CHANNELIZATION OF A LARGE ALPINE RIVER: WHAT IS LEFT OF ITS ORIGINAL MORPHODYNAMICS?

Journal:	*Earth Surface Processes and Landforms*
Manuscript ID	ESP-16-0446.R2
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	30-Oct-2017

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CHANNELIZATION OF A LARGE ALPINE RIVER: WHAT IS LEFT OF ITS ORIGINAL MORPHODYNAMICS?

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Abstract

The Adige River drains 12,200 km^2 of the Eastern Alps and flows for 213 km within this mountain range. Similarly to other large rivers in Central Europe, the Adige River was subject to massive channelization works during the 19th century. Thanks to the availability of several historical maps, this river represents a very valuable case study to document to what extent the morphology of the river changed due to channelization and understand how much is left of its original morphodynamics. The study was based on the analysis of 7 sets of historical maps dating from 1803-1805 to 1915-1927, on geomorphological analysis, on the application of mathematical morphodynamic theories and on the application of bar and channel pattern prediction models. The study concerns 115 km of the main stem and 29 km of its tributaries. In the pre-channelization conditions, the Adige River presented a prevalence of single-thread channel planform. Multi-thread patterns developed only immediately downstream of the main confluences. During the 19th century, the Adige underwent considerable channel adjustment, consisting of channel narrowing, straightening, and reduction of bars and islands. Multi-thread and single-thread reaches evolved through different evolutionary trajectories, considering both the channel width and the bar/vegetation interaction. Bar and channel pattern predictors showed a good correspondence with the observed patterns, including the development of multi-thread morphologies downstream of the confluences. Application of the free-bar predictor helped to interpret the strong reduction – almost complete loss – of exposed sediment bars after the channelization works, quantifying the riverbed inclination to form alternate bars. This morphological evolution can be observed in other, Alpine rivers of similar size and similar massive channelization, therefore, a simplified model for large rivers subjected to channelization is proposed, showing that a relatively small difference in the engineered channel width may have a strong impact on the river dynamics, specifically on bar formation.

Keywords: evolutionary trajectories, historical mapping, river channelization, bar theory, channel pattern predictor, Alpine rivers.

Introduction

Study of historical evolution of river channels has been a central theme in geomorphology for decades (Petts, 1989; Wyżga, 1993; Surian and Rinaldi, 2003; Liébault and Piégay, 2002; Surian et al., 2009a; Scorpio et al., 2015; David et al., 2016). Most studies, at both Italian and European level, have addressed reaches characterized by originally wide braided morphology, while studies analyzing rivers with original single-thread or anastomosed morphologies are very few, i.e. the Rhine River (VanUrk and Smit, 1989, Frings et al., 2011) and Po River (Marchetti, 2002). Even analyses performed on large Alpine river systems (Surian et al., 2009a; Comiti et al., 2011; Ziliani and Surian, 2012) have focused especially on reaches with a predominantly braided morphology, excluding the work by Campana et al. (2014).

Most recent studies have shown that a sound understanding of channel evolution may be obtained by coupling the reconstruction of evolutionary trajectory of channel morphology with the analysis of driving factors (Ziliani and Surian, 2012; Scorpio and Rosskopf, 2016). Channelization has been a major driver of channel adjustments. In Europe, channelization has been planned since the 18th century, fixing new channel widths to satisfy the need of ensuring river navigation, flood protection and increasing the sediment transport capacity (Vischer, 1989; VanUrk and Smit, 1998; Vautier, 2000; Hohensinner et al., 2004; Zawiejska and Wyzga, 2010; Klosch and Habersack, 2016). Most common effects of channelization are channel narrowing, bed-level lowering, and simplification of channel morphology (e.g. from multithread to single thread channel) (Hohensinner et al., 2004; Zawiejska and Wyzga, 2010), but aggradation has been documented in some cases (Siviglia et al., 2008; Davies et al., 2013).

Existing studies suggest that (i) predicting morphological effects of channelization in gravel-bed rivers is not straightforward and (ii) channel width is a key parameter controlling river morphodynamics (Garcia Lugo et al., 2015). Nonetheless, the extent to which channelization may modify channel morphodynamics (e.g. bar formation and channel pattern) is still not well documented.

Also most Alpine rivers were largely modified by human interventions starting from the 19th century (Wohl, 2006), to ensure flood protection, reclaim agricultural land, and to facilitate transportation of goods. Direct modification of the river morphology through embankments, planform straightening, sediment mining and dam construction produced notable channel adjustments in Alpine rivers (Surian et al., 2009a; Comiti, 2012; Ziliani and Surian, 2012; Campana et al., 2014). Land use and climate change in the catchment further impacted on sediment production and flow regimes and, therefore, on channel morphology (Bravard, 1989; Liébault and Piégay, 2002; Arnaud-Fassetta, 2003).

The Adige River (Eastern Alps, Italy) represents a suitable case study to address the effect of channelization on channel morphology in mountain fluvial systems. This river was subject to massive channelization works by the Austrian Administration (under the Habsburg Empire) during the 19th century. Thanks to the availability of several large scale historical maps it was possible to analyze channel planform characteristics before channelization and to reconstruct channel adjustments during and after channelization. The main aims of this study are: (i) to document to what extent the morphology of the river has changed due to channelization; (ii) to understand how much is left of its original morphodynamics and iii) to gain insight in the physical processes controlling the channel changes. To achieve these objectives, the results from the historical analysis were compared to the estimates of an analytical model (Colombini et al., 1987) and of two channel pattern predictors (Crosato and Mosselman, 2009; Eaton et al., 2010). Additionally, a practical outcome of this study is to inform river managers about the possible trajectories of this river, for instance if a restoration project (e.g. channel widening of different magnitude) were carried out.

Study area

The Adige River (*Etsch* in German) is the second longest river in Italy, with a total length of approximately 410 km, flowing from the Central-Eastern Alps to the Adriatic Sea. The catchment has an area of about 12,200 km^2, a maximum elevation of 3905 m a.s.l. (Ortler/Ortles massif), and it is mainly composed of metamorphic (Alpine Paleozoic basement, mostly gneiss and micaschists) and volcanic (porphyric) rocks in the upper part, and of sedimentary rocks (especially limestone and dolomites) in the medium part.

The basin hosts 185 glaciers covering currently a total surface of about 130 km^2, approximately 1% of the total area, but about 6.5% at the upstream end of the study reach, which impart nivo-glacial characteristics to the flow regime of its upper reaches and tributaries. Along the entire course of the river, minimum flows occur in winter and large floods typically in autumn associated with long-lasting cyclonic fronts. The mean annual precipitation in the Adige basin ranges between 400 and 900 mm (Adler et al., 2015), and the mean annual discharge at the outlet into the sea is 235 m^3/s.

During the Little Ice Age (the peak of which occurred around the middle 19th century (Grove, 2004), Alpine glaciers reached their maximum extension ever reached after the Last Glacial Maximum. Afterward, they started to decrease in area and volume as a consequence of the progressive global warming (Fischer et al., 2015). In South Tyrol (the upper Adige catchment), the loss of glacier area was 376 km^2, between the Little Ice Age and 1969, corresponding to an area loss of about 40% (Fischer et al., 2015).

An analysis carried out on precipitation variability in Northern Italy indicates a general drying trend from the wet early 19th century to the dry mid-20th century (Brunetti et al., 2000; 2001; 2006). Afterward, until the early 2010s, precipitations slightly increased, but data do not show prominent and long-lasting trends (Brunetti et al., 2006).

Remarkably, the average slope of the Adige River segment flowing within the Alpine range is quite lower compared to other rivers of the Eastern Italian Alps (Brenta, Piave, Tagliamento), most likely as it crosses this mountain range along its wider section. Also, compared to other large river systems of the Alps, the Adige features an anomalous longitudinal profile, likely because of the presence of several knickpoints (Robl et al., 2008), and valley widths are large (1-2 km), likely due to the strong carving action of Quaternary glaciers (Fuganti et al., 1996; Bassetti and Borsato, 2005).

The Adige River has been subjected to a strong channelization and reduction of the river bed area. Small-scale land reclamation and channel bank works were already carried out in the Middle Age. However, they were limited to discontinuous portions of banks close to the human settlements, and they were mostly made of wood and fagots (Autoritá di Bacino dell´Adige, 1995). A massive channelization scheme aiming at land reclamation and flood hazard mitigation was planned since the mid-18th century, and implemented starting from the first decades of the 19th century. Most of the channelization works took place between the 1820s and the 1880s, and especially following a major flood that hit the entire basin in 1882. Indeed, the Adige River can be nowadays considered one of the most altered rivers in Italy, not only due to channelization but also to the presence of many hydropower reservoirs and check-dams along its tributaries that make both flow and sediment regimes highly modified (Zolezzi et al., 2009, Chiogna et al., 2016). It is relevant to point out that hydropower dams as well as check-dams for sediment trapping were mostly built after 1930s-1940s, i.e. after the period considered in this paper (i.e. 1800s-1920s).

The valley segment analyzed in this paper extends from the city of Meran/Merano (Autonomous Province of Bolzano/South Tyrol) to the village of Calliano (Autonomous Province of Trento), for a total length of about 115 km (Figure 1), and with the elevation ranging from 295 m to 170 m a.s.l. Catchment area increases from 2,000 km^2 at the upstream end to 11,400 km^2 at the downstream limit.

The valley bottom presents an average width of 1.5-2 km, and is bordered by steep slopes composed of porphyry and limestones or by alluvial fans built by tributaries. Downstream from the city of Merano, channel slopes are quite low (<0.2 %) and rather constant for about 200 km, despite the river flows through relatively high mountains peaks. Currently, this segment of the Adige River features a straight to sinuous pattern and an average channel width of 58-82 m. As retrieved from the Corine Land Cover database produced for 2012, the portion of the catchment drained by the study segment is composed of 84% by forests and semi-natural areas (47% forests; 18% shrubs and/or herbaceous vegetation associations; 19% open space with little or no vegetation), 14% by agricultural areas and 2% by artificial surfaces. Along the study segment, several important (up to 4,164 km^2 in drainage area) tributaries flow into the Adige River, developing small to large alluvial fans. The terminal reaches of these tributaries across their alluvial fans were also investigated in the present analysis (Figure 1). Total analyzed channel length is about 29.2 km. Similarly to the Adige River, also the final reaches of the main tributaries were interested by channelization during the 19^{th} century.

Methods

GIS-based morphological characterization of the river network

The study was based on the analysis of 7 sets of historical maps dating between 1803 and 1927 (Table 1 and Figure 2). All sets cover the entire valley bottom in the segment from Merano to Calliano. Historical maps come from several archives (Table 1), and were digitized using flatbed cold-light scanner in multi-resolution format (bit depth RGB 24 bits, TIFF master files 600 dpi). Afterwards, each map sheet was rectified in a GIS environment using the historical cadastral map of 1856-1861 as reference map, as this was provided already in UTM-ETRS89 coordinates by the Autonomous Province of Bozen/Bolzano and the Autonomous Province of Trento. A total of 212 map sheets were georeferenced using from 10 to 20 Ground Control Points (GCPs), mostly located in the proximity of the channel and by means of the application of a second-order polynomial transformation. Root mean square position errors (RMSE) of residuals were in the order of 1–27 m, with higher errors associated with the older maps.

The positional accuracy could appear important for such fine scale maps (from 3 to 10 times the graphic error). Nevertheless, it should be underlined that this kind of maps presents additional inaccuracies principally due to the material degradation of the paper as well as to their digitization phase. Paper degradation – the more relevant issue – is typical of maps being over 200 years-old and is caused by two types of deformation: i) shrinkage of the original map due to paper dehydration, and ii) stretching of the original map due to several subsequent reproductions by heliography. The reference Habsburg Cadastre map (scale 1:2.880, corresponding to a graphic error of 0.576 m) was checked measuring the distance between 2 points inside the range of 1 km, both graphically on the map and by surveying on the terrain. A mean positional error of 6-8 m per km was observed (Mastronunzio and Dai Prà 2016a; 2016b).

The geomorphological analysis of the Adige River was subdivided into two steps: i) GIS-based morphological characterization of the Adige River before channelization, (see Table 1); ii) characterization of its evolution during the channelization works (until 1927).

The very large scale (1:3.456) map surveyed in 1803-1805 by the Austrian empire (“Nowack-Plan”) – the most accurate of our database – was taken as a reference for channel segmentation.

The study river segment (115 km long) was divided into 42 homogeneous reaches (ranging in length from 1 to 5 km), following the approach described by Rinaldi et al. (2013, 2015a), which takes into account the occurrence of discontinuities as confluences with relevant tributaries, changes in lateral confinement, in valley orientation, in valley slope and in channel width and planform pattern. Channel pattern classification was also based on Rinaldi et al. (2013, 2015b), whereby the following channel types were included: braided (B), anabranching (A), wandering (W), sinuous with alternate bars (SAB), sinuous (S), meandering (M) and straight (St). Six macro-reaches were later defined for the analysis of the evolution of the channel during the channelization works, based on channel morphologies, valley orientations, confluences and similarity with neighboring reaches. They range in length from 10 to 24 km.

