Reduced braiding of rivers in human-modified landscapes: converging trajectories and diversity of causes

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Abstract

We analyse recent morphological evolution of braiding rivers of disparate regions of the Earth to develop and address the hypothesis that braiding of rivers tends to be reduced by human presence and related activities. Firstly, through a large-scale literature survey we observe generalised paths of bed degradation, channel narrowing and shift towards single-thread configuration in braided reaches due to multiple anthropogenic stressors. Secondly, we select three rivers from different geographic contexts characterised by complementary anthropic stressors for a detailed analysis (the lower Waitaki River in New Zealand, the middle Piave River in Italy and the lower Dunajec River in Poland) which shows that these rivers have undergone very similar trajectories of morphological change. In previous works, these morphodynamic changes have been related to the alteration of the fundamental physical processes of braided rivers, due to anthropogenic changes in constraints and controls. Here, a closer analysis of these alterations shows that analogous morphological evolutionary trajectories can result from very different paths of causation, i.e., from different management causes and different alteration of physical processes. Through the use of pattern predictors we analyse observed morphological trajectories and potential for recovery. We highlight the role of different geographic contexts as sources of constraints and drivers to the river evolution, with reference both to the physical and human environment, showing that the observed similar trajectories are the product of different local conditions and characteristics. These observations have implications for river management and restorations.

1 Introduction

Rivers represent one of the most dynamic elements among freshwater systems, because of their intrinsic tendency to change their form as a response to environmental and anthropic conditions that vary over multiple time and spatial scales. River channel forms indeed result from a complex array of mutually interacting bio-physical processes that are tied to flow and sediment supply regimes (??), vegetation dynamics (??), anthropic interventions (??) as well as more permanent geographic controls related to the geological setting. River systems are classified on the basis of their form and dynamics through a taxonomy of river channel patterns (e.g., ????). This is further complicated by the observation that such diversity spans a continuum of channel patterns (??), with new classifications proposed even very recently (?).

In this paper we focus on braiding rivers (?), and we address the hypothesis that braiding of rivers is reducing on a worldwide basis mainly due to anthropogenic modifications to their processes and boundaries. Such a hypothesis is implicit in previous works (?) and has been proposed in others (?), although it has received little quantification so far.

Braiding rivers mostly occur in geologically young, eroding mountain and piedmont areas and are indicators of active valley bottoms still undergoing geologically rapid construction (?). In light of this, they are probably the most dynamic among river patterns - as witnessed by their continuously shifting channel mosaic and rapid, decadal-scale responses to external changes (?), making them highly sensitive to anthropogenic, particularly hydro-morphological stressors. Due to their physical diversity and high morphological turnover rates, braiding rivers support highly valuable freshwater ecosystems, the ecological significance of which has been probably underrated until recently (?).

This paper investigates a worldwide tendency to a reduction of river braiding through a review and analysis of the scientific literature performed at two main levels. First, we collect published information on changing braided river systems worldwide and provide a comprehensive assessment of the recorded trends, channel adjustments and reported causal factors. Secondly, we perform an in-depth analysis of three case studies selected from disparate geographic context to investigate the underlying dynamics. We observe similarity in their trajectories of morphological evolution which, however, result from different paths of causation (i.e., different changes imposed through management measures, which had a different sequence of impacts over processes and shapes in the three rivers). Finally, through application of pattern predictors (**??**), for the three case studies we analyse their observed trajectories of morphological change and attempt to assess perspectives for recovery.

We conclude by discussing the implications of our analysis of causal factors and how the multiple relationships between natural and anthropogenic factors can drive the observed reduction in river tendency to braid.

2 Methods

2.1 Literature review and analysis

The literature review was conducted at two levels. Firstly, we performed an extensive bibliographic search for information showing overall trends in channel adjustments of braiding rivers from all over the world. Results of this large-scale survey were organised to extract the following reach-scale information (where available):

- absolute and percentage variation of the channel width;
- mean and maximum bed elevation change;
- type of planform observed at different stages of the river evolution: (B) braided, (T) transitional or (S) single-thread;
- reported management causes (”stressors”) for observed trajectories, grouped into four macro-categories: (i) damming (Da), gravel mining (GM), torrent control works (TC); (ii) bank protection (BP), channelisation (Ch), straightening (St), embankments (Em); (iii) land use change (LC), reforestation (Re), invasive alien vegetation (IAV); (iv) effects of glacial retreat after the little ice age (LIA);
- likely direction of changes (i.e., increase or decrease) in the main controls over channel patterns (formative discharge, Q, and bedload sediment yield, Q_b) according to the classification of **?**.

Along with the planform type, we report data on changes in braiding index for those rivers for which this was available from the cited literature (not generally the case for all rivers in our inventory). Furthermore, braiding index data are likely to be affected by bias and errors, for instance, due to uncertainties in the discharge at the time the data was collected (**?**). Even when a braiding index record is available, we cannot observe any precise relationship with the reported planform type. In fact, trying to draw general thresholds between planform styles based on the number of low-flow channels is not a viable approach (see **??**), and some scatter in the definition of planform type used by different authors must be expected. Still, reported data of planform type and braiding index changes can be used to highlight general trends and tendencies.

Macro-categories of drivers of morphological change (i) to (iv) were defined to group different drivers of morphological change by their nature and main effects over channel patters. Macro-category (i) includes interventions which produce direct anthropogenic modifications on control variables (**?**), such as the magnitude and temporal patterns of flow and sediment inputs to the river channel. Macro-category (ii) includes interventions that limit the lateral mobility of the river channel and its lateral connectivity with sediment sources or have a direct impact on channel morphology. Macro-category (iii) accounts for land cover changes that have indirect consequences on control variables. Macro-category (iv) is a natural (non-anthropogenic) driver of change in sediment and flow due to climate variability over the last few centuries. The above categorisation of impacts and causes is to a certain extent a result of the literature search, in that it was continually updated and revised while progressively achieving outcomes. While applying the categorisation of data, we followed the views and interpretation of the authors of the searched bibliographic items.

We use the categorisation of **?** to analyse the impact of the above causes on channel pattern controls (sediment and water supply). Among the above reported ("stressors"), damming (Da) determines both a decrease in the water supply under formative conditions (Q^-) and sediment yield (Q_s^-); gravel mining (GM) and torrent control works (TC) reduce the sediment delivery (Q_s^-). Bank protection (BP), channelisation (C), and straightening (St), which indeed may perturb the river sediment regime, cannot be considered in this categorisation, which only focuses on rivers having banks made of the same material as the bed. Catchment reforestation (Re), possibly by invasive alien vegetation (IAV), is another cause of sediment supply decrease Q_s^-, while land use change (LC) can in general determine both an increase (Q^+) or decrease (Q^-) in the sediment yield, as well as changes in runoff (Q^+, Q^-). Finally, glacial retreat after the little ice age (LIA) causes significant increase in sediment yield (Q^+).

We assigned a level of alteration complexity and a related numerical score for every analysed reach as "low" (score = 0.33), "moderate" (score = 0.66) or "high" (score = 1) depending on the reach having been subjected to one, two or three macro-categories of anthropogenic hydro-morphological drivers of change. We then employed a Principal Component Analysis (PCA), an eigenvector-based multivariate statistical technique that allows to reduce the dimensionality of a set of data by identifying the so called "principal directions" and the corresponding data variance along them. They are obtained through linear transformations of an original data matrix of n "observations" and p "variables", being in our case $n = 43$ river reaches with available stressor information and $p = 11$ types of stressors, as previously defined. Only binary entries were allowed in the matrix $\mathbf{A}$, each element A_{np} being either equal to 0 (stressor p not affecting the reach n) and to 1, viceversa. The principal components are mutually orthogonal and hierarchically arranged linear combinations of the variable values such that the projection of the data on the first principal component account for a higher variance compared to the projection on the second component, and so on. The aim of the PCA application were therefore (i) to detect possible regularities or recurrent association among stressors, and particularly if similar combinations of stressors were common to different river reaches; (ii) to detect possible relations between stressors combinations and documented morphological transitions, from braided to transitional or to single-thread patterns; and (iii) to use such information to investigate possible relations between pattern change and the broad drivers of channel adjustments as in the classification of ?. For those reaches for which quantitative information was available, we established a relation between the first two components of the PCA and the reported magnitudes of channel adjustments. We quantified univariate relations among these parameters through a second-order polynomial quantile regression to identify the correlation with the imposed drivers of change and possible thresholds in the reported channel adjustments.

Secondly, based on the outcomes of the large-scale analysis, we selected three case studies for detailed analysis. These are: the middle Piave River in North-Eastern Italy, the lower Waitaki River in New Zealand's South Island, and the lower Dunajec River in the Polish Carpathians (Figure ??). The general characteristics of these study rivers will be described in Section ??. They have been selected as representative of a wide range of geographic contexts and of varied and diverse types of anthropogenic impacts. The choice is further motivated by the availability of historical data and analyses attempting to semi-quantitatively explain the path of causation from management impacts to observed morphological change. This is not generally the case for the rivers in our large-scale survey, which prevents application of the same detailed analysis to most of our rivers sampled in the large-scale survey.

For the three study rivers we extracted detailed temporal patterns of morphological change. Furthermore, we focused our literature review on analysing the relationships between management causes, impacted bio-morphodynamic processes, and observed morphodynamic changes in order to show how similar morphological change could result from different causes. Although such a conclusion could have been partly anticipated by observing that different drivers produce analogous alterations in the control variables Q and Q_s (?), our study will extend beyond these straightforward conclusions in that it will allow analysis of the impact of causes (such as channelisation) which cannot be treated using Schumm's categories, and to reveal the feedback effects of braiding process alteration on control variables.

The literature data used for this detailed analysis on the evolution of the three study rivers (Piave, Waitaki, Dunajec) were obtained as follows. For the lower Dunajec River, from Figure 4 in ? we obtained a time series of average bed elevation at cross-section A (corresponding to the Żabno gauging station), and from Figure 3 therein we digitised the time evolution of reach-averaged channel width at low flow and the number of flow threads.

For the middle Piave River, we used the bed elevation and planform width adjustment data of two sub-reaches (Reach 1 and Reach 4) listed in Tab. 4 in ?. These, among the 9 reaches considered therein, are those which experienced the maximum bed degradation (Reach 1) and aggradation (Reach 4) in the period 1926-2006 for which data were available. We also digitised (from Figure 4 in the same paper) changes in the width of unvegetated active channel, marginal vegetation, and island relative to the total width of river corridor. Finally, we extracted a record of braiding index from ?.

For the lower Waitaki River, we extracted data from a report of ? at three reaches. This included data on bed-level change collected at the Kurow gauging station, in the reach located immediately downstream of the Waitaki Dam (Figures 3.3 and 3.4 in the report). We used width change data at two more reaches, namely the 16 km-long "Duntroon reach" and the 10 km-long "Coastal reach". We also digitised a time series of land-cover data in Figure 4.2 in the report, and used the number of flowing channels for the Coastal reach from Figure 4.7.

2.2 Pattern predictors

Pattern (or planform) predictors have been used to determine future evolutionary trajectories of the three study rivers. By pattern predictor we mean a method which provides thresholds for the river controls (e.g., slope or stream power) which help discriminate between pattern configurations. Starting from the pioneering work of **?**, who established an empirical threshold based on the bankfull discharge to discriminate between braiding and single-thread rivers, numerous, progressively refined predictors have been put forward. Improvements concern the inclusion of: a characteristic bed material size, usually the median diameter d_{50} (**??**); bank cohesion due to bank soil characteristics or "pseudo-cohesion" due to vegetation (**???**); more thresholds to discriminate also between braiding and anabranching rivers (**?**) or a multitude of transitional patterns (**?**). As an aside, the hard threshold of all the above deterministic predictors may struggle to cope with the scatter of data of pattern transitions, which could suggest the validity of a probabilistic approach (**?**). Nonetheless, in the present work we consider the predictors of **?** and of **?**.

None of these predictors presents the sediment feed as an independent control variable. This may be an important point: in fact, as shown by the statistical regression pattern predictor approach of **?**, discriminators based only on slope and discharge can only effectively identify meandering rivers, whereas adding surrogates of sediment transport estimates improved the prediction of other patterns. However, as argued by **?**, channel slope is used by most predictors as a proxy for sediment transport because slope data are way more available than sediment transport data. In fact, the predictors of **?** and **?** can be equivalently recast in a form having the bedload concentration within the flow as an independent entry.

Indeed, when pattern predictors' control variables such as the formative discharge, reach slope, and (where applicable) vegetation characteristics have been imposed, and with a hypothesis over the cross-section shape (which underlies all pattern predictors), then the reach sediment transport is constrained. This is a consequence of the hypothesis of long-term equilibrium underlying all predictors, i.e., that the riverbed slope and cross-section shape has adjusted to the sediment feed available. Therefore, pattern predictors are perfectly adequate for our analysis aiming to address long-term equilibrium states under a persistent setting of control variables.

