow diversion, with site A and B showing lower proportion of mobile clast after the first survey (**H2d**). Nevertheless, this effect has not been observed after following surveys. All those arguments drive us to conclude on the complete validation of hypothesis (**H2**). Indeed, all criteria have been validated at least for one period. In summary, magnitude and temporality of water diversion affects transport regime, with flow diversion during floods leading to reduced transport rates and mobility proportion, whereas peak flow preservation by flushing actions restores 'normal' bedload behaviour.

Finally, we formulated the hypothesis (**H3**), on the role of channel configuration, because the study reach encompasses a wide variety of grain size and morphological contexts, both having a potential influence on bedload behaviour. On the role of grain size, we hypothesised coarse boulders prevent scouring, exert hiding on smaller grains and then induce size selective transport, and reduce the transport efficiency (i.e. increase the amount of energy needed for moving one grain over a given distance). The role of boulders in controlling the scour layer depth is very well verified from the experiments with active tracers columns (**H3a**). Sites A and B, which present similar grain size

distribution, exhibited significantly lower active layer thickness than sites C and D, as expected. Active layer was nevertheless larger at site B than site A. In parallel, and according to our hypothesis, we observed a stronger dependence of sediment transport to sediment size at site A than at other sites for all considered periods (**H3b**). During period experiencing small floods (i.e. S0-S1), the size-dependence was higher at sites B and C than at site D. Conversely, for periods showing larger floods (i.e. S1-S3), bedload was transported more evenly with few effects of sediment size at site B, C and D, whereas size-dependence has persisted at site A. We then estimate that size-dependence is not only related with bed grain size, as stronger flood hydrology can lessen its effects on bedload transport. This sequence also explains why we did observed smaller scour depth at site A than site B, although grain size context is similar at both sites: the preserved ‘natural’ hydrology at site B due to flushing actions promotes deeper bed scour. Transport efficiency, assessed through the use of EEI, was lower at site A than other sites, which show similar EEI, for all periods. This observation supports the idea that the proportion of energy spent in moving particles at site A is lower than at other sites, probably due to dissipation on coarse immobile boulders which therefore behave as hidlers. In the same hypothesis, we also proposed that bedload transport can be significantly influenced by channel morphology, as demonstrated in numerous previous studies. Contrarily to site A, C and D, which show rather plane-bed features, site B morphology is characterised by active wandering patterns, known to convey bedload more efficiently than plane-beds. Over the entire study period, transport distances corroborate this hypothesis (**H3d**). Those arguments apparently validate the hypothesis (**H3**), on the role of boulders in reducing, and of wandering channels in promoting, bedload transport.

Hypothesis	Metric	Criterion	Observation
H1	Transport rates (H1a)	$TR_A < TR_B ; TR_C < TR_D$	(S0-S3) $TR_A < TR_B ; TR_C ; TR_D$ (S0-S6) $TR_B < TR_C ; TR_D$
	Field-Formula ratio (H1b)	$FF_A < FF_B ; FF_C < FF_D$	(S0-S3) $FF_A < FF_B ; FF_C < FF_D$ (S0-S6) $FF_B < FF_C < FF_D$
H2	Transport rates (H2a)	$TR_A < TR_B ; TR_C ; TR_D$	(S0-S3) $TR_A < TR_B ; TR_C ; TR_D$ (S0-S6) $TR_B < TR_C ; TR_D$
	Transport rates (H2b)	$TR_A ; TR_B < TR_C ; TR_D$	(S0-S1) $TR_A ; TR_B < TR_C ; TR_D$
	Transport capacity (H2c)	$TC_{A-REAL} < TC_{A-NATURAL}$	(S0-S3) $TC_{A-REAL} < TC_{A-NATURAL}$
	Mobility (H2d)	$M_A ; M_B < M_C ; M_D$	(S0-S1) $M_A ; M_B < M_C ; M_D$ (S1-S3) $M_A = M_B = M_C = M_D$
H3	Active layer (H3a)	$D_{S-A} ; D_{S-B} < D_{S-C} ; D_{S-D}$	(S0-S5) $D_{S-A} < D_{S-B} < D_{S-C} ; D_{S-D}$
	Size dependence (H3b)	$SD_A ; SD_B > SD_C ; SD_D$	(S0-S1) $SD_A > SD_B ; SD_C > SD_D$ (S1-S3) $SD_A > SD_B ; SD_C ; SD_D$
	EEI (H3c)	$EEI_A ; EEI_B > EEI_C ; EEI_D$	(S0-S3) $EEI_A > EEI_B ; EEI_C ; EEI_D$ (S0-S6) $EEI_B = EEI_C = EEI_D$
	Transport distance (H3d)	$TD_B > TD_A ; TD_C ; TD_D$	(S0-S3) $TD_B > TD_A ; TD_C ; TD_D$ (S0-S6) $TD_B > TD_C ; TD_D$

Table 3.6. Summary of hypotheses, metrics and criteria used to test those hypotheses, and observations. Observations in green fully agree with hypotheses. Observations in orange only partially agree with hypotheses.

3.5.2. Uncertainties and limitations

In evaluating the respective contribution of multiple factors in inducing different transport regime, we point several uncertainties and limitations. From a conceptual aspect first, the definition of explicit criteria to state whether a hypothesis is valid or not is very challenging since very few criteria are completely discriminatory, in other terms, influenced by one and only one factor. For instance, flood hydraulics plays a major role in sediment transport, thus affects most of the criteria we defined. In our case, bed scouring or size-dependence seemed to be first controlled by bed surface grain size, but hydrology also contributed in increasing scouring and promote full mobility, independently from grain size. Accordingly, we then suggest that the only way to characterise respective contribution of each factor is to apply a deductive reasoning considering a range of spatial and temporal conditions. In some cases, some more evidences are needed to state on the role

of a given factor, requiring to produce new metrics, as for instance the field-formula ratio used in this study. We acknowledge that the use of this ratio can not alone allow to state whether a given reach experiences supply-limited or transport-limited conditions in absolute terms, since the choice of formula may lead to large differences. Nevertheless, we found acceptably relevant to investigate the downstream pattern of this ratio, as a way to spatially assess how lacking sediments are, and evaluate if one site experiences a more supply- or transport-limited condition than another. From a methodological aspect, we also agree that this study may suffer from discontinuous data acquisition (i.e. sites were not all surveyed for same periods), increasing the variability and introducing bias in the inter-site comparison. We nevertheless emphasise that tracer experiments in rivers are subjected to the intrinsic and unavoidable difficulties of studying bedload transport in the field. In the same vein, we assessed scour-depth only over a long period and not after each flood due to logistical issues, giving an approximate and time-integrated value. Also, we analysed it only at one cross-section for each site, although it may show important spatial variability. Together with uncertainties in active layer results, the reduction of tracers recovery rates through time may also play an important role in overall bedload volumes estimations. Altogether, uncertainties and limitations, they being conceptual or methodological, must force to exercise caution on obtained results and derived conclusions. Nevertheless, we still believe the approach followed here is more robust than those followed commonly.

3.5.3. Bedload behaviour and operational implications on the Upper Garonne

To go further in the representation of the Upper Garonne sediment transport regime, we propose the following bedload behavioural model on the basis of our results, field observations, and existing literature.

A first level of control is exerted by channel configuration and especially bed surface grain size distribution, which being inherited from past fluctuations in hydro-sedimentary dynamics, does not fundamentally change at the study time-scale (~3 years). Therefore, bed surface grain size, and especially the coarse tail of the distribution, directly influences bedload transport. As boulders and bed armouring inhibit full transport (i.e. deeper bed scouring, MacKenzie *et al.*, 2016; Vázquez-Tarrío *et al.*, 2021; Recking *et al.*, 2022), bedload behaves as patches of ‘fine’ mobile material (i.e. typically below 200 mm, re. D_{84}) circulating between immobile protruding elements, with the size of the bedload being significantly smaller than the one of the bed (‘travelling bedload’ sensu Piton & Recking, 2017; Recking, 2016). At upstream sites (i.e. those showing boulders), increasing stream energy dissipates (1) on large boulders (Monsalve *et al.*, 2017), (2) through moving coarser

grains (MacKenzie *et al.*, 2016), and (3) moving those grains over larger distances (Vázquez-Tarrió & Batalla, 2019). At downstream sites, as boulders become less predominant, the proportion of the bed mobile for frequent floods increases, and full-mobility conditions are more frequently achieved. Stream energy therefore dissipates through scouring the bed over larger depth rather than through transporting sediment over larger distances (Recking *et al.*, 2022).

Overlapping those ‘fixed’ conditions, sediment supply constitutes a second level of control (Gomez & Soar, 2022). At the upstream site of Lès (site A), the structural sediment deficit related with dams construction on the most upper catchment, and hillslopes afforestation, considerably constrains sediment furniture to some tributaries locally displaying active erosional processes (e.g. Arriu Unhòla, Arriu Varradòs), while lateral confinement between rip-raps prevents lateral migration. Therefore, and contrarily to downstream sites which benefit from multiple intermediate sources (i.e. Plan d’Arem reservoir, bank erosion, tributaries), bedload material at Lès almost totally originates from upstream supply. Itself decreased, transport efficiency is then very low ($< 0.5\%$ as per Gomez & Soar (2022) ; Fig. 3.6). From an operational perspective, and if we consider site B as a reference in terms of functionality (Bulteau *et al.*, 2022; Bulteau *et al.*, under review), sediment supply should be increased 10-fold to reach similar bedload transport rates, regardless of the hydrology (i.e. if flood events are sufficiently competent to transport sediments). Although flow competence is importantly decreased by water diversion, there is still large differences between transport rates and transport capacity. Reasonably, we then propose that at site A, gravel augmentation at a rate equalling the transport capacity ($\sim 700\text{ m}^3$ between S0 and S3, with transport rates approaching 100 m^3 over the same period) is a good option that should allow to counteract the effects of long-term decreased supply from the catchment on downstream reaches. At the site of Fos (site B), located in the by-passed reach of the Plan d’Arem dam, intermittent supply during flushing actions constitutes a major sediment source, which together with material supplied to the system by bank erosion, is responsible for a large increase in bedload transport rate compared to the uppermost site. The role of this supply is primarily important at this site, and drawdown flushing actions clearly increase transport efficiency (Fig. 3.6). Considering the long-standing upstream sediment deficit, this reach strongly depends on the sediments stored within the reservoir, as well as perennality of bank erosion processes, which operationally implicates to pursue with on-going dam management. In the future, as an equilibrium may be reached between sediment inputs and outputs into and from the reservoir, progressive increase of sediment remobilisation rate through flood management improvement, potentially coupled with direct intervention (i.e. dredging), will be required. In appearance, the Pique River does not provide as much sediment as initially stated, as we did not observed any increase in transport rates between sites C and D. We nevertheless

acknowledge that this conclusions has to be taken with caution since transport rates over such a small time-period than the one of the study (i.e. 3 years) are more likely controlled by transitory fluctuations in sediment availability due to sediment pulse, bank erosion, or scour-fill processes rather than downward cumulative contribution of multiple sediment sources (i.e. tributaries ; Lisle, 2007). Those sites transport bedload more efficiently than upstream ones ($> 1\%$, Fig. 3.6).

Finally, flood hydrology exert a third level of control on sediment transport. In the case of the Upper Garonne, we highlighted three different degrees in sediment transport magnitude due to flood hydraulics perturbation by water diversion. At the upstream site, permanent diversion reduces the transport capacity by 50 to 60 % during moderate flood events (S1-S2 and S2-S3), and by 80 % when taking into account periods of lower hydrology. Reduced flood hydrology also lessens scouring and mobility proportion. In other terms, regardless of the supply (i.e. if there is enough sediment to be transported), restoring natural flood hydrology may increase transport rates at this site 2- to 5-fold. Nevertheless, such strategy should be disregarded as (1) there is no evidence it would lead to increase transport rates because of few sediments available for transport, and (2) it may also exacerbate the effects from sediment deficit. At the site of Fos (site B), transport rates are directly controlled by the operation of flushing actions. Transport rates are comparable with downstream transport rates when flushing action are operated, whereas they are in the same order of magnitude than upstream transport rates without flushing actions. Separating the effects of peak flow restoration from those of sediment supply during flushing actions is challenging and has not been investigated in this study. Increased bedload rates are then considered a combined consequence of both dynamics. As suggested in the previous paragraph, the current management has to be maintained and potentially improved in the future. At the two downstream sites, the hydrology is not affected by water diversion. Sediment transport then relates directly with flood hydraulics, the higher the energy, the larger the transport rates. In this paper, we provide few operational recommendations for those two downstream reaches since such recommendations should be regarded in the light of further geomorphic diagnosis on most downstream reaches (i.e. downstream of the study area).

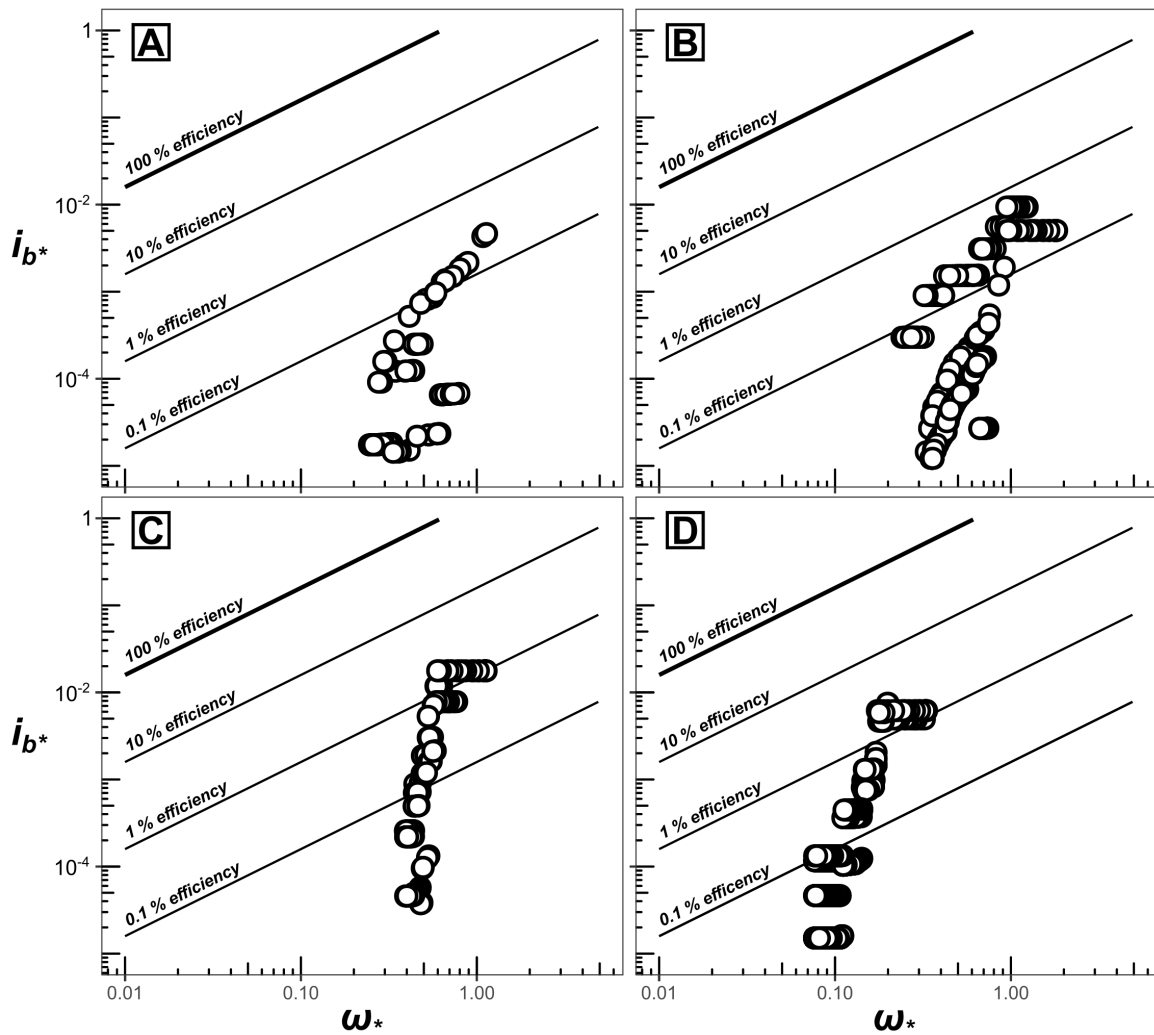


Figure 3.6. Variation of dimensionless bedload transport rate (i_{b^*}) with dimensionless specific stream power (ω_*) as per Gomez & Soar (2022). A, B, C and D are study sites.

3.6. Conclusion

This study constitutes a very first attempt to separate the effects of multiple factors in controlling transport regime. The hypothetico-deductive framework we based on allowed to rather correctly achieve this objective, and we consider the effects of channel configuration, sediment supply and flow diversion are sufficiently well characterised and distinguished to further propose operational recommendations for river managers. We must acknowledge that achieving such characterisation is a real challenge, and that uncertainties remain, justifying for further investigations in this field of research which seems to us of great scientific and operational interest.

To improve those works, we propose to consider more simple contexts, focusing on shorter river reaches, in order to reduce the variability inherent to multi-factorial analysis. For instance, the specific role of sediment supply could be assessed through studying a river reach that encompasses a significant supplying tributary with no major changes in slope, grain size, and flow conditions. Similarly, the role of water diversion, or any other type of flood regime modifications, could be

specifically assessed in a river which presents two upstream and downstream reference sections (i.e. conveying the whole river discharge) and an impacted one (i.e. under derived conditions), all presenting similar morphological features.

To conclude, we strongly emphasise the importance of hypothesis-driven approaches in this type of study to avoid any misinterpretations on the cause-effects relationships potentially linking a given factor with transport regime.

3.7. References

Arnaud, F., Piégay, H., Béal, D., Collery, P., Vaudor, L., Rollet, A.-J., 2017. Monitoring gravel augmentation in a large regulated river and implications for process-based restoration. *Earth Surface Processes and Landforms*, 42(13): 2147-2166. DOI: 10.1002/esp.4161.

Arnaud, F., Piégay, H., Vaudor, L., Bultingaire, L., Fantino, G., 2015. Technical specifications of low-frequency radio identification bedload tracking from field experiments: Differences in antennas, tags and operators. *Geomorphology*, 238: 37 – 46.

Ashmore, P. E., Church, M., 1998. Sediment transport and river morphology: A paradigm for study. In P. C. Klingeman, R. L. Beschta, P. D. Komar, & J. B. Bradley (Eds.), *Gravel-bed rivers in the environment*: 115 – 148. Highlands Ranch, CO: Water Resources Publications LLC.

Batalla, R. J., Vericat, D., 2011. A review of sediment quantity issues: Examples from the River Ebro and adjacent basins (Northeastern Spain). *Integrated Environmental Assessment and Management*, 7(2): 256 – 268. DOI: 10.1002/ieam.126.

Buffington, J.M., 1996. An alternative method for determining subsurface grain size distributions of gravel-bedded river. American Geophysical Union 1996 Fall Meeting, supplement to EOS. *AGU Trans.* 77 (46).

Brenna, A., Surian, N., Mao, L., 2019. Virtual velocity approach for estimating bed material transport in gravel-bed rivers: Key factors and significance. *Water Resources Research*, 55, 1651–1674. DOI: 10.1029/2018WR023556.

Brenna, A., Surian, N., Mao, L., 2020. Response of A Gravel - Bed River To Dam Closure: Insights From Sediment Transport Processes And Channel Morphodynamics. *Earth Surface Processes and Landforms*, 45(3): 756-770. DOI: 10.1002/esp.4750.

Brousse, G., Liébault, F., Arnaud-Fassetta, G., Vázquez-Tarrío, D., 2018. Experimental bed active-layer survey with active RFID scour chains: Example of two braided rivers (the Drac and the Vénéon) in the French Alps. *E3S Web of Conferences* 40:04016. DOI :10.1051/e3sconf/20184004016.

Bulteau, T., Batalla, R.J., Chapron, E., Valette, P., Piégay, H., 2022. Geomorphic effects of a run-of-the-river dam in a multi-driver context: The case of the Upper Garonne (Central Pyrenees). *Geomorphology* 408:108243. DOI: 10.1016/j.geomorph.2022.108243.

Bulteau, T., Marteau, B., Batalla, R.J., Chapron, E., Valette, P., Piégay, H., under review. Effects of repeated drawdown flushing on riverbed fine sediment dynamics downstream from a dam. *Anthropocene*.