The 7 sets of maps were digitized recognizing the occurrence of active channels, bars, islands, and artificial structures in contact with banks. The quality and accuracy of the maps allowed the recognition of bare alluvial sediments (classified as bars) and vegetated fluvial deposits included in the active channel area (classified as islands). Two geodatabases related to the pre- and during-channelization conditions, respectively, were derived. The first aimed at a detailed analysis of the morphological patterns as mapped in 1803-1805. Twelve parameters were used to characterize the morphology of each reach as defined in Table 2. The second database was based on the six macro-reaches, and focused on channel evolution from 1803-1805 to 1915-1927, i.e. on the effects of the channelization works, before other major anthropic alterations took place (e.g. hydropower dams). A subset of 6 parameters was considered in this case, namely: average channel width (W), bar ratio (B), island ratio (I), sinuosity index (SI), braiding index (BI), anastomosing index (AI), (see also Table 2). In addition, the proportion of channel affected by training structures as levees and ripraps, either on one or two banks, was evaluated as the ratio between the length of the training works in direct contact with channel banks and the total bank length measured along both banks (Bwk).

The potential influence of tributaries on the observed changes was investigated reconstructing the morphological dynamics of the main tributaries (Passirio/Passer, Valsura/Falschauer, Rio di Nova/Naifbach, Talvera/Talfer, Isarco/Eisack, Noce, Avisio, Fersina, see Figure 1). Note that both Italian and German names are provided here only for the rivers lying in the Autonomous Province of Bolzano. Their terminal segments (23 reaches in total) flowing across their alluvial fans before joining the Adige were characterized through the following parameters: channel width excluding islands (W), total channel width including island (Wt), bar ratio (B), island ratio (I), basin area (BA) and bank length affected by work (Bwk).

Analysis of morphological characteristics and evolution

The geodatabases described above were processed through univariate and multivariate statistical analysis, as well as in terms of evolutionary trajectories. The univariate analysis was used to evaluate the variability of parameters in space and time. Multivariate analysis consisted of a Principal Component Analysis (PCA) and a hierarchical clustering analysis (HCA) and were applied to the databases characterizing the Adige River before the channelization works. The PCA was used to reduce the dimensionality of the initial datasets, through linear combinations of the original variables. The first four components resulting from the PCA were used to perform a hierarchical clustering analysis aimed at grouping reaches with homogeneous properties. A Principal Component Analysis (PCA) was also used to investigate the relation between the initial six variables analyzed for the tributaries in 1803-1805.

In order to investigate the relationship between observed channel changes and controlling factors, the available information on natural as well as on anthropic pressures in the Adige River basin (from the reach to the catchment scale) was collected. River discharge and sediment transport data were not available for the analyzed period, therefore, the potential influence of climatic variations on channel evolution was inferred from i) local historical flood events (available from the Autonomous Province. of Bolzano); ii) recent studies on past climate trends in the Alps (Brunetti et al., 2000, 2001, 2006); and iii) glaciological evidences (Fischer et al., 2015), similarly to what done by Marchese et al. (2017).

Bank protection and land cover changes were considered as the main anthropic factors. Despite few retention check-dams were already built in the late 19th century in some of the Adige's tributaries, torrent control works were widely constructed only after WWI and more intensively after WWII (see also Comiti, 2012 and Campana et al., 2014), and the oldest hydropower structure in the catchment dates to 1926. Finally, forest cover changes at the catchment scale were analyzed putting together the existing literature on specific sub-catchments of the Adige basin (Tasser et al., 2007; Marchese et al., 2017) with unpublished results deriving from the comparison of two land use maps (1855 and 1970) covering the entire Autonomous Province of Bolzano (65% of the considered Adige basin area). Forest areas in the former map (the Cadastral map above mentioned) were digitized based on an automatic and supervised detection process available within ArcGIS (Image Analysis tool).

Application of analytical morphodynamic models and channel pattern predictors

A morphodynamic analytical theory for river bars and two rational channel pattern predictors were applied to the 42 reaches as well as to the six macro-reaches described earlier. In particular, we compared results from the theory of free bars proposed by Colombini et al. (1987), the physics-based river bar and channel pattern predictor proposed by Crosato and Mosselman (2009), and the rational channel pattern predictor proposed by Eaton et al. (2010). For the sake of readability in the following we will refer to these three approaches, respectively as "free-bar predictor", "hybrid-bar predictor" (e.g. Durò et al., 2016) and "channel pattern predictor". The free and the hybrid bar predictors are based on the linear solution of the complete 2D (depth-averaged) morphodynamic equations for longitudinal and transverse momentum together with the continuity equations for water and sediments.

The free-bar theory (Colombini et al., 1987) predicts free bars to occur in idealized, infinitely long channels because of an intrinsic instability of the system resulting from the interaction between the water flow and the mobile channel bed. Only in enough wide and shallow channels, such instability arises, leading to free-bar formation. Despite being strictly valid for indefinitely long and straight channels, the free-bar predictor can be applied to predict the tendency of an alluvial river to form alternate bars. The key parameter controlling such instability is the width to depth ratio (β) of the channel at bar-forming conditions. When β exceeds a critical value β_c bars will develop, while for $\beta < \beta_c$ bars are damped and the flat bed is stable. The threshold depends on the reach-averaged values of the Shields parameter, a measure of sediment mobility, and of the ratio between a representative reach-averaged sediment size and flow depth. For sake of clarity, it is important to remark that in some theoretical papers the same symbol β is used to denote the half channel width to depth ratio, instead of the width to depth ratio as in the present paper.

The hybrid-bar predictor allows the estimation of the most likely number of bars that will form in a cross-section, considering a straight channel reach with a finite length. The number of bars in a cross-section is represented through a "bar mode", denoted with m in the following. The basic unit $m = 1$, represents the case of alternate bars, while larger values of *m* correspond to a larger number of bars in each cross-section, increasing from central bars ($m = 2$) to multiple bars ($m > 3$). The hybrid bar predictor (Crosato and Mosselman, 2009) returns a numerical value of the bar mode *m* through the equation (1):

$$m = \left[0.17 g \frac{(b-3)}{\sqrt{\Delta D_{50}}} \frac{W^3 S_c}{CQ}\right]^{1/2}, \quad (1)$$

where W is the channel width, g is gravitational acceleration, C is the dimensional Chezy coefficient for hydraulic resistance, Q is a bar-forming value of flow discharge, D_{50} is the median sediment size, Δ is the submerged relative density, S_c represents the river slope and *b* quantifies the degree of nonlinearity of the bedload transport equation, expressed as a relation between bedload rate and flow velocity. For the present analysis we used $b = 10$, as suggested for gravel bed rivers (Crosato and Mosselman, 2009).

The rational channel pattern predictor proposed by Eaton et al (2010) is derived from the combination of principles of hydraulic geometry and an extremal hypothesis of maximum sediment transport efficiency (Millar, 2005). It first adopts the value of $\beta = 50$ previously proposed as threshold value discriminating between single- and multi-thread channels. As a result the method yields a critical value of the channel slope S_N for a river pattern characterized by N separate parallel channels, indicating in $N = 4$, the threshold between stable (meandering/anabranching) and unstable (braided) multiple-thread channels.

The expression for such discriminant function reads:

$$S_N = 0.40N^{0.43}\mu'^{1.41}Q^{*-0.43}, (2)$$

where μ' indicates the dimensionless bank strength as ratio between the critical shear stress for the bank toe and the critical shear stress for the channel bed, and Q^* is a dimensionless discharge, defined as:

$$Q^* = \frac{Q}{D_{50}^2\sqrt{\Delta g D_{50}}}, (3)$$

The study of Eaton et al. (2010) also proposes a theoretical relation to predict the number of channel anabranches N (their equation 8), which can then be explicitly expressed in terms of the flow discharge Q, the sediment size D_{50} and the channel slope S:

$$N = 2.09\ Q\ S^{2.32}\ D_{50}^{-2.5}\mu'^{-3.28} \qquad (4),$$

a relation which, however, has not been explicitly tested by the authors. Rigorous estimation of the parameter μ' would require targeted field measurements or existing data to quantify the critical shear stress at the bank toe and at the channel bed, which are not available, particularly in relation to the historical conditions. As also implicit in the work of Eaton et al. (2010), the parameter μ' can be used as a calibration parameter. We therefore explored the effect of changing μ' in the meaningful range suggested by Eaton et al (2010), i.e. from 1 (no significant vegetation effect on bank cohesion) to 5 (very high bank reinforcement by vegetation). The pattern of every reach has been computed through equation (2) for several values of μ' in the range 1 to 5, and the percentage of correctly predicted patterns has been assessed. A unique representative value of $\mu' = 1.5$ for the whole segment was chosen as it maximizes the number of correctly predicted reach morphologies.

To compare the outputs of the hybrid bar predictor (most probable bar mode m) and of the channel pattern predictor (type of channel pattern) we adopted the threshold values for the bar mode m proposed by Crosato and Mosselman (2009). The lower threshold, $m = 1.5$, indicates a transition zone between single-thread and transitional channel planforms. The upper threshold, $m = 2.5$, indicates a transition zone between transitional and braided patterns. The hybrid bar predictor does not discriminate between stable (i.e., anabranching) and unstable (i.e., braided) channel patterns, a distinction which is made by the channel pattern predictor.

Both free and hybrid-bar predictors and the channel pattern predictor require similar, reach-averaged, input parameters: formative discharge, channel slope, and the sediment size representative for the channel bed surface, D_{50} (Table 3). In addition, the bar predictors require an input reach-averaged channel width, while the channel pattern predictor needs an estimate of the relative bank strength. It is here worth to mention that both bar theories and pattern predictor refer to channels which are under equilibrium with respect to the hydrological regime and sediment supply. Presently, the Adige is strongly armored and its surface median grain size cannot be assumed representative for the 19th century channel bed material. Therefore, we used the sub-surface grain size distribution to estimate the input sediment size for the bar and channel pattern predictors, assuming that it was less impacted by human interventions. As no historical information on the grain size is available, the median sediment size D_{50} was estimated from samples collected from six different locations well distributed along the 115 km study reach, thus yielding a representative grain size value for each macro-reach. In the light of the intrinsic uncertainties in determining an input grain size value, we assessed the sensitivity of the outcome of the bar and pattern predictors to the sediment size by increasing D_{50} up to 50%. Formative discharge values were estimated from historical daily discharge records available at the gauging stations of Ponte Adige, Bronzolo and Trento S. Lorenzo (see Figure 1). These three stations were selected because of the long period covered by the measurements, approximately from 1920 to 2010, and because of their location, which isolates the discharge contribution of the main lateral tributaries. To cope with the intrinsic uncertainty associated with the estimate of a constant value of a “formative discharge”, the discharge values with recurrence interval greater than 2, 5, and 10 years (Q_2, Q_5, Q_{10}) were computed for each station by fitting the streamflow records with a Gumbel distribution. Because of the absence of relevant lateral tributaries within the macro-reaches and because of the relative position of the gauging stations, data from Ponte Adige (located in M2) are representative of macro-reaches M2 and most of M1, Bronzolo (located in M3) of M3 and M4, Trento S. Lorenzo (located in M6) of M6 and also M5, for which the overestimation associated with the confluence of the Avisio River (between M5 and M6) does not have significant effects on the predictors outcomes. To roughly address the lack of consistent hydrological data for the 19th century, we used the 20th century records as a reference, and we hypothesized a possible two-fold increase of the flood frequency during the LIA, on the basis of the available historical flood events database mentioned above. This means, for instance, that the value of Q_{10} during the 19th century was computed as the value of Q_{20} obtained from the present record.

This choice stems from available datasets from the Bolzano Province, which highlight higher frequencies of floods, in the period between the 1860s and the end of the 1880s, especially during the 1880s (Figure 9c and 1882, 1883, 1885, 1888, 1889, 1890, Turri and Ruffo, 2005). The data in Figure 9c consider both the floods occurred in the overall Adige basin, and the flood events only occurred in the reaches from 1 to 25 (within the Bolzano Province). Though such observations clearly differ in accuracy and consistency from the present flow records, they represent the only available source of information to formulate reasonable hypotheses for the estimation of input streamflow values for the application of the bar and pattern predictors.

The increasing floods coupled to the increasing population density led to the first phase of massive embankment and rectification along the Adige as in other larger unconfined rivers (Hohensinner et al., 2004; Zawiejska and Wyzga, 2010; Hohensinner et al., 2013a; Hohensinner et al., 2013b).

Results

Channel morphology before channelization

In 1803-1805, the Adige River in the segment under investigation was characterized by a prevalence of single-thread patterns (73% in terms of total length), represented by sinuous (34%), sinuous with alternate bars (24%) and meandering (15%) channel morphologies. Multi-channel patterns represented 27% of the length, with braided dominating over anabranching (9% vs 5%). The transitional wandering morphology characterized 13% of the channel length.

Descriptive univariate and multivariate analysis were used to characterized the Adige, from a geomorphological point of view.

