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Channel changes of the Adige River (Eastern Italian Alps) over the last 1000 years and identification of the historical fluvial corridor

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ABSTRACT
A 1:50,000-scale geomorphological map of the Adige/Etsch River valley bottom (NE Italy) is presented. The study area is 115 km long, and it extends between the villages of Merano/Meran and Calliano, including also the terminal segments of 9 major tributaries of the Adige River. Presently, the Adige shows a sinuous to straight morphology owing to massive channelization occurred during the nineteenth century. Fluvial geomorphological features have been mapped through a detailed-scale comparative multi-temporal analysis carried out on several historical maps dating since the eighteenth century, previous thematic maps, geological maps of the Italian 'CARG' project, orthophotos (2011) and high – resolution DEMs. The map shows the active river channel, dating to 1803–1805 (before channelization), to 1856-1861 (during channelization) and under present conditions, as well as several paleo-channels dating up to the thirteenth century. The analysis led to define the corridor of historical channel changes, a fundamental tool for river management purposes.

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Paleo-channels; channel pattern; planform changes; valley bottom mapping; historical map; river management

1. Introduction

Many studies have analyzed the planform modifications of European rivers over a timescale of decades or centuries and most of them documented remarkable channel changes from the late nineteenth or early twentieth century onwards (Arnaud et al., 2015; Aucelli, Fortini, Rosskopf, Scorpio, & Viscosi, 2011; Comiti et al., 2011; Kiss & Blanka, 2012; Latapie et al., 2014; Ollero, 2010; Provansal et al., 2014; Rădoane, Obreja, Cristea, & Mihailă, 2013; Rovira, Batalla, & Sala, 2005; Scorpio et al., 2015; Surian, Ziliani, Comiti, Lenzi, & Mao, 2009; Zawiejska & Wyzga, 2010). Recently, some studies have analyzed the channel evolution by coupling the reconstruction of its evolutionary trajectory and the analysis of possible controlling factors (David, Labenne, Carozza, & Valette, 2016; Scorpio & Rosskopf, 2016; Serlet et al., 2018; Ziliani & Surian, 2012).

Although geomorphological maps are considered as valuable tools providing essential support to river and floodplain management (Wheaton et al., 2015), to date in Italy a limited number of maps have been proposed to analyze geomorphological modifications of a valley bottom (Furlanetto & Bondesan, 2015; Magliulo & Cusano, 2016; Piacentini, Urbano, Sciarra, Schipani, & Miccadei, 2016; Rosskopf & Scorpio, 2013). Indeed, geomorphological mapping of paleo-channels sets a baseline to analyze the evolution of alluvial plains, especially for the identification of fluvial morphodynamic corridors (Rinaldi, Gurnell, et al., 2015), an essential tool for flood hazard prediction when coupled with hydraulic simulation for mapping inundation areas. Quantitative, spatially explicit information of areas that could be affected by channel dynamics is particularly valuable in heavily managed floodplain areas, where the signature of its past morphodynamics has been largely obscured by anthropic activities.

This study is focused on the Adige (Etsch in German) River, the second longest river in Italy. Currently, the Adige features a straight to sinuous pattern and an average channel width of 58–82 m (Scorpio et al., 2018). Similarly to other large rivers in the Alps and in Central Europe (Adami, Bertoldi, & Zolezzi, 2016; Eschbach et al., 2018; Hohensinner, Habersack, Jungwirth, & Zauner, 2004; Kiss, Balogh, Fiala, & Sipos, 2018; Zawiejska & Wyzga, 2010), the Adige River was subjected to massive channelization works during the nineteenth century, to ensure flood protection, to reclaim agricultural land, and to facilitate navigation and terrestrial transportation. The Adige boasts the availability of a huge number of accurate large scale historical maps (Mastronunzio & Dai Prà, 2016a, 2016b; Scorpio et al., 2018) – besides earlier paintings

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and subsequent aerial photos – covering most of its valley bottom, thereby offering a robust opportunity to identify its morphodynamic corridors through sequential information covering a long time period. The Adige River represents an ideal case-study to reconstruct channel dynamics of a large Alpine River over the last 1000 years.

