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Geomorphology

Can we wrongly link armouring to damming? A need to promote hypothesis-driven rather than expert-based approaches in fluvial geomorphology

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Corresponding Author:	Daniel Vázquez Tarrío, Ph.D. University of Oviedo Oviedo, SPAIN
First Author:	Daniel Vázquez Tarrío, Ph.D.
Order of Authors:	Daniel Vázquez Tarrío, Ph.D. Michal Tal Elsa Parrot Hervé Piégay
Abstract:	<p>Present-day river forms and processes are in many cases conditioned by the consequences of anthropogenic modifications such as dams, embankments and gravel-mining. Fluvial geomorphologists have typically investigated the effects of these human impacts using a so-called expert-based approach, whereby observed association or synchronicity between geomorphological changes and a given, preidentified impact, are interpreted as evidence of causation. This approach has important limitations when the effects of multiple human interventions interact along the same river corridor or overlap with legacy natural changes affecting the sediment - water balance. In such situations, the establishment of causal links between channel morphology and single impacts is not as straightforward as commonly assumed and the conclusions are susceptible to 'confirmation biases'. In this paper we highlight this risk through an assessment of human impacts on the Rhône river within a multi-driver context. The French Rhône is a perfect example of an Anthropocene river impacted by two main development phases during the 20th century: embankments (1890s -1930s) followed by a series of multiple dams (1950s -1990s). We began by laying out several geomorphologically consistent hypotheses for the geomorphological trajectory of the Rhône over the 20th century. Next, we tested these hypotheses against grain-size data collected in the field in a structured and hypothesis-oriented way. Using this hypothesis-driven and deductive attribution analysis we identified the relative impacts of the different development phases on the present-day grain-size distribution and in particular on armouring in the Rhône river, and proposed a hierarchy of dominant drivers of geomorphological change along the Rhone over the last century and a half. Our results led us to conclude that in the case of the Rhône, the effect of dams on armouring was negligible compared to a legacy of natural heritages and embankments.</p>

1 **Can we wrongly link armouring to damming? A need to promote hypothesis-driven**
2 **rather than expert-based approaches in fluvial geomorphology**

3 **Authors:** Daniel Vázquez-Tarrió^{a,b,*}, Michal Tal^c, Elsa Parrot^a and Hervé Piégay^a

4 ^a University of Lyon, CNRS UMR 5600 EVS, Site ENS, Lyon, F-69362 France

5 ^b Geology Laboratory, Dpto. Producción Agraria (ETSIAAB), UPM, Madrid, Spain
6 (*present address*)

7 ^c Aix Marseille Univ, CNRS, IRD, INRAE, Coll France, CEREGE, Aix-en-Provence,
8 13545 France

9 **Abstract**

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33 **Keywords:** Rhône river, Grain-size, Armouring, Dams, Anthropocene rivers, geomorphic
34 change, attribution studies, inference-based approach, deductive approach

1. Introduction

Many rivers worldwide are influenced by human modifications such as gravel mining, dams, and embankments, that were carried out extensively during the last couple of centuries. In this context, fluvial geomorphology has sought to identify cause and effect in the morphological response of river channels to natural and human drivers of change, and has traditionally done so using abductive and/or inductive (inference-based or expert-based) approaches (Schumm, 1991; Downs and Piégay, 2019). Under such strategies, the main causes of channel evolution were typically inferred from the observation of patterns identified in uncontrolled data sets, and causal factors were determined based on expert judgement of their temporal synchronicity and spatial proximity with observed channel responses (Rhoads and Thorn, 1996). While these exploratory approaches had an important role in advancing the discipline of fluvial geomorphology and served to increase our awareness of the geomorphological effects of human interventions (e.g., dams, embankments, land use, bank protection, instream aggregate mining), they were subject to important limitations. The challenge of convincingly attributing single impacts to specific drivers of change are evident when we consider the case of rivers impacted by multiple stressors, particularly when the effects of these multiple drivers overlap and/or interact through time. Contingency also plays a role, as the exact sequence in which various human disturbances on a river corridor have occurred will impact present-day geomorphological conditions. Such things complicate the establishment of robust models for the attribution of effects to specific drivers in rivers, despite a desire to achieve a complete understanding of present-day environmental change (Cendrero et al., 2020) and the importance, particularly in river management, of assigning responsibility to observed changes. Studies based on a deductive approach in which the previously accumulated geomorphological knowledge would be used to formulate well-posed and ‘falsifiable’ hypothesis to be tested against field data collected in a structured and hypothesis-oriented way are still lacking. Meanwhile, recent technological advances (GIS, catchment-scale digital data, new surveying methods and analytical models) have enabled researchers to obtain more structured field data, opening the door for more hypothesis-controlled determinations of cause and effect models of change in fluvial geomorphology (Vericat et al., 2017).

Research aimed at understanding the impacts of dams on rivers has no doubt been affected by these epistemic tendencies in fluvial geomorphology. Dams drastically alter the supply

68 of sediment and flow to rivers downstream and hydraulics upstream (Petts, 1979;
69 Williams and Wolman, 1984; Kondolf, 1997; Brandt, 2000; Vörösmarty et al., 2003;
70 Graf, 2005, 2006; Magilligan and Nislow, 2005; Petts and Gurnell, 2005; Nilsson et al.,
71 2005; Schmidt and Wilcock, 2008; Dade et al., 2011; Kondolf et al., 2014). Due to the
72 general incompleteness (and in some cases complete lack) of historical data on hydraulics,
73 topography, and grain-size, fluvial geomorphologists have traditionally been compelled
74 to disentangle the effects of dams based on an interpretation of the present-day state of
75 the river or at best the morphological trajectories of recent decades. The study of the
76 geomorphological effects of dams was typically conducted through case studies which
77 sought simple and unique associations between observed trajectories in one or more
78 channel features (surface grain-size, bed elevation, slope) and changes in sediment and
79 water supplies imposed by a dam (Downs and Piégay, 2019). While this data-driven
80 approach contributed to a solid body of knowledge on the geomorphic effects of dams, it
81 had its limitations. Furthermore, the fact that covariation does not imply causation should
82 not be precluded. In other words, the observed synchronicity between dams and
83 geomorphic change does not directly translate into causation. It is very common,
84 particularly in European fluvial settings, for dams constructed during the 20th century, to
85 be on rivers previously subjected to a long history of anthropogenic influences and human
86 management related to catchment-scale land-use changes, river navigation, irrigation
87 and/or flood control going back to at least the Industrial Revolution (Frings et al., 2009,
88 2014a, 2014b; Arnaud et al., 2015; Vázquez-Tarrío et al., 2019). Additionally, in many
89 cases, multiple dams were constructed along the same river (e.g. Skalak et al., 2013;
90 Vázquez-Tarrío et al., 2019). These complexities mean that simple associations between
91 morphological evolution and a single dam are insufficient to establish solid conceptual
92 models attributing geomorphic signals to dams. Furthermore, such models require
93 considering and identifying the individual impacts of other drivers of change (e.g., natural
94 trends in hydrology driven by climate change, previous river regulation, interactions
95 amongst multiple dams; Downs and Piégay, 2019). It's quickly obvious how the
96 abductive, data-driven, study-case approach traditionally used in fluvial geomorphology
97 is limited in its ability to disentangle these multiple drivers and to attribute single impacts
98 to a specific one such as dams. In this regard, dams have rarely been studied in terms of
99 their interactions with other dams and / or within the context of previous management
100 (Skalak et al., 2013). Considering that dams represent one of the most conspicuous human
101 impacts on natural rivers today and are considered a major driver of their

geomorphological trajectories during the Anthropocene (Nilsson et al., 2005; Syvitski and Kettner, 2011; Poff, 2014; Wohl, 2020), a more systematic and structured approach to assessing their impacts is necessary and timely.

When investigating the effects of human impacts on rivers, important questions exist. For example, do similar anthropogenic changes give rise to identifiable trends in river metrics such as grain size, width or depth? Or, do different rivers submitted to comparable stressors present unique and specific forms or bed textures? Under which circumstances could we expect this? To us, it is obvious that a classical, expert-driven approach based on associating the observed geomorphic patterns to the occurrence of a given human impact is limited in such situations in which the effects of multiple human works interact, or anthropogenic stressors overlap with natural trends in hydrology or climate or a legacy of past climatic conditions or prior human disturbances (Brierley, 2010). In this respect, the goal of this study is to formulate and validate ‘falsifiable’ hypotheses to assess potential effects of specific drivers (anthropogenic or natural) on a large, heavily managed and multi-dammed river. In taking this approach, we illustrate how determining cause and effect and interpreting observed trends are not straightforward and rather quite complicated in the case of rivers subject to overlapping stressors. Nevertheless, we show that a deductive approach is well suited for attributing impacts to different drivers in a robust manner and establishing a hierarchy amongst different drivers of change and disentangling the effects of multiple dams and development phases. We use the Rhone River in France as a study case to illustrate this approach and we focus our analysis on present day grain size distributions (GSDs). The Rhone river is very well suited to such a study due to extensive embankments constructed at the end of the 19th century (end of the Little Ice Age) to promote navigation followed by the construction of multiple diversion dams during the second half of the 20th century for hydropower (Bravard and Gaydou, 2015). In addition, its long management history has resulted in an extensive dataset. We begin by formulating several plausible hypotheses for the impacts of different development phases on channel morphology. These hypotheses were established by considering longitudinal trends in present-day channel GSD along the Rhône as either resulting from riverbed adjustments to dams and / or embankments, or, instead, as being solely a legacy of the geologic and glacial history of the catchment. We then compared how these hypotheses were supported or refuted by observed grain-size trends in a large dataset using testable hypotheses.

Our hope is that this study will encourage studies of late-Anthropocene fluvial geomorphology to move beyond case studies towards hypothetic-deductive approaches and promote the development of long-term data depositories and shared methodologies, thereby reducing the dependence on expert judgement and providing a powerful way to establish more generalizable cause-effect attribution-models of geomorphic evolution under different drivers of change during the Anthropocene.

2. The Rhône river

2.1. A complex natural setting

One of Europe's major rivers, the Rhone River originates at the Rhone Glacier in the Swiss Alps at an altitude of 1763 m and discharges into Lake Geneva approximately 200 km downstream. About 50 km downstream of Lake Geneva it crosses into France (Figure 1 and 2) and flows 512 km to the Camargue delta and its mouth at the Mediterranean Sea. The Rhone is the largest supplier of flow and suspended sediment to the Western Mediterranean Sea (Eyrolle et al., 2012) and represents one sixth of all the runoff to it as a whole. The catchment area within France is approximately 90,500 km² and mean annual discharge varies from about 200 m³/s at the upstream (fully regulated by transboundary water management agreements) to 1700 m³/s near the mouth.

The Rhone is predominantly an Alpine river, with 50% of the catchment located above 500 m and 15% above 1500 m. Along its path, the Rhone traverses three mountain ranges: the Alps, the Jura, and the Massif Central, and receives inputs from several major tributaries that drain them: the Ain, Saône, Isère, Ardèche and Durance. The shape of the long profile of the Rhone (Figure 2A) attests to its highly varied basin and heterogeneous legacy of tectonics, varied lithologies, and glacial histories. The upper Rhone was last covered by the Wurm Glacier while the middle and lower Rhone have not been glaciated since the early Pleistocene (see Bravard, 2010 and Notebaert and Piégay, 2013 for more details about the basin's geological history). The sum result is a river that naturally alternates between V-shaped valleys and wide alluvial plains, outwash plains and bedrock gorges, sediment supply of varying texture and lithologies, and reaches with more or less strictly imposed bed slopes.

The French Rhône is naturally divided into five main sectors reflected in the pre-management (pre-Girardon) low-water slope and active channel widths (low flow and

unvegetated bars; Figure 2B). The boundaries and main characteristics of these natural sectors are as follows: i) the upper Rhône extends from Lake Geneva to the confluence with the Ain River. Upstream of the confluence with the Guiers River, the upper Rhône flows between the Alps and the Jura, and its channel is characterised by a steep slope and relatively narrow floodplain. Between the confluence with the Guiers and the Ain, the river flows over an old glacial umbilicus - average slope is low (0.00001 m/m) and the valley width is quite large, ii) the Ain -Miribel sector extends from the confluence with the Ain to the confluence with the Saône. It is steep-sloped (0,001 m/m) and largely controlled by the coarse sediment inputs from the Ain river (which drains the Jura mountains), iii) the middle Rhône extends from the confluence with the Saône to the confluence with the Isere. It consists of a generally narrow floodplain, old fluvial terraces, and a moderate valley slope 0.0005 m/m, iv) the lower Rhône extends from the Isère confluence to the start of the delta at Arles. It has an average slope of 0,0006 m/m and variable channel width, v) the delta from Arles to the Mediterranean, with a gentle slope (<0.00009) and dominantly sand-bedded.

2.2. Phases of human development in the Rhône river

Superimposed on the Rhone's complex natural system are over a century and a half of intense modifications of the main channel (Cortier and Couvert, 2001; Fruget and Dessaix, 2003; Parrot, 2015; Dépret et al., 2017; Vázquez-Tarrío et al., 2019; Vauclin et al., 2020). The first period of major channel modifications (1860-1930) was for the purpose of facilitating navigation along the Rhone between Lyon and the delta which back then was a wide multi-thread channel. This was achieved by narrowing the channel in order to increase shear stresses, thereby discouraging deposition and increasing the transport of coarse sediment downstream (often referred to as river training). Narrowing was engineered through a system of channel embankments consisting of submersible longitudinal and transverse dykes, weirs, groynes, and cross-beams (Figure 3A and 3B; Poinart and Salvador, 1993; Bravard and Peiry, 1993; Bravard, 2010; Dépret et al., 2017; Tena et al., 2020). These structures on the Rhone are collectively referred to in French as the 'casiers Girardon' after the engineer who designed the compartments (*casiers*) formed by the dikes and groynes to fill in with sediment. The casiers Girardon were highly successful at trapping fine sediments during floods, gradually expanding the floodplain and concentrating the flow into a narrow channel. While the Rhône downstream of Lyon

(middle and lower Rhône) was subjected to a systematic and extensive campaign of channel narrowing, the upper Rhône was only sporadically embanked.

The first dam built on the Rhône was the Cusset dam-plant along the Jonage Canal that went into operation in 1899. During the first half of the 20th century, two more dams were built close to the France-Swiss border: Chancy-Pougny (Franco Swiss) and Verbois (Swiss), went into operation in 1924 and 1944 respectively. However, the major wave of dam building on the Rhône kick-started in 1948, with the construction of the Génissiat hydroelectric dam. Nineteen dams and power plants were built on the French Rhône between 1948 and 1986 (Klingeman et al., 1994; Poinsart, 1992; Petit et al., 1996). These dams are operated by the Compagnie Nationale du Rhone (CNR), the holder of the concession contract from the State. Most of the hydropower plants are run-of-the-river plants with little or no storage; the role of the dams is to divert flow to canals leading to them (Figure 3C). The diverted flow bypasses the original channel (referred herein as the bypassed channel) and the two re-join downstream of the power plant (herein referred to as the Total Rhone). The sequence repeats itself at each dam. The only three exceptions to this general scheme are Genissiat (high-head storage dam) and the Seyssel and Vaugris dams which are combined run-of-the-river dams and power plants with no diversion canal. Each coupled dam – power plant scheme specifies a minimum residual flow that must be maintained in the original channel and a maximum discharge that can be diverted to the plant. During normal flow conditions, most of the flow is diverted to the canal. Since sediments do not enter the canal, they remain trapped upstream of the dam. When the discharge exceeds maximum capacity of the power plant, the dam's sluice gates are opened from the bottom in order to allow all the discharge to flow into the bypassed channel. During such high flows, sediments that accumulated upstream of the dam are flushed downstream (Bravard and Clemens, 2008). It is important to note that while the majority of dams on the Rhone are not storage dams, they still generate hydraulic backwater zones upstream, with implications for sediment transport across this zone during typical floods (Dépret et al., 2019; Vázquez-Tarrío et al., 2019). In summary, dam construction starting in the 1950's introduced a divergence in the hydro-sedimentary dynamics amongst subreaches of the Rhone: i. bypassed subreaches with reduced flood frequencies, average discharges, and sediment supply, ii. Total Rhone subreaches that continue to receive the natural discharge, and iii. Total Rhone subreaches receiving the

natural discharge but subject to hydraulic backwater effects associated with the downstream dam.