As expected, univariate descriptive analysis shows that the analyzed variables present specific ranges for each channel morphology (Figure 3). Among these, channel width decreases from the braided and anabranching pattern to the sinuous and meandering (Figure 3a). Channel width of multi-thread reaches is wider also when including the vegetated islands (Figure 3b) especially for the anabranching reaches. The islands ratio is obviously higher in the anabranching reaches, followed by braided reaches (Figure 3c) and then it becomes very small in other patterns. More interesting is to note how the bar ratio features an average value exceeding 0.3 in the multi-thread reaches as well as in the sinuous with alternated bars reaches, and below 0.3 in the sinuous and meandering reaches (Figure 3d). On average, the width of the alluvial plain is about 1470 m, and the largest values occur in correspondence to sinuous with alternate bars and anabranching morphologies (Figure 3e). Wandering reaches are characterized by the narrowest alluvial plain. However, when normalized by channel width (i.e. confinement index), sinuous with alternate bars and sinuous reaches are the least confined, and braided and wandering patterns feature the highest confinement (i.e. the lowest confinement index, figure 3f). Valley and channel slopes (S_v, S_c) are higher in the multi-thread morphologies and decrease for transitional and single-thread patterns. In particular, valley slope is on average 0.31 % for the braided, 0.17 % and 0.13 % for the wandering and anabranching, respectively, and it is as low as 0.08 % in the meandering and sinuous reaches (Figure 3g). Univariate distribution of the distance from the main upstream tributary (Figure 3h) indicates that braided and wandering patterns are more likely to be located few hundreds of meters downstream of the main confluences, whereas this distance exceeds 1000 m for single-thread reaches.

A multivariate analysis was carried out using the 1803-1805 dataset on channel morphology, using the 12 variables reported in Table 2. The PCA led to 4 principal components, representing

85% of the total variance, with the first component accounting for 46%. This mainly presents a negative correlation with channel width, also when including islands (W and W_{tot}), with bar ratio (B) and with braiding and anastomosing indices (BI, AI) (Figure 4a). As expected, such dominant component summarizes the quantitative channel characteristics that are used in the definition of the channel pattern. The second component represents 17% of the total variance and seems to characterize the width of the river corridor. In particular, it shows a negative correlation with the alluvial plain width (AP) and the confinement index (CI) (Figure 4a). The third component represents 12% of total variance, and results to be negatively correlated with valley (S_v) and channel slopes (S_c), thus possibly reflecting the "potential energy" condition of the reaches. Finally, the fourth component, accounting for 9% of the total variance, is negatively correlated with the sinuosity index (S) and positively with the distance from the first main tributary upstream (T), and thus it could be associated with the role of lateral forcing in terms of sediment supply. Figure 4a shows also the correlation of each reach with the first and second components (axes), with a clear difference between single-thread reaches, on the right side of the plot, and multi-thread morphologies on the left side of the plot.

A hierarchical clustering analysis was performed on all the Adige reaches using the first 4 components resulting from the PCA analysis described above. The result of this clustering are four groups of reaches sharing high similarities in terms of overall morphological characteristics as well as external factors (Figure 4b and Table 4). Group 1 (16 reaches) comprises reaches with single-thread morphologies, especially sinuous and sinuous with alternated bars (Table 4). Group 2 (13 reaches) is similar to the previous one as it is characterized by single-thread morphologies, but in this case meandering and sinuous patterns prevail. The most significant parameter for this group is the high sinuosity index (Table 4). Reaches belonging to groups 1 and 2 are located at considerable distance from the main upstream tributary (Table 4). Group 3 (only 2 reaches) includes two multi-thread reaches with anabranching and braided morphologies, respectively. They are characterized by high presence of bars and islands. Group 4 (11 reaches) includes multi-thread reaches characterized by wandering and braided morphologies. These reaches are located immediately downstream of the main tributaries.

The location of these four groups along the Adige suggests that they are not randomly distributed. Indeed, these groups were the basis to combine the initial reaches into macro-reaches, which overall show a longitudinal alternation between multi-thread and single-thread reaches (Figures 4b and 4c). Division in macro-reaches is based on distribution of channel morphologies from upstream to downstream and on similarity with neighboring reaches. More specifically, macro-reaches M1, M3, M5 (Figures 4b and 4c) are composed by alternate multi-thread and single-thread morphologies, but in general the multi-thread reaches prevail in length. Macro-reaches M2, M4 and M6 are exclusively composed of reaches characterized by single-thread morphologies (Figures 4b and 4c).

Figure 5 visually compares the outcomes of the hybrid-bar and channel pattern predictors with observations of the channel pattern before channelization, and the outcomes of the hybrid-bar predictor with observations after channelization. The observed and predicted morphologies are denoted with different intensities of blue in the lower part of the figure, with increasing intensity of blue corresponding to increasing morphological complexity. Overall, predictions of pre-channelization channel morphology compare rather well with observations. The comparison has been considered successful when an observed multi-thread (i.e., braided, anabranching) or a single-thread (i.e., straight, sinuous, meandering) pattern is correctly predicted. Specifically, the dominant morphology for every macro-reach (M1 to M6) is correctly predicted by both predictors in 5 out of 6 cases, and for a total length of 88% of the analyzed river segment. The two predictors are less performing when the pattern of every single reach is compared, with the channel pattern predictor of Eaton et al. (2010) correctly reproducing a slightly higher proportion (55.5% ± 3.5%, considering the uncertainty of discharge and grain size) of patterns in comparison with the hybrid bar predictor of Crosato and Mosselman (48%±5%).

Despite these local discrepancies at the individual reach scale, both predictors suggest the tendency of the Adige River to develop multi-thread morphologies immediately downstream of the confluences with major lateral tributaries, whose locations are denoted with vertical black arrows in Figure 5. Also the observed tendency to a single-thread pattern further downstream of the major confluences is broadly predicted. Such tendency is consistent with observations from the 1803-1805 map, already shown in Figures 4 and 5, downstream of the confluences with the Valsura, Isarco and Noce rivers, and with the exception of the observed patterns immediately downstream of the confluence with the Fersina River that does not determine relevant changes in Adige channel morphology.

Channel evolution during the 19th century

The analysis of channel evolution during the 19th until the early 20th century is presented referring to the 6 macro-reaches defined in the previous section (see Figure 4). In order to analyze the temporal changes, the evolutionary trajectories relative to the morphological parameters were reconstructed (Figure 6). The parameters describing the channel morphology and the abundance of bars and islands show dramatic changes between 1803 and 1917. However, some differences in their evolutionary trajectories are separately highlighted for macro-reaches characterized by multi-thread and single- thread patterns in 1803.

Channel width in the macro-reaches characterized by an initial multi-thread pattern (Figure 6a) shows fluctuations until 1847. Between 1847 and 1855 the channelization took place in most of these reaches, and thus narrowing started, progressing further until 1905, when channel widths were reduced by - 40% to - 70% of the initial value. The narrowing trend was concurrent to important and progressive pattern changes (Figure 6b). The multi-thread morphologies were gradually substituted by sinuous and straight morphologies. By 1905, the multi-thread morphologies were only 6%, while they were 67% in 1803.

Remarkably, channel widths in the single-thread macro-reaches were quite stable until 1870 (Figure 6e). Afterwards, the narrowing started reaching - 40% by 1905, and it strongly slowed down between 1905 and 1917. In these macro-reaches, meandering, sinuous and sinuous with alternate bars morphologies were largely replaced by straight, artificial channels (Figure 6f).

Modifications in channel width also affected bar and island occurrence and the related braiding, anabranching, and sinuosity indices. Bar and island ratios decreased at a faster pace between 1816 and 1855. Indeed, islands almost completely disappeared by 1855, earlier compared to the disappearance of bars (Figures 6c and 6g). Multi-thread reaches maintained a relevant bar ratio up to 1905 (Figure 6c), whereas in the single-thread macro-reaches (Figure 6g) bar ratio was highly reduced already in 1855. Especially after 1847, bars in the single-thread reaches disappeared also without any significant decrease in channel width (Figure 6e and 7g).

The post-channelization channel morphology is correctly predicted for 88% of the 42 individual reaches by the hybrid-bar predictor of Crosato and Mosselman (2009), such percentage being almost identical in terms of length of predicted morphology of macro-reaches.

Overall, the analysis showed a strong simplification of the channel system between the beginning of the 19th century and the beginning of the 20th century.

Morphology of the main tributaries and their evolution

The terminal reaches of the main tributaries of the Adige River were investigated considering their morphology in 1803-1805 and the channel evolution over the analyzed period.

A PCA analysis was performed, obtaining a reduction of the initial six variables (W, W_{tot}, BA, B, I, Bwk) to 2 principal components representing 80% of total variance. The first component (44% of total variance) shows a negative correlation with channel width, also including islands (W and W_{tot}), and the island ratio (I), similarly to what we obtained for the first component of the Adige River in 1803-1805. The second component represents 36% of total variance, has a negative correlation with the bar ratio (B) and a positive correlation with the basin area (BA).

The evolutionary trajectories analyzed in terms of average channel width, bar ratio and islands ratio for all these tributaries show an overall channel narrowing and simplification of channel morphology between 1803 and 1917 (Figure 7). Channel widths decreased mostly between 1847 and 1855 when, compared to 1803, they reached values of – 57% on average, and maximum of – 85% (Figure 7a). Between 1803 and 1855 bar cover declined (Figure 7b) from 70% of the total area to 30% on average. The decrease in bar ratio slowed down between 1855 and 1870 (Figure 7b) and then again accelerated between 1905 and 1917. Island ratio started to decrease already from 1803 (when it was equal to 8% on average considering all the tributaries), as in 1816 it reached values of about 1%. Few exceptions are present, such as the anabranching reaches belonging to terminal reaches of the Valsura and Avisio rivers. Island ratios were stable with high values (30%) until 1847, as in the case of the the Valsura, and for the Avisio until 1905.

Therefore, channel morphology in these terminal reaches underwent severe modifications (Figure 7d). Between 1847 and 1855, anabranching channels disappeared, braiding markedly decreased, and straight morphologies significantly increased. Since 1855, straight channels were the prevalent patterns. Embankments in studied tributaries increased especially between 1803 and 1870, whereas afterwards they remained rather stable (Figure 7c).

Application of free-bar predictor

Figure 8 shows the results of the application of the free-bar predictor to the six macro-reaches before and after channelization, in terms of the difference $\beta - \beta_c$ between the width to depth ratio β and its critical value for free bars formation β_c. Positive values of this parameter imply bed instability, thus bar formation, whereas negative values are associated with flat bed. As specified in the method section, we considered Q_2, Q_5, Q_{10} to characterize the present hydrological regime, and Q_5, Q_{10}, and Q_{20} to take into account an approximate twofold increase of flood frequency during the LIA. In Figure 8, blue filled circles refer to the pre channelization configuration with the present hydrology, the red asterisks show the effect of increasing the discharge to the hypothesized LIA values, and finally the black open circles correspond to the post channelization conditions. Higher points of each set refer to the lower discharge value in the examined range, as in this condition the width to depth ratio β is higher and the critical threshold β_c is lower. Outcomes of the model clearly show a tendency to form bars with any combination of parameters in the pre channelization configuration (positive values), whereas present conditions are likely to be slightly unstable for the three most upstream macro reaches and clearly stable (no bar formation) for the three more downstream. Strictly speaking, only for M6 (pre-channelization) and M3 (post-channelization) the choice of formative discharge may be relevant to predict whether the width to depth ratio β crosses the bar stability threshold β_c. However, it has to be remarked that such threshold must not be intended as a sharp border, also in relation to the uncertainties in the input parameters and in the assumptions of the theory. The analysis of the effect of modifying the sediment size proved no major impact on the free-bar predictor, with small variations of the $\beta - \beta_c$ parameter (up to 10%), and larger overall variations of each of the parameters β and β_c (within 25%). Most importantly, the examined variability in sediment size did not produce changes in the tendency of the macro reaches to form free bars.

These results compare well with observations from historical maps. Bars were present along the whole study reach before channelization (e.g. figure 3d), both in multi-thread (Figure 6c) and single-thread macro reaches (Figure 6g). Moreover, macro-reaches M1, M3, M5 showed a higher morphological complexity compared to macro-reaches M2, M4, M6, and are characterized by higher values of the difference $\beta - \beta_c$, which theoretically corresponds to a higher morphological complexity of the river pattern.

Figure 8 also shows the theoretical effect of channel narrowing associated with channelization, when looking at the corresponding markers that refer to the discharge with the same return interval. Indeed, artificial narrow width strongly reduced the tendency of the Adige River to develop free bars (i.e., the difference $\beta - \beta_c$), especially for the braided and wandering sections, which were subjected to the most intense reduction of their width. In the new configuration, macro-reaches M4, M5 and M6, lie below the bar-forming threshold for all the analyzed discharges, in agreement with the observation that bars are not observed anymore after channelization (Figure 6c and 6g).

Discussion

Adige River before channelization: insights from historical analysis and theoretical approaches

The analysis of the Adige River morphology before channelization showed the presence of homogeneous macro-reaches, characterized by prevalence of single-thread or multi-thread patterns. At the very beginning of the 19^{th} century, i.e. before major human disturbances, the Adige River already presented a prevalent single-thread planform morphology within its montane basin, in contrast to other large rivers of the Southern Alps characterized by steeper valley slopes (Surian et al., 2009b; Comiti et al., 2011; Ziliani and Surian, 2012; Moretto et al., 2014). Sinuous and sinuous with alternate bars were the dominant patterns in the upper and middle part of the studied segment. The river channel was quite rich in bars, suggesting a relatively high supply from the catchment. Meandering was prevalent in the most downstream reaches, where the large point bars at meander bends may also indicate a regular bedload transport.