This paper presents a geomorphological map of a 115 km long segment of the Adige valley bottom in NE Italy and, through its analysis, specifically aims to: (1) assess the planform characteristics of paleo-channels over approximately the last 1000 years; (2) reconstruct channel adjustments during the channelization; (3) assess how channel morphology has changed over the investigated period; (4) delineate the historical river corridor in the framework of an integrated river management, in the perspective of matching flood risk mitigation with environmental restoration.

2. Study area

The Adige River flows to the Adriatic Sea, crossing the Eastern Italian Alps and the Po Plain, with a length of 410 km. Its catchment is 12,200 km^2 in area, and is mainly composed of gneiss, micaschists and porphyric rocks in the upper part, limestone and dolomites in the medium part, and alluvial deposits in the lower part.

The mean annual precipitation ranges between 400 and 900 mm within the catchment (Adler et al., 2015). Minimum annual discharge is 235 m^3/s, at the outlet into the Adriatic Sea, occurring in winter, and increasing in spring and summer owing to snow and glacier melting. Most large floods tend to occur in autumn (Zolezzi, Bellin, Bruno, Maiolini, & Siviglia, 2009).

The analyzed valley sector crosses the upper part of the catchment, and extends from the city of Meran/Merano (Autonomous Province of Bolzano/South Tyrol) to the village of Calliano (Autonomous Province of Trento), with a total length of about 115 km (Figure 1).

At Calliano, the catchment drains an area of 11,400 km^2. Channel elevation ranges from 295 to 170 m a.s.l. The valley bottom has an average width of 1.5–2 km, and it is bordered by steep slopes, mainly due to fluvial and glacial erosion during the Pleistocene, or by alluvial fans built by tributaries.

Along the study segment, several tributaries flow into the Adige River, developing alluvial fans of different sizes. Main Tributaries are the Passirio/Passer-Bach, Valsura/Falschauerbach, Rio di Nova/Naifbach, Talvera/Talfer-Bach, Isarco/Eisack-Fluss, Noce/Ultz, Avisio, Fersina and Rio Cavallo/Rosskopf-Bach (Figure 1). The lowermost reaches of these tributaries crossing their alluvial fans onto the Adige valley bottom were included in this study.

3. Methods

The geomorphological map focuses on fluvial forms, mainly on paleo-channels, inferred on the basis of a multi-temporal analysis conducted on historical