Gravel mining in the main channel of the Rhone as well as in lower sections of some of the main tributaries was widespread from the 1950s to the late 1990s. The Rhone River between the Mediterranean Sea and Lyon is first and foremost a navigation corridor. To maintain it as such, the CNR widened the mouths of major tributaries (Ardèche, Drome, Durance) in order to promote deposition. These artificial deltas are then dredged in order to prevent coarse sediments from reaching the main channel (Dépret et al., 2019). Each power plant contains a lock that is maintained to enable ships to reach the level of the canal. Upstream of Lyon the Ain and the Arve still deliver coarse sediments to the Rhône. A recent compilation of mining data conducted by the CNR estimated the total volume of sediment mined from the Rhone's main channel over this period to be approximately 50 million m³ (Coeur, 2017).

3. Study approach

As stated in the introduction, the main goal of this paper is to apply a hypothetical-deductive approach to assess impacts of human pressures on large rivers and the attribution of specific impacts to different drivers of change. We consider the classical approach typically used in fluvial geomorphology, one based on detailed descriptions of patterns in geomorphic changes and its subsequent association to a previously identified, synchronous and specific human impact to be limited in many cases. In the case of the Rhone, several questions can be posed. For example, how do the observed geomorphic patterns or GSD trends relate to dams, gravel mining, river training or glacier heritage? And how do the effects of dams enhance, counteract or interact with the consequences of channel embankments and/or natural legacies (following Holocene glaciation or the Little Ice Age)? We have little doubt that when it comes to the Rhone River, we are up against the limits of an abductive approach. As such, we applied a different strategy. We started by posing a set of explicit, 'falsifiable' hypotheses and then testing these against field data. We consider this approach, already suggested by other researchers (e.g. Schumm, 1991), to be the most adequate, rigorous, and least-biased for establishing robust cause-effect models of river response to multiple drivers in a highly managed river such as the Rhône based solely on present-day observations. Our approach involved three distinct sequential steps. First, we identified and selected a single geomorphological parameter

out of those commonly used to study the impact of human pressures on rivers - vertical bed evolution, planform morphology, grain-size, armouring and bed texture. We chose GSD due to the fact that grain-size samples could be collected all along the Rhône. In addition, GSD is a metric whose potential responses to forces acting on the Rhône are well-known and described in the scientific literature. Next, we formulated explicit and ‘falsifiable’ hypotheses for potential adjustments in grain-size in response to human management on the Rhône river. These hypotheses were based on the current scientific understanding (i.e., existing literature) and collective knowledge of the Rhône’s management history and could be tested against the present-day observations. Lastly, we defined the best strategies and metrics for testing the hypotheses in order to determine the likeliest scenario.

3.1. Grain-size distribution as a metric of channel adjustment to water/sediment balances

Various metrics for assessing the geomorphological impacts of river management have been employed (e.g., channel width, bed slope, bed elevation, etc.; Schmidt and Wilcock, 2004). Given its important role on river habitat, bed roughness, river hydraulics and sediment transport, grain-size is a metric that has received a lot of attention amongst fluvial geomorphologists. In this section we summarize the current understanding of how grain-size relates to flow and sediment supply and adjusts to shifts in these.

In gravel-bed rivers, the streambed surface is typically coarser than the underlying bed material, a pattern of inverse grading typically referred to as armouring. Armouring arises from the intrinsic adjustment of riverbeds to bedload supply. It is a mechanism that enables the transport of all the supplied load, and as a result the possibility of a riverbed in equilibrium, in spite of size-selective entrainment (Parker and Klingeman, 1982; Dietrich et al., 1989; Church and Ferguson, 2015; Venditti et al., 2017; Vázquez-Tarrío et al., 2020). Surface coarsening and armouring is typically quantified through the ‘armour ratio’, i.e, the ratio between a given percentile (e.g. D_{50} , D_{84}) of the surface GSD and the same percentile in the subsurface GSD. Armour ratios tend to increase when sediment supply decreases relative to bedload transport capacity (e.g., Dietrich et al., 1989; Venditti et al., 2017; Vázquez-Tarrío et al., 2020). Hence, surface coarsening is one major mechanism of bed adjustment to shifts in the sediment/water balance. Typical armour ratios for undisturbed gravel-bed rivers in humid temperate regions are around 1.5-2.5, whereas larger armour ratios are commonly reported in rivers with limited

sediment supplies, such as reaches located downstream of dams (Ferguson, 2004; Hassan et al., 2006; Houbrechts et al., 2012; Vázquez-Tarrió et al., 2020). As such, large armour ratios ($\gg 3$) are considered a good indicator of the effects of dams on the sediment transport regime downstream of them and their wide-spread presence has led to a well-established conceptual model whereby the streambed tends to coarsen downstream of dams in gravel-bed rivers (i.e., ‘hungry-waters’ ; Kondolf, 1997) due to disruption of the sediment continuity. As such, observed present-day armouring constitute a proxy for the impacts of dams as well as other human works that alter water and sediment balances triggering bed textural changes. Examples include sediment trapping in gravel-pits resulting in ‘hungry-water’ effects and enhanced surface coarsening downstream. Similar effects are seen in cases of river embankments and flood protection works that decouple channels and banks reducing sediment supply from bank erosion and secondary channels, constituting a nice example of equifinality: the same degree of surface coarsening arising from different controls: sediment starvation following sediment-supply reductions resulting from dam construction or shear stress increase due to embankments and flood protection works. Embankments are often associated with channel straightening and narrowing or widening, altering sediment transport capacities and leading to bed textural changes (e.g., Frings et al., 2009; Bravard, 2010; Arnaud et al., 2015).

Gravel-bed rivers respond to reductions in sediment supply not only through vertical sorting (armoring), but also through the development and expansion of coarse fixed patches (Nelson et al., 2009; Yager et al., 2015). Differences in grain-size distribution between the wetted channel and the bars can be considered as a measure of these cross-sectional sorting patterns and a proxy for bed patchiness (Singer, 2008), and can be related to sediment supply conditions (Dietrich et al., 2005; Nelson et al., 2009, 2010). Related to this, bars can be regarded as either the result of self-organization of more mobile sediments rapidly transiting along the riverbed (capacity-limited conditions; Church and Jones, 1982), or as relict features resulting from the concentration of bedload into a narrow band of the channel following sediment supply reductions leading to thalweg incision and lateral disconnection of the elevated bars (supply-limited conditions; Singer, 2008). The former could be in the case of a river with abundant sediment stocks due to a legacy of past climatic conditions (e.g., reaches downstream of glaciers), or important inputs of coarse sediment supplied by mountain tributaries (e.g. tectonically active regions). The latter could be in the case of rivers draining recently reforested watersheds

or ones strongly regulated by dams, with important discontinuities in sediment transport. In the case of the former, we should not expect large differences in grain-size between bars and the wetted channel, while in the latter, sharp contrasts may arise from flow stage differences between relatively shallow bars and deeper wetted channels, leading to stronger winnowing of fine sediment in the wetted channel and thus a coarser bed.

3.2. Posing testable and refutable hypotheses

Based on the known historical trajectory of the Rhône river (section 2.2) and the existing literature (section 3.1), we formulated two pairs of dichotomous (i.e., ‘yes/no’) hypotheses, independent of one another, of channel evolution over the XXth century. A first pair (hypotheses 1 and 2) concerns the effects of embankments, while a second pair (hypotheses 3 and 4) concerns the riverbed response to dams. Although gravel mining on the Rhone was extensive, we chose not to investigate extensively its impacts on channel morphology in this study due to its high spatial variability and localized impact on the bed. The four hypotheses are as follows and are also summarized in Figure 4:

- Hypothesis 1: We assume that the channel was adjusted to the natural flow and sediment supply at the end of the 19th century prior to channel embankment (Bravard, 2010). Embankments narrowed the channel in the Rhône river, concentrating the flow in a narrow band of the main channel. We further hypothesize that embankments reduced lateral sediment supply from secondary channels and bank erosion. The sum of these effects resulted in bed coarsening during this first major phase of human management.
- Hypothesis 2: We again assume that the channel was adjusted to the natural flow and sediment supply before river training started at the end of the 19th century. However, in contrast to hypothesis 1, here we hypothesize that embankments had no further effect on riverbed texture. This may have been the case if, for example, available in-channel stocks of sediment were able to keep pace with increased in transport capacities resulting from channel narrowing.
- Hypothesis 3: We postulate that dams significantly disrupted sediment continuity in the main channel of the Rhône, decreasing sediment supply to the bypassed channels and triggering ‘hungry-water’ effects that lead to surface coarsening.
- Hypothesis 4: We postulate that dams had no effect on surface coarsening. Indeed, in addition to decreasing sediment supply to the bypassed channel, run-of-the-river dams also reduce the frequency of channel-forming flows. It is plausible that

this reduction inhibits channel coarsening in response to dams. Furthermore, if hypothesis 1 were to be true, that the bed was likely already coarse and less mobile by the time the dams were constructed, this would further limit surface coarsening.

After posing different plausible hypotheses of bed evolution (Figure 4), we moved on to considering how to test and confirm or refute them. Given that the lower and middle Rhône were embanked while the upper Rhône was not, one possible way to discriminate between hypotheses 1 and 2 would be to compare surface armoring between the upper and middle/lower Rhône. If embankments did not significantly impact riverbed texture, then there should be no significant differences in the observed degree of surface coarsening in the upper Rhone compared to the middle / lower Rhône. If differences are observed, this would refute hypothesis 2. However, this would not directly confirm hypothesis 1. In this regard, observed differences between the upper and the middle/lower Rhône could also be linked to natural differences in stream gradient or flow competence. Nevertheless, the comparison of grain-size trends between the gravel-bars and the channel may provide a way to discriminate between them: if embankments narrowed the channel and disconnected gravel-bars from the wetted channel, we could expect some divergences in surface coarsening between gravel-bars and the wetted channel in the middle/lower Rhône, but not in the upper Rhône. Similarly, to discriminate between hypotheses 3 and 4 (pertaining to the dams), one strategy would be to compare armour ratios between the middle/lower Rhone (embanked and dammed) and the upper Rhône (only dammed): if a higher degree of surface armouring were to be observed in the lower/middle compared to the upper Rhône, this would support the idea that coarsening in the Rhône was mostly linked to embankments. Another way to investigate the effect of dams on surface coarsening would be to analyse whether GSD in the bypassed channels is coarser in comparison to the non-bypassed channel further downstream. In fact, if hungry waters (*sensu* Kondolf, 1997) downstream of dams were responsible for some armoring in the Rhône river, then we should expect the GSD in the bypassed reaches to be coarser and more depleted of fines, as a consequence of the combination of fine sediment winnowing by hungry waters and sediment trapping in the downstream reservoir. If such differences were to be observed between the bypassed and the non-bypassed channel, they would confirm hypothesis 3 and refute hypothesis 4. Finally, another potential evidence allowing to discriminate between hypothesis 3 and 4 would be to look at how the degree of surface coarsening correlates to the age of the dam. Although armoring is commonly

assumed to develop within 5-10 years following dam closure (e.g., Williams and Wolman, 1984; Grant, 2012), in those settings where gravel mobility is particularly slow, armouring could take longer to develop (e.g., Rollet et al., 2014). In this regard, given that many dams on the Rhône are coupled to a diversion canal that reduces the magnitude and frequency of coarse sediment mobility (Vázquez-Tarrío et al., 2019), we could imagine that armoring may have developed slowly in the Rhone. That said, if the degree of surface armoring were to be higher the older the dam, it would support hypothesis 3.

Not only should the individual pairs of hypotheses be tested, their cross combinations (i.e. scenarios) should be tested as well. For instance, in a Rhone River bed that adjusted through time to both embankments and dams (hypotheses 1 + 3), resemblance between present-day GSD and pre-management GSD will be weak or inexistent. The pre-management signal will be largely erased and GSD would covary with present-day water-surface slope. Also, the observed degree of surface coarsening will be less important in the upper Rhône compared to the middle + lower Rhône. In addition, the degree of bed patchiness (difference between main channel GSD and bar GSD) will be more important in the middle + lower Rhône compared to the upper Rhone. Finally, GSD in the bypassed reaches will be coarser and more depleted of fines and the degree of surface armouring will correlate with the age of the dam.

In a Rhone River bed in which embanked reaches were stable at the time of construction of the dams (hypotheses 1 + 4), then the observed degree of surface coarsening will be less important in the upper Rhône compared to the middle + lower Rhône. The degree of bed patchiness will be more important in the middle and lower Rhône compared to the upper Rhone. Conversely, in a Rhone River bed adjusted predominantly to the presence of dams (hypotheses 2 + 3), there would be no difference in the observed degree of surface coarsening between the upper and middle / lower Rhône. GSD will covary with present-day slope. Variability in surface coarsening would be related to differences in flow regulation amongst dams and subsequent flow diversion (i.e., the resulting balance between reduction in sediment supply and decreases in channel-altering flow frequency). GSD in the bypassed reaches will be coarser and more depleted of fines and the degree of surface armoring may correlate with the age of the dam.

Finally, in a Rhone River bed unimpacted by either embankments or dams (hypotheses 2 + 4), present-day GSD will resemble pre-management GSD. It will also covary with pre-management waterslope.

We are aware that these hypotheses might seem obvious to experienced researchers, as they are commonly informally used by geomorphologists. However, by explicitly posing them and testing each one against the available data, our goal was to avoid one of the major pitfalls of common expert-driven approaches, which is confirmation bias. To the extent that the same GSD patterns could reasonably be explained by different stressors or scenarios (equifinality, see above), it would be easy to be misled by our own preconceptions. As such, each researcher could attribute GSD trends observed in the Rhône to his or her preferred causal factor, with no more empirical basis other than the finding of covariation and cooccurrence that does not necessarily imply causality. Through these different hypotheses, we considered how the Rhône would have evolved if the different stressors had or had not had any effect on the grain size and thus evaluate what provides the most consistent framework with the contemporary grain size conditions.

4. Data collection

All the data used in this study were collected and compiled through the Rhône Sedimentary Observatory (OSR) – a multi-partner collaboration between river managers and research scientists created in 2009 with a mission to understand the spatial and temporal variability of sediment dynamics in the French Rhone and aid river managers in the development of sustainable management policies.