Indeed, at the beginning of the 19^{th} century, sediment supply entering the main Alpine rivers from their headwaters was probably very high – i.e. higher than in both preceding and subsequent centuries – due to the effects of the Little Ice Age, to a lower forest cover, as well as to the very limited presence of controlling works (Comiti, 2012). High sediment dynamics at the basin scale is evidenced by the abundance of bars in the terminal reaches of the main tributaries of the Adige River, where most reaches presented complex planforms (wandering or braided patterns), even when controlled by bank protection. Such morphologies testify the large sediment amount produced and transported to the outlet of these sub-catchments during the 19^{th} century. A remarkable feature of the Adige planform before channelization was the presence of anabranching reaches, characterized by multiple, relatively stable secondary channels with large forested islands. At that time, this pattern was quite common in mild-sloping (0.1–0.3%), wide valleys of the Alps (Comiti, 2012; Campana et al., 2014) as well as in other large European rivers, such as the Danube (Hohensinner et al., 2013a and 2013b).

Before channelization, tributaries had a major effect on the Adige River morphology, imparting multi-thread patterns (braided and anabranching) immediately after their confluences (Figures 4 and 10). This was likely due to the high amount of coarse sediments carried by the (much steeper) tributaries, which induced transient sediment deposition in the Adige River, promoting the formation of numerous large gravel bars and islands. Downstream of these multi-thread reaches, transitional reaches 1-2 km long would generally follow, developing then into a single-thread pattern. Multi-thread reaches were in most cases characterized by a dense cover of riparian vegetation.

Both the hybrid bar and the channel pattern predictors were able to consistently estimate the channel pattern before the major embankment works, at the scale of the macro-reaches (Figure 8). Both predictors use the width to depth ratio as the controlling parameter, though with a fundamental difference: the channel pattern predictor computes an equilibrium channel width, which is instead given as input to the hybrid pattern predictor as resulting from the analysis of the historical maps. At the macro-reach scale, the equilibrium width predicted by Eaton et al. (2010) does not differ much from the one resulting from the historical analysis, which suggests the Adige River may have had a bankfull width that was approximately in equilibrium with the hypothesized discharge, slope and grain size.

Both predictors are based on a somehow similar assumption of dynamic equilibrium of the river channel, which refers to the spatial scale of long enough river reaches characterized by nearly homogeneous boundary conditions. Therefore, it seems reasonable that the predictive ability of the predictors is higher at the macro-reach scale compared to the scale of the local reach, because smaller differences among individual reaches are filtered and only the average properties are retained at the macro-reach scale.

The sequence of different planform configurations, from braided/anabranching to sinuous with alternate bars and finally to sinuous or meandering reaches (Figure 4), represents an interesting example of the longitudinal shift from multithread to single-thread observed also in other river systems (Church, 2002; Beechie et al., 2006; Beechie and Imaki, 2014). The cause for this shift has been associated to decreasing channel slope and thus transport capacity, and/or increasing sediment supply and grain size (Schumm, 1985; Rice and Church, 1998; Church, 2002; Benda et al., 2003; 2004; David et al., 2016).

As to the Adige River, because sediment supply from tributaries is only implicitly incorporated in the predictors within the input values of channel slope, discharge, coarse sediment size (and channel width for the hybrid bar predictor), the comparison between prediction and observation suggests that tributaries affect the downstream channel morphology mostly by delivering coarse sediments to a much lower energy channel, thus determining local bed steepening.

Evolutionary trajectory of the Adige River

The performed analysis shows that the Adige River underwent notable channel changes between the 19th and the beginning of the 20th century, which occurred through three distinct phases (Figure 9). The macro-reaches initially presenting a multi-thread pattern show slightly different evolutionary trajectories compared to those with a prevalent single-thread morphology (Figure 9). In particular, as expected, channel narrowing was on average significantly higher in the multi-thread macro-reaches where it was up to -87%, compared to the single-thread macro-reaches where it was up to -50%.

During the first phase, between 1803 and 1847, channels were quite stable, with a few multi-thread reaches experiencing minor widening between 1803 and 1816 (Figure 9a). During this first phase, the presence of bank protections increased from values not exceeding 10% in 1803 to about 30% in 1847 (Figure 9a). Furthermore, channel widths and channel morphologies in tributaries remained stable in this period (Figure 9b). On the other hand, a considerable reduction seems to have occurred in the areal extension of bars, both in Adige River and its tributaries (Figure 9a and 9b). Although bars shown in the maps are influenced by the variability of discharge - that exposes or submerges part of river bed at different flows-, we are convinced that reduction or even absence of bars is clearly evident and is explained as correlated with the low width-to-depth ratio imposed to the channelized channel (see the section *Application of free-bar predictor)*.

The period between 1847 and 1905 corresponds to the second phase of adjustment, but some differences in time and intensity of processes can be considered within this phase. Between 1847 and 1855, multi-thread and tributary reaches underwent a first important channel narrowing, while the single-thread reaches remained stable (Figure 9). Anabranching reaches had progressively turned into wandering and single-thread patterns, with a much lesser extent of bars and islands. Overall, we think that most of the channel changes observed during this period (1847-1855) in the Adige River and its tributaries can be associated to channelization works, which already suffered a consistent increase (80% of stabilized banks in the tributaries and 40%

in the Adige River, in 1855; Figure 9a and 9b). Between 1855 and 1870, channel widths in the single-thread reaches on average decreased, in the multi-thread on average was constant and in terminal reaches of main tributaries slightly increased (Figure 9). In the Adige River some increase of sinuous with alternate bars reach appeared at the expense of sinuous reaches, while the meandering reaches were replaced by straight configurations; also in the tributaries the increase of sinuous with alternate bars morphologies is visible. Although several large floods occurred during the 1870s and the 1880s (Figure 9c), no appreciable widening trend is visible between 1870 and 1905. Not even the extreme 1882 flood (Turri and Ruffo, 2005; probably characterized by >100 yr recurrence interval in the main river and in many tributaries) had any remarkable effect on the Adige channel morphology, already fixed by levees. The same 1882 event instead caused widening in the wider, uncontrolled Piave River (Comiti et al., 2011). Between 1905 and 1917 (the "third phase"), narrowing reached maximum values in all reaches (Figure 9) and channels were laterally stable, because channelization works were completed at that time.

Recently, Marchese et al. (2017) analyzed the channel changes of 17 tributaries of the upper Adige river basin from 1850s to 1950s, and found a net tendency – despite large intra- and inter-catchment variability – for channel pattern simplification and narrowing mostly from 1850s to 1920s. Reaches of the Adige, located upstream the segment analyzed in this paper, suffered narrowing between 1850s and 1920s and remained in equilibrium, or were interested by narrowing or some widening between 1920s and 1950s. Final configuration was a pattern simplification and a prevalent narrowing from 35% to 90 % in the entire period from 1850s to 1950s (Marchese et al., 2017). This tendency was attributed to climatic reasons (i.e. warmer and drier period following the peak of the LIA, with less flood events and reduced sediment supply from glaciers), in agreement with previous studies in larger rivers (Rumsby and Macklin, 1996; Arnaud-Fassetta, 2003; Gob et al., 2008; Astrade et al., 2011). Forest cover expansion – and thus a reduced sediment supply from hillslopes – had likely a minor or no role at all in the Adige River (Marchese et al., 2017), given its limited magnitude (14% from 1855 to 1970, and thus surely less until 1920s, Comiti, 2012), much lower compared to other Alpine basins in Italy and France (Descroix and Gautier, 2002; Liébault and Piégay, 2002; Comiti et al., 2011). Nonetheless, we argue that the channelization has largely prevailed over the climatic factors in determining bar reduction and pattern change and in the main Adige River from early 1800s to the early 20th century, and the results of the models on the role of channel width in bar formation seems to support such a conclusion. In addition, relevant differences are evident when comparing the Adige's evolutionary trajectory with those determined for the Tagliamento (Ziliani and Surian, 2012) and Piave rivers (Comiti et al., 2011), which drain similar large basins (>2000 km^2) in the Eastern Italian Alps – and thus share similar climatic variations – but were not affected by channelization works in the 19th century. In fact, the Tagliamento and Piave rivers were affected by limited channel width variations (not exceeding 7%) in this period, notwithstanding a much more substantial basin land use change (i.e. natural afforestation due to agricultural abandonment since the end of the 19th century) than in the Adige catchment (Tasser et al., 2007).

Channelization of large Alpine rivers: the Adige in a broader perspective

Channelization of large Alpine rivers occurred systematically in the 19th century in almost all Alpine countries. Table 5 synthesizes the relevant information on observable morphological changes for six major large Alpine rivers located in 5 different countries (France, Switzerland, Liechtenstein, Austria, Italy). Table 5 also reports available reach-averaged values of streamflow *Q*, longitudinal slope *S*, channel width *W,* and sediment size D_{50} needed as input for the bar and pattern predictors, together with the resulting values of the width to depth ratio β and of its threshold for free bars formation β_c.

While embankments almost prevent any lateral planform change, still one morphological "degree of freedom" is left in channelized rivers in terms of the development of bars within the levees. While in the Rhone, Inn and Drau, like in the Adige, almost no bars can be observed at present (e.g. references in Table 5, and Figure 6c and 6g); the Alpine Rhine and the Isére reacted in a completely different way to channelization, developing regular sequences of alternate bars along tens of river kilometers (Jäggi, 1984, Vautier, 2000, Jaballah et al., 2015, Jourdain et al., 2016, Adami et al., 2016), thus suggesting a pronounced divergence of the related evolutionary trajectories (Figure 10).

The application of the free-bar predictor (Colombini et al., 1987) to the Adige, the Drau, the Upper Rhone, the Inn, the Alpine Rhine and the Isère offers a reliable explanation of such diverging trajectories. In the Alpine Rhine and in the Isère, the difference $\beta - \beta_c$, which measures the morphodynamic instability of the river bed, is always positive within a broad range of bar-forming discharge values, implying bar formation (Figure 10b and 10c), as observed (Adami et al., 2016, Serlet et al., 2017). In contrast, together with outcomes from the Drau, the results of the present work (Figure 8 and Figure 10b and 10c) indicate that for most of its length, the study segment of the Adige is characterized by a reach-averaged width to depth ratio β smaller than the critical value β_c for bar formation. The Inn and the Rhone fall closer to the theoretical threshold. The free-bar predictor can also be used to predict the minimum channel width necessary to develop bars. The predicted ranges of such minimum width are 75-95 m for macro-reach M4, 88-108 m for M5 and 91-111 m for M6, instead of the actual 65 m, 75 m and 70 m, respectively, and considering bar-forming discharges between Q_2 and Q_{10}. On average, the application of the free-bar predictor suggests that the designed width of the channelized Adige is approximately 20 m below the threshold for bar formation, which would have led to a completely different fluvial landscape (e.g. Figure 10), and possibly management history, in the last century.

The above comparison indicates the diversity of the morphological responses of these gravel-bed rivers to channelization and how this is sensitive to the newly imposed channel width, or, more precisely, width to depth ratio. Figure 10 conceptually summarizes the lessons learned from the analysis performed on the Adige in the present work and attempts to provide a more general illustration of gravel-bed river response to channelization, also based on the comparison reported in Table 5 and integrating existing theoretical and observational knowledge.

Figure 10a shows the example of the Adige River, which was characterized by repetitive downstream sequences of different planform morphologies before channelization, induced by tributary confluences. The upper panel shows the qualitative downstream trend of the channel width (or, equivalently, width to depth ratio under bar-forming conditions). The lower horizontal dashed line refers to the threshold setting the transitions between a flat bed configuration (n. 1 in panel b) and a bed morphology with free alternate bars (n. 2 in panel b). After channelization, the morphology of the Adige, as well as of the Drau, mainly evolved into a flat-bed configuration (n.1 in panel b), while the Isère and the Rhine fell above the threshold for free alternate bars, thus displaying a similar configuration to n.2. Should channelization result into much higher values of the width to depth ratio, the response of the bed morphology may increase in spatial complexity, from alternate bars to low-flow braiding/ wandering, as illustrated by morphology n.3 in b).

Though not examined in detail in the present work, all the three bars and pattern predictors indicate that this occurs when a second, higher transition range of the width to depth ratio is crossed, as illustrated by the higher horizontal dashed line in a), which sets the transition between morphologies n.2 and n.3 in b). Three actual examples of the possible responses to channelization (n. 1, 2 and 3) taken from real-world channelized rivers are shown in Figure 10c.

Conclusions

Many large rivers in Europe underwent heavy modifications for land reclamation and flood mitigation through centuries. As a consequence, the study of pre-alteration morphological patterns and the related channel evolution following anthropic modifications is rather challenging. This study provides a novel contribution for the understanding of Alpine river dynamics because it deals with a different system compared to those already analyzed in the literature and it integrates different approaches (i.e. reconstruction of evolutionary trajectory by using historical maps; analytical model for free-bar prediction; channel pattern predictors).