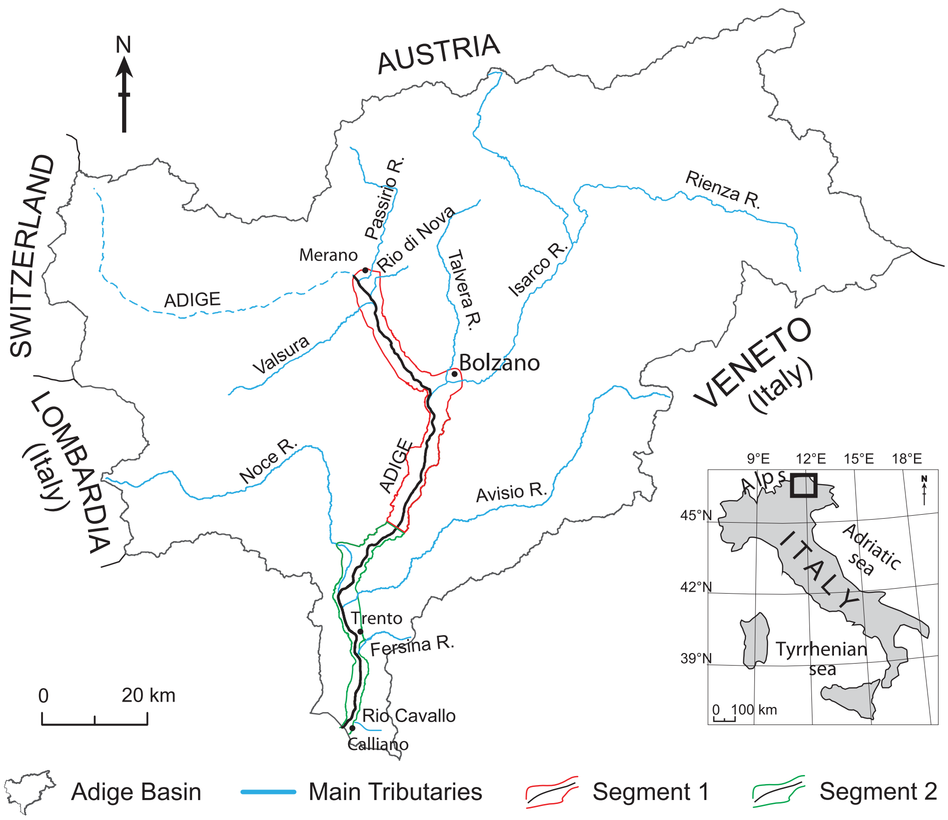


Figure 1. Location of the studied Adige River segments and of the analyzed tributaries.

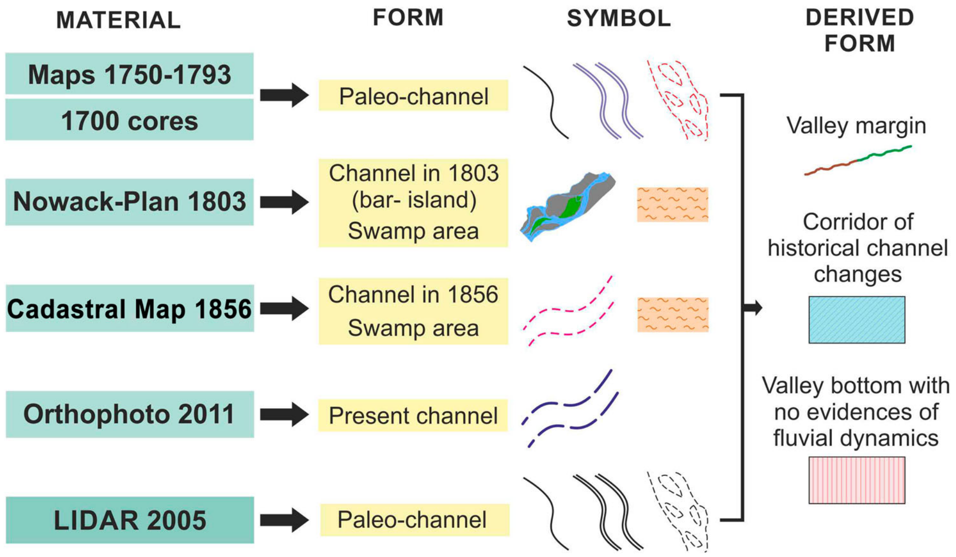


Figure 2. Flow-chart showing methodology and materials adopted in the study.

topographic maps, orthophotos, high-resolution digital elevation models (DEMs), geological maps and geological surveys. The overall methodology and materials used to map channels and paleo-channels are graphically summarized in Figure 2.

Cartographic materials covering the entire valley bottom from Merano to Calliano were: two sets of historical maps dating 1803–1805 and 1856–1861, a set of orthophotos from 2011 and DEMs provided by the Autonomous Provinces of Bolzano (Ufficio Informatica Geografica e Statistica) and Trento (www.territorio.provincia.tn.it/portal/server.pt/community/lidar/847/lidar/23954) derived from LiDAR surveys carried out in 2013 and 2007, respectively. DEMs have a spatial resolution of 2.5 m per pixel. The analysis took advantage of a number of historical maps dating from 1750 to 1861, mostly retrieved within the ETSCH-2000 project in several historical archives and, in more limited portions, shown in Werth (2014).