4.1. Grains size distributions

As part of a field campaign carried out by the OSR between 2011 – 2013 in collaboration with the CNR, we sampled the bed of the Rhone in order to characterize the grain size distribution along its entire length from Lake Geneva to the Mediterranean Sea. The field campaign was designed to apply standardized methods adapted to the different facies encountered along the river: navigable Total Rhone subreaches, navigable bypassed subreaches, unnavigable bypassed subreaches, the surface and subsurface of bars. As such, sampling was based on two different strategies. The plan laid out was to sample the bed at uniform intervals (approximately every 5 km) along all the bypassed and Total Rhone subreaches (diversion canals were not sampled). Sampling would be densified upstream and downstream of the dams and near major confluences (resulting in an average spacing of 1-3 km between samples). Sampling would take place on riffles

(typically representing the bar head or locally highest thalweg elevation). Sampling locations were determined in advance based on the most recent bathymetry available.

The majority of sampling was conducted from a boat (operated by the CNR) using their triangular dredge (similar to a KC triangular dredge) with frame dimensions of 50 x 50 x 50 cm. The frame consists of triangular teeth that guide material into a mesh bag (500 μ m diameter) with a capacity of 50 – 60 L. The sampling protocol we established called for three samples to be collected at each location. However, due to conditions in the field this was not always possible. In the end, a total of 260 viable dredge samples were collected at 120 discrete locations, equivalent to an average of 2.3 samples per site. Each sample was analysed separately volumetrically (mass) based on standard Wentworth size fractions; the coarse fraction was measured in the field using calipers and gravelometers and the finer fraction was sieved in the laboratory. The results were combined to obtain a single representative grain size distribution at each site.

Given that many reaches of the bypassed Rhone are unnavigable during low flow, we waded as far into the channel as was safe to do so and sampled the surface of the bed using the Wolman pebble count method (Wolman, 1954) to sample at least 100 randomly selected particles. A total of 34 Wolman counts of the active channel surface were conducted. Pebble counts were also conducted on the surface (55 samples) of exposed and accessible bars present in the bed at the time the field work was carried out. In addition, an adaptation of the Wolman pebble count method (Buffington, 1996) was followed to sample subsurface GSD. The coarse surface layer of the bed was removed, and a minimum of 100 pebbles were picked and measured. According to Rollet (2007), this method of sampling the subsurface is comparable to the surface Wolman count if the following precaution is taken in order to avoid oversampling the fine sediments in the subsurface: the fine matrix is sampled only when its thickness is greater than 2,5 cm (approximately the length of the tip of the finger to the first knuckle). If the matrix thickness is thinner than this, only the first particle encountered, excluding the matrix, is measured. The measure is always conducted by the same observer.

When conducting a volumetric sample of grain size, the total mass of sediments that should be sampled to be statistically representative is proportional to the maximum grain size present in the bed (i.e., D_{\max} ; Church et al., 1987; Bunte and Abt, 2001). According to Church et al., 1987, for a D_{\max} up to 128 mm, the mass of D_{\max} should not exceed 1% of the total sampled mass. For D_{\max} greater than 128 mm, then the mass of D_{\max} should

not exceed 5% of the total sampled mass. A comparison of the D_{\max} at each dredge site with the total sampled mass shows that 73% of all sites were within 5% of this rule and 30% of all sites were within 1% of this rule. According to Kellerhals and Bray (1971), the particle-size distributions determined from volume-by-weight and grid-by-number samples are equivalent in the sense that there is no need to apply a correction factor when comparing counts by-number with counts by-volume or by-mass (Bunte and Abt, 2001). Nevertheless, to the extent that sample procedures are different (and submitted to different biases), in this work we restricted ourselves to comparisons of data collected using the same procedure: data from Wolman counts or data from dredge samples.

4.2. Compilation of additional available data

A historical data of low flow water surface elevations at 1 km spacing as well as average water surface slope between successive points was previously made available to the OSR by the DREAL (Direction Régionale de l'Environnement, de l'Aménagement et du Logement). The dataset comes from a fascicule (known as the Armand Fascicule after the division engineer at the time) that was part of a monograph published by the French Corps of Bridges and Roads (Ponts et Chaussées) in 1910. The data are from 1867-1868 for the Upper Rhone (KP -159 to 0) and 1902-03 for the Lower Rhone (KP to 330) and provide a historical reference low flow slope close to the time river embankment began. Altitudes were based on the Bourdalouë reference system and were converted to the present-day reference system (NGF_IGN69). No information is available about how the measurements were made or their uncertainties.

We compiled available bathymetric data for the middle and lower Rhône (Figure 5). The earliest channel bathymetry we were able to reconstruct for the Rhone River is based on a series of maps produced by the Compagnie Nationale du Rhone (CNR) from measurements conducted by the French Corps of Bridges and Roads (Ponts et Chaussées): in 1897 from Lyon to Montélimar and 1907 - 1908 from Montélimar to the Mediterranean Sea. The French Navigation Authority (Voies Navigables de France - VNF) manages the reach between Saint Vallier and Vallabrègues and thus produced and owns the maps for this sector. The maps are only available for the navigable portion of the river downstream of Lyon. Scans of the maps were provided to us by the CNR Regional Direction based in Avignon, while paper versions of the maps were provided by the VNF. The maps were painstakingly georeferenced as precisely as possible in GIS based on comparison with recent IGN (Institut Géographique National) topographic maps and orthophotos.

Antonelli (2002) estimated the vertical resolution of these data as ± 10 cm. The data reported in these maps consist of flow depths along cross sections and elevations of local water surfaces. The depth corresponding to the deepest point at a cross section and its location was digitized every 500 m. Bed elevation corresponding to the thalweg was calculated by subtracting flow depth from water surface elevation. These thalweg points were used to construct a long profile of the bed, herein referred to as profile 1, representing bed elevation between 1897 – 1908: synchronous with the period channel embankments were being constructed but likely before they would have had any significant impact.

The CNR and VNF began surveying channel bathymetry along a reach coinciding with dam construction (1951) and have continued to survey the bed at increasingly close intervals. Figure 5 shows the spatial and temporal distribution of bathymetric data since the year corresponding to dam construction. The most recent bathymetric data (1999 – 2010) are available (in numerical form) through the 'BDT Rhone' (Rhone Topographic Data Base), compiled as part of the 'Plan Rhone' and managed and distributed by IGN. Historical bathymetry was provided to the OSR directly by the CNR and the VNF. These data have a vertical precision of ± 10 to 20 cm. From these data we constructed two long profiles based on thalweg elevation extracted every 500 m. A profile (herein referred to as profile 2) was constructed using bathymetry coinciding with the construction of each dam. We consider this long profile to represent the reference state of the bed along each reach prior to the impact of the dams and widespread gravel mining. Another profile (herein referred to as profile 3) was compiled from the most recent data available along each reach (1999 – 2010) and thus represents the present-day bed of the Rhone.

A differential analysis of the long profiles we compiled allowed us to study bed evolution in response to the two main periods of management works in the channel. We characterized bed evolution in response to embankments based on the difference in bed elevation between profile 2 and profile 1 (roughly, 1900-1950/1980, depending on the reach), and bed evolution in response to dams based on the difference in bed elevation between corrected profile 3 and profile 2 (1950/1980 – present, depending on the reach). Since the oldest maps (based on data from 1897 – 1908) do not exist upstream of Lyon, analyses of bed evolution in response to embankments were only carried out for the Rhone downstream of Lyon.

Finally, we used a recent compilation of historical gravel mining data (locations and volumes) conducted by the CNR Coeur (2017) for the Rhone downstream of Lyon in order to estimate the overall contribution of mining to the changes in bed elevation measured in the post dam period. We did this by assuming the volumes were extracted uniformly over the corresponding river kilometer and estimated the thickness of this layer by dividing by the surface area (i.e. channel width at the cross-section times 500 m – the average distance between two cross-sections) at that location. We used these estimates to correct changes in bed elevation over the post-dam period so as not to account for mining, as well as to estimate changes in bed elevation since mining operations ceased.

5. Results

5.1. General trends in grain size distributions

Median grain-sizes of samples collected with the dredge in the navigable channel and Wolman counts in the wadable channel are close to each other (Figure 6A); indeed, there are no statistically significant differences between both groups of data ($p\text{-value}=0.70 > 0.05$, Wilcoxon rank sum test). These observations suggest that dredge samples are comparable to samples of the streambed surface. This resembles the findings and observation of Singer (2008) using a comparable dredge sampler (Cooper Scooper), that in well armoured streambeds the GSD determined from dredge samples are close to the GSD of the surface sediment, but with a better representation of fines.

The D_{50} for samples collected with a dredge and Wolman surface samples show a common longitudinal trend (Figure 6 and 7): we observe fining in the upper Rhône, followed by coarsening around the confluence with the Ain confluence likely due to the coarse sediment load of this major tributary. Next, the D_{50} fines slightly between the confluence with the Ain River and Lyon, but clearly coarsens again in the middle Rhône. This coarsening is also observed in terms of a relative increase in particles > 64 mm in the middle Rhône (Figure 7). Finally, from the lower Rhône to the delta we observe downstream fining that is typical of natural rivers.

5.2. General trends in grain size distributions compared to pre-management and present-day water slopes

The downstream coarsening observed in channel surface GSD along the Rhône is not consistent with typical downstream fining trends reported for natural rivers. However,

figure 8 reveals how the longitudinal trend of GSD along the Rhone is comparable to pre-management water slope but different from present-day water slope for a 2-year flow (Figure 8). It also corresponds to the main compartmentalization of river channel slope and width (comparison of figures 2, 6, 7 and 8).

These similarities and differences suggest that present-day GSD in the Rhône is heavily influenced by pre-dam conditions (natural and/or embankments). Thus, present-day surface GSD in the Rhône appears to reflect the controls of channel morphology (slope, width) and tributary contributions on longitudinal sediment-fluxes prior to channel development. Nevertheless, as can be observed in figure 6, dams do exert some influence on GSD as seen by periodic drops in grain size upstream of dams associated with sediment trapping and siltation in the reservoirs.

5.3. Trends in the degree of surface coarsening and armour ratios

The median size of the subsurface samples available for the Rhône is less variable than that of the surface samples (coefficient of variation 0.25 in subsurface samples versus 0.34 in surface data; Figure 6). It nevertheless exhibits similar trends: some fining in the upper Rhône, followed by a slight coarsening in the middle Rhône (from 9.4 mm in the Ain-Miribel reach, to 9.8 mm in the middle Rhône). In addition, subsurface sediments are finer than those in the bed surface (average of 10.5 mm versus 22.0 mm respectively), as is expected in a gravel-bed river (Figure 6 and 9). The degree of this surface coarsening (armouring) varies along the river corridor. Armour ratios, estimated as the ratio between the surface and subsurface D_{50} , increase in the middle and lower Rhône compared to the upper Rhône and the Ain-Miribel sector (an average of 1.9 versus 3.1, respectively; Figures 9A and 10). Furthermore, despite damming of the upper Rhône in the 1970s and 80s, armour ratios in the upper Rhône are low (~1.5 - 2.5). Finally, data show a large scatter when armour ratios are plotted versus the date of dam construction (Figure 10) and no correlation is observed between the degree of armouring and the age of the dam. Rather, armour ratios seem to segregate according to longitudinal position along the Rhône (Figures 9A and 10), with smaller ratios in the upper Rhône and Ain-Miribel sector, and larger armour ratios in the middle Rhône. The trends in armour ratios in the Rhône correspond to trends observed in the pre-management slope, with armour increase from the Ain-Miribel sector to the middle Rhône. However, they also correlate with the potential effects of river training (i.e., embankments) at the beginning of the 20th century,

which affected the middle and lower Rhône but not the upper channel or the Ain-Miribel sector.

5.4. Trends in the degree of bed patchiness

Grain-sizes show differences in patterns of segregation between channel and bar surfaces along the Rhône corridor (Figure 9B). In the upper Rhône, channel D_{50} is slightly finer in the wetted channel but there is large overlap between gravel-bar and wetted-channel GSD. Along the Ain-Miribel sector, the trend is reversed - D_{50} is coarser in the wetted channel compared to bars. It's worth noting that despite this reversal, D_{50} in the wetted-channel hardly changes between the Upper Rhône and the Ain-Miribel sector. A slight coarsening is nevertheless observed most likely in response to the coarse sediment inputs from the Ain (although grain-size segregation between channels and bars is typically due to the progressive fining of bars rather than coarsening of the wetted-channel). In the middle and lower Rhône valleys (downstream of Lyon), the GSD of both the channel and the bars coarsens considerably. While this could be the result of natural variations in valley slope and as such flow competence along the Rhône river, differences between the D_{50} of bars and the channel are also more pronounced in the middle/lower Rhône than in the upper Rhône, and the wetted channel is also more armoured than the gravel-bars. These differences do not occur in the upper Rhône and the Ain-Miribel sector (the wetted channel and gravel-bars have comparable armour ratios). Thus, in addition to surface coarsening, we observed a higher degree of bed patchiness and lateral disconnection between channel and bars in the middle and lower Rhône that is in sharp contrast with the upper Rhône.

These results suggest contrasting sediment transport regimes in the Rhône upstream and downstream of Lyon. The increased bed patchiness in the middle/lower Rhône points towards bed incision and active channel narrowing that decreased the frequency of bar mobility in the middle and lower Rhône. The implication of this is that bars in the middle and lower Rhône may be relict features (i.e., abandoned terraces) from a previous regime characterised by more mobile sediments and it may explain why there is a clear difference in armour ratios between the bars and the channel in the middle/upper Rhône.

5.5. Reach-scale patterns of grain-size sorting

A comparison between reach-averaged dredge GSD in the bypassed and the non-bypassed reaches shows that the median sizes of these sub-reaches are very similar (Figure 11). This result disproves the hypothesis that sediment starved waters below dams

coarsened the grain-size in the bypassed Rhône. Here again, it is important to recall that diversion dams on the Rhône river not only disrupted the longitudinal sediment continuity, but also lowered the magnitude and frequency of peak flows, which likely decreased the frequency and magnitude of bedload transport. This reduction in transport may have actually preserved the predam GSD in the bypassed subreaches of the Rhône. Indeed, in some reaches the D_{50} of the non-bypassed subreach is slightly larger than in the bypassed channels.

5.5. General trends in bed elevation in the middle and lower Rhône valley

Historical and recent topo-bathymetric data available for the middle and lower Rhône Rhône river downstream made it possible to analyse vertical bed evolution in response to the different phases of management (Figure 12 and 13). The results indicate widespread and relatively uniform incision in response to embankments (average rate of 1.7 cm/yr), followed by a slightly slower rate of incision and a more variable bed response during the post dam period (average rate of 1.2 cm/yr). It is important to note that incision rates over the post dam period include the impacts of gravel mining, which was systematic and sustained in several reaches along the Rhône, in particular near the confluences with major tributaries (Coeur, 2017). As such, incision rates are lower (average rate of 0.5 – 0.9 cm/yr) when changes in bed elevation due to gravel mining are neglected from the analysis of vertical bed elevation changes (Figures 12 and 13), suggesting that most of the bed elevation changes reported during the second half of the XXth century were related to gravel-mining. We also looked at changes in bed elevation after commercial mining ceased, which shows that the bed of the Rhône tends to be globally stable but with strong local variability likely attributed to channel maintenance (i.e., local dredging and flushing flows).