2.2.1 Predictor of ?

The predictor of **?**, incorporating the rational theory of **?** and empirical thresholds between patterns configurations, establishes two planform thresholds that are expressed in terms of slope, namely

$$S_{sa} = 0.40\mu'^{\,1.41}\,Q^{*\,0.43} \qquad , \qquad S_{ab} = 0.72\mu'^{\,1.41}\,Q^{*\,0.43}\,, \tag{1}$$

where S_{sa} is the slope threshold between single-thread and anabranching configurations, and S_{ab} is the threshold between anabranching and braiding configurations. The river is predicted to be braided if $S > S_{ab}$, anabranching if $S_{sa} < S < S_{ab}$, and single-thread if $S < S_{sa}$. In (**??**), Q^* is a dimensionless discharge, defined after **?** as

$$Q^* = \frac{Q}{\sqrt{\Delta g d_{50}}\, d_{50}^2}\,, \tag{2}$$

where Q is the bankfull discharge, g the acceleration due to gravity, $\Delta = \rho_s/\rho_w - 1$ the reduced sediment density, ρ_s and ρ_w being the sediment and water density, d_{50} is the median sediment

Table 1: Values of friction angle ϕ' [°] and related μ' values to be used in the predictor of **?** (equations (**??**) and (**??**)). The ϕ' values for the categories "vegetation type I" to "vegetation type IV" have been computed by **?** after **?**. The bare gravel ϕ' value is the mean value given by **?**.

Category	Bare gravel	vegetation type I	vegetation type II	vegetation type III	vegetation type IV
Description		grassy banks with no trees or bushes	$1-5\%$ tree/ shrub cover	$5-50\%$ tree/ shrub cover	$> 50\%$ tree/shrub cover or incised into floodplain
ϕ', mean value	35.0	39.9	43.7	48.0	55.6
μ'	1.00	1.19	1.36	1.60	2.09

diameter, and μ' is a parameter which accounts for the presence of vegetation on the bank strength, defined, after **?**, as

$$\mu' = \frac{\tan\phi'}{\tan\phi} \,, \tag{3}$$

where ϕ is the friction angle of the bare bank material and ϕ' that of the vegetated bank (Table **??**).

The above breakdown of the dependencies suggests that the river configuration depends on four independent controls:

- a representative discharge value Q, to be practically specified as the flood discharge with a return period of either 2.3 years ($Q_{2.3}$, equal to the mean annual flood) or two years (Q_2);
- the median bed material size d_{50};
- the bank cohesion parameter μ', related to the vegetation cover;
- the channel slope S.

For our applications, we set the μ' parameter according to five scenarios, namely a "bare gravel" scenario plus four scenarios with increasing vegetation density. These scenarios are defined in Tab. **??**. The time evolution of the μ' parameter is used to represent the trend towards vegetation encroachment observed in the Piave and Waitaki Rivers.

2.2.2 Predictor of ?

The predictor of **?** does not account for vegetation cover, but includes the river width, W as an input variable, since thresholds are expressed in terms of stream power per unit width, ω, defined as

$$\omega = \frac{\rho g Q S}{W} \,. \tag{4}$$

A regime width scaling function $W \propto \sqrt{Q}$ is proposed in **?** for those rivers which are able to adapt their width to the formative discharge, to remove the dependence on width as an independent control. However, here we retain W as an independent input to address the effect of imposed width changes to the Dunajec River.

As an aside, the approach of using a unique regime width across different channel patterns (first used by **?**), although necessary to remove width as an independent control, has been deemed unacceptable by **?**, who pointed out that very different width scaling functions apply

Table 2: General characteristics of the catchments of the Dunajec, Piave and Waitaki Rivers.

Name	Catchment area [km^2]	Length [km]	Annual precipitation [mm]	Discharge [m^{3}s^{-1}]
Dunajec	6804	250	900 – 1200 (Tatra mountains) 600 – 650 (Carpathian foreland)	8.8, 147 (average, peak: upper course) 37.8, 495 (average, peak: middle course) 85.5, 940 (average, peak: lower course)
Piave	3899	220	1000 – 2000 (average 1350)	$\sim 700, \sim 4000$ (Q_2, max. hist. peak: middle course)
Waitaki	12000	230	4000 (headwater lakes) 549 (catchment average)	$\sim$ 370 (average, Waitaki Dam) 1350 (mean annual flood, pre-dam) 1110 (mean annual flood, post-dam)

to different channel patterns. They instead propose that theoretically correct discriminators could be developed based on observation of pattern-specific bedform processes.

The predictor establishes three thresholds, namely

$$\omega_{IA} = 90 d_{50}^{0.42} \quad , \quad \omega_{SC} = 285 d_{50}^{0.42} \quad , \quad \omega_{BM} = 900 d_{50}^{0.42} \, . \tag{5}$$

For increasing unit stream power, channels are discriminated between laterally immobile channels with no bars ($\omega < \omega_{IA}$), meandering channels with scrolls ($\omega_{IA} < \omega < \omega_{SC}$), moderately braided and meandering channels with scrolls and chutes ($\omega_{SC} < \omega < \omega_{BM}$), and highly braided channels ($\omega > \omega_{BM}$).

3 Study areas

In this section we describe the three study rivers that will be considered in our detailed analyses of trajectories and causation of morphological change: the lower course of the Dunajec River (Poland), the middle course of the Piave River (Italy), and the lower course of the Waitaki River (New Zealand). Maps of the three study rivers are shown in Figure **??**, characteristics of their catchments are summarised in Tab. **??**, and timelines reporting anthropogenic interventions on the river courses are shown in Figure **??**.

3.1 Lower Dunajec River (Poland)

The Dunajec is a 7th order gravel-bed river and tributary of the Vistula. Rising in the Tatra Massif, it drains the Inner and Outer Carpathians. Its catchment lies mainly in Poland, while the headwaters are partially located in Slovakia. The river has had many anthropogenic interventions along its entire course, increasingly carried out in the last $\sim$ 150 years (**?**). One of the major interventions is channelisation, which has been undertaken since the late 19th century and has generally straightened channels and reduced their length. In the upper and middle course, gravel mining was also common in the 20th century. Furthermore, the land use generally changed in the 20th century, with a marked increase of forest cover. Finally, in 1997, the river was impounded with the closure of a dam in the upper course. For simplicity, here we consider the lower course, which was not subject to gravel extraction and thus was only affected by channelisation and straightening.

In 1870, the lower course had a braided configuration in its uppermost reach, but braiding intensity progressively decreased downstream until it became a single-thread channel at the confluence with the Vistula. This may have been the result of an ongoing, downstream-progressing

Figure 1: Map of the three study reaches: a) lower Dunajec River, Poland; b) middle Piave River, Italy; c) lower Waitaki River, New Zealand.

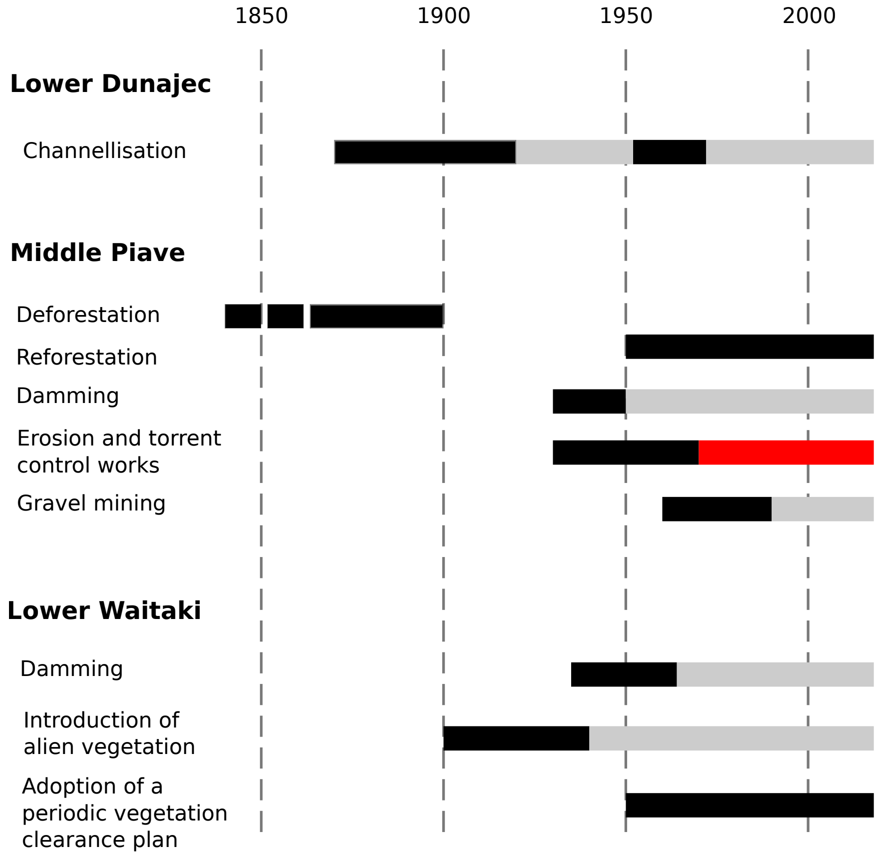

Figure 2: Timelines of anthropogenic interventions on the lower Dunajec, middle Piave and lower Waitaki Rivers. Black bars indicate interventions being put into place (e.g., dam construction). Grey bars refer to the period when interventions are no longer carried out, but still exert influence. The red bar, associated with torrent and erosion control works in the Piave, indicates increased intensity of these interventions from the 1970s.

transformation of a formerly single-thread channel into a braided river (?), as observed in the nearby Raba River due to an influx of coarse material from the upstream reaches during the 19th century (?). By the early 1900s, channelisation had shortened the river by 10% and reduced the average width by 30%, forming a single-thread channel throughout almost the entire lower course. During the early 20th century, groynes and longitudinal stony dikes were added, which further reduced the bankfull channel width. After a temporary increase in width due to a hiatus in channel management works during and after World War II, renewed channelisation through until the 1970s further reduced the river width and completed the change to a single-thread channel. Post World War II planform changes were accompanied by significant degradation, which in the late 1980s exposed bedrock in some sections.

3.2 Middle Piave River (Italy)

The Piave River drains the Eastern Italian Alps, from the Italian-Austrian border to the Adriatic sea. Having been inhabited since prehistoric times, its basin has a long history of anthropogenic modifications (forest harvesting, crop cultivation, transport of logs in streams). Like in other Italian Alpine rivers, massive deforestation of the catchment started in the late Middle Age and peaked between the 18-19th century (?). In more recent times, natural reforestation since the 1950s followed the decline in mountain agriculture. Flow regulation has taken place with the construction of numerous dams on the Piave and its tributaries, which alter the flow regime and intercept sediment from more than 50% of the catchment. Dam operations did not significantly change the channel-forming discharge (i.e., discharges with a recurrence interval around 2 years), but have significantly reduced low flows and the frequency of smaller floods (?). Channelisation of the lower river course in the Venetian Plain started in the Middle Ages, but effective erosion and torrent control works on the upper basin were carried out only from the 1930s, most intensely from the 1970s. Finally, extensive gravel extraction was carried out between the 1960s and 1990s, with official records grossly underestimating the actual extracted volumes (?).

The river can be divided into three reaches: a steeper and more confined incised upper course, a (formerly) braided middle course, and a lowland sand-bed course. We are here concerned with a portion of the middle course of the river, flowing in the Alpine valley known as “Vallone Bellunese”, which, like many other Italian rivers, underwent dramatic narrowing and degradation over the last ~ 70 years (?). Overall, adjustments in the middle Piave followed the general pattern for Italian rivers identified by ?: i) a first period (19th century) characterised by very small changes; ii) a phase (1870-1950) of river narrowing without significant incision essentially driven (for most Italian rivers) by land use change, and, more importantly in the case of the middle Piave, by river training measures undertaken in the 1940s (?); iii) a phase of dramatic adjustments (more rapid narrowing accompanied by incision) driven by sediment depletion induced by gravel mining; and iv) a final phase (1990s-present) of widening after abandonment of in-stream mining. The channel recovery identified by ? was challenged by ?, who noticed that widening has almost ceased in very recent years.

In addition to these changes, over the 20th century a dramatic spread of vegetation in the floodplain has taken place along the study reach. This has caused an increase in the surface area of islands (?), and the river, once multi-thread and braided, has assumed a wandering/single-thread configuration in some reaches. A detailed analysis of changes by ? shows that the observed incision does not correlate with narrowing, either spatially or temporally. The obvious question, whether vegetation spread was initially induced by incision, or incision was initially induced by vegetation spread after the strengthening of channel banks, was investigated by **?**. They dismissed the second hypothesis as inconsistent with the transport capacity of the river, and deemed the first hypothesis as plausible. In their view, which we adopt in the present work, it must have been degradation within channels, which was determined essentially by the sediment depletion due to in-stream gravel mining, that induced flow concentration within the main braids, which in turn encouraged vegetation encroachment, thus eventually causing the narrowing of the unvegetated active corridor.