Two sets of historical maps dating 1803–1805 (scale 1: 3,456; 'Nowack-Plan' surveyed by the Austro-Hungarian empire, hereafter and in the map: 1803) and 1856–1861 (scale 1: 2880; Cadastral map; hereafter and in the map: 1856) (Figure 3) have been retrieved from the Tiroler Landesarchiv (Innsbruck, Austria) and from the Tiroler Landesmueum Ferdinandeum (Innsbruck, Austria), respectively. They were digitized using flatbed cold-light scanner in multi-resolution format. The Nowack map (1803) was then rectified in a GIS environment using the historical cadastral map of 1856 as reference map, as this was provided already in UTM-ETRS89 coordinates by the Autonomous Province of Bozen/Bolzano and the Autonomous Province of Trento (see Scorpio et al., 2018). Root mean square position errors (RMSE) of residuals were in the order of 1–9 m as for the map of 1803 and 6–27 m as for the map of 1856. Older maps (1750–1793), often portraying localized and limited sectors of the Adige Valley were not georeferenced, but only consulted in comparison with the other maps (1803 and 1861) and the DEMs.

Active channels, bars and islands were digitized as they were mapped in 1803. Bare alluvial sediments included within the channel were classified as bars, while vegetated fluvial deposits were classified as islands. Channel banks were edited for active channel in 1856 and 2011. DEMs and contour lines interpretation supported the mapping and allowed the identification of a number of paleo-channels that date back before 1803 (Figure 4). In addition to the official geological map of the Italian Geological Survey 1:50,000, the analysis took advantage of the digital database of the geological map 1:10,000 of the 'CARG' project (sheet 013 Merano, 026 Appiano, 043 Mezzolombardo) provided by the 'Ufficio Geologia e prove materiali' of the Autonomous Province of Bolzano-Bozen. Besides, some paleo-channels could be dated by comparison with historical maps surveyed before 1803 (maps in 1750–1793) or by consulting descriptions, pictures and paintings referring to the Adige valley as reported in Werth (2014), which allowed us to identify channels active before the 1750s. All the mapped channel features are summarized in Table 1.

Mapping was performed according to state-of-art fluvial geomorphological mapping methods (Brancaccio et al., 1994; Rinaldi, Surian, Comiti, & Bussettini, 2013; Wheaton et al., 2015). The classification proposed by Rinaldi et al. (2013) and Rinaldi, Surian, Comiti, and Bussettini (2015), was adopted to classify the channel pattern, as: braided, anabranching, wandering, sinuous with alternate bars, sinuous, meandering and straight.

Depending on the clarity of their footprints, paleo-channels were mapped indicating both banks or only reporting their centerline.