Before the massive channelization, at the beginning of the 19th century, the Adige presented a prevalence of single-thread patterns, except for reaches downstream of the main confluences, which showed multi-thread morphologies. Channelization, between the 19th century and the beginning of the 20th, caused channel morphology simplification and narrowing. Simultaneously, a large proportion of bars and islands disappeared, not only because of the decrease of sediment delivery, but mostly because of the new channel widths imposed by channelization works. The free-bar predictor indeed showed that before channelization, morphodynamic instability was promoting the occurrence of free-bars in all reaches, regardless of their morphologies. The new channel widths had completely modified the picture by reducing the width to depth ratio below the instability threshold and, as a consequence, the tendency of the Adige to develop free bars. The present study therefore suggests the potential of bar theories, and of analogous simplified morphodynamic modelling, to gain insights in fluvial processes and predict hypothetical future trajectories as well as threshold ranges of key parameters like the channel width, which may be subject to modification in the future within flood protection or river restoration projects based on the increasingly adopted strategy of "giving more room to the river".

At the same time, the study provides novel insights into the morphological response of large gravel-bed rivers to channelization, confirming that the analysis of evolutionary trajectories is fundamental to understand morphological modifications and their control factors.

Acknowledgements

This study was funded by the Autonomous Province of Bolzano with the project: "ETSCH-2000: Historical changes in channel morphology over 2 Millennia".

Authors are grateful to the reviewers and to the editor whose comments and critical appraisals significantly helped to improve the paper. The paper has benefitted from comments and suggestions by Erik Mosselman.

The authors gratefully acknowledge Pierpaolo Macconi and Omar Formaggioni for the provided maps and data on historical flood events; and Martino Salvaro, Stefano Pellegrini and Andrea Grillo for the field measurements and data analysis.

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Table 1

Key features of historical maps dataset

Year	Title	Author	Archive	Scale	Number of georeferenced maps	RMSE (m)
1803-1805	Oeconomische Karte des Etschstromes und der umligenden Gegend in der Grafschaft Tirol […] (*alias*: Nowack-Plan)	Nowack	TLA	1:3,456	131	1-9
1816-1821	Zweite Militär-Landesaufnahme (Franziszeische Landesaufnahme) (*alias*: Reininger-Geppert Karte)	Reininger-Geppert/ KuK Militär-Geographiches Institut	KA	1:28,800	15	10-17

1847-1848	Karte der Etschregulierung in 14 Blaettern von Meran bis Borghetto suedliche Rovereto	Claricini Dornpacher	TLMF	1:20,736	14	6-27
1856-1861	Cadastral map (Franziszeischer Kataster/Austrian Land Cadastre)	KuK Generaldirektion des Grundsteuerkatasters	PAT/South Tyrol	1:2,880	>300	1.5-4.5
1870-1871	Dritte Militär-Landesaufnahme (Franzisco-Josephinische Landesaufnahme/Neue Aufnahme)	KuK Militär-Geographiches Institut	BEV	1:25,000	14	10-17
1904-1912	Vierte Militär-Landesaufnahme (Präzisionsaufnahme)	KuK Militär-Geographiches Institut	BEV	1:25,000	14	10-21
1915-1927	IGM serie 25v (*alias*: "Tavolette")	IGM (Istituto Geografico Militare)	UniTN	1:25,000	24	10-13

List of acronyms: RMSE = RMS error; TLA = Tiroler Landesarchiv (Innsbruck, Austria); KA = Kriegsarchiv (Vienna, Austria); TLMF = Tiroler Landesmueum Ferdinandeum (Innsbruck, Austria); PAT: Cadastre Service, Autonomous Province of Trento (Italy); South Tyrol = Cadastre Dept., Autonomous Province of Bolzano (Italy); BEV = Bundesamt für Eich- und Vermessungswesen (Vienna, Austria); UniTN = Dept. of Humanities, University of Trento (Italy)

Table 2

Variables calculated from the digitized features, in 1803-1805

Variable	Symbol	Description
Average channel width	W	Ratio between the reach polygon area and its length (excluding islands)
Total average channel width	W_{tot}	Ratio between the reach polygon area and its length (including islands)
Bar ratio	B	Ratio between the area occupied by bars and the reach area
Island ratio	I	Ratio between the area occupied by the islands and the entire reach surface
Sinuosity index	SI	Ratio between the distance measured along the channel and the distance measured

		along the valley bottom
Braiding index	BI	Average number of active channels separated by bars
Anastomosing index	AI	Average number of active channels separated by vegetated islands
Alluvial plain width	AP	Ratio between the valley polygon area and its length
Confinement index	CI	Ratio between the alluvial plain width and the channel width (Rinaldi et al., 2013)
Distance from tributary	T	Channel length between the downstream vertex of the reach and the nearest upstream tributary
Valley slope	Sv	Average valley slope computed from the present valley bottom elevation
Channel slope	Sc	Average channel slope computed from the present valley bottom elevation

First geodatabase detailing morphological pattern before channelization.

Table 3

Parameters used for the bar and channel pattern predictors for the 6 macro-reaches

Macro-reach	W pre (m)	W post (m)	Sc (%)	D_{50} (mm)	Q_2 (m^3/s)	Q_5 (m^3/s)	Q_{10} (m^3/s)	Q_{20} (m^3/s)
1	202 ± 95	58 ± 12	0.3	10.5	219	298	350	402
2	81± 19	75 ± 11	0.081	10.5	219	298	350	402
3	137 ± 50	82 ± 9	0.18	6.05	581	757	874	1005
4	115 ± 16	64 ± 6	0.066	16.54	581	757	874	1005
5	149 ± 44	73 ± 20	0.093	13.2	769	1072	1272	1438

6	121 ± 18	69 ± 8	0.083	11.13	769	1072	1272	1438

W = channel width, pre- and post- channelization, Sc = channel slope, D_{50} = median subsurface grain size, Q_2, Q_5, Q_{10}, Q_{20} = daily streamflow value with recurrence interval > 2 , 5, 10 and 20 years.

Table 4

Minimum/Average/Maximum values of the morphological parameters (as reported in Table 2) for the 4 homogeneous groups in the Adige River in 1803-1805

	Group 1	Group 2	Group 3	Group 4
W (m)	60/ 102/ 135	68/ 111/ 148	249/ 310/ 372	83/ 167/ 291
W_{tot} (m)	60/ 104/ 145	74/ 114/ 150	486/ 504/ 522	83/ 208/ 327
AP (m)	805/ 2085/ 3505	295/ 928/ 1598	1366/ 1674/ 1982	386/ 1178/ 2524

T (km)	5 / 17/ 37	2/ 12/ 40	0.5/ 5.5/ 10	0.5/ 4.5/ 11.7
S_v (%)	0.01/ 0.09/ 0.21	0.01/ 0.08/ 0.26	0.13/ 0.33/ 0.54	0.02/ 0.23/ 0.52
S_c (%)	0.01/ 0.08/ 0.18	0.01/ 0.06/ 0.18	0.12/ 0.32/ 0.53	0.01/ 0.21/ 0.5
B (m^2/m^2)	0.0/ 0.28/ 0.57	0.06/ 0.21/ 0.45	0.63/ 0.68/ 0.72	0.32/ 0.50/ 0.61
I (m^2/m^2)	0.0/ 0.02/ 0.24	0.0/ 0.03/ 0.28	0.31/ 0.7/ 1.1	0.0/ 0.23/ 0.84
SI	1.03/ 1.11/ 1.34	1.04/ 1.43/ 2.24	1.02/ 1.03/ 1.05	1.02/ 1.14/ 1.40
BI	1/ 1.13/ 1.67	1/ 1.08/ 1.36	2.64/ 3.68/ 4.71	1.29/ 1.94/ 3.50
AI	1/ 1.11/ 2.14	1/ 1.04/ 1.27	3/ 3.46/ 3.92	1.00/ 1.36/ 2.08
CI (m/m)	13.5/ 20. 5/ 35.1	2.6/ 8.1/ 13.2	3.7/ 5.8/ 8.0	1.9/ 7.7/ 18.52

Table 5

Morphological response of selected reaches of large Alpine rivers to massive channelization works initiated in the 19th century and representative, reach-averaged hydro-morphological conditions for the application of bar and pattern predictors.

River name	Segment location: between	Pre-channelization morphology	Observable riverbed morphology under low	Q (m^3/s)	S (%)	W (m) designed	D_{50} (mm)	β	$β_c$

			flow conditions [6]						
Alpine Rhine (Switzerland, Liechtenstein, Austria)	Confluences with Landquart and Ill rivers	Wandering, anabranching [1]	Alternate bars, mostly non-vegetated [7]	1600	0.2	95	40	24.9	21.7
Isere (France)	Albertville and Grenoble	Braided [2]	Alternate bars, mostly vegetated [2]	800	0.15	100	50	35.2	11.6
Rhone (Switzerland)	Sion and Martigny	Braided, anabranching [3]	No bars	650	0.1	70	23	21	22.4
Drau (Austria)	Lienz and Villach	Anabranching, sinuous [4]	No bars	570[4]	0.2	40	32	11.4	22.8
Inn (Austria)	Innsbruck and Kufstein	Sinuous with bars [5]	Few bars, not systematic	724	0.1	90	20	26.4	24.2
Adige / Etsch (Italy)	Trento and Rovereto	Sinuous, anabranching, meandering	No bars	1200	0.09	70	11	15.4	29.3

Sources of information: [1] Meyer-Peter et al. (1937); [2], Vautier (2000); [3] Stäuble et al. (2008); [4], [5] Second Military Survey, www.mapire.eu, ; [6] Google Earth; [7] Adami et al. (2016); [8] Klosch and Habersack (2016).

Captions

Figure 1. Location of the Adige River and of the analyzed tributaries. Codes for gauging stations: 1 = Ponte Adige; 2 = Bronzolo; 3 = Trento. Catchments areas and total studied reaches length in the tributaries : Passirio = 414 km^2, 2.2 km; Rio di Nova = 17.4 km^2, 2.6 km; Valsura = 282.4 km^2; 2.9 km; Talvera = 418 km^2, 2.7 km ; Isarco = 4164.4 km^2, 6.6 km; Noce = 1366. 67 km^2, 6.4 km; Avisio = 940 km^2, 2.9 km; Fersina = 170 km^2, 2.9 km.

Figure 2. Examples of maps used in the multi-temporal analysis. Reaches number 2 and 3 (a), reaches number 7 and 8 (b), reach number 22 (c).

Figure 3. Statistical distribution for: channel width (a), total channel width (b), island ratio (c), bar ratio (d), alluvial plain width (e), confinement index (f), valley slope (g) and distance from the main upstream tributary (h), for the channel morphology types (42 reaches) in 1803-1805. Codes for channel patterns: B: braided: A: anabranching; W: wandering; SAB: sinuous with alternate bars; S: sinuous; M: meandering.

Figure 4. Results of the PCA on the 42 reaches of the Adige River, in 1803-1805 (a). Distribution of channel morphologies (b), and of homogeneous groups (c) for the 42 reaches and segmentation into six macro-reaches (M1-M6). Dashed lines indicate main tributaries.

Figure 5. Comparison of the patterns obtained by applying the hybrid-bar predictor (Crosato and Mosselman, 2009) and the channel pattern predictor (Eaton et al., 2010) with those observed in the 42 reaches, for both the configurations before (PRE) and after (POST) channelization.

Figure 6. Channel width changes (a, e); channel morphology distribution (b, f); bar ratio statistical distribution (c, g); island ratio statistical distribution (d, h) between 1803 and 1917, in multi-thread and single-thread macro-reaches. Codes for channel patterns as in Figure 3.

Figure 7. Univariate statistical distribution of tributaries channel width variation, here defined as the ratio between the channel width in a year and the channel width in 1803-1805 (a), bar ratio (b), bank work ratio (c), and channel morphology (d), between 1803-1805 and 1917. Codes for channel patterns as defined in Figure 3.

Figure 8. Results of the free-bar predictor applied to the 6 macro reaches. Positive values of the difference β-β_c denote unstable channel bed, thus bar formation, while negative values are related to a flat channel bed. Blue filled circles refer to the pre channelization configuration with the present hydrology (Q_2, Q_5, Q_{10}), the red asterisks show the effect of increasing the discharge

to the hypothesized LIA values (Q_5, Q_{10}, Q_{20}), black open circles correspond to the post channelization conditions (using Q_2, Q_5, Q_{10}).

Figure 9. Channel width, bar ratio, and rectification works evolutionary trajectories between 1803-1805 and 1917, for the Adige river (a) and for the tributaries (b). Yearly number of floods occurred in the Adige basin and in the main stem (c). Subscript 1803 indicates values observed on the Novak map.

Figure 10. Conceptual diagram of large gravel bed rivers response to channelization, inspired from the example of the Adige River. a) (Upper panel) Qualitative downstream trend of the unconfined channel width (equivalently, of the width to depth ratio under bar-forming conditions), and related downstream variability in channel morphology, with the discontinuity due to the inflow of a lateral tributary delivering high coarse sediment input. The horizontal dashed lines illustrate two threshold values that set the transitions between the corresponding morphologies 1, 2 and 3 sketched in panel (b). The lower panel of (a) shows an actual example of such downstream morphological variability observed in the Adige River downstream the confluence with the Isarco River (from Novack historical map, lower panel). c) Examples of channelized rivers showing different morphological responses to channelization: 1 Kugart River, near Jalal-Abad, Kyrgyz Republic (Siviglia et al., 2008); 2 Alpine Rhine close to Vaduz (Liechtenstein); 3 Adige near Auer/Ora in South Tyrol, Italy. Flow is from left to right. Source: Google Earth.