The impact of the frequency reduction of floods of small recurrence interval (around 1.1. to 1.5 years) may still have been relevant both to the morphodynamics and vegetation dynamics, as these floods were found by **?** to be important drivers of the dynamics of the similar Tagliamento River (**?**). It is likely that at present the reduced sediment transport capacity due to flow regulation constrains the river's potential for recovery of a more complex morphology. Still, gravel mining was the most important driver which initially produced the dramatic morphologic change observed in the Piave (**?**); hence, in the following analysis of causal factors we will focus on the impact of gravel mining.

3.3 Lower Waitaki River (New Zealand)

The Waitaki River is the fourth largest river and the largest braided river in New Zealand. It is located in New Zealand's South Island and drains the Southern Alps. The three headwater lakes (Tekapo, Pukaki, Ohau), along the North-western catchment boundary, dominate the flow, which creates a natural damping effect to the flow regime compared to other braided rivers in the region (**?**).

The Waitaki has been intensely used for hydropower, with the construction of numerous dams, control structures and canals along its upper catchment. Hydropower development commenced in 1935 with the construction of Waitaki Dam. A more modified flow regime was established in 1953 after the construction of gates across the outlets of Lakes Tekapo and Pukaki, with further storage control of Lake Pukaki added in 1979 (**?**).

We are here concerned with the lower Waitaki, i.e., the 70 km long reach running from the most downstream dam, Waitaki Dam, to the sea. The lower Waitaki first transits through a confined bedrock gorge, then around Kurow it steepens slightly and assumes a braided configuration to the coast. 80% of the lower Waitaki's discharge passes through Waitaki Dam, and it fluctuates daily according to power demand.

With respect to the pre-dam flow regime, the dam-impacted flow regime is steadier, with a four-fold reduction since 1953 in the frequency of floods exceeding 1250 m^3s^{-1} (which is the threshold at which the bed becomes fully mobilised) and a 40% reduction in their average duration. Furthermore, the dams have reduced by 50% the sediment feed to the lower Waitaki (**?**). The lower course of the river has responded by recovering gravel from its own banks in the braidplain, by degrading by about 3 meters in its upper section (Kurow reach, just downstream Waitaki Dam), and by bed armouring in the same reach. At the same time, the dam-impacted flow regime has reduced the bedload transport capacity by $\sim 50\%$. This explains why, after initial degradation, the Kurow reach appears presently to be vertically stable (apart from temporary changes induced by major floods in 1994-1995 that were large enough to break the armour layer), and the degradational wave appears not to be propagating downstream.

The lower Waitaki experienced a dramatic change in vegetation cover that eventually severely impacted the morphodynamics and planform shape of the river (?). Before 1940, the lower Waitaki riverbed was largely bare and windswept, up to 2 km wide. By 1950, the active bed had become increasingly congested with alien vegetation (introduced originally by European settlers) such as crack willow (*Salix fragilis*). Broom (*Cytisus scoparius*), gorse (*Ulex europaeus*) and other weeds had also established in the riverbed and on the riparian margins. With the construction of the Waitaki Power Station, fluctuating river flows were able to move willow debris onto the braided river islands and river margins, promoting willow establishment on these areas. This led to the erosion of surrounding land as floods tended to break away from the main river path. A program of vegetation control for flood safety started in the 1950s, and between 1954 and 1969 a 500 m wide “fairway” was cleared in the middle of the river. Since then, interventions have included scarifying and loosening-up gravel bars and islands with earth-moving machinery to encourage river flow within the cleared corridor, cutting temporary pilot channels, and protection of banks with willow trees, pied rail retards, shingle stopbanks and planting to reinforce the margins of the corridor. Since the late 1970s, the maintained corridor width has been reduced to 400 m. Currently, willow growth is controlled by aerial spraying on a three-year rotation, and by “snagging” by machine when stranded willows pose a threat in terms of flow diversion, island formation or bank erosion. Over decades, there have been trends for the total area of riverbed to reduce (by conversion to farmland) and for the width of unvegetated corridor to reduce due to the spread of scrub (broom and gorse) into the corridor.

The decrease in flood frequency due to the development of the Upper Waitaki scheme and the control strategy of only maintaining a narrow cleared corridor (since 1960) are likely responsible for the observed reduction in unvegetated width. Nowadays, the river occupies only a narrow corridor of unvegetated bars and islands between woodland (crack willows). Together with vegetation spread, a tendency towards simplification of the braided configuration has been observed, to the extent that the river now flows in a few main central braids and has a more stable morphology than in the past. Although major floods (e.g., 1994 and 1995) are still capable of clearing vegetation (see ?), it is questionable whether the river could presently sustain a braided configuration in the absence of vegetation management.

4 Results

4.1 A worldwide inventory of impacted gravel-bed braided rivers

Morphological changes in braided rivers due to the impact of anthropogenic stressors have been increasingly reported in the literature over the last few decades. In Tab. ?? we summarise the available literature. Most contributions concern rivers in Europe, and, within Europe, the Alpine and pre-Alpine region (e.g., Italy, France, Austria, Switzerland). This abundance reflects the overall magnitude of changes observed in that region, where most braided reaches have been heavily impacted. Contributions from other regions of Europe (e.g., the Polish Carpathians, Spain, Scotland, Corsica) and elsewhere (e.g., the United States, New Zealand, Chile) document similar stories. Relevant published data could not be found for other impacted gravel-bed braided rivers in other continents, including Asia (Japan, South Korea, Nepal) and South America (Peru, Bolivia).

In terms of broad anthropogenic stressors, Tab. ?? indicates that 95% of the reaches we examined experienced a reduction in sediment supply, with 59% also experiencing a reduction in peak flows because of hydrological alteration caused by dams. The remaining 36% did not experience alteration of channel-forming flows but did have reduced sediment supply. Only 5% of reaches (two reaches, the Willamette and Pine Creek) were subject to an increased sediment supply, and different patterns of flow alteration.

In terms of the river overall response, information on absolute width variation was available for 35% of the examined reaches, while relative width change and absolute bed level change were reported for 78% and 71% of the analysed reaches, respectively. For almost all reaches in the database, observed planform transitions and likely causes were reported (100% and 86% of the analysed reaches, respectively).

The time scale of channel adjustment was typically several decades for all examined reaches, and the size of the analysed stream varied across two orders of magnitude (with reach-averaged channel widths varying from tens of meters to several kilometres). The great majority of impacted river reaches showed a combination of channel narrowing and riverbed incision (using the terminology proposed by ?). For 55% of the analysed river reaches, quantitative information on both the percentage width change and on the absolute mean/maximum recorded riverbed incision was available.

Alteration values for all rivers reported in Tab. ?? indicate average narrowing by 61%of the initial width, average mean bed lowering by 1.9 m, and average maximum bed lowering by 3.9 m. More than half (59%) of the analysed cases underwent a morphological transition from a braided (B) to a single-thread (S) channel pattern, while in 23% of the reaches the morphological transition was less severe, moving from a braided to a wandering/transitional (T) style. Only 18% of the reaches kept their original braided morphology.

Finally we analysed the causes driving the reported channel adjustments, using the macro-categories of cause defined in Section ??. Causes were very different among reaches, likely reflecting specific development pathways in different geographical contexts. Apart from a few reaches (5%) for which glacier retreat associated with the end of the Little Ice Age was reported as a cause of the river evolution, 41% of the reaches have been subject to all macro-categories of alteration, 24% of the reaches have been subject to at least two different macro-categories of alteration cause, while the presence of a single, well identified macro-category of alteration was documented for the remaining 35% of the reaches. Interestingly, average and maximum reported riverbed incision and percentage width reduction do not seem to be related to the complexity of alteration causes, with mean and maximum values being very similar for all rivers, whether subject to a combination of different types of anthropogenic macro-categories of stressors or subject to one single well-identified category.

Results of the PCA performed on the presence/absence matrix of anthropogenic stressors (Tab. ??) in every analysed reach are reported in Figure ??. Principal component 1 accounts for almost 27% of variability among reaches; it negatively correlates with torrent control works, bank protection and land use change (TC, BP, LC), which are jointly associated with at least 24% of the analysed reach, and positively correlates with channelisation, straightening and embankments (Ch, St, Em), which have jointly primarily affected a smaller percentage of reaches. Only 18% of initially braided reaches maintained their initial pattern, despite overall reduction in flow and sediment supply (red colour). Half of them were minimally correlated with the presence of specific stressors, while the remaining half strongly correlated with the combined

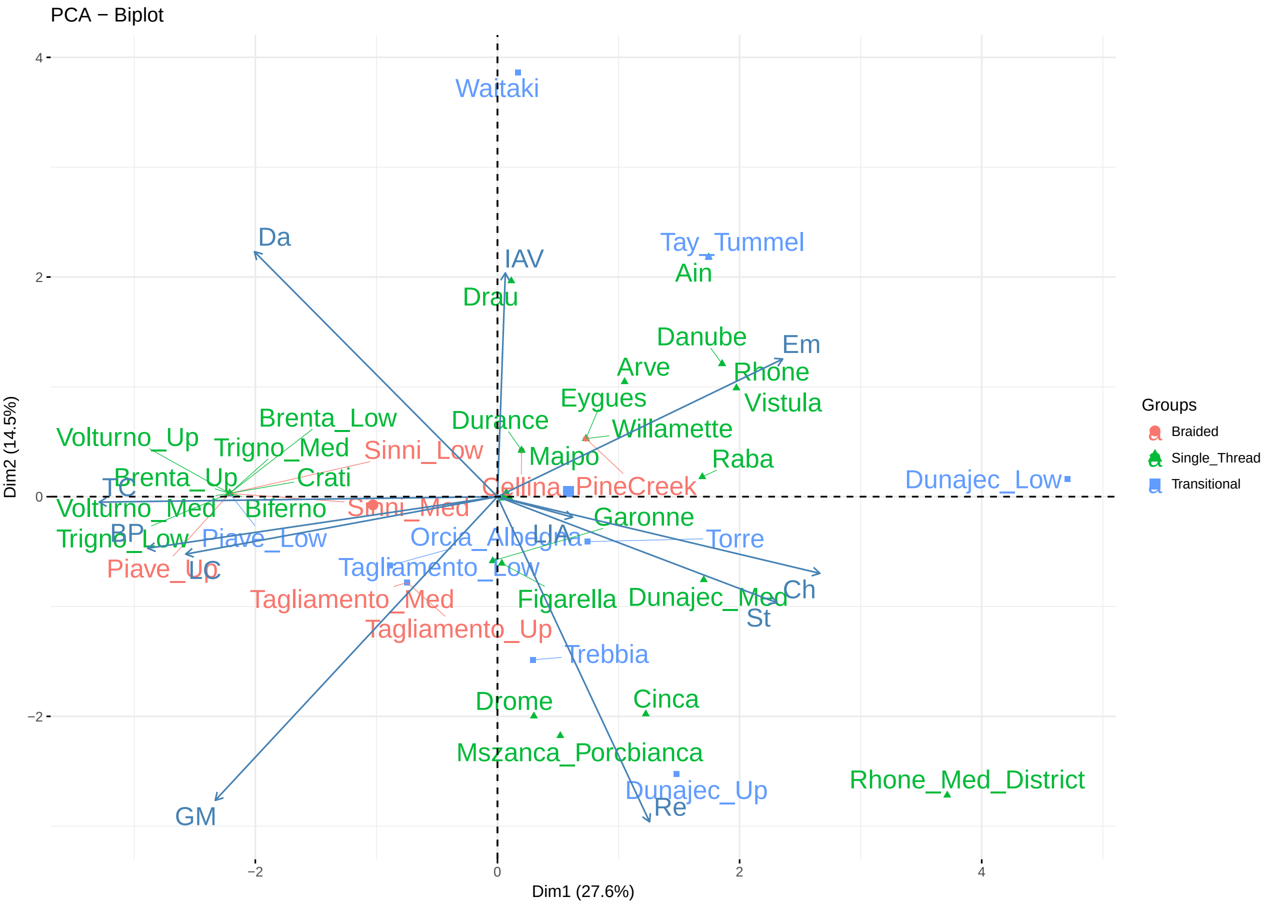

Figure 3: Results of the Principal Component Analysis on the 42 river reaches (Tab. ??) for which information on the management causes driving channel adjustment was available. Colours refer to the morphological pattern of every reach after channel adjustment, all being formerly braided. Acronyms are the same as in Section 2.1: Da= damming; GM= gravel mining; TC= torrent control works; BP= bank protection; Ch= channelisation; St= straightening; Em =embankments; LC = land use change; Re = reforestation; IAV = invasive alien vegetation, LIA = little ice age.