A comparison of figures 9 and 13 highlights how trends observed in the rate of bed elevation changes in the middle and lower Rhône correlates with those reported in the armour ratios: the lower Rhône was more incised than the middle Rhône throughout the 20th century and exhibits larger armour ratios in the wetted channel.

5.6. Summary of observations

Our results demonstrate that downstream patterns in GSD correspond globally to those observed in the pre-management low flow slope and the main natural compartmentalization of the river valley continuum. They also show that trends in GSD

and armouring in the middle and lower Rhône are uncorrelated to the age of dams or present-day water slope for a 2-year flow (Figures 8 and 10), suggesting that dams did not have a large influence on present-day GSD. This idea is reinforced by our observation of significant coarsening in the bypassed reaches compared to the non-bypassed ones (Figure 11). The sum of these observations suggests that the atypical downstream coarsening observed in bar samples in the middle and lower Rhône predates the dams and corresponds with predam hydraulic conditions. The hypothesis that dams did not significantly impact present-day GSD is further supported by an important reduction in incision rates post-dams relative to incision rates post-embankments (Figures 12 and 13). Furthermore, our analysis of GSD in the wetted-channel showed a coarsening in the middle Rhône relative to the lower Rhône, opposite of the trend observed in bars (Figure 9B). This result suggests that the wetted-channel continued coarsening after bars became disconnected from the channel in the middle Rhône, further supporting the idea that the channel was affected by drivers post-dating the pre-management channel but pre-dating the construction of dams. Channel narrowing and embankments here again are the usual suspects. Finally, generally low armour ratios (~1.5 - 2.5, fig. 9A and 10) and a low degree of bed patchiness in the upper Rhône (fig. 9B), despite extensive damming in the 1970s and 1980s, supports the idea that dams did not significantly impact surface grain-size on the Rhône river.

The sum of these observations points towards a combination of hypothesis 1 and 4 (from the four initially formulated, see figure 2) as the most plausible explanation of the present-day GSD trends observed in the Rhône. The Rhône river is characterized by a clear compartmentalization into two main sectors: an upper sector (up until the city of Lyon) with strong sediment delivery from alpine sediment sources and a large influence of the effects of the Little Ice Age. This upper sector did not undergo straightening and narrowing during the first development phase at the end of the 19th century. Downstream of this sector is a lower sector that consists of a naturally wider valley. Embankments were installed along this sector at the beginning of the XXth century which increased channel shear stress triggering bed incision (figure 13) and surface coarsening. The dams constructed in the second half of the XXth century were superimposed on a river adjusted to previous disturbances and did not significantly impact surface GSD.

6. Discussion

6.1. Plausible scenarios of grain-size response to management impacts in the Rhône river

Several plausible scenarios of channel adjustment, each associated with different GSD trends, in response to the two main phases of management since the end of the 19th century (Figure 4) can be put forward based on the testable hypotheses that we formulated (section 3.2):

i) *Scenario 1 (bed evolution in response to combined effects of embankments + dams)*: This scenario describes the Rhone's trajectory if the data confirms that hypotheses 1 and 3 are the most likely. In this scenario, the middle and lower Rhone River underwent bed adjustments in response to embankments followed by dams. In the beginning of the 20th century, channel embankments concentrated the flow and sediment flux into a narrow band of the main channel of the Rhone. The resulting increase in bed shear stresses, together with the abandonment of secondary channels and the lateral disconnection from sediment stores in the margins triggered bed incision and led to streambed coarsening in the middle and lower Rhône (not in the upper Rhône). Subsequently, dams further reduced sediment availability in the main channel enhancing bed incision and surface coarsening in the middle and lower Rhône and initiating coarsening in the upper Rhône.

ii) *Scenario 2 (bed evolution in response to embankments only)*: This scenario describes the Rhone's trajectory if the data confirms that hypotheses 1 and 4 are the most likely. In this scenario, channel embankments had an important effect on bed incision and surface coarsening in the middle and lower Rhône. This wave of surface coarsening resulted in a bed that was paved and relatively immobile at the time of dam construction. As such, dams led to no additional adjustments in the channel in previously embanked reaches and only had the potential to impact the (non-embanked) upper Rhone. However, diversion dams in the Rhône reduced sediment supply to the downstream as well as the frequency of sediment transport and channel-forming flows. This would have contributed to a relatively unchanged bed surface after dam construction in both the upper and middle and lower Rhône.

iii) *Scenario 3 (bed evolution in response to dams only)*: This scenario describes the Rhone's trajectory if the data confirms that hypotheses 2 and 3 are the most likely. In this scenario, the Rhone River underwent adjustments in response to the dams – the embankments that preceded had no significant impact on the channel. This scenario is

based on the possibility that in the post-embankment period (first half of the twentieth century), sediment supplies from tributaries were relatively unaltered and large stores of sediment were available from inputs during the Little Ice Age (Bravard, 1992; 2010), resulting in minimal GSD adjustments. It is further posited that these supplies were diminished by the time of dam construction, resulting in channel coarsening downstream of the dams.

iv) *Scenario 4 (no dams, neither embankments had any impact on bed evolution):*

This scenario describes the Rhone's trajectory if the data confirms that hypotheses 2 and 4 are the most likely. In this scenario, neither embankments nor dams had an impact on channel GSD in the Rhone River. Any changes in channel morphology reflect an adjustment to natural changes in hydrology and/or sediment, such as those resulting from land use changes and headwater afforestation during the XXth century.

Each of these four scenarios is therefore associated with slightly different GSD trends. Our analysis of the grain-size data available for the Rhône shows three clear trends: i. a downstream coarsening pattern along significant portions of the river; ii. a larger degree of surface armouring in the lower/middle Rhône compared to the upper channel; and iii. a higher degree of bed patchiness in the lower and middle Rhône and bars that are systematically finer than the wetted channel. Coupling these observations with our hypothesis-driven analysis and existing historical data on bed elevation changes lead us to conclude that present-day GSD trends in the Rhône cannot be attributed to one unique driver, but rather, are the result of a more complex scenario in which bed evolution was predominantly driven by natural legacies combined with embankments. We further conclude that diversion dams had little to no impact. In other words, we conclude that the scenario 2 best describes the historical trajectory of the Rhone.

The natural legacies affecting the Rhône's GSD trends are geological, and in particular related to the geomorphological configuration of the valley and its glacial history. The upper Rhône valley was covered by glaciers during the last glacial period. As such, the geomorphic configuration of the upper Rhône valley is controlled by this history, alternating wide glacial basins and umbilicus sculpted by glacial erosion filled with Holocene lacustrine sediments generating wide and low sloped floodplains, upstream of valley constrictions imposed by more resistant bedrock. Furthermore, given the upper Rhône's proximity to Alpine sediment sources, it likely received intense coarse sediment input from the Alpine foothills, particularly important during the Little Ice Age (Bravard

and Peiry, 1993; Bravard, 2010). The combination of a glacial heritage and high sediment supply lead to the formation of large alluvial plains in the upper Rhône. In this context, the downstream fining reported for the upper Rhône could be considered as representing progressive sorting of relatively mobile sediment introduced into the main channel by alpine tributaries while propagating downstream the alluvial valley. Indeed, according to fig. 8B, downstream fining in the upper Rhône is more evident when looking at gravel-bars, signifying that sediment introduced into the channel quickly self-organized as migrating bars that became progressively sorted by size-selective transport and/or abrasion while travelling downstream. Hence, it appears that the Rhône river's highly particular and conspicuous grain-size trend of downstream coarsening in the middle valley is a legacy of its geological and glacial heritage, as well as tributary inputs (Figures 9 – 13).

Human pressures also had a notable influence on present-day GSD. The first wave of river training works most likely enhanced surface coarsening in the middle Rhone during the first half of the 20th century, up to such a point that there was little potential for further bed adjustments when the dams were constructed (second half of the 20th century). In other words, at the time of dam construction, the bed surface had likely already coarsened in the middle and lower Rhône and any further adjustment in response to the dams was minimal. In fact, flow diversion at dams considerably reduced the frequency and magnitude of floods and as a result bed mobility downstream (Vázquez-Tarrío et al., 2019), thereby attenuating the potential action of 'hungry waters' and contributing to stabilising the pre-dam bed state. Consequently, reduced bed mobility due to flow regulation by dams most likely contributed to 'freezing' (i.e. maintain) the bed surface GSD in its pre-dam bed state.

As such, we conclude that dams did not have a 'direct' control on present-day GSD along the Rhône River and that the GSD footprint of the dams is minimal compared to pre-management conditions and embankments. The observed trends in GSD are well explained by other drivers, including the natural configuration of the river valley and the consequences of river training. This is further confirmed by bed elevation changes observed downstream of Lyon following the river training period. This conclusion does not, however, preclude dams from being a major driver of hydro-sedimentary functioning in the present-day Rhône river. Dams along the Rhône regulate flow, disrupt sediment continuity, and impose a dramatic planform configuration on the river channel. The

multiple dams lead to a sequence of independent compartments along the Rhone with severely disrupted sediment continuity between them (Dépret et al., 2019; Vázquez-Tarrío et al., 2019).

Apart from embankments and dams, the Rhône river was subject to other potential drivers of change that may have impacted surface texture, such as gravel-mining and land-use changes at the catchment scale. Gravel-mining was widespread along the main stem of the Rhône during the second half of the XXth century. Our analysis suggests that gravel-mining had some impact on bed elevation along the Rhône but to a lesser degree than embankments (see figures 12 and 13 showing lower incision rates in the second half of the XXth century). Furthermore, as with dams, gravel-mining was carried out along the Rhône after the channel was already narrowed by embankments, so the bed surface was probably already coarsened and further adjustment in response to gravel extractions were minimal. On the other hand, the Rhône river basin experienced important changes in land cover during the XXth century, notably upland afforestation and torrential control works in the headwater channels (Provansal et al., 2014). This driver was not explicitly analyzed in our work. While these land-use changes may have had an influence on the present-day channel, we think that they are minimal for the following reasons. Land-use changes started in the beginning of the XXth century at a time when the Rhône and its main tributaries had large sediment stocks following the end of the Little Ice Age (Bravard and Peiry, 1993; Bravard, 201). Furthermore, the time required for these changes to impact the main channel given a distance of ~100-200 km between the headwater areas and the main channel and typical transfer times of coarse-sediment of ~1 km/year would render them imperceptible. Summarizing, from the plausible scenarios, scenario 2 (Figure 4) is the one most likely to have governed the geomorphic trajectory followed by the Rhône during the 20th century. However, our analysis of present day GSD also highlights the complexity on the Rhône river in which interactions and overlap between natural legacies (geologic and landscape conditions), climate memory (Little Ice Age), and multiple human disturbances impose the boundary conditions within which present-day geomorphological processes operate in the river. It also makes clear how consideration of history, contingencies, and non-linear causal relations is fundamental to understanding complex systems such as the Rhône river.

6.2. Advantages and limitations of a hypothesis-driven approach for disentangling the effects of multiple human pressures: implications for future studies

Many research challenges exist across a wide range of disciplines with regard to identifying and separating the signal of human-forcings from natural variability, and tackling these challenges has been the core focus of many studies in a wide range of disciplines from ecology to climate change studies (Smokorowski and Randall, 2017; Downs and Piégay, 2019). For instance, in climate change studies the focus has been on attributing human activities to observed long-term changes in climate parameters (surface temperature, precipitation, circulation), as well as extreme events (storms, hurricanes, heat waves) (Zhai et al., 2018). Similarly, in ecological monitoring studies, the search for the quantification of environmental impacts lead to the development of the Before-After-Control-Impact (BACI) design, considered to be a statistically powerful experimental design for environmental impact research (Underwood, 1992; Smokorowski and Randall, 2017) and that is being increasingly applied in fluvial geomorphology (see recent work by Marteau et al., 2022).

Common to all of these studies is the use of a relatively simple, but rigorous and powerful, hypothesis-driven framework to attribute and quantify human-induced anthropogenic influences to observed changes in complex, multicausal and non-linear systems (e.g. climate, ecosystem function, biodiversity). Underlying the BACI approach, for example, is the following hypothesis: if human disturbances had a significant effect, then we can expect to observe differences between the trajectory followed by a site with human impacts and a comparable site with no human impacts. This hypothesis is then compared against field data. Similarly, in climate-change attribution studies, the following hypothesis lies at their core: if human activity has induced long-term changes in climate trends, then the observed trends should be consistent with the results of numerical and physical models considering human-induced changes but not consistent with the results of models excluding human disturbances.

Hence, simple hypothesis-deductive, causation frames have been proven to be a very effective tool for detecting and attributing changes to anthropogenic influences in many environmental and Earth-surface sciences. We can assume that applying such a framework in fluvial geomorphology would yield interesting results. However, up to our knowledge, the study of human impacts in fluvial geomorphology has been (and still is) in many cases dominated by the classical approach: a detailed description of the

trajectories followed by rivers during the last decades (going back to the date of the oldest maps or aerial photographs available), and their subsequent attribution to a preidentified single human disturbance (e.g., dams, embankments, land-use changes) (Downs and Piégay, 2019). At this point, it is worth reiterating that *detection* of a human signal does not necessarily imply *attribution*, as is nowadays well recognized in climate change studies. Detection implies identifying a trend that cannot be solely explained by natural variability, while attribution means that the detected trend cannot be explained if a specific pre-identified human disturbance is excluded. As has been recently recognized by others (e.g. Downs and Piégay, 2019; Martin-Vide et al., 2021), this distinction is important and has many implications for studies in fluvial geomorphology.

In the case of the Rhône river, the reported GSD tendencies are not easily explained by simple, straightforward associations between the observed GSD trends and different potential drivers of changes. For example, conspicuous differences observed between the upper and the lower/middle Rhône are not explained by dams or gravel mining alone, in so far as both were widespread along the entire river corridor. River embankments may explain coarsening in the middle Rhône, but the question of why dams did not result in coarsening in the upper Rhône (not embanked prior to dams) remains. Continuing on, natural controls provide a likely explanation of the general downstream trend in GSD (corresponding to the main compartmentalization of channel slope and valley width along the river) but fails to provide a satisfactory explanation of the observed GSD segregation between bars and channel in the middle/lower Rhône and the bed incision observed. Rather than simple, linear associations between GSD trends and specific controls, our analysis highlights how the overlap and interaction amongst multiple stressors and landscape history play an important role in the Rhône. The importance of the order in which different phases of human development was also implicit in the testable hypotheses that were proposed. Had embankments been constructed in the Rhône after the dams, present-day GSD trends might be different. Likewise, had the geological/geomorphologic context been different, the impact of human disturbances would have been different, i.e., if the Rhône river was located in a region of lower relief and a more arid climate (rather than a European Alpine setting), it is possible to imagine a very different geomorphic trajectory (contingency factors).

Given the complex nature of interactions in river systems over long time periods, uncertainties will inevitably exist, however, we are convinced a hypothesis-deductive

approach constitutes our best chance for a structured, rigorous and systematic strategy to disentangle the effects of multiple human pressures from natural variability in rivers. Posing explicit testable hypotheses provides a powerful framework for moving beyond simple detection of associations to robust attribution of effects in fluvial geomorphology and this is what we sought to illustrate in this study. We explicitly formulated several plausible hypothesis to explain the geomorphological trajectories followed by the Rhône river during the last couple of centuries, which were based on a set of factors that were *detected* in previous research to have an influence on the Rhône river trajectory (dams, embankments, natural legacies). We then tested these hypotheses and examined how they fared when confronted with available data. Finally, we *attributed* the observed trends in data to the most consistent scenario. This hypothesis-driven approach is more complex than the one followed in the BACI design, which may be overly simplistic in the case of an overlap amongst multiple stressors and/or previous landscape legacies along a river corridor, resulting in divergent trajectories between the impacted and control reaches that cannot be solely attributed to the preidentified human disturbance..