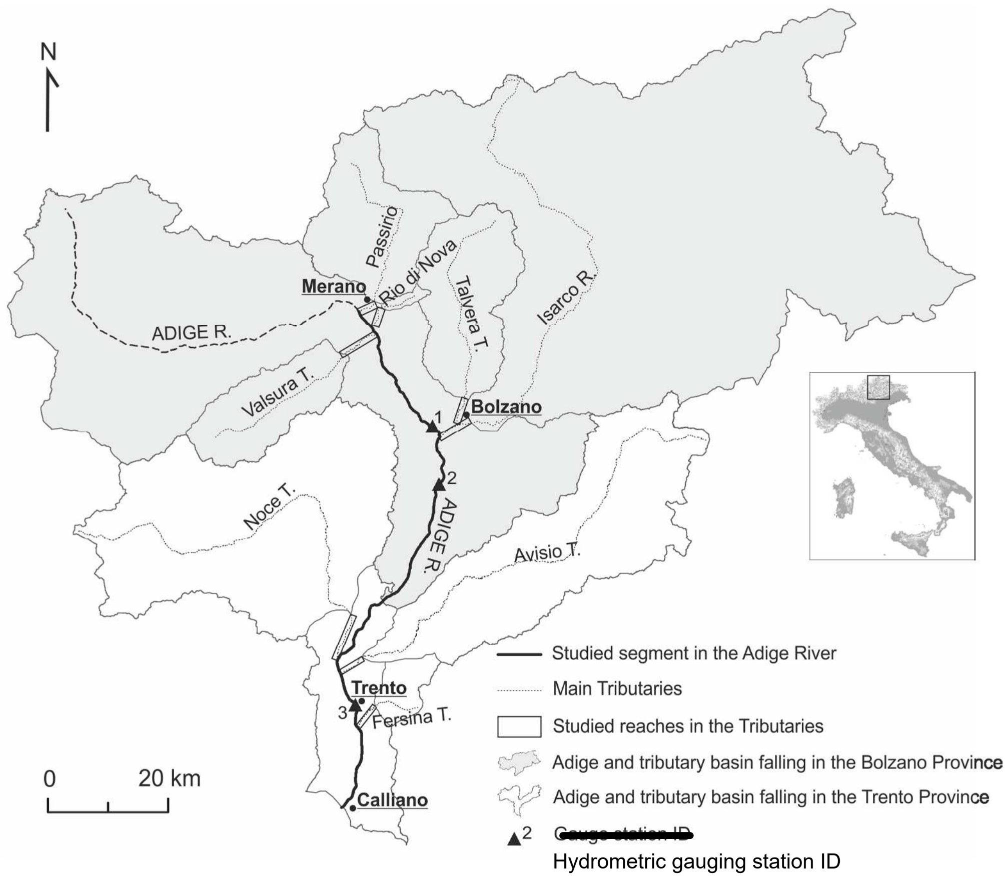

Figure 1. Location of the Adige River and of the analyzed tributaries. Codes for gauging stations: 1 = Ponte Adige; 2 = Bronzolo; 3 = Trento. Catchments areas and total studied reaches length in the tributaries : Passirio = 414 km2, 2.2 km; Rio di Nova = 17.4 km2, 2.6 km; Valsura = 282.4 km2; 2.9 km; Talvera = 418 km2, 2.7 km ; Isarco = 4164.4 km2, 6.6 km; Noce = 1366. 67 km2, 6.4 km; Avisio = 940 km2, 2.9 km; Fersina = 170 km2, 2.9 km.

174x149mm (300 x 300 DPI)

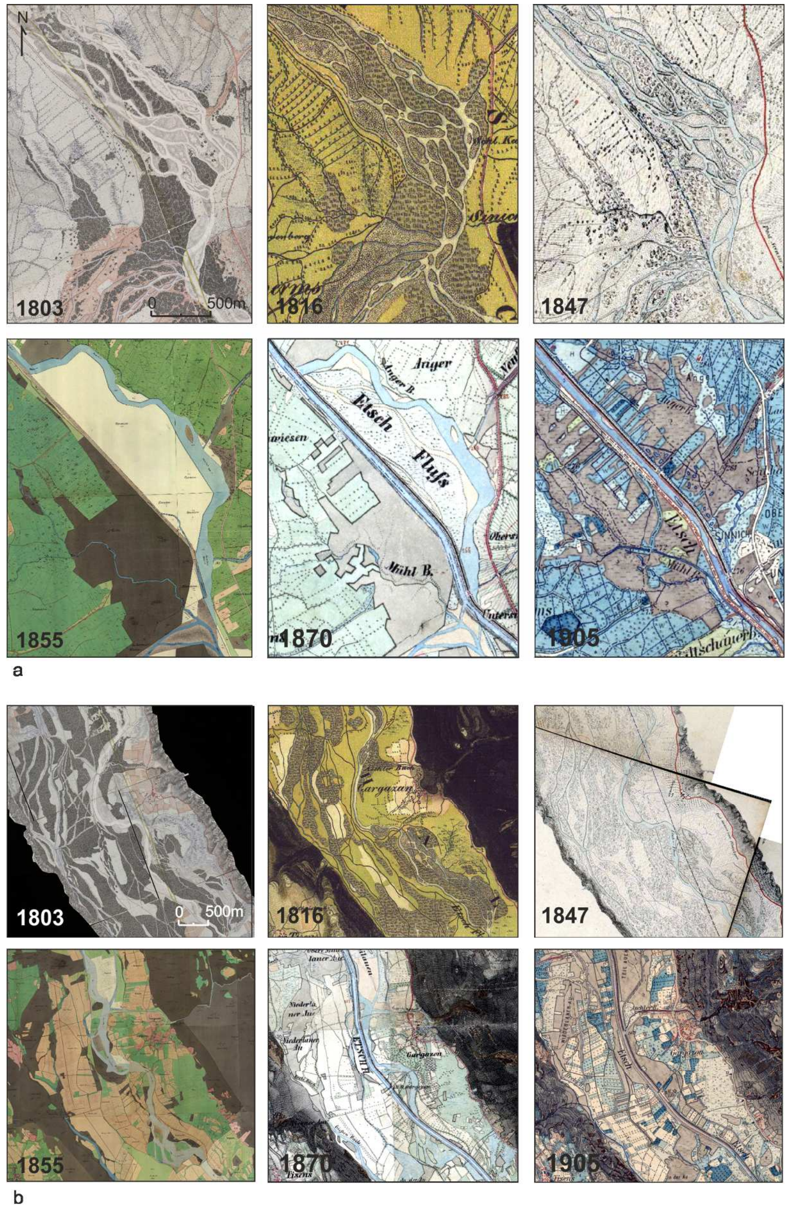

Figure 2. Examples of maps used in the multi-temporal analysis. Reaches number 2 and 3 (a), reaches number 7 and 8 (b), reach number 22 (c).

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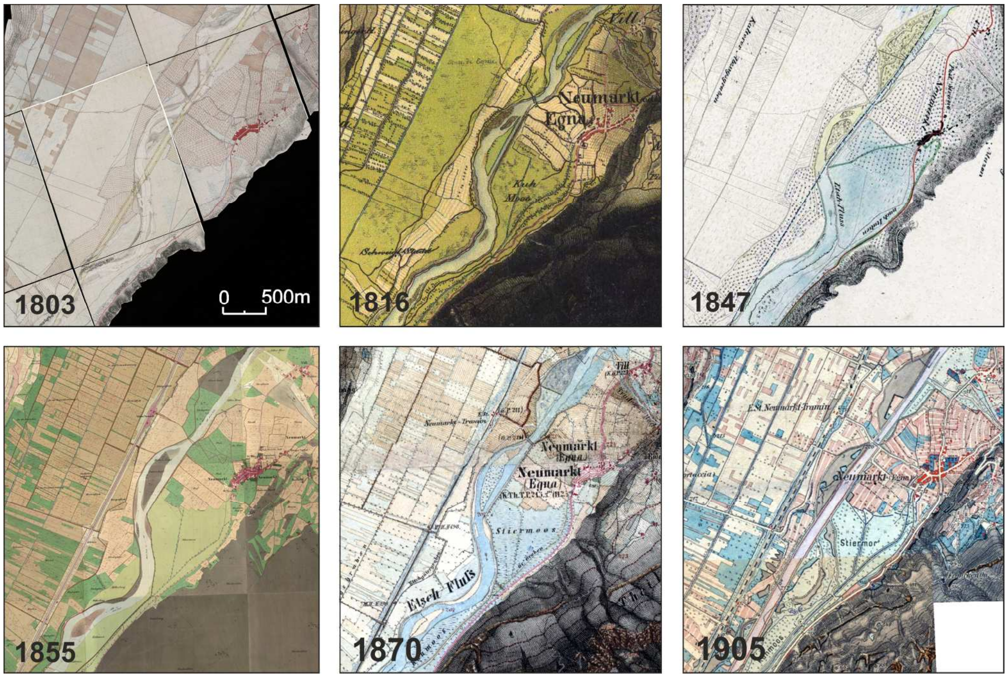


c

Figure 2. Examples of maps used in the multi-temporal analysis. Reaches number 2 and 3 (a), reaches number 7 and 8 (b), reach number 22 (c).

179x124mm (300 x 300 DPI)

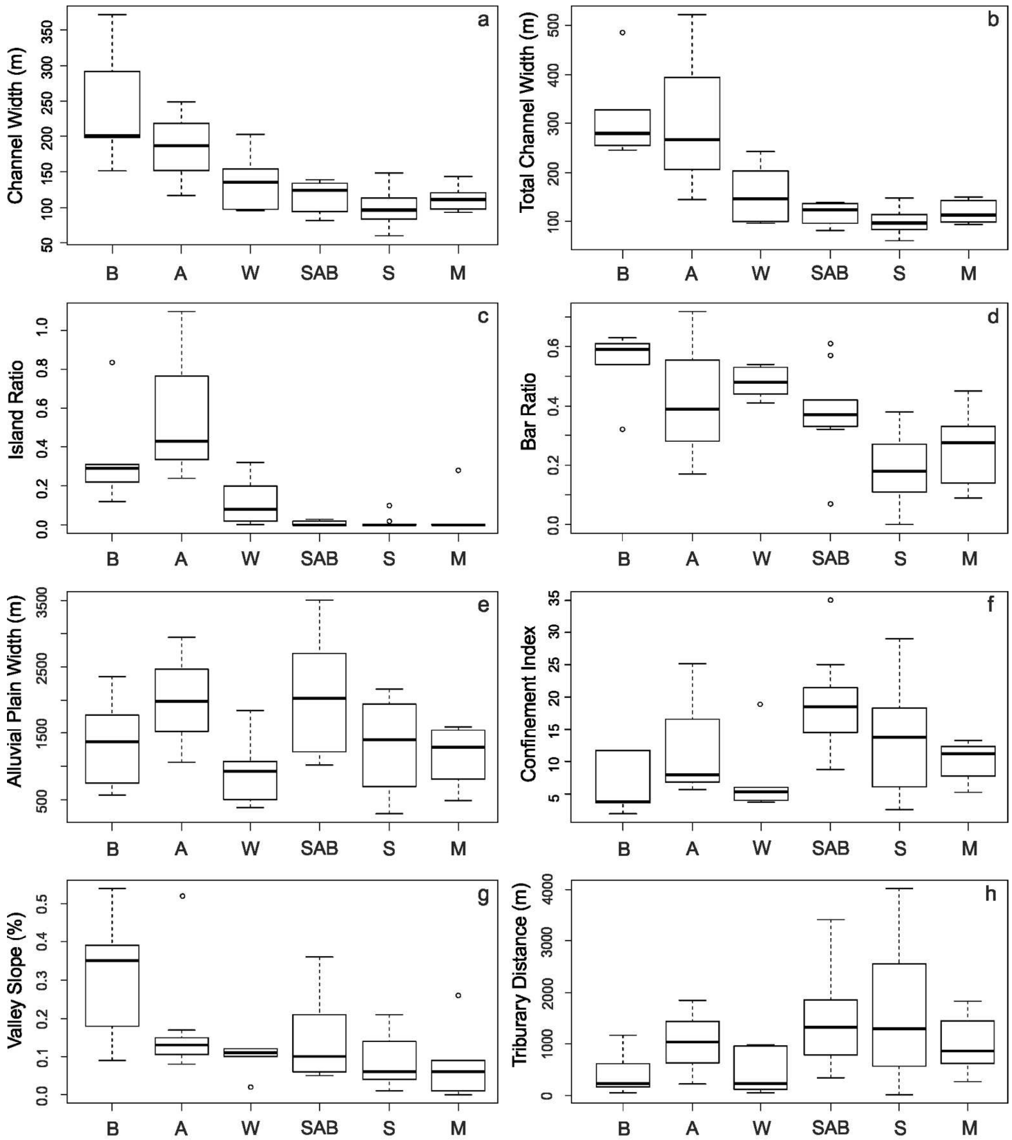


Figure 3. Statistical distribution for: channel width (a), total channel width (b), island ratio (c), bar ratio (d), alluvial plain width (e), confinement index (f), valley slope (g) and distance from the main upstream tributary (h), for the channel morphology types (42 reaches) in 1803-1805. Codes for channel patterns: B: braided: A: anabranching; W: wandering; SAB: sinuous with alternate bars; S: sinuous; M: meandering.