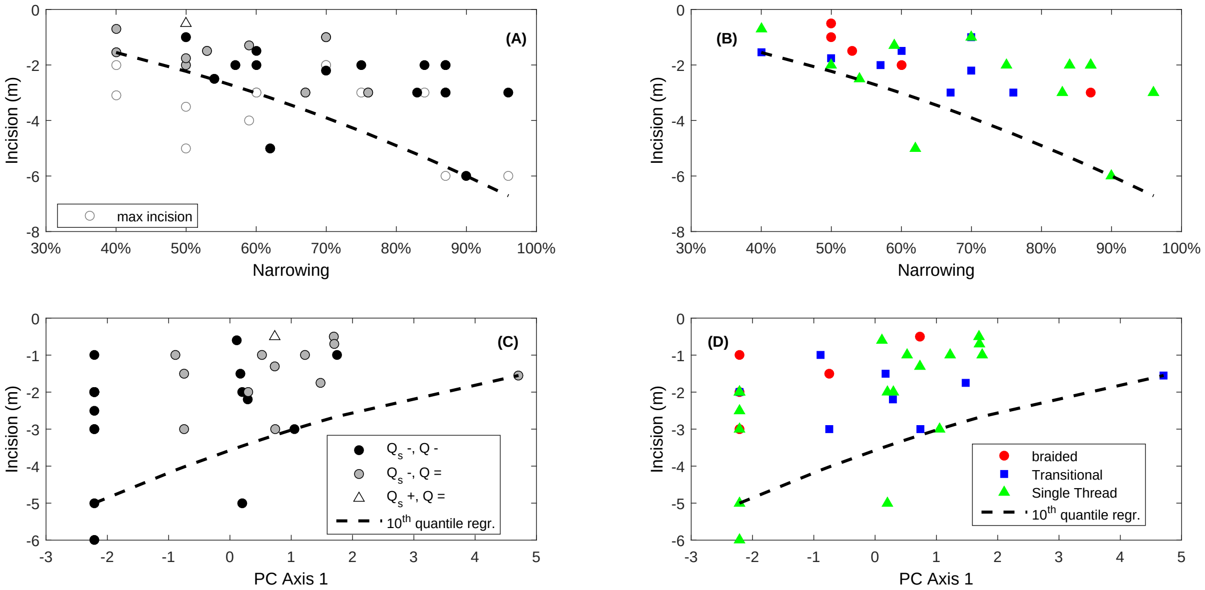

Figure 4: Scatter plots of percentage width reduction and documented average bed incision (A,B: information available for 27 river reaches); and of the first Principal Component score (PCA1) and riverbed incision (C,D: information available for 32 reaches). Dashed lines are 2^{nd} order polynomial regression on the lowest 10^{th} quantile. Different markers and colours refer to different types of broad morphological drivers of alteration (*sensu* ?; greyscale, panels A,C) and last observed channel pattern (coloured markers, panels B,D)

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presence of torrent control works, bank protection and land use change. A more complex scenario is related to braided reaches that underwent a real channel metamorphosis (59% of the whole set), because of their shift from a braided to a single-thread channel pattern (green colour in Figure **??**). For 8 out of 29 cases, such a transition was highly correlated with the effects of torrent control works, bank protection and land use change, while the remaining 21 reaches underwent pattern transition in the absence of any clear association with a specific combination of stressors. Principal Component 2 was positively correlated with the spread of invasive alien vegetation and damming (IAV, Da) and negatively correlated with reforestation and gravel mining (Re, GM). Damming and gravel mining also negatively correlated with Principal Component 1, though to a lesser extent compared with torrent control works, bank protection and land use Change. Furthermore, damming and gravel mining are almost orthogonal in the PCA1-PCA2 space of Figure **??**.

Apart from a few cases, reaches did not specifically correlate with one single stressor, with most reaches showing a combination of multiple alterations. Exceptions are the lower Tagliamento (association with gravel mining) and the Waitaki River in New Zealand, showing high association with invasive alien vegetation. Apart from these cases, reaches with the highest association with multiple stressors reflect the combination of either Ch, St, Em or TC, BP, LC. All reaches of the Dunajec in Poland well represent the former case, while many river reaches in Southern Italy together with the Piave (NE Italy) well represent the latter one.

Figure **??** relates reported values of average incision with percentage channel narrowing (A,B), and with the Principal Component 1 (C,D). Different colours and symbols denote the different direction of flow and sediment supply alteration (A,C) and the morphological pattern that eventually resulted from channel adjustment for every reach (B,D). A lower incision threshold, which decreases with increasing narrowing (A,B) and increases with increasing PCA1 value, can be detected when applying a lower quantile regression to the data points. A nonlinear (2^{nd} order polynomial) 10^{th} quantile regression has been applied to both datasets, highlighting the presence of positive (A,B) and negative (C,D) "floors" in the dataset. Such lower incision threshold decreases with the increasing combination of torrent control works, bank protection and land use change and, to a slightly lesser extent, with damming and gravel mining.

Figure **??**A suggests that higher narrowing tends to be associated with reduction in both sediment supply and peak flow (black filled circles), while reduction in sediment supply only (grey filled circles) results in more limited narrowing. Instead, a similar behaviour cannot be clearly detected in relation to either average or maximum (empty circles) channel incision. Figure **??**B also shows that channels subjected to more pronounced narrowing (75% to 95%) turned their initial braided morphology into a single-thread pattern (green triangles), with transitional morphologies appearing for intermediate narrowing values (approximately 55% to 75%). Most reaches that kept their initial braided morphology have experienced narrowing between 50% and 60%, though exceptions are present in all cases.

Figure **??**C shows that the alteration of both sediment supply and peak flow rates is either negatively correlated with the PCA1 value or slightly positively related with it. As already evident in Figure **??**, no clear trend emerges between channel pattern alteration and the PCA1 score. Finally, no relevant relation is found between narrowing, incision and the other main PCA scores, for Axis 2 and 3.

Tab. **??** summarises the association between the observed changes in channel pattern and the categories of **?** of flow and sediment supply alteration, for a subset of the reaches (42) for which all information is available. Most reaches (95%) have experienced reduction of the upstream sediment supply, and nearly two thirds (59%) have also experienced a reduction in the peak flows. Only 2 reaches (5%) have seen an increase in sediment supply. Such differences in alteration are associated with some differences in the morphological behaviour: 68% of reaches with both Q_s^- and Q^- turned into a single thread pattern, 16% to transitional and 16% kept their braided morphology. These figures are 53%, 33% and 13% for reaches subjected only to Q_s^-. The complexity of alteration did not differ much on average between the two groups, which experienced an average level of alteration around 0.7 (meaning that two macro-categories of alteration have been present). The two rivers experiencing an increase in sediment supply turned into single-thread rivers when the flow was also reduced (Willamette River) and kept braided when the flow regime was not appreciably altered (Pine Creek).

Table 3: Worldwide database of impacted braided and transitional rivers, as retrieved from the available literature. Contractions in the table are as follows. Width change: N=narrowing; W=widening. Elevation change: D=degradation; A=aggradation; Configuration change: B=braided; T=transitional; S=single thread; N.A.=not available. (Management) causes: Da=damming; LC=land use change; GM=gravel mining, BP=bank protection, TC=torrent control works, Ch=channelisation, St=straightening, Em=embankment, Re=reforestation, IAV = introduction of alien vegetation, LIA=glacier retreat associated with the end of the little ice age. Rivers used herein as case examples are named in bold.

ID			Morphological change:			(Management) cause	References	Change in controls
Country	Name	(Reach)	Width	Elevation	Configuration			
Italy	Brenta	upper	N by 322 m, 54%	D by 2.5 m	B to S	LC, GM, BP Da, TC	?	Q^-, Q_s^-
		lower	N by 265 m, 62%	D by 5 m	B to S		?	
	Piave	middle	N by 321 m, 50%	D by 1 m	B B.I. from 3.9 (1900s) to 1.3 (1990s)	LC, GM, BP, Da, TC	? ? ?	Q^-, Q_s^-
		lower	N by 546 m, 57%	D by 2 m	B to T			
	Cellina	(middle)	N by 479 m, 54%	N.A.	B	Da, GM	?	Q^-, Q_s^-
	Tagliamento	upper	N by 1205 m, 61%	N.A.	B	GM, LC BP	? ? ?	Q_s^-
		middle	N by 660 m, 53%	D by 1.5 m	B			
		lower	N by 303 m, 67%	D by 3 m	B to T B.I. from > 9.5 (early 1800s) to 3 (early 2000s)			
	Torre		N by 431 m, 76%	D by 3 m	B to T	GM	?	Q_s^-
	Ticino, Scrivia and others in the Piedmont region	middle	N by $10-30\%$	moderate D	B	N.A.	?	N.A.
	Po	upper	N by 56%	slight-moderate D	B	N.A.	?	N.A.
	Orcia, Albegna	middle	N by $60-80\%$	D by $0-2$ m	B to T	GM, TC, LC	?	Q_s^-
	Sesia, Cervo Orco, Stura L.	middle	N up to $70-90\%$	slight-moderate D, but locally up to $5-8$ m	B to T	N.A.	?	N.A.
	Secchia, Taro and others in the Emilia-Romagna region	middle	moderate-severe	D up to $3-4$ m, but locally D up to 12 m	B to T	N.A.	?	N.A.
	Trebbia	lower	N up to 700 m, 70%	D up to 2.2 m	B to T B.I. from ~ 2.5 (1810) to ~ 1.5 (early 2000s)	Re, BP, LIA, Da, GM	?	Q^-, Q_s^-
	Trigno	middle	N up to 75%	D by $2-3$ m	B to T and S	LC, Da, GM, TC, BP	?	Q^-, Q_s^-
		lower	N up to 90%	D > 6 m				
	Biferno	lower	N up to96%	D up to 6 m	B to T and S			
	Volturno	upper	N up to 84%	D by $2-3$ m	B to T and S			
		middle	N up to 87%					
	Sinni	middle	N up to 60%	D by $2-3$ m	B			
		lower	N up to 87%	D by $3-6$ m	B			
	Crati	middle	N up to 87%	D by $2-3$ m	B to T and S			

Table 3 (continued)

ID			Morphological change:			(Management) cause	References	Change in controls
Country	Name	(Reach)	Width	Elevation	Configuration			
Switzerland	Aare		N.A.	N.A.	B to S	Ch	? ?	N.A.
	Linth		N.A.	N.A.	B to S	Ch		
	Rhine		N.A.	N.A.	B to S	Ch	? ?	N.A.
Austria	Danube		N by 440 m, 60%	N.A.	B to T and S	Ch, Da	? ?	Q^-, Q_s^-
	Drau		N.A.	D by 0.6 m (average), up to 1.5 m	B to S	Da, LC, TC, Em	? ?	Q^-, Q_s^-
France	Rhône		N.A.	N.A.	B to S	Ch, Da	? ?	Q^-, Q_s^-
	Drôme		N by 150 m, 50%	D by $2-5$ m	B to T and S B.I. from > 2 (1940s) to < 1.5 (1991)	Re, TC, GM	? ? ? ?	Q_s^-
	Ain		N.A.	D by $1-2$ m	B to S	Em, Da	? ?	Q^-, Q_s^-
	Durance	lower	N.A.	D by 2 m	B to S	Da, GM	? ? ?	Q^-, Q_s^-
	Figarella		3 m	N.A.	B to S	GM, LC	? ?	Q^-, Q_s^-
	Arve	middle	N by 250 m, 83%	D by 3 m (average), up to 10 m	B to S	GM, Da, Em	? ?	Q^-, Q_s^-
	Garonne		W by $\sim$ 15m, 11%	D by 0.8-1.6 m A in the riparian zone	B to S B.I. from $\geqslant 2$ (pre-1969) to 1 (1986)	GM, BP	? ?	Q_s^-
	Eygues	lower	N by 200 m, 59%	D by 1.3 m (average), up to 4 m	B to T/S	LC	? ?	Q_s^-
	Numerous reaches in the Rhône-Mediterranean district		N by 33% (upper Drôme) N by 66% (Durance)	N.A.	B to T and S (mainly in the Isére Rhône, Durance, Arve, and Verdon rivers)	Em, Ch, GM BP, St, Re	?	Q^-, Q_s^-

Table 3 (continued). [1] **?** uses the braiding index definition by **?** as two times the total length of bars within reach divided by the reach length at mid-channel.