6.3. Epistemic implications for fluvial geomorphology

Philosopher Charles S. Peirce (1878) identified three different types of logical reasoning in science: i. inductive; ii. deductive; and iii. abductive. Induction involves inferring general or universal rules from the regularities found in observed data, assuming that these regular patterns would be valid for comparable situations or datasets. Induction involves a ‘bottom-up’ or ‘data-driven’ approach: we start by observing and searching for patterns in empirically collected data, we then extract general rules that we apply for prediction. Deductive reasoning is the opposite process of reasoning, and is largely based on the use of conditionals. When using a deductive approach, general rules or statements are first posed and then reduced to their ultimate conclusion. Deduction involves an ‘up-down’ or ‘hypothesis-driven’ scheme of thought, where hypotheses are first formulated and afterwards their conclusions are checked against observed data. Finally, abductive reasoning consists of choosing the most likely explanation or precondition from a limited set of data. Abduction is a kind of ‘heuristic’ reasoning (Tversky and Kahneman, 1974), and is commonly described as ‘inference to the best explanation’.

These three different ways of reasoning each have their pros and cons. The major drawback of induction is the so called ‘skeptical problem’ of induction, with its roots in the work of David Hume (1739, 1748) and later rediscovered in the philosophy of science

by Karl Popper (Chalmers, 1976; de los Campos, 2021). Induction assumes that our general observations of regularities are enough to justify some expectations or predictions, but indeed there is no logical basis ensuring that future observations will be the same as those in the past. Deduction is unaffected by this concern, as long as predictions are logically (conditionally) rooted in the hypothesis: if the hypothesis is true, we can be 100% sure of our conclusions. Indeed, when hypotheses are formulated and stated in such a way that they can easily be ‘falsified’ against empirical data, they provide a powerful tool for science. However, deduction only reveals what is already contained in the initial hypothesis and does not produce new information (Agrippa’s trilemma), so this approach becomes limited when confronted with new and unstructured problems. Abductive reasoning provides a solution for the latter, as long as expert judgement is used to determine the most reasonable explanation for observed phenomena based on a combination of prior sources of knowledge. However, there are always several explanations for the same observed patterns, and nothing ensures that expert explanations are actually true. So, unlike deductive reasoning, abduction has a strong charge of subjectivity and a high risk of ‘confirmation bias’ (Wason, 1960; Tversky and Kahneman, 1974; Ioannidis, 2005; Plutynski, 2011; Curtis, 2012; Ball, 2017), i.e., the inherent cognitive tendency in humans to search for evidences that confirm their preconceptions and ignore those that question them.

In order to avoid the risks of ‘confirmation biases’ when exploring the origin of landforms, a long epistemological tradition in geomorphology has argued for the use of multiple hypothesis (Haines-Young and Petch, 1983; Kennedy, 2006). And this methodological paradigm can be traced back to classical works by Gilbert (1886; 1896); and Chamberlin (1890) who considered a “multiple working hypothesis” method the only way to avoid the confirmation biases inherent in using a single ruling hypothesis, brilliantly summarized and illustrated by S. Schumm (Schumm, 1991; Schumm and Piégay, 2003). However, up to our knowledge, despite this long-standing tradition, fluvial geomorphology studies focused on the trajectories of change in rivers, as in many other branches of earth sciences and geology (Raab and Frodeman, 2002; Curtis, 2012; Polson and Curtis, 2010; Baker, 2014) have been largely dominated by inductive or abductive approaches. Hence, structured and hypothesis-driven research designs have not been common, limiting the opportunities for fluvial geomorphologists to develop robust, causal-attribution models of geomorphological changes and river’s sensitivity to

anthropic and natural drivers (Downs and Piégay, 2019) and testing them in new areas of study.

We believe our study case provides a nice example of the clear risks and drawbacks of not using a deductive approach. In logical terms, induction involves inferring a *rule* after observing several times that the same *precondition* is followed by the same *conclusion*. Had we approached the Rhône data following an inductive or abductive approach, we would have likely gotten confused as illustrated in the following example on the application of the inductive approach to the Rhône:

- *Precondition*: Many rivers worldwide exhibit downstream fining.
- *Rule*: All rivers exhibit downstream fining
- *Conclusion / Observation*: The Rhône is a river, so the Rhône must exhibit downstream fining.

As such, we would have been surprised to observe downstream coarsening in the Rhône when we looked at the data (Figure 6), and this would have obliged us to conflate induction with abduction and as such search for a new explanation. As experts in fluvial geomorphology, we know that dammed rivers are typically armored, so we would have likely proceeded as follows (abduction):

- *Conclusion*: The Rhône River exhibits coarsening
- *Rule*: All dammed rivers exhibit coarsening
- *Precondition*: The Rhône River is dammed, so this may explain the observed coarsening

We can see how, in logical terms, the abduction step involved determining the *precondition* (the Rhône has dams and this explains coarsening) using the *conclusion* (the Rhône exhibits coarsening) and the *rule* (rivers with dams exhibit coarsening), assuming that the chosen rule is the right explanation for our study case. However, we could have also reasoned that rivers that were narrowed coarsened, or searched for any other alternative and plausible explanation. The problem is the large amount of subjectivity in this way of approaching the problem, which has the potential to lead to conclusions heavily biased by our scientific background and our previous experience with the study site, leaves us exposed to ‘confirmation bias’ (Wason, 1960).

We are aware that the previous example is quite simplistic and can be much more nuanced. However, our goal is to highlight the following basic point: had we started by

looking at the Rhône data in an unstructured way, and then tried to come up with the best explanation for the observed patterns (figure 6), we would have quickly become confused and hesitated between the many possible explanations for the observed trends (tributaries, embankments, dams, glacial heritage...etc). Is the downstream coarsening pattern observed in the Rhône a consequence of sediment starvation following intense dam construction in the second half of the XXth century? Is it the result of river embankments? Or is it mostly controlled by local controls (gravel-mining, tributary inputs)? What is the role of natural legacies? Does the complex interaction amongst all these drivers explain the large variability in Rhône's GSD? Our analysis shows that using a classical approach would not have allowed us to arrive at a robust scheme for the geomorphological trajectory of the Rhône river during the last century and a half, but rather only a list of potential drivers without the ability to distinguish amongst their respective contributions. Rather, the 'multiple-working hypothesis' approach followed here provided us a structured way to tackle our research problem, identify new directions for future research, and is likely the most appropriate approach when dealing with rivers with long and complex histories of human management.

7. Conclusions

In this paper we sought to reconstruct the geomorphic trajectory followed by the French Rhône over the last century and a half based on present-day trends in grain-size from measured field data. Instead of moving from the data to conceptual models ('bottom-up' approach), as is commonly done in many geomorphological studies, we took a hypothetical-deductive 'top-down' approach: we started by posing hypothetical but geomorphological coherent scenarios for geomorphic trajectories in the Rhône river that we then tested against GSD collected in the field in a structured way.

According to our analysis, a complete understanding of trajectories in the Rhône river necessitates an understanding of how the effects of dams interacted with the previous history of management, at both the local and river corridor scale. Dams on the Rhone imposed a hydro-morphologically novel configuration which undoubtedly conditions present-day transfers of water and sediment. However, we did not find a unique direct cause-effect signature of dams on grain-size. Rather, we observed a highly variable and multi-scale response related to the impacts of multiple stressors and a combination of the Rhone's natural legacy with an earlier phase of management (embankments).

Several phenomena can explain this. First, the existence of an earlier development phase (embankments) that already had a substantive response on the riverbed. Secondly, dams on the Rhône river are mostly run-of-the-river dams that divert flow to a canal. Hence, there are a series of factors linked to this particular hydropower scheme that modulate the exact nature of riverbed response on a reach-by-reach basis including how flow frequency and peak flows are altered by the dam (and as a result the frequency and magnitude of bed mobility), sediment stocks available in the channel, the influence of tributaries, and the age of the dam. Consequently, far from showing a clear and homogenous picture, post-dam evolution in the Rhône has been highly heterogeneous. This fact thwarts attempts to draw a general picture of the exact downstream effects of diversion dams on a large river such as the Rhône.

We think that this study reinforces that cause-effect understanding of river channel evolution during the Anthropocene must focus on the cumulative impact of multiple drivers for change, as outlined by Downs and Piégay (2019), with a special focus on how geomorphological processes coevolved with human activities.

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clarify how the evidence-based approach is necessary to make fluvial geomorphology more robust and responsible.

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FIGURE & TABLE CAPTIONS

Figure 1. Location of the study reach, the main tributaries, the embankments, and the hydroelectric construction in the Rhône watershed basin. KP (Kilometric point) is the riverbank mark unit, corresponding to the localisation in the riverbank. KP 0 is located in Lyon.

Figure 2. A) Long-profile of the Rhône river, from Lake Geneva to the Mediterranean Sea. B) Pre-Girardon low flow slope and active channel width of the French Rhône river. The water slope data comes from a fascicule (known as the Armand Fascicule after the division engineer at the time) that was part of a monograph published by the French Corps of Bridges and Roads in 1910 (Ponts et Chaussées, 1910). The data date from 1867-1868 for the Upper Rhone (KP -159 to 0) and 1902-03 for the Lower Rhone (KP to 330). Active channel width data were extracted from Bravard (2010). Bravard (2010) based on the 1:10 000 scale map elaborated by the “Ponts et Chaussées” (Bridges and Roads) public administration between 1857 and 1866.

Figure 3. (A and B) Aerial (A) and oblique (B) view of a typical Girardon channelization system. (C) Example of the typical planform configuration of the dominant hydropower scheme in the Rhône river. DD: Diversion dam. DC: Diversion canal. BCh: Bypassed channel. HP: Hydropower plant. TR: Non-diverted channel.

Figure 4. Conceptual framework used in the present research with the main hypothesis and the proposed analysis for hypothesis testing.

Figure 5. Available topo-bathymetrical data for the Rhône river. Red crosses indicate the location and date of construction of dams.

Figure 6. Longitudinal trends in grain-size in the Rhône river channel. Regression lines were derived from a third-order polynomial fit.

Figure 7. Relative percentage of different size classes within the dredge samples.

Figure 8. Longitudinal trends in D_{50} for the dredge samples, compared to the pre-management (1867-1868 for the Upper Rhone and 1902-03 for the Lower Rhone) low water surface slope and the present-day water surface slope for a 2-year flood (extracted from Vázquez-Tarrió et al., 2019).

Figure 9. A) Armour ratio for the main compartments defined in the Rhône’s longitudinal corridor. Armour ratios have been estimated as the ratio between the median size for the surface (D_{50s}) and the subsurface (D_{50ss}) sediment. B) Patterns of bed segregation between the bars and the wetted channel along the Rhône’s corridor.

Figure 10. Armour ratio plotted versus the date of the upstream dam construction. Armour ratios have been estimated as the ratio between the median size for the surface (D_{50s}) and the subsurface (D_{50ss}) sediment. A) Armour ratios estimated based on gravel-bar samples. B) Armour ratios estimated based on channel samples.

Figure 11. Reach-averaged D_{50} of the dredge samples in the non-diverted channel plotted versus the reach-averaged D_{50} of the bypassed channel.

Figure 12. Cumulated changes in the rate of thalweg elevation changes in the Rhône downstream of Lyon, following the different phases of human development.

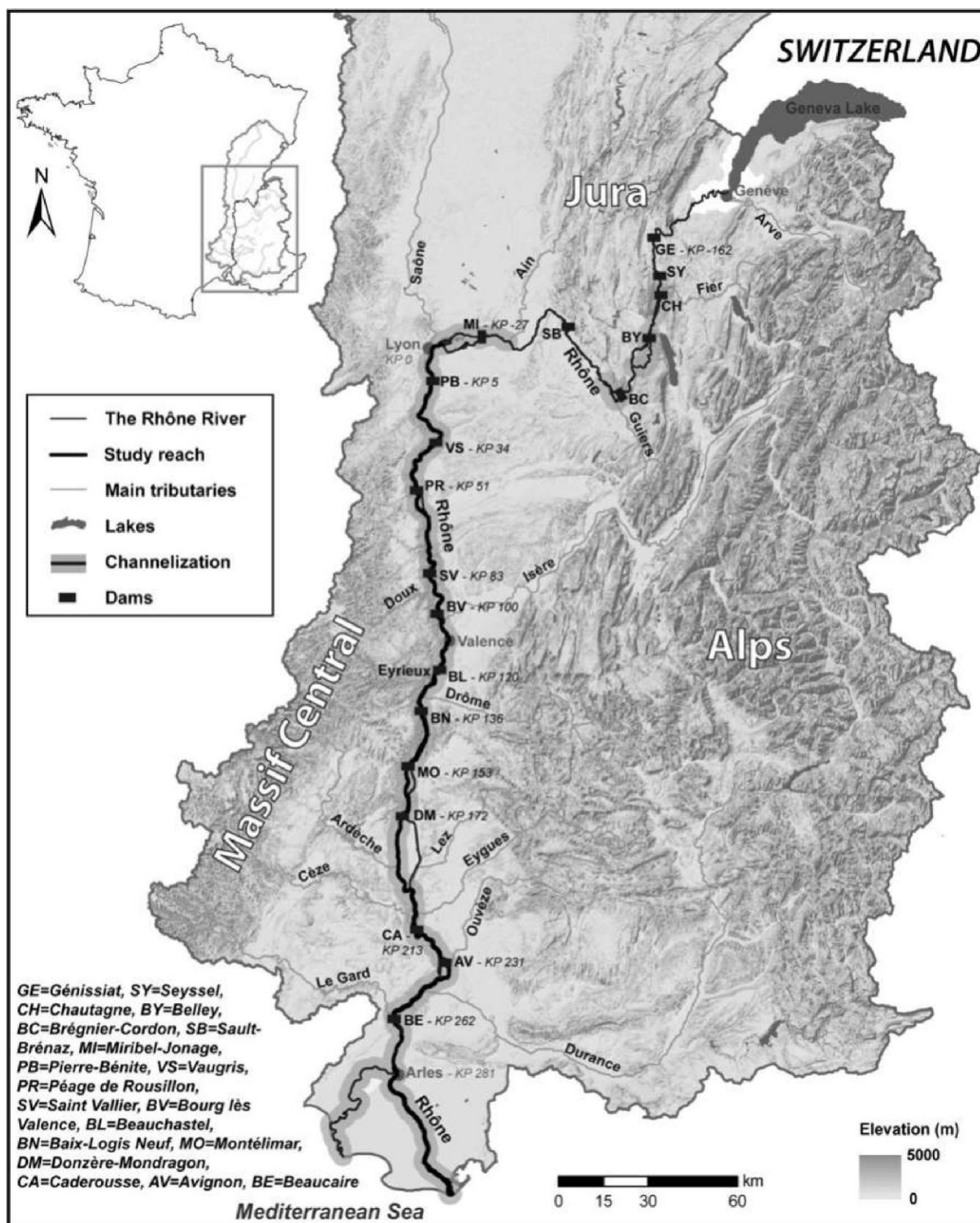
Figure 13. Rates of thalweg elevation changes in the Rhône downstream of Lyon, following the different phases of human development.

