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ABSTRACT

In this paper, we evaluate morphological changes related to the Plan d'Arem dam (1970), a run-of-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 yr after its construction, with channel narrowing at a rate of 0.9% yr^{-1} until the 2010s. 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 caused by 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.

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 and 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

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morphology, and specific contributions of each of these activities are fairly well characterized (e.g., Downs and 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 and Piégay, 2019), including reduction in peak flow frequency and magnitude and associated sediment delivery following the post-Little Ice Age (LIA) climate change, hillslope afforestation (spontaneous/man-made), river damming, channel training, and in-stream gravel mining. The trend towards stabilization is characterized by bar encroachment and increased bank resistance (Williams and 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 and Piégay, 2019).

Dams, which are one of the most widespread causes of fluvial system alterations, can be dichotomized 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 and 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 1), the U.S. (Kondolf and Curry, 1986; Jenkins et al., 1988; Kondolf, 1997), Asia (Haddeland et al., 2007; Ma et al., 2012), South America (Agostinho et al., 2004; Stevaux et al., 2009), and Oceania (Jellyman and 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 and 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. Dépret et al. (2018) and Vazquez-Tarrio 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 and 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 bypassing modality, i.e., the nature of the water intake infrastructure, may then also exert certain downstream effects through bypassing.

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., 2014; 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 analyzed the hierarchy of geomorphic controls to validate our working hypotheses (stated below).

Table 1
Literature covering multi-driver studies in Europe. RoR dams appears 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.

	Time period	Study area	Climate change	Large dams	RoR dams	Check dams	Torrent control works	Channelization	In-stream mining	Forest cover changes	Grazing	Land-use changes
Liébault et al., 2005	1800–2000	North Island (NZ) South Alps (FR)	X				X			X		X
Marchese et al., 2017	1850–1950	South Tyrol (IT)	X									
Provansal et al., 2014	1860–1990	Rhône river (FR)	X	X	X			X	X			
Preciso et al., 2012	1930–2000	Reno river (IT)	X				X		X			X
Ibisate et al., 2013	1930–2010	Aragón River (SP)		X	X							X
Liébault and Piégay, 2002	1945–2000	SE France	X	X			X			X	X	X
Boix-Fayos et al., 2007, 2008	1950–2000	Rogativa River (SP)				X				X		X
Kiss and Blanka, 2012	1950–2010	Hernád River (HU)	X	X								
Batalla, 2003	Review	NE Spain		X					X			

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 km^2 at the confluence with the Neste, and encompasses a wide range of elevation from 415 to 3220 m a.s.l. (Fig. 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 and 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 Béat glacial lock, where the slope decreases to 0.7% and the channel shows sinuous and wandering patterns. Downstream of St Béat, the valley enlarges significantly, reaching 2, 4, and 3

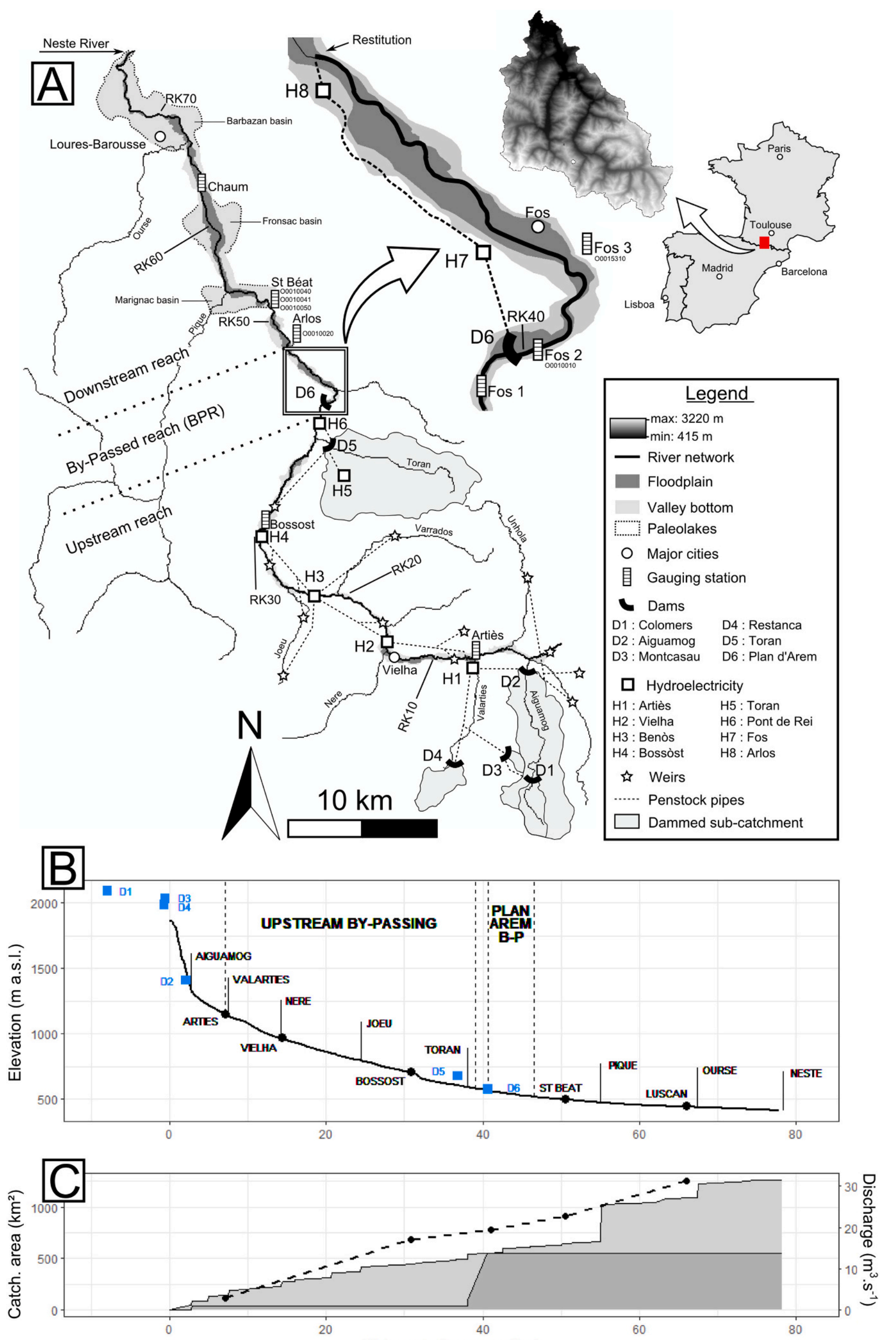

Fig. 1. A) Location of the study site and spatial distribution of hydroelectricity production infrastructures. B) Length profile in 2014. Blue squares: dams. Black dots: main villages. Vertical lines: main tributaries. C) Cumulative catchment area (light-grey shading), cumulative disconnected area (dark-grey shading), and evolution of the mean discharge (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 Béat 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. 1C). 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 hm^3. The Valarties, Nere, Varrados, and Joeu tributaries are then major contributors, increasing the water yield to 538 hm^3 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 hm^3 at the Spanish catchment outlet (1931–1935 and 1948–1969). At St Béat gauging station, the annual water yield increases to 715 hm^3 (1921–1929 and 1948–2018). Finally, the Pique makes another important contribution and increases the water yield to 984 hm^3 at the Chaum gauging station (1993–2019).

At the catchment headwaters, a network of small dams (D1–D4, Fig. 1B) constructed between 1955 and 1965 impound 4.2 hm^3 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 $m^3\ s^{-1}$ at H1 and H2, 23 $m^3\ s^{-1}$ at H3 and H4, and 48 $m^3\ s^{-1}$ at H6 (see Fig. 1 for HPP locations; Daumas, 1962). Although the effect of this bypassing 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 $m^3\ s^{-1}$. 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 $m^3\ s^{-1}$), 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 hm^3. After 40 yr of operation, the capacity has been reduced to a critical value of 0.10 hm^3, requiring stakeholders to dredge sediment and to implement drawdown flushing actions to control sediment accumulation. When the discharge overpasses 70 $m^3\ s^{-1}$ (~1-yr flood), operators stop electricity production and open the bottom gate to lower the lake level and maximize sediment transfer by restoring critical slope conditions. Therefore, drawdown flushing may minimize 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 m^3 over the period 1993–2012, with 40,000 m^3 on the Arriu Joeu. Therefore, we can reasonably assume that gravel extractions did not exceed 100,000 m^3 (taking into account declared works and estimating non-declared works), although the actual volume extracted remains unknown.

3. Materials and methods

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 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 summarizes the main characteristics of each of these sub-reaches.

The before-after design was used to state four hypotheses considering three distinct periods (Fig. 2). 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.

Table 2
Main characteristics of the three sub-reaches studied for the BACI approach.

Sub-reaches		Upstream	BPR	Downstream
Characteristics	River kilometer	2.7–39.6	40.7–46.6	46.6–78.2
	Length (km)	36.9	5.9	31.6
	Mean riverbed slope	2%	0.7%	0.3%
	Style in 1940s	Wandering/ sinuous	Wandering/ sinuous	Sinuous/ straight