ID			Morphological change:			(Management) cause	References	Change in controls
Country	Name	(Reach)	Width	Elevation	Configuration			
Poland	Raba		N.A.	D by $0.5 - 3.5$ m	S to B to S	Ch, LC	**??** **?**	Q_s^-
	Dunajec	upper	N by $\sim 50\%$	D up to 3.5 m	B to T/S B.I. from 1.1 (1878) to ~ 1 (1979)	Ch, GM, LC, Re	**?** **?**	Q_s^-
		middle	N by $20 - 60\%$	D by $0.7 - 2$ m	B to S B.I. from > 2.5 (1938) to ~ 1 (1979)	Ch, GM		
		lower	N by 40%	D by 3.1 m	B/T to T/S B.I. from ~ 1.3 (1878) to ~ 1 (1979)	Ch, Em, St		
	Mszanka, Porębianca	middle, lower	N by 70%	D by 2 m	B to S	RT, GM, LC	**?** **?**	
	Vistula	middle	N.A.	N.A.	S to B to S	LIA, LC, Em	**?** **?**	Q_s^-
Scotland	Tay and Tummel		N by 34%	N.A.	B to T or S B.I.[1] from up to 1.8 (1863) to < 0.9 (1976)	Em, Da	**?** **?**	Q^-, Q_s^-
Spain	Cinca		N.A.	D up to 2 m	B to S	LC, Re, GM	**?** **?**	Q_s^-
New Zealand	**Waitaki**	lower	N up to 965 m, by 60% from 1936 (active corridor)	D up to 3 m	B to T B.I. from up to 11.6 (1926) to 6.7 (2001)	Da, IAV, BP	**?**, **?**, **?**	Q^-, Q_s^-
US-OR	Willamette (middle fork)	upper	W up to $\sim 200\%$ (1946-1967) N up to $\sim 50\%$ (1967-1979)	A	S to T or B T or B to S	LC	**?**	Q^+, Q_s^+ (1946-1967) Q^-, Q_s^- (1967-1979)

Table 3 (continued)

ID		Morphological change:			(Management) cause	References	Change in controls
Country	Name (Reach)	Width	Elevation	Configuration			
US-ID	Pine Creek	W by $\sim$ 50% (1933-2002)	A by 1 m	B	LC	**?**	Q_s^+
Chile	Maipo	N by $\sim$ 550m, $\sim$ 46% (average, 1980-2011)	D by 5m, (average) up to 20m (locally) (1980-2011)	B to T or S B.I. from 2-5.5 (1954) to 1-5 (2015)	GM, Da	**?**	Q^-, Q_s^-

Table 4: Summary table linking the direction of peak flow (Q) and sediment supply (Q_s) alteration with observed pattern change and complexity of hydromorphological alteration for the 42 reaches with available information (superscript + indicates increase, - indicates reduction).

		Final pattern			Avg. alteration
	N. of reaches	braided	transitional	single-thread	complexity
ALL	42	17%	21%	62%	0.73
$Q_s^- Q^-$	25	16%	16%	68%	0.77
Q_s^-	15	13%	33%	53%	0.71
$Q_s^+ Q^-$	1	0%	0%	100%	0.33
Q_s^+	1	100%	0%	0%	0.33

4.2 Converging Morphological Trajectories

The three study rivers have disparate geographic contexts (both in terms of physical and socio-economic conditions) and have experienced different sequences of anthropogenic modifications. Nonetheless, as we will show here, their evolutionary trajectories show a substantial convergence. In fact, the broad effects of these modifications, namely narrowing of the braidplain and loss of braiding complexity, are the same in all three cases. Also, the three rivers have experienced bed incision, at least in some reaches, and two of them (Piave, Dunajec) show incision correlated with loss of braiding complexity. Finally two of the river (Piave and Waitaki) feature a shifting balance between vegetation encroachment and hydro-morphodynamic processes.

To show this convergence, we will examine time trends of four indicators extracted from the literature data. To assess incision we consider changes in bed elevation. To assess narrowing, we consider temporal variation in braidplain width, which, to be comparable among rivers of different size, is non-dimensionalised with the initial (maximum) value in each river's case. To assess the change in braiding complexity, we analyse braiding index (i.e., the number of wetted channels) averaged along the reaches of interest. Since the braiding index varies with discharge even over a steady morphology, when contemporary discharge data are available, as for the Waitaki river, we plot time series of the braiding index measured at similar discharge values. Finally, we assess the change in vegetation cover by plotting changes in the width of the unvegetated, bare gravel, active channel. While doing so, we will provide additional information to that included in Tab. ??, showing the morphological modifications which occurred in each river, the time frame of these modifications and, (for the Piave River), the existence of different phases of alteration and partial recovery; and we will also introduce trends in vegetation cover. We plot the time series of these four indicators in Figure ?? and comment on them in detail in the following sections.

4.2.1 Incision

The variation in bed elevation for the three rivers is shown in Figure ??a.

For the Dunajec River, the width-averaged elevations at the considered cross-section show a degradational trend from ∼ 1919 to ∼ 2000, which relates to incision of the main channel.

The two reaches of the Piave River experienced degradation between 1926 and 1991. After 1991, Reach 1 kept degrading while Reach 4 aggraded, slightly exceeding the initial elevation. This recovery can be linked to the end of gravel exploitation. All the other reaches in the original

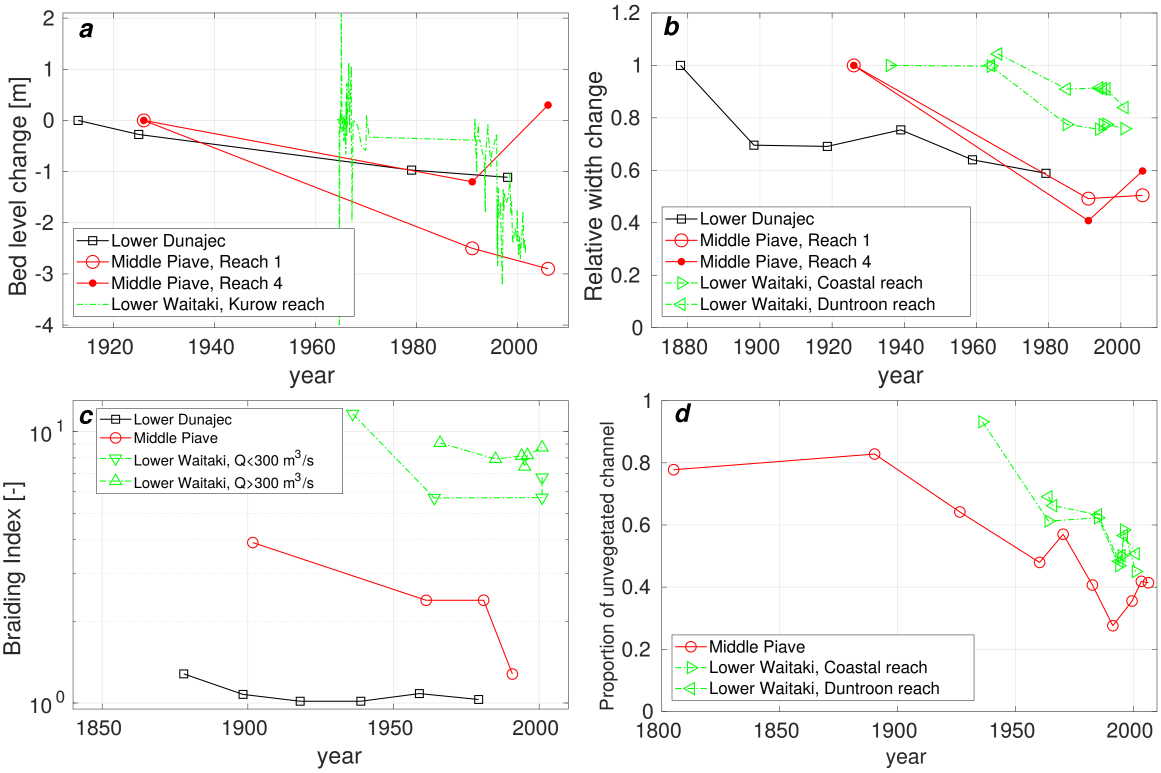


Figure 5: Comparison of morphological evolution trajectories in the Piave (Italy), Dunajec (Poland), Waitaki (New Zealand) Rivers: time trends for a) bed level change with respect to the first available value; b) braidplain width, scaled with the first available value for each river; c) braiding index (in semi-logarithmic scale); d) width of unvegetated channel, scaled with contemporary total river width.

data of ? have an intermediate behaviour between Reaches 1 and 4, however, with prevalence of degradation even over the second period.

Bed level data for the Waitaki River at Kurow reach are based on flow gaugings available since $\sim$ 1965, in two distinct series (1964 to 1971 and 1991 to 2001), and with much finer temporal detail than at the other two rivers. The first data set, apart from very rapid variations associated with high frequency sampling, does not show any clear trend. Fluctuations here are typical of the errors of the order of 1 meter associated with flow gaugings (?), although the drop in January 1967 was associated with a flood. No significant net change occurred between 1971 and 1991, suggesting a period when the bed was essentially stable. In contrast, in the second period: degradation by 1 cm/year was observed through 1991-1995; a sharp fall in bed level occurred in December 1995 over a major flood; an apparently stable period was observed through 1996 to early 1998; a further drop by about 6 cm happened in 1998 following two milder floods; and then quasi-steady levels with some hints of degradation were observed. ? interpret this sequence as the consequence of armour breakup following the 1995 flood, concluding that, whereas bed armouring has prevented the reach from massive degradation after dam construction, large floods, able to disturb the armour layer, have the potential for causing further degradation until the armour layer is re-established.

It should be noticed that, while significant degradation was observed in the Kurow reach, this was not accompanied by a significant reduction of braiding index at the same location, since the Kurow Reach, being laterally confined, had never had a highly braided configuration. In contrast, the more intensely braided lower reaches of the Waitaki did not undergo any generalised degradation, as the propagation of the dam-induced degradational wave was impeded by the development of bed armouring in the Kurow reach, by overall reduction of the transport capacity due to reduction in the frequency and magnitude of floods, and by the river ability to recover gravel from bars and banks in the lower reaches. On the other hand, in these lower reaches severe loss of braiding complexity and transition towards a single-thread style was observed - accompanied by localised incision within the main channels, but without generalised bed degradation of the entire reaches. Therefore, a straightforward relationship between generalised bed degradation and loss of braiding complexity cannot be established for the Waitaki River.

Figure **??**a shows that loss of braiding complexity in (formerly) braiding reaches can be accompanied by degradation. This is true for two out of our three study rivers (the Piave and the Dunajec), although for different reasons: increase in transport capacity in the Dunajec, and mainly sediment depletion due to gravel mining in the Piave. It is notable, however, that many reaches subject to loosing braiding complexity have been shown to do so without significant bed degradation. This is the case of the Waitaki River, where bed degradation caused by lack of sediment supply due to damming has been limited to the confined Kurow reach located immediately downstream of Waitaki Dam, but has not been observed along the rest of the 70-km long span of river between Waitaki Dam and the coast. Indeed, observations from many Italian rivers including the Piave (?) show that the first narrowing phase (before the onset of gravel mining) happened without significant degradation.

In regard to bed degradation, we conclude that the picture is more complex than for other morphological changes. Reaches loosing braiding complexity may also display degradation, since, as we will show later in Section **??**, degradation in itself favours and can drive loss of braiding complexity. However, loss of braiding complexity and narrowing can happen for a wider array of causes (such as, for instance, vegetation encroachment in the Waitaki), which may not necessarily imply degradation.

4.2.2 Narrowing

Figure ??b reports the relative variation in braidplain width with respect to the first available width measurement.

For the Dunajec River, starting from the last decades of the 19th century, width is seen to decline over time as a consequence of the aforementioned channelisation and bank protection works. A sudden reduction of width is observed between $\sim$ 1880 and $\sim$ 1900, followed by a stability phase ($\sim$ 1900-$\sim$ 1920). A widening phase due to abandonment of works during and immediately after World War II is then followed by another narrowing phase due to renewed channelisation.

The two reaches of the Piave River show a marked width reduction until 1991, then a later phase of widening which is interpreted as a recovery phase after the end of gravel mining. It is noteworthy that more recent data (?), not plotted here, do not support the view that the river will be able to fully recover its pre-impacted width. In fact, channel recovery is constrained by occurrence of formative discharge which has been strongly altered by a complex regulation scheme made of several dams and diversions.

Finally, data from the Waitaki River's Duntroon and Coastal reaches show that the river width has been steadily declining, except for a modest temporary increase in the Duntroon reach following a 100 year flood in 1995.

In summary, the three rivers, despite having been subjected to very different anthropogenic alterations, are all generally threatened by a narrowing river corridor (except for some, still questionable, recovery in the Piave).

4.2.3 Decrease in braiding complexity

In Figure ??c we plot time series of braiding index for our three rivers using a semi-logarithmic scale, so as not to miss in the plot the small-scale variation in the series of the least braided river (the Dunajec).

The Dunajec River generally shows a decrease in braiding complexity with time. The reduction is initially quite rapid, and eventually, after a slight temporary increase before 1960 the trend tends to a steady state. The Piave shows a dramatic adjustment in braiding index values which witnesses its change from a braiding to wandering/single-thread style.

Concerning the Waitaki, for which data collected at very different discharge values are available, we split the series between data collected at discharges smaller and greater than 300 m^3s^{-1}. This is because the Waitaki data were collected based on snapshots and are subject to the discharge on the day of photography, with additional noise added due to large floods (e.g. in mid 1990s) resetting the BI to some degree. The separation of the data into two clusters (smaller and greater than 300 m^3s^{-1}) represents modal and recession conditions, respectively. As the observed braiding index is more sensitive to discharge at low flows and tends to stabilise at higher flows, the higher-flow cluster is less likely to be discharge-influenced. Despite some scatter in the lower-flow cluster, the Waitaki data show a reduction in braided complexity, with the higher-flow cluster showing a $\sim$ 40% reduction in the number of flowing channels.