Table 1. Main characteristics of the main Rhône’s channel sectors.

Secteur	Average Slope	Main tributaries	Observations
Upper Rhône	Variable	Guiers	From Lake Geneve to Ain's confluence. Valley width variable: gorges alternate with glacial umbilicus
Ain-Miribel	0.001	Ain	From Ain's to Saône's confluences. Coarse sediment inputs from the Ain.
Middle Rhône	0.0005	Saône	From Saône's to Isère's confluences. Narrow floodplain, old fluvial terraces.
Lower Rhône	0.0006	Isère, Drôme, Ardèche, Durance, Gardon	From the Isère confluence to the head of the delta. Variable channel width.
Delta	<0.00009	-	From Arles to the Mediterranean Sea. Dominantly sand-bedded.

Table 1. Main characteristics of the main Rhône's channel sectors.

Figure1



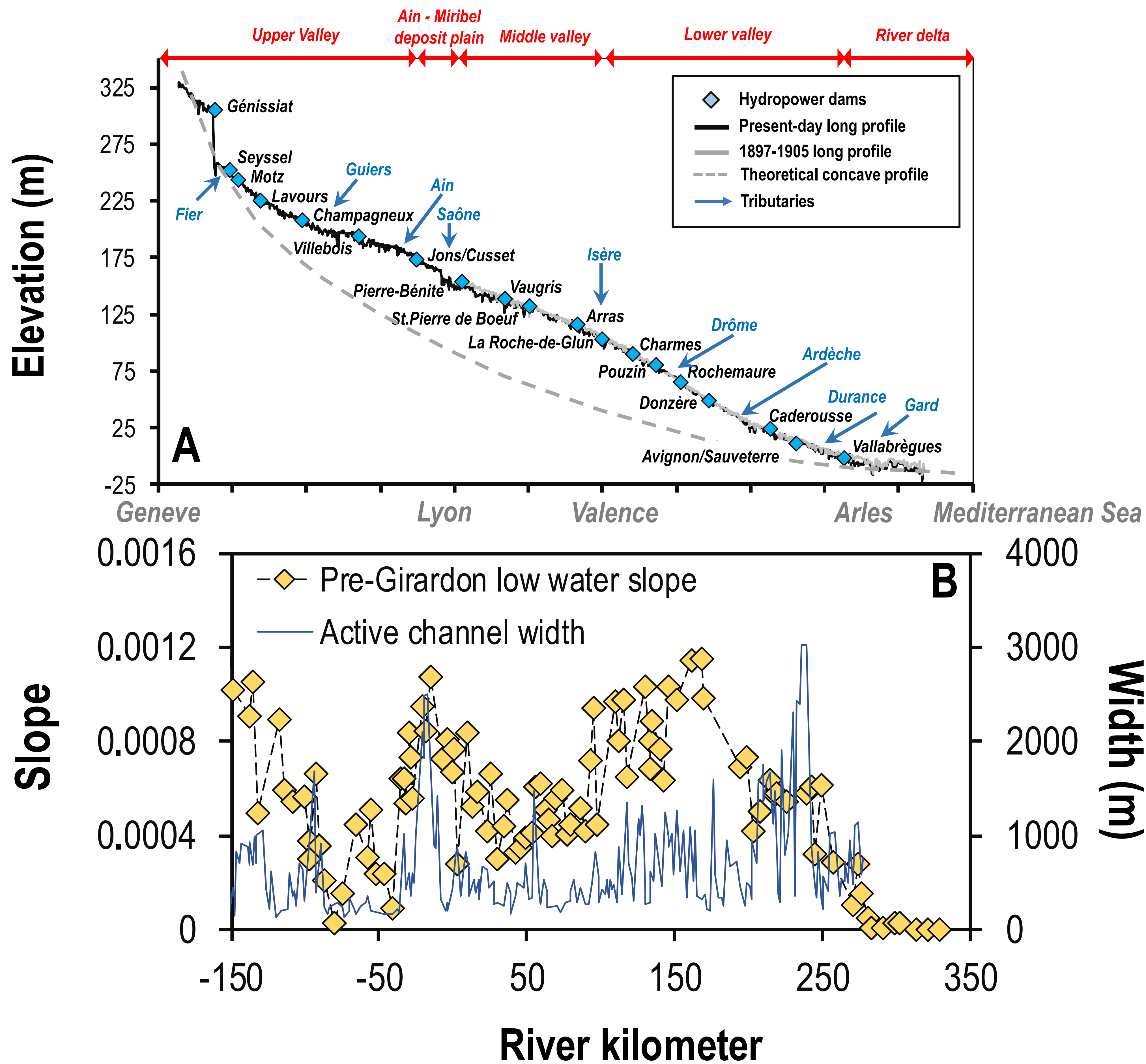


Figure3

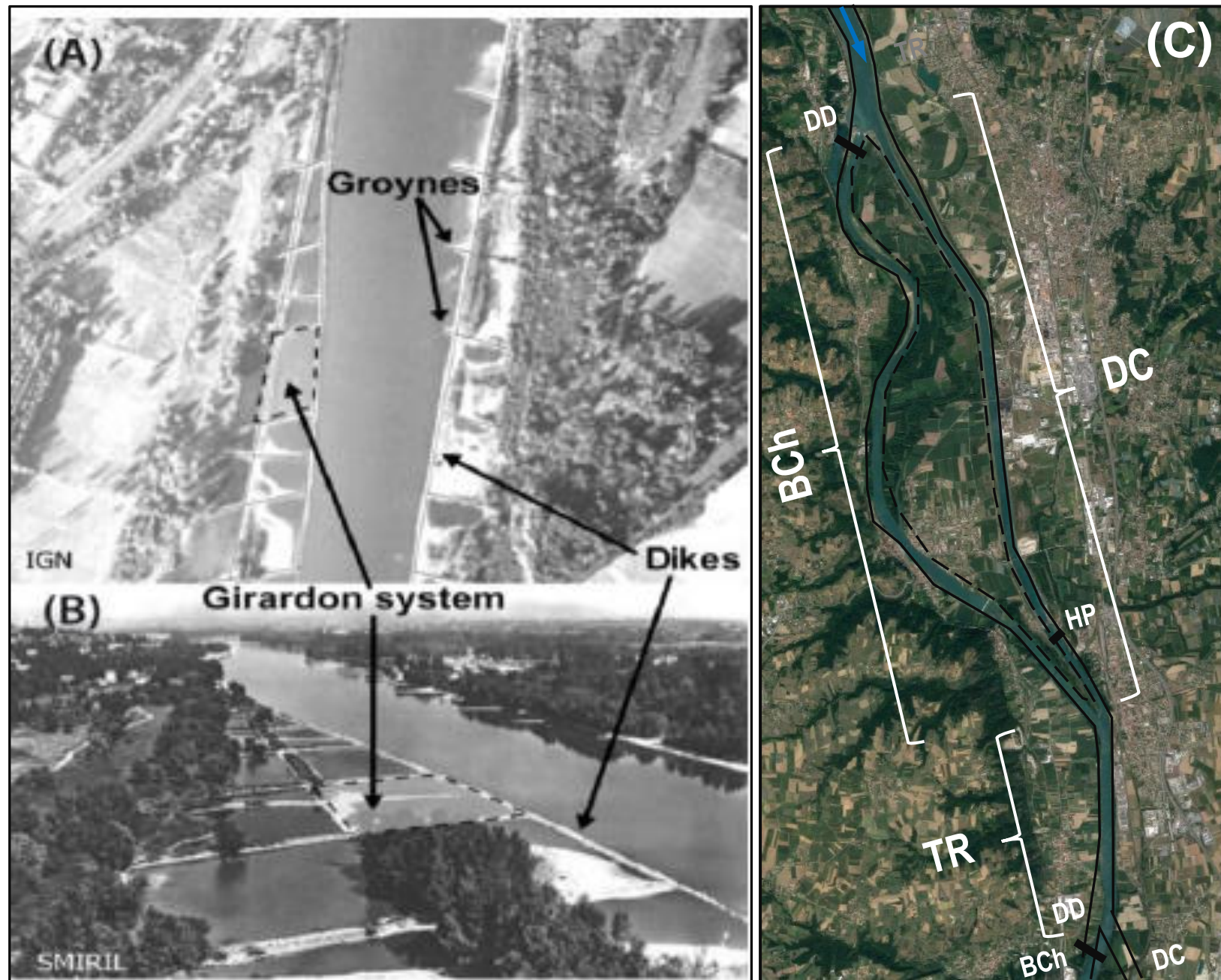


Figure4

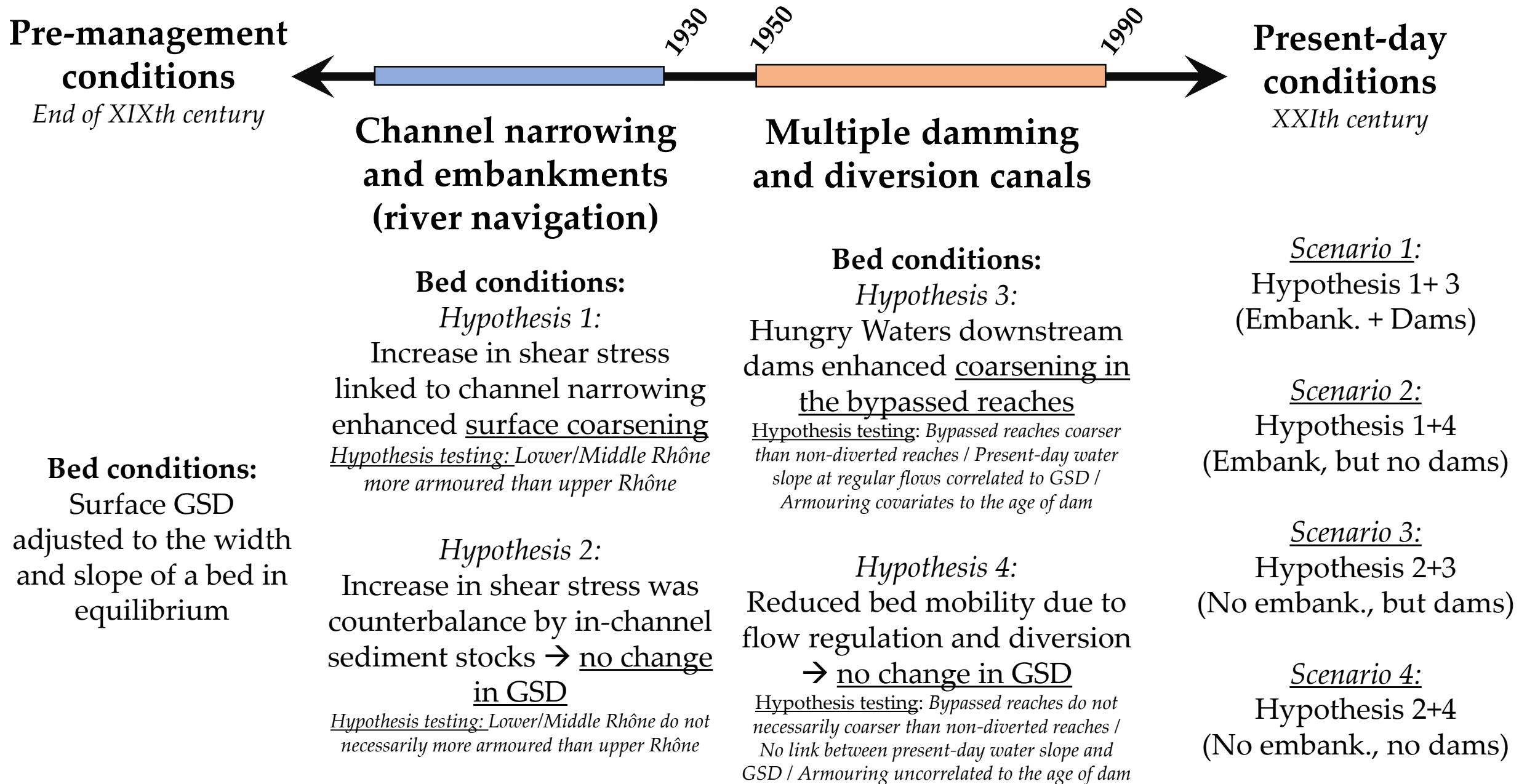


Figure5

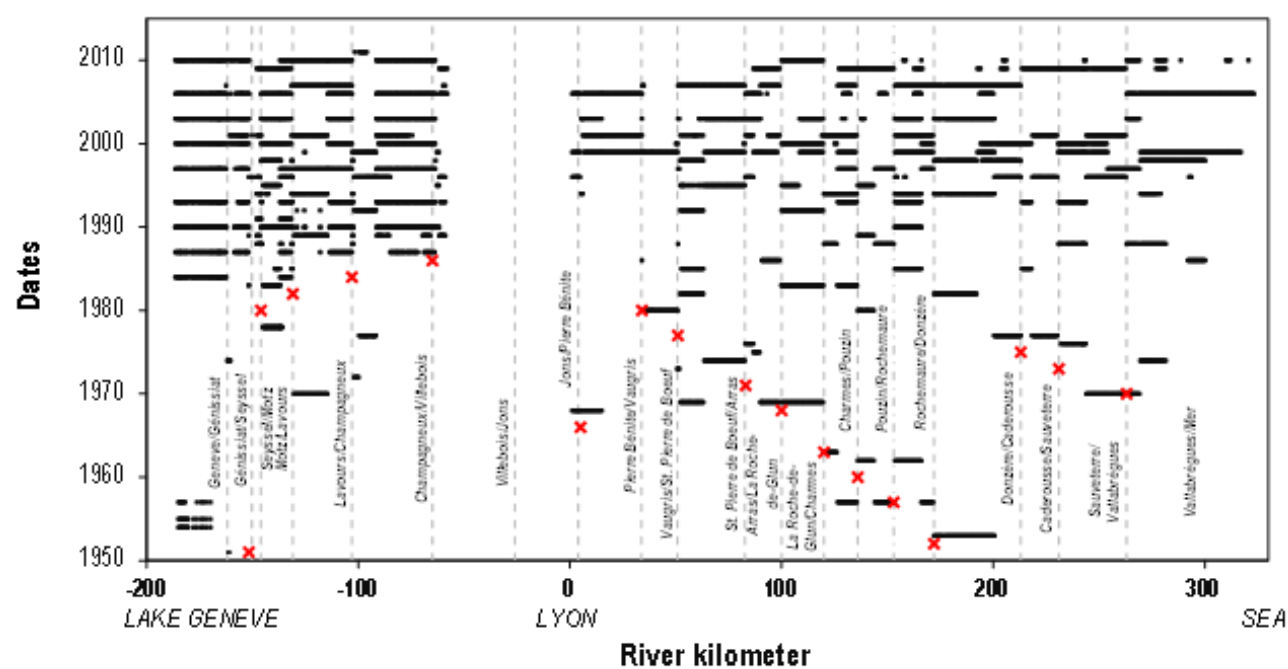


Figure6

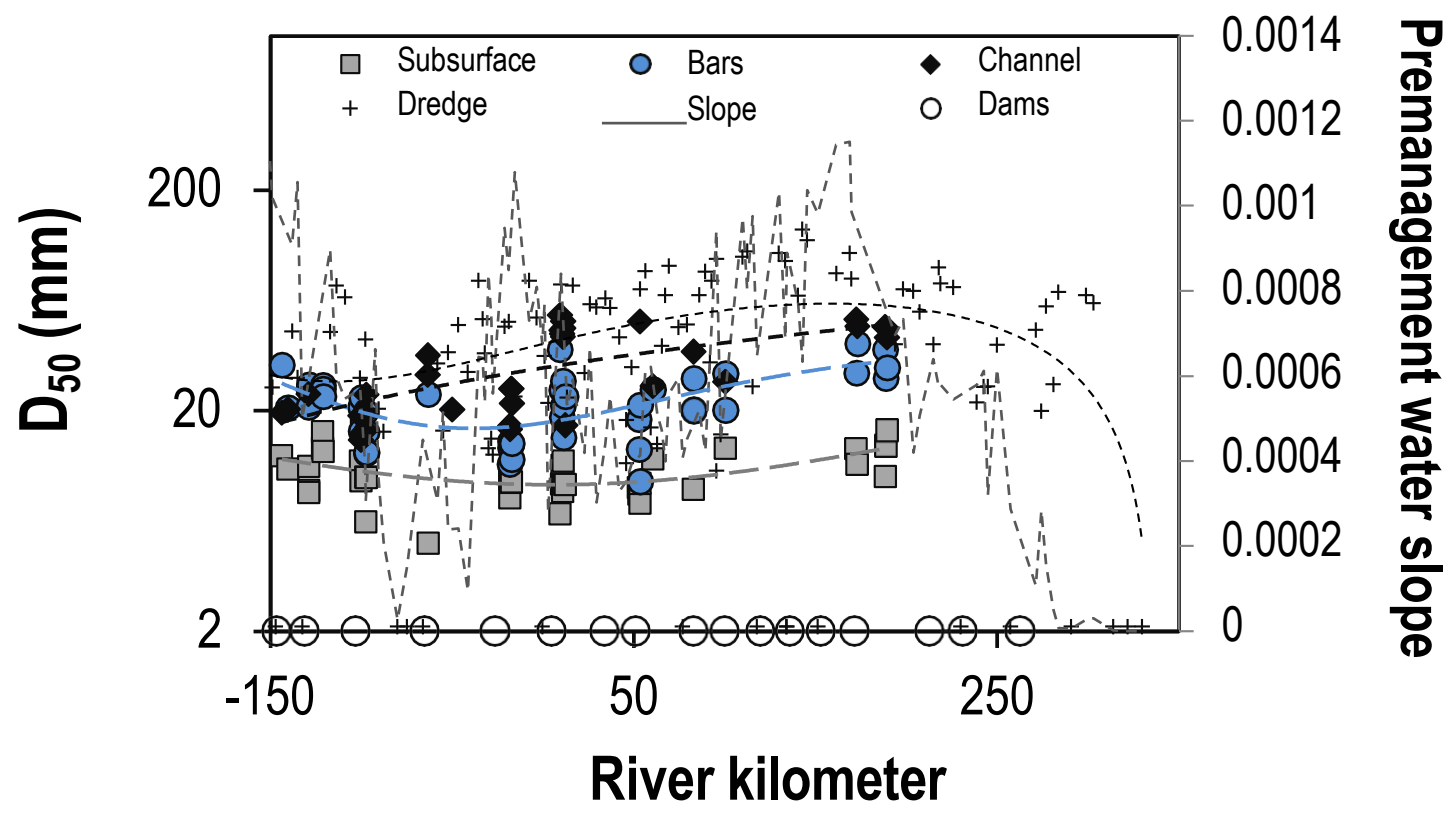


Figure7

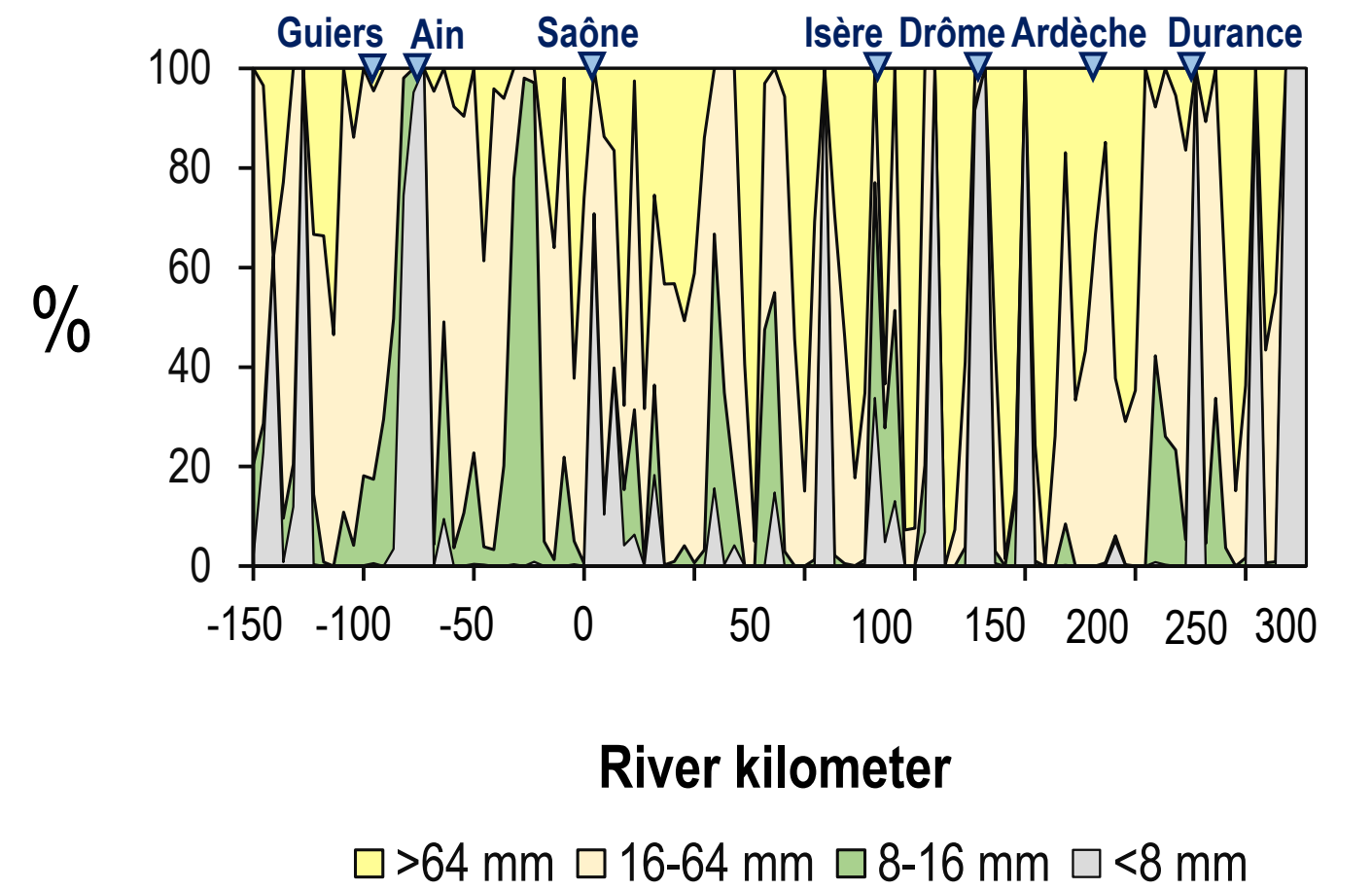


Figure8

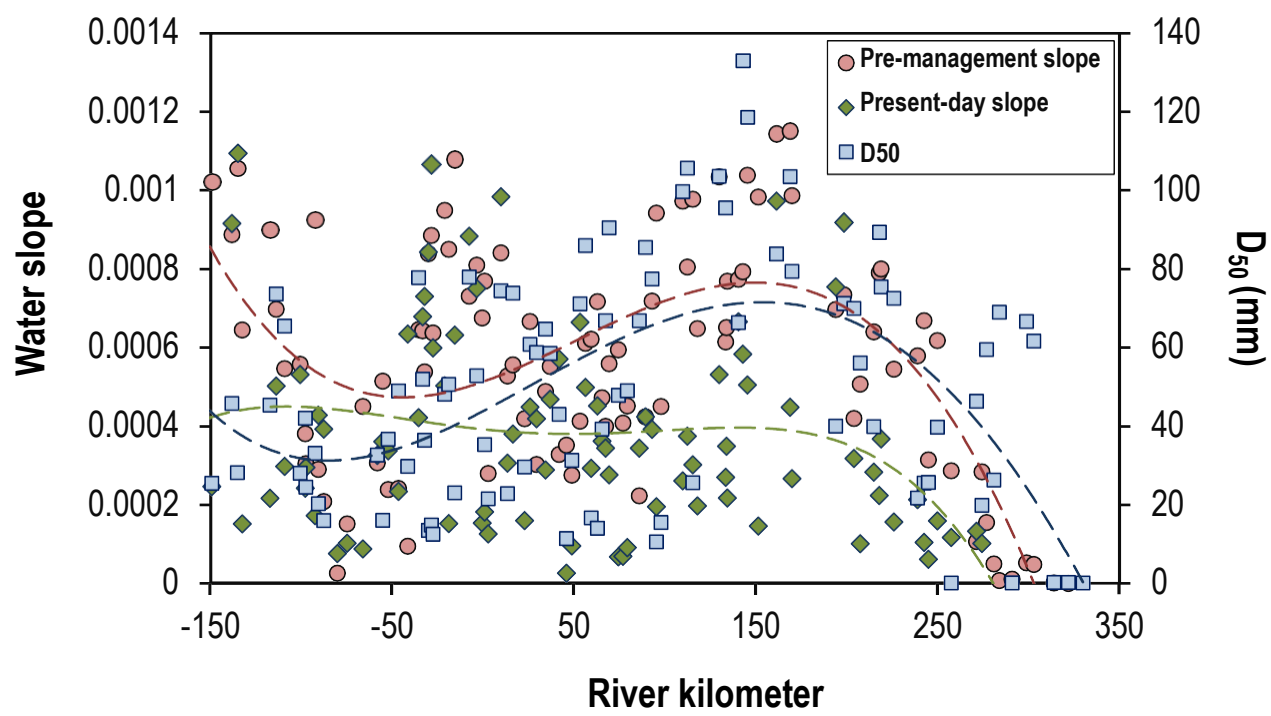


Figure9

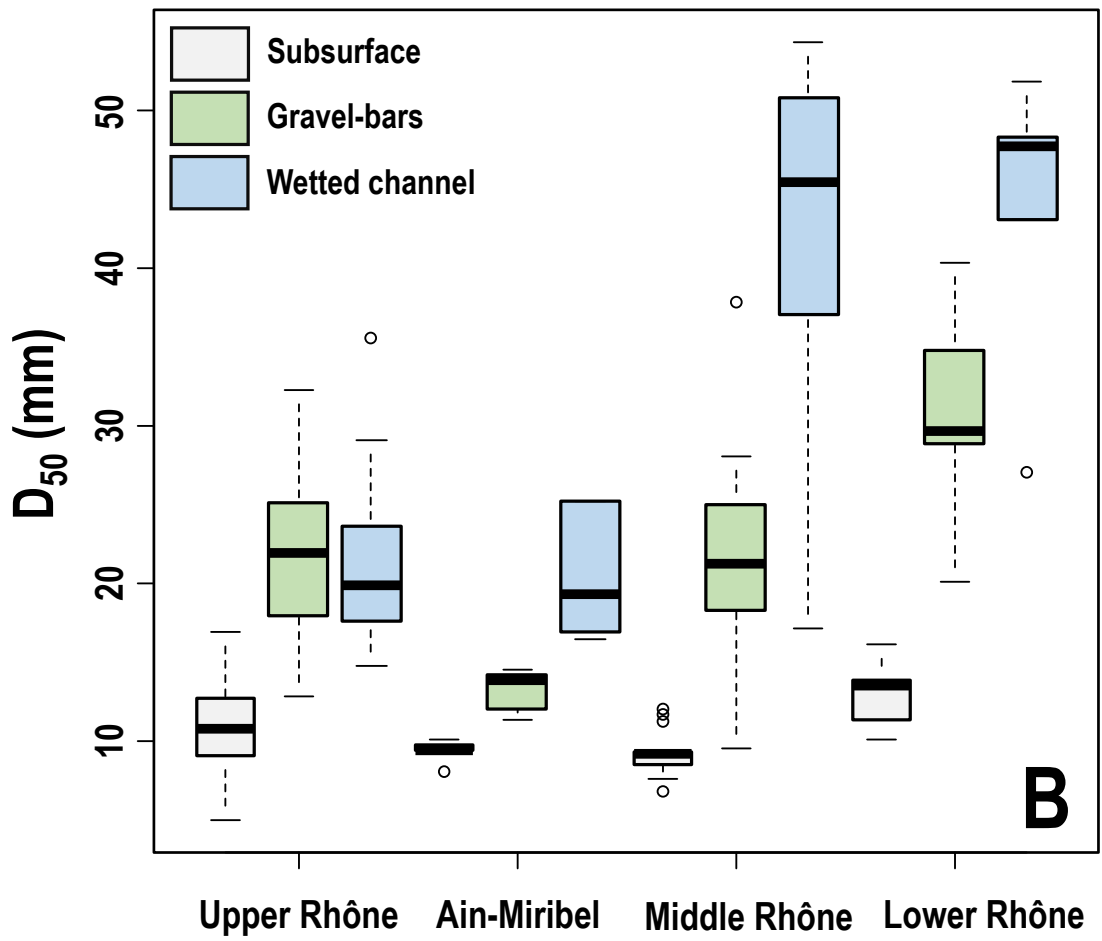
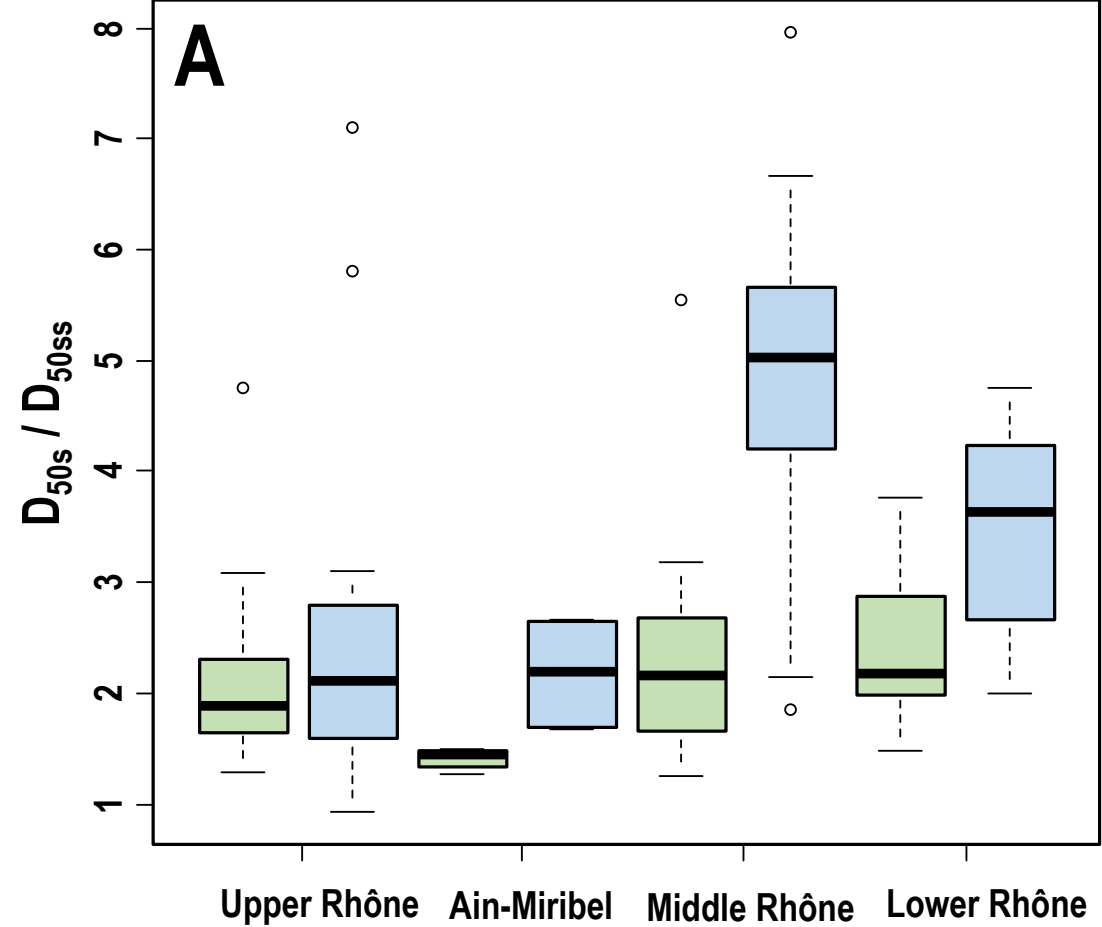