170x193mm (300 x 300 DPI)

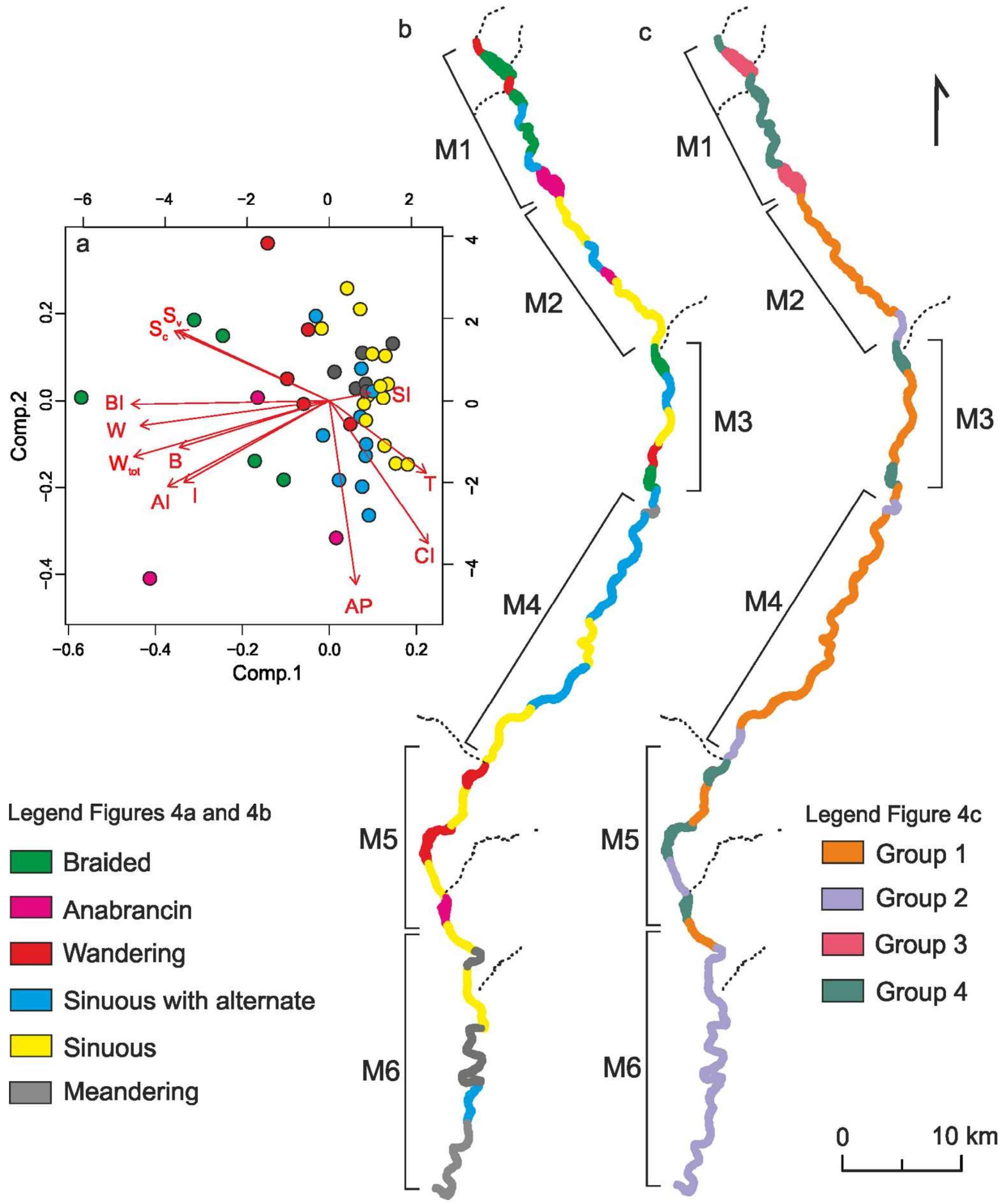
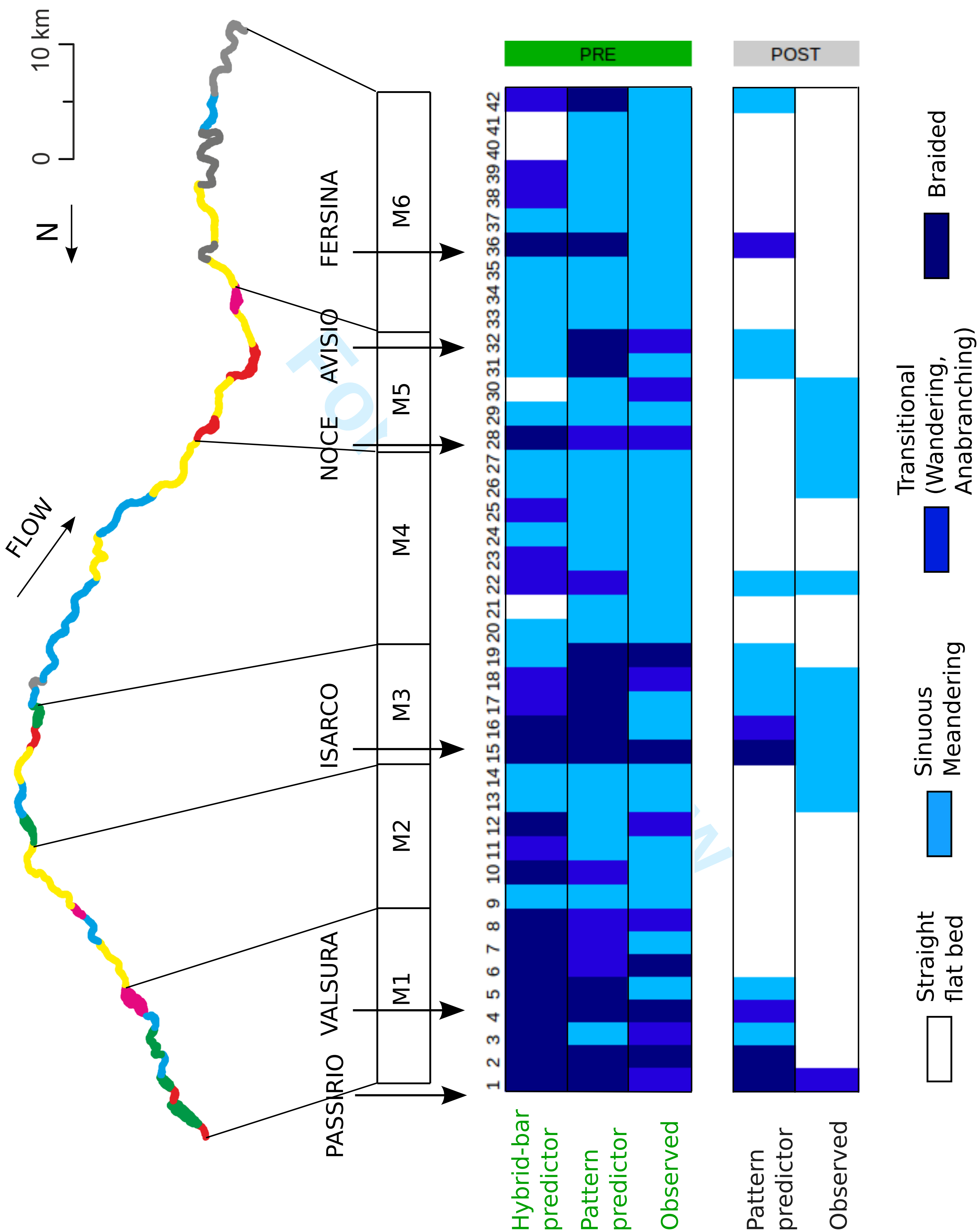


Figure 4. Results of the PCA on the 42 reaches of the Adige River, in 1803-1805 (a). Distribution of channel morphologies (b), and of homogeneous groups (c) for the 42 reaches and segmentation into six macro-reaches (M1-M6). Dashed lines indicate main tributaries.

152x181mm (300 x 300 DPI)


10 km
0
N
FLOW
FERSINA
AVISIO
NOCE
ISARCO
VALSURA
PASSIRIO
M6
M5
M4
M3
M2
M1
PRE
POST
Hybrid-bar predictor
Pattern predictor
Observed
Pattern predictor
Observed
Braided
Transitional (Wandering, Anabranching)
Sinuous Meandering
Straight flat bed

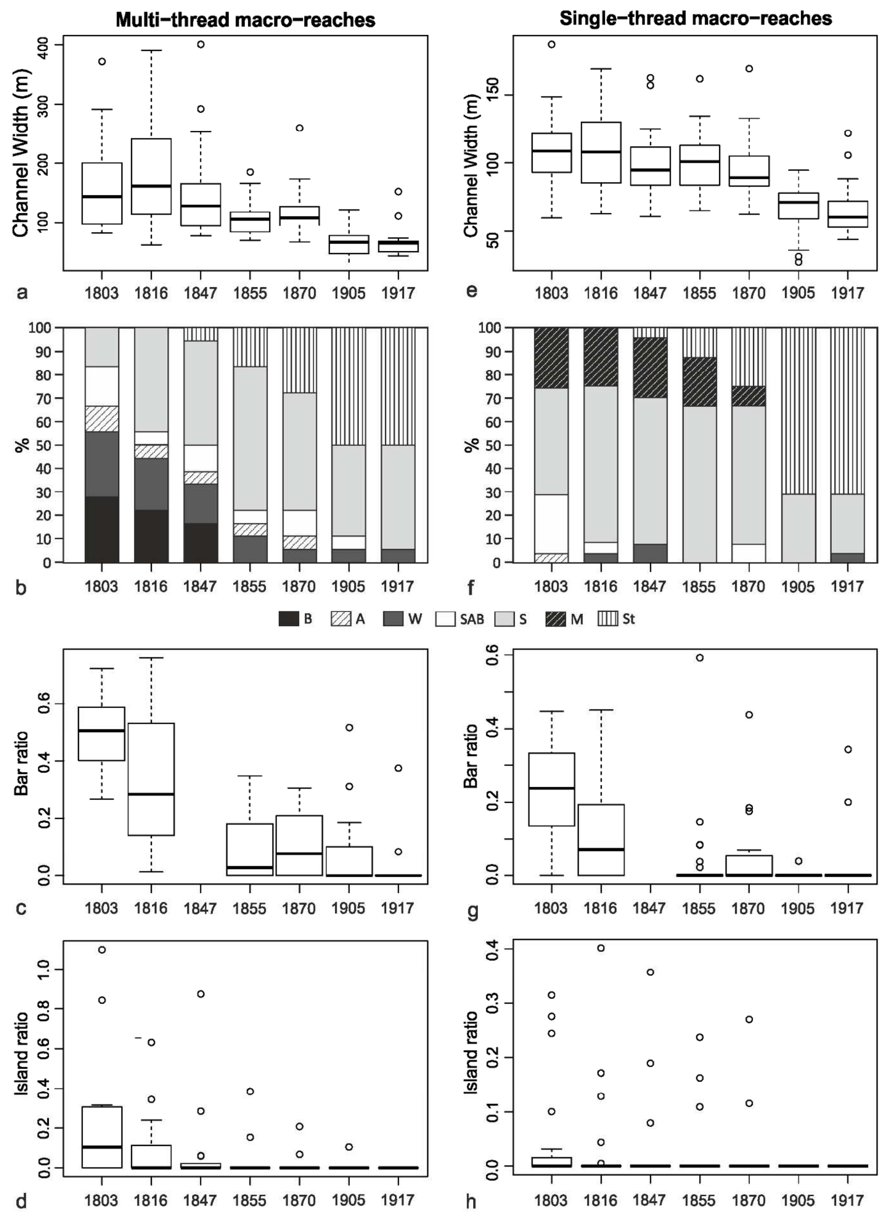


Figure 6. Channel width changes (a, e); channel morphology distribution (b, f); bar ratio statistical distribution (c, g); island ratio statistical distribution (d, h) between 1803 and 1917, in multi-thread and single-thread macro-reaches. Codes for channel patterns as in Figure 3.