Generally, all three rivers showed significant changes in planform. Moreover, the changes appeared greater where vegetation processes interacted with morphological changes (Piave and Waitaki) compared to where the river was only affected by hydro-morphodynamic changes (Dunajec).

4.2.4 Change in unvegetated river width

In Figure **??**d we plot the time series of unvegetated river width scaled with the full river width for the Piave and the Waitaki. All the data series illustrate a significant decrease of unvegetated width over time, to almost 50% of the original value, at a quasi-steady rate. This reflects the vegetation encroachment which took place in both rivers in the past decades.

4.3 Analysis of management causes and process alteration

Having observed that the three study rivers display analogous evolutionary trajectories, we now aim to better understand how management causes impacted physical processes, and how the altered processes eventually determined the observed morphological changes. To this end we propose a simple schematic classification which highlights the conceptual and causal relationships between management causes, process alteration, and morphological change. This will provide a framework for a comparative analysis of the three rivers, yielding the conclusion that similar trajectories can stem from very different anthropogenic drivers. This methodology is similar to the diagnostic chain that is often used for river assessment and restoration (e.g., fluvial audits methods of Sear, Downs, Newson, Gregory and others, see **?**). However, here it is tailored for the specific context and features of braided rivers with changing morphology.

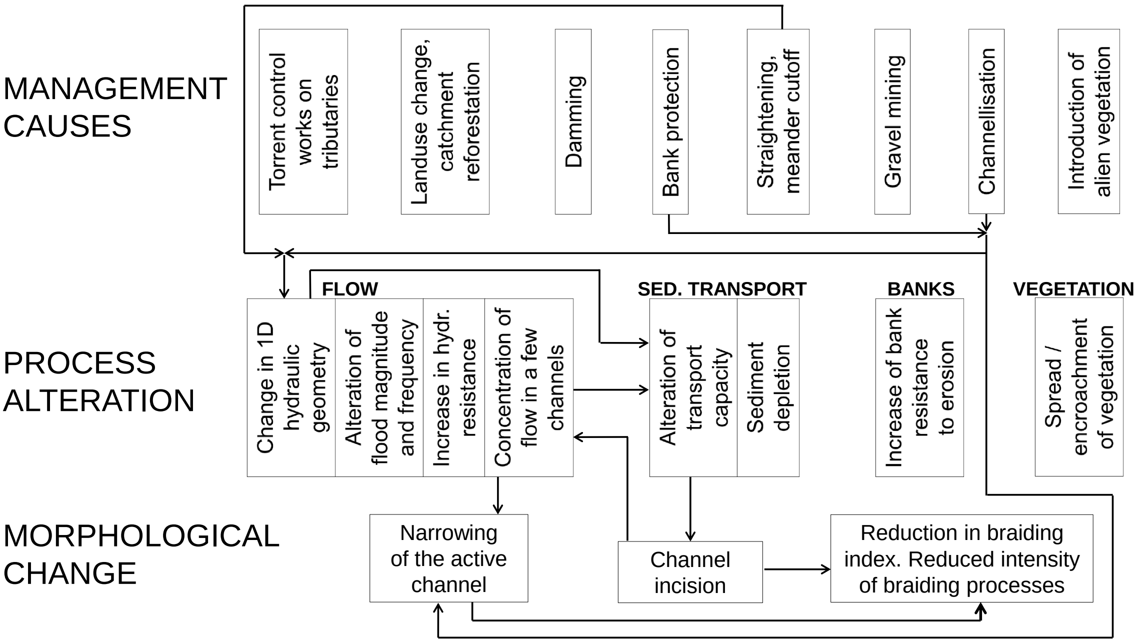
The scheme, applied individually to each river, is shown in Figure **??**. Moving from top to bottom, it presents an array of management causes, process alterations, and morphological changes. Altered processes are grouped into more general categories, namely alterations of flow, sediment transport, bank, and vegetation processes. Arrows connect management causes, process alterations, and morphological changes, which highlights the feedbacks between alterations at various hierarchical levels.

Herein we only list the items that are relevant to the history of our three rivers, but more general versions of the scheme in Figure **??** could be devised for applications to other rivers and river types. The proposed conceptual scheme could provide a practical tool for determining the limiting factors or pressures on recovery, selecting restoration measures, or helping decide to allow autonomous river recovery, which are some of the compelling issues for river restoration identified by **?**.

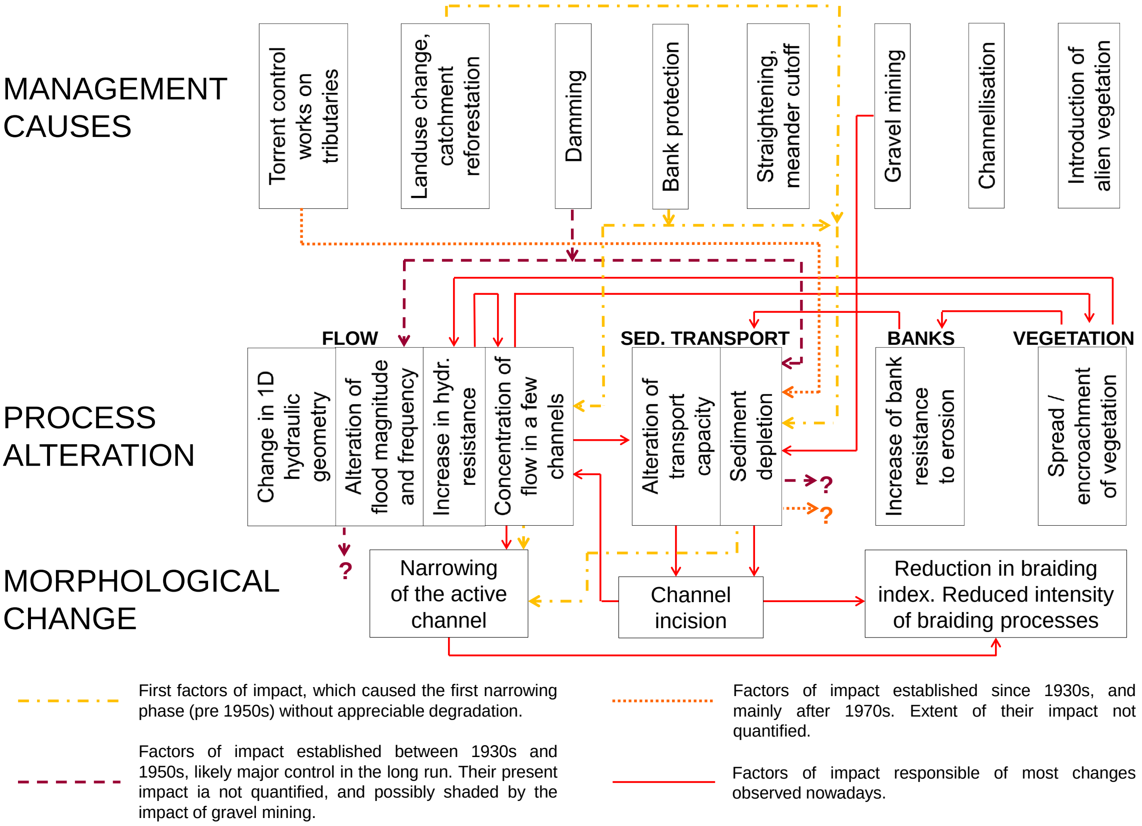
4.3.1 Lower Dunajec

As shown in Figure **??**a, the management activities causing change in the lower Dunajec River involved straightening its course (thus increasing its slope), and embankment construction and channelisation (which both narrowed the active channel directly). Furthermore, all three causes contributed to altering the one-dimensional hydraulic geometry, which increased the transport capacity and led to channel incision. We can also infer a positive feedback mechanism by which channel incision may have enhanced the flow concentration, further increased the transport capacity, and resulted in more incision. Finally, narrowing and incision determined a reduction

a) Lower Dunajec



b) Middle Piave



First factors of impact, which caused the first narrowing phase (pre 1950s) without appreciable degradation.

Factors of impact established between 1930s and 1950s, likely major control in the long run. Their present impact ia not quantified, and possibly shaded by the impact of gravel mining.

Factors of impact established since 1930s, and mainly after 1970s. Extent of their impact not quantified.

Factors of impact responsible of most changes observed nowadays.

Figure 6: Path of causation of morphological changes in endangered braided rivers. a) lower Dunajec River, Poland. b) middle Piave River, Italy. c) (next page) lower Waitaki River, New Zealand.

c) Lower Waitaki

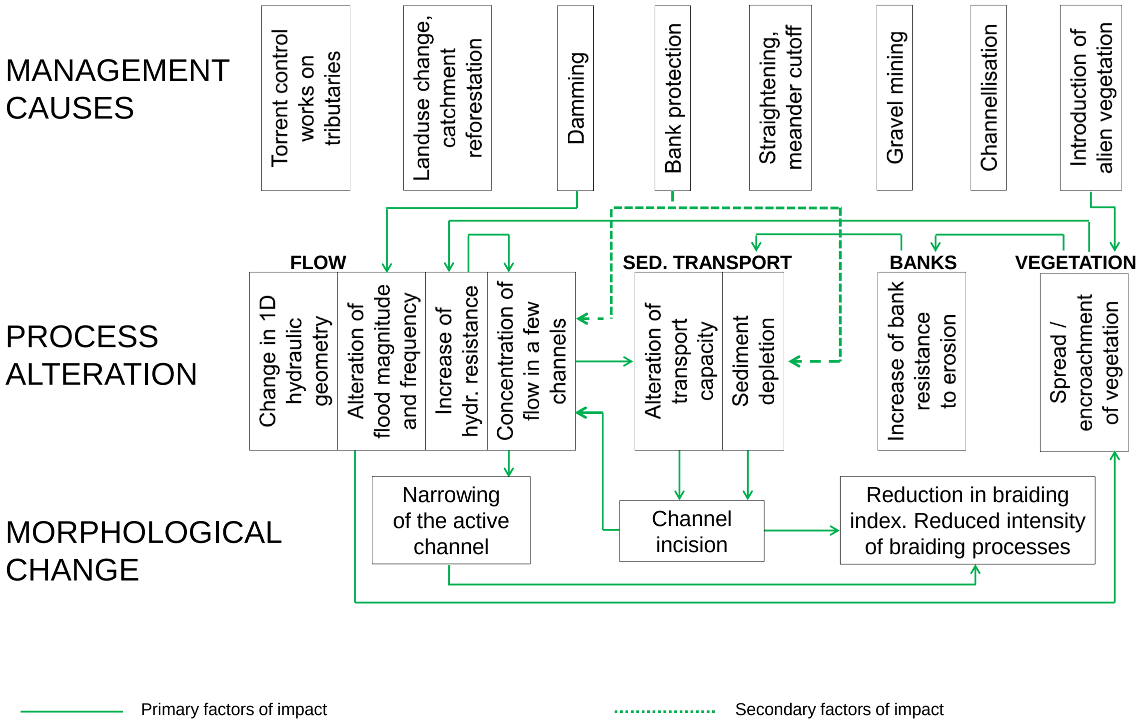


Figure ?? (continued)

in braiding complexity. In other words, the changes observed in the Dunajec, as described by ? and ? result from quite straightforward interactions between flow and sediment transport processes, triggered by an imposed change in the river width and slope.

4.3.2 Middle Piave

The Piave River (Figure ??b) has responded to a more complex sequence of causes, experiencing alterations due to virtually all possible factors. However, with the help of the quantitative analyses by ? and ?, and focusing on the order of magnitude of different impacts and their temporal sequence, we are at least able to discriminate four main categories of factors (represented by different line styles in our chart).

The first factor of impact (dash-dotted arrows) caused the first narrowing phase, without appreciable degradation (??). This originated from land use change (natural catchment reforestation), which provoked a sediment supply deficit to the river, and, more importantly, from the construction of bank protection structures (groynes) which reduced lateral connectivity - thus causing more sediment depletion and possibly favouring flow concentration in the central braids during floods.

Dams are another factor of impact (dashed arrows). Established massively across the catchment between 1930s and 1950s, the Piave dams altered flood magnitude and frequency and sediment delivery and will likely be a major control for the main river in the future, once the sediment deficit finally arrives the main river (?). Dams did not alter the frequency of channel-forming floods, but reduced the frequency of smaller floods, which may still have an impact on the river morphodynamics (?) and constrain the river's capability to recover its planform pattern. However, the role of flood frequency alteration on producing the dramatic morphological changes observed in the last 50 years is shaded by the more prominent role of in-stream sediment depletion due to gravel mining - which is why we do not pursue a detailed analysis of these drivers in Figure ??b.

Torrent control works on tributaries (dotted lines) were carried out from the 1930s and more intensely from the 1970s. Their effect is once again to reduce sediment delivery to the main course. The extent of that has not been quantified, but will likely take over as main control contribute (together with sediment blockage by dams and with alteration of sediment production due to catchment reforestation) to constraining the river shape in the long term.

Following ?, the major factor of impact on the middle Piave River has been gravel mining (now stopped). Besides its effects on sediment depletion and then channel incision, it was also able to trigger a cascade of consequences by contributing to the alteration of other processes.

As we have shown, channel incision induced flow concentration within the main channels. This, in turn, favoured the spread of vegetation by rendering floods less able to clear it. The spread of vegetation had a feedback on other processes and crucially contributed to morphological changes. A feedback loop was established between increase in vegetation cover, increase in flow resistance over the vegetated patches, concentration of flow in the main channels, increase in transport capacity within channels, further degradation, and further vegetation spread. Moreover, a similar feedback loop was established by the action of roots strengthening channel banks. By reducing lateral erosion, this added to the sediment depletion budget, which once again induced channel incision. Such a path of causation ultimately explains the shift from a braided to a transitional/single-thread configuration over a few decades, with narrowing and incision driving the reduction in braiding index.

Such a path of causation ultimately explains the shift from a braided to a transitional/single-thread configuration over a few decades, with narrowing and incision driving the reduction in braiding index.

4.3.3 Lower Waitaki

At a glance, it would be reasonable to infer that the lower course of the Waitaki River has experienced a similar set of processes as the Piave River. However, a deeper analysis shows that the path of causation is totally different. We illustrate changes for the Waitaki in Figure ??c. The major management causes (solid lines) were the construction of several dams and the introduction of alien vegetation on the river banks. The reduced magnitude of floods, combined with the invasive nature of alien vegetation, induced a rapid spread and encroachment of vegetation. This, in turn, enhanced the strength of channel banks, making them less prone to lateral erosion, which promoted sediment depletion and channel incision. Furthermore, due to the increased flow resistance on vegetated patches, vegetation spread caused the concentration of flow into the main braids, thus increasing the transport capacity therein and once again promoting incision.

Besides these major management causes and their impacts, bank protection including riverside tree planting may have played an additional role in concentrating flow into a few central braids and enhancing sediment depletion (dashed line in Figure ??c). However, we assume this effect to have been less important than vegetation encroachment.

Concentration of flow into a few channels accompanied narrowing of the active corridor and the observed reduction in braiding complexity.

4.4 Prediction of Future trajectories

After assessing the present morphological state through the analysis of past morphological trajectories and management causes, we now aim to determine whether the observed changes would spontaneously reverse should the factors of alteration be removed. Answering this question is a prerequisite before planning restoration in these rivers. Analogous questions should also be asked when planning mitigation measures prior to the establishment of new anthropogenic interventions on currently undisturbed rivers.

Here, we seek an answer by applying the pattern predictor of **?** to the three rivers and also the predictor of **?** to the Dunajec.

4.4.1 Piave and Waitaki Rivers

For application of the predictor of **?** to the Piave and Waitaki Rivers we represent the observed trend for vegetation spread by changing the value of the bank resistance parameter μ'. For both rivers the “bare gravel” scenario is representative of the unimpacted initial condition (circa year 1890 for the Piave and 1937 for the Waitaki), and the “vegetation type IV” scenario represents the present state (see Table **??**). In fact, as shown in Figure **??**d, the Piave River up to 1890 was unvegetated over more than 80% of its width, and the Waitaki River in 1937 was 90% unvegetated, whereas in recent years the unvegetated corridors of both rivers occupy less than 50% of their width (and, in the case of the Waitaki, merely by virtue of regular vegetation removal).

For the lower Waitaki, an analogous exercise was performed by **?** but applying the predictor of **?** instead. As in their work, we use a slope of 0.3%, a mean annual flood discharge (equal to $Q_{2.3}$) of 1000 $\mathrm{m^3s^{-1}}$ as a surrogate of the bankfull discharge, and median bed material diameter of 0.023 m.

For the middle Piave, we estimate the formative discharge as the two-year return period discharge, which is equal to 695 $\mathrm{m^3s^{-1}}$ (**?**), and we consider the data of two reaches reported by **?**: the braided Belluno reach has a slope of 0.33% and a median diameter of 0.045 m; the wandering Praloràn reach has a slope of 0.048% and a median diameter of 0.040 m.

The results are shown in Figures **??**a and **??**b for the Waitaki and Piave Rivers, respectively. In both, slope is plotted as functions of the bank resistance parameter μ'. The thresholds of equation (**??**), depicted by a full line and a dashed line, separate the plot area into regions of single-thread, anabranching, and braiding configurations. Both thresholds have slope increasing with μ', indicating that the slope required to achieve an increasingly complex planform configuration increases with vegetation cover. For the Piave River (Figure **??**b), two slightly different sets of threshold lines are indicated, corresponding to the different bed material diameters in the Belluno and Praloràn reach.

On both plots, horizontal dash-dotted lines indicate the actual slope. Once again, for the Piave two slopes are used to represent the two reaches. On these lines, we show by coloured dots the match between the μ' value under the five scenarios and actual slope. Moving from left to right, with progressively increasing bank resistance (μ' increasing from 1 to 2.09), these dots represent the evolution of the equilibrium configuration for the two river systems.

As we see from Figure **??**a, the Waitaki River has changed equilibrium configuration from braiding to anabranching, i.e. a less active multi-thread configuration with stable, vegetated islands. This is in line with the field observations, by which the braiding activity has been steadily decreasing over the last decades, and with the conclusions of **?** that vegetation encroachment has determined a change of equilibrium configuration for the Waitaki. However, it also partially differs from **?** in that they found the present equilibrium configuration to be single-thread, based on the less refined predictor of **?**, which does not discriminate between anabranching and single-thread behaviours.

The Piave (Figure **??**b) has followed a similar path, and, at least in the milder-sloping Belluno reach, according to these calculations, should have shifted to a single-thread configuration. This, however, is not supported by the field evidence that this reach retains some degree of braiding activity - which may indicate that the morphodynamic impact of increased vegetation cover for this incising river is not as strong as forecast by the predictor of **?**.

We now address the question as to whether autonomous recovery of the original planform configuration is possible if the management causes which determined past morphological changes (i.e., flow alteration and alien vegetation introduction in the Waitaki, gravel mining in the Piave) are removed. Such a recovery would be represented for both rivers in Figure **??** by a shift back to smaller values of the μ' parameter associated with a decrease in vegetation cover.

Regarding the Waitaki, there is some evidence that complete elimination of invasive vegetation could allow the river to restore its braiding planform complexity. In fact, where the vegetation is presently cleared (in a central corridor of a few hundred meters width) the river can sustain some braiding, even with the presently dam-dampened flow regime. However, this restoration could by no means be spontaneous, in that floods (even with significant periodic releases engineered to clear vegetation) cannot effect significant vegetation removal (**?**). As preservation of braiding in the central corridor is subject to the adoption of a strict and continual vegetation removal program, restoration of braiding throughout the river would only be allowed by its extension to the full river width.

Like the Waitaki case, there is evidence that the Piave River would not spontaneously reverse its recent changes following cessation of gravel mining. After severe sediment depletion, the Piave is presently disconnected from its sediment sources, both upstream and lateral. In the present, the rarity (due to the damped flow regime) of significant floods (5-10 year return period) able to effectively clear vegetation, means that vegetation significantly contributes to stabilisation of the river corridor by impeding gravel recovery by lateral shifting of channels. Indeed, natural widening of the Piave corridor, which had initially been observed after the end of gravel mining activity, has recently stopped (**?**) suggesting that the river is too disconnected from its sediment sources to support further widening. Besides, it is likely that morphological recovering is hampered by alteration of flood magnitude and frequency.

In summary, the Waitaki and Piave Rivers appear to have been forced onto a different evolutionary trajectory by anthropogenic intervention. The changes they have experienced could be reversed, but only at the price of more intervention and continual management, which poses questions over the feasibility of such restoration.

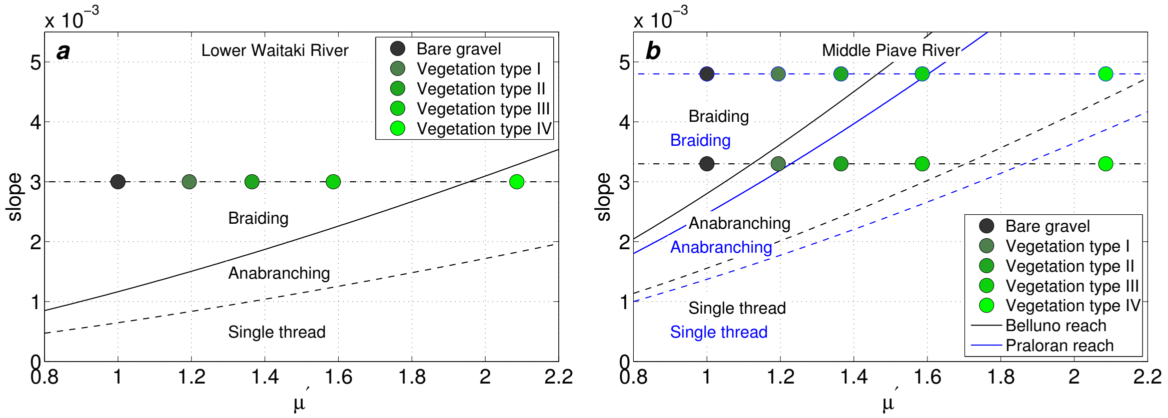


Figure 7: Application of the predictor of ? (a) to the Waitaki River, and (b) the Piave River. The thresholds of equation (??) are represented by a full line and a dashed line.

4.4.2 Dunajec River

As for the Piave and Waitaki, in the Dunajec we initially applied the predictor of ?. We used a bankfull discharge estimated from the Q_2 of 495 $\mathrm{m^3s^{-1}}$ (?), assumed a median bed material diameter of 0.025 m and a slope of 0.3%. We estimated the slope value knowing that slope in the Lower Dunajec (measured at the Żabno gauging station) is about 28 times lower than in the uppermost part of the Upper Dunajec (?), which has average slope between 0.8% and 1.1%. For the median diameter we had to assume a reasonable value as we could not find any literature data; however, we verified that using different values (in the range between 0.02 and 0.04 m) our conclusions would not change.

Results are shown in Figure ??a. Since the presence of vegetation has not been reported for the lower Dunajec, and this has not changed throughout the observed time frame, we assume the "bare gravel" scenario to be representative of both the past and current situation. Under this scenario, the river lies within the region of braiding rivers. As vegetation cover has not changed, μ' is not a significant parameter for the evolution of the Dunajec River, and no changes in the river's braiding tendency can be inferred from the predictor of ?. In fact, the lower Dunajec, because its width is artificially set as a constraint, violates one of the conditions under which the predictor is derived, namely that the river shall be able to achieve a dynamic equilibrium with the prescribed governing conditions (?).

For comparison, we applied the predictor of ?. Results are reported in Figure ??b, where the thresholds of equation (??) are represented by solid horizontal lines. A dashed line indicates the available unit stream power for the Dunajec as a function of the imposed width. We highlight by a grey dot the initial condition of the unconstrained river, for which we assume $W = 152$ m as the reach-averaged value reported in ?, and by a red dot the present, channelised configuration ($W = 90$ m). Both configurations lie within the regions of moderately braiding channels, and the present configuration is more deeply located within this region.

We conclude that the imposed reduction in river width has not affected the potential of the river to recover a fully braided configuration should the training structures be removed. This is confirmed by the observations by ? that the river enlarged when channelisation works and maintenance were paused during World War II. The Dunajec, unlike the Piave and Waitaki, seems not to have been shifted onto a new trajectory. Therefore, in the Dunajec case restoration

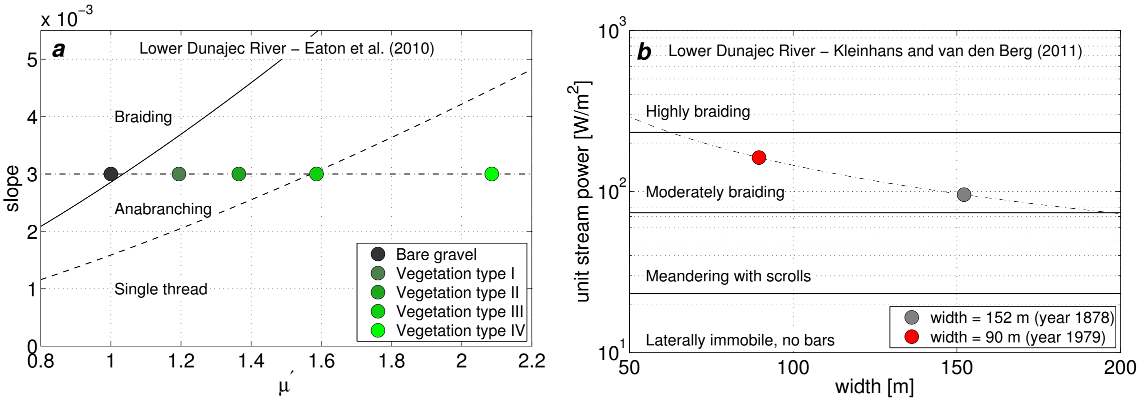


Figure 8: (a) Application of the predictor of **?** (equation (**??**)), and (b) of the predictor of **?** (equation (**??**)) to the Dunajec river.

strategies that are able to be implemented rather easily (i.e., structure removal) may prove successful in recovering braiding processes and the original planform.

5 Discussion

In this section we discuss two issues: the implications of our analysis of causal factors for braided river management and restoration; and whether braiding reduction in rivers should be considered a worldwide tendency.

5.1 Implications of the analysis of causal factors

As highlighted in Section **??** (Figure **??**), arrays of different management causes have been applied to the three focus rivers, yielding very different alterations of processes, yet being able to end up with very similar morphological changes (see Figure **??**). This shows that converging morphological trajectories can stem from very disparate management causes.

The Waitaki, Piave and Dunajec river reaches have been selected as representative cases, subjected to complementary combination of anthropogenic stressors, as shown by the outcomes of the PCA reported in Figure **??**. More in detail, the Piave and Waitaki Rivers, which are characterised by an opposite path of causation, provide an instructive example. In the Piave, it was the channel incision, mainly due to gravel mining, which favoured vegetation encroachment and then the narrowing of the active corridor and loss of planform complexity. In the Waitaki, it was the spread of invasive vegetation encouraged by flood dampening which induced concentration of flow into the central braids, channel incision, confinement of the braidplain, and finally simplification of the river planform.

The Dunajec River, unlike the other two, provides an example in which vegetation processes are not relevant to the river evolution, which is determined instead by changes in purely hydromorphodynamic controls. Still, like the Waitaki but unlike the Piave, the confinement of the river in its central region and narrowing of the active corridor eventually determined loss of braiding complexity and incision.

The analysis of the larger set of reviewed river reaches indicates that the reaches have been subjected to two macro-categories of anthropic drivers of alteration, which confounds attempts to elucidate the effects of a single stressor. The PCA analysis associated with reported incision data (Figure **??**c,d) suggests that gravel mining, land use change, torrent control works (negatively correlated with PC Axis 1 score) are also negatively correlated with a higher incision threshold, suggesting that (only when these stressors are dominant) a higher level of incision could be expected, although this does not represent a sufficient condition for high incision.

These observations have key implications to the design of restoration measures. Effective river restoration must rely on restoring braiding processes in the first instance. This requires careful analysis of the causal links between management measures, process alteration and morphodynamic change for the particular river at hand. In fact, as our analyses of the Piave and Waitaki show, rivers sharing analogous morphological trajectories and, at a glance, similar factors of impact have not necessarily experienced the same alteration process. Therefore, a particular restoration measure may prove successful in one river but not in others. For instance, whereas there is some evidence that complete vegetation removal in the Waitaki may restore the natural river braiding activity, this may not be the case in the Piave because it has suffered of massive sediment depletion. In fact, only the improvement of lateral sediment connectivity through the removal of bank protection structures, and possibly the adoption of a more natural flood regime through alternative dam management plans would allow morphological recovering in the Piave River. In this fashion, the classification scheme proposed in Figure **??**, despite being limited for design, may be a valuable tool for simple conceptual analysis.

Note that an individual analysis of factors of impact is valid if different magnitudes in the extent of the river response to different stressors can be identified, and/or different temporal and spatial scale can be linked to the action of each stressor, as done by **?** in the analysis of the Piave, and as we do here. Here, a rough analysis of spatial and temporal scales allowed us to exclude the processes triggered by changes at the catchment and basin scale from those having the dramatic and, by geological time frames, immediate impacts that we have documented in Figure **??**. For instance, the role of dams in reducing the sediment load has been neglected, under the argument that the propagation speed of a sediment deficit signal is too low for affecting the selected reaches within the time frame of available observations. Indeed, in the case of the Waitaki, observations show that the river bed has degraded by 3 meters in the reach immediately downstream of Waitaki Dam, but then bed armouring has prevented further local erosion. The estimates of **?** show that the river in the braided segment located further downstream retains a capacity to recover gravel from bars and banks of individual channels. Thus the sediment supply deficit has not yet progressed to the coast. However, as pointed out by **?** for the Piave, basin and catchment-scale modifications of the sediment regime may eventually take over as the main control on the river morphology in the long run.

5.2 Reduced river braiding in human-modified landscapes: a worldwide trend?

The overall picture rendered by this paper could, at a first glance, support the idea that river braiding is tending to be reduced worldwide because of direct and indirect human action. This is certainly true and evident in Europe, where most braided reaches have been heavily impacted by multiple stressors. Since the extent of impacts is directly related to the pressure connected to anthropogenic development, the situation is likely to worsen in the near future in certain areas, e.g., the Balkans, the Amazon, Mekong, Congo and Zambezi River basins, where hydropower development is about to dramatically increase (??), with likely alterations of flow and sediment supply rates. However, in general, the picture is less clear as discussed below.

The cases analysed in this paper suggest that the planform evolution of rivers strongly relates to the local combination of physical and human geographic conditions. An example of the interaction between natural and anthropogenic constraints is as follows.

Sediment availability is widely recognised as a natural control over the river capability to sustain a braided planform. The sediment balance can be altered in multiple ways, as we have seen, e.g., by straightforward depletion (gravel mining), reduced connectivity with streamwise (dams, check dams) and lateral (embankment) sediment sources, and the further interactions with flow and vegetation which we have analysed in the previous sections. However, in the long term, the ultimate controlling factor appears to be the stability of slopes and control of sediment delivery from tributaries. Indeed, the lithology setting, assumed as a proxy for the sediment production capacity of catchments, has been found the primary control over channel patterns (single-thread or braided) by ?, where braiding is enabled by lithology types enabling the highest sediment concentrations. In Europe, hill slopes have generally been stabilised very efficiently, ultimately resulting in a long-term constraint over the ability of rivers to sustain a braided pattern. However, elsewhere, hill slope stabilisation is not necessarily viable, for example where the rate of tectonic uplift is higher and the rock is less compact, giving rise to greater sediment production, e.g., New Zealand (?). In such cases, stabilisation depends on trade-offs between technical difficulty and cost, the value of reclaimed land and settlements, and the value given to natural landscapes. In these cases, it is then the interaction of natural and anthropogenic constraints which drives management and, ultimately, the tendency towards de-braiding. When aggressive management cannot be afforded, then a river may prove unmanageable and more prone to naturally preserve its braiding planform. It follows that the tendency of reduced river braiding mainly pertains to Europe, which in general is less active geologically and presently has a higher value of land and settlements.

Even when the same anthropogenic constraint is applied, dramatically different morphological changes can be produced, depending on the natural setting. As highlighted by ?, narrowing and channelisation can induce degradation, as we observe in this paper for the Dunajec and for many other rivers in Europe, or aggradation, as seen in multiple contexts (e.g., ???). In fact, as ? prove, confinement speeds up evolution of the river reach following its pre-existing trajectory: river reaches having a natural tendency towards degradation will degrade (and, similarly, aggradation-prone reaches will aggrade) at faster pace after confinement. Hence, the behaviour of a confined river ultimately depends on the amount of sediment supply. This has important consequences for river management, implying that embankment and training strategies will be effective only in naturally degrading or vertically stable rivers, since these, after confinement, will degrade and may tend to loose braiding complexity. Conversely, rivers showing aggradation even at their natural width will aggrade even faster, undermining the effectiveness of embankment and training strategies.

An interesting trend linking the ? categories with observed braiding reduction emerges from the information reported in Figures ??a,b and from Table ??. Figure ??a indicates that the highest narrowing corresponds to reduction in sediment supply and peak flows, while just the reduction of peak flows has little impact on channel width reduction. Transition to a single thread pattern occurred in 68% of cases when both Q_s and Q were reduced. The reduction in flow seems therefore to play some role in controlling pattern change from braided to more simplified planform styles, though only to a certain extent, because, even in the absence of flow reduction, pattern transition has frequently occurred and eventually lead to a transitional instead of a single-thread channel pattern.

In this discussion, we have implicitly assumed that braided planforms provide more highly valued landscapes, and this is certainly true of their ecological and morphological characteristics. However, it can in some cases be debated whether braiding was the natural setting of rivers, or whether instead it results from previous anthropogenic impacts or even naturally shifting climatic conditions such as the Little Ice Age. In Europe, a millenia history of changing controls and constraints on rivers due to the combination of anthropogenic and natural factors make it hard or even impossible to define such a natural state (for Italian rivers, see **?**, and references therein). Even in the uncommon case of reaches which have not suffered from severe anthropogenic impacts, in the long term shifting climatic conditions are likely to completely alter the natural setting thus rendering the search for a reference natural state pointless. An example is pro-glacial rivers (e.g. **?**). In practice, periodic shifts in planform have been reported for a number of rivers, which implies that reduced braiding or "de-braiding" may be followed by an opposite "re-braiding" phase, characterised by an increase in braiding intensity. Assessment of such long-term cycles requires a careful assessment of historical data (e.g., **?**). In this regard, the role of the local geography is once again key. According to the results of braiding predictors presented in this paper, we can argue that a river with the same slope, hydrological regime, and sediment size as the Waitaki but placed in Europe would hardly ever have been braided because the vegetation regarded as invasive in New Zealand would have always been naturally present. Now, after vegetation spread, the Waitaki braided configuration is maintained at the price of mechanical and chemical interventions, and it could be argued that this does not represent a natural state for the river.

6 Summary and Conclusions

In this paper we have analysed the worldwide recent (multidecadal) morphological evolution of gravel-bed braided rivers subject to general and increasing anthropogenic pressure. Most of the analysed reaches are located in Europe, and, within Europe, in the Alpine arc, while others are in North America, South America and New Zealand. Despite being incomplete (we are aware that other braided reaches in the same and other regions of the Earth, e.g., Asia, are undergoing morphological changes, but international literature is not available for these) the database supports the hypothesis of an overall tendency towards reduction of the braiding character in human-affected landscapes. Most of the analysed river reaches have undergone degradation, narrowing, and a shift towards single-thread configuration. A Principal Component Analysis of the presence/absence of all possible hydromorphological stressors in the reviewed reaches shows the difficulty in generalising cause-effect relations across different river contexts, and observed behaviours correlated with single dominant stressors only occasionally. The analysis pointed out the possible existence of a lower incision threshold that negatively correlates with channel narrowing; furthermore, transitions from braided to single-thread morphologies have been mostly occurring when both the upstream sediment supply and the peak flood frequencies have been reduced.

We then focused on three study rivers (the middle Piave in Italy, the lower Waitaki in New

Zealand, and the lower Dunajec in Poland) in disparate geographic contexts, for which abundant previous data and analyses were available. For these we compared trajectories of morphological change over time, observing similar patterns of bed degradation, channel narrowing, loss of braiding complexity, and, in two of the study cases (the Piave and the Waitaki) significant increase in vegetation cover. Notably, despite showing similar patterns of bio-morphodynamic changes, these rivers have been subject to very different kinds of anthropogenic pressure. We then analysed the relationships between management causes, alteration of physical processes, and observed changes. These observations have implications for environmentally-targeted management and restoration, as we have highlighted in the discussion. Since very similar morphological change can stem out of very different alterations of processes driven by different management causes, we argue that precise knowledge of the history of anthropogenic modifications in a river is key for effective restoration of its processes and shapes.

We applied pattern predictors to represent observed morphodynamic trajectories, and to try and predict whether these changes are reversible. The predictor of **?**, which has a parameter related to vegetation cover, was fruitfully applied to the Waitaki and Piave Rivers, where vegetation spread was a significant driver of morphodynamic change, but was not useful on the Dunajec, where the dominating factor was channelisation. Applying the predictor of **?** to the Dunajec river, retaining the river width as a free parameter in the definition of specific stream power, we were able to represent changes induced by narrowing due to lateral confinement. We speculate that configuration changes in the rivers which have undergone vegetation encroachment (Piave, Waitaki) are much less reversible than those purely determined by embankment (as in the Dunajec). In fact, whereas narrowing of the Dunajec has not reduced its tendency to braiding (should bank protection be removed), vegetation spread has shifted the Piave and Waitaki on a different trajectory. Although vegetation control measures can be established, as presently done in the Waitaki, complete removal of vegetation (especially, alien vegetation) looks hardly feasible in practice.

Regarding our initial hypothesis that braiding of rivers is reducing worldwide due to increased anthropogenic pressure, although we provide strong elements in support of this thesis, in fact, as we discuss here, the picture is blur. In detail, the hypothesis appears to be true for Europe, but the same does not apply to other regions where pressure has been lower. We conclude that the reduction of the braiding character of rivers flowing in one region ultimately lies in the relationship between the natural and socio-economic context of that region. Local geographical constraints determine the natural configuration of a river and the amount of human pressure on rivers regulates what is economically feasible, hence ultimately driving the long-term river evolution.

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