Cassel, M., Piégay, H., Lavé, J., 2016. Effects of transport and insertion of radio frequency identification (RFID) transponders on resistance and shape of natural and synthetic pebbles: applications for riverine et coastal bedload tracking. *Earth Surface Processes and Landforms*, 42(3): 399 – 413. DOI: 10.1002/esp.3989

- Casserly, C. M., Turner, J. N., O' Sullivan, J., Bruen, M., Magee, D., O'Coil  ir, S., Kelly-Quinn, M., 2021. Coarse sediment dynamics and low-head dams: Monitoring instantaneous bedload transport using a stationary RFID antenna. *Journal of Environmental Management*, 300: 113671. DOI: 10.1016/j.jenvman.2021.113671
- Church, M., Hassan, M. A., 1992. Size and distance of travel of unconstrained clasts on a streambed. *Water Resources Research* 28: 299–303. DOI: 10.1029/91WR02523.
- Claude, N., Rodrigues, S., Bustillo, V., Br  h  ret, J.-G., Macaire, J.-J., Jug  , P., 2021. Estimating bedload transport in a large sand–gravel bed river from direct sampling, dune tracking and empirical formulas. *Geomorphology*, 79: 40 – 57. DOI: 10.1016/j.geomorph.2012.07.030.
- D  pret, T., Pi  gay, H., Dugu  , V., Vaudor, L., Faure, J.-B., Le Coz, J., Camenen, B., 2019. Estimating and restoring bedload transport through a run-of-river reservoir. *Sci. Tot. Env.* 654: 1146 – 1157. DOI: 10.1016/j.scitotenv.2018.11.177.
- du Boys, P., 1879. Le Rh  ne et les rivi  res    lit affouillable –  tude du r  gime du Rh  ne et de l' action exerc  e par les eaux sur un lit    fond de graviers ind  finiment affouillable. *Annales des Ponts et Chauss  es*, 49: 141–95.
- Einstein, H., 1942. Formulas for the transportation of bed load. *Transactions of the American Society of Civil Engineers*, 107: 561–597.
- Emmet, W.W., 1980. A field calibration of the sediment-trapping characteristics of the Helley-Smith bed-load sampler. *USGS Professional Papers* 1139. DOI: 10.3133/pp1139.
- Eschbach, D., Grussenmeyer, P., Koehl, M., Guillemin, S., Schmitt, L., 2021. Combining geodetic and geomorphic methods to monitor restored side channels: Feedback from the Upper Rhine. *Geomorphology*, 374: 107372. DOI: 10.1016/j.geomorph.2020.107372.
- Evans, E., Wilcox, C., 2014. Fine sediment infiltration dynamics in a gravel-bed river following a sediment pulse. *River Res. Applic.* 30: 372–384. DOI: 10.1002/rra.2647.
- FAAPPMA31, 2015. Etat des lieux post « crue 2013 » de l'inventaire des zones potentielles de fray  res    salmonid  s sur la Garonne amont, proposition de suivis et d'am  nagement vers une optimisation de la fonctionnalit   de ces zones. Study report. In French. 28 p.
- Frings, R., D  ring, R., Beckhausen, C., Sch  ttrumpf, H., Vollmer, S., 2014. Fluvial sediment budget of a modern, restrained river: The lower reach of the Rhine in Germany. *CATENA*. 122. 91-102. DOI : 10.1016/j.catena.2014.06.007
- Frings, R. & Ten Brinke, W. B.M., 2017. Ten Reasons to set up Sediment Budgets for River Management. *International Journal of River Basin Management*. 16. 1-23. DOI : 10.1080/15715124.2017.1345916.
- Gaeuman, D., 2012. Mitigating downstream effects of dams. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), *Gravel-bed Rivers. Processes, Tools, Environments*. John Wiley and Sons, Chichester, UK, pp. 182–189.
- Gayraud, S., Philippe, M., 2003. Influence of bed-sediment features on the interstitial habitat available for macroinvertebrates in 15 French streams. *International Review of Hydrobiology* 88(1): 77-93. DOI: 10.1002/iroh.200390007.
- Geay, T., Belleudy, P., Gervaise, C., Habersack, H., Aigner, J., Kreisler, A., Seitz, H., Laronne, J. B., 2017. Passive acoustic monitoring of bed load discharge in a large gravel bed river. *J. Geophys. Res.-Earth*, 122: 528–545, DOI: 10.1002/2016JF004112.
- Geay, T., Zanker, S., Misset, C., Recking, A., 2020. Passive Acoustic Measurement of Bedload Transport: Toward a Global Calibration Curve? *J. Geophys. Res.-Earth*, 125: e2019JF005242, DOI: 10.1029/2019JF005242

- Gilet, L., Gob, F., Virmoux, C., Gautier, E., Thommeret, N., Jacob-Rousseau, N., 2021. Morpho-sedimentary dynamics associated to dam removal. The Pierre Glissotte dam (central France). *Sci. Tot. Env.*, 784: 147079. DOI: 10.1016/j.scitotenv.2021.147079.
- Gomez, B., Soar, J.P., 2022. Bedload transport: beyond intractability. *R. Soc. Open Sci.*, 9: 211932. DOI: 10.1098/rsos.211932.
- Haschenburger, J. K., Church, M., 1998. Bed material transport estimated from the virtual velocity of sediment. *Earth Surf. Processes and Landforms*, 23(9): 791 – 808. DOI: 10.1002/(SICI)1096-9837(199809)23:9<791::AID-ESP888>3.0.CO;2-X
- Hassan, M. A., 1990. Scour, fill, and burial depth of coarse material in gravel bed streams. *Earth Surface Processes and Landforms* 15, 341–356. DOI: 10.1002/esp.3290150405.
- Hassan, M. A., Bradley, D. N., 2017. Geomorphic controls on tracer particle dispersion in gravel-bed rivers. In D. Tsutsumi & J. B. Laronne (Eds.), *Gravel-bed rivers: Processes and disasters* (pp. 209–233). Hoboken, NJ: John Wiley. DOI: 10.1002/9781118971437.ch6
- Hassan, M. A., Roy, A. G., 2016. Coarse particle tracing in fluvial geomorphology. In G. M. Kondolf, & H. Piégay (Eds.), *Tools in fluvial geomorphology* (pp. 306–323). Hoboken, NJ: John Wiley. DOI: 10.1002/9781118648551.ch14.
- Hinton, D., Hotchkiss, R.H., Cope, M., 2018. Comparison of Calibrated Empirical and Semi Empirical Methods for Bedload Transport Rate Prediction in Gravel Bed Streams. *J. Hydraul? Eng.*, 144(7): 04018038. DOI: 10.1061/(ASCE)HY.1943-7900.0001474.
- Imhoff, K.S., Wilcox, A.D., 2016. Coarse bedload routing and dispersion through tributary confluences. *Earth Surf. Dynam.*, 4: 591–605. DOI: 10.5194/esurf-4-591-2016.
- Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2 : 256–280. DOI : 10.1002/2013EF000184.
- Kondolf, G.M., Wolman, M.G., 1993. The sizes of Salmonid spawning gravels. *Water Resources Research* 29: 2275 – 2285. DOI : 10.1029/93WR00402.
- Lamarre, H., Roy, A., 2008. A field experiment on the development of sedimentary structures in a gravel-bed river. *Earth Surface Processes and Landforms*, 33 : 1064 – 1081. DOI : 10.1002/esp.1602.
- Lamarre, H., Macvicar, B., & Roy, A., 2005. Using passive integrated transponder (PIT) tags to investigate sediment transport in gravel-bed rivers. *Journal of Sedimentary Research* 75, 736–741. DOI : 10.2110/jsr.2005.059.
- Lane E.W., 1955. The importance of fluvial morphology in hydraulic engineering. *American Society of Civil Engineers Proceedings Separate* 81(745): 1 – 17.
- Laronne, J.B., Outhet, D.N., Duckham, J.L., 1992. Determining event bedload volumes for evaluation of potential degradation sites due to gravel extraction, N.S.W., Australia. *Erosion and Sediment Transport Monitoring Programmes in River Basins, Proceedings of the Oslo Symposium, August 1992, IAHS* 2010: 87-94.
- Leguern, J., Rodrigues, S., Geay, T., Zanker, S., Hauet, A., Tassi, P., Claude, N., Jugé, P., Duperray, A., Vervynck, L., 2021. Relevance of acoustic methods to quantify bedload transport and bedform dynamics in a large sandy-gravel-bed river. *Earth Surf. Dynam.*, 9: 423–444. DOI: 10.5194/esurf-9-423-2021.

- Leopold, L.B., Emmet, W.W., 1977. 1976 Bedload Measurements, East Fork River, Wyoming. Proceedings of the National Academy of Sciences 74(7): 2644-2648. DOI: 10.1073/pnas.74.7.2644.
- Liébault, F., Laronne, J.B., 2008. Evaluation of bedload yield in gravel-bed rivers using scour chains and painted tracers: the case of the Esconavette Torrent (southern French Prealps). *Geodinamica Acta*, 21: 23–34. DOI: 10.3166/ga.21.23-34.
- Liébault, F., Piégay, H., Cassel, M., Arnaud, F., in press. Bedload tracing with RFID tags in gravel-bed rivers: 20 years of field and laboratory experiments. *Gravel Bed Rivers* 9.
- Lisle, T.E., 2007. The evolution of sediment waves influenced by varying transport capacity in heterogeneous rivers. In *Gravel-bed rivers VI: from process understanding to river restoration* (Habersack, H., Piégay, H., Rinaldi, M.): 443–469.
- MacKenzie, L.G., Eaton, B.C., Church, M., 2018. Breaking from the average: Why large grains matter in gravel-bed streams. *Earth Surface Processes Landforms*, 43: 3190–3196. DOI: 10.1002/esp.4465.
- Mao, L., Picco, L., Lenzi, M. A., Surian, N., 2017. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. *Earth Surface Processes and Landforms*, 42(4): 595–611. DOI: 10.1002/esp.4000
- McQueen, R., Ashmore, P., Millard, T., Goeller, N., 2021. Bed Particle Displacements and Morphological Development in a Wandering Gravel-Bed River. *Water Resources Research*, 57(2): e2020WR027850. DOI: 10.1029/2020WR027850.
- Meyer-Peter, E., & Müller, R., 1948. Formulas for bedload transport. In *Proceedings of the 2nd Meeting of the International Association of Hydraulic Structures Research (IAHSR)*, Stockholm, Sweden, 7–9 June 1948: 39–64.
- Monsalve, A., Yager, E.M., Schmeeckle, M.W., 2017. Effects of bed forms and large protruding grains on near-bed flow hydraulics in low relative submergence conditions. *Journal of Geophysical Research: Earth Surface*, 122: 1845–1866. DOI: 10.1002/2016JF004152.
- Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., Trustrum, N.A., 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Res Appl* 21(7):693–717. DOI: 10.1002/rra.878.
- Papangelakis, E., Hassan, M., 2016. The role of channel morphology on the mobility and dispersion of bed sediment in a small gravel bed stream. *Earth Surface Processes and Landforms*, 41: 2191 – 2206. DOI: 10.1002/esp.3980.
- Papangelakis, E., MacVicar, B., 2020. Process-based assessment of success and failure in a constructed riffle-pool river restoration project. *River Res. Applic.*, 36(7), 1222-1241. DOI : 10.1002/rra.3636.
- Parker, G., 1990. Surface-based bedload transport relation for gravel rivers. *J. Hydraul. Res.* 28 (4): 417–436. DOI: 10.1080/00221689009499058.
- Parker, G., Clifford, N.J., Thorne, C.R., 2011. Understanding the influence of slope on the threshold of coarse grain motion: Revisiting critical stream power. *Geomorphology*, 126: 51-65. DOI: 10.1016/j.geomorph.2010.10.027.
- Peeters, A., Houbrechts, G., de la Court, B., Hallot, E., Van Campenhout, J., Petit, F., 2021. Suitability and sustainability of spawning gravel placement in degraded river reaches, Belgium. *Catena*, 201: 105217. DOI: 10.1016/j.catena.2021.105217.
- Peeters, A., Houbrechts, G., Hallot, E., Van Campenhout, J., Gob, F., Petit, F., 2020. Can coarse bedload pass through weirs? *Geomorphology*, 359: 107163. DOI: 10.1016/j.geomorph.2020.107131

- Piton, G., Recking, A., 2017. The concept of travelling bedload and its consequences for bedload computation in mountain streams. *Earth Surf. Process. Landforms*, 42: 1505–1519. DOI: 10.1002/esp.4105
- Pyrce, R. S., Ashmore, P.E., 2003. The relation between particle path length distributions and channel morphology in gravel-bed streams: a synthesis. *Geomorphology*, 56: 167–187. DOI: 10.1016/S0169-555X(03)00077-1.
- Recking, A., 2013a. Simple Method for Calculating Reach-Averaged Bed-Load Transport. *Journal of Hydraulic Engineering*, 139(1) : 70 – 75. DOI: 10.1061/(ASCE)HY.1943-7900.0000653.
- Recking, A., 2013b. An analysis of nonlinearity effects on bed load transport prediction. *J. Geophys. Res. Earth Surf.* 2013, 118: 1264–1281.
- Recking, A., 2016. A generalized threshold model for computing bed load grain-size distribution. *Water Resour. Res.*, 52 (12): 9274–9289. DOI: 10.1002/2016WR018735.
- Recking, A., Piton, G., Vazquez-Tarrío, D., Parker, G., 2016. Quantifying the Morphological Print of Bedload Transport. *Earth Surf. Process. Landforms*, 41: 809–822. DOI: 10.1002/esp.3869.
- Recking, A., Vázquez-Tarrío, D., Piton, G., 2022. The contribution of grain sorting to the dynamics of the bedload active layer. *Earth Surface Processes and Landforms*. DOI: 10.1002/esp.5530.
- Rickenmann, D., 2017. Bedload transport measurements with geophones, hydrophones, and underwater microphones (passive acoustic methods). In D. Tsutsumi & J. B. Laronne (Eds.), *Gravel-bed rivers: Processes and disasters* (pp. 185–208). Hoboken, NJ: John Wiley. DOI: 10.1002/9781118971437.ch7
- Rickenmann, D., Turowski, J. M., Fritschi, B., Wyss, C., Laronne, J., Barzilai, R., Habersack, H., 2014. Bedload transport measurements with impact plate geophones: Comparison of sensor calibration in different gravel-bed streams. *Earth Surface Processes and Landforms*, 39(7): 928–942. DOI: 10.1002/esp.3499
- Schumm, S.A., 1977. *The fluvial system*. New-York, Wiley - Interscience, 338p.
- Schneider, J.M., Turowski, J.M., Rickenmann, D., Heggin, R., Arrigo, S., Mao, L., Krichner, J.W., 2014. Scaling relationships between bed load volumes, transport distances, and stream power in steep mountain channels. *Journal of Geophysical Research: Earth Surface*, 119: 533–549. DOI: 10.1002/2013JF002874.
- Tsakiris, A.G., Papanicolaou, A.N., Moustakidis, I.V., Abban, B.K., 2015. Identification of the burial depth of radio frequency identification transponders in riverine applications. *Journal of Hydraulic Engineering*. DOI:10.1061/(ASCE)HY.1943-7900.0001001.
- Vericat, D., Batalla, R.J., 2006. Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology*, 79: 72-92. DOI: 10.1016/j.geomorph.2005.09.017.
- Vázquez-Tarrío, D., Batalla, R.J., 2019. Assessing Controls on the Displacement of Tracers in Gravel-Bed Rivers. *Water*, 11: 1598. DOI: 10.3390/w11081598.
- Vázquez-Tarrío, D., Menéndez-Duarte, R., 2014. Bedload transport rates for coarse-bed streams in an Atlantic region (Narcea River, NW Iberian Peninsula). *Geomorphology*, 217(4): 1–14. DOI: 10.1016/j.geomorph.2014.04.015.
- Vázquez-Tarrío, D., Piqué, G., Vericat, D., Batalla, R. J., 2021. The active layer in gravel-bed rivers: An empirical appraisal. *Earth Surf. Process. Landforms*, 46: 23–343. DOI: 10.1002/esp.5027.
- Vázquez-Tarrío, D., Recking, A., Liébault, F., Tal, M., Menéndez-Duarte, R., 2019. Particle transport in gravel-bed rivers: Revisiting passive tracer data. *Earth Surf. Process. Landforms*, 44: 112–128. DOI: 10.1002/esp.4484.
- Wilcock, P.R., 1997. Entrainment, displacement, and transport of tracer gravels. *Earth Surface Processes and Landforms* 22: 1125–1138. DOI: 10.1002/(SICI)1096-9837(199712)22:12<1125::AID-ESP811>3.0.CO;2-V.

Wolman, M.G., 1954. A method of sampling coarse river bed material. Trans. Am. Geophys. Union 35(6): 951–956. DOI: 10.1029/TR035i006p00951.

Wooster, J.K., Dusterhoff, S.R., Cui, Y., Sklar L.S., Dietrich, W. E., Malko, M., 2008. Sediment supply and relative size distribution effects on fine sediment infiltration into immobile gravels. Water Resour. Res., 44, W03424, DOI:10.1029/2006WR005815.

Wong, M., Parker, G., 2006. Reanalysis and correction of bed-load relation of Meyer-Peter and Mueller using their own database. J. Hydraul. Eng. 132 (11): 1159–1168. DOI : 10.1061/(ASCE)0733-9429(2006)132:11(1159).

CHAPTER 4. Assessment of the effects of the Plan d’Arem dam on fine sediment interstitial storage dynamics.

Paper under review. Bulteau, T., Marteau, B., Batalla, R.J., Chapron, E., Valette, P., Piégay, H., under review. Effects of repeated drawdown flushing on riverbed fine sediment dynamics downstream from a dam. Anthropocene.

Abstract

Sediment accumulation upstream of dams is frequently a problem, impelling dam managers to implement strategies such as drawdown flushing to limit this process,. If this operation may successfully control reservoir filling, important fine sediment releases could induce riverbed clogging downstream of the dam, especially in by-passed sections where transport capacity is reduced due to water diversion. In this study, we investigate the effects of drawdown flushing downstream of the Plan d’Arem run-of-the-river dam (Upper Garonne, Spain – France border) using a multi-control and impact strategy to consider a range of spatial and temporal conditions in order to separate effects of the dam from potential other factors. Drawdown flushing has been undertaken three times during the study period over a short span of time (2 months). We couple bed material sampling which provides direct information on bed composition, with airborne infrared thermal imagery to better interpret whether fine sediment deposits in the bed are associated with clogging or not. We also measure bed surface grain size and bed mobility in order to investigate their potential role in controlling fine sediment dynamics. We identify surface grain size and water diversion as main factors controlling fine sediment spatial distribution, with coarse-grained bed-surface and by-passing promoting fine sediment enrichment. As a result, sites located upstream and within the by-passed reached of the Plan d’Arem dam show higher fine sediment interstitial storage than sites downstream of the restitution. Results from thermal imagery contradict the clogging effect of such deposits, as reaches with the most important sediment storage host a high number of cold-water patches, indicating water exchanges with the hyporheic zone. Post-flushing bed composition indicates systematic export of fine sediments from the bed matrix for all sites after the first operation, to reach site-specific minimal fine sediment rate, still low after the second and the third flushing. These observations indicate a low risk of clogging related to dam management that could be explained by the fact that the fine sediment is mainly composed of sand.

Keywords: RoR dam, drawdown flushing, riverbed clogging, TIR mapping, Upper Garonne River

4.1. Introduction

In mountain streams, fine sediments (< 2 mm) are commonly transported as suspended load (Walling & Moorehead, 1989; Owens *et al.*, 2005), with this transport occurring mostly during flood events (Marteau *et al.*, 2018). These sediments partly originate from erosion within the catchment, and partly from the resuspension of sediment stored within the riverbed matrix (Wood & Armitage, 1997). The deleterious effects of large quantities of fine sediments in river channels are well documented in the scientific literature (see Wood & Armitage 1997 for a detailed review), with riverbed clogging being one of the problems. Clogging can be defined as the deposition of fine organic and inorganic particles on the benthic zone and their infiltration within the hyporheic zone (Gayraud *et al.*, 2002) in gravel-to-cobble-bed rivers, leading to a reduction of pore volume, consolidation of the sediment matrix, and decreased permeability of the stream bed (Brunke & Gonser, 1997). Early attempts to describe the dynamics of this process date back to the 1980's (Bloesch & Burns, 1979; Bretscko & Klemens, 1986), when anthropogenic fine-sediment inputs to river systems increased in response to the intensification of agricultural practices (Owens *et al.*, 2005, Collins & Zhang, 2016). Over the last two decades, riverbed clogging has become a growing concern in fluvial ecology, and harmful effects are now well documented in the scientific literature, from case studies (MacDonald & McDonald, 1987; Soulsby *et al.*, 2001; Gayraud *et al.*, 2003; Greig *et al.*, 2005; Hedrick *et al.*, 2007; Coulombe-Pontbriand & Lapointe, 2014) to review papers (Wood & Armitage, 1997; Owens *et al.*, 2005; Wharton *et al.*, 2017). In brief, clogging-associated biological impacts ensue from the decreased connectivity between the surface and the hyporheic zone, which notably results in reduced intra-gravel O₂ concentrations. When this occurs, the variety and abundance of benthic macro-invertebrates and the available habitats for fish spawning and egg incubation decrease. Moreover, clogging may persist across time because reduced intra-gravel flows are unable to flush out interstitial fine sediments, and bed-consolidation inhibits bedload transport during floods, and thus also flushing (Brunke, 1999).

However, some effects of riverbed clogging still need studying, one of these being the thermal regime of the river, which can potentially be affected by clogging (Brunke & Gonser, 1997; Packman & MacKay, 2003; Caissie, 2006), and which to the best of our knowledge, has not been specifically studied. Caissie (2006) classifies factors influencing the thermal regime into four categories. Directly conditioning the potential amount of exchangeable energy between air and surface water, atmospheric conditions (1) appear as the main factor of influence at the macro-scale. Other factors, mainly relief and riparian vegetation (2), can reduce the direct effect of solar radiance on surface temperature through the sun-shading effect they exert. Finally, in-stream flow conditions such as discharge (3) and hyporheic flows (4) can influence surface temperature through the three-

dimensional mixing of water bodies from different sources at different temperatures. The latter may be particularly affected by human activities, as water retention and diversion have profoundly affected the hydrology of rivers, with sometimes significant effects on thermal regime (Hockey *et al.*, 1982; Bartholow, 1991; Sinokrot & Gulliver, 2000 – cited in Caissie, 2006), and modifications in sediment yield caused by river engineering and land use changes can promote enrichment of fines over and into the bed, with potential effects on hyporheic exchanges. A loss of permeability caused by clogging reduces hydraulic conductivity within the hyporheic zone, potentially preventing the upwelling of cooler (in summer) hyporheic water towards the surface. However, groundwater inflow originating from deeper and longer pathways at the valley scale (Poole, 2010) may be able to flush through the bed matrix and create cold patches (Schälchli, 1992) in the flow channel. The presence/absence of patches of cooler water in areas where groundwater inflows are found and hyporheic exchanges are expected can then be an indication of the presence/absence of hyporheic water exchanges, thus providing a potential method for an initial assessment of the degree of riverbed clogging.

In Europe, the Water Framework Directive adopted in 2000 aims at providing a “good ecological status” for hydrosystems by 2027, with clogging suspected to be one cause of limited achievements since 2015 (Noack, 2021). Recent developments in understanding interstitial fine-sediment storage and its release processes point towards a highly dynamic process that often shows large spatio-temporal variability (Misset *et al.*, 2021). Consequently, assessment of the temporal dynamics of clogging often implies important field efforts with high-frequency sampling (e.g., Marteau *et al.*, 2018) and extrapolation of field observations over long reaches, which leads to substantial uncertainties (Misset *et al.*, 2021). The complexity of the interacting factors influencing clogging increases the difficulty of producing general clogging threshold values (above which a substrate should be considered as clogged) based on only a few measurements (Descloux, 2011). Such thresholds may be developed considering ecological aspects (e.g., macro-invertebrate abundance and diversity, survival of eggs; Coulombe-Pontbriand & Lapointe, 2014; Seitz, 2020), or the degree of perturbation to physical functioning (e.g., thermal exchanges). Moreover, metrics that are commonly used to assess clogging (percent fines, porosity, hydraulic conductivity, O₂ level) only allow assessment of specific aspects of the process (e.g., sediment dynamics in Piqué *et al.*, 2014 and Marteau *et al.*, 2018; biological effects in Coulombe-Pontbriand & Lapointe, 2014) within a given area that can be characterised by macro-scale (i.e., topography, hydrology, geology, nature and intensity of human disturbances), meso-scale (i.e., river morphology), and micro-scale (i.e., grain size distribution) parameters.

Furthermore, issues concerning fine sediment are increasingly important in dam management, especially in regard to accumulation within the reservoir (Annandale, 2013; Wang & Kondolf, 2014), and sometimes also downstream from the dam (Owens *et al.*, 2005). Siltation is responsible for a loss of total reservoir storage capacity of 0.5%–1% yr⁻¹ worldwide (Morris *et al.*, 2008), impelling dam managers to implement methods to limit such accumulation, such as drawdown flushing (see Kondolf *et al.*, 2014 for details). Recent research topics involving the assessment of clogging downstream from dams include armoured sections affected by coarse sediment starvation and infrequent bed mobility, delivery of fine sediment by downstream tributaries and its accumulation in a section with reduced transport capacity (Loire *et al.*, 2019), and drawdown flushing performed by dam managers to prevent reservoir siltation (Loire *et al.*, 2021).

To better assess clogging along river reaches, more case-studies and methodological developments are needed to link discrete field observations with larger-scale physical behaviour, especially with regard to multiparameter approaches (Seitz, 2020). To help fill this thematic and methodological gap, we aimed to assess the effects of a dam on riverbed clogging by combining field measurements and airborne infrared thermal imagery (TIR). We focussed on the Plan d’Arem run-of-the-river (hereafter RoR) dam (Upper Garonne, Central Pyrenees, Spain–France border area) because it potentially combines two of the three processes generating clogging downstream of dams: i) sediment starvation due to sediment trapping within the reservoir, and ii) drawdown flushing operations that result in potential changes in riverbed composition. We hypothesised that dam effects on grain size could be separated from other factors using a control–impact sampling strategy, while airborne TIR imagery could help in interpreting whether fine sediment interstitial storage (hereafter referred to as FSIS) can be defined as clogging by looking at the distribution and characteristics of cold water patches.