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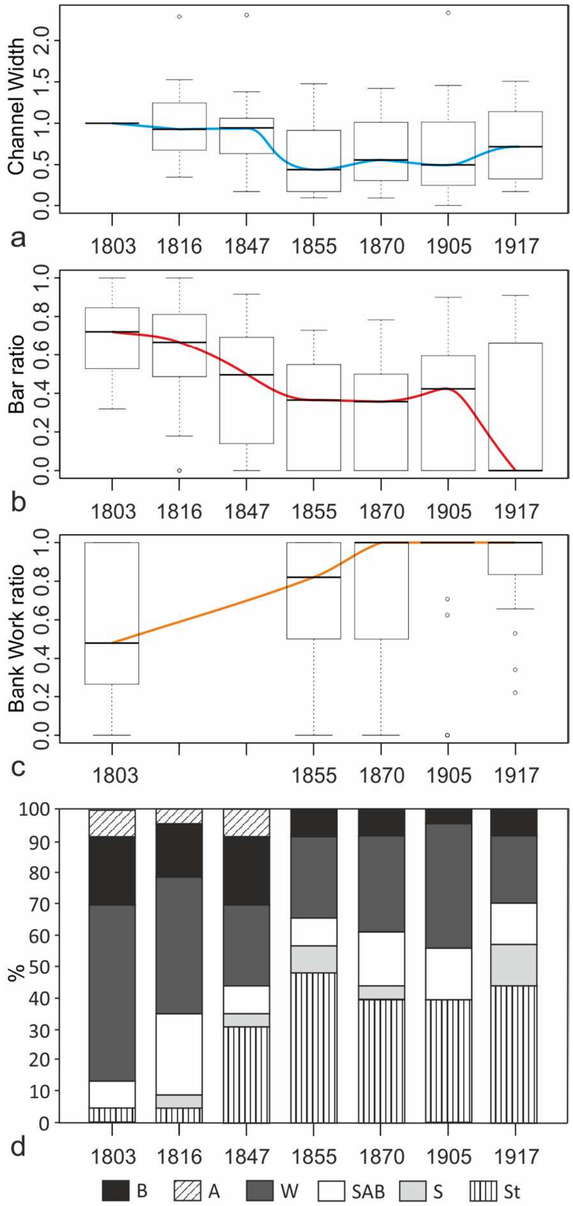
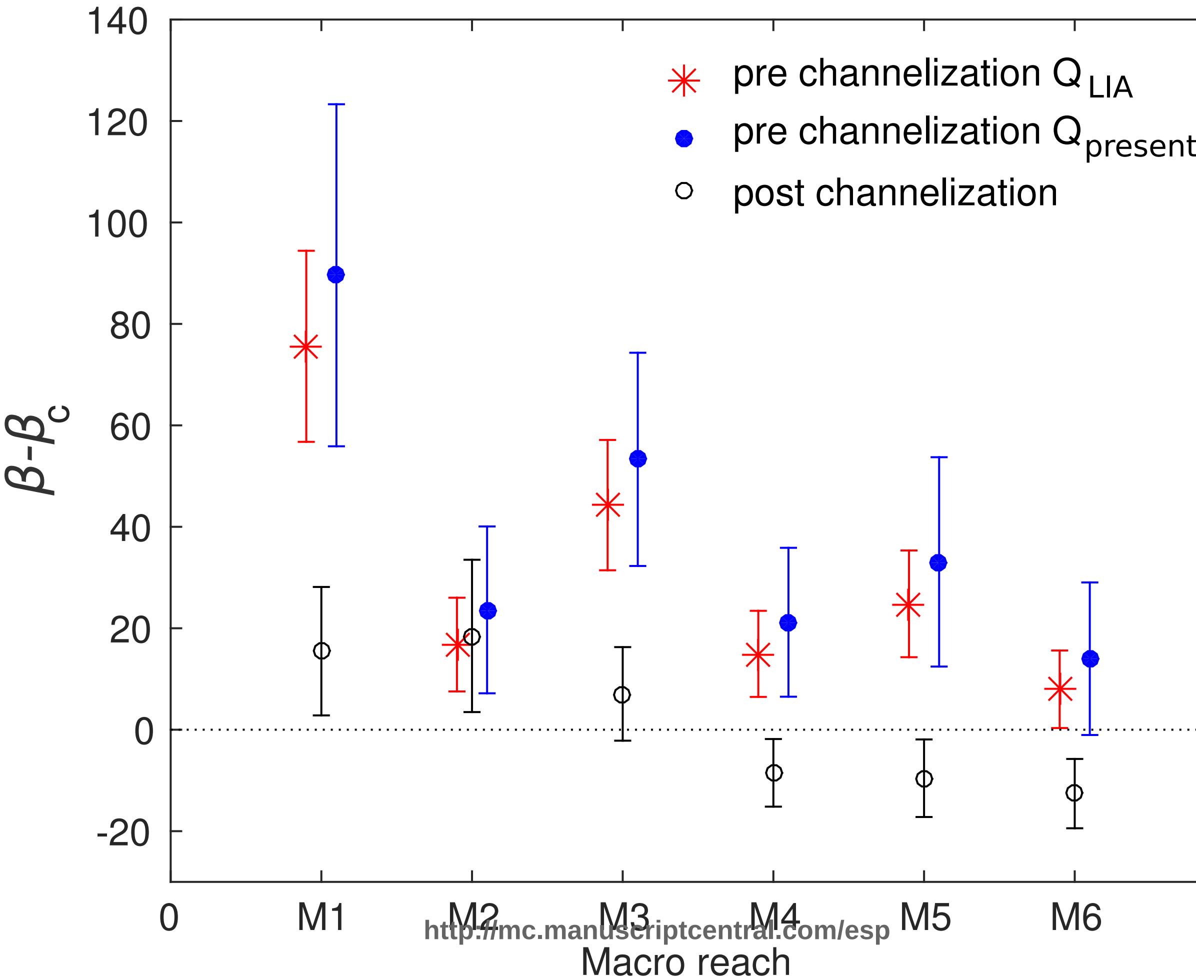


Figure 7. Univariate statistical distribution of tributaries channel width variation, here defined as the ratio between the channel width in a year and the channel width in 1803-1805 (a), bar ratio (b), bank work ratio (c), and channel morphology (d), between 1803-1805 and 1917. Codes for channel patterns as defined in Figure 3.

83x176mm (300 x 300 DPI)


140
120
100
80
60
40
20
0
-20
β-β_c
pre channelization Q_LIA
pre channelization Q_present
post channelization
0
M1
M2
M3
M4
M5
M6
Macro reach

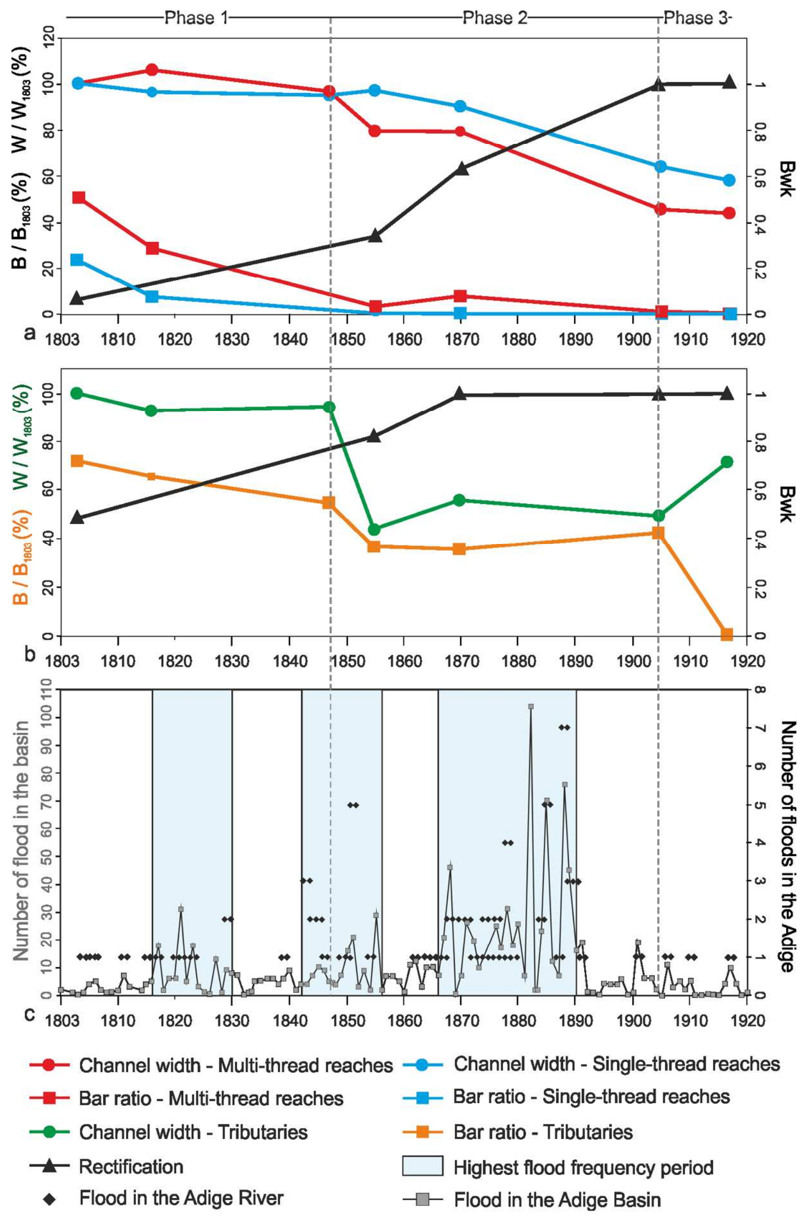


Figure 9. Channel width, bar ratio, and rectification works evolutionary trajectories between 1803-1805 and 1917, for the Adige river (a) and for the tributaries (b). Yearly number of floods occurred in the Adige basin and in the main stem (c). Subscript 1803 indicates values observed on the Novak map.

129x198mm (300 x 300 DPI)

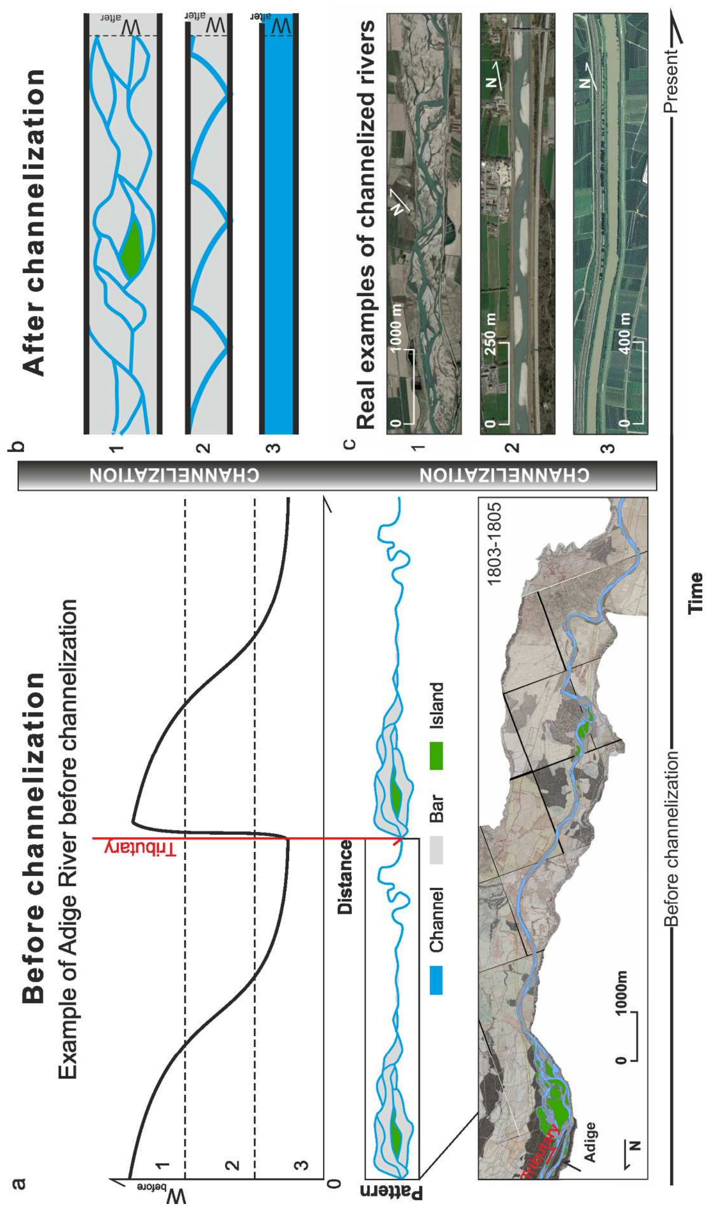


Figure 10. Conceptual diagram of large gravel bed rivers response to channelization, inspired from the example of the Adige River. a) (Upper panel) Qualitative downstream trend of the unconfined channel width (equivalently, of the width to depth ratio under bar-forming conditions), and related downstream variability in channel morphology, with the discontinuity due to the inflow of a lateral tributary delivering high coarse sediment input. The horizontal dashed lines illustrate two threshold values that set the transitions between the corresponding morphologies 1, 2 and 3 sketched in panel (b). The lower panel of (a) shows an actual example of such downstream morphological variability observed in the Adige River downstream the confluence with the Isarco River (from Novack historical map, lower panel). c) Examples of channelized rivers showing different morphological responses to channelization: 1 Kugart River, near Jalal-Abad, Kyrgyz Republic (Siviglia et al., 2008); 2 Alpine Rhine close to Vaduz (Liechtenstein); 3 Adige near Auer/Ora in South Tyrol, Italy. Flow is from left to right. Source: Google Earth.

135x230mm (300 x 300 DPI)