Figure10

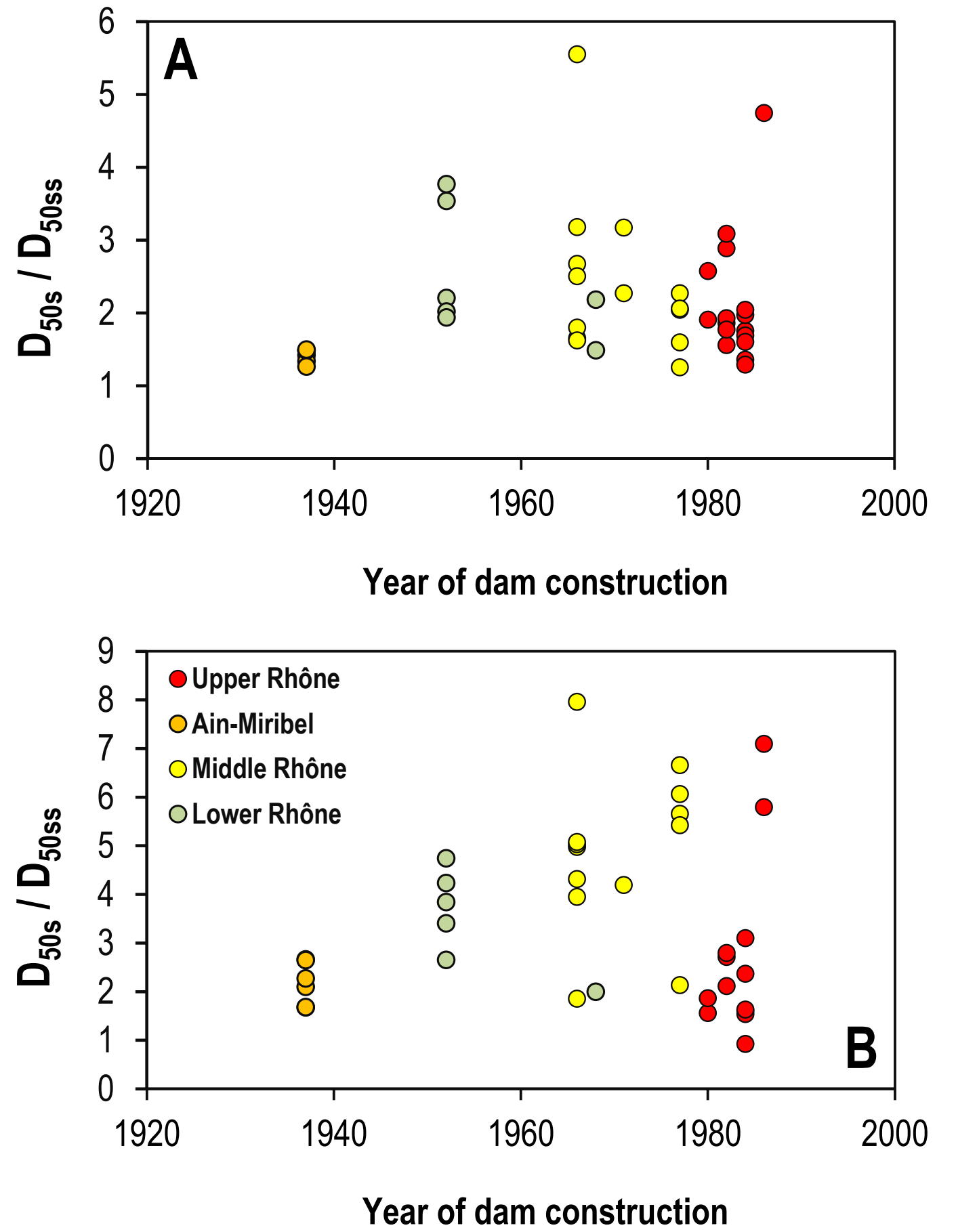


Figure11

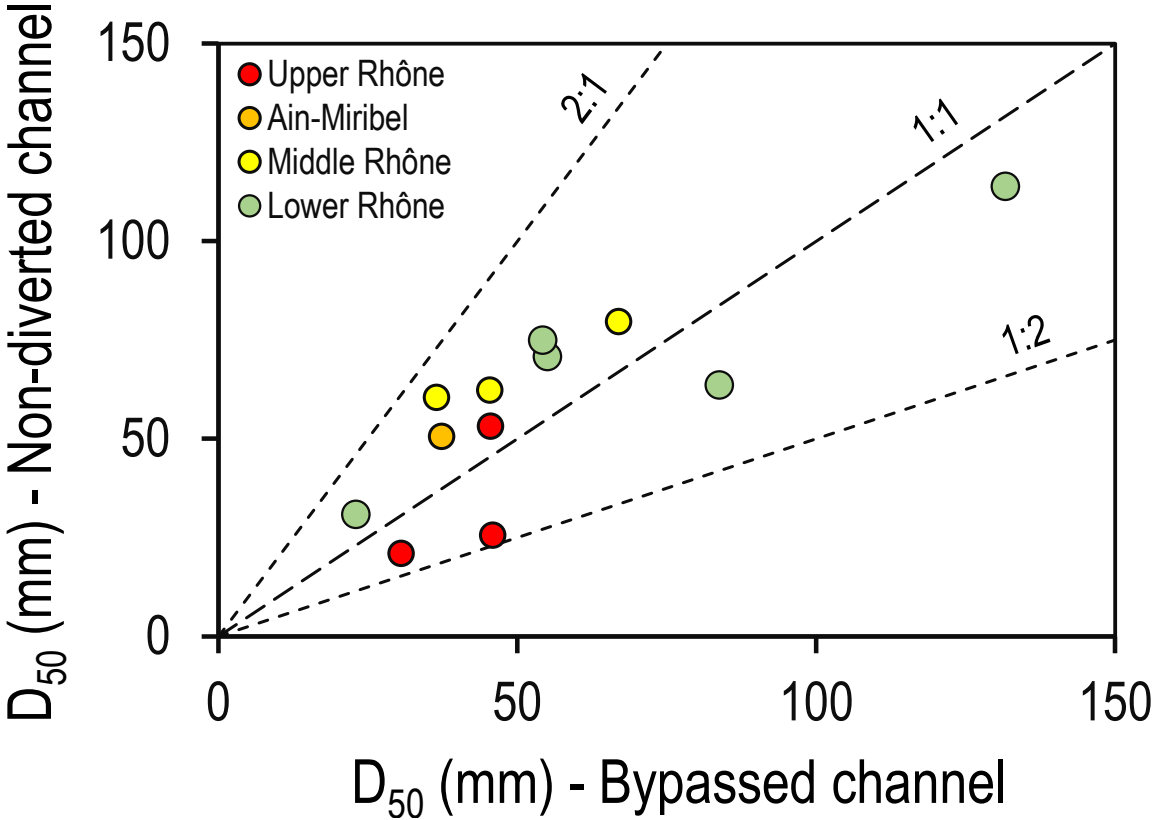


Figure12

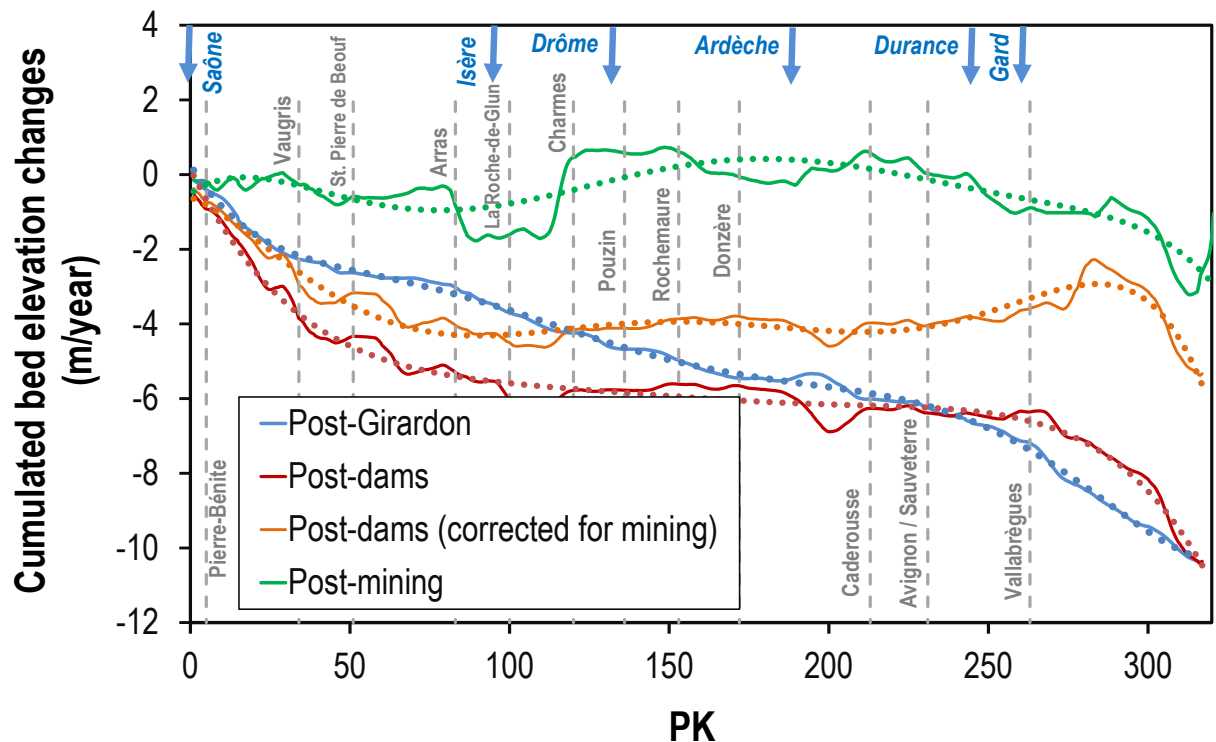
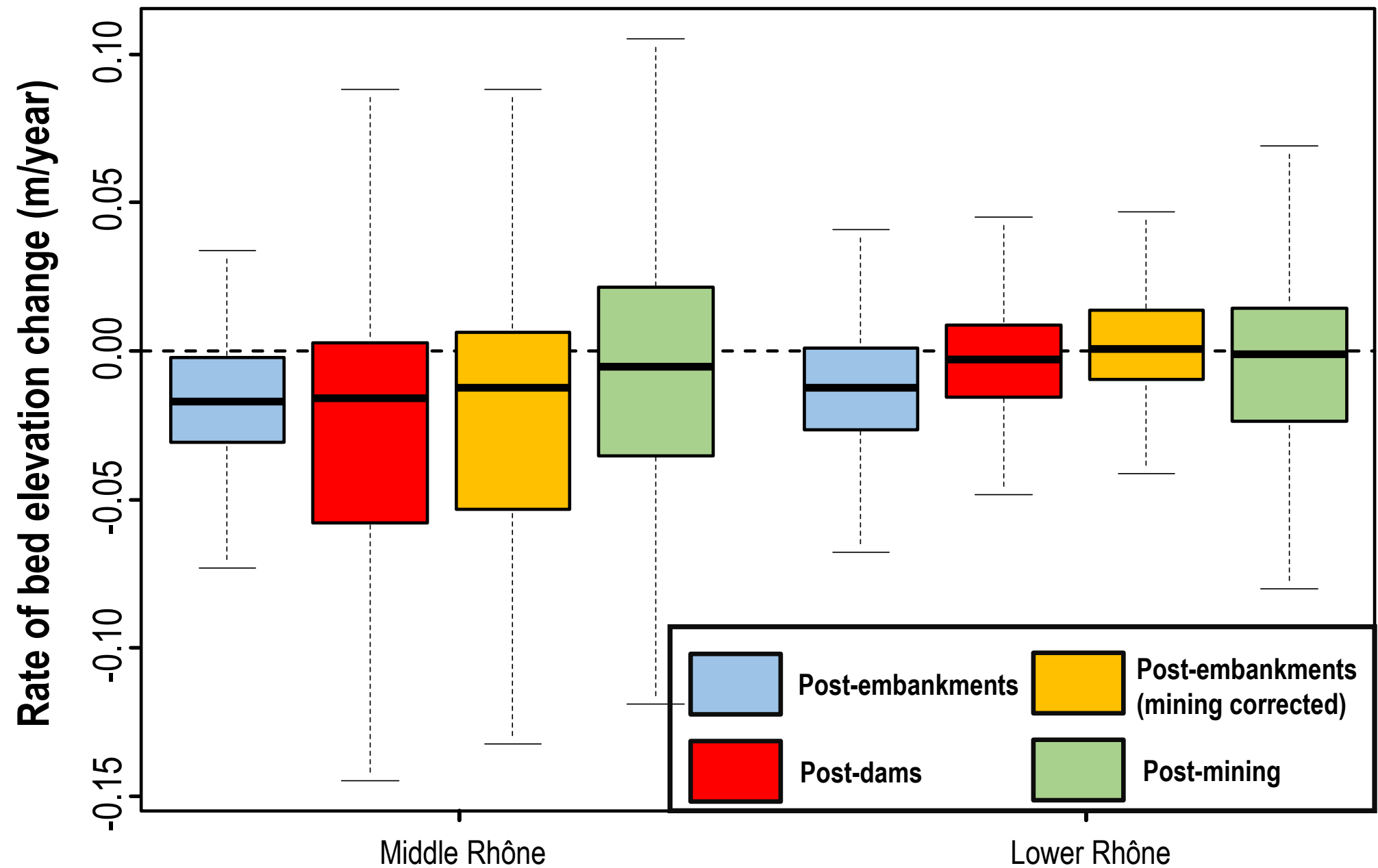


Figure13



Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: