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What remains today of pre-industrial Alpine rivers? Census of historical and current channel patterns in the Alps

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Abstract

To date, no survey on the diverse channel patterns existing prior to the major phase of river regulation in the mid-19th–early 20th century has been elaborated at the scale of the whole European Alps. The present paper fills this knowledge gap. The historical channel forms of the 143 largest Alpine rivers with catchments larger than 500 km^2 (total length 11,870 km) were reconstructed based on maps dating from the 1750s to 1900. In the early 19th century, one-third of the large Alpine rivers were multi-channel rivers. Single-bed channels oscillating between close valley sides were also frequent in the Alps (28%). Sinuous and even more so meandering channels were much rarer. Historical river patterns generally followed an upstream–downstream gradient according to slope condition, floodplain width and distance from the sources. The local occurrence of certain channel patterns, however, primarily reflected the tectonic/orographic conditions. Multi-channel reaches were widespread within the whole Alpine area, alternating with confined and oscillating reaches. This demonstrates that most areas were mainly transport-limited rather than supply limited. Sinuous and meandering reaches were more frequent in the north-eastern Alps and were characterized by lower denudation rates and less sediment delivery.

Channel straightening caused the loss of about 510 km of river course length, equivalent to 4.3% of the historical extent. Multi-channel stretches are currently a mere 15% of their historical length, and 45% of the larger Alpine rivers are intensively channelized or have been transformed into reservoirs. Channelization measures differed from one country to another. Human pressures directly affected both local channel geometry and the upstream controls (i.e., sediment supply). Accordingly, individual multi-channel reaches also evolved into single-thread channels without any local human interventions.

KEYWORDS

Alpine rivers, channel patterns, historical GIS, historical state, river training

1 | INTRODUCTION

The typology of channel patterns or river styles (the planform geometry) is commonly used to classify rivers because it is very integrative in terms of geomorphic functioning (Brierley & Fryirs, 2005; Church, 2002; Kondolf, Montgomery, Piégay, & Schmitt, 2016). Such typologies are usually based on the number of flow channels within the floodplain and on channel sinuosity. Channel shifts, lateral valley confinements or un-vegetated bar extents are additional parameters considered. River pattern types can also be used as a proxy for specific ecological functioning because each type is characterized by specific habitat templates and dynamics (Amoros & Petts, 1996; Thorp, Thoms, & Delong, 2006). Characterizing channel patterns and their evolution at a regional scale is, therefore, meaningful to assess potential human pressures on river systems. Historical maps facilitate tracing channel planform changes through longer time periods (Bravard & Bethemont, 1989; Hohensinner, Jungwirth, Muhar, & Schmutz, 2011). Although historical sources often show great inaccuracies in geographical position and depicted riverine structures, they provide the only possibility to reveal past channel forms at larger scales.

Numerous studies on the historical morphological state of Alpine rivers prior to river regulation programmes have been published in recent decades (Habersack & Piégay, 2007). Most of them focus on individual river sections or on the human-induced transformation of specific river systems (Arnaud, Schmitt, Johnstone, Rollet, & Piégay, 2019; Bertrand, Piégay, Pont, Liébault, & Sauquet, 2013). To date, investigations that cover several Alpine catchments on a regional scale have been conducted for various countries (e.g., Muhar, Schwarz, Schmutz, & Jungwirth, 2000; Müller, 1995; Piégay, Alber, Slater, & Bourdin, 2009). Surprisingly, no overview study is available on historical and current channel patterns covering the entire Alpine sphere. Moreover, a large-scale study on the physical controlling factors associated with different Alpine channel patterns is also missing. The present study aims to fill this knowledge gap.

One of the most comprehensive investigations on Alpine channel styles was completed by Muhar, Kainz, Kaufmann, and Schwarz (1996) and Muhar, Kainz, and Schwarz (1998) for rivers with catchments larger than 500 km^2 in whole Austria. Accordingly, braided channel reaches made up 23% and meandering reaches even 25% in the early 19th century. Braided rivers in the French Alps were analysed in detail by Piégay et al. (2009), who distinguished seven types of channel braiding. Around 1800, at least 1,214 km of the river courses showed braided patterns. Controlling factors for the evolution of different braiding types were discussed, but other channel forms were not included in the study. Similar studies were conducted by Surian et al. (2009) for 12 alluvial rivers in northern Italy as well as by Comiti (2012) and Marchese, Scorpio, Fuller, McColl, and Comiti (2017) for mountain rivers in the Italian Alps. For Swiss Alpine rivers, the "Hydrological Atlas of Switzerland" (HADES) provides the best overview of the fluvial morphology at the mid-19th century and around 1990 (Koblet, 1995). It does not, however, provide quantitative data on the distribution of the former channel styles. Comparing the available studies reveals a focus on braided and to a minor extent

transitional, that is, "wandering," river sections. This hinders drawing conclusions on the importance of such rivers with respect to the whole spectrum of Alpine channel forms.

This lack of basic data on Alpine fluvial morphology prior to industrialization means that our knowledge about anthropogenic impacts also remains fragmentary. Martinet and Dubost (1992) reported that only approximately 10% of the reaches of large rivers in the Alpine region can be classified as "near-natural," a conclusion also supported by vegetation studies on Alpine braided rivers in Germany (Müller, 1991, 1995). Muhar et al. (2019) recently highlighted that at least 41% of the Alpine rivers with catchments larger than 10 km^2 have been hydrologically and/or morphologically human transformed. At minimum, 23% have experienced some type of severe morphological alteration. Despite the diverse basic data and methods used for the previous studies, a common conclusion is that larger rivers generally suffer more intensive human transformations than smaller rivers or upstream headwater sections (Gurnell, Surian, & Zanoni, 2009; Muhar et al., 2019; Piégay et al., 2009; Surian et al., 2009).

The different methodological approaches used in the past hinder a direct comparison of the data or an Alpine-wide census of historical and current channel patterns. Against this background, the present study is the first methodologically coherent evaluation of channel pattern types prior to industrialization, that is, the onset of systematic river regulation programmes in the first half of the 19th century (Brown et al., 2018). We analysed the 143 largest rivers with catchment areas exceeding 500 km^2 in the whole Alpine arc in Europe based on numerous historical sources. Our study addresses both the pre-industrial channel patterns and the regional and longitudinal (upstream–downstream) differences of human-induced channel changes. In differentiating distinct channel pattern types, we follow a hypothetical continuum of channel patterns along a river's course (based on Church, 1992, and Ward & Stanford, 1995; Figure 1). In particular, the resulting GIS dataset helps answer the following research questions:

(1) What channel patterns were characteristic of large Alpine rivers prior to major human modification?

(2) Which physical factors promoted the evolution of the observed channel forms?

The geographical location of a river section within the Alpine complex might play a role in the spatial distribution of channel patterns. For example, rivers draining to the north and east must follow
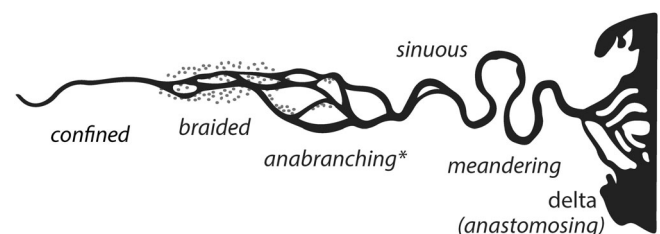

FIGURE 1 Simplified scheme of channel pattern types from the steep headwater to the lowland or delta in an Alpine lake (*potentially anabranching in wide Alpine valleys at sufficient river flow; compare Section 3)

much longer distances to the sea (Figure 2). Beyond the regionally varying orographic setting (e.g., altitude, valley slope, valley width), the magnitude of the sediment supply governs channel evolution (e.g., Brierley & Fryirs, 2005; Buffington & Montgomery, 2013; Pont et al., 2009). Different lithological zones show varying areal denudation rates and sediment availability (Hinderer, Kastowski, Kamelger, Bartolini, & Schlunegger, 2013). We, therefore, also investigated the local geological conditions and those in the upstream catchments of the individual river reaches. For example, one might expect that historically braided rivers were more frequent in bedload-abundant Alpine areas formed by sedimentary rocks (Mueller & Pitlick, 2013, 2014). In this context, karst mountain ranges such as the Northern and Southern Limestone Alps are commonly held to favour multi-channel rivers. Today, this assumption is supported by some of the last remaining large braided rivers such as the Fiume Tagliamento in north-east Italy (Ward et al., 1999).

(3) How have the Alpine channel patterns been human modified over time?

Historically, land use management and river engineering practices have varied regionally (Haidvogl, Pont, & Zwitter, 2019). Rivers in the Alpine countries today, therefore, reflect different forms and intensities of human pressure. The underlying question here is whether patterns in modification trajectory can be identified by country, channel type or longitudinal location along the river courses. This is tested against the generally supposed upstream–downstream gradient of increasing intensities of human interventions (Gurnell et al., 2009; Muhar et al., 2019).

The present study provides a solid basis for more detailed future investigations on the history of Alpine rivers. It highlights the importance of specific river types in different countries or geographical regions of the Alps. It contributes to our current understanding of the role of physical channel controls for the genesis of specific channel planforms. Finally, it helps to identify river reaches that were most intensively transformed along the river profiles. This is an important step forward in discussing the impacts of human interventions on Alpine river systems on a larger scale.

2 | GEOGRAPHIC AND HISTORICAL CONTEXT

2.1 | Study site

The study includes the 143 largest rivers with catchment sizes over 500 km^2 within the area defined by the Alpine Convention. This includes rivers whose catchments are partly—or in some cases largely—located outside of the Alpine area (Figure 2). The area specified by the international Alpine Convention measures approx. 190,000 km^2. Beyond the main Alpine complex, it also includes some smaller areas of the Alpine foreland at its fringes. Limestone Alps and regions predominantly formed by dolomite and marble make up the largest part (36%) of the overall area (based on the "International Geological Map of Europe"; Asch, 2003). The Central Alps comprising crystalline and Palaeozoic rocks cover the second largest share (31%), followed by the sedimentary rock zone formed by Flysch, Faltenmolasse and Bünden schist (20%). The Molasse zone, marine sediments, together with inner-Alpine basins cover only 11%, and the smallest areas are formed by volcanic material in northern Italy (2%). Figure 2 shows the tectonic structure of the Alpine complex with the high Central Alps mostly in the centre, confined by the lower Limestone Alps to the north and to the south. The outer—and in particular the northern—fringes of the Alps are formed by the foothills of the Alps (Flysch zone); the Molasse is the lowest zone. Several distinct longitudinal valley furrows have developed along major tectonic faults that run in SW–NE or W–E direction. Rivers leaving the Alpine arc
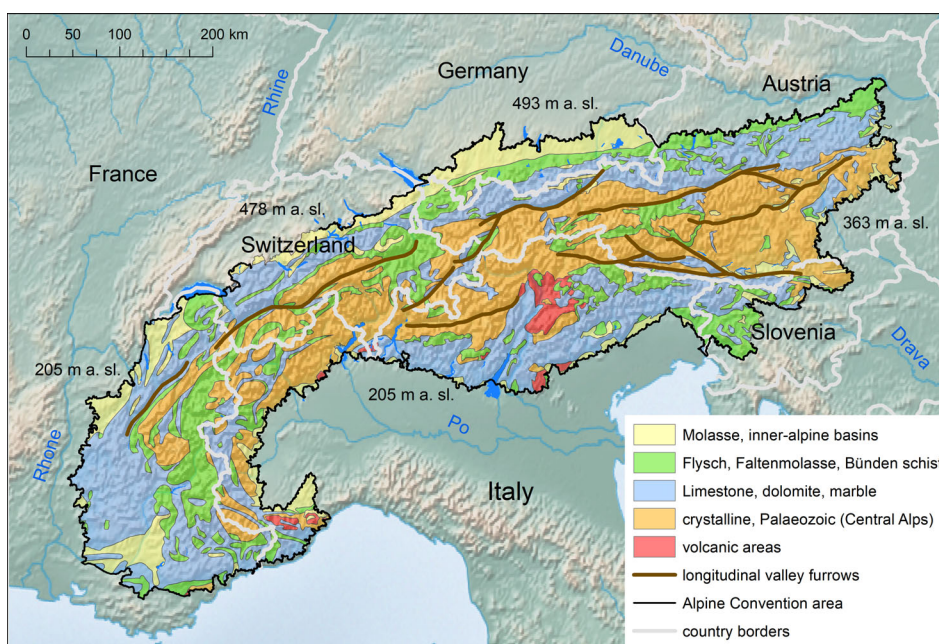

FIGURE 2 Study site within the Alpine Convention area (black line), geological zones, predominantly tectonically induced longitudinal valley furrows (dark brown lines) and country borders (white lines). Indicated sea levels refer to median altitudes of the rivers at the boundary of the study site (background map: Natural Earth, 2011)

towards the Danube River in the north show the longest distance to the delta (i.e., Black Sea). This is reflected by the highest median altitudes of the river sections at the boundary of the study site (493 m a. s.l.). Analogously, rivers flowing to the west and discharging via the Rhone River into the Mediterranean Sea as well as those flowing to the Po River in the south and finally to the Adriatic Sea show the lowest altitudes (205 m a.s.l.). Today, the total length of all Alpine rivers with catchments larger than 10 km² is almost 60,000 km; Austria's Alps host the largest share (32%; Muhar et al., 2019). The largest catchment (13,400 km²) is that of the Drava River, followed by the Rhone River with approx. 13,000 km².

2.2 | Human drivers of channel changes

Notable human impacts on Alpine river systems started with the establishment of first human settlements and associated forest clearings for arable land during the late Neolithic and Bronze Age between 5,000 and 2,500 BP (Comiti, 2012; Jarman, Bailey, & Jarman, 1982). These induced erosion processes, re-deposition of sediments in larger valley floors and consequently affected channel patterns (Goudie & Viles, 2016; Jacob et al., 2009). These processes intensified predominantly in the Italian and French Alps during Roman Times (Tinner et al., 2003). Humans again became a major geomorphological agent during the Middle Ages, when land reclamation, deforestation and salt and ore mining were significantly promoted also north of the Alpine crest (Comiti, 2012; Haidvogl et al., 2019). The significantly increased sediment supply caused a phase of intensified aggradation and braiding in several Alpine river systems (Bravard, 1989; Gurnell et al., 2009). Smaller streams were rerouted or water was abstracted from larger rivers to mills for energy extraction. In early Modern Times, direct human interventions in form of embankments, flood protection dikes and channel cut-offs increased, but larger channelization measures were only sparsely implemented before the 18th century (Girel, 2008; Vischer, 1989). Systematic channelization programmes started along several Alpine rivers in the early or mid-19th century, although most were first channelized in the late 19th century. The main purposes for the ambitious hydraulic projects were flood protection, land reclamation and the enhancement of the waterways for log driving and rafting (Haidvogl et al., 2019; Hauer et al., 2019). Such river training measures substantially reduced braided river sections throughout the Alpine sphere (Piégay et al., 2009; Surian et al., 2009). Further river straightening programmes and the construction of dams and reservoirs for hydropower production during the 20th century additionally impaired the Alpine river systems (Comiti, 2012).

3 | MATERIAL AND METHODS

3.1 | Differentiation of channel pattern types

In analysing the historical and current channel patterns, we largely applied the classification scheme defined by Muhar et al. (1996, 1998) for Austrian rivers. It proved to be a useful typological framework for

identifying channel types based on historical maps (Table 1). Because the historical sources often do not enable a detailed differentiation of certain channel patterns, the category "multi-channel rivers" includes all its various morphological sub-types such as bar-braided, island-braided, anabranching and anastomosing. Thus, it also comprises very slow-flowing, delta-type river reaches with multiple branches and riverbeds characterized by sand, silt and clay. These latter anastomosing channels made up only very small reaches in the Alps. Braided, bedrock-confined reaches without floodplain pockets are also included in the "multi-channel" category. Muhar et al. (1996, 1998) identified a new "oscillating" river type that can be best described as "moderately confined single-channel river" (compare "partly confined rivers" in Brierley & Fryirs, 2005; Buffington & Montgomery, 2013). At first view, such rivers are similar to sinuous ones, which typically develop distinct river bends in wide valleys or alluvial plains. Moderately confined single-channel rivers, however, are constrained by close valley sides, older and higher river terraces, or alluvial fans of confluent tributaries. Most of them, therefore, oscillate between the valley sides and cannot freely form larger river bends. For better readability of the text, tables and figures, we apply the short term "oscillating" because it best describes the channel configuration shown by the historical sources.
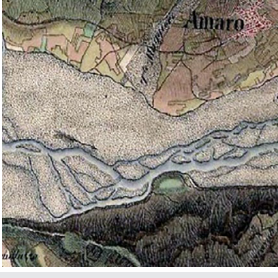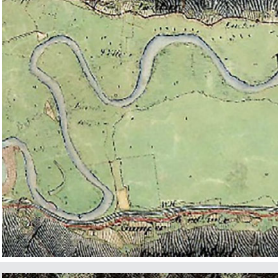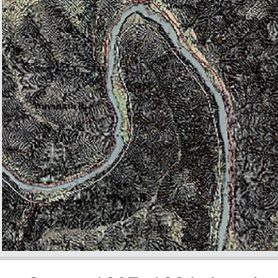
Based on the historical maps, we could not clearly identify the so-called "wandering gravel-bed rivers," which show a transitional channel form between fully braided and oscillating/sinuous patterns (Desloges & Church, 1989; Nanson & Knighton, 1996). Depending on map accuracy, they were most likely grouped with multi-channel rivers when a gravel corridor was mapped, in other cases also with oscillating rivers. Compared to typical braided rivers, they have fewer flow branches. Usually, one main flow channel is clearly dominant and the active channel, that is, water-covered area and un-vegetated sediment bars, is narrower.

Evaluating the current human-modified river courses called for defining additional channel patterns because they deviate substantially from the natural channel forms. Arch-shaped or arched regulated channels are largely bank protected and show forms similar to naturally oscillating rivers. The river bends, however, are mostly flatter and less pronounced to facilitate regulation. This applies even more so to river stretches that were subject to linear straightening. These have often been given what is known as a standard cross-section during regulation. They are mostly devoid of bars and, therefore, appear very monotonous today, resembling canals. Another human-caused channel form refers to dammed-up river reaches, including both impoundments of run-of-river power plants and large lake-like reservoirs.

3.2 | Data sources

We analysed the past channel types in the Alpine arc based on numerous historical maps ranging from 1750 to ca. 1900 (Table 2). They mostly stem from before the onset of systematic river regulation programmes in the 19th century. The scales of the cartographic sources differ considerably between 1:2,500 and 1:100,000. Fortunately, the large Alpine regions of the former Habsburg Monarchy

TABLE 1 Classification of historical river planform types (channel patterns) [Colour table can be viewed at wileyonlinelibrary.com]

Channel type	Example	Characteristics of fluvial morphology
Confined		Single-channel river that is forced to follow a narrow valley Typically in the upper reaches and the headwaters In narrow gorges and V-shaped valleys (bedrock-confined channels) Confinement may also be caused by older and higher river terraces Steep slopes and strong currents
Moderately confined single-channel ("oscillating") (wandering[a])		Sinuous single-channel river confined by close valley sides The valley floor provides space to oscillate, building striking outer and inner bend banks Changes in direction are usually caused by valley sides, alluvial cones or terrace systems Wide inside banks with gravel bars in river bends and small islands in wider stretches
Multi-channel (braided, anabranching, anastomosing, wandering[a])		Divided into several flow channels, caused by high sediment deposition (largely gravel) Sub-types depend on channel shift intensity and vegetation cover: bar-braided or island-braided Anabranching: mixed type of braided and sinuous-meandering channels, individual flow channels are usually separated by large vegetated islands Anastomosing: similar to anabranched, but much lower flow velocity, usually found in river deltas, also at entrance into lakes
Sinuous		Transitory type between multi-channel/oscillating rivers and free meandering Largely unconfined alluvial river Dominant sinuous single-channel without or scattered meander bends The channel sinuosity is between 1.1 and 1.5 In wider river reaches, braiding with islands may occur locally
Meandering		Strongly winding course of the river within a wide floodplain showing a sinuosity greater than 1.5 Meander bends can wander and thereby cut-off isolated oxbow lakes Lateral erosion causes steep outside banks; inside banks show sediment bars which are separated from each other by sections without bars Sand, silt and clay are dominant due to the low flow velocity
Incised meander		Single-channel river flowing in meander-shaped valleys

[a]See Section 3; details: Second Military Survey 1807–1836, Austrian State Archive/Kriegsarchiv.

TABLE 2 Historical sources and contemporary datasets used for the study

Map	Date	Scale/resol.	Coverage
Carte de Cassini	1750–1815	1:86,400	France
First Military Survey	1773–1785	1:28,800	Eastern Austria, Slovenia, partly Northern Italy
Schmitt'sche Karte	1792–1797	1:57,600	Southern Germany
Second Military Survey	**1807–1836**	**1:28,800**	**Austria, Slovenia, North-east Italy**
Flurkarte (cadastral maps)	**1808–ca.1830**	**1:2,500**	**Bavaria (Southern Germany)**
Franziszeischer Kataster	**1817–1830/61**	**1:2,880**	**Austria, Slovenia, North-east Italy**
Positionsblätter	**1817–1841**	**1:25,000**	**Bavaria (Southern Germany)**
Carte de l'Etat-Major	**1818–1866**	**1:80,000[a]**	**France**
Dufourkarte	1844–1864	1:100,000[b]	Switzerland
Siegfriedkarte	1870–ca.1900	1:50,000	Switzerland
Local/regional historical maps	ca.1770–1850	Diverse	Switzerland, North-west Italy
Orthophotos	2008–2017	Diverse	Total Alpine sphere
International Geological Map of Europe	2003	1:5,000,000	Total Alpine sphere
EU Digital Elevation Model v1.1	2011/16	25 m	Total Alpine sphere
Digital Elevation Model Austria	2019	10 m	Austria
Google Earth	2008–2017	—	Total Alpine sphere
Areal denudation rates	2013	—	Most of the Alps east of Geneva
CCM2 River/Catchment Database 2.1	2008	—	Total Alpine sphere
Mean annual precipitation	1801–1830	—	Total Alpine sphere
Mean annual temperature	1801–1830	—	Total Alpine sphere
European Flood Hazard Map (Q200)	2013	—	Total Alpine sphere
Austrian Flood Hazard Map (HORA, Q200)	2014	—	Austria

Note: Bold: historical maps covering the larger part of the study site at a sufficient scale.
[a]Original survey: 1:40,000.
[b]Original survey: 1:50,000.

(Austria, Slovenia and the Southern Alps in north-east Italy) are well covered by the First and Second Military Surveys (1773–1785 and 1807–1836) and the very accurate maps of the "Franziszeische Kataster" (cadastral survey, mostly 1817–1830, partly 1850–1861). The cadastral maps were produced by military surveyors to calculate land taxes and show the land cover/uses of each plot of land. In order to ensure comparability throughout the empire, elaborate mapping instructions were issued (Fuhrmann, 2007). Parallel to the cadaster, the later "k.k. Militärgeographische Institut" produced the Second Military Survey with a scale of 1:28,800. It was dedicated for military use and, therefore, primarily focuses on the geographical situation and landscape structures, such as water courses and terrain topography. Both map series optimally complement each other, yielding the most important sources for the present study (covering half of the study area).

Similar map series are available for the German Alps, where the accurate cadastral maps ("Flurkarte") and the less detailed "Positionsblätter" were produced between 1808 and 1817 (Table 2). The French regions of the Alps are also well covered by two carto-graphic sources that were created consecutively between 1750 and 1866. The "Carte de Cassini" from the 18th century lacks information for small rivers, but provides a valuable supplement to the "Carte de l'État-Major" 1818–1866 created by military surveyors at an original scale of 1:40,000 (Bravard & Bethemont, 1989; Lefort, 2004; Piégay et al., 2009).

For Switzerland, the "Dufourkarte" (1844–1864) and the "Siegfriedkarte" (1870–ca.1900) provided the main sources for identi-fying historical channel patterns. The former was elaborated in an original scale of 1:50,000 by military cartographers and the "Eidgenössische Topographische Bureau" (Gugerli & Speich, 2002). Because the available reproduction shows a scale of only 1:100,000, we additionally used the more detailed but younger "Siegfriedkarte" (also known as "Topographischer Atlas der Schweiz"). This map series is based on the original "Dufourkarte" surveys, but was considerably updated. Because both map series lack details in some areas, we con-sulted additional historical local maps from various Swiss archives. For the Western Alps in Italy, however, no coherent collections of maps are available from the late 18th or early/mid-19th century. Here, we relied on numerous local and regional maps from various archives dat-ing from 1770 to 1850.

Altogether, most of the study site is covered by maps originating from around 1820/30. Some older maps, such as the First Military Survey (1773–1785) or the "Schmitt'sche Karte von Südwestdeutschland" (1792–1797), complement the historical data

basis and provide additional information on potential earlier channel changes. In rare cases, we also consulted historical topographical literature and views for additional information on the former channel forms.

The current state of the Alpine rivers is assessed based on numerous orthophotos from recent years and Google Earth, which facilitated a more detailed three-dimensional investigation of riverscape structures. The 3D-analyses were also supported by the European Digital Elevation Model (EU-DEM v1.1) with a spatial resolution of 25 m, that is, the analysis of channel slopes and altitudes (European Environment Agency, 2016). To validate the accuracy of the European DEM, a more precise DEM (10 m) covering entire Austria served as reference (data.gv.at—Open Data Austria). We used a GIS dataset of the "International Geological Map of Europe" to identify the geological zones, longitudinal valley furrows associated with tectonic faults, and the lithology in the catchments (Asch, 2003; Figure 2). Mechanical denudation rates in different lithological regions were identified according to Hinderer et al. (2013). This dataset only covers most parts of the Alps east of Geneva and is spatially less precise than the geological map. Moreover, the "CCM2 River and Catchment Database for Europe v2.1" provided the basis for calculating drainage densities upstream of the analysed river sections (Vogt et al., 2007). The HISTALP dataset was used to calculate the mean annual precipitation and temperature between 1801 and 1830 (Chimani, Böhm, Matulla, & Ganekind, 2011; Chimani, Matulla, Böhm, & Hofstätter, 2013). Finally, the "European Flood Hazard Map" published by the EC Joint Research Centre and the more precise "Austrian Flood Hazard Map HORA" for 200-year floods helped to identify the widths of the valley bottoms along the studied river courses (Alfieri et al., 2013; BMLFUW, 2014).

3.3 | GIS and data analyses

Historical and current channel patterns of the 143 study rivers were identified according to the morphological attributes specified in Table 1 using ArcGIS 10.6. To determine the relevant rivers and their associated catchments, we used a GIS polyline-dataset comprising the current channel axes that were compiled in the project "Strategic Planning for Alpine River Ecosystems" (Muhar, Grüner, Böck, Scheikl, & Becsi, 2018). Already geo-referenced historical maps were available only for most of Austria, Slovenia and north-east Italy (WMTS-Services for the First and Second Military Surveys; see Table 2). Covering the remainder of the Alpine area would have required geo-referencing more than 1,000 map sheets, an unfeasible task due to the high costs and long processing time. The historical channel patterns were, therefore, mostly identified with non-georeferenced maps using orthophotos as basemaps for proper geographical positioning. Historical channel types were added to the attributes of the GIS polylines. Afterwards, the lengths of the historical river sections were calculated with MS Excel based on the current section lengths, which were corrected for changes in channel

lengths due to river straightening measures. Mean correction factors were calculated based on the defined ranges in sinuosity for the individual channel types (Table 1). A factor of 1.1 was applied for multi-channel sections, 1.2 for sinuous and 1.65 for meandering river stretches. Confined channels and incised meanders were not corrected because they were generally not affected by straightening measures. The same holds true for oscillating channels, which, in most cases, were arch-shaped regulated and showed almost the same sinuosity. For the thereby resulting potential error range, see Section 5.

For further analysis, the 3,045 morphologically homogeneous channel sections were divided into 16,590 sectors with maximum lengths of 1,650 m (historical length, referring to maximum 1,000 m current length). The mean altitude of each river sector was calculated based on the elevations of their upper/lower ends using the DEM. Mean historical channel slope was determined by the same method additionally including historical sector lengths. Because very short segments would potentially show errors in slope, those shorter than 100 m were excluded from the analysis. Sectors located in currently dammed-up river sections were also excluded because the DEM shows the backed-up water level rather than the bottom. Altogether, 3,270 out of the 16,590 river sectors were discarded for all analyses related to channel slopes. In order to evaluate the potential error range due to the relatively coarse 25 m DEM, altitudes and channel slopes were additionally calculated for the Austrian river sectors based on a 10 m DEM.

Further GIS analyses included modelling the catchment size upstream of each river sector based on the 25 m DEM, upstream drainage densities using the CCM2 dataset, per cent proportions of the five geological zones in the upstream catchments, distances from the sources, drainage densities, mean annual rainfall and temperature (1801–1830), current areal denudation rates and associated annual sediment yields (m^3 per km^2 catchment size). The mean valley bottom width was modelled for each river sector. As a first approximation, a 3D plain was constructed 5 m above the channel axes and intersected with the DEM. This method produces geometric artefacts, in particular, in very flat and very steep terrain, and therefore needs manual revision. For that, the European and Austrian flood hazard maps for 200-year floods functioned as a reference. The resulting dataset comprises the areas and mean widths of the valley bottoms associated with each river sector.

The initial step in the data analysis was producing a correlation matrix showing cross-correlation of the different potential physical controls for each channel pattern type. We then performed a hierarchical classification to highlight clusters of correlated variables. In order to identify significant differences between the historical channel pattern types, the first three axes of a principal component analysis (PCA) were analysed and Wilcoxon (rank-based correlation) tests were applied. When exploring human-induced channel pattern changes, we then created a mosaic plot and associated chi-square tests to highlight main differences between current and historical channel pattern types according to country.

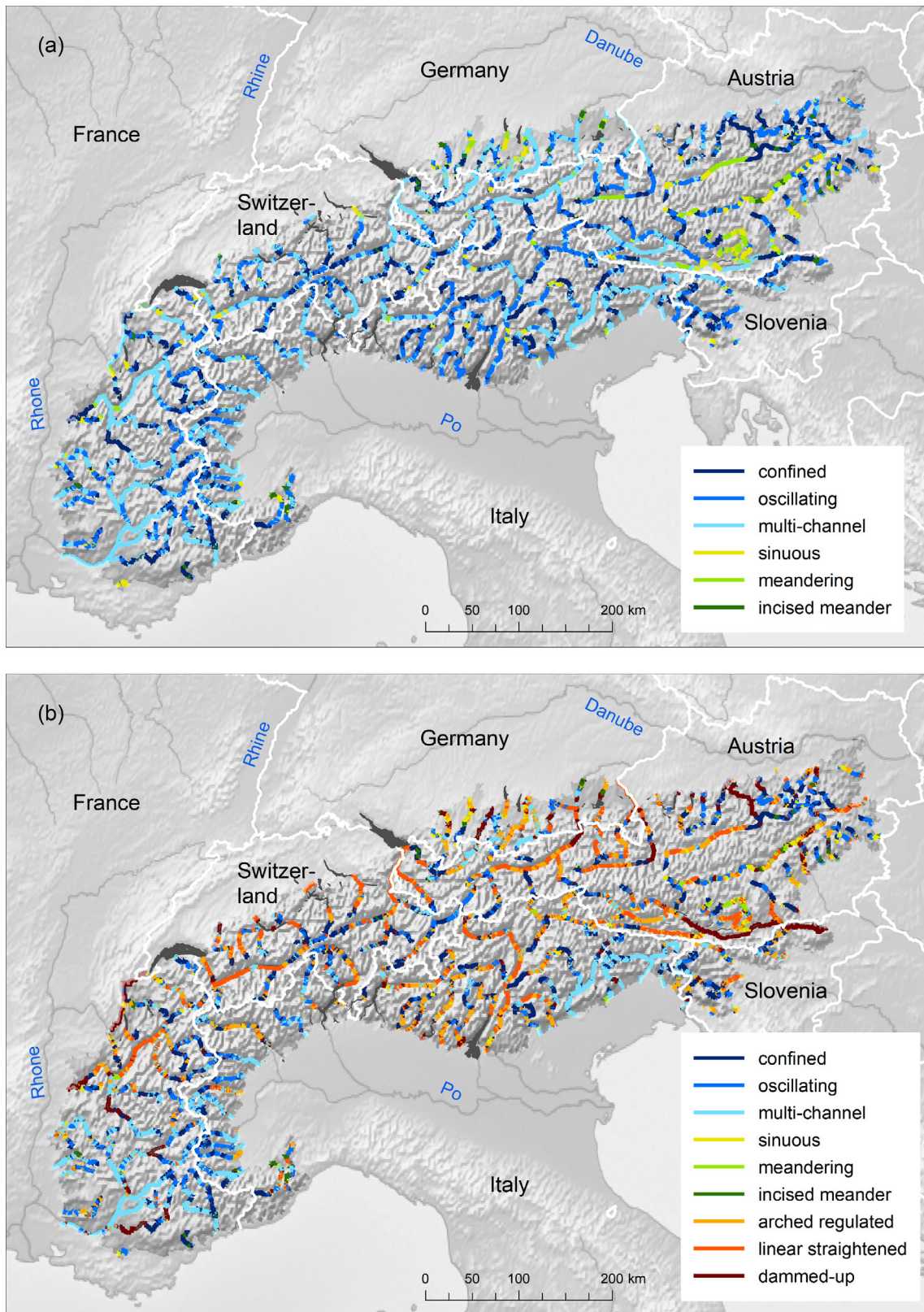**FIGURE 3** (a) Historical channel patterns of the 143 largest rivers in the Alps in the early 19th century; (b) channel patterns in 2017. Most of the remaining near-natural channel sections are affected by channel narrowing, flow abstraction and other human interventions today (grey lines: rivers outside the Alpine sphere, white lines: country borders, dark grey features: lakes; background map: Natural Earth, 2011)

4 | RESULTS

4.1 | What channel patterns were characteristic of large Alpine rivers prior to major human modification?

The spatial arrangement of the 143 largest rivers highlights the principal configuration of the complex historical—and also current—Alpine channel network (Figure 3a). Several long river systems that run almost parallel to the Alpine arc are evident. Such running waters in longitudinal valley furrows are primarily located in the Austrian Eastern Alps, but also in the Swiss Alps at the Alpine Rhine and the Rhone. These river systems are joined by numerous other, largely shorter ones, which flow more or less transversally, starting from the Alpine divide or the longitudinal valleys towards the edge of the Alps. In the early 19th century, the total lengths of all investigated rivers were approximately 11,870 km.

Within the network of the large Alpine rivers, the quantitative importance of the individual channel patterns differed from region to region. Almost a quarter of these featured confined channels. They are still present in the upper regions of the Alps but also in lower-lying narrow canyon sections. About a third of the studied network was occupied by multi-channel rivers (defined here as a fairly large class including different sub-types) in the early 19th century (Figure 4). This observation concurs with the widespread notion that this planform type was significantly representative of Alpine rivers prior to industrialization (Comiti, 2012; Liébault & Piégay, 2002). Oscillating river sections were comparably frequent in the Alps, that is, 28% of the total channel length. These were neither braided nor freely meandering.

They characterized the landscape of many Alpine valleys because the run of the river constantly altered its course between the sides of the valley. Sinuous and even more so meandering waterbodies were much rarer in the Alps, making up 7 and 5%, respectively, of the studied river courses. The side valleys also once featured sinuous or even meandering flowing waters. Nonetheless, examining only the larger main rivers shows that they were less significant. Only 2% of the total channel length were incised meanders, which can also be described as geologically fixed meander bends.

Importantly, the different channel patterns were not equally distributed (Figure 3a). The Austrian Eastern Alpine region featured significantly more sinuous and, in particular, meandering river stretches than the rest of the Alps (each type 11% related to all large rivers in the Austrian Alps; Table 3). The German Alpine area also featured high shares of meandering rivers, but even more outstanding were the numerous sinuous river sections (16%) as well as the comparably high proportion of incised meanders. The situation in the Swiss Alps differed entirely: here, only 6% of the larger rivers were sinuous, and none were meandering. In France, Italy and Slovenia, these river types were below the Alpine average.

The situation of multi-channel rivers was different. The French Alps showed the highest percentage, that is, 44% of the length of the large rivers. In Switzerland, Germany and Italy, they also made up between 35% and 39%. In Slovenia, in contrast, only 20% of the investigated river continuum showed forms of multiple channels. Finally, oscillating channel patterns were relatively equally distributed in Austria, France, Germany and Switzerland (between 23 and 26%), but showed much higher values in Italy (35%) and Slovenia (38%).
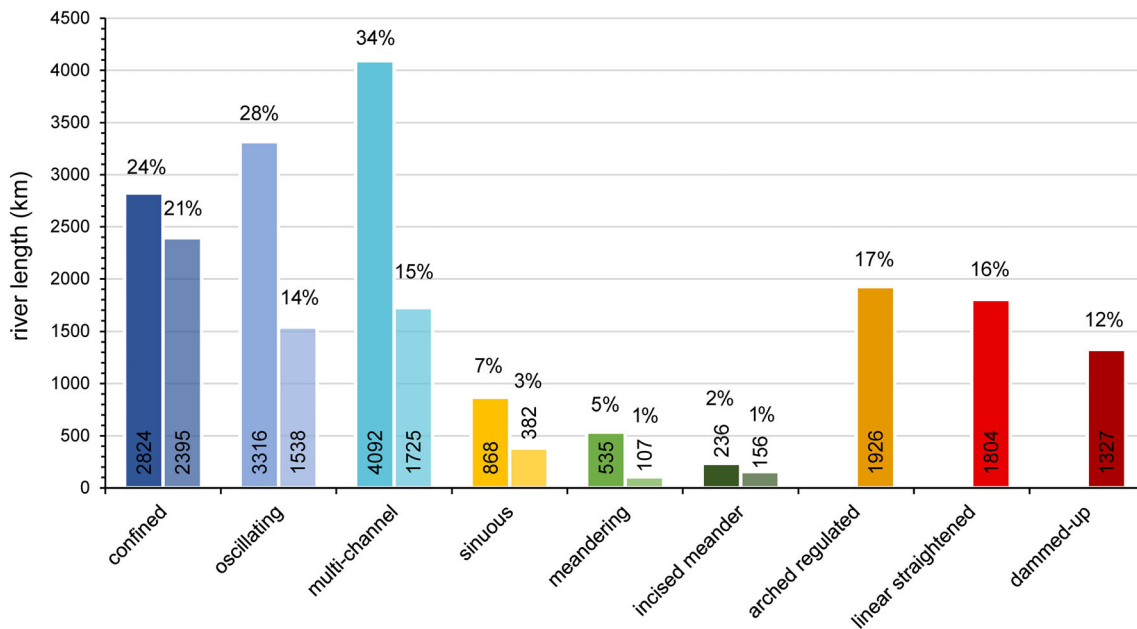

FIGURE 4 Distribution of channel planform types in the Alps in the early 19th century and in 2017 (left bars: historical, right bars: 2017; per cent values indicate the relative shares of the individual river types in total river lengths at the respective time)

TABLE 3 Lengths of historical and current channel patterns per Alpine country (in km and % of total river length in the respective country)

Austria	Early 19th century		2017		Difference	
Channel pattern	km	%	km	%	km	%
Confined	868	24	715	21	−153	−18
Oscillating	920	25	465	14	−455	−49
Multi-channel	938	26	95	3	−843	−90
Sinuous	413	11	183	5	−230	−56
Meandering	394	**11**	62	**2**	−332	−84
Incised meander	91	3	65	2	−26	−29
Arched regulated	—	—	604	18	+604	+18[a]
Linear straightened	—	—	687	20	+687	+20[a]
Dammed-up	—	—	490	15	+490	+15[a]
Total	3,624	100	3,366	100	−258	−7

France	Early 19th century		2017		Difference	
Channel pattern	km	%	km	%	km	%
Confined	636	25	482	19	−154	−24
Oscillating	610	24	394	**16**	−216	−35
Multi-channel	1,129	**44**	673	**27**	−456	−40
Sinuous	111	4	58	2	−53	−48
Meandering	41	2	22	1	−19	−47
Incised meander	31	1	31	1	0	0
Arched regulated	—	—	263	11	+263	+11[a]
Linear straightened	—	—	224	9	+224	+9[a]
Dammed-up	—	—	343	14	+343	+14[a]
Total	2,558	100	2,490	100	−68	−3

Germany	Early 19th century		2017		Difference	
Channel pattern	km	%	km	%	km	%
Confined	71	9	59	8	−12	−17
Oscillating	176	23	83	12	−93	−53
Multi-channel	306	39	92	13	−214	−70
Sinuous	122	**16**	72	**10**	−50	−41
Meandering	58	7	6	1	−52	−90
Incised meander	45	**6**	24	**3**	−21	−46
Arched regulated	—	—	173	**24**	+173	+24[a]
Linear straightened	—	—	89	12	+89	+12[a]
Dammed-up	—	—	126	17	+126	+17[a]
Total	778	100	724	100	−54	−7

Italy	Early 19th century		2017		Difference	
Channel pattern	km	%	km	%	km	%
Confined	747	24	685	22	−62	−8
Oscillating	1,107	35	382	12	−724	−65
Multi-channel	1,118	35	732	24	−386	−35
Sinuous	135	4	55	2	−80	−59
Meandering	28	1	9	<1	−19	−68
Incised meander	30	1	27	1	−3	−10
Arched regulated	—	—	619	20	+619	+20[a]

TABLE 3 (Continued)

Channel pattern	km	%	km	%	km	%
Linear straightened	—	—	383	12	+383	+12[a]
Dammed-up	—	—	203	7	+203	+7[a]
Total	3,165	100	3,095	100	−70	−2
Slovenia	**Early 19th century**		**2017**		**Difference**	
Channel pattern	**km**	**%**	**km**	**%**	**km**	**%**
Confined	154	**34**	120	**27**	−34	−22
Oscillating	170	**37**	58	13	−112	−66
Multi-channel	93	20	45	10	−48	−52
Sinuous	15	3	10	2	−5	−33
Meandering	13	3	8	**2**	−5	−38
Incised meander	13	3	2	<1	−11	−85
Arched regulated	—	—	96	21	+96	+21[a]
Linear straightened	—	—	29	7	+29	+6[a]
Dammed-up	—	—	81	**18**	+81	+18[a]
Total	458	100	449	100	−9	−2
Switzerland	**Early 19th century**		**2017**		**Difference**	
Channel pattern	**km**	**%**	**km**	**%**	**km**	**%**
Confined	349	27	335	**27**	−14	−4
Oscillating	333	26	155	12	−178	−53
Multi-channel	509	39	88	7	−421	−83
Sinuous	73	6	5	<1	−68	−93
Meandering	—	—	—	—	—	—
Incised meander	25	2	7	1	−18	−72
Arched regulated	—	—	172	14	+172	+14[a]
Linear straightened	—	—	392	**32**	+392	+32[a]
Dammed-up	—	—	84	7	+84	+7[a]
Total	1,289	100	1,237	100	−52	−4

Notes: Bold values: maximum percentage compared to other countries. The indicated reductions of historical channel patterns refer to minimum values. Thus, formerly braided rivers in France were reduced by 47% (Figure 9), but new, largely less braided ones were identified for 2017 in other river sections (see Section 5.3).

[a]Percentage related to current river length.

4.2 | Which physical factors promoted the evolution of the observed channel forms?

The prerequisite for answering this research question is to consider the physical factors behind the evolution of the different channel patterns. This helps highlight notable differences between the historical channel types with respect to the individual attribute. Subsequent multivariate analysis shows which of these factors significantly contributed to the occurrence of certain channel forms.

Only a partial differentiation of the historical river types can be made based solely on the altitudes of the river sectors (Figure 5a). As commonly supposed, confined channels with a median altitude of 754 m a.s.l. stand out because they are mostly located in headwater sections. Incised meanders with a median of 459 m a.s.l. build the lower end of the spectrum. They were and still are typical landscape features in the lower-lying foothills of the Alps, such as the Southern Bavarian Moraine Landscape.

The catchment size upstream of each river sector inversely reflects the altitudinal pattern (Figure 5b). Here, confined and oscillating channels generally featured the smallest catchments because many of them are located in the headwaters. On the other end of the spectrum of channel types, incised meanders and freely meandering channels showed the largest median upstream drainage areas.

A more pronounced general differentiation can be made based on the distances of the individual river sectors downstream of the source (Figure 5c). Increasing median distances of confined channels as the shortest, and meandering/incised meanders as the longest, largely
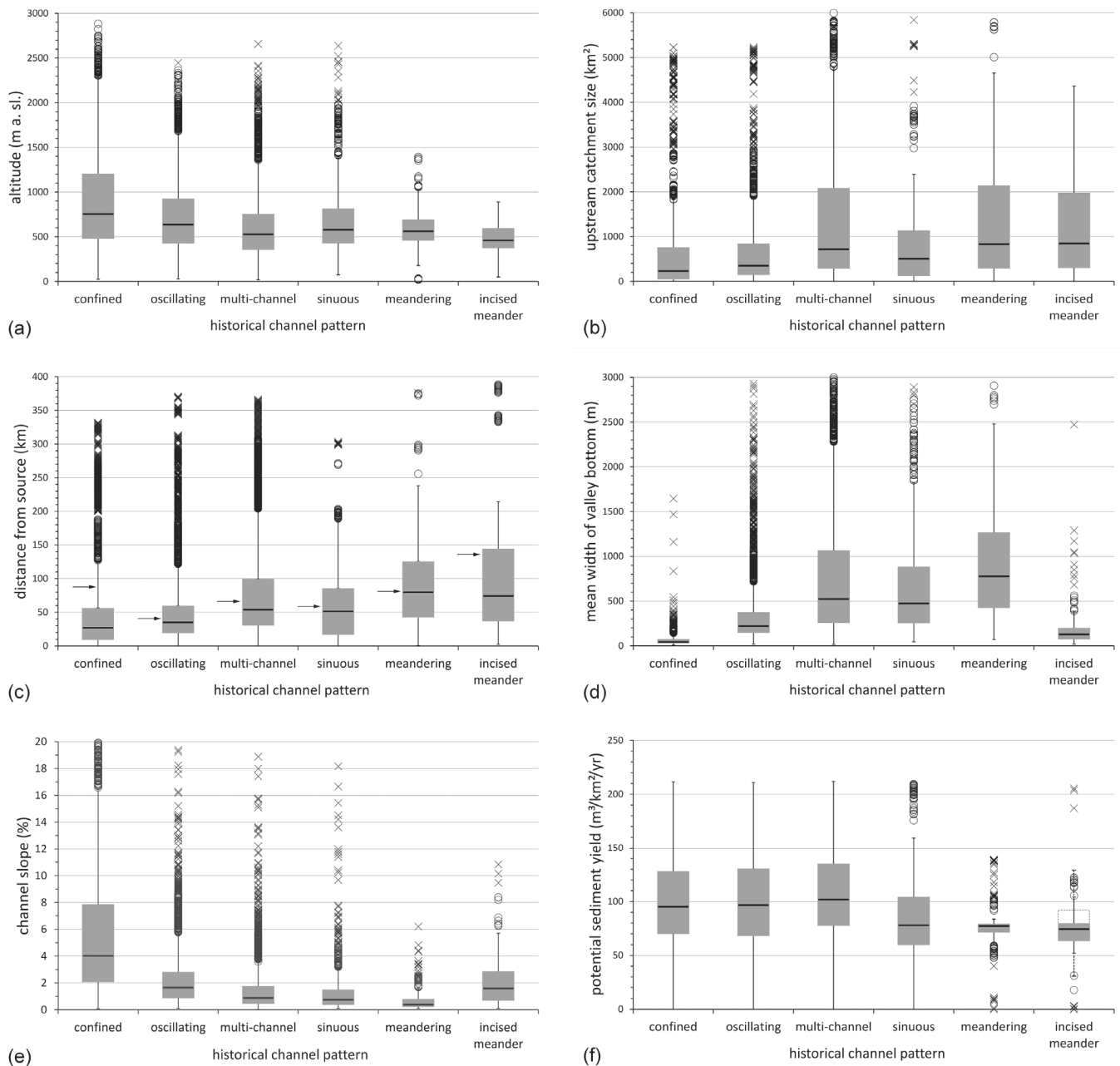
FIGURE 5 (a) Historical channel types and related altitudes (m a.s.l.) of the 143 largest Alpine rivers; (b) upstream catchment sizes of channel sectors (km^2); (c) distances downstream of the source (km; arrows refer to the median values of river sectors that were later arch-shaped regulated, linear straightened or dammed up; see Section 4.3); (d) mean width of valley bottom (m); (e) channel slope (%); and (f) potential sediment yield (m^3 km^{-2} year^{-1}; values do not consider potential sediment deposition in upstream river reaches; dashed: values including incised meanders directly outside of the area covered by the basic data). In order to improve readability, extreme outliers exceeding the maximum values of the Y-axis are not shown in some of the figures (see Figure S1 in supporting information for histograms of all analysed physical attributes)

reflect the idealized sequence of channel patterns shown in Figure 1. This pattern also inversely reflects the pattern of altitudes (Figure 5a).

The mean width of the valley bottom showed extraordinary ranges between a few metres in confined sections up to 8,600 m at the Rhine River. Except for multi-channel and sinuous rivers, the median values differed significantly (Figure 5d). By definition, confined sections were located in the narrowest valleys (median width 43 m). Incised meanders that were also largely confined featured the second

narrowest valley bottoms (median 127 m). Generally, meandering sections were located in the broadest valleys (777 m).

As commonly supposed, confined channels showed the highest median channel slope (4.0%; Figure 5e). Oscillating river stretches featured much lower values (1.7%). Multi-channel and sinuous rivers were characterized by even lower values (0.9 and 0.75%, respectively). Meandering reaches showed the lowest channel slopes (median value of 0.4%). In contrast, incised meanders had (or still

have) much greater channel slopes. The latter follow the slope of the meander-shaped valley floor and are constrained by the valley sides. Because the calculation of channel slopes is very sensitive to elevation errors of the used 25 m DEM, we validated the results using the more precise Austrian DEM (see Section 5).

The historical channel patterns were not equally distributed within the geological zones (compare Figure 2 and Figure S3 in supporting information). The Molasse zone at the outer fringes of the Alps including inner-Alpine basins featured the greatest proportion of multi-channel rivers (46%). Sinuous rivers and incised meanders also showed the highest proportions in the Molasse zone. In the much larger Limestone Alps, the multi-channel rivers made up 38%. In contrast, the Central Alps were distinguished by oscillating and meandering rivers, which made up 31 and 9%, respectively. Altogether, geological zones dominated by sedimentary rocks (Molasse, Flysch, limestone, etc.) and volcanic bedrock showed much higher shares of multi-channel rivers than the Central Alps, which mainly consist of crystalline and metamorphic rocks (gneiss). For further multivariate analyses, we also determined the per cent shares of the geological zones in the upstream catchments of each river sector (see Figure S4).

The Alpine lithological regions defined by Hinderer et al. (2013) provide a rough measure for potential sediment availability. Based on current denudation rates, the median annual sediment yield corrected for catchment size (m^3 km^{-2} $year^{-1}$) ranged between 74 m^3 for incised meanders and 102 m^3 for multi-channel rivers (including both bedload and suspended load; Figure 5f). Sinuous and meandering sections showed significantly lower yields than confined, oscillating and multi-channel reaches.

Based on all key physical factors, we performed a correlation matrix using ranks. This yielded very strong correlations and anti-correlations between a series of variables (Figure 6a and Figure S2 in supporting information). Catchment size is positively correlated with current total sediment load (m^3 $year^{-1}$), distance from source and also valley bottom width, but anti-correlated with channel slope. Another set of variables shows decreasing areal denudation rates and sediment yields at increasing latitudinal and longitudinal geographical positions (i.e., in the more northern located Eastern Alps). A third set of variables features negative correlations between mean annual precipitation and altitude and drainage density. Precipitation also decreases in the Central Alps and in volcanic areas (Northern Italy). These three sets of correlated variables are very well identified on the hierarchical clustering dendrogram, which is built based on a pseudo-distance matrix with values $X(i,j)$ = 1 − correlation(variable i, variable j) (Figure 6b).

The three sets of correlations then structure the first three axes of a PCA (56% of explained variance). Comparing the scores on each of the three axes with the different channel pattern types reveals that the first axis very clearly distinguishes the confined, oscillating and all other channel patterns combined from one another. This differentiation is based on catchment size and upstream–downstream gradient, that is, decrease in channel slope, distance from source and increase in floodplain width (Figure 7a). The channel patterns are positioned along the first axis according to an energy gradient and potential room

for sediment deposits. Multi-channel, sinuous, meandering and incised meander classes are less distinguishable by this gradient. Generally, they are observed in reaches with lower channel slopes and altitudes, wider floodplains and higher total sediment load. The sinuous class is positioned in between oscillating and multi-channel classes, potentially located slightly upstream at a higher altitude than the multi-channel class (compare medians in Figure 7a). Historically, sinuous reaches also had slightly shorter downstream distances than multi-channel reaches (51 km vs. 54 km; Figure 5c).

Confined, oscillating and multi-channel patterns are then distinguished from the three others on the second and the third axes of the PCA (Figure 7b,c). The main factors associated with the second axis are related to the current sediment yield and to the position in the
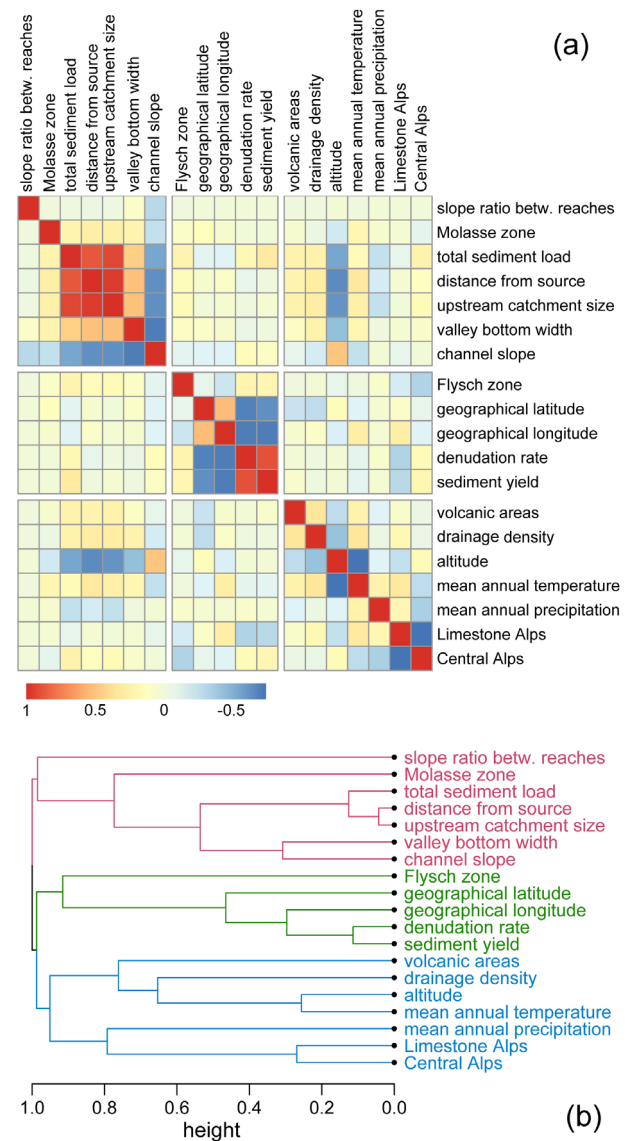

FIGURE 6 (a) Correlation matrix based on ranks (Spearman correlation coefficients) with three groups of clustered channel-controlling factors in the X- and Y-axes; (b) visualization of the three sets of correlated variables on a hierarchical clustering dendrogram
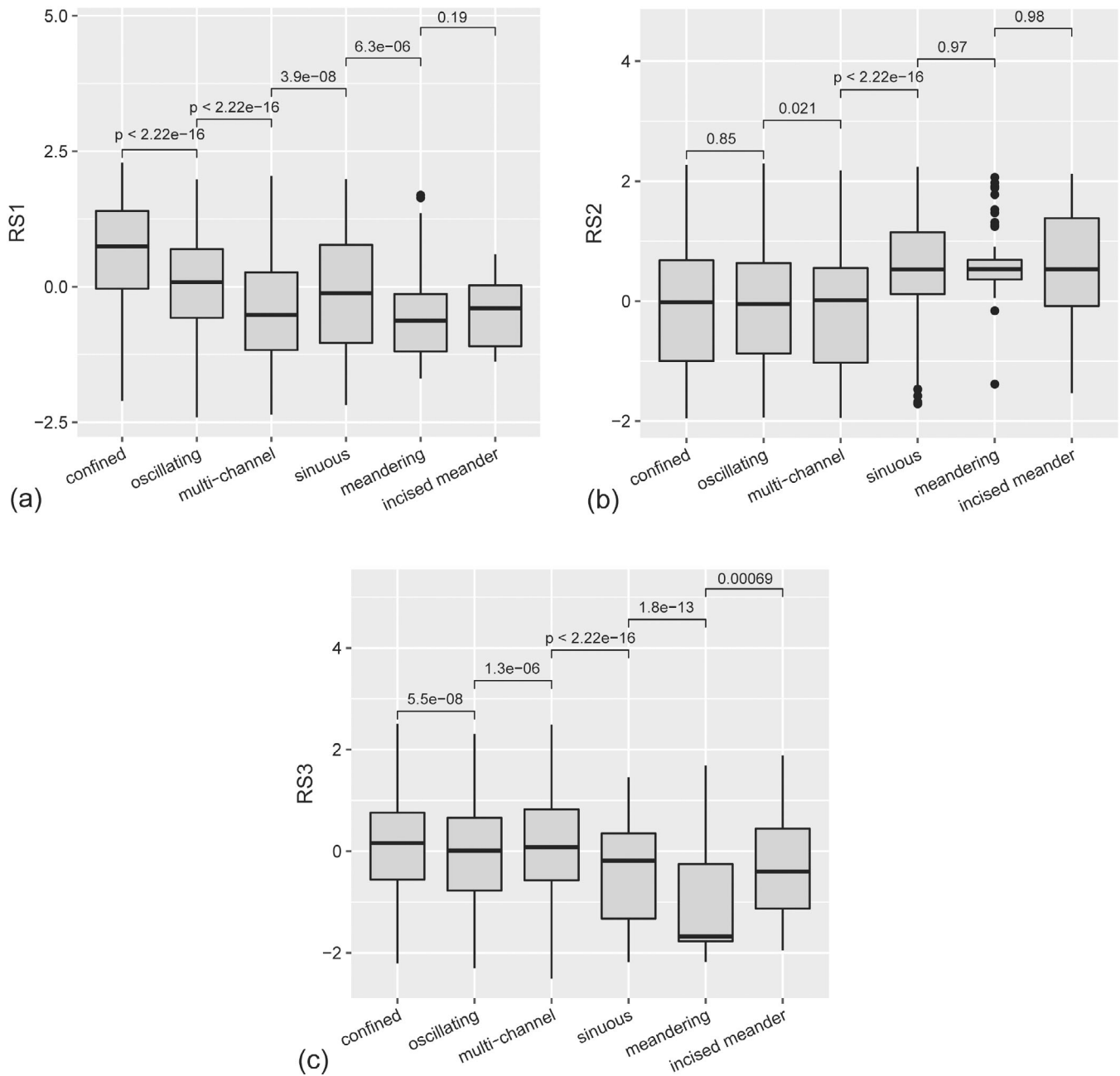
FIGURE 7 Distribution of row (individuals') scores (RS) on the first three components, that is, the first (a), second (b) and third (c) axes, of the PCA performed on the physical characters of river reaches and their upstream catchments. The distributions are specified for each historical channel pattern type. The *p* value of Wilcoxon tests (rank-based correlation tests) reveals whether significant differences are present between neighbouring channel pattern classes

north-eastern part of the Alps. This area is characterized by less sediment delivery, which would explain the main difference between sinuous and multi-channel reaches. The lithological regions defined by Hinderer et al. (2013) allow a less significant differentiation in confined/oscillating/multi-channel with long-term denudation rates of 106 mm/1,000 years on the one side and the remaining channel types with 80 mm/1,000 years (median values) on the other. The third axis is useful to distinguish meandering reaches from sinuous ones (Figure 7c). Here, however, a significant differentiation based on altitude, drainage density and areas with less precipitation (Central Alps) can be made only for a subset of such river reaches. Including other

variables, such as channel slope and sediment yield, enables a more comprehensive distinction of the two channel types. The different geological zones constituting the studied sub-catchments fail to satisfactorily distinguish channel patterns.

In combination with the PCA, the sequence relation diagram in Figure 8 provides additional information on the physical factors behind the historical Alpine channel evolution. It highlights how often a specific type of channel pattern changed downstream to another pattern. Most frequently, 54.6% of the confined river sections were followed downstream by oscillating reaches, and the latter primarily by multi-channel sections. In turn, 55.8% of the latter featured
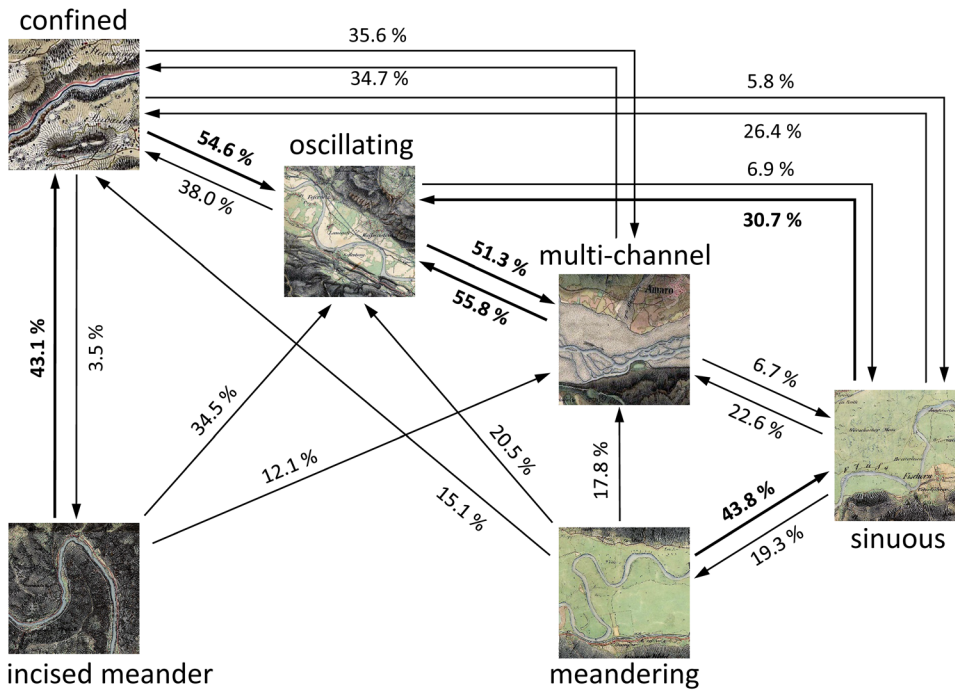
FIGURE 8 Sequence relation diagram of longitudinal river pattern changes. Numbers refer to the percentage shares related to all observed changes of a specific channel pattern type. Bold arrows indicate the most frequent transition type of each river type (only the most important three or four transition types are shown per channel pattern; details: Austrian State Archive/Kriegsarchiv)

downstream oscillating and about a third of them confined channels. Thus, the sequence diagram reveals that the three channel pattern types were repeatedly arrayed after each other. Sinuous sections in most cases were not followed by meandering reaches, but rather by oscillating or confined ones. Finally, meandering river sections most frequently turned into sinuous but also oscillating ones. This sequence demonstrates that the Alpine area cannot be distinguished into main areas with active bedload delivery and others with much less. Rather, most parts of the Alps provide abundant sediments, but show certain transport-limited river sections characterized by wider valley bottoms and lower channel slopes. Such conditions favoured the evolution of multi-channel patterns. Steeper sections with narrower valley bottoms, in turn, promoted confined or oscillating patterns with much higher transport capacities. In several areas of the Eastern Alps, significantly more sinuous and meandering river sections were present, where in other Alpine regions multi-channel patterns would most likely have developed. This did not occur, probably as a consequence of the lower sediment delivery due to drier catchments and lower denudation rates and associated sediment yield.

4.3 | How have the Alpine channel patterns been human modified over time?

Since the early 19th century, the large Alpine rivers lost a stretch of about 510 km, namely 4.3% of the original extent, due to channel straightening. Two hundred years ago, 86% of the larger Alpine river courses were formed by confined, oscillating and multiple channels. Today, these types contribute only 50% (Figures 3b and 4). Multi-channel sections, historically 34% of the river courses, were reduced to 15%. In absolute numbers, these particularly "space-occupying"

waterbodies—which include braided, anabranching and anastomosing river sections—showed the strongest decline. In total, 2,370 km (58%) of the formerly branched rivers have been straightened and regulated. Meandering rivers suffered the greatest percentage loss of previous course length: 80% or 430 km. In contrast, regarding planform geometry, confined waters were the least frequently affected by human interference. Only 15% of these were turned into reservoirs. This value does not consider human impacts due to smaller consolidation and retention check-dams.

The analysis of the current river courses reveals three new forms of channel patterns that did not exist almost 200 years ago (see Section 3). To date, with respect to rivers with catchments exceeding 500 km^2, about 3,730 km were arched or linear regulated (33% of the current river course length). Moreover, at least 1,330-km-long reaches (12%) were transformed into reservoirs. Human modifications were not equally distributed along the river courses, but generally increased the further downstream a river sector is located. For example, confined channels historically showed median distances from the source of 27 km. The human interventions along these channels, however, were generally implemented much further downstream (median distance 87 km; compare arrows in Figure 5c). In the case of confined channels, the predominant form of human intervention was weir and impoundment construction. This is even more the case for incised meanders, where the historical median downstream distance was 74 km and that of the intensively modified sections now is 136 km. Multi-channel sections were also affected by humans, primarily in more downstream locations (historically 54 km vs. currently 67 km). Here, channel patterns were transformed by reservoir construction as well as by arch-shaped and linear straightening. Along oscillating and meandering rivers, the transformation to one of the three human-created channel types was more uniformly distributed (Figure 5c).

Across the Alps, the current river courses show an irregular distribution of intensively channelized and dammed-up river sections (Figure 3b). Human interventions took on differing forms and intensities in the various Alpine countries. Thus, the country-wise analysis helps to reveal nationally varying approaches in Alpine river management (Table 3 and Figure 9). Accordingly, in Slovenia, Germany and Austria, large Alpine rivers are subject to particularly intensive energy use. In these countries, 15–18% of the larger river courses were dammed up. This is clearly reflected by the series of reservoirs along several rivers in the Eastern Alps, but also on the Rhone downstream of Lake Geneva. In contrast, in Switzerland, very straight (linear) channelized rivers are most frequent. Today, they amount to 32% of the large Alpine Swiss river continuums. In Austria, all three most intensively human-modified channel forms together total of 53%. Interestingly, the same value of 53% is valid for Switzerland and Germany, although the proportions of linear, arched and dammed stretches differ. France has the greatest proportion of natural and near-natural channel forms. Here, two-thirds of the network length is still confined, oscillating, braided, sinuous or meandering, although most of these have been significantly narrowed by river training or are affected by water abstractions and channel dredging.

Focusing on multi-channel rivers, Austria and Switzerland lost an astounding 90 and 83%, respectively, of former extents (Table 3). Italy and France, in contrast, lost only between 35 and 40% of such sections. Importantly, however, these numbers hide the fact that between 44 and 47% of the formerly braided sections have been lost in the latter two countries (Figure 9). The different numbers point to a partial compensation by the emergence of new, less braided reaches in other river sections. The differences can be also attributed to channel classification problems, that is, regarding historical and current transitional wandering gravel-bed rivers.

Linear straightening of multi-channel rivers was fairly frequent in Switzerland and Austria, whereas arch-shaped regulation was more frequent in Slovenia and Germany (Figure 9). Multi-channel sections were most frequently transformed into reservoirs in Germany, Austria and France. Note that none of the multi-channel sections became meandering, confined or incised meanders. Some, however, did become oscillating (maximum value of 10% in Slovenia and Italy).

5 | DISCUSSION

5.1 | Inaccuracies of the basic data and potential errors

Using so many different data sources entails manifold potential pitfalls. Firstly, the used historical maps originate from various sources and partly different time periods. Secondly, the current datasets, that is, the used DEM, can also show geographical errors. And thirdly, the GIS methods we applied may produce additional inaccuracies that affect the results. Most of these potential sources of error proved to be minimal.

Most of the historical map series were produced by military cartographers working with very elaborate survey instructions (Fuhrmann, 2007; Gugerli & Speich, 2002; Lefort, 2004). The creation of hundreds or even thousands of sheets of maps necessitated numerous actors who—despite detailed instructions—no doubt deployed different levels of accurateness in their field work. The resulting map series are, therefore, not as homogeneous in some sections as originally intended. In some of the Austrian cadastral maps, for example, in-stream structures such as gravel bars are depicted, while they are missing in the adjacent map sheet. This, however, was not a major problem because we focused on the geometry of the active channel rather than on in-stream structures. Another illustrative example is the River Bléone in southern France. Single map sheets of the "Carte de l'État-Major" do not indicate a braiding character, but the up- and downstream, subsequent sheets do so. Instead, a wide water-covered channel is depicted. In such cases, when we were unable to find a logical reason for the deviating channel pattern and that stretch is still braiding today, we also assumed a historically multi-channel pattern. Another question arises whether the very high proportions of meandering and sinuous sections in the Austrian Alps
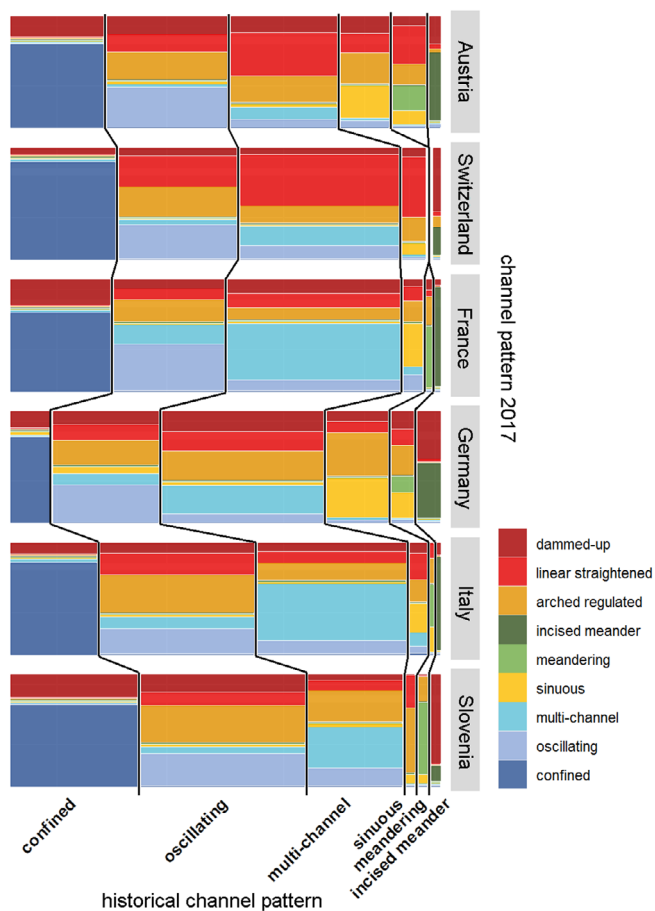

FIGURE 9 Transformation of channel patterns between the early 19th century (x-axis) and 2017 (y-axis) per Alpine country (based on the number of river sectors)

might be due to varying accuracies of the historical maps (Figure 3a and Table 3). The same map collections, however, were used both for the Austrian and also Italian and Slovenian Southern Alps, where far fewer such channel patterns were recorded. Nevertheless, we cannot exclude that some historical channel patterns are falsely classified. In particular, the classification of transitional wandering gravel-bed rivers as multi- or oscillating channel was not always clear. This problem was also evident for current transitional channel forms.

Another source of inaccuracies is the partly differing time periods covered by the maps. Some sources, such as the two mentioned Swiss maps, stem from the mid-19th or late 19th century, respectively, when several reaches had already been channelized. Nevertheless, they often show relicts of the former fluvial landscape in the form of cut-off river branches or other fluvial structures. In such cases, we relied on those riverine structures to draw conclusions about the former channel patterns. Older maps from the 18th century were also used for reaches that had already been channelized by the early 19th century. They helped to better understand natural or human-caused channel changes at that time. Nonetheless, it was not always clear whether the identified channel changes derived from (semi-)natural fluvial processes or direct human interventions. In some cases, a literature research helped clarify the uncertainties (compare Hohensinner, Sonnlechner, Schmid, & Winiwarter, 2013 in the interpretation of historical maps from the fluvial morphological perspective).

The mean correction factors applied to calculate the historical lengths of river sectors based on current channel lengths are also a source of potential inaccuracy (see Section 3). These factors differ for individual channel types and were defined based on the historical maps. Typical sinuosity ranges were also considered (Table 1). In order to validate the applied correction factors, 320 sample sections were selected in regions where geo-referenced maps were already available and GIS vectorizations of the historical river courses were possible. This approach yielded a factor of 1.06 for multi-channel sections (instead of 1.10 as applied in this study), 1.23 for sinuous sections (compared to 1.20) and 1.62 for meandering ones (compared to 1.65). Because two-thirds of the samples are located at Austrian rivers and almost all others in Italy and Slovenia, they do not reflect the whole range of Alpine channel forms. Thus, the originally applied mean correction factors were maintained. In addition, the potential error ranges were evaluated using minimum or maximum correction factors for channel sinuosity. Accordingly, the total historical channel length would yield 228 km (−1.9%) smaller or 269 km (+2.3%) greater values than presented in this study. Similarly, minimum correction factors for historical channel lengths would result in slightly steeper channel slopes for multi-channel (+0.02%), sinuous (+0.07%) and meandering river reaches (+0.04%). In contrast, maximum correction factors would yield slightly lower slopes (−0.04% for each of the three channel types). Thus, the potential errors do not significantly affect the proportions of the channel lengths associated with different channel types. The pattern of channel slopes per river type is also very robust.

The GIS analyses revealed that the used 25 m DEM was less accurate in some areas than originally thought. In order to check the precision in elevation, we, therefore, additionally calculated the altitudes and channel slopes for the Austrian river sectors with a more accurate 10 m DEM (almost 4,900 sectors out of 16,590). The newly calculated slopes were significantly lower for all channel types (ranging between −1.00% for confined and −0.17% for multi-channel and meandering reaches; for details see supporting information). Nevertheless, the relative differences of slopes between the individual channel types remained largely stable. The resulting median altitudes were between 3 and 9 m lower for oscillating, multi-channel, sinuous and meandering rivers. The corresponding altitudes for confined channels and incised meanders, which are generally located in narrow valleys, were between 17 and 22 m lower. In light of the Austrian samples, the slope values presented in Section 4 and in Figure 5e generally seem to be too high, and the relative differences between the analysed channel types are probably smaller.

5.2 | Physical channel controls and regional organization

Alpine-wide, the data analysis showed that confined, oscillating and all other channel types combined together generally followed an upstream–downstream gradient defined by increasing distance from the source, channel slope and floodplain width. As the valley bottom widened, more space was available for the (temporal) deposition of sediments. In larger, generally further downstream located Alpine valleys, the relationship between up-/downstream gradient and channel patterns was less significant. Here, multi-channel, sinuous or meandering reaches developed prior to human modifications. Our data show that the geographical position (i.e., NE-position) and sediment yield significantly affected which type of channel pattern originally evolved. Including channel slope, the historical channel types can be clearly differentiated within four domains defined by sediment supply and available space (Figure S5).

A closer examination of the numerous sinuous and meandering rivers in the NE-located Austrian Alps reveals that most were in longitudinal valley furrows (Figure 2). That specific type of Alpine valley is typically associated with major tectonic faults that fostered glacial excavation during the Ice ages (Fiebig, Hohensinner, & Muhar, 2019). Post-Ice age lakes in glacially over-deepened valley floors were gradually filled with sediments. These long and wide valleys, with their low gradients, provided better geomorphic conditions for the development of meandering or sinuous reaches compared to rivers perpendicular to the Alpine divide, which are mostly located in steeper terrain. Thus, the longitudinal valleys represent "landscape templates" that provide enough space and adequate gradients of the valley bottom for the formation of extensive braiding or anabranching river landscapes. In the Eastern Alps, however, the multivariate analysis reveals that limited sediment supply at least partly prevented the evolution of such fluvial systems. Instead, it significantly favoured the development of sinuous and meandering river sections. Most of these were located in the north-eastern Alps, that is, in the Eastern Central Alps or directly at the boundary to the Northern Limestone Alps (Figure 2). According to Hinderer et al. (2013), both areas today feature the

lowest median denudation rates in the entire Alps (only 80 and 64 mm per 1,000 years, respectively). In this respect, the high proportions of sinuous and meandering channels in Austria's Central Alps can be interpreted as a product of lower sediment supply and adequate tectonic/geomorphic framework conditions.

In Germany and Austria, the Northern Limestone Alps feature the lowest denudation rates and thus, supposedly, the lowest sediment supply. Rivers there, however, showed more braided sections and significantly fewer meandering and sinuous courses (Figure S3). Because those rivers run towards north, they generally show shorter and partly steeper courses than in the Eastern Central Alps. They also feature shorter downstream distances from the sediment sources.

Long sections of the rivers Rhone and Rhine in Switzerland and Inn in western Austria also run in longitudinal valley furrows but did not form longer sinuous or meandering reaches. Here, the main differences to those in eastern Austria are the generally higher denudation rates (sediment delivery) of up to 212 mm/1,000 years, the closer location to sediment-rich (formerly) glaciated areas, and higher and steeper terrain (Ehlers, Gibbard, & Hughes, 2011; Hinderer et al., 2013). Due to the higher sediment supply in the Western Alps, meandering patterns there generally developed further downstream (and outside of the study site) than in the Austrian context.

In the Molasse zone, both multi-channel and sinuous rivers featured the greatest relative proportions among the different Alpine regions. Besides encompassing a few inner-Alpine basins, the Molasse is located at the outer fringe of the Alpine complex, where the rivers tend to lose sediment transport capacity in the much wider, unconfined floodplains. Such conditions favour the formation of multi-channel rivers (Lane, 1955). The reason for the large proportions of incised meanders and meandering sections in the Molasse zone lies in the evolution of the Southern Bavarian Moraine Landscape (Figure S3). Here, lakes were filled after the Würm glacial, and the flat valley floors emerging from these favoured the creation of sinuous and meandering waterbodies. The delineation of the study area, that is, of the region specified by the Alpine Convention, also helps explain the low proportions of sinuous and meandering rivers in Switzerland. Here, the defined limits are more restrictive and exclude more of the Alpine foreland than in Germany. Sinuous-meandering waterbodies outside of this region are therefore not included. The fact that the Alpine Convention area does not directly coincide with the Alpine geological complex partially affects the country-wise census of channel patterns.

Multiple channels were formerly widespread within the Alpine arc, demonstrating that the mountain area generally delivered abundant sediment regardless of the geological conditions or orography (except in the case of the NE-Alps). Local contrasts between multi-channel and oscillating patterns (the most common patterns) are evident, demonstrating that local factors, such as valley confinement, control the probability of sediment accumulation regardless of differing sediment supply. One region in northern Italy is characterized by a major SW–NW lateral displacement fault with the Sarca, Adige and Chiese River valleys. It showed significantly more oscillating reaches than multiple ones, reflecting a difference in valley morphology (confinement) rather than a difference in sediment supply.

Interestingly, multi-channel and sinuous reaches were very similar in several physical attributes. Sinuous reaches generally showed slightly lower channel slopes (0.75 vs. 0.90%) and narrower floodplain widths. The data also indicate that reduced sediment supply promoted the genesis of that channel pattern also outside of the sediment-limited NE-Alps (Figure S5b).

The above-described examples show that the observed distribution of historical channel patterns in the Alps cannot be explained primarily by differing lithological conditions and sediment availability (compare Notebaert & Piégay, 2013). Other controls related to Alpine tectonic structure, such as valley confinement, topography (altitude, steepness), (former) occurrence of glaciated areas or vegetation cover, probably had more influence on the morphological configuration of the Alpine rivers in the early 19th century. In this respect, discontinuum concepts are more meaningful than continuum concepts to explain the regional occurrence of channel patterns (Poole, 2002).

Evaluating all 16,590 river sectors independently for whether subsequent reaches show the same channel pattern or not yields an almost textbook-like longitudinal sequence (compare Figure 1 and Figure 5c). Focusing solely on the channel pattern changes yields more informative insights into the longitudinal sequence. Rivers flowing in the straighter longitudinal valley furrows featured a significantly different sequence than rivers in other, mostly shorter and/or more sinuous valleys (see Figure S6). Independent of the valley type, channel pattern changes occurred at the following median distances from the source: confined (20 km), sinuous (22 km), oscillating (29 km), multi-channel (33 km), meandering (43 km) and, finally, incised meanders (47 km). Accordingly, 50% of the channel changes into multi-channel patterns, for example, occurred closer than 33 km to the source. This "synthesized channel pattern sequence" of all large Alpine rivers highlights that no clear downstream gradient in valley width and channel slope was evident. Channel form changes occurred particularly frequently after rivers traversed a steep and narrow valley. At the next lower valley floor, they often returned to the channel pattern they featured upstream of the steep valley (compare Figure 8). Confluences of large tributaries can be another cause for discontinuities in channel patterns (Bravard, 2010; Brierley & Fryirs, 2005; Liébault, Piégay, Frey, & Landon, 2008). The historical sources reveal that several bedload-abundant tributaries amplified the braiding intensity of the main stem. With increasing downstream distance to the confluence, the deposition processes and, therefore, the braiding intensity were gradually reduced.

The scheme of channel pattern types from the steep headwater to the lowland illustrated in Figure 1 provides a generalized perspective, one that was rarely met in nature. It potentially applies for rivers in valleys that are not affected by major tectonic faults with uplift/subsidence processes, do not stretch across several lithological zones, and that were largely homogeneously shaped by glaciers. In most cases, such conditions apply only for individual river sections but not for whole courses. In particular, longer Alpine rivers run through "polygenetic valleys"—several valley fragments that were pieced

together as a consequence of Alpine orogeny and glacial reshaping (Fiebig et al., 2019). Such "inherited landscapes" commonly feature discontinuities related to transitions between various physiographic zones rather than smoothly declining valley floors (Notebaert & Piégay, 2013). Thus, longitudinal profiles of Alpine valleys typically show several stepwise declining valley floors (Hohensinner et al., 2019). The channel pattern in each of these valley floors integrates both the upstream physical controlling factors and the local geomorphic setting.

5.3 | Regional and longitudinal differences in human modifications

From a modern viewpoint, it appears appropriate to consider waterbodies before the era of industrialization as "near-natural" or fairly natural in term of riverscape features—but by no means pristine. The channel geometry and bedload delivery of the rivers of the Alpine arc have been changed by humans for centuries—by local regulation, the construction of weirs and mills, as well as by deforestation, farming and overgrazing in the catchment. Climate-caused water flow fluctuations and sediment delivery due to associated basin vegetation adjustment have also led to significant morphological changes (see Section 2; Petts, Möller, & Roux, 1989; Mauch & Zeller, 2008).

Three forms of severe human interventions into channel morphology took place between the early 19th and early 21st century: linear river straightening of alluvial river sections resulting in straight and monotonous canals, less rigorous straightenings in the form of arch-shaped regulations, and the transformation of river reaches to different kinds of reservoirs. As illustrated by Figure 4, confined channels were least affected from the early 19th century until today: they are more frequently located in the upper reaches in deeply incised Alpine valleys, where minimal human demands meant less regulation. Human interventions primarily affected sections more distant from the source (see Figure 5c; arrow refers to the median longitudinal location of identified human channel modifications along formerly confined river sections). In almost all cases, the construction of large dams or smaller run-of-river power plants with reservoirs was the cause for the transformation of confined channels. In contrast, meandering rivers were subject to the most intensive human pressure because they are usually located in wider, fertile valley floors that are particularly attractive for intensive agriculture or new settlements. Along formerly meandering rivers, no significant upstream–downstream focal points of human interventions are evident (see arrow in Figure 5c). In contrast, historically oscillating, braiding or sinuous river reaches were primarily human transformed in more downstream sections. This is even more valid for incised meanders: they were largely modified downstream for hydro-energetic use. These findings support the notion of increasing downstream intensities of human pressures on river systems (Gurnell et al., 2009; Muhar et al., 2019; Schinegger, Trautwein, Melcher, & Schmutz, 2012). In downstream reaches, adjoining land can be more intensively used and the local and regional socio-

economic demands gain weight (Haidvogl et al., 2019; Tockner, Pusch, Borchardt, & Lorang, 2010).

Altogether, dam and reservoir construction affected at least 12% of the total historical length of the large Alpine rivers. This represents a rough estimate because delineating dammed-up reaches involves methodological pitfalls. While their downstream end is clearly marked by the dam or weir, the transition to the lotic stretch upstream usually lacks clear boundaries. The relatively dynamic stretches at the head of a reservoir are often poorly recognizable as part of the reservoir based on orthophotos. Moreover, several smaller reservoirs not visible in the orthophotos might not have been identified as such. Importantly, a considerably greater number of weirs and impoundments are located on brooks and smaller rivers, where the construction of hydropower stations is less likely to interfere with other human interests. River reaches downstream of reservoirs are usually heavily affected by water abstraction (residual water), reduced sediment supply and truncated fluvial dynamics (Ward & Stanford, 1995). For example, the entire Swiss stretch of the Rhone is seriously affected by hydropower plants, even in its undammed reaches (Costa, 2018).

According to Muhar et al. (2019), Alpine-wide at least 23% of all rivers with catchments larger than 10 km^2 are severely modified today. In comparison, the present study shows that arched regulated, linear straightened and dammed-up sections amount to 45% of the large Alpine rivers. Importantly, this includes only morphological modifications, such as river straightening, damming and artificial channel narrowing. Accordingly, large rivers suffered a much higher intervention intensity than smaller catchments. Considering also human interventions into river flow, 72% of the Alpine rivers with catchments between 500 and 1,000 km^2, and 86% of those larger than 1,000 km^2 are severely affected today. The present study, however, did not examine hydrological alterations.

The different countries historically followed different paths of land use management and river training. This is reflected in varying forms and intensities of human pressure across the Alpine sphere (Haidvogl et al., 2019). Within the six countries examined, the large Alpine rivers in Austria, Germany and Switzerland are most severely affected (see Section 4). The hydraulic engineering practices differed substantially in France and Italy, where the rivers were less intensively channelized. Those two countries, therefore, show the highest proportions of rivers remaining in a more natural state. Nevertheless, most of them are more or less severely affected by artificial channel narrowing, water abstraction, gravel dredging or other interventions contributing to channel incision.

These country-wise differences reflect varying socio-economic pressures and political decisions regarding the use of the Alpine rivers. Since the late 19th century, great proportions of the rural population in the French and Italian Alps have moved to larger cities (Bätzing, Perlik, & Dekleva, 1996; Comiti, 2012). This might be a reason why France and Italy invested less in local river training. The strategy in the other countries was different: systematic regulation programmes were implemented beginning in the 19th century in order to secure arable land or to reclaim new land in the valley bottoms. This required

large-scale corrections and stabilization of the river courses (Baumann, 1960; K. Oberste Baubehörde, 1888).

The major reduction of braided rivers in the French Alps (by 53%; Piégay et al., 2009) is largely reflected by the present study, which yielded a loss of 47%. Taking potential channel classification errors along with newly originated braided reaches at other river sections into account yields a net loss of 40%. One potential explanation for the different values is that our study omitted smaller rivers and differently classified wandering gravel-bed rivers. The GIS analysis revealed a significant narrowing of braided channels at larger rivers in the French and Italian Alps, as also reported by Piégay et al. (2009) and Surian et al. (2009). In some stretches, channel narrowing was caused by hydraulic constructions (embankments or levees). In others, no constraining constructions were visible but can be assumed at least locally. Upstream sediment retention, land cover changes or gravel dredging were contributing or even dominant causes behind that narrowing process (Surian & Cisotto, 2007). According to Surian et al. (2009), channel narrowing and incision drastically altered channel patterns, leading to wandering or single-channel rivers in several originally braided reaches. Channel incision may also have led to self-constraining within the formerly broader river bed. Based on the channel pattern types distinguished here, this would mean that formerly multi-channel sections have turned into oscillating or sinuous single-channel ones. Our data show approx. 210 km of such transformations in the French and Italian Alps, corresponding to 9% of the formerly large braided river length there. Accordingly, multiple channel decline is linked not only to sectional training of river courses but partly also (up to between 5 and 10% depending on the country) to significant reductions in bedload supply inducing channel planform changes from multi- to single-bed channels.

6 | CONCLUSION

This study provides a first methodologically coherent census of channel pattern types in the entire Alpine sphere before the Industrial era, that is, the onset of systematic river regulation programmes. Based on the compiled dataset, we draw new conclusions about the large-scale characteristics of Alpine rivers:

(1) In the early 19th century, one-third of the 143 largest Alpine rivers (total length of 11,870 km) featured multi-channel (braided) sections. Oscillating rivers, a channel type typically not explicitly addressed in river classification schemes, made up the second highest share (28%). The Eastern Alps featured significantly higher proportions of sinuous and meandering river reaches than the rest of the Alps. These reflect a regionally lower sediment supply and certain tectonically glacially shaped valley forms. This demonstrates that the complex geological and tectonic configuration of the Alpine arc fosters a regionally and country-wise varying pattern of channel forms.

(2) Textbook-like sequences of channel patterns along the river courses (Figure 1) were rarely met. Channel planforms were significantly influenced by the physiographic conditions in the basins, that is, by their orogenetic and glacial background and the associated valley width. Nevertheless, confined, oscillating and all unconfined alluvial channel types combined generally followed a distinct upstream–downstream gradient (i.e., distance from source, channel slope and valley width). Most parts of the Alps provide abundant sediments but show certain transport-limited river sections characterized by wider valley bottoms and lower channel slopes. Such conditions favoured multi-channel patterns. Sinuous and, in particular, meandering reaches showed lower channel slopes and prevailed in areas with less sediment supply.

The erodibility of the geological basement and thus sediment supply were a basic factor for the evolution of distinct channel forms. Nonetheless, other factors such as the terrain relief of the catchment, (former) glaciation, land cover or valley morphology no doubt affected channel patterns more significantly.

(3) Human interventions tremendously modified the Alpine river systems. Until today, approximately 510-km-long river sections or 4.3% of their historical extent have been lost due to channel straightening. River types that once occupied large areas of the valley floors, such as braided, sinuous or meandering ones, experienced the strongest reduction. As a consequence, only 15% of the large Alpine rivers still show multiple channels. Today, 45% of the rivers are linear or arch-shaped straightened, or were transformed into reservoirs. Rivers in Austria, Germany, Switzerland, the northern French Alps and Trentino-Alto Adige (Northern Italy) suffered most from human transformation. Moreover, most of the still braided or oscillating waterbodies are, in fact, regulated. River channels have been severely narrowed for land reclamation, water is being abstracted for energy production, irrigation or water supply, and bed material is being dredged. Multi-thread channels also evolved to single-thread channels due to a modification of upstream controls (flood regime and bedload delivery).

The presented data provide a first overview over the past and current state of running waters covering the entire Alpine sphere. Further research will be necessary in order to integrate smaller river systems with catchments between 100 and 500 km^2 according to the available historical sources. Moreover, the analysis can be improved by incorporating additional controlling factors and hydro-morphological attributes.

DATA AVAILABILITY STATEMENT

Basic data are partly subject to third party restrictions. Selected data are available on request.

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REFERENCES

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P., & Feyen, L. (2013). Advances in pan-European flood hazard mapping. *Hydrological Processes*, 28(13), 4067–4077.

Amoros, C., & Petts, G. E. (1996). *Fluvial Hydrosystems*. London: Chapman and Hall.

Arnaud, F., Schmitt, L., Johnstone, K., Rollet, A.-J., & Piégay, H. (2019). Engineering impacts on the upper Rhine Channel and floodplain over two centuries. *Geomorphology*, 330, 13–27.

Asch, K. (2003). The 1: 5 million international geological map of Europe and adjacent areas: Development and implementation of a GIS-enabled concept. *Geologisches Jahrbuch*, SA 3. E. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.

Bätzing, W., Perlik, M., & Dekleva, M. (1996). Urbanization and population in the Alps. *Mountain Research and Development*, 16(4), 335–350.

Baumann, F. (1960). Vorgeschichtliches zum ostalpinen Flußbau. *Schriftenreihe des österreichischen Wasserwirtschaftsverbandes*, 42, 29–52.

Bertrand, M., Piégay, H., Pont, D., Liébault, F., & Sauquet, E. (2013). Sensitivity analysis of environmental changes associated with riverscape evolutions following sediment reintroduction: Geomatic approach on the Drôme River network, France. *International Journal of River Basin Management*, 11(1), 19–32.

BMLFUW – Bundesministerium für Land- u. Forstwirtschaft, Umwelt u. Wasserwirtschaft (2014). Hochwasserrisikozonierung Austria – HORA. Report. Vienna: BMLFUW.

Bravard, J.-P. (1989). La metamorphose des rivieres des Alpes francaises a la fin du Moyen-Age et a l'epoque moderne. *Bulletin de la Societe Geographie de Liege*, 25, 145–157.

Bravard, J.-P. (2010). Discontinuities in braided patterns: The river Rhône from Geneva to the Camargue delta before river training. *Geomorphology*, 117, 219–233.

Bravard, J.-P., & Bethemont, J. (1989). Cartography of rivers in France. In G. E. Petts, H. Möller, & A. L. Roux (Eds.), *Historical change of large alluvial rivers: Western Europe* (pp. 95–111). Chichester, England: John Wiley & Sons.

Brierley, G. J., & Fryirs, K. A. (2005). *Geomorphology and river management. Applications of the river styles framework*. Oxford: Blackwell.

Brown, A. G., Lespez, L., Sear, D. A., Macaire, J.-J., Houben, P., Klimek, K., … Pears, B. (2018). Natural vs anthropogenic streams in Europe: History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. *Earth-Science Reviews*, 180, 185–205.

Buffington, J. M., & Montgomery, D. R. (2013). Geomorphic classification of rivers. In J. Shroder & E. Wohl (Eds.), *Treatise on geomorphology. Fluvial geomorphology* (Vol. 9, pp. 730–767). San Diego, CA: Academic Press.

Chimani, B., Böhm, R., Matulla, C., & Ganekind, M. (2011). Development of a longterm dataset of solid/liquid precipitation. *Advances in Science & Research*, 6, 39–43.

Chimani, B., Matulla, C., Böhm, R., & Hofstätter, M. (2013). A new high resolution absolute temperature grid for the Greater Alpine Region back to 1780. *International Journal of Climatology*, 33, 2129–2141.

Church, M. A. (1992). Channel morphology and typology. In P. Calow & P. E. Petts (Eds.), *The rivers handbook* (Vol. 1, pp. 126–143). Oxford: Blackwell.

Church, M. A. (2002). Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, 47(4), 541–557.

Comiti, F. (2012). How natural are Alpine mountain rivers? Evidence from the Italian Alps. *Earth Surface Processes and Landforms*, 37, 693–707.

Costa, A. (2018). *Basin-scale sediment dynamics of an Alpine catchment: Understanding the impacts of hydroclimatic forcing and hydropower* (PhD thesis No. 25087). Zurich: ETH Zurich.

Desloges, J. R., & Church, M. A. (1989). Wandering gravel-bed rivers. *The Canadian Geographer*, 33(4), 360–364.

Ehlers, J., Gibbard, P. L., & Hughes, P. D. (2011). *Quaternary glaciations – Extent and chronology. A Closer Look* (Vol. 15), Amsterdam: Elsevier.

European Environment Agency (2016). European Digital Elevation Model (EU-DEM), version 1.1, compiled in the frame of the EU Copernicus programme. https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem

Fiebig, M., Hohensinner, S., & Muhar, A. (2019). The development of Alpine Rivers and valleys during earth history. In S. Muhar, A. Muhar, G. Egger, & D. Sigrist (Eds.), *Rivers of the Alps – Diversity in nature and culture* (pp. 46–55). Bern: Haupt Verlag.

Fuhrmann, S. (2007). Digitale historische Geobasisdaten im Bundesamt für Eich- und Vermessungswesen (BEV) – Die Urmappe des Franziszeischen Katasters. *Österreichische Zeitschrift für Vermessung und Geoinformation*, 1, 24–35.

Girel, J. (2008). River diking and reclamation in the Alpine Piedmont. The case of the Isère. In C. Mauch & T. Zeller (Eds.), *Rivers in history. Perspectives on waterways in Europe and North America* (pp. 78–88). Pittsburgh, PA: University of Pittsburgh Press.

Goudie, A. S., & Viles, H. A. (2016). Holocene floodplain sedimentation related to accelerated erosion. In A. S. Goudie & H. A. Viles (Eds.), *Geomorphology in the Anthropocene* (pp. 155–161). Cambridge: Cambridge University Press.

Gugerli, D., & Speich, D. (2002). *Topografien der Nation. Politik, kartografische Ordnung und Landschaft im 19. Jahrhundert*. Zurich: Chronos.

Gurnell, A., Surian, N., & Zanoni, L. (2009). Multi-thread river channels: A perspective on changing European alpine river systems. *Aquatic Sciences*, 71, 253–265.

Habersack, H., & Piégay, H. (2007). River restoration in the Alps and their surroundings: Past experience and future challenges. *Developments in Earth Surface Processes*, 11, 703–735.

Haidvogl, G., Pont, D., & Zwitter, Z. (2019). The history of human use and interference – Alpine rivers as resource and risk factor. In S. Muhar, A. Muhar, G. Egger, & D. Sigrist (Eds.), *Rivers of the Alps – Diversity in nature and culture* (pp. 36–45). Bern: Haupt Verlag.

Hauer, C., Wagner, B., Schober, B., Haun, S., Noack, M., Haidvogl, G., … Habersack, H. (2019). Floods and flood protection. Past events and future strategies. In S. Muhar, A. Muhar, G. Egger, & D. Sigrist (Eds.), *Rivers of the Alps – Diversity in nature and culture* (pp. 238–247). Bern: Haupt Verlag.

Hinderer, M., Kastowski, M., Kamelger, A., Bartolini, C., & Schlunegger, F. (2013). River loads and modern denudation of the Alps – A review. *Earth-Sciences Reviews*, 118, 11–44.

Hohensinner, S., Becsi, R., Egger, G., Fiebig, M., Knopper, F., Muhar, A., & Piégay, H. (2019). The many faces of Alpine rivers. In S. Muhar, A. Muhar, G. Egger, & D. Sigrist (Eds.), *Rivers of the Alps – Diversity in nature and culture* (pp. 86–111). Bern: Haupt Verlag.

Hohensinner, S., Jungwirth, M., Muhar, S., & Schmutz, S. (2011). Spatiotemporal habitat dynamics in a changing Danube River landscape 1812-2006. *River Research and Applications*, 27, 939–955.

Hohensinner, S., Sonnlechner, C., Schmid, M., & Winiwarter, V. (2013). Two steps back, one step forward: Reconstructing the dynamic Danube riverscape under human influence in Vienna. *Water History*, 5(2), 121–143.

Jacob, J., Disnar, J.-R., Arnaud, F., Gauthier, E., Billaud, Y., Chapron, E., & Bardoux, G. (2009). Impacts of new agricultural practices on soil erosion during the Bronze Age in the French Prealps. *The Holocene*, 19(2), 241–249.

Jarman, M. R., Bailey, G. N., & Jarman, H. N. (1982). *Early European agriculture. Its foundation and development*. Cambridge: Cambridge University Press.

K. Oberste Baubehörde im Staatsministerium des Innern. (1888). *Der Wasserbau an den öffentlichen Flüssen im Königreich Bayern*. Munich: Max Kellerer's h. b. Hof-Buch-u. Kunsthandlung.

Koblet, R. (1995). 5.5 Influence of civil engineering on rivers and lakes. In University Bern & Bundesamt für Umwelt (Ed.), *Hydrological Atlas of Switzerland (HADES)*. Bern: University Bern.

Kondolf, G. M., Montgomery, D. R., Piégay, H., & Schmitt, L. (2016). Geomorphic classification of rivers and streams. In M. Kondolf & H. Piégay (Eds.), *Tools in fluvial geomorphology* (2nd ed., pp. 133–158). Chichester, England: John Wiley & Sons.

Lane, E. W. (1955). The importance of fluvial morphology in hydraulic engineering. Proceedings of the American Society of Civil Engineers, 81, paper no. 745.

Lefort, J. (2004). *L'aventure cartographique*. Paris: Belin Pour la science.

Liébault, F., & Piégay, H. (2002). Causes of 20th century channel narrowing in mountain and Piedmont rivers of Southeast France. *Earth Surface Processes and Landforms, 27*, 425–444.

Liébault, F., Piégay, H., Frey, P., & Landon, N. (2008). Tributaries and the management of main-stem geomorphology. In S. P. Rice, A. G. Roy, & B. L. Rhoads (Eds.), *River confluences, tributaries and the fluvial network* (pp. 243–270). Chichester, England: John Wiley & Sons.

Marchese, E., Scorpio, V., Fuller, I., McColl, S., & Comiti, F. (2017). Morphological changes in Alpine rivers following the end of the Little Ice Age. *Geomorphology, 295*, 811–826.

Martinet, F., & Dubost, M. (1992). Die letzten naturnahen Alpenflüsse. *CIPRA, Kleine Schriften, 11*, 10–58.

Mauch, C., & Zeller, T. (2008). *Rivers in history: Perspectives on waterways in Europe and North America*. Pittsburgh, PA: University of Pittsburgh Press.

Mueller, E. R., & Pitlick, J. (2013). Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate. *Journal of Geophysical Research: Earth Surface, 118*, 2325–2342.

Mueller, E. R., & Pitlick, J. (2014). Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions. *Journal of Geophysical Research: Earth Surface, 119*, 1516–1541.

Muhar, S., Grüner, B., Böck, K., Scheikl, S., & Becsi, R. (2018). *SPARE synthesis report: "Balancing river protection needs, ecosystem functions and human uses"*. European Regional Development Fund (ERDF) – Interreg Alpine Space, 31. Vienna: University of Natural Resources and Life Sciences.

Muhar, S., Kainz, M., Kaufmann, M., & Schwarz, M. (1996). *Ausweisung flusstypspezifisch erhaltener Fließgewässerabschnitte in Österreich – österreichische Bundesgewässer*. Vienna: BMLF & Wasserwirtschaftskataster.

Muhar, S., Kainz, M., & Schwarz, M. (1998). *Ausweisung flusstypspezifisch erhaltener Fließgewässerabschnitte in Österreich – Fließgewässer mit einem Einzugsgebiet >500 km² ohne Bundesflüsse*. Vienna: BMLF, BMUJF & Wasserwirtschaftskataster.

Muhar, S., Schwarz, M., Schmutz, S., & Jungwirth, M. (2000). Identification of rivers with high and good habitat quality: Methodological approach and applications in Austria. *Hydrobiologia, 422*(423), 343–358.

Muhar, S., Seliger, C., Schinegger, R., Scheikl, S., Brändle, J., Hayes, D. S., & Schmutz, S. (2019). Status and protection of rivers: A pan-Alpine review. In S. Muhar, A. Muhar, G. Egger, & D. Sigrist (Eds.), *Rivers of the Alps – Diversity in nature and culture* (pp. 302–319). Bern: Haupt Verlag.

Müller, N. (1991). Auenvegetation des Lech bei Augsburg und ihre Veränderungen infolge von Flussbaumaßnahmen. *Augsburger Ökologische Schriften, 2*, 79–108.

Müller, N. (1995). River dynamics and floodplain vegetation and their alterations due to human impact. *Archiv für Hydrobiologie Supplement, 101*, 477–512.

Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms, 21*, 217–239.

Natural Earth (2011). *Free vector and raster map data at 1:10m, 1:50m, and 1:110m scales*. https://www.naturalearthdata.com

Notebaert, B., & Piégay, H. (2013). Multi-scale factors controlling the pattern of floodplain width at a network scale: The case of the Rhône basin, France. *Geomorphology, 200*, 155–171.

Petts, G. E., Möller, H., & Roux, A. L. (1989). *Historical change of large alluvial rivers: Western Europe*. Chichester, England: John Wiley & Sons.

Piégay, H., Alber, A., Slater, L., & Bourdin, L. (2009). Census and typology of braided rivers in the French Alps. *Aquatic Sciences, 71*(3), 371–388.

Pont, D., Piégay, H., Farinetti, A., Allain, S., Landon, N., Liébault, F., … Richard-Mazet, A. (2009). Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: The case of the Drôme River basin (S.E. France). *Aquatic Sciences, 71*(3), 356–370.

Poole, G. C. (2002). Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. *Freshwater Biology, 47*(4), 641–680.

Schinegger, R., Trautwein, C., Melcher, A., & Schmutz, S. (2012). Multiple human pressures and their spatial patterns in European running waters. *Water and Environmental Journal, 26*, 261–273.

Surian, N., & Cisotto, A. (2007). Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy. *Earth Surface Processes and Landforms, 32*, 1641–1656.

Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L., Turitto, O. & Ziliani, L. (2009). Channel adjustments in Northern and Central Italy over the last 200 years. *The Geological Society of America*, Special Paper *451*, 83–95.

Thorp, J. H., Thoms, M. C., & Delong, M. D. (2006). The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. *River Research and Applications, 22*(2), 123–147.

Tinner, W., Lotter, A. F., Ammann, B., Conedera, M., Hubschmid, P., van Leeuwena, J. F. N., & Wehrli, M. (2003). Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. *Quaternary Science Review, 22*(14), 1447–1460.

Tockner, K., Pusch, M., Borchardt, D., & Lorang, M. S. (2010). Multiple stressors in coupled river-floodplain ecosystems. *Freshwater Biology, 35*(1), 135–151.

Vischer, D. (1989). Impact of 18th and 19th century river training works: Three case studies from Switzerland. In G. E. Petts, H. Möller, & A. L. Roux (Eds.), *Historical change of large alluvial rivers: Western Europe* (pp. 19–40). Chichester, England: John Wiley & Sons.

Vogt, J., Soille, P., de Jager, A., Rimaviciute, E., Mehl, W., Foisneau, S., … Bamps, C. (2007). A pan-European river and catchment database. EC Joint Research Centre, Report EUR 22920 EN, Luxembourg.

Ward, J. V., & Stanford, J. A. (1995). The serial discontinuity concept: Extending the model to floodplain rivers. *Regulated Rivers: Research & Management, 10*, 159–168.

Ward, J. V., Tockner, K., Edwards, P. J., Kollmann, J., Bretschko, G., Gurnell, A. M., … Rossaro, B. (1999). A reference river system for the Alps: The "Fiume Tagliamento". *Regulated Rivers: Research & Management, 15*, 63–75.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.