4.2. Study area

The River Garonne (Garona) is located in the Central Pyrenees and flows over Spain and France (Fig. 4.1). The mountain catchment has an area of 1265 km² and encompasses a wide range of elevations from 415 to 3220 m a.s.l (Fig. 4.1.C). The study reach starts at river kilometre 35 (RK35), 35 km downstream from the headwaters and close to the village of Bossòst (Spain), and extends until RK66. The Pique River (the main tributary) meets the Garonne River at RK55, which increases both the catchment area and annual water yield by around 50%. From the upstream limit of the study site to the village of St Béat (RK50), the Garonne River flows within a narrow valley less than 1 km wide, with alternation of wider reaches and a narrower glacial lock. Downstream

from St Béat, the valley widens significantly, especially in the Marignac and Fronsac basins (RK53-56 and RK58-63, respectively), where the valley width reaches up to 3 km.

At the catchment headwaters, a network of dams (built between 1955 and 1965) and penstock pipes feed successive hydropower plants (hereafter HPP), completely by-passing the natural channel until RK39 and producing hydropeaks (Fig. 4.1.B). The Plan d'Arem RoR dam located at RK40 started operation in 1970, and is the only dam directly impounding the mainstem of the Garonne. The dam has two functions: to feed the two downstream HPPs of Fos and Arlos (Fig. 4.1.B), and to buffer the effect of upstream hydropeaking by delivering a smoothed hydrograph to the Garonne River. From this dam, water travels to downstream HPPs through a penstock pipe and an aerial canal, after which it returns to the Garonne. The main channel is then by-passed for 6 km, with a minimum ecological discharge of $4 \text{ m}^3\text{s}^{-1}$. Because of its size and position on the Garonne mainstem, the Plan d'Arem dam disrupts sediment conveyance (Bulteau *et al.*, 2022). Moreover, diversion of the discharge for electricity production also affects the river's hydrology (as is the case for the upstream by-passing) by decreasing base and peak flows by up to $34 \text{ m}^3\text{s}^{-1}$, the maximum operating discharge of the Fos-Arlos hydroelectric complex. When the construction of the dam and the derivation canal was achieved in 1970, the water storage capacity was 0.35 hm^3 . Since then, the dam reservoir has been continuously filling with sediments, mostly fine sand, silt, and clay. After over 40 years of operation, its capacity was reduced to a critical value of 0.053 hm^3 in 2013, leading managers to dredge sediment and implement drawdown flushing actions to reduce sediment accumulation. When discharge exceeds $70 \text{ m}^3\text{s}^{-1}$ (ca. 1-year flood), operators stop electricity production and open the bottom gate to lower the lake level and maximise sediment transfer, thereby restoring critical slope conditions. Drawdown flushing actions have minimised the effects of the dam on the downstream reach, since they have no impact on peak flows and a relatively low impact on sediment transfer, while limiting sediment accumulation within the dam lake (Bulteau *et al.*, 2022). The recent hydrology of the Garonne River was marked by an exceptional flood on June 18th 2013, when discharge peaked at $350 \text{ m}^3\text{s}^{-1}$ at St Béat, which corresponds to a 100-year return period flood. Before that flood, the river system was undergoing channel adjustments that were largely related to upstream damming and afforestation (Bulteau *et al.*, 2022). These adjustments consisted mainly of channel narrowing, bed incision, and coarsening. The 2013 flood had major morphological effects, with a complete reshaping of the channel planform and major sediment inputs, which seem to have remained since, because of the drawdown flushing.

The Garonne River channel presents various degrees of geomorphic activity over the study reach, with the by-pass reach (hereafter BPR) showing higher diversity and dynamism than sections downstream of the restitution. The BPR is characterised by a relatively wide active channel due to

active bank erosion processes, with gravel bars occupying 21 % of the active channel and there being only limited bed incision. Downstream reaches show mainly straight channels, significant incision, and a low proportion of gravel bars (ca. 10 %; Bulteau *et al.*, 2022).

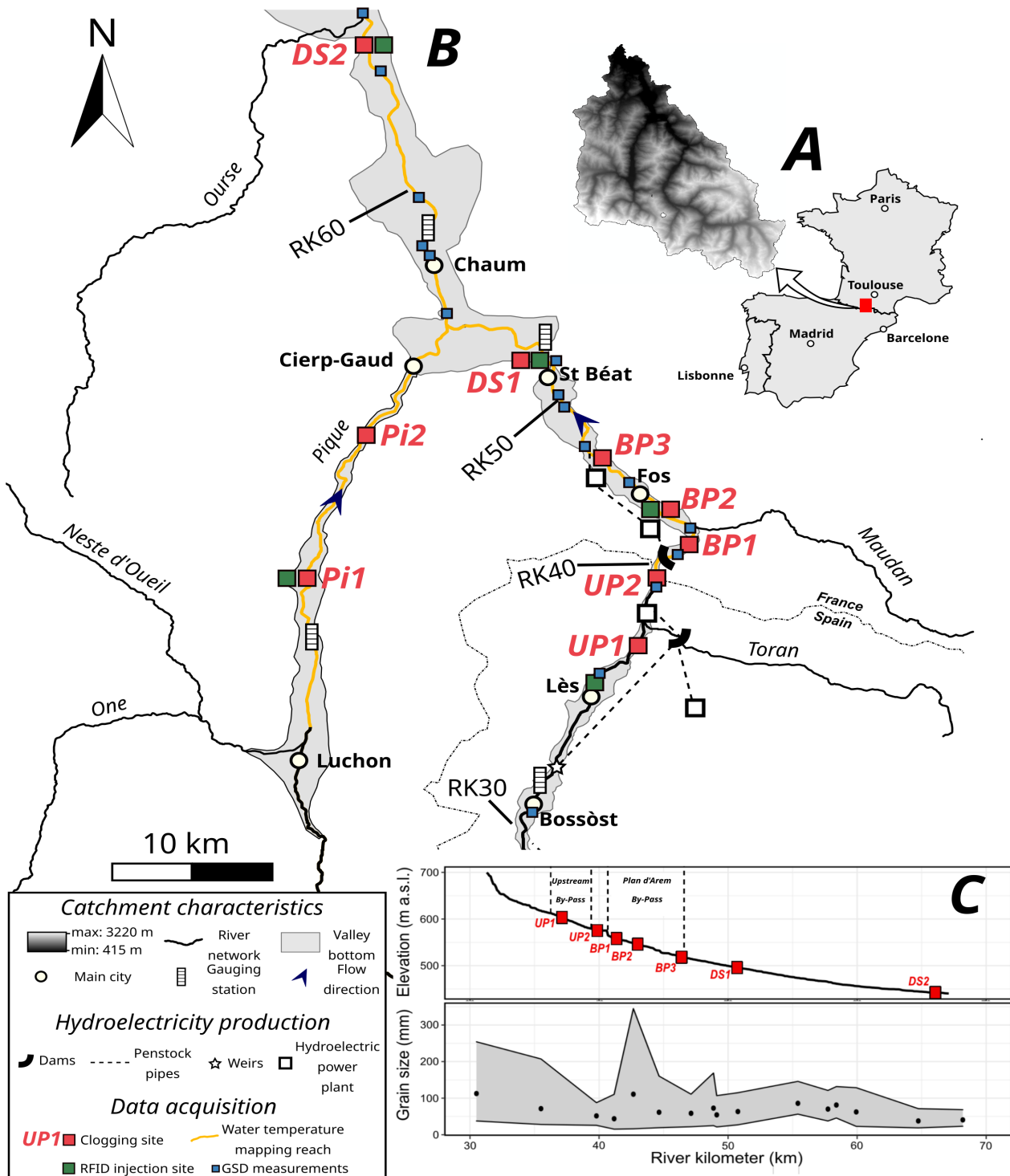


Figure 4.1. Study reach presentation. **A.** Location in Western Europe. **B.** Catchment characteristics and location of hydroelectric infrastructure and instrumented sites for data acquisition. **C.** Longitudinal pattern (above) and grain size distribution (below): dots are D_{50} , grey ribbon symbolises the D_{10} - D_{90} range.

4.3. Material and Methods

4.3.1. Site selection and sampling strategy

To assess the effects on the riverbed of the Plan d’Arem dam and the associated by-passing on fine sediment dynamics with a focus on clogging, a multi-control–impact sampling strategy was undertaken. This strategy relied on selecting sites upstream from the dam (UP1–2; Control 1), within the by-passed reach (BP1–3; Impact 1), and downstream of the restitution (DS1–2; Impact 2). To this scheme, we added two other sites on the Pique River (Pi1–2: Controls 2 and 3): one in a full-discharge reach, and the other in a by-passed reach. The nine selected sites (Fig. 4.1) are presented in Table 4.1, and were sampled on between two and eight occasions between April 2019 and November 2021, according to the river hydrology and dam operations (Fig. 4.2). Hydrological data from the stations of Bossòst, Fos, St Béat, Chaum, and Cier-de-Luchon (Fig. 4.1; sources: SAIH Ebro, EDF, HydroPortail) were compiled at a 1-hour resolution. Since riverbed sediment storage often shows large variability depending on the sampled morphological unit, we chose to systematically sample plane-beds because this unit typically shows less variability than riffle-pool beds (Marteau *et al.*, 2018). To catch potential intra-site variability, three samples along a transect were taken for each site and for each sampling occasion. We further assessed local variability at sites UP1 and DS1 by taking seven and eight samples, respectively, in a 4 m² grid during the campaign of November 2021.

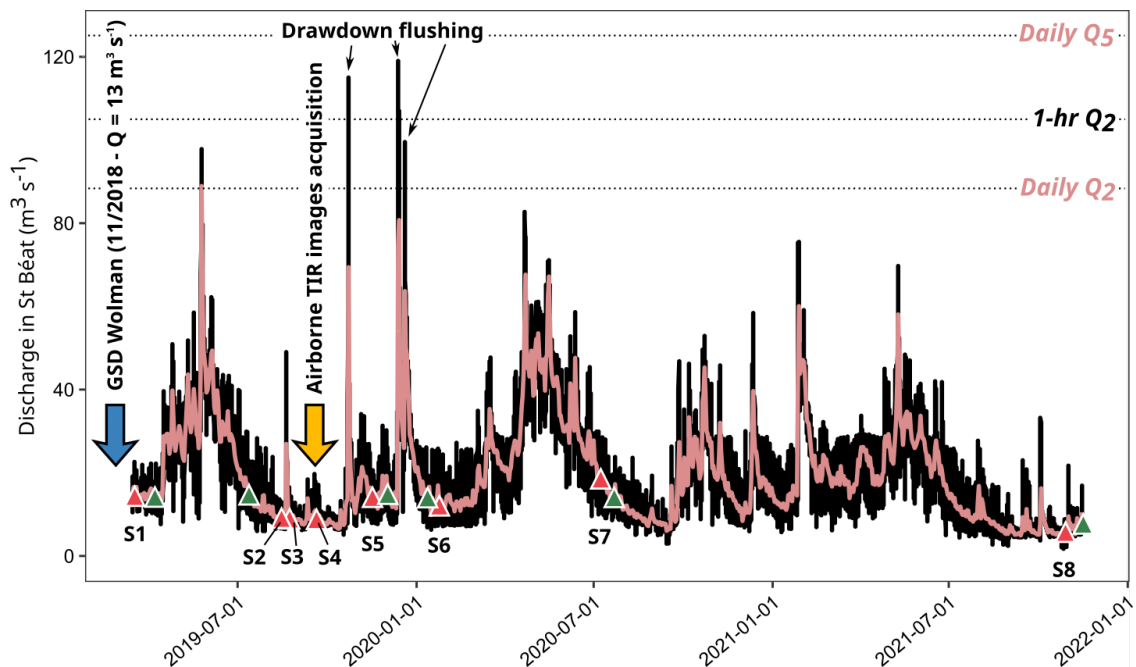


Figure 4.2. Hydrology over the study period and field campaigns for clogging measurements (red triangle), RFID surveys (green triangle), GSD, and TIR mapping (the various techniques are described in the following sections). Black line: 1-hour discharge. Red line: daily mean discharge. Dashed lines: selected reference flood return-periods.

Site	Position	Flow regulation	Location relative to Plan d'Arem	Channel slope	D ₁₆ (mm)	D ₅₀ (mm)	D ₈₄ (mm)	No. campaigns	No. samples
UP1	42°49'47.6"N 0°43'42.9"E	By-passed	Upstream	0.008	21	64	179	3	8
UP2	42°51'04.4"N 0°44'07.3"E	Full discharge	Upstream	0.005	25	51	87	6	18
BP1	42°51'32.1"N 0°44'46.1"E	By-passed	BPR	0.007	11	39	106	3	9
BP2	42°52'06.5"N 0°44'29.4"E	By-passed	BPR	0.007	11	74	240	7	18
BP3	42°53'13.4"N 0°42'47.0"E	By-passed	BPR	0.007	-	-	-	4	11
DS1	42°54'56.6"N 0°41'29.3"E	Full discharge	Downstream	0.007	27	63	115	7	21
DS2	43°00'41.3"N 0°36'59.1"E	Full discharge	Downstream	0.002	20	39	69	7	20
Pi1	42°50'44.6"N 0°36'07.9"E	Full discharge	Other river	0.004	26	44	77	7	21
Pi2	42°53'53.2"N 0°37'33.8"E	By-passed	Other river	0.01	29	77	134	2	6

Table 4.1. Characteristics of the sediment sampling sites

4.3.2. Sedimentological analysis

4.3.2.1. Interstitial storage of fine sediment

The fine sediment proportion of the riverbed was estimated using a method that allowed sampling of the entire grain size distribution (hereafter GSD) over a defined area. This involved a hybrid method (Fig. 4.3.A) that combined manual sampling for coarse sediments (McNeil & Ahnell, 1964; Rex & Petticrew, 2011) with water sampling for fines (considered as suspended sediments) (Lambert & Walling, 1988; López-Tarazón *et al.*, 2011; Piqué *et al.*, 2014; Marteau *et al.*, 2018). This method relied on a cylinder-corer, in this study one of 16 cm diameter and 70 cm in height with 2 cm-long teeth at the bottom, adapted from the method developed by McNeil & Ahnell (1964). Prior to bed material sampling, a 500-mL clear water sample was taken and considered as a blank to assess the suspended sediment concentration of the river for subsequent subtraction from the suspended sediment concentration of the test water samples. The sampler was driven into the streambed to a depth of approximately 15 cm to isolate the sampled area from river flow, thus

limiting the fine sediment losses during sampling. Coarse sediments contained in the sampler were manually removed into a clean bucket until the upper limit of the sampler teeth was reached. The water column in the sampler (D_w) was measured and two replicate samples of 500 mL of turbid water were taken after stirring and waiting for around 10 seconds (i.e., for the sand to re-deposit). Immediately after sampling, the collected coarse sediments were wet-sieved at 64, 45, 32, 22, 16, and 8 mm. Before weighting, each fraction was cleaned with clear water to collect any sand and finer particles that may have remained stuck to coarser material. Material finer than 8 mm, typically representing 0–2 kg of the sediment per sample, was then brought to the laboratory for drying at 130°C for 4 hours, followed by dry-sieving at 4, 2, 1, 0.5, 0.25, 0.125, and 0.05 mm. Water samples were filtered using 1.2- μm glass microfiber filters. The filters were dried at 110°C for 4 hours and weighed to determine the concentration in the samples. The quantity of fines released from the bed was then calculated as follows (López-Tarazón *et al.*, 2011):

$$\text{(Eq. 4.1)} \quad B = C \times V$$

where B is the quantity of fines released from the bed (in kg), C is the concentration in the samples (in kg L^{-1}), and V is the volume of water in the corer (in L).

The sediment mass calculated from the water sample filtration was added to the grain size distribution obtained from the finest fraction (< 0.05 mm) of the coarse sediment sieving. Calculation of the percent of fines (< 2 mm) required prior truncation of the sample at 64 mm (Rice, 1995; Bunte & Abt, 2001).

Considering the high variability in FSIS between sites, assessment of the temporal trends required a nondimensionalisation of the observations. To do this, a simple min-max procedure was used, given its simplicity and its relevance to our data (Eq. 4.2). P_i^* gives a value between 0 and 1 that reflects the proportion of the considered fraction of a given site at a given date in comparison with the minimum and maximum values observed at that site over the entire study period:

$$\text{(Eq. 4.2)} \quad P_i^* = \frac{P_i - P_{\text{MIN}}}{P_{\text{MAX}} - P_{\text{MIN}}}$$

with P_i^* is the nondimensionalised proportion of the considered fraction for a given site and sample, P_i is the proportion of the considered fraction for a given site and a given sample, P_{MIN} is the minimum proportion of the considered fraction for a given site, and P_{MAX} is the maximum proportion of the considered fraction for a given site.

4.3.2.2. *Bed texture and mobility*

The surface GSD is known to influence near-bed flow conditions, having significant effects on bedload mobility and FSIS (Staudt *et al.*, 2017; Raus *et al.*, 2019). We assessed GSD over the study reach by sampling 20 bar heads in winter 2019, picking 100 particles (Wolman, 1954; Rice & Church, 1998; Bunte & Abt, 2001) on both surface and subsurface layers (Buffington, 1996). Bed mobility can be an important factor influencing FSIS and the release of sediment from the streambed. The sediment sampling sites were then equipped with natural passive RFID tracers and resurveyed on three to five occasions to determine critical discharges (Fig. 4.2). Field data helped in calibrating a generalised threshold model (GTM) (Recking, 2016; Vazquez-Tarrío *et al.*, 2019) that allowed determination of critical discharge for various size classes. Together with passive radiofrequency identification (RFID) tracers, active RFID tracers were injected into the substrate column (seven particles, z-axis = 30 mm, column height = 210 mm) to assess the maximum active layer between April 2019 and November 2021 (Brousse *et al.*, 2018; Boutault, 2020).

4.3.3. **Surface temperature mapping**

4.3.3.1. *Data acquisition*

Airborne thermal infrared (TIR) remote sensing has successfully been used to map river surface temperature over long reaches during the last two decades (see review by Dugdale, 2016). As stated in the introduction, it is known that riverbed clogging may disrupt surface-subsurface water interactions, notably the upwelling of colder groundwater and hyporheic flows. Mapping of river temperature can thus be used to identify, localise, and characterise the presence/absence of cold-water patches (also called thermal anomalies) generated by upwelling. To maximise the temperature contrast between surface and subsurface water (i.e., to better distinguish temperature anomalies), the TIR survey was carried out during a warm summer day (15/09/2019, up to 27.4°C in Bagnères-de-Luchon, close to the study area, see details in www.infoclimat.fr) at around 13:00 central European time. A thermal imaging camera (VarioCam HR Research 600®, InfraTec GmbH, Dresden, Germany, 640 × 480 pixels) with a standard 30-mm lens and a DSLR camera (D7000, Nikon®, 4928 × 3264 pixels) with a 35-mm lens were mounted on an autogyro (ELA® 07S) to collect both thermal images and classic photographs. Both sensors were set to take images in time-lapse mode every 1–2 s. The survey lasted for 1 hour (12:35–13:35), long enough to cover the entire study reach back and forth to ensure sufficient overlap. The thermal images were corrected for differences in the ‘true’ kinetic temperature using an empirical calibration ($R^2 = 0.87$) comparing radiant temperature (from TIR images) with temperature measured by 15 submerged VEMCO

Minilog II® loggers placed in the river (~10 cm below the surface, logging at 5-minute intervals) over the entire survey. For more details on the airborne TIR survey, see methods in Marteau *et al.* (2022a, 2022b).

4.3.3.2. TIR data processing

Both RGB and thermal orthomosaics were created separately using structure-from-motion photogrammetry (SfM) with Agisoft MetaShape® software (version 1.6.0), and were exported at 0.1 m pixel⁻¹ for the RGB orthophotographs and 0.4 m pixel⁻¹ for the thermal orthomosaic (Fig. 4.3.B – Step 1). After manual digitisation of the main channel components (active and wetted channels, gravel bars, islands), the channel centreline was automatically detected using the FluvialCorridor 10.1 ArcGIS® toolbox (Roux *et al.*, 2015). To produce a longitudinal temperature profile, a 3.2-m-wide buffer was created along this centreline and segmented at 100 m steps (Fig. 4.3.B – Step 2). The median temperature and standard deviation were extracted for each polygon.

The main goal of the TIR mapping was to detect cold-water patches. To do this in a semi-automated way, the surface temperature was compared with the local median temperature, and areas colder than the local median were considered to be thermal ‘anomalies’. However, only anomalies below a threshold of 0.43°C were considered as cold patches. Calculation of this threshold was approached as a limit of detection, and was based on known uncertainties stemming from camera accuracy, empirical correction, and local variability (see Supp. Mat. in Marteau *et al.* (2022b) for more details on the threshold calculation). Cold patches were then individually classified from the orthophotographs according to their shape, size, and position within the channel (Fig. 4.3.B – Step 3). We differentiated four types of cold patches likely to provide information on the presence/absence of clogging, with inspiration from Torgersen *et al.* (2012) and Wawrzyniak *et al.* (2016). ‘Riffle exfiltration’ refers typically to cold water that infiltrates upstream of a riffle crest and exfiltrates downstream in the upwelling zone, after circulating within the hyporheic zone. A ‘lateral seep’ can be observed along the banks at the channel margin, and corresponds to groundwater input into the channel. Although not directly influenced by clogging, lateral seeps are dominant where riverbed incision is high and hyporheic control is low. ‘Bar exfiltration’ is somewhat similar to riffle exfiltration but with cold water coming from inside-bar flows and exfiltrating at the bar margin. A ‘pool’ corresponds to cold water coming from a stratified pool.

4.3.3.3. Segmentation

Analysis of the longitudinal temperature profile was first performed by looking at changes in thermal gradients. To do this, the temperature profile was segmented into sections of homogeneous gradient or “trend” using the EnvCpt® package in R (Killick *et al.*, 2021). The resulting

segmentation was further tested for changes in variance, which could indicate changes in underlying processes, despite a constant trend or gradient. Finally, geographical constraints were added when necessary to simplify the analysis, such as those associated with the restitution of diverted water and a confluence with a major tributary. The thermal gradients and cold-water patch characteristics were then analysed for each sub-reach and linked with the geomorphological variables at the different scales to assess how these parameters could help interpret the degree of alteration caused by clogging from a “functional” perspective.

4.3.4. Geomorphic analysis

A dataset from Bulteau *et al.* (2022) was used to characterise the local-to-large-scale geomorphic settings and assess their potential for controlling fine sediment dynamics and water temperature patterns. The river planform (namely, the active channel width, wetted channel, and islands) were digitised from the orthophotographs (see Section 4.3.5). Gravel bars were then extracted by subtracting the wetted channel from the active channel area. The valley width was digitised from aerial photos taken in 2016 (French National Geographic Institute). Patterns of vertical evolution were extracted from two low-flow long profiles of water surface elevation taken in 1922 and 2014, and the main zones of bed degradation were identified.

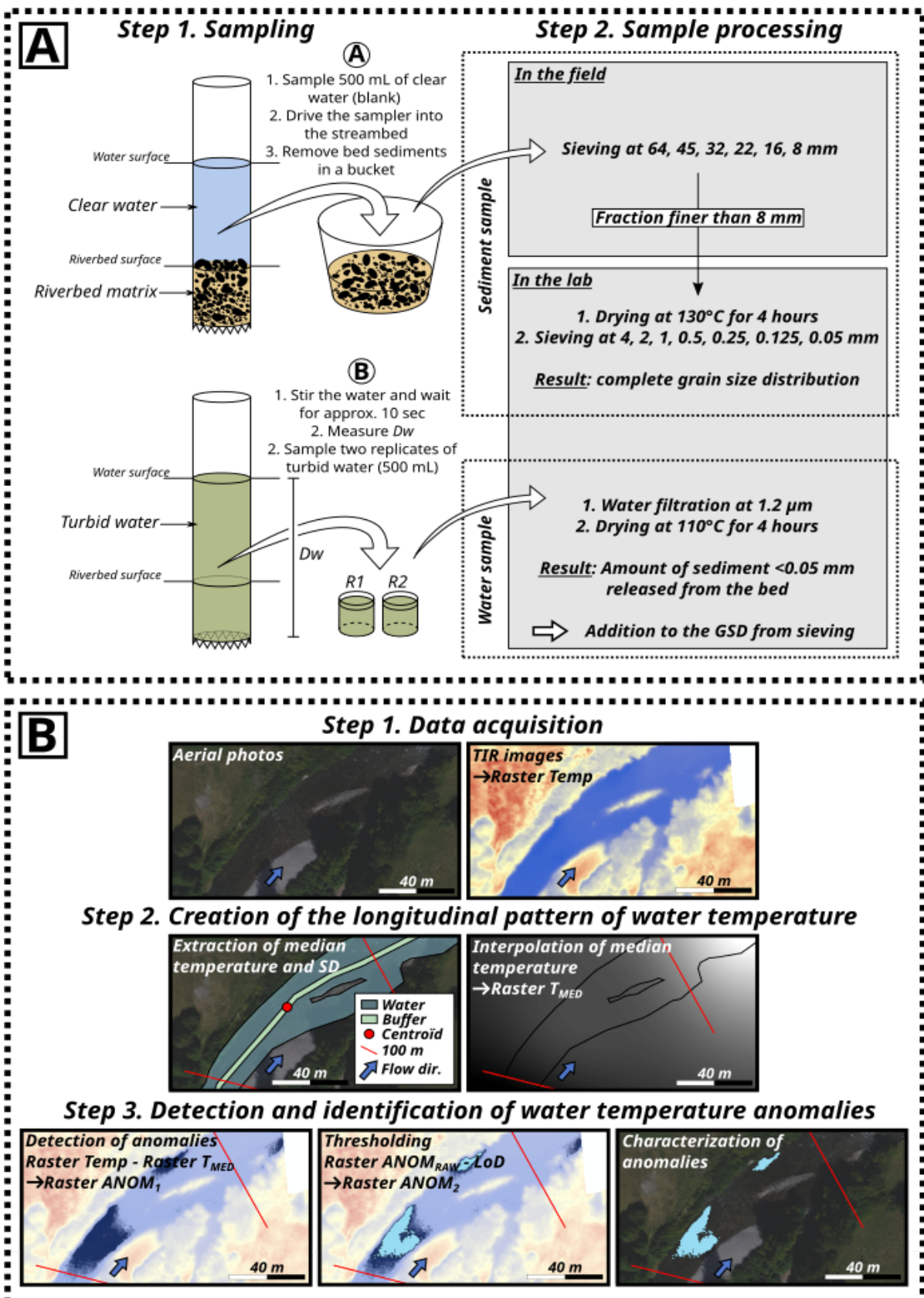


Figure 4.3. A. Method for estimating the fine sediment proportion. B. Method for characterising the temperature over the study reach.

4.4. Results

4.4.1. Fine sediment interstitial storage

4.4.1.1. Longitudinal pattern

Riverbed storage showed a decreasing trend from upstream to downstream for all size classes (silt and clay, sand, and gravel) considered as fines (< 8 mm), with gravels being somewhat less affected (Fig. 4.4). The average silt and clay, sand, and gravel proportions decreased from 0.34 %, 17.8 % and 18.3 %, respectively, at UP1, to 0.15 %, 6.5 %, and 9.9 % at DS2. The BPR showed higher proportions of these size classes than upstream and downstream reaches, locally demonstrating fine sediment enrichment (Fig. 4.4). D_{16} was rather similar across all sites (20–27 mm), except in the BPR where it fell to 11 mm, confirming the enrichment of the BPR with finer fractions, as indicated by the surface GSD. This enrichment could be largely explained by the effects of by-passing on hydrology and bed mobility. Sediment tracing provided information on bedload behaviour over all sites, and over a range of discharges involving partial to total mobility of the injected tracers. Table 4.2 summarises the main results from the sediment tracing, which help in explaining the spatio-temporal dynamics of the fine sediment. Indeed, computation of the exceedance frequency for moving particles of 2 mm ($Q_{c_{2mm}}$) showed that sand mobility occurred for only 6.5 % of the time in the BPR, mostly during flood events, while this threshold was surpassed 34 %, 11 %, and 98 % of the time at the UP, DS1, and DS2 sites, respectively.

Sites	UP	BP	DS1	DS2	Pil
n	331	315	334	322	293
Recovery rate (%)	39–47	33–51	12–32	12–36	25–53
$Q_{c_{2mm}}$ ($m^3 s^{-1}$)	15	25	35	10	-
$Q_{c_{8mm}}$ ($m^3 s^{-1}$)	25	35	48	20	-
$Q_{c_{D50}}$ ($m^3 s^{-1}$)	45–50	55–65	75	80	30
$Q_{c_{D84}}$ ($m^3 s^{-1}$)	60–70	70–90	87	120	40
Active Layer Thickness (m)	0.06	0.10	0.19	0.15	0.05

Table 4.2. Characteristics of the bedload transport over the study sites

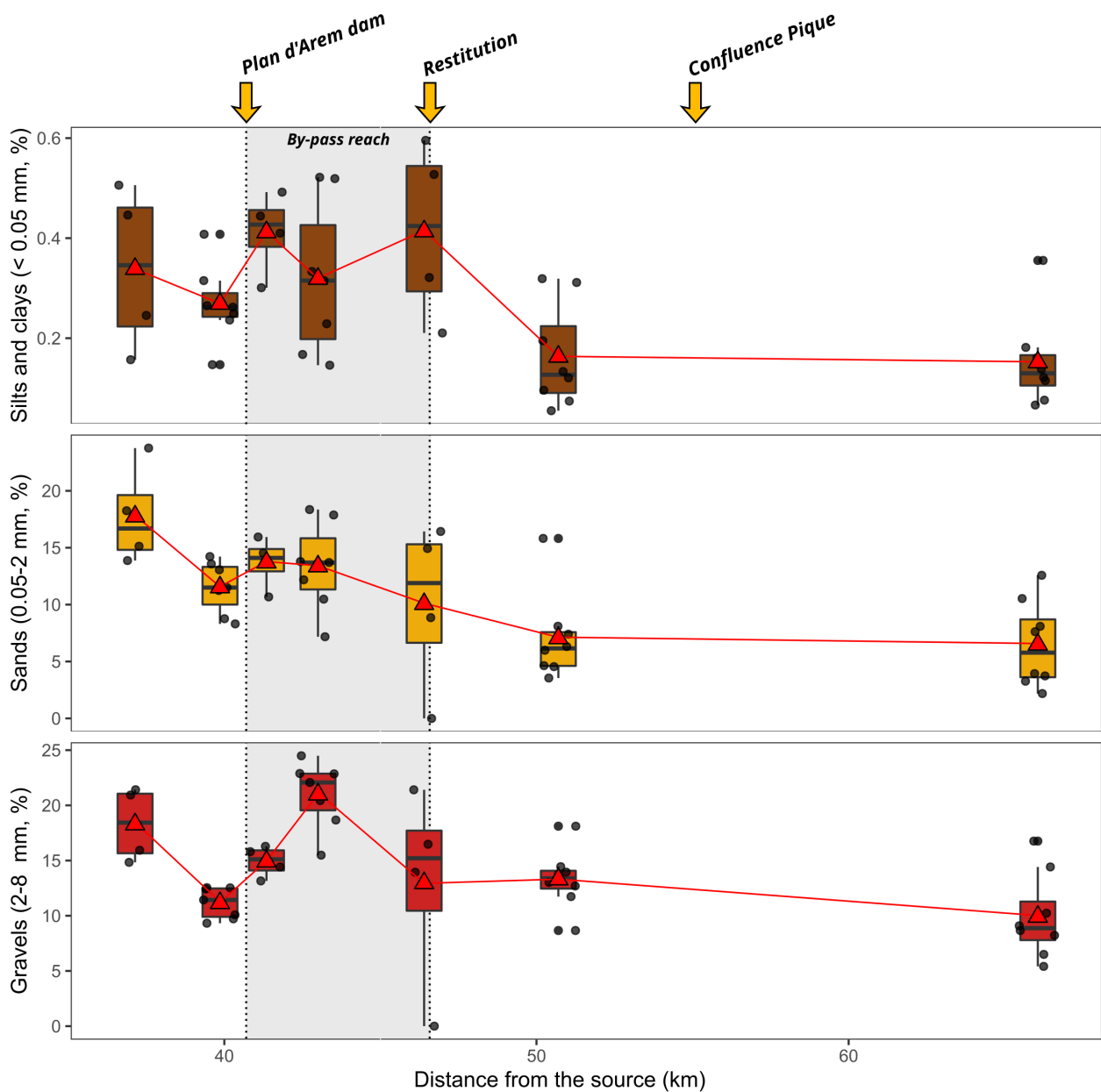


Figure 4.4. Longitudinal pattern of fine sediments in the river-bed

Through its effects on roughness and near-bed flow conditions, surface GSD seems to influence storage over various aspects. The following observations should be considered to be unrelated to the Plan d'Arem dam because they concern reaches both upstream and downstream, as well as the two control stations on the Pique River. The proportion of gravel (measured from the 'volumetric' cylinder-corer method) was positively correlated with coarse particle size (measured from 'areal' Wolman method and truncated at 8 mm; e.g., D_{84} , $R^2 = 0.64$, Fig. 4.5.c), an observation that was less evident with smaller fractions ($R^2 = 0.17$ and 0.24 for silt-clay and sand, respectively, Fig. 4.5.a & 4.5.b). Although the D_{84} value did not seem to influence the proportions of silt and clay, we observed a positive correlation between D_{84} and the standard deviation for this fraction ($R^2 =$

0.64), indicating an indirect effect of surface GSD on the intra-site variability of silt and clay (Fig. 4.5.d).

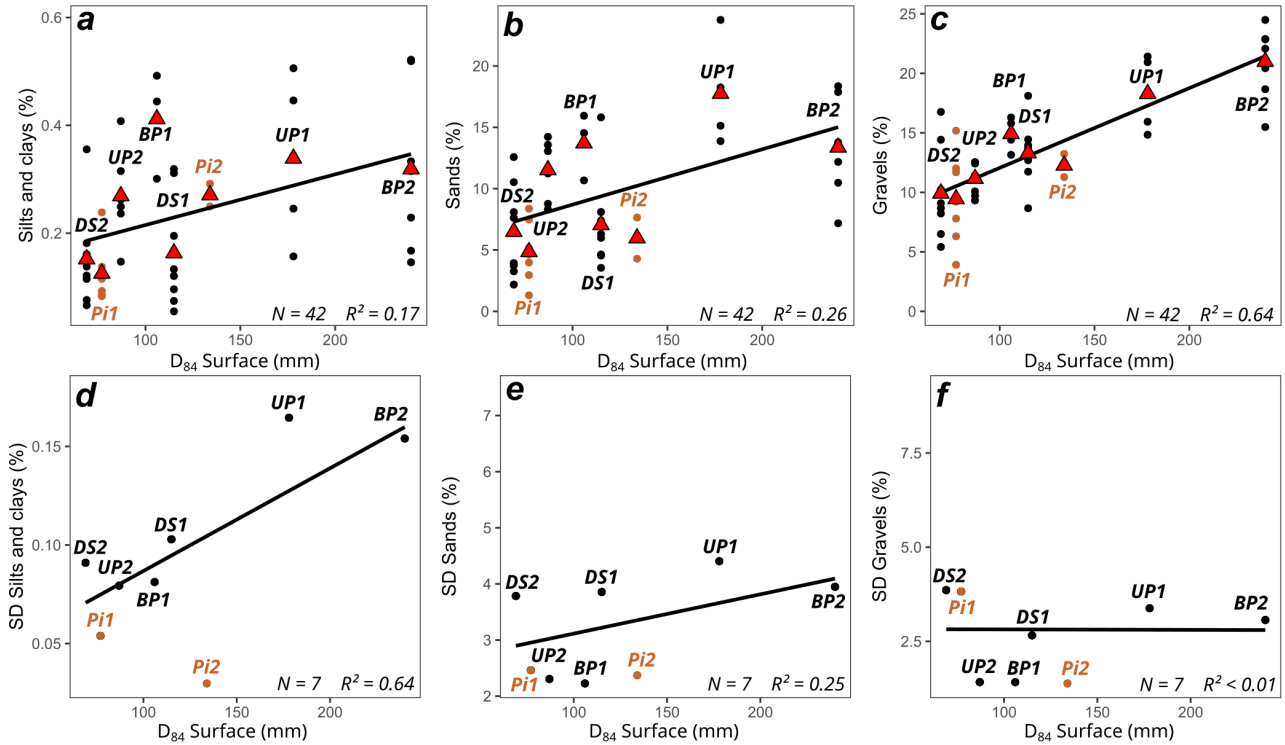


Figure 4.5. Effects of surface GSD on inter-site and intra-site variability of FSIS.

4.4.1.2. Temporal dynamics

A remarkable temporal variability in the fine sediment proportion in the bed was observed. Sand and gravel displayed similar trends: proportions of both fractions were positively correlated for the BP1 and BP2 sites ($R^2 = 0.94$ and 0.67 , respectively), which may mean that the processes of storage and release were similar and occurred simultaneously. This correlation was less obvious at other sites, with R^2 values of <0.01 to 0.29 . For all sites, competent floods ($Q > Q_{cD84}$) corresponding to sufficiently high flood-discharge to trigger drawdown flushing actions at the Plan d’Arem dam resulted in: (1) a decrease in sand and gravel proportions if no other flood event had occurred shortly before, or (2) in the case of two consecutive competent floods, the stability of sand and gravel proportions after the second event. Considering sites UP2, BP2, DS1, DS2 to focus on sites surveyed before the first drawdown flushing (23/10/2019), the pre-flood FSIS levels seemed to exert an important modulatory effect on the observed post-flood values. Average P_{s4}^* values were high, at 0.7 for sands and 0.64 for gravels. Over the period S4–S5 (Fig. 4.2), during which a major flood occurred (23/10/2019; Q_2) following 5 months with low-to-moderate discharge, the FSIS decreased significantly over all sections, with a difference in $\Delta P_{s5}^* - P_{s4}^*$ of between -0.3 and -0.91

for sands (-0.65 on average), and between -0.24 and -0.84 for gravels (-0.50 on average). The resulting P_{S5}^* values were low, equal to 0.05 on average for sands, and 0.14 on average for gravels. The following period (S5–S6), which was marked by two floods of similar intensity that also triggered flushing actions, then showed a relative stability in FSIS, with a slight increase, but remaining lower than the levels at S4, with the difference in $\Delta P_{S6}^* - P_{S5}^*$ being between -0.01 and $+0.45$ for sands ($+0.16$ on average) and between $+0.09$ and $+0.35$ for gravels ($+0.17$ on average). The effects of smaller floods, typically just sufficient enough to initiate motion of the D_{50} , were site dependant and less clear. At UP1, the sand and gravel proportion increased between S6 and S7, a period marked by spring snow-melt but no discharge above Q_{CD50} , then decreased between S7 and S8, a long period with no competent flood except the small event of May 2021 (Q_I ; Fig. 4.6). The sand and gravel behaviour during small floods is more evident at the other sites, with the proportion of these fractions systematically increasing during the non-competent flood period, as was the case for periods S1–S2, S6–S7, S6–S8, and S7–S8 for sites UP2, BP1, and BP2. Finally, the sand and gravel responded differently to non-competent flood periods at sites DS1 and DS2, with the sand proportion being roughly stable between S6 and S8, but the gravel proportion fluctuating more over the same period.

The behaviour of silt-clay differed between sites and from that of sand and gravel. The proportion of silt and clay positively correlated with sand at sites UP1 and BP1 ($R^2 = 0.6$ and 0.77 , respectively), negatively correlated with sand at BP2 ($R^2 = 0.45$), and did not correlate significantly at the other sites (R^2 between <0.01 and 0.15). Downstream from the Plan d’Arem dam, the highest proportions of silt and clay were observed at S5, between two competent floods that involved flushing actions, but these proportions dropped at S6 after the second competent event, indicating that flushing actions may temporarily increase clogging although fines are subsequently remobilised. No clear trend was observed in silt and clay over non-competent flood periods, with the proportion of this fraction either (1) increasing, as between S7 and S8 at BP1 and DS2, and between S1 and S4 at BP2, or (2) decreasing, as between S7 and S8 at UP1, and between S6 and S8 at DS1 and UP2. It is worth keeping in mind that surveys S7 and S8 were one and a half years apart, which is a long period considering the high temporal variability of the processes analysed, and which must force us to exercise caution when interpreting the results.

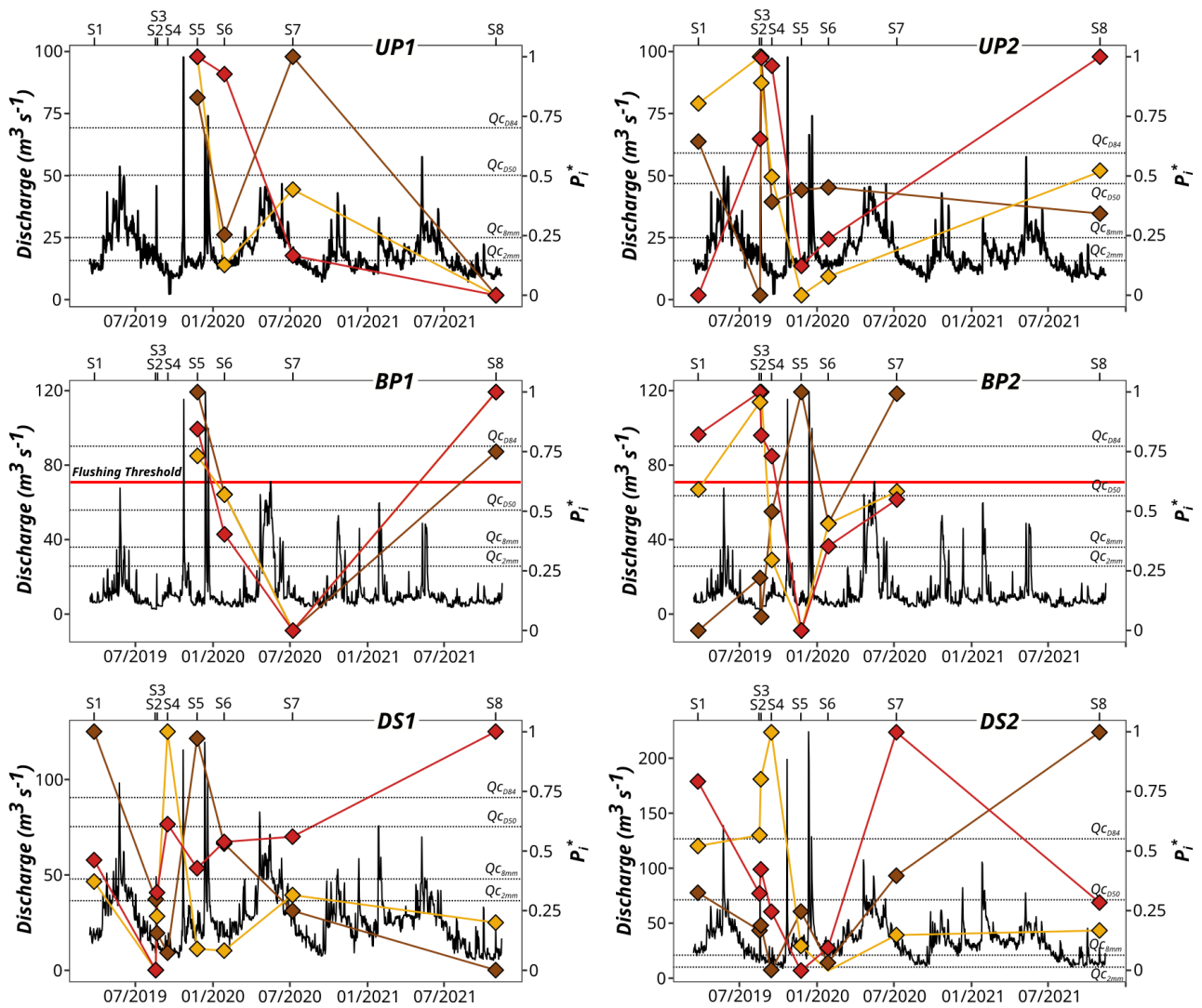


Figure 4.6. Temporal variability of FSIS. Brown: silt and clay. Yellow: sand. Red: fine gravel. The red horizontal line on the BP graphs corresponds to the discharge threshold triggering drawdown flushing actions at the Plan d’Arem dam.

4.4.2. Longitudinal pattern of water temperature

The longitudinal profile of water temperature was segmented into eight sub-reaches characterised by similar gradients and considered as homogeneous (Fig. 4.7). Upstream from the Plan d’Arem dam, reach A is marked by a negative temperature gradient ($-1^{\circ}\text{C km}^{-1}$), although this may not reflect any significant trend considering the shortness of this reach (~ 700 m). Reach B, corresponding to the reservoir, shows a positive gradient ($+0.32^{\circ}\text{C km}^{-1}$) due to high insulation and a longer residence time. The water temperature drops at the dam outlet, reducing by approximately 1.4°C . Over reaches C and D, the BPR recorded an important increase in water surface temperature, rising from 13.1°C at the dam outlet to 15°C at the restitution, with the gradient becoming less important heading downstream (Fig. 4.7.A). Note that this observation was not related to water diversion because the dam did not operate on the day of the TIR mapping and the BPR therefore

conveyed the entire discharge from upstream. Reach E was marked by a large variability in water temperature ($\Delta T_{\text{MIN}} - T_{\text{MAX}} = 2.24^{\circ}\text{C}$) and an overall negative gradient of $-0.14^{\circ}\text{C km}^{-1}$, with the highest temperature recorded between RK49 and RK50 due to an old water diversion. From RK52.6 to the downstream limit of the study reach, we identified three reaches characterised by a low temperature gradient (-0.07°C to $+0.05^{\circ}\text{C km}^{-1}$), with locally important variability of about $\pm 1^{\circ}\text{C}$.

Observation of the cold patch types and density provides comprehensive information on thermal functioning. River morphology exerted substantial effects on the distribution of cold patches (see Appendix 4.1). The highest density of cold-patches associated with riffle upwelling was observed in the BPR, especially in reach C with $276 \text{ m}^2 \text{ ha}^{-1}$, indicating a zone of rather active exchanges between surface water and the hyporheic zone. We also observed less cold patches over reaches F, G, and H (83 , 114 , and $116 \text{ m}^2 \text{ ha}^{-1}$, respectively), with an important proportion of patches being attributed to lateral seeps over reach H (44% , $51 \text{ m}^2 \text{ ha}^{-1}$). The two reaches located at RK53–55 and RK59–62 were characterised by the absence of cold patches, which coincided with valley widening (Fig. 4.7.B).

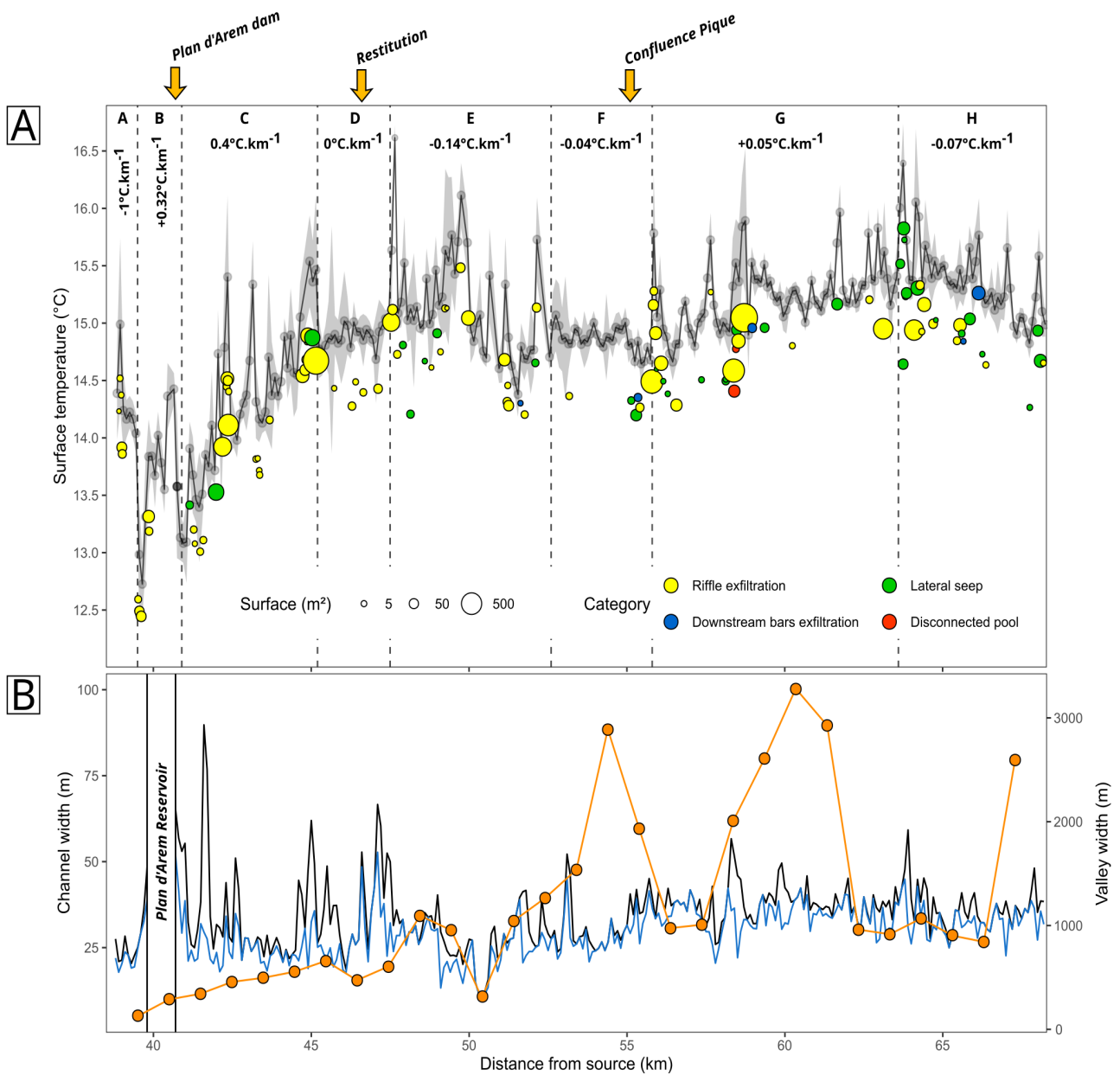


Figure 4.7. A. Longitudinal patterns of active (black line) channel width, wetted channel width (blue line), and valley bottom width (orange line and dots). **B.** Longitudinal patterns of active (black line) channel width, wetted channel width (blue line), and valley bottom width (orange line and dots).

4.5. Discussion

4.5.1. Is there interstitial storage of fine sediment downstream from the Plan d'Arem dam?

The FSIS within the coarse sediment matrix of the channel showed a general decreasing downstream trend over the study reach. Fine sediments mostly consisted of sandy material, typically representing 4 % to 20 % of the sample mass, and perhaps even less of the total bed material considering the sampler mouth size and sample truncation. Silt and clay accounted for less

than 0.5 % of sample mass, and for an average of 4.7 % of the fines. These proportions are rather low in comparison with values given in the literature; for example, Gayraud & Philippe (2003) found an average of 1.03 % of silt and clay in the bed material of 15 French streams, Ryan & Packman (2006) showed that silt and clay represented 6 % to 25 % of fines on two streams from an urbanised watershed in the USA, and Descloux *et al.* (2011) found that fines comprised between 8.3 % (unclogged) and 55.2 % (very clogged) of freeze core samples.

The main effect of the Plan d'Arem dam on FSIS is caused by changes in the local hydraulics through water diversion. This lowers the exceedance frequency for mobility of the finer fractions (e.g. sand), resulting in fine sediment enrichment in the BPR (Impact 1). Sediment storage drops downstream from the restitution because of the restored transport capacity, and remains rather low over the rest of the study reach (Impact 2), providing further evidence that water diversion leads to higher magnitude changes in FSIS than the dam itself. Drawdown flushing actions and associated fine sediment releases may temporarily increase storage, but subsequent floods are sufficiently competent to mobilise the bed material and flush the deposited material, with FSIS levels being lower after flushing actions than at the end of long low-flow periods. Nevertheless, the role of suspended sediments in controlling riverbed clogging is frequently discussed, and other factors such as connectivity with sediment sources (Marteau *et al.*, 2018), hydrology (Piqué *et al.*, 2014), and local hydraulics and sediment characteristics (Misset *et al.*, 2020) often exert stronger effects.

The surface GSD was partly independent of the Plan d'Arem dam, and appeared to be a dominant factor controlling fine sediment storage and release through two main processes. Large structural elements, reflected by a high D_{84} , have hiding effects that allow fines to settle and rest under flow conditions that would otherwise lead to sediment transport in the absence of cobbles and boulders. This results in sites with coarser grain size showing higher FSIS, especially when sand and fine gravel are considered. Additionally, coarse features create local fixed-bed conditions, with patches of mobile material moving and settling in-between over a depth of approximately 10 cm, binding fine sediment enrichment to this layer. Conversely, sites with a smaller surface GSD and better particle sorting show a higher mobility (even total mobility) of bedload and higher scouring (>15 cm, Table 4.2). These observations on bedload mobility relate to the specific dynamics of the FSIS behaviour, which shows higher intra-site variability in sites characterised by the presence of large structural elements, especially for silt and clay. A number of authors reported the importance of bed matrix grain size and distribution, as well as bed mobility, in the control of incipient deposition and depth of fine sediment infiltration (Wharton *et al.*, 2017), which supports our observations. Coarse beds were shown to promote initial particle deposition and intrusion within the

top layer (Evans & Wilcox, 2014), but the poor sorting often observed in sufficiently-supplied coarse-bed natural streams leads to reduced porosity (Wooster *et al.*, 2008). Similarly, Gayraud & Philippe (2003) found a significant positive correlation between the sediment sorting index, which increases as sediment sorting decreases, and the proportion of silt-clay ($\rho = 0.30$), sand ($\rho = 0.77$), and gravel (defined as 2–16 mm; $\rho = 0.46$, where ρ is the Pearson correlation coefficient).

Following our first hypothesis, we can then separate potential effects of the dam on FSIS from other factors using a multi-control–impact sampling strategy. By reducing the sediment matrix mobilisation, peak flow lowering has more of an effect on FSIS in the by-passed reach than does sediment starvation. The FSIS in the by-passed reach was lower than that observed upstream from the dam at sites with similar bed texture and hydrological conditions (i.e. by-passed), which can be attributed to fine sediment trapping by the dam.

4.5.2. Can the observed fine sediment interstitial storage be defined as clogging when thermal patterns are examined?

We observed the longitudinal structure of thermal gradients and cold patch distributions over the study reach that was not affected by the observed FSIS in the by-passed reach. The geomorphological setting described by Bulteau *et al.* (2022) provides information on large-scale to local-scale features that can explain river temperature patterns. At the valley-scale, the geology, which notably controls the valley width, causes the groundwater table to drop, with river water feeding the aquifer where the valley is large. The dominant downward direction of exchanges in these areas results in the absence of cold patches, but has no impact on thermal gradients, although it seems to lessen the local variability of surface temperature. At a more local-scale, we identified the Plan d’Arem dam as a key factor controlling the downstream surface temperature. The dam outflow is cold, but then rapidly warms up within approximately 4 km, to reach an equilibrium temperature of ca. 14.5°C–15°C until the downstream end of the study reach. The surface temperature rises locally in areas of heavy re-working (e.g., St Béat village, RK48-50) and upstream of weirs and bridges (RK56, RK58, and RK64). The by-passed reach is also located in a wide valley characterised by a fairly wide active channel with a series of riffles showing significant cold water upwelling. This reach with significant hyporheic (i.e., vertical) exchanges contrasts with areas of incision further downstream that show more lateral seeps due to outflow of the local aquifer from the banks (i.e., lateral exchanges).

FSIS does not seem to be a factor explaining the thermal gradients and cold-patch distribution. Reaches with the highest storage (e.g., the BPR) host a number of cold-water patches, indicating that storage does not inhibit water exchanges with the hyporheic zone. As the fine

sediments recorded in our field area were mostly sandy-granular, the hydraulic conductivity was not substantially altered (Wharton *et al.*, 2017). Similarly, with a global D_{50} comprised of between 1.6 and 5.6 mm, and the fines D_{50} comprised of between 0.6 and 0.8 mm (UWITECH, 2014), the sediments stored in the Plan d'Arem present non-cohesive characteristics, even though they are rather fine-grained. Although this aspect has not been specifically studied, we hypothesise that the thin and mobile alluvial material resulting from fresh sediment supply during drawdown flushing actions provides the physical support required for hyporheic exchanges to occur. Together with the higher diversity of morphological features (large gravel bars, riffles), these inputs explain the higher density of cold patches in the BPR. The bed armouring that is punctually observed in the study reach is not generalised, which explains the high temporal variability, as a highly armoured and degraded bed would have led to a relatively continuous build-up in fine sediment storage with little or no release of fines (Brunke, 1999).

Our second hypothesis stating that airborne acquisition of temperature data can help interpret whether fine interstitial sediment storage can be defined as clogging is then validated, and underlines the fact that we need to be very careful when directly interpreting FSIS as clogging.

4.5.3. Methodological issues

The coupling of field sediment sampling and TIR mapping provided an interesting method for assessing clogging. Field sediment sampling provided direct and discrete information on riverbed composition and was easily repeatable over time to assess temporal dynamics, whereas the TIR mapping was used as a proxy to assess whether FSIS can be considered as clogging in a more holistic way. In the light of our results, we agree with the conclusion drawn by Seitz (2020) on the need to move towards multi-parameter approaches to correctly assess clogging over various aspects. As an illustration of this, if using sediment sampling only, the BPR would have been considered as suffering from high clogging because it showed the highest FSIS values, a conclusion that was invalidated by the thermal observations of functional water exchanges.

FSIS is a complex problem to assess because it is time and space contingent. To control these conditions, a multi-control and impact strategy is needed with consideration of a range of (1) spatial conditions in terms of grain size, relative position to the dam, and water diversion, and of (2) a range of temporal conditions in terms of sediment mobility, hydrology, and dam operation. Embracing the different forms of variability is the only way to properly assess the respective effects of all these factors and distinguish between the relative contributions of each of them in controlling FSIS.

The variety of morphological contexts and human disturbances does not always allow for such distinction on the basis of spatial segmentation and inter-comparison of homogeneous reaches, and therefore other complementary approaches are needed to provide additional information to that provided by the spatio-temporal framework. In our case, although the observed effects of surface GSD on FSIS were apparently independent from the dam, *in-situ* study of the bedload behaviour and calculation of critical discharges for various size classes were required to distinguish the effects of surface GSD from those of water diversion, especially given that the sections with the coarsest surface layer on both the Garonne (Control 1, Impact 1) and Pique (Control 3) rivers were also the by-passed sections. The repetition of high-frequency FSIS measurements is the only way to overcome the generally large intra-site variability and to improve the robustness of the method.

Finally, a more detailed assessment of the direct unitary effects of drawdown flushing actions and their persistence through time and space, which could not be conducted given the limited number of field campaigns, would provide further information on how dam operation and management could help control the dynamics of fine sediment storage.

4.6. Conclusions

The present study aimed to characterise the fine sediment storage and release processes in the vicinity of a RoR dam, and their potential role in inducing riverbed clogging. This was accomplished by coupling sediment sampling with the acquisition of TIR images. This innovative approach, in line with previous recommendations for using multi-parameter approaches when studying riverbed clogging, relied on a spatio-temporal sampling framework to identify and assess the relative contribution of individual factors on the control of interstitial fine sediment dynamics. The upper reach of the Garonne River is subjected to varying levels of FSIS, both spatially and temporally, and sometimes at rather high levels, but none of these conditions can be labelled as ‘clogged’ according to the definition given in the introduction. Drawdown flushing is likely to play a role in maintaining sediment dynamics downstream from dams because the preservation of flood discharges and partial sediment routing through the reservoir and the dam itself counteract the classical effects of peak flow lamination and sediment starvation that occur downstream from dams. Although such encouraging results offer interesting management perspectives, the authors would like to emphasise the unique character of each study site, and the requirement for *in-situ* study and careful diagnosis before implementing any new dam management procedure.

4.7. References

- Annandale, G. W., 2013. *Quenching the Thirst: Sustainable Water Supply and Climate Change*, CreateSpace, North Charleston, S. C.
- Bartholow, J. M., 1991. A modelling assessment of the thermal regime for an urban sport fishery. *Environmental Management*, 15: 833–845.
- Beschta, R.L., Jackson, W.L., Knoop, K.D., 1981. Sediment transport during a controlled reservoir release. *J. Am. Water Resour. Assoc.* 17, 635–641. DOI : 10.1111/j.1752-1688.1981.tb01270.x.
- Bloesch, J., Burns, N.M., 1979. A critical review of sedimentation trap technique. *Zool. Hydrol.* 42:15-55.
- Boutault, F., 2020. Etude de l'impact cumulé des facteurs d'anthropisation sur la Dordogne moyenne et préconisations en vue de la restauration écologique du cours d'eau. University of Lyon, France. <https://doi.org/10.13140/RG.2.2.10836.32643>. Ph.D. Dissertation.
- Bretschko, G., Klemens, W., 1986. Quantitative methods and aspects in the study of the interstitial fauna of running waters. *Stygologia*. 2:279-316.
- Brousse, G., Liébault, F., Arnaud-Fassetta, G., Vázquez-Tarrío, D., 2018. Experimental bed active-layer survey with active RFID scour chains: Example of two braided rivers (the Drac and the Vénéon) in the French Alps. *E3S Web of Conferences* 40:04016. DOI :10.1051/e3sconf/20184004016.
- Brunke, M., 1999. Colmation and depth filtration within streambeds: retention of particles in hyporheic interstices. *Int. Rev. Hydrobiol.* 84:99-117.
- Brunke, M., Gonser, T., 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* 37:1-33.
- Buffington, J.M., 1996. An alternative method for determining subsurface grain size distributions of gravel-bedded river. American Geophysical Union 1996 Fall Meeting, supplement to EOS. *AGU Trans.* 77 (46).
- Bulteau, T., Batalla, R.J., Chapron, E., Valette, P., Piégay, H., 2022. Geomorphic effects of a run-of-the-river dam in a multi-driver context: The case of the Upper Garonne (Central Pyrenees). *Geomorphology* 408:108243. DOI: 10.1016/j.geomorph.2022.108243.
- Bunte, K., Abt, S., 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics and streambed monitoring. In: General Technical Report RMRS-GTR-74. U.S. Department of agriculture, Forest service, Rocky mountain research station, Fort Collins, CO, 428 p.
- Caissie, D., 2006. The thermal regime of rivers: a review. *Journal of Freshwater Biology* 51: 1389–1406. DOI: 10.1111/j.1365-2427.2006.01597.x.
- Collins, A. L., Zhang, Y., 2016. Exceedance of modern 'background' fine-grained sediment delivery to rivers due to current agricultural land use and uptake of water pollution mitigation options across England and Wales. *Environmental Science & Policy* 61:61–73. DOI: 10.1016/j.envsci.2016.03.017.
- Coulombe-Pontbriand, M., Lapointe, M., 2004. Geomorphic controls riffle substrate quality, and spawning site selection in two semi-alluvial salmon rivers in the Gaspé Peninsula, Canada. *River Res Appl* 20:577-590. DOI: 10.1002/rra.768.

Descloux, S., 2011. Le colmatage minéral du lit des cours d'eau: méthode d'estimation et effets sur la composition et la structure des communautés d'invertébrés benthiques et hyporhéiques. University of Lyon. France. Ph.D. Dissertation.

Descloux, S., Datry, T., Philippe, M., Marmonier, P., 2010. Comparison of different techniques to assess surface and subsurface streambed colmation with fine sediments. *International review of Hydrobiology* 95: 520-540. DOI: 10.1002/iroh.201011250.

Dugdale, S.J., 2016. A practitioner's guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations. *Wiley Interdisciplinary Reviews: Water* 3(2): 251–268. DOI: 10.1002/wat2.1135.

Evans, E., Wilcox, C., 2014. Fine sediment infiltration dynamics in a gravel-bed river following a sediment pulse. *River Res. Applic.* 30: 372–384. DOI: 10.1002/rra.2647.

Gayraud, S., Herouin, E., Philippe, M., 2002. Colmatage minéral du lit des cours d'eau: revue bibliographique des mécanismes et des conséquences sur les habitats et les peuplements de macroinvertébrés. - *Bull. Fr. Pêche Piscic.* 365/366:339-355.

Gayraud, S., Philippe, M., 2003. Influence of bed-sediment features on the interstitial habitat available for macroinvertebrates in 15 French streams. *International Review of Hydrobiology* 88(1): 77-93. DOI: 10.1002/iroh.200390007.

Greig, S.M., Sear, D.A., Carling, P.A., 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny : Implications for sediment management. *Sci Tot Env* 344: 241-258.

Hedrick, L. B., Welsh, S. A., Anderson, J. T., 2007. Effects of Highway Construction on Sediment and Benthic Macroinvertebrates in Two Tributaries of the Lost River, West Virginia, *Journal of Freshwater Ecology*, 22(4): 561-569. DOI: 10.1080/02705060.2007.9664817.

Hockey J. B., Owens I. F., Tapper N. J., 1982. Empirical and theoretical models to isolate the effect of discharge on summer water temperatures in the Hurunui River. *Journal of Hydrology (New Zealand)*, 21: 1–12.

Killick, R., Beaulieu, C., Taylor, S., Hullait, H., 2021. EnvCpt: Detection of Structural Changes in Climate and Environment Time Series year. R package version 1.1.3.

Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2 : 256–280. DOI : 10.1002/2013EF000184.

Lambert, C.P., Walling, D.E., 1988. Measurement of channel storage of suspended sediment in a gravel-bed river. *Catena* 15:65-80. DOI: 10.1016/0341-8162(88)90017-3.

Loire, R., Piégay, H., Malavoi, J-R., Beche, L. A., Dumoutier, Q., Mosseri, J., Kerjean, C., 2019. Unclogging improvement based on interdate and interreach comparison of water release monitoring (Durance, France). *River Res Appl* 35(8) :1107-1118. DOI: 10.1002/rra.3489.

Loire, R., Piégay, H., Malavoi, J-R., Kondolf, G. M, Bèche, L. A., 2021. From flushing flows to (eco)morphogenic releases: evolving terminology, practice, and integration into river management. *Earth-Science Reviews* 213: 103475. DOI: 10.1016/j.earscirev.2020.103475.

López-Tarazón JA, Batalla RJ, Vericat D (2011) In-channel sediment storage in a highly erodible catchment: the River Isábena (Ebro Basin, Southern Pyrenees). *Z Geomorphol* 55(3):365–382. DOI :10.1127/0372-8854/2011/0045.

MacDonald, D. D., McDonald, L. E., 1987. The influence of surface coal mining on potential Salmonid habitat in the Fording River, British Columbia. *Water Quality Research Journal* 22(4): 584-595. DOI: 10.2166/wqrj.1987.047.

Marteau, B., Batalla, R.J., Vericat, D., Gibbins, C., 2018. Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river. *J Soils Sediments* 18(7): 2614-2633. DOI : 10.1007/s11368-017-1911-1.

Marteau, B., Michel, K., Piégay, H., 2022. Can gravel augmentation restore thermal functions in gravel-bed rivers? A need to assess success within a trajectory-based before–after control–impact framework. *Hydrol. Process.* 36(2). DOI :10.1002/hyp.14480.

Marteau, B., Chandresris, A., Michel, K., Vaudor, L., Piégay, H. 2022. Riparian shading mitigates water warming but cannot revert thermal alteration in lowland rivers. *Earth Surface Processes and Landforms* 47(9): 2209-2229. DOI: 10.1002/esp.5372.

McNeil, W.J., Ahnell, W.H., 1964. Success of Pink Salmon spawning relative to size of spawning bed material. United States Fish and Wildlife Service, Special Scientific Report-Fisheries No. 469.

Misset, C., Recking, A., Legout, C., Viana-Bandeira, B., Poirel, A., 2021. Assessment of fine sediment river bed stocks in seven Alpine catchments. *Catena* 196:104916. DOI:10.1016/j.catena.2020.104916.

Morris, G.L., Annandale, G., Hotchkiss, R., 2008. Reservoir Sedimentation. In *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*; Am Soc of Civil Engineers: Reston, VA, USA: 579–612.

Noack, M., 2021. Clogging of Riverbeds – from Complex Field Conditions to Isolated Processes in the Laboratory. *Publications of the Institute, Polish Academy of Sciences* 434(E-11):21-23. DOI: 10.25171/InstGeoph_PAS_Publs-2021-009.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., Trustrum, N.A., 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Res Appl* 21(7):693–717. DOI: 10.1002/rra.878.

Packman, A.I., MacKay, J.S., 2003. Interplay of stream-subsurface exchange, clay particle deposition, and streambed evolution. *Water Res Research* 39(4):1097. DOI: 10.1029/2002WR001432.

Piqué, G., López-Tarazón, J.A., Batalla, R.J., 2014. Variability of in-channel sediment storage in a river draining highly erodible areas (the Isábena, Ebro Basin). *J Soils Sediments* 14: 2031–2044. DOI: 10.1007/s11368-014-0957-6.

Poole GC. 2010. Stream hydrogeomorphology as a physical science basis for advances in stream ecology. *J North Am Benthol Soc* 29(1):12–25. DOI: 10.1899/08-070.1.

Raus, D., Moulin, F., Eiff, O., 2019. The impact of coarse-grain protrusion on near-bed hydrodynamics. *J. Geophysical Research: Earth Surface, Am. Geophysical Union* 124(7) : 1854-1877. DOI: 10.1029/2018JF004751.

Recking, A., 2016. A generalized threshold model for computing bed load grain-size distribution. *Water Resour. Res.* 52(12), 9274–9289. DOI: 10.1002/2016WR018735.

Rex, J.F, Petticrew, E.L., 2011. Fine Sediment Deposition at Forest Road Crossings: An Overview and Effective Monitoring Protocol. In: Manning, A., 2011. *Sediment transport in aquatic environments*. IntechOpen, ISBN 9789535149224, 348 pp.

- Rice, S., Church, M., 1998. Grain-size along two gravel bed river: statistical variations, spatial patterns and sedimentary links. *Earth Surf. Process. Landf.* 23, 345–363. DOI: 10.1002/(SICI)1096-9837(199804)23:4<345::AID-ESP850>3.0.CO;2-B.
- Roux, C., Alber, A., Bertrand, M., Vaudor, L., Piégay, H., 2015. "Fluvial Corridor" : a new ArcGis Toolbox Package for multiscale riverscape exploration. *Geomorphology* 242:29-37. DOI: 10.1016/j.geomorph.2014.04.018.
- Ryan, R.J., Packman, A.I., 2006. Changes in streambed sediment characteristics and solute transport in the headwaters of Valley Creek, an urbanized watershed. *Journal of Hydrology* 323: 74-91. DOI: 10.1016/j.jhydrol.2005.06.042.
- Schälchli, U., 1992. The clogging of coarse gravel river beds by fine sediment. *Hydrobiologia* 235/236: 189-197.
- Seitz, L., 2020. Development of new methods to apply a multi-parameter approach – A first step towards the determination of colmation. University of Stuttgart. Germany. Ph. D. Dissertation.
- Sinokrot B. A., Gulliver J. S., 2000. In-stream flow impact on river water temperatures. *Journal of Hydraulic Research* 38: 339–349.
- Soulsby, C., Youngson, A. F., Moir, H. J., Malcolm, I. A., 2001. Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. *Sci Tot Env* 265: 295-307.
- Staudt, F., Mullarney, J.C., Pilditch, C.A., Huhn, K., 2017. The rôle of grain-size ratio in the mobility of mixed granular beds. *Geomorphology* 278: 314-328. DOI: 10.1016/j.geomorph.2016.11.015.
- Torgersen, C.E., Ebersole, J.L., Keenan, D.M., 2012. Primer for identifying cold-water refuges to protect and restore thermal diversity in riverine landscapes. EPA scientific guidance handbook (February): 91p. DOI: EPA 910-c-12-001.
- UWITECH, 2014. Carottage cryogénique 2014. EDF R&D. Technical report. 4 p.
- Vázquez-Tarrío, D., Fernández-Iglesias, E., Fernández García, Marquínez, J., 2019. Quantifying the Variability in Flow Competence and Streambed Mobility with Water Discharge in a Gravel-Bed Channel: River Esla, NW Spain. *Water* 11, 2662. DOI: 10.3390/w11122662.
- Walling, D.E., Moorehead, P.W., 1989. The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiologia* 176/177: 125-149.
- Wang, H.W., Kondolf, G.M., 2014. Upstream sediment-control dams: Five decades of experience in the rapidly-eroding Dahan River Basin, Taiwan, *J. Am. Water Resour. Assoc.* DOI: 10.1111/jawr.12141.
- Wharton, G., Mohajeri, S. H., Righetti, M., 2017. The pernicious problem of streambed colmation: a multi-disciplinary reflection on the mechanisms, causes, impacts, and management challenges. *WIREs Water* 4(5): e1231. DOI: 10.1002/wat2.1231.
- Wawrzyniak, V., Piégay, H., Allemand, P., Vaudor, L., Goma, R., Grandjean, P., 2016. Effects of geomorphology and groundwater level on the spatio-temporal variability of riverine cold water patches assessed using thermal infrared (TIR) remote sensing. *Remote Sensing of Environment* 175: 337–348. DOI: 10.1016/j.rse.2015.12.050.
- Wolman, M.G., 1954. A method of sampling coarse river bed material. *Trans. Am. Geophys. Union* 35 (6), 951–956. DOI: 10.1029/TR035i006p00951.
- Wood, P.J., Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. *Environ Manag* 21(2):203–217. DOI: 10.1007/s002679900019.

CHAPTER 5. Synthesis and discussion

5.1. Research context and approaches

The work conducted during this PhD aimed at characterising the hydrological, sedimentary and morphological dynamics of the Upper Garonne, and their interactions with human activities, with focussed attention given to the Plan d’Arem dam management.

The crucial role of a robust diagnosis in providing baseline data and analytical references prior to implementing restoration actions that improve bio-geomorphic functioning of a fluvial reach is well-recognised (Downs et al., 2011; Rollet et al., 2013; Downs & Piégay, 2019). Achieving such diagnosis is however a real challenge where heterogeneous morphological contexts and multiple anthropisation factors overlap and make the attribution of one degradation to one factor more complex (Vázquez-Tarrío *et al.*, 2022b). Along the Upper Garonne reach, the variability of morphological contexts tied with the large reduction of slope gradient downward, as well as the multiplicity of drivers, provided a very good field for scientifically exploring how to achieve multi-scale diagnosis that allow for the design of restoration actions.

Midway from the Garonne source and the confluence with the Neste River is located the Plan d’Arem run-of-river dam. After the reservoir has experienced intense siltation and almost complete sediment filling, drawdown flushing actions have restored some sediment transport through the dam. Here again, very few references are available on the effects of RoR dams on hydro-sedimentary dynamics (Csiki and Rhoades, 2010, 2014; Ibisate et al., 2013), and most of the studies have addressed this aspect remotely (Dépret et al., 2019; Vázquez-Tarrío *et al.*, 2022a), making the case-study of the Upper Garonne unique in this domain. Various aspects of dam-to-river relationships were explored, either morphological response to varying management strategies (Chapter 2), effects of the dam on downstream bedload dynamics (Chapter 3), and fine sediment interstitial storage response to drawdown flushing actions (Chapter 4). Our results considerably increase the knowledge base on the Plan d’Arem dam, and we argue that some of the methods we applied are transposable in other contexts or for studies focussing on evaluating RoR dam effects.

This PhD has also been the place for some methodological developments. First, and in response to the recent call for a shift from inductive to deductive reasoning (Dépret et al., 2021; Vázquez-Tarrío *et al.*, 2022b), we attempted in this study to rigorously apply hypothesis-driven approaches in assessing causal connections over a broad range of spatial and temporal scales. More on a data acquisition aspect, we introduced some novelty in the bedload flux quantification and the assessment of riverbed clogging. In investigating the former, we applied the virtual velocity method

with time-integration of mass fractional transport rates, as proposed by Wilcock (1997) and more recently improved by Italian geomorphologists (Mao et al., 2017; Brenna et al., 2019, 2020; Brenna & Surian, 2023). We tried to simplify its application using a discharge-based calibration of the GTM model (Recking, 2016). Measurement of active layer thickness also relied on the use of columns of tracers equipped with active RFID tags, a method that has only recently been developed and still unpublished at the time of writing (Brousse et al., 2018; Boutault, 2020). Furthermore, we developed a new methodology for assessing riverbed clogging, relying from one side on the in-situ quantification of fine sediment amount within the bed matrix (i.e. providing fundamental information on the nature of fine sediments that may induce clogging), and from the other on the acquisition of temperature data (i.e. allowing to approach clogging dynamics from a process perspective based on surface and subsurface water fluxes and interaction).

According to the quantification of hydro-sedimentary process degradations and their adverse effects on river geomorphic functioning, the work conducted in this PhD constitutes the baseline for further river management orientations. In the following sections, we summarise main scientific outcomes from the study, and after some complementary data exploration, propose practical recommendations for river managers.

5.2. Main scientific outcomes of the research

The Upper Garonne is a responsive mountain river reach which adjusted its morphology differently according to (1) its initial potential and (2) nature and intensity of human disturbances, through planform simplification, bed incision, and sediment coarsening.

Before the intensification of catchment and river anthropisation in the second half of the 20th century (i.e. before headwater dams construction, *pre-1955*), the entire study reach was already experiencing a first reduction phase of hydro-sedimentary fluxes associated with catchment-scale land-use changes (i.e. afforestation), modification of agricultural practices (i.e. grazing abandonment), and climate change (i.e. post-LIA decrease in annual precipitations), similarly to most East-European mountain catchment within this period (Liébault & Piégay, 2002; Marchese et al., 2017). In response, the channel simplified according to its initial characteristics. Upstream Vielha, the channel, that exhibited a wandering channel morphology and local braiding, narrowed. From Vielha to the confluence with the Pique River, the channel showed somewhat a lower response due to lower potential to adjust (i.e. channel laterally confined due to geological features). Downstream from the confluence, the channel, that formerly presented riffle-pool morphology and

locally multiple-channel pattern, narrowed as a consequence of the disconnection of secondary channels. At the end of this period, the potential of the channel for lateral adjustment was rather attained at the lowermost reach, whereas upstream reaches still presented rooms for vegetation encroachment and further adjustment.

Headwater dams and water diversion network (1955 – 1965) triggered a second phase of hydro-sedimentary flux reduction that cumulated with the effects of catchment-scale changes and exacerbated channel narrowing rates upstream from the Plan d'Arem dam. This reach then continuously narrowed until the 1990's, afterward few changes were observed until the 2013-flood. Conversely, downstream reaches exhibited lower response to damming, due to (1) restored flood hydrology downstream of the diversion network and (2) initially lower adjustment potential.

Downstream from the Plan d'Arem dam (i.e. by-passed reach), the channel width remained stable for approximately 15 years after dam and diversion scheme completion (1970), afterward it narrowed until the 2013 flood.

In general, the flood of the 18th June 2013 resulted in resetting the system to pre-degraded conditions. Again, morphological response to the flood, as well as temporality of post-flood adjustments, differ greatly between reaches.

Most intense adjustments were observed upstream from the Plan d'Arem dam, where channel morphology recovered 1940-like features. Nevertheless, post-flood benefits were partially lost, due to intense post-flood river training works and the post-flood lack of change of dams' and catchment management practices. The by-passed reach, that also importantly widened, experienced otherwise post-flood adjustments, there consisting in channel stability and even widening because of (1) preserved natural flood hydrology and (2) partially restored sediment supply following the changes in Plan d'Arem dam management, which allowed for (3) post-flood lateral migration processes to be maintained. Finally, the most downstream reach responded less intensively to the flood than the upper ones. Despite its exceptional magnitude, formerly terrestrialised secondary channels did not re-open because of major bed incision, a result supporting previous research on the inability of large floods to restore side channels under very incised contexts (Arnaud et al., 2015; Eschbach et al., 2021). However river bank erosion triggered by the flood is still active, and no major changes in channel width were observed since then.

Current bedload transport regime well reflects this complex and reach-specific evolution. Bedload transport measurement is a promising complementary field research strategy that helps in achieving robust river diagnosis.

Channel characteristics play major role on bedload transport mechanisms, especially grain size distribution which exerts a direct control on (1) the depth over which the bed scours and (2) the proportion of mobile clasts. Past and on-going sediment supply control overall bedload rates, and water diversion then plays a modulatory role. The upper reach (RK0 – RK40) is nowadays affected by a long-term and structural sediment deficit, which coupled with the permanency of water diversion, lead to largely reduced bedload (22 – 128 mm) transport rates, which approximated $100 \text{ m}^3 \text{ yr}^{-1}$ during the study period (S0-S3, see Chapter 3). If we may expect that transport rates downstream of the Plan d’Arem dam were in the same order of magnitude before the 2013-flood, intermittent supply and preserved flood hydrology due to flushing actions seem to have maintained post-flood conditions. Bedload rates then show important increase downward, reaching approximately $1100 \text{ m}^3 \text{ yr}^{-1}$ (during S0-S3, $400 \text{ m}^3 \text{ yr}^{-1}$ when calculated over the entire study period, i.e. S0-S6, see Chapter 3) in the by-passed reach, and $1400 \text{ m}^3 \text{ yr}^{-1}$ (during S0-S3, $700 \text{ m}^3 \text{ yr}^{-1}$ when calculated over the entire study period, i.e. S0-S6, see Chapter 3) downstream of the restitution.

Combination of sediment sampling and airborne temperature data acquisition allowed to characterise the potential role of the Plan d’Arem dam in inducing riverbed clogging downstream.

Examination of longitudinal pattern of fine sediment interstitial storage indicated that both by-passed reaches, upstream and downstream from the Plan d’Arem dam, present significantly a higher proportion of fine sediments within the bed matrix. Such enrichment has been attributed to decreased transport capacity due to water diversion and coarser grain size context. As so-called ‘fines’ on the Upper Garonne is mostly constituted by sandy granular material, we observed fines do not prevent hyporheic exchanges. Temperature longitudinal pattern seems more controlled by valley morphology (i.e. valley width, transverse structures), and the highest density of cold-water patches was observed in the by-passed reach of the Plan d’Arem dam, due to well-developed riffle-pool morphology and mobile bedforms. When operated under current parameters (i.e. lake-level lowering to $573.5 \pm 0.5 \text{ m a.s.l.}$; nominal elevation is 577.5 m a.s.l.), drawdown flushing actions do not induce riverbed clogging downstream the dam.

RoR dam adverse effects can be significantly reduced if the size of the reservoir allows for lake-level lowering and critical slope restoration during floods (see Section 5.3).

Because they have a water storage capacity representing typically less than few days of average runoff, and if equipped with bottom gates, small dams can be emptied during frequent floods without unsafely increasing flood peaks (Kondolf et al., 2014). Under such conditions, some of the input and stored sediments can also be routed through the dam, including coarse bedload fractions (sands and coarser). On the Upper Garonne, the Plan d'Arem dam has seen its water storage capacity preserved since drawdown flushing actions started. Furthermore, the reach downstream the dam is nowadays the most active and functional reach amongst the study reach, either morphologically (Chapter 2), thermally (Chapter 4), and biologically (Duclos, 2018).

Therefore, when possible, drawdown flushing actions is probably the most desirable choice for dams management as it combines multiple benefits, including (1) an extended life for reservoirs (Morris & Fan, 1998), (2) lessened sediment starvation effects downstream of the dam (Kondolf et al., 2014), and this for (3) a financial cost that, even being sometimes substantially high, only corresponds to production losses at the time flushing actions are performed (Loire et al., 2021), and has to be put into perspective with the cost for restoration of dam-induced degradations (Jacobson & Berkley, 2011).

Feedbacks on the Hypothesis-Driven Methodology

In assessing the Upper Garonne hydro-sedimentary dynamics over multiple spatial and temporal scales, we have been particularly focusing on how to rigorously apply hypothetico-deductive approaches, and how such approach can be supported by *Control-Impact* sampling strategies. If such research design is a basic pre-requisite in some other hard sciences, its application in fluvial geomorphology is still very recent (Vázquez-Tarrió *et al.*, 2022b, Boutault *et al.*, in prep), justifying for some feedbacks on conceptual and methodological implications.

Within fluvial anthroposystems, ecosystem services made by functional river corridors to human societies are considered against a background in which human activities have modified the hydrosystems such profoundly that anthropisation can not be considered an external factor any more (Piégay, 2016). From a river restoration perspective, the restoration of pre-degradation (i.e. pre-industrialisation) conditions is not only a very difficult objective to achieve since very few data are available to characterise such conditions, but is also an overall lack of meaning as it disregards the natural evolution of fluvial systems implying the impossibility to return to past conditions, as well as the multiple activities that have settled along and controlled rivers. More from an epistemological view, returning to 'past pristine conditions' implicitly assumes that anthropisation

fundamentally leads to dysfunctional hydrosystems whereas biological communities have adapted and reached new equilibrium that is sometimes functional. Furthermore, such conditions may have to be artificially maintained (Dufour & Piégay, 2009). Within this scope, river diagnosis and ensuing actions have to be conducted with the objective of achieving a functional trajectory, characterised by dynamism and complexity, that ensures multiples functions and services, and which must be minimally perennial. Such actions then rely on the most precise understanding of causal connections between one factor and one response, as well as of the reaction and relaxation time to perturbation, and changes downstream propagation.

Conceptually, the need to promote deductive approaches has emerged as a potential solution to give robustness to assessments of unit effects of a given factor on a given dynamics in contexts where the multiplicity of factors is such that inductive approaches leave open the door for expert interpretation, likely to introduce confirmation bias in studies depending on the personal experience of the involved expert (Vázquez-Tarrío *et al.*, 2022b). The successive combination of inductive and deductive approaches therefore aims at further understanding causal connections and characterising morphological response kinetic. In a first step, the inductive approach allows for a pre-representation of the general geomorphic evolution of the river in response to cumulative anthropisation factors. At this stage, a set of potential drivers are identified, but their respective contribution has to be weighted if confirmed, or unvalidated. This is the role of the deductive approach. After such preliminary assessment, a set of hypotheses is defined on the respective role of each factor in the observed morphological response, together with a set of discriminatory criteria that must allow for validation, rejection, or relativisation of hypotheses. Such criteria may often take the form of ‘*If-Else*’ statements, and are supported by complementary data acquisition and processing, be they historical (e.g. digitalisation of channel components on aerial photographs at given key-dates) or original (e.g. bedload or grain size measurements, modelling, dating, etc). The deductive part of the diagnosis then allows to eliminate some factors from the general equation, and to sharpen the attribution of one morphological response to a reduced set of drivers, supported by an array of converging evidences.

It is within this framework that the *BACI* approach comes in. This method relies on the comparison of an *Impacted* condition with a *Control* one. This comparison can be conducted either spatially (i.e. upstream and downstream) and temporally (i.e. before and after) to discriminate the respective role of a given factor in affecting the river geomorphic evolution. The main issue there arising is in the definition of the ‘*Control*’. Contrarily to some other sciences, the historical branch of fluvial geomorphology relies on the re-interpretation of existing data, that may have been collected several decades before the diagnosis is conducted (e.g. water surface elevation profile,

aerial photographs), with a spatial and temporal resolution which may not match with the definition of an appropriate ‘*Control*’. For instance, in the Central Pyrenees, oldest aerial photographs often date back to the 1940’s, with only some short reaches covered since the 1920’s, whereas the period 1900-1940 has been the place for major hydroclimatic fluctuations and land use changes, likely to greatly influence the ‘*Control*’ conditions if taken from a static perspective. In the same vein, the natural variability inherent to fluvial system may also lead to considering a ‘*Control*’ that is strongly influenced by other factors (e.g. large flood occurring shortly before aerial photographs are taken). To overcome this difficulty, the *BACI* approach has to be applied from a trajectorial perspective, quantifying the deviation in the temporal trajectory of the ‘*Impacted*’ reach in comparison to the ‘*Control*’ reach, and assuming this deviation is the result of the considered factor (Marteau *et al.*, 2022).

Through multiple repetition of this deductive scheme, the river geomorphic evolution clarifies gradually with the elimination of potential drivers from the global equation. In fact, the hypothetico-deductive approach arguably allows to testify that a given factor is not involved in a given response, but can not certify that another factor is responsible for this response, and we may only say that this factor is the most probable. The deductive approach is then a kind of safeguard that aims at avoiding confirmation bias through the multiplication of arguments pointing toward a same direction.

5.3. Management perspectives (scenarios) and knowledge gaps

In the light of the results achieved during this PhD, we propose a few recommendations for river and dam management in an adaptative perspective. Such proposals are very preliminary, and a 6 months’ extra-work will be conducted from April to September 2023 after consultation of all involved actors.

Adaptative management is defined as a ‘*systematic process of continuous practices improvement*’ (Holling, 1978 ; Arnaud, 2012), within which post-action monitoring plays a crucial role in evaluating the efficiency of conducted actions to further revise and improve them. Implementing adaptative management relies on a four step framework that consecutively encompasses (1) a preliminary diagnosis to spatially and temporally assess river degradations, (2) the definition of pragmatic restoration objectives in line with the diagnosis, (3) the conduct of restoration actions in order to achieve the objectives, and (4) post-actions monitoring. Results from monitoring therefore provide important feedbacks and must allow to adjust each step of the previously described sequence (Fig. 5.1). Therefore, the actions proposed hereafter are accompanied by a monitoring proposals and potential adjustments depending on monitoring results.

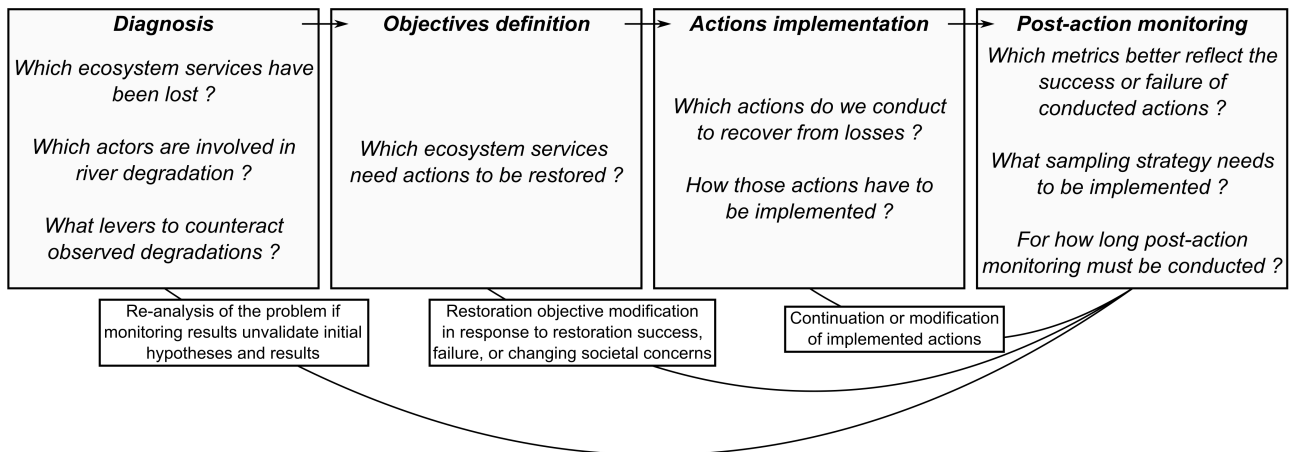


Figure 5.1. Adaptive management strategy with consecutive steps and feedbacks

One of the main concern arising from the diagnosis conducted during this PhD relates with the unbalanced rivers' hydrology, which is still relatively unaffected downstream from the set of dams, relatively to the structural sediment deficit observed on the upper catchment, a factor likely to aggravate the effects of such deficit. In order to preserve post-2013 flood habitat improvement, the main objective of future actions rely on the perennial management of punctual sediment sources. To achieve this objective, two main levers are identified. Actions, monitoring design and knowledge gaps are summarised at the end, in Fig 5.3.

Lever 1. Mitigating the effects of long-standing sediment deficit with sustainable management of existing sediment sources.

Along the Upper Garonne continuum, some sediments sources are still supplying the system, implying a principle of parsimony in the way they are solicited to avoid rapid dry up. The main objective of future sediment management is then to allow for a minimally functional flux to be maintained as a way to preserve associated ecosystem services, notably in terms of habitats. Proposals regarding sediment sources management are geographically described hereafter.

Sediment production upstream from the Plan d'Arem dam (Spain)

Upstream from the Plan d'Arem dam, torrential processes still constitute locally productive sediment sources. Four main un-dammed tributaries are identified as potential contributors (i.e. the Arriu Unhòla, the Arriu Nere, the Arriu Varradòs, and the Arriu Joèu), but there sedimentary activity has experienced considerable reduction since the second half of the 20th century (see Chapter 2). Therefore, a first recommendation is to avoid any sediment withdrawal from the catchment, in order

at least to preserve natural inputs. In the case punctual torrential processes threaten people and assets safety, it is important to consider re-injecting dredged material to the river system in the areas less sensitive to flood-risk.

The reach extending from Vielha (RK15.9) to the confluence with the Arriu Jocu (RK24.4) presents suitable characteristics for re-injection, since the river there is importantly incised and laterally confined. With an active channel area of nearly 13.5 ha, and considering re-injected volumes equal to the annual transport capacity ($\sim 700 \text{ m}^3$; see Chapter 3), bed elevation of this reach should theoretically raise by less than 1 cm.

Torrential material re-injection involve a set of complementary data acquisition to evaluate the perennality of this source and monitor the effects of re-injections. First, the torrential dynamics still have to be characterised. This characterisation may be conducted through topographical acquisitions that should provide general information on the sedimentary activity of these sources (i.e. sediment budget), and coupled with sediment tracing to more precisely evaluate sediment mobility and potential interactions between sediments and transverse structures. Geochemical analysis should also be conducted to ensure re-injected material is not contaminated, notably by heavy metals.

Secondly, to evaluate the effects of potential re-injections, a monitoring program has to be designed, and should involve the evaluation of (1) re-injected material mobility, (2) effects of re-injection of flood water levels, and (3) changes in bed composition (i.e. grain size, clogging).

In line with the principles of adaptative management, some modifications to re-injection modalities could be made on the basis of post-action monitoring results. Considering the large reduction in bedload transport capacities due to water diversion (see Chapter 3), the transport of re-injected material may be very limited with potential effects on flood water levels. Therefore, some modifications in upper dams management practices during floods may be considered, and could simply consist in defining threshold discharges over which water diversion has to be stopped in order to increase flow competence and assist sediment transport. Again, sediment mobility and flood water levels need monitoring to evaluate the effects of dam management modifications and feed the adaptative management strategy.

Sediments stored within the Plan d'Arem reservoir

The sediments stored within the tail of the Plan d'Arem reservoir constitute a potential source of readily available material to buffer the effects of the upper catchment sediment deficit. In order to evaluate this potential, some complementary data analysis were conducted.

A first analysis aimed at estimating the volume of coarse sediments stored within the tail, a crucial information for the assessment of the perennality of this source. To do so, existing bathymetric datasets were re-investigated. In a first step, we attempted to estimate the longitudinal limit between coarse and fine sediments on the basis of bed elevation longitudinal pattern comparison and freeze-core samples taken in 2014 before emergency dredging operations (Fig. 5.2.A). We then estimated this limit is located from 300 m to 600 m downstream from the reservoir entrance, depending on the considered period. In order to calculate volumes, we selected DEMs having the highest upward extent (i.e. 1997, 2007, 2018), and created DoDs from these DEMs. Sediment budget from DoDs allowed to estimate that around 24.000 m³ were stored between 1997 and 2007 within the 600 m downstream from the reservoir entrance, and that some more 30.000 m³ were stored within the uppermost 300 m between 2007 and 2018, bringing overall volume to around 54.000 m³ (~2600 m³ yr⁻¹). We acknowledge that such estimation has important uncertainties. The limit between coarse and fine sediments is obviously not so abrupt, as this deltaic deposit probably shows intercalation of silt-to-sand with sand-to-gravel layers along a given vertical profile (Morris & Fan, 1998). Similarly, sediment grain size exhibits important lateral variability, and field observations clearly indicated that margins show finer sedimentation dominated by sands. Finally, results from bedload tracing experiments allowed to estimate annual bedload rates close to 100 m³ yr⁻¹ for size-fractions 22-128 mm, whereas we calculated 2600 m³ yr⁻¹ from bathymetric datasets (all size fractions). We then propose to consider those 54 000 m³ as a maximum that also includes significant amount of silt, sand and fine gravel.

This volume of potentially available sediments has to be placed into perspective with sediment transport rates downstream the dam. Indeed, the by-passed reach is largely dependant from the reservoir supply, which results in a thin layer of mobile sediments underlaid by a coarse armoured layer, legacy from past sediment starvation. Under current dam management, this layer, although very mobile, seems to be perennially sustained by upstream supply. Considering annual bedload yield downstream the dam is in the order of 1000 m³ (see Chapter 3) and that post-2013 flood habitat conditions have improved and maintain 10 years after (see Chapter 2), one proposal could be to consider this 1000 m³ yr⁻¹ yield as a target for future dam management. In this perspective, the 54.000 m³ of sediments stored within the tail of the reservoir should allow for supplying the downstream reach for around 50 years.

In turn, a second important question arises in relation with the ability of drawdown flushing actions to convey sediments through the reservoir and the dam. To explore this question, data from sediment tracing were re-investigated, together with bathymetric datasets produced since 2014.

In order to estimate the transparency of the dam to coarse fractions, dam managers commissioned a private company to conduct a sediment tracing experiment. A total of 800 tracers, ranging from 32 mm to 176 mm, were injected upstream the dam, all along the reservoir continuum in October 2017. Tracer mobility was surveyed twice, in March 2018 (S1) after the dam operated one flushing action, and in April 2019 (S2), after a notably high-flow snow-melt period in spring 2018 during which the dam operated flushing actions four times (Fig. 5.2.C). After S2, a total of 92 different tracers were found downstream from the dam. Among them, 59 had already crossed after S1, and among those 59, 57 were injected in the vicinity (i.e. < 400 m) of the dam (i.e. only 2 tracers injected in the reservoir tail passed through the entire reservoir and the dam). Despite the very high frequency of flushing actions between S1 and S2, only 2 tracers found upstream the dam at S1 were relocated downstream at S2. Finally, after S2, among the 300 tracers injected in the reservoir tail, only 5 were found downstream from the dam. Those initial results seem to indicate rather contrasted efficiency of drawdown flushing actions in conveying coarse sediments downstream from the dam. Tracer behaviour highly depended on their initial location, the closest their position to the dam, the more efficient the transit is. The zone where the reservoir is the widest (i.e. from approximately 300 m upstream from the dam to the dam) exerts a significant effect on tracers' immobility. These results from sediment tracing need to be more profoundly described and interpreted, but such initial assessment already indicates partial efficiency of drawdown flushing to convey sediments. Main blockage lies on the reservoir planimetric V-shape which slows down sediment migration. The main practical issue here arising is then to increase the energy slope at the time flushing actions are performed to promote sediment transport within the accumulation zone and at the dam outlet. To do so, a better understanding of the sedimentary response to flushing actions is required. During flushing actions, bathymetric datasets indicate two main channels self-form within stored sediments. The longer one (~ 500 m from the point the reservoir starts to widen) runs along the left bank before turning southward to flow along the dam and reach the outlet. The shorter one directly flows eastward and reaches the dam outlet after a ~ 300 m run. Frequent channel avulsion occurs at a sub-year interval, according to the initial topography at the time flushing actions are performed. In order to maximise sediment transfer during flushing actions, we may then reasonably acknowledge that ensuring the perennality of the shorter flood channel (i.e. right-bank) is the best option since energy slope is necessarily higher for this channel than the other because of smaller length and fixed downstream conditions. Therefore, we investigated the vertical evolution of this channel and its relation with flushing actions.

Since flushing actions are operated, reservoir tail and right bank channel bed elevation longitudinally organise along four main zones: the free-flowing tail (0 – 350 m, $S = 0.003 \text{ m m}^{-1}$;

Fig. 5.2.B) for which flow velocity is still high, the dam-influenced tail (350 – 800 m, $S = 0.005 \text{ m m}^{-1}$) where flow velocity drastically decreases under the effect of the dam, the accumulation zone (800 – 1050 m, $S \sim 0 \text{ m m}^{-1}$), and the turbulent zone, corresponding to the last 80 m upstream from the dam for which sediments are profoundly scoured due to bottom gates operation. The dam-influenced tail presents relatively stable elevation during the period 2014 – 2022, which indicates that during flushing actions, the slope (i.e. 0.005 m m^{-1}) is sufficient to allow upstream supply to be conveyed downstream and not to accumulate within this zone. We may then propose to consider a minimum slope of 0.005 m m^{-1} from the reservoir tail to the dam as a target to optimise sediment transfer. Although the elevation longitudinal pattern is relatively stable since 2014, the accumulation zone appears importantly scoured on the bathymetry conducted in January 2018. The high-flow snow-melt period of spring 2018 has conducted to fill the right channel and restore pre-2018 conditions (i.e. preferential channel flowing leftward). Therefore, and although the right channel conveys sediments more efficiently than the other, its perenniality is very limited and should be improved. Current dam management during floods (Fig. 5.1.B) consists in lowering the lake level at $Z = 573.50 \text{ m a.s.l.}$ Under such conditions, the average slope from the reservoir tail to the dam is 0.003 m m^{-1} . In line with the idea of increasing this slope to 0.005 m.m^{-1} , the lake level has to be lowered at $Z = 571.50 \text{ m a.s.l.}$, two meters below current management (Fig. 5.2.B) to achieve long profile equilibrium.

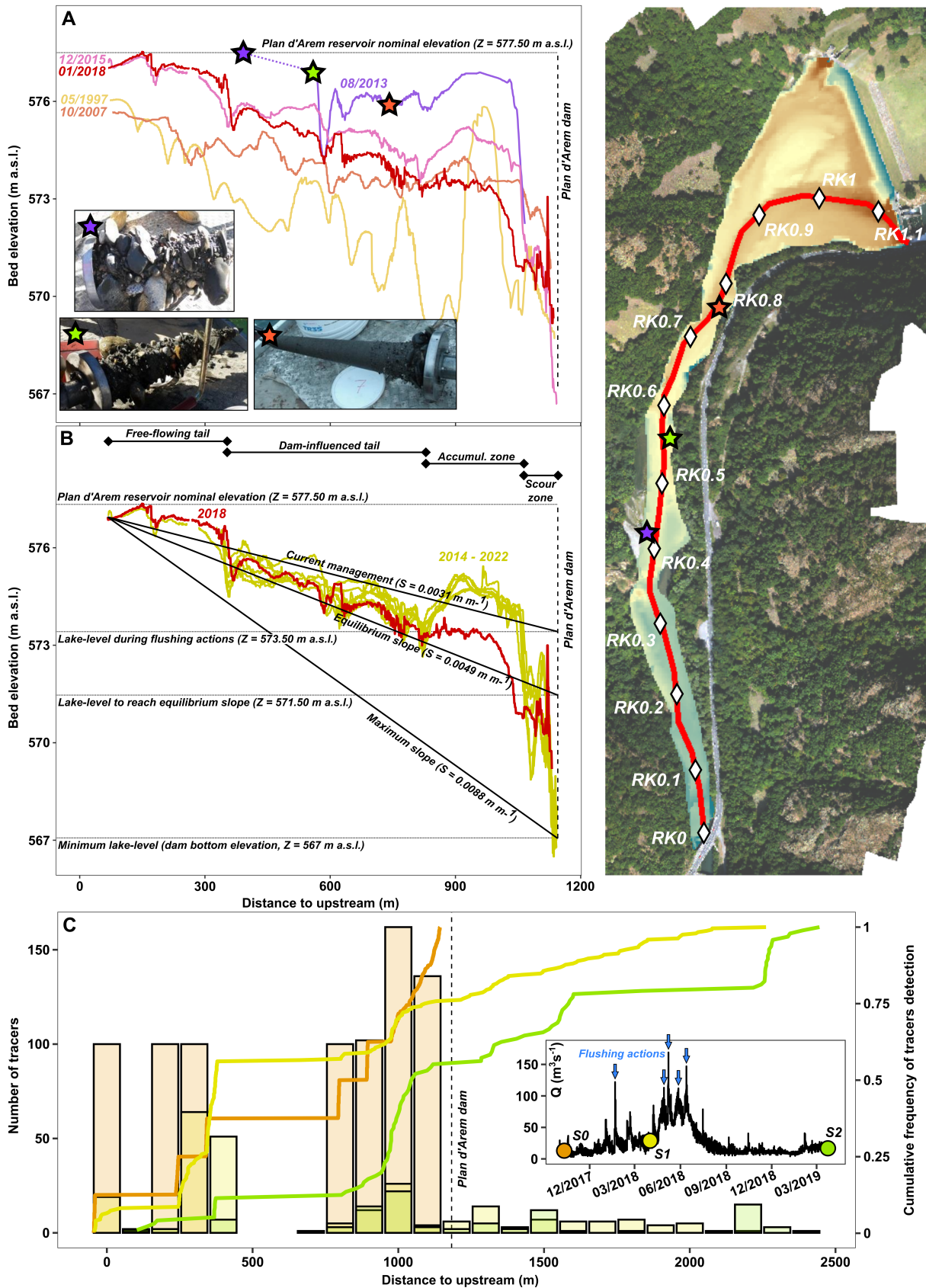


Figure 5.2. Characterisation of the sediment response to drawdown flushing actions. **A.** Longprofile evolution between 1997 and 2018. **B.** Longprofile adjustments to drawdown flushing actions from 2014 to 2022. **C.** Downstream propagation of tracers seeded within the reservoir.

Progressive transition from current to future dam management must take into account two important aspects of the Upper Garonne fluvial dynamics. From one side, sediments stored within the reservoir nowadays constitute a very precious source of material which must be parsimoniously managed to ensure sediment supply for as long as possible. From the other, if current management does not lead to riverbed clogging downstream, the effects of progressive lake-level lowering on the interstitial compartment can not be predicted. In the light of those considerations, such lowering has to be carried very progressively, for instance by 0.5 m steps, to avoid large release of fine sediments and rapid consumption of available stock. Moreover, progressive lowering could be considered in the light of flood hydrology, awaiting for moderate to large floods (e.g. $Q > 120 \text{ m}^3\text{s}^{-1}$) to move to the next step.

In theory, the progressive lowering of the reservoir level during floods should first release the fine sediments stored near to the dam, afterwards regressive erosion may allow to mobilise coarse grains from the tail. In order to spatially predict the size of the largest mobile clast, a preliminary work of hydro-sedimentary modelling was conducted by Meritxell Puig (research engineer, University of Lleida, Spain), using the IBER3D model. Under fixed topographic (bathymetry in July 2019), flow ($Q = 100 \text{ m}^3\text{s}^{-1}$), and dam management (lowering at $Z = 573.50 \text{ m}$ a.s.l.) conditions, various scenarios were tested. The first run considered the original bathymetry without any changes. Other scenarios considered a transverse structure under diverse positions and lengths at the reservoir entrance to concentrate the flow in the shorter (i.e. right-bank) channel. The results, presented in Appendix 5.1, indicate that under current conditions, the maximum mobile clast displays large spatial heterogeneity, with maximum values of nearly 20 mm at the lake entrance. The transverse structure virtually simulated has important effects on sediment mobility within the shorter channel, increasing the critical diameter to about 40 mm. We acknowledge that the construction of this structure is practically non-feasible, but this model tends to confirm the importance of preferentially maintaining the right channel in order to improve sediment conveyance through the reservoir.

Furthermore, the calibration of the model, as well as general Plan d'Arem dam management, would require further analyses of sediment grain size distribution within the reservoir. This aspect has also been investigated during the PhD, through geophysical measurements. In October 2019, an acquisition of high-resolution seismic reflection was conducted (Appendix 5.2), together with surface sediment sampling with Ekman sampler. Disappointingly, the organic-rich material deposited at the reservoir bottom thwarted the possibility to correctly map the different sediments layers, and thus to extrapolate the grain size of underlying sediments. A second acquisition using a Ground-Penetrating Radar from the boat was conducted in June 2021 in collaboration with the

University of Pau (France), in order to map the bedrock bottom. Again, the nature of the stored sediments, together with a reduced water column, do not allowed for significant improvement of our knowledge about the geometry of stored sediments (Appendix 5.3).

In terms of post-action monitoring, frequent bathymetric surveys have to be maintained, at least until the targetted equilibrium slope is attained, afterward survey frequency could be reduced. Dam management modifications also imply monitoring the effects of those modifications on river geomorphic conditions, including evolution of channel planforms, bed surface grain size, and interstitial fine sediment storage. In France, a set of new aerial photographs is nowadays produced every 3 to 5 years, allowing for rather fine characterisation of planform changes. In the case better precision is required, aerial photographs at intermediate dates can be acquired privately. Bed surface grain size and interstitial fine storage measurements should be conducted every year, on the minimal basis of two campaigns per year. The first campaign should be conducted at the end of winter (i.e. in February), and the second after snowmelt (i.e. in July). In the case the second campaign reveals important fine sediment enrichment within the bed matrix consecutively to flushing actions, another campaign should be conducted at the end of the autumn (i.e. in November) in order to assess the persistency of such enrichment and the risk of lithophilic fishes spawning gravels clogging.

Lever 2. Identification of other potential sediment sources, estimation of available stock, and characterisation of action levers to solicit these sources

Sediment sources described in Lever 1 are likely to diminish while being used. Furthermore, if such sources allow for rapid supply of reaches located in their immediate vicinity, most downstream reaches may benefit from this supply after a certain time only. For instance, the reach located downstream the confluence with the Pique River (RK55) may receive sediments from Plan d'Arem (RK40) after a 15 to 30 years delay, considering an average bedload migration of 500 to 1000 m yr⁻¹. Therefore, the contribution of complementary sediment sources is required in order to supplement uppermost sources starvation and smoothen the effects of discontinuous supply.

River lateral mobility downstream from the Plan d'Arem dam

Although lateral channel mobility cannot contribute to an overall increase in sediment supply in transport-limited regimes, it locally leads to the diversification of habitat mosaic and the furniture of spawning gravels.

From the Plan d'Arem dam to the confluence with the Neste River, we identified nearly 2 km of active eroded banks. Quantity of input sediments from this reach still have to be more finely

quantified, but we already estimated that left-bank erosion between RK51.7 and RK51.9 have supplied approximately 700 m³ of coarse material between July 2019 and March 2022, making bank erosion a potentially interesting lever of actions if eroded material do not redeposit immediately after erosion. Therefore, a better characterisation of bank erosion dynamics, both in terms of erosion and deposition rates should be achieved to quantitatively assess the potential of this source in buffering sediment deficit effects. If results confirm this source has an interesting potential, land acquisition and rip-raps removal may be considered, with some 30.7 km of river banks protected against lateral erosion by rip-raps downstream the Plan d'Arem dam. Such actions must be obviously conducted in the light of the associated risks, especially where rip-raps protect urban areas or industrial activities. Once land acquired, post-action monitoring may account for measurement of planforms changes and mobility of eroded material.

Sediments stored with Upper Pique basin check-dams

In this PhD, the role of the Pique River in the Garonne hydro-sedimentary dynamics has only been rapidly overviewed. This zone is particularly sensitive due to the presence of the Luchon urban areas. The sediment production of this catchment is still unknown while issues in check-dams management require for some sediment transport quantification and assessment of check-dams transparency. Hydrological, sedimentary and morphological effects of hydroelectric dams need to be evaluated. An integrated project of study and management of this river will be launched in 2024 to answer those questions, and together with the results of this PhD, should permit to go further in designing restoration actions. More generally, the Garonne management from the confluence with the Pique River and the confluence with the Neste River has to be considered under the perspective of downstream changes in hydro-sedimentary conditions, due to (1) the anthropisation of main Pyrenean tributaries (i.e. Neste, Salat, Ariège, and Hers Rivers), (2) multiple RoR damming (i.e. dams from St Gaudens to Toulouse), themselves affected by siltation, and overall (3) extremely severe sediment deficit in the area of Toulouse after gravel mining (Steiger *et al.*, 1998; Jantzi *et al.*, 2017).

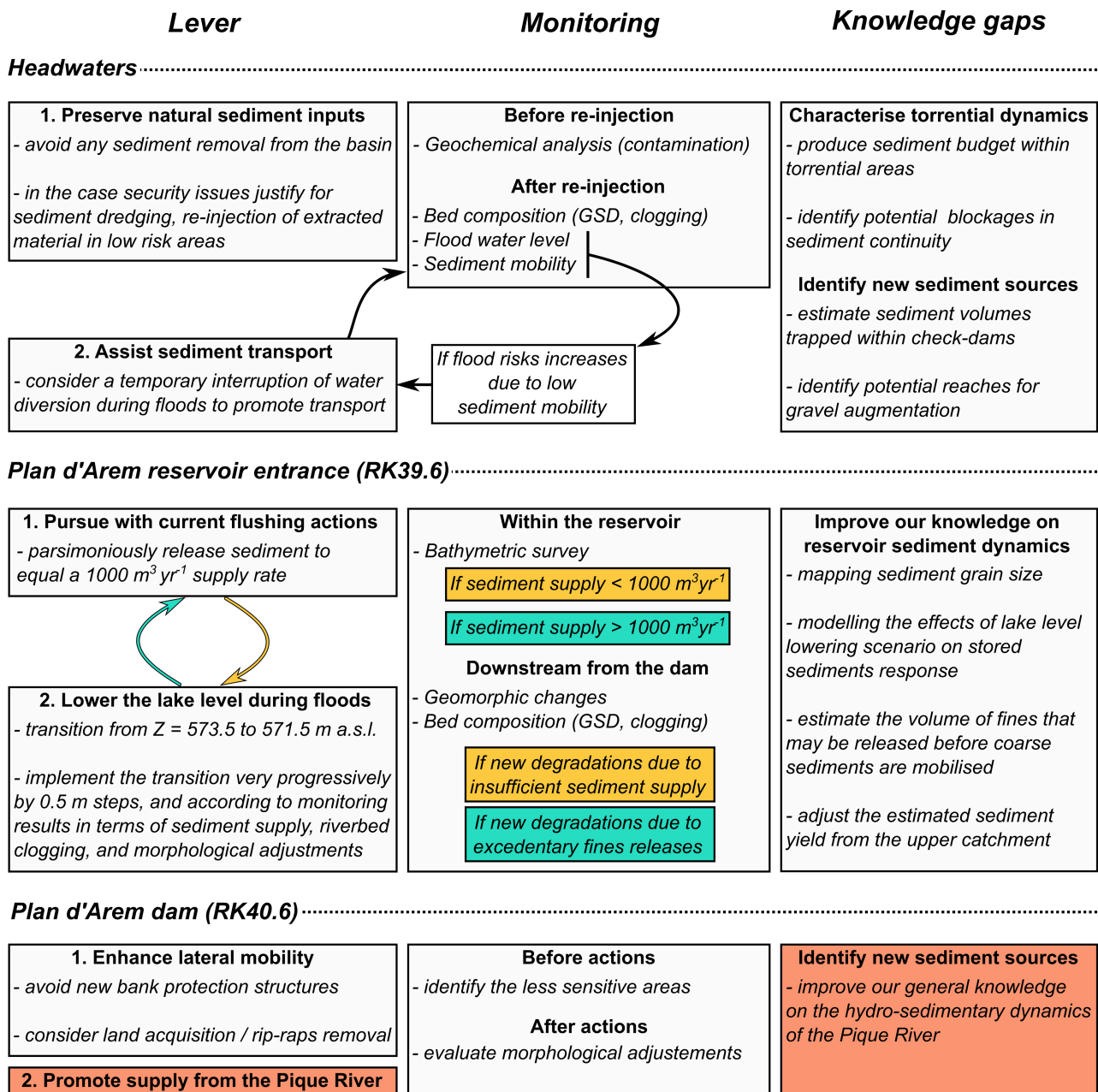


Figure 5.3. Summary of action levers, monitoring and knowledge gaps for Upper Garonne sustainable sediment management

5.5. References

- Arnaud, F., 2012. Approches géomorphologiques historique et expérimentale pour la restauration de la dynamique sédimentaire d'un tronçon fluvial aménagé: le cas du Vieux Rhin entre Kembs et Breisach (France, Allemagne). PhD Dissertation. University Lyon 2. 280 p.
- Arnaud, F., Piégay, H., Schmitt, L., Rollet, A.J., Ferrier, V., Béal, D., 2015. Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: the Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology*, 236: 163–177. DOI: 10.1016/j.geomorph.2015.02.009..
- Boutault, F., 2020. Etude de l'impact cumulé des facteurs d'anthropisation sur la Dordogne moyenne et préconisations en vue de la restauration écologique du cours d'eau. University of Lyon, France. DOI : 10.13140/RG.2.2.10836.32643. Ph.D. Dissertation.
- Boutault, F., Piégay, H., Bulteau, T., Lascaux, J.-M., in prep. Understanding drivers of change, a preliminary step to assess anthropised river responsiveness and recovery. The Middle Dordogne River, France. *Geomorphology*.
- Brenna, A., Surian, N., 2023. Coarse sediment mobility and fluxes in wide mountain streams: Insights using the virtual velocity approach. *Geomorphology*, 427: 108625. DOI: 10.1016/j.geomorph.2023.108625
- Brenna, A., Surian, N., Mao, L., 2019. Virtual velocity approach for estimating bed material transport in gravel-bed rivers: Key factors and significance. *Water Resources Research*, 55, 1651–1674. DOI: 10.1029/2018WR023556.
- Brenna, A., Surian, N., Mao, L., 2020. Response of A Gravel - Bed River To Dam Closure: Insights From Sediment Transport Processes And Channel Morphodynamics. *Earth Surface Processes and Landforms*, 45(3): 756-770. DOI: 10.1002/esp.4750.
- Brousse, G., Liébault, F., Arnaud-Fassetta, G., Vázquez-Tarrío, D., 2018. Experimental bed active-layer survey with active RFID scour chains: Example of two braided rivers (the Drac and the Vénéon) in the French Alps. *E3S Web of Conferences* 40:04016. DOI :10.1051/e3sconf/20184004016.
- Csiki, S., Rhoads, B.L., 2010. Hydraulic and geomorphological effects of run-of-river dams. *Prog. Phys. Geogr.*, 34(6): 755–780. DOI: 10.1016/j.geomorph.2013.10.009.
- Csiki, S., Rhoads, B.L., 2014. Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology*, 206: 215–229. DOI: 10.1177/0309133310369435.
- Dépret, T., Piégay, H., Dugué, V., Vaudor, L., Faure, J.-B., Le Coz, J., Camenen, B., 2019. Estimating and restoring bedload transport through a run-of-river reservoir. *Sci. Tot. Env.*, 654: 1146 – 1157. DOI: 10.1016/j.scitotenv.2018.11.177.
- Dépret, T., Virmoux, C., Gautier, E., Piégay, H., Doncheva, M., et al., 2021. Lowland gravel-bed river recovery through former mining reaches, the key role of sand. *Geomorphology*, 373: 107493. DOI: 10.1016/j.geomorph.2020.107493.
- Downs, P.W., Singer, M.S., Orr, B.K., Diggory, Z.E., Church, T.C., Stella, J.C., 2011. Restoring ecological integrity in highly regulated rivers: the role of baseline data and analytical references. *Environ. Manag.*, 48: 847–864.
- Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late "Anthropocene": implications, limitations, prospect. *Geomorphology*, 338: 88–104. DOI: 10.1016/j.geomorph.2019.03.021.

- Duclos, G., 2018. Mise à jour de l'inventaire des zones potentielles de frayères de Salmonidés sur la Garonne amont – Etat des lieux sur le transport solide et la recharge sédimentaire post crue 2018. FDAAPPMA31. MS thesis.
- Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration : forget natural references and focus on human benefits. *River Research and Applications*, 25 : 568-581. DOI : 10.1002/rra.1239
- Eschbach, D., Grussenmeyer, P., Koehl, M., Guillemin, S., Schmitt, L., 2021. Combining geodetic and geomorphic methods to monitor restored side channels: Feedback from the Upper Rhine. *Geomorphology*, 374: 107372. DOI: 10.1016/j.geomorph.2020.107372.
- Holling C. S., 1978. *Adaptive environmental assessment and management*. Wiley & Sons, New York, 377 p.
- Ibáñez, A., Diaz, E., Ollero, A., Acín, V., Granado, D., 2013. Channel response to multiple damming in a meandering river, middle and lower Aragon River (Spain). *Hydrobiologia*, 712: 5–23. DOI: 10.1007/s10750-013-1490-0.
- Jacobson, R.B., Berkley, J., 2011. Conceptualizing and communicating ecological river restoration. In: Simon, A., Bennet, S., Castro, J. (Eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses and Tools: AGU Geophysical Monograph*, vol. 194, pp. 9–28.
- Jantzi, H., Carozza, J.-M., Probst, J.-L., Valette, R., 2017. Les extractions de granulats dans le lit mineur de la moyenne Garonne toulousaine durant la seconde moitié du XX^e siècle. *Sud Ouest Européen*, 44: 83-96. DOI: 10.4000/soe.3418ff.
- Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2 : 256–280. DOI : 10.1002/2013EF000184.
- Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and Piedmont Rivers and streams of Southeastern France. *Earth Surf. Process. Landf.* 27, 425–444. DOI: 10.1002/esp.328.
- Loire, R., Piégay, H., Malavoi, J.-R., Kondolf, G. M., Bèche, L. A., 2021. From flushing flows to (eco)morphogenic releases: evolving terminology, practice, and integration into river management. *Earth-Science Reviews* 213: 103475. DOI: 10.1016/j.earscirev.2020.103475.
- Mao, L., Picco, L., Lenzi, M. A., Surian, N., 2017. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. *Earth Surface Processes and Landforms*, 42(4): 595–611. DOI: 10.1002/esp.4000
- Marchese, E., Scorpio, V., Fuller, I., McColl, S., Comiti, F., 2017. Morphological changes in Alpine rivers following the end of the Little Ice Age. *Geomorphology* 295, 811–826. DOI: 10.1016/j.geomorph.2017.07.018.
- Marteau, B., Michel, K., Piégay, H., 2022. Can gravel augmentation restore thermal functions in gravel-bed rivers? A need to assess success within a trajectory-based before–after control–impact framework. *Hydrol. Process.* 36(2). DOI :10.1002/hyp.14480.
- Morris, G.L., Fan, J., 1998. *Reservoir Sedimentation Handbook. Design and Management for Dams, Reservoirs, and Watershed for Sustainable Use*. McGraw-Hill Book Co., New York.
- Piégay, H., 2016. System approaches in fluvial geomorphology. In *Tools in Fluvial Geomorphology*. Eds. Kondolf, G.M. & Piégay, H., Wiley & Sons, New-York. 568 p.
- Recking, A., 2016. A generalized threshold model for computing bed load grain-size distribution. *Water Resour. Res.*, 52 (12): 9274–9289. DOI: 10.1002/2016WR018735.

Rollet, A.J., Piégay, H., Dufour, S., Bornette, G., Persat, H., 2013. 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. *River Res. Appl.*, 30: 939–953. DOI: 10.1002/rra.2689.

Steiger J., James M., Gazelle F., 1998. Channelization and Consequences on Floodplain System Functioning on the Garonne River, SW France. *Regulated Rivers*, 14: 13-23.

Vázquez-Tarrío, D., Tal, M., Parrot, E., Camenen, B., 2022a. Effects of continuous embankments and successive run-of-the-river dams on bedload transport capacities along the Rhône River, France. *Sci Total Environ.*, 658: 1375-1389. DOI: 10.1016/j.scitotenv.2018.12.109.

Vázquez-Tarrío, D., Tal, M., Parrot, E., Piégay, H., 2022b. Can we incorrectly link armouring to damming? A need to promote hypothesis-driven rather than expert-based approaches in fluvial geomorphology. *Geomorphology*, 413: 108364. DOI: 10.1016/j.geomorph.2022.108364.

Wilcock, P.R., 1997. Entrainment, displacement, and transport of tracer gravels. *Earth Surface Processes and Landforms*, 22: 1125–1138. DOI: 10.1002/(SICI)1096-9837(199712)22:12<1125::AID-ESP811>3.0.CO;2-V.

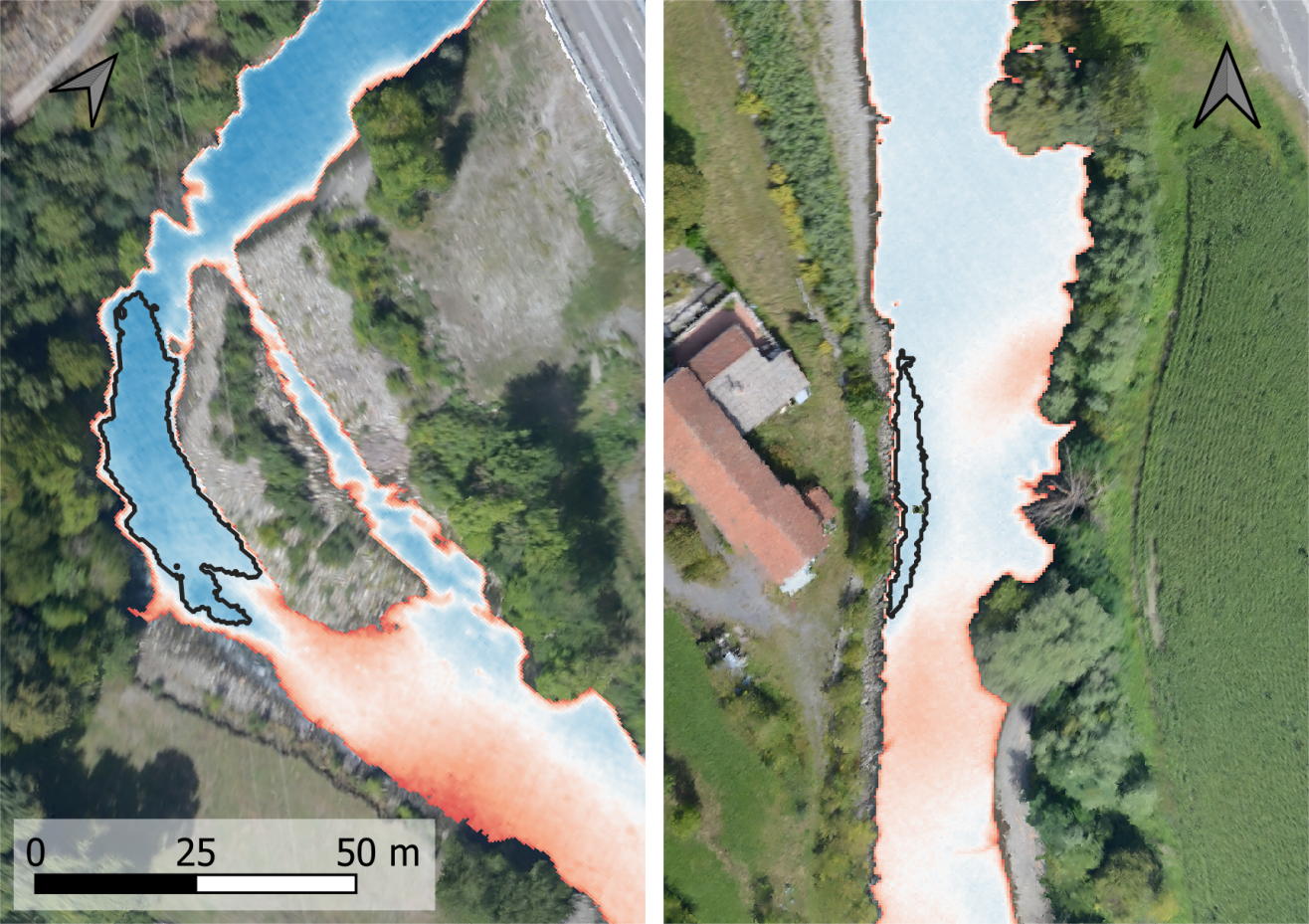
GENERAL CONCLUSION

The general objective of this PhD was to understand the multiple interactions between natural processes and anthropisation factors in affecting the hydro-sedimentary regime of the Upper Garonne. Methodologically, this study of fluvial geomorphology relied on the combination of historical and experimental approaches, both conducted under a hybrid reasoning between induction and deduction. This framework allowed for achieving a sufficient degree of understanding of involved geomorphic processes, and for providing some management guidelines that would help in preserving and improving the ecosystem services normally ensured by this fluvial anthroposystem.

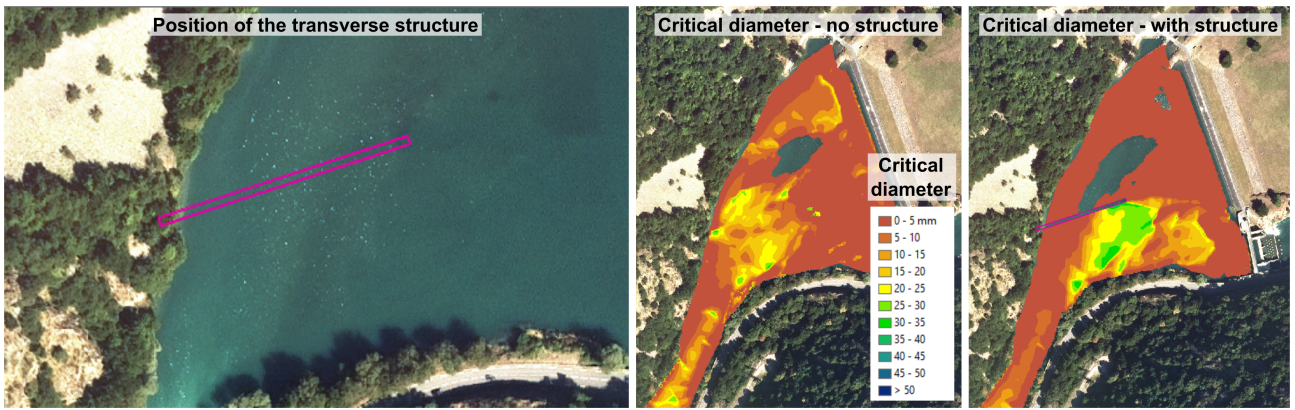
Over the 20th century, the Upper Garonne catchment has experienced multiple modifications which cumulated and conducted to a general reduction of sediment supply to the river system. Such reduction has been accompanied by increasing alteration of the flood regime due to dams construction and large water diversion, which decreased the transport capacity and contributed in reducing overall sediment supply. Downstream from the dams, the combination of limited sediment supply with rather undisturbed flood regime aggravated the effects of sediment deficit. In turn, the river system responded to these changes in hydro-sedimentary regime through multi-step adjustments, consisting in channel narrowing, bed incision and coarsening, and secondary channel abandonment. As a whole, these adjustments conducted to notable losses of ecosystem services (i.e. riparian, fishes, and macroinvertebrates habitats). In parallel, the Plan d'Arem dam experienced very rapid reduction of the reservoir water storage capacity due to sediment infilling, with important adverse effects on dam functions. In June 2013, a 100-year return period flood restored the system to 1940-like conditions, with significant improvement of habitat conditions. After the flood, changes in the Plan d'Arem dam management allowed for the conservation of these improvements, whereas the reach upstream rapidly returned to pre-flood degraded conditions.

In order to counteract the effects of the generalised sediment deficit, several levers of actions were identified. Main recommendation relies on the sustainable management of existing, and potentially rapidly mobilisable, sediment sources. Such management must be conducted under an adaptative management framework, in which feedbacks brought by post-action monitoring must help in evaluating past actions and sharpening future ones. Apart from the technical considerations for river restoration, we emphasize the pre-dominant role of an integrative transborder management of this fluvial reach. Indeed, if sediment inputs from the uppermost catchment are nowadays very reduced, this mountainous area is still punctually productive. Sediment management must then be considered in the light of reach specific issues, in order to find common ground and move forward with sustainable solutions matching the contrasted interests of multiple river actors.

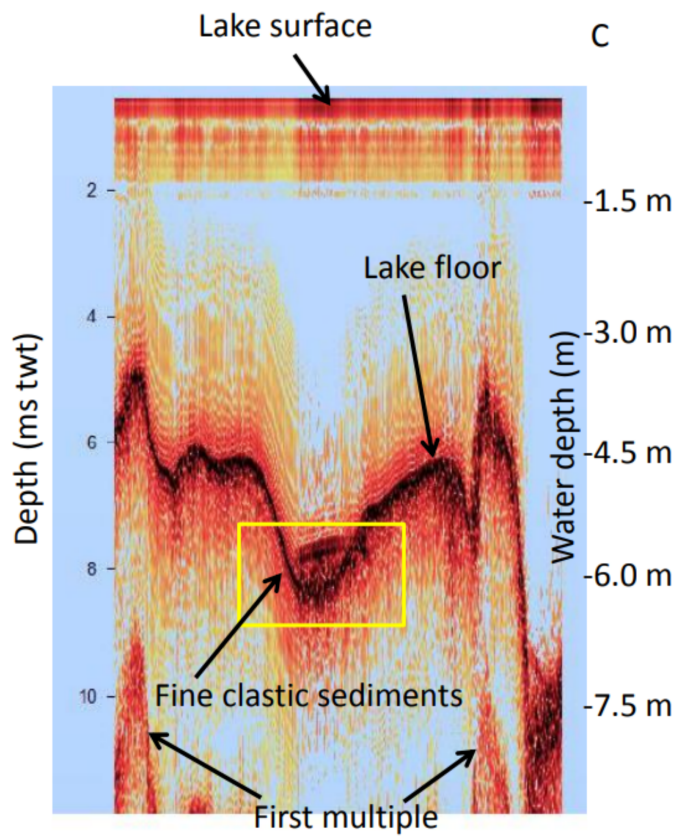
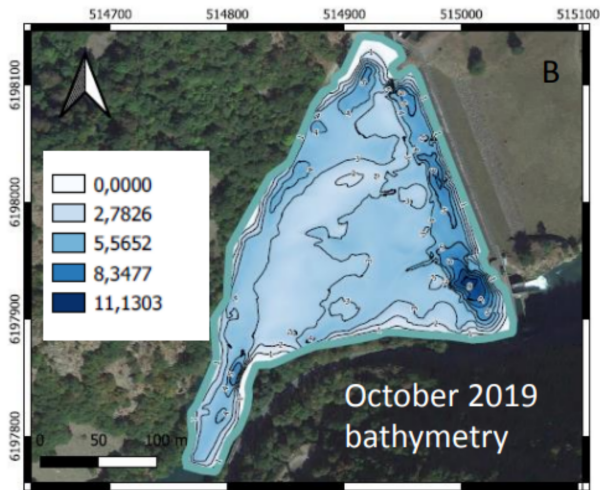
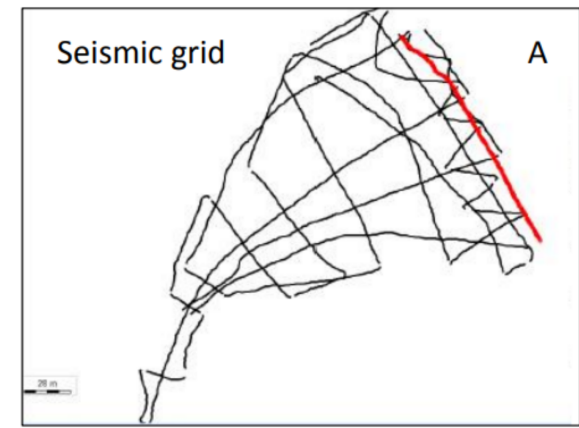
APPENDICES



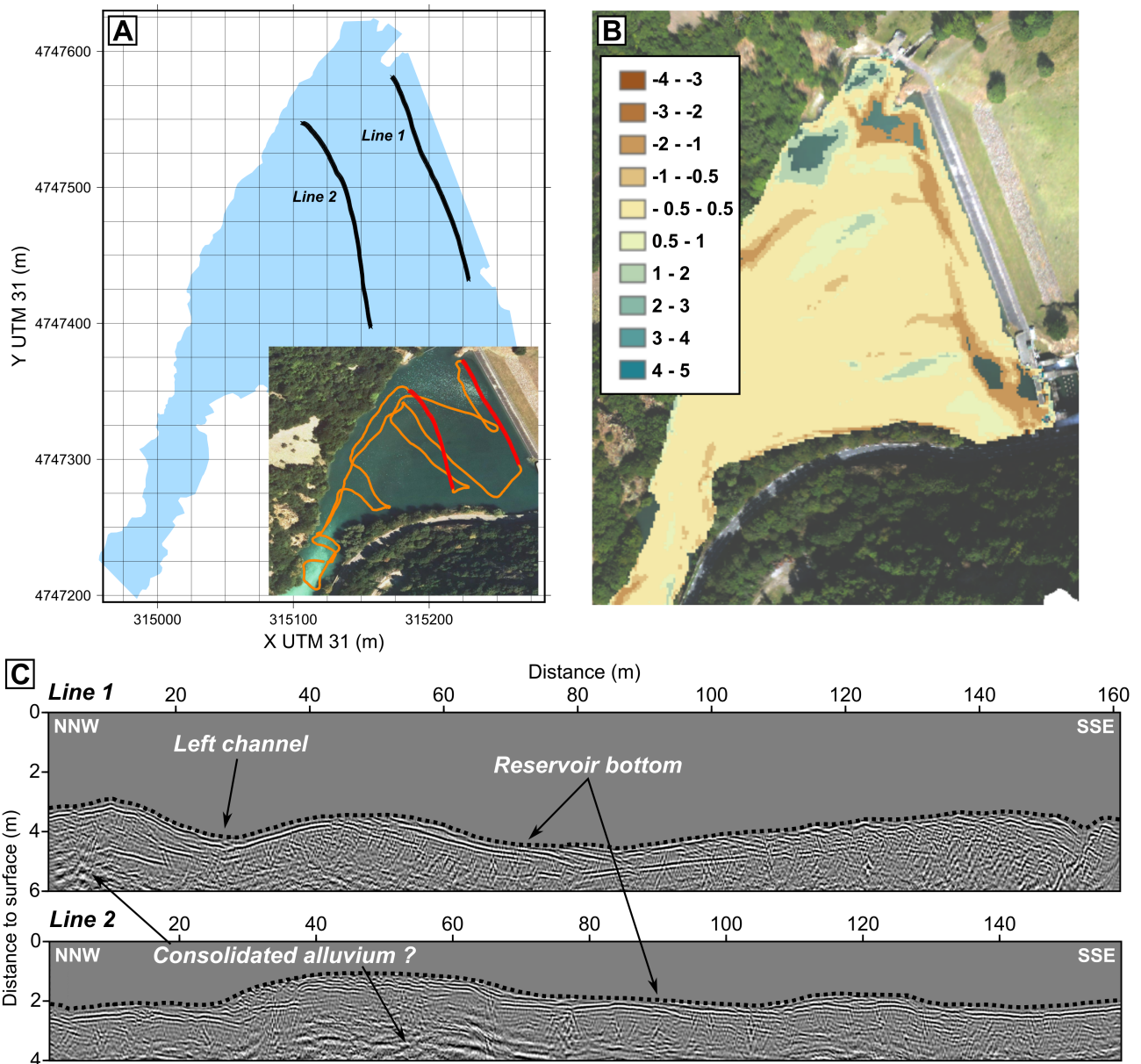
Appendix 4.1. Illustration of thermal images with thermal anomalies: riffle exfiltration (left) and lateral seep (right)



Appendix 5.1. Preliminary results of hydro-sedimentary modelling (IBED3D)



Appendix 5.2. A. Data acquisition grid of high-resolution seismic reflection. B. Map of the water depth created from seismic acquisition. C. Imaging some fine clastic sediments deposited along the dam.



Appendix 5.3. A. Data acquisition grid for GPR. **B.** DoD between 2014 (post-dredging) and 2021 (GPR acquisition). DoD indicate that only minor changes in reservoir bottom elevation occurred between 2014 and 2021, in the order of 0.5 m. **C.** Results from GPR acquisition. On the line 2, we observed fine sediments underlaid by some coarser material. This coarse material could have first be interpreted as the consolidated sediments after dredging. Nevertheless, this zone has only experienced minor silting since the dredging operation. In addition, examination of previous bathymetric datasets indicates that this material was not present in 1997. Therefore, we consider this material are sediments deposited since the dam construction and at times remobilised, rather than pre-dam initial valley floor.