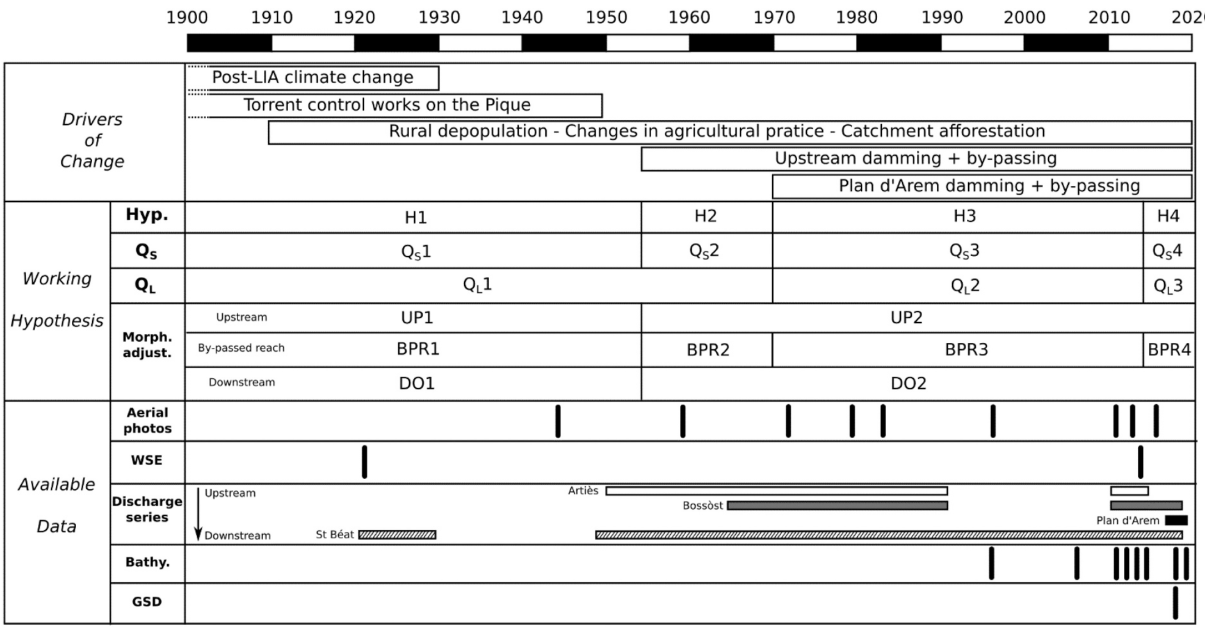

Fig. 2. Chronology of drivers, expected changes in Q_S, Q_L, and river morphology, and available datasets (Boutault, 2020). WSE: Water surface elevation. Bathy: Bathymetry of the Plan d'Arem lake. GSD: Grain size distribution.

3.1.1. *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 hypothesize 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 (***UP1***, ***BPR1***, ***DO1***).

3.1.2. *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.

3.1.3. *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 and 1997, flushing actions were operated, although they targeted mid-flows. We therefore hypothesize 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 to 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. 1A, "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 and 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 bypassing 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 conn channel morphology.

3.2. *Assessment of drivers of change*

3.2.1. *Modification of flood frequency and magnitude*

3.2.1.1. Precipitation. To appreciate potential changes in precipitation over the study period, we used the daily precipitation series of Arties (see Fig. 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.

3.2.1.2. Upstream damming and by-passing. Over the time that river discharge has been monitored, eight gauging stations have registered daily discharges (Fig. 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. 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 $m^3 s^{-1}$ and up to 10 $m^3 s^{-1}$ 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 analyzed, 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.

3.2.1.3. Plan d'Arem by-passing. Providing information on dam management, the 1-h discharge series at Plan d'Arem operating station (Electricité De France, personal comm.) was analyzed 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 $m^3 s^{-1}$, 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, ~34 $m^3 s^{-1}$, when managed without flushing.

3.2.2. Change in sediment delivery

3.2.2.1. 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 and 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.

3.2.2.2. Catchment afforestation. Afforestation of the Plan d'Arem catchment was assessed for 3 dates: 1957, 1987, and 2017 (Table 3). Orthophotos 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.

3.2.2.3. 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 4). The compiled dataset, together with grain size measurements (cf Section 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 4).

3.3. Assessment of channel geomorphic responses in space and time

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 5), the active

Table 3
Available data for characterization of land-use changes.

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

Table 4
Available bathymetric datasets for the Plan d'Arem reservoir.

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

Table 5
Available data for the characterization of the Upper Garonne River planform evolution. Shaded cells correspond to photos in Spain (UP reach). White cells correspond to photos in France (BPR and DS reaches).

Common date	Real date	Discharge (m^3/s)	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	

channel width (active gravel bars and wetted channel), wetted channel, and islands were digitized 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 characterize the morphological adjustments following the Plan d'Arem dam construction, the active channel was digitized 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 consecutives dates and sub-reaches.

Table 6
Available data for the characterization of vertical evolution of the Upper Garonne river.

Year	Date	Discharge (m^3/s)	Source	Accuracy (m)
1922	3–15/10	–	Grandes Forces Hydrauliques	0.1
2014	09/2014	7–13	Véodis-3D	0.02

3.3.2. *Vertical evolution*

Two profiles of the water surface elevation, from 1922 and 2014, are available to assess the vertical mobility of the Garonne River over the study period (Table 6), but only downstream of the Plan d'Arem Dam (RK40.6–RK78.2, Fig. 1). Because both were produced in autumn, at the driest period of the year, they can be considered representative of channel bed elevation. A total of 50 common points were extracted and compared between the two dates to allow interpolation of the full profiles and quantify the vertical mobility of the channel bed in 100-m steps.

3.3.3. *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 armoring ratio was calculated as the ratio between the surface median grain size ($D50_{surf}$) and the subsurface median grain size ($D50_{sub}$).

4. Results

4.1. Temporality and intensity of changes of potential drivers

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. 3), indicating a climatic fluctuation during the ***Q_L1*** period. A Kruskal-Wallis test indicated that these changes are statistically significant (p-value = 0.012).

4.1.2. Changes in peak flows

4.1.2.1. 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. 4, Table 7, ***Q_L1***). 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 Joeu rivers, provide important contributions to the supply of water to the Garonne main course, mitigating the effects of upstream dams on hydrology. At St Béat 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 1970s. We observed Q_2, Q_5, Q_{10}, and Q_{20} increases of 2%, 8%, 11%, and 13%, respectively.

4.1.2.2. Upstream by-passing. At Bossòst, an average discharge of 8 m^3 s^{-1} (ranging from 7 to 10 m^3 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 Q_1 (70–77.5 m^3 s^{-1}), Q_2 (77.5–85 m^3 s^{-1}), Q_5 (85–90 m^3 s^{-1}), and Q_{10} (90–95 m^3 s^{-1}) were lowered by 8% to 10% (***Q_L1***).

4.1.2.3. 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 m^3 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 m^3 s^{-1}, corresponding to 37% of Q_2, 28% of Q_5, and 24% of Q_{10}. 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***).

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

4.1.3.1. 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

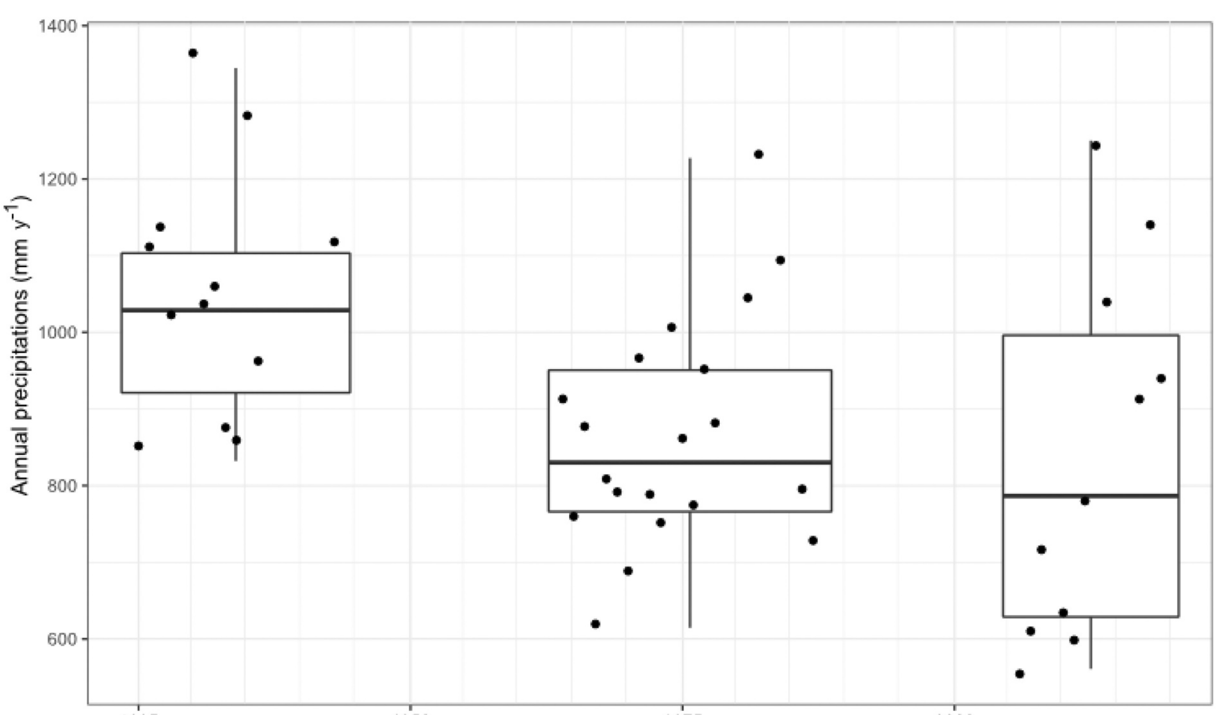

Fig. 3. Annual precipitation at Arties over 1925–2019.

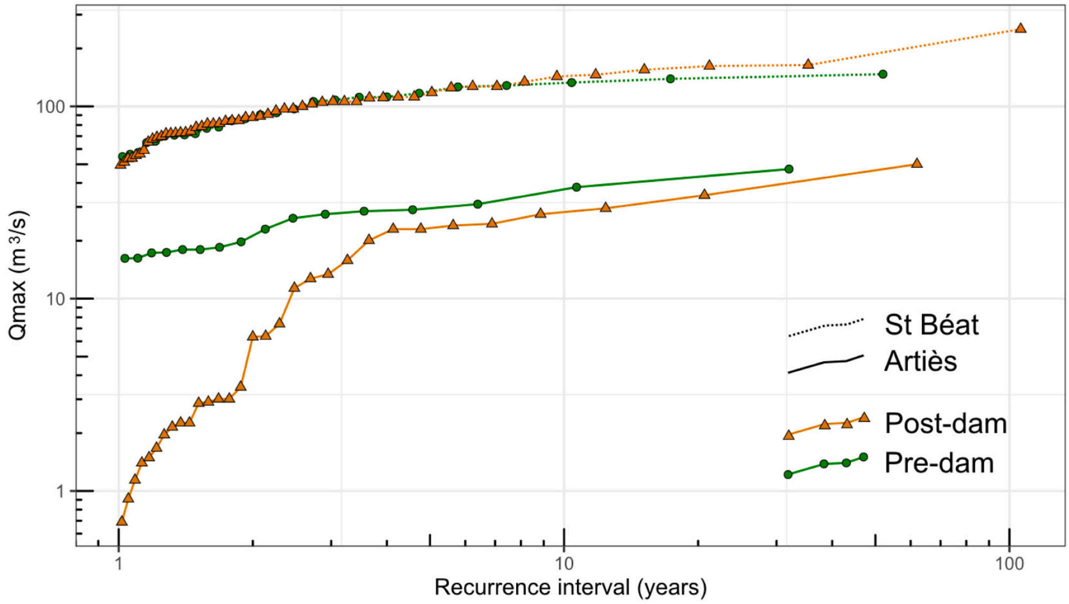

Fig. 4. Changes in flood magnitude and frequency downstream from the headwater dams.

Table 7
Changes in flood magnitude and frequency downstream from the headwater dams.

		Q_2 ($m^3 s^{-1}$)	Q_5 ($m^3 s^{-1}$)	Q_{10} ($m^3 s^{-1}$)	Q_{20} ($m^3 s^{-1}$)
Arties	Pre-dam (1950–1965)	23	31	36	41
	Post-dam (1965–1991/ 2011–2015)	10	21	28	35
	δ	0.42	0.66	0.77	0.84
St Béat	Pre-dam (1921–1930/ 1948–1965)	89	113	129	144
	Post-dam (1965–2018)	91	123	144	164
	δ	1.02	1.08	1.11	1.13

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. 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 stabilizing 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. 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.

4.1.3.2. Catchment afforestation. Currently, forest is predominant lower than 1600 m a.s.l. (Fig. 6), occupying 87.4% of the catchment surface, followed by meadows that account for 9.1%. From 1600 to 2600 m a.s.l.,

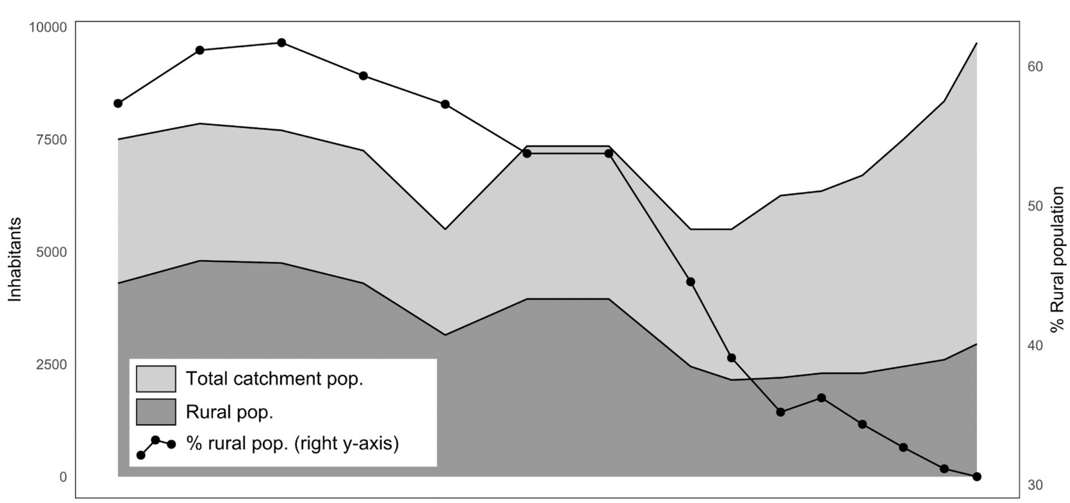

Fig. 5. Evolution of the population on the upstream catchment. Dark-grey area: Rural population. Light-grey area: Total population. Dotted line: Percent of population considered rural.

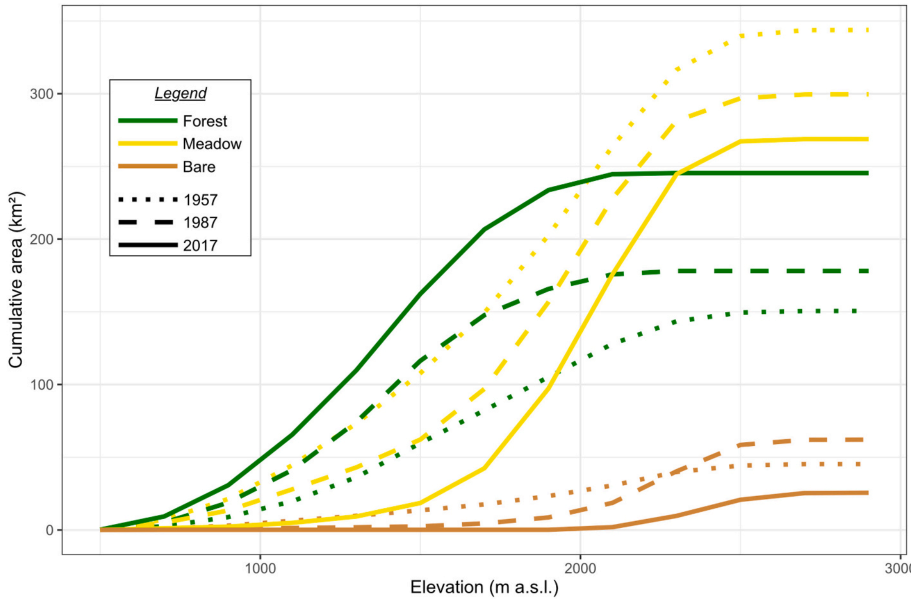

Fig. 6. Altitudinal distributions of land use in 1957, 1987, and 2017.

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 characterizing 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 stabilized 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. 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.

4.1.3.3. 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, ~0.369 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. 7B). 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 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 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

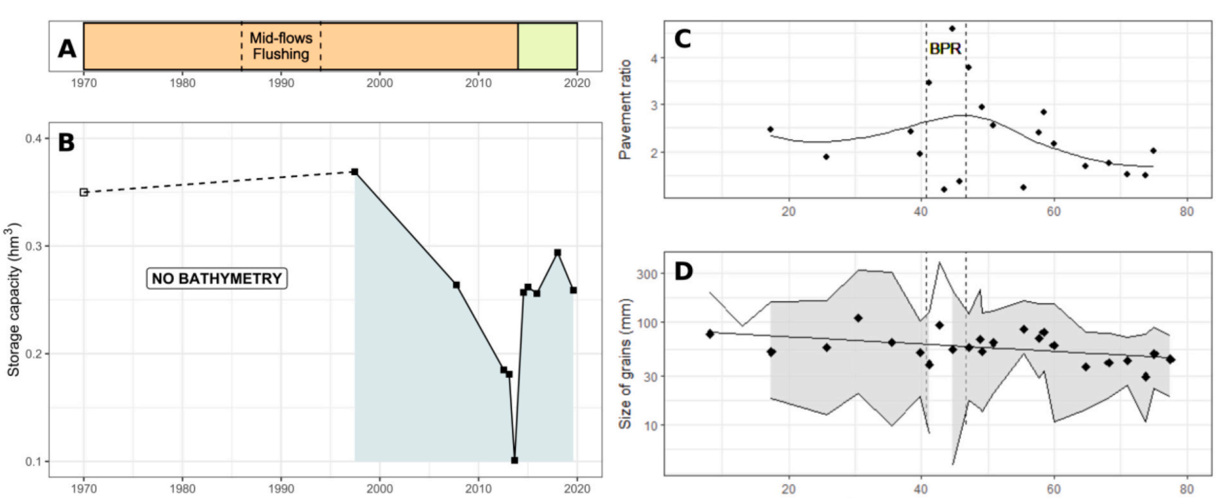

Fig. 7. A) Plan d'Arem dam management. Orange: no drawdown flushing. Green: Drawdown flushing. B) Water storage capacity. C) Longitudinal pattern of armoring ratio. D) Longitudinal pattern of grain size distribution. Black dots: D_{50}. Grey area: D_{10}–D_{90} range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 m^3 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 hm^3 in 2014 and 2019, respectively – although the discharge exceeded Q_2 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 characterized 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 armoring ratio (D_{50surf}/D_{50sub}) are found within the BPR or in its extreme vicinity (Fig. 7C). 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.

4.2. Geomorphic channel response

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. 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.

4.2.2. Channel planform

4.2.2.1. 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 8), 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 colonization 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 generalized 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. 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 $m^3 s^{-1}$, whereas the discharge was 19–60 m^3/s 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.

4.2.2.2. 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

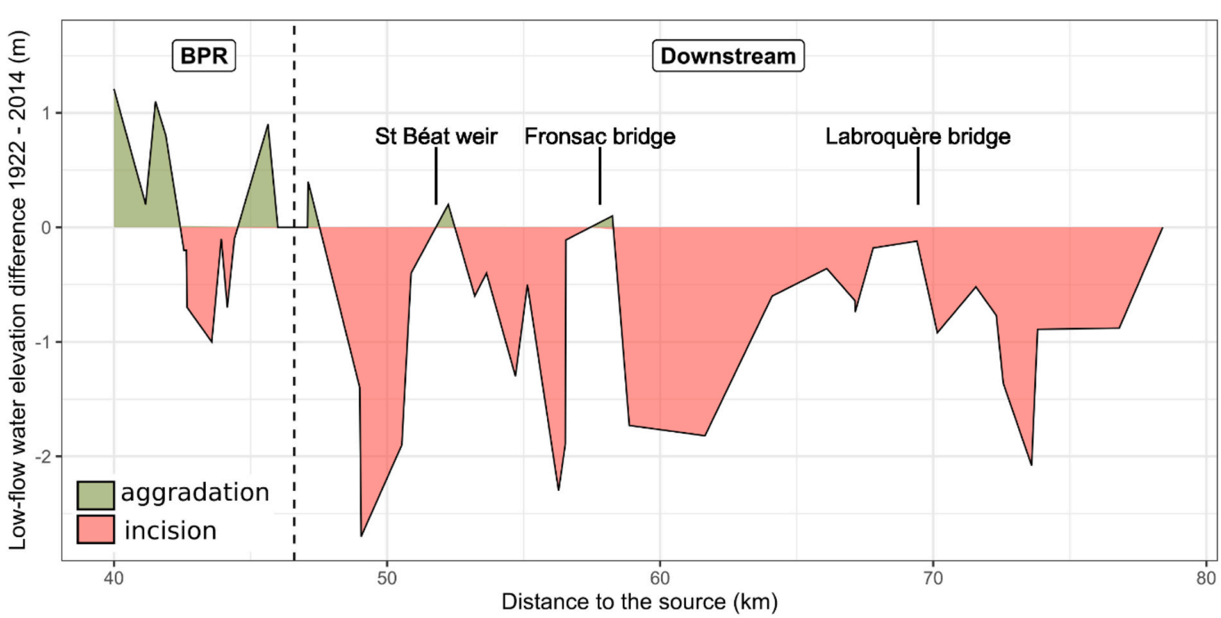

Fig. 8. Water surface elevation differences between 1922 and 2014 in BPR and DS reaches. Dashed line is Plan d'Arem dam.

Table 8
Summary of channel planform changes over the 1944–2016 period for the three subreaches (US: upstream, BPR: by-passed reach, DS: downstream). Shaded cells correspond to photos in Spain (UP reach). White cells correspond to photos in France (BPR and DS reaches).

Period	Reach	Change in active channel area (%)	Mann-Whitney-Wilcoxon *p*-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

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.

4.2.2.3. Downstream reach. Finally, the downstream reach presents a simpler trend of channel evolution (Fig. 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 by-passing 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%.

5. Discussion

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 ($\boldsymbol{Q_S1}$). 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

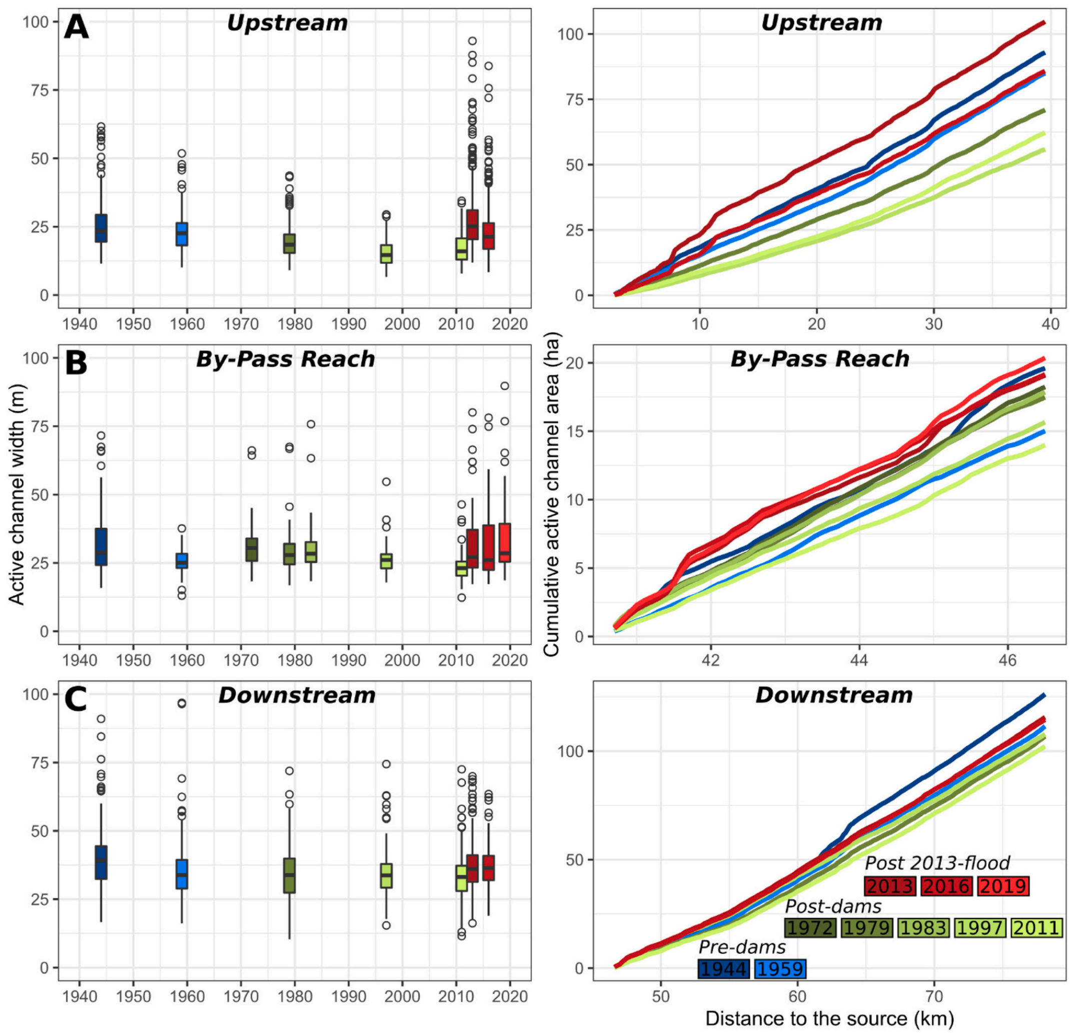

Fig. 9. Changes in the active channel width (left) and cumulated channel area (right) for the upstream reach (A), by-passed reach (B), and downstream reach (C).

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 $\boldsymbol{Q_S}$ and $\boldsymbol{Q_L}$. 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 (***DS1***) 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 (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 (***UP1***, ***BPR1***, ***DS1***), respectively. Altogether, these results allow us to validate hypothesis H1 (Fig. 10).

Hypothesis H2 stated that upstream damming resulted in decreased peak flow frequency (Q_L*1*) and sediment transfer efficiency (Q_S*2*). 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_L*1*). 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_L*1*), and that combined with sediment trapping by the dam itself and by-passing all along the upstream reach (Q_S*2*), 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. 10). Tributaries located downstream of the chain of dams buffer their effects on hydrology and sediment supply. BPR and

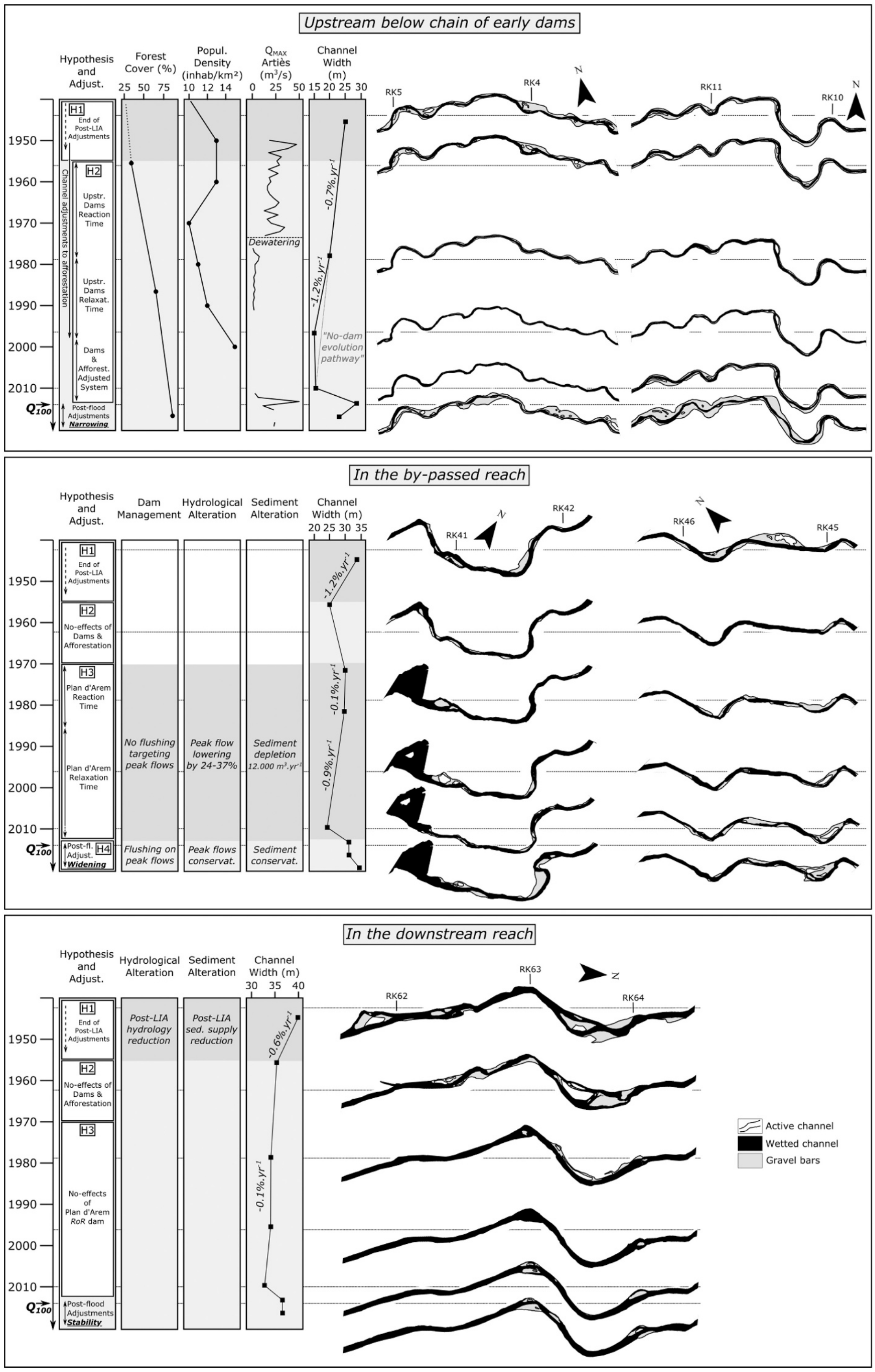

Fig. 10. Synthesis of a working hypothesis and changes in drivers and associated morphological responses in upstream, by-passed, and downstream reaches. Morphological maps highlight the role of the catastrophic 2013 flood on refurbishing the channel planform, mostly in the upstream reach.

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 generalization of plant and tree colonization on lower areas, typically lower than 1000 m a.s.l. and corresponding to valley bottoms, thereby stabilizing 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, Llena 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 generalized sediment deficit. This deficit affected channel morphology through channel width reduction, incision and armoring, 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 anthropization, 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 ($\boldsymbol{Q_L2}$), and trapped around 11,000 m^3 of sediment per day of discharge above Q2 ($\boldsymbol{Q_S3}$). 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 armoring ratio reaching up to 3. Those results indicate that a thin alluvial mattress of fresh sediments delivered from Plan d'Arem circulates over an armored 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 armored 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 ($\boldsymbol{Q_L2}$), 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 1980s, allowing us to estimate a reaction time of around 15 yr. These results allow us to conclude that hypothesis H3 is valid (Fig. 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 $m^3\ s^{-1}$) 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 ($\boldsymbol{Q_S4}$) and preserving peak flow magnitude ($\boldsymbol{Q_L3}$). 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. 10).

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 armoring 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 m^3 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 $m^3\ s^{-1}$ 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 organized 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.

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 characterization 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 set 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 hypothesize that the channel morphological response to afforestation would be greater if the afforestation rate is high and the catchment rapidly afforested, and if slope colonization 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 1950s and lasted until the 1990s, whereas within the BPR, channel adjustments started during the 1980s. 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.

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) Hypotheses 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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