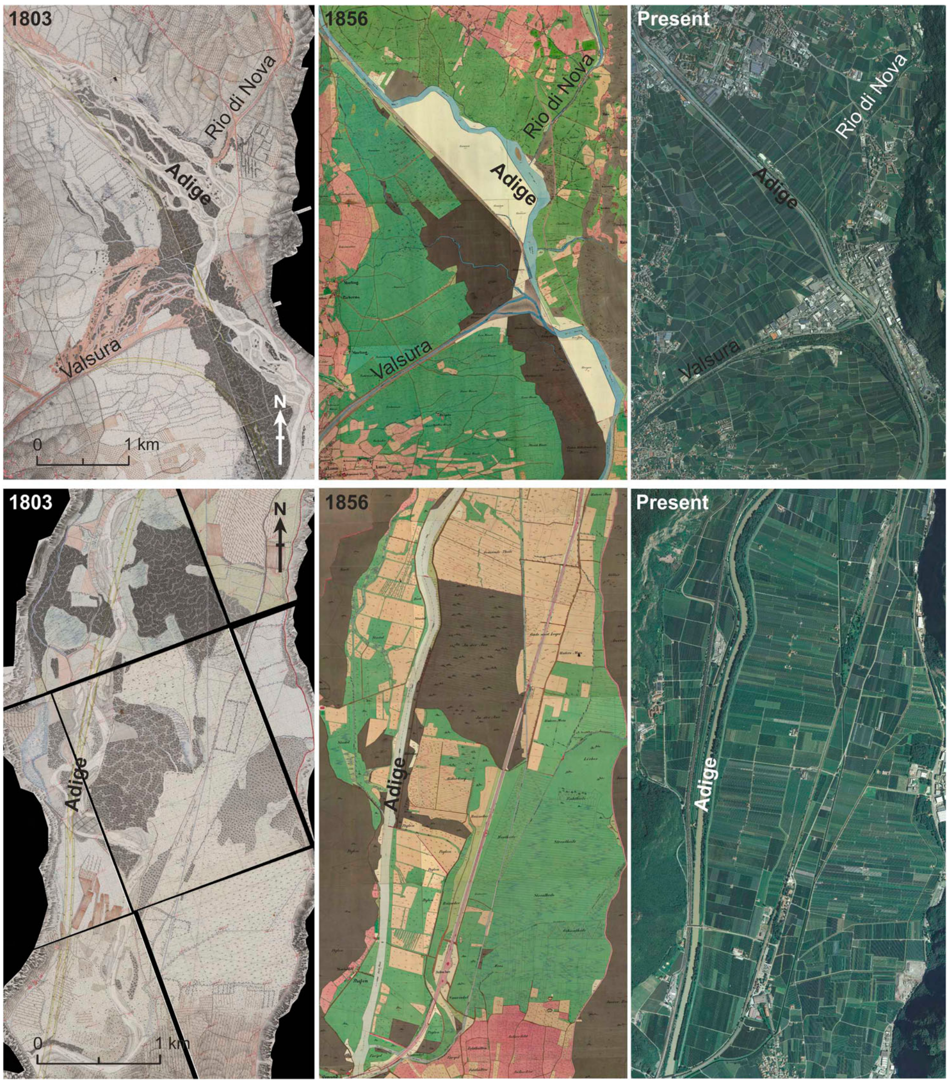


Figure 3. Examples of the historical maps and recent orthophotos used in the analysis. Upper panel refer to the uppermost area of Segment 1, while lower panels refer to the reach just downstream cross-section C-C′, also in Segment 1. Archives for maps: Tiroler Landesarchiv, Innsbruck, Austria (Nowack, 1803 map); Tiroler Landesmueum Ferdinandeum, Innsbruck, Austria), Cadastre Service, Autonomous Province of Trento and Cadastre Dept., Autonomous Province of Bolzano, Italy (Cadastral map, 1856 map); Autonomous Provinces of Bolzano and Trento (orthophotos 2011).

A geodatabase was associated to every mapped form. As to paleo-channels, the attributes table contains: morphology, the age of activity, source for channel identification and interpretation (map, DEM, orthophoto).

A multi-temporal analysis was performed in a geographic information system using the ESRI ArcGIS 10.4 software. Channel changes occurring over approx. the last 1000 years were identified by overlaying the geomorphologic layers referring to different periods. The approach was based on overlaying historical positions of channels, and considering the position of paleo-channels, using GIS analysis, as described by Piégay, Darby, Mosselman, and Surian (2005) and Rinaldi, Gurnell, et al. (2015). The historical river corridor was defined by examining the channel position and its shifting over such period.

Moreover, identification of historical river corridor elements took advantage of consulting more than 1700 borehole data collected by the Autonomous Province of Bolzano-Bozen (Ufficio Geologia e prove materiali) and by the Autonomous Province of Trento (Servizio Geologico, Ufficio Studi Sismici e Geotecnici). Such geological information allowed us to reconstruct the valley floor stratigraphy and the occurrence of gravel and sand deposits characterizing channels and floodplains.

Other mapped geomorphological features in the valley floor were: present valley bottom margins, fans, swamps and portions of the valley bottom with no evidence of historical fluvial dynamics. According to Wheaton et al. (2015), the valley bottom margin were defined as the margins between a bedrock hillslope, or colluvial deposits or fans and the alluvial sediment stores that make up the valley floor. In the Main Map, the valley bottom margin was classified as in contact with the bedrock (in brown), with talus, glacial and other Quaternary deposits (in orange), or in contact

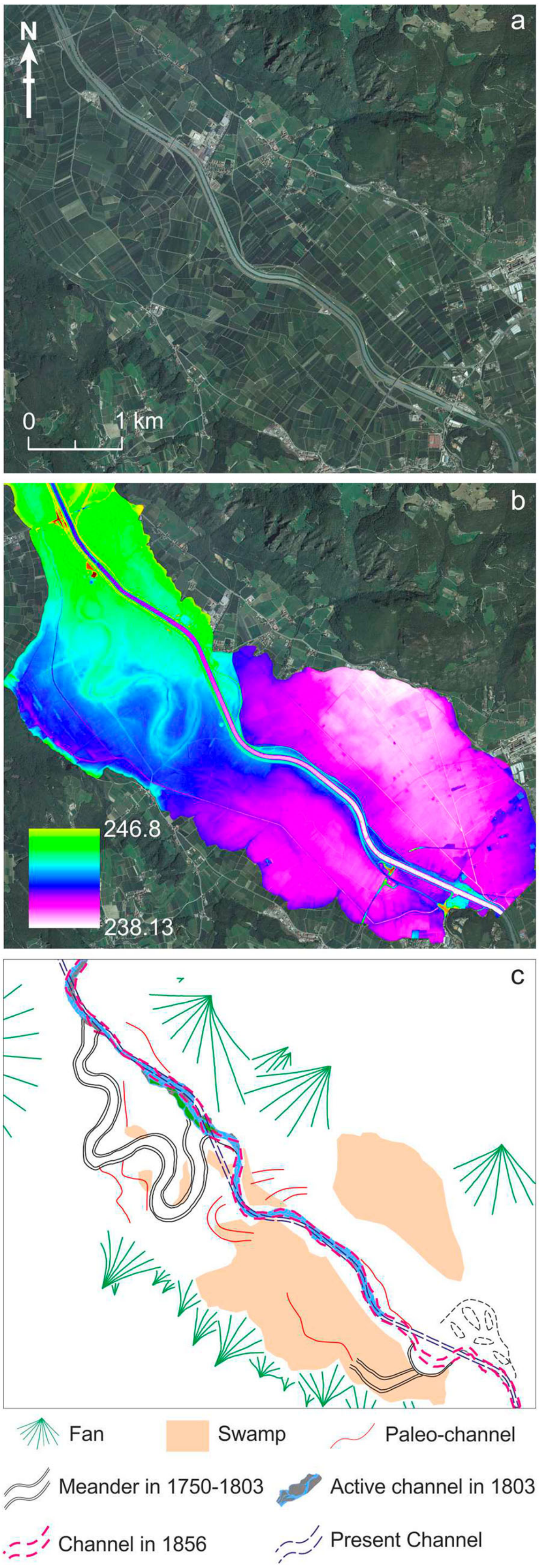


Figure 4. Example of mapping showing the Adige River valley bottom in the segment between Andriano and Bolzano (Segment1). (a) Orthophotos 2011, pattern of cultivated fields allows to recognize traces of paleo-channels. (b) Use of DEM: paleo-meanders are evident as well as two swamps areas (different shade of pink and white colors). (c) Geomorphological map, which includes also information from historical maps.

with fans (in green). Scarps related to processes of channel migration and lateral erosion were also mapped. Areas not showing clear evidences of historical fluvial dynamics are those where neither signs of paleo-channels were recognized nor geological cores report deposits such as gravels and sands characterizing active channels of the Adige River. Alluvial fans, debris-flow fans and fans of mixed origin (featuring both fluvial and debris-flow processes) were mapped with the same symbol because they fall outside of the historical river morphodynamic corridor and their detailed classification does not represent the main focus of this study. Swamp areas were mapped as those reported as active in the 1803 and 1856 historical maps (Figures 2 and 4).

Original mapping was carried out at very detailed scale (about 1:2000), whereas the final map was reduced to a scale of 1:50,000 and divided into two segments (Segment1 and Segment 2 in the Main Map and Figure 1). Segment 1 refers to the sector of the Adige valley floor lying within the territory of the Aut. Province of Bolzano-Bozen, and Segment 2 represents the Adige valley floor located within the Aut. Province of Trento. All geomorphic features were projected on a hillshade map derived from DEMs. Eleven cross-sections oriented perpendicular to the valley and a channel longitudinal profile were extracted from the DEMs, and are shown in the Main Map.

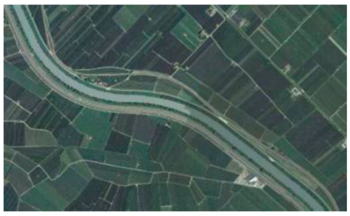
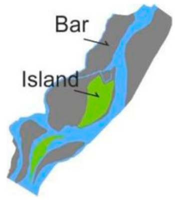
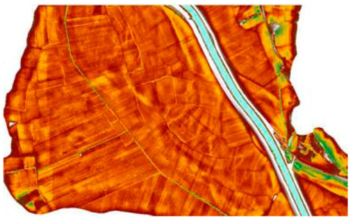
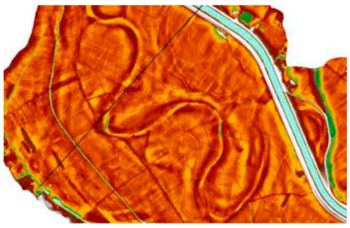
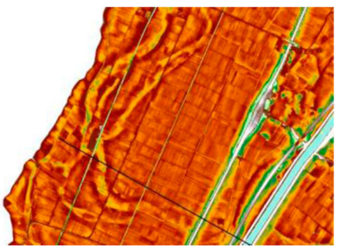
4. Results

4.1. Geomorphic features

The main focus of Main Map is the fluvial landforms related to the Adige River dynamics.

Paleo-channels active before 1803 were mapped considering their morphology and, when possible, the time span during which they were active (Table 1). Different colors were used to distinguish paleo-channels of different ages. In particular, paleo-channels active between 1200 and 1400 are shown in violet, paleo-channels active between 1500 and 1750 in yellow, and paleo-channels active between 1750 and 1803 are reported in black (see Main Map). Paleo-channels with unknown age are represented in red. All the recognized paleo-channels were mapped, including those with unknown age, because of their relevance for the delineation of the historical river corridor (see below). Paleo-channels were also characterized in relation to their prevailing channel morphology. Their morphology was classified as: 'single-thread', when characterized by a sinuous or meandering pattern; 'multi-thread' when showing evidences of braiding, wandering and anabranching morphology; as 'unknown morphology', when it was not possible to detect a clear and unambiguous pattern (Table 1 and Main Map). Anabranching reaches were

Table 1. Channels and paleo-channels definition.

Form	Description	Example	Symbol
Present channel	Delimitation of channel banks from the most recent available orthophotos (2011)		
Channel in 1856	Delineation of channel banks from the Cadastral map (1856)		
Channel in 1803	Delineation of channel banks, low-flow channels, bars and islands Bar = exposed sediment with no vegetation Island = surface located within the channel and covered by woody vegetation		
Paleochannel	Traces of paleo-channel identifiable from DTM, orthophotos, pictures and old maps. When possible time span of activity (using different colors) and morphology (using different symbol) was assigned	Paleo-channel with Unknown morphology 	
		Single-thread channel 	
		Multithread channel 	

combined with braided reaches because they show features referring to high energy environment ('high energy anabranching' proposed by Rinaldi, Surian, et al., 2015; Rinaldi, Bussettini, Surian, Comiti, & Gurnell, 2016).

At present, some paleo-channels lie at an elevation lower than the surrounding areas of the valley floor. The recognized fluvial landforms and their variations in time outline meander migration and the subsequent lateral erosion, as shown in the Main Map, from

Magrè/Margreid to the end of Segment 1 in the Main Map, or from the confluence with the Fersina River to Aldeno (see Segment 2, Main Map).

The accurate 1803 map allowed us to draw the active channel at that time with high level of detail, including bars and islands. Generally, channel banks in 1803 have variable heights ranging from 1 to 2 m (see also cross-sections in the Main Map).

The active channel boundaries in 1856 were marked with a fuchsia dashed line. Most river reaches in the study area were already channelized at that time, with dominant sinuous and straight patterns (Scorpio et al., 2018).

The present channel is shown as a blue dashed line. The Main Map highlights a widespread presence of a single-thread morphology (straight to slightly sinuous), due to the massive channelization works carried out in the nineteenth century.

The river corridor including the historical channel changes (light blue color in the Main Map) represents a key outcome of the mapping exercise, as it includes valley floor areas where river planform dynamics occurred more consistently, either during high magnitude events or by progressive channel shifting. The historical corridor is a fundamental information layer for land planning and management, as it is a key step for the delineation of the morphodynamic river corridor (Rinaldi, Surian, et al., 2015), necessary for planning sound river restoration and flood mitigation interventions.

The Main Map highlights the absolute lack of fluvial terraces.

Scarps related to processes of channel shifting and lateral erosion are mapped in the Passirio River and Rio di Nova alluvial fans (upper Segment 1, Main Map), nearby Romagnano (Segment 2) and at the boundary of the Rio Cavallo alluvial fan (lower Segment 2, Main Map).

Swamp areas present in the early 1800s were reclaimed for agricultural purposes by implementing artificial surface drainage systems between mid eighteenth century and the beginning of the twentieth century (Werth, 2014). Nowadays they vanish, but ground preserves sediment deposits due to the persistence of the swamp areas. These swampy areas have been active for millennia (Avanzini et al., 2007, 2010, 2012; Bargossi et al., 2010; Werth, 2014), some of them, probably since the beginning of the Holocene. Most of them were located at the edges of the valley bottom and in the interspace between two contiguous fans (see Segment 1, Main Map, close to the Andriano fan). They represent areas where the fluvial dynamics have been infrequent or occasional due to the physical lateral constraints exerted by the valley confining elements (Avanzini et al., 2007). On the other hand, few swamps are located in former meanders or channel, already abandoned in 1803 as those close to the villages of Romagnano and Aldeno (Segment 2, Main Map).

4.2. Quaternary deposits and sedimentation rates

Published geological maps (Avanzini et al., 2007, 2010, 2012; Bargossi et al., 2010) indicate that alluvial sand deposits are widespread in the Adige River valley bottom. In the swampy areas, silt and alternations of silt and sand containing levels of peat prevail instead, whereas fans are composed of gravel and alternations of gravel, sand and silt.

The analysis carried out for the Italian 'CARG' project (http://www.isprambiente.gov.it/it/cartografia/carte-geologiche-e-geotematiche/carta-geologica-alla-scala-1-a-50000), suggests that sedimentation rates during the Holocene were not uniform in space and time in the Adige valley, depending on depositional environment, local conditions (e.g. role of tributaries), and varying climatic conditions. On average, in the last millennium sedimentation rates were evaluated in the range of 2–3.5 m/1000 years (Avanzini et al., 2012; Bargossi et al., 2010) for the fans; in the range of 1.5–2 m/1000 years for the swamps (Bargossi et al., 2010), and approximately 2–3 m/1000 years in the alluvial plain (Avanzini et al., 2007, 2010, 2012; Bargossi et al., 2010). Available C^{14} dating is summarized in Table 2.

Therefore, data from the available boreholes were analyzed in the upper 3–5 m from the ground surface, to identify the occurrence of gravel layers that should indicate the location of paleo-channels. However, being the valley highly anthropized especially for agricultural purposes, boreholes profiles for some areas should be considered affected by direct human alteration.

Overall, the boreholes profiles show that gravels only appear in the proximity of either the present channel or of the channel active in 1803. In some cases, gravels were identified in the older paleo-channels. Examples are: the paleo-channel active in 1500–1750, nearby cross-section A-Á in the Segment 1, Main Map; the reach between Laives/Leifers and Ora/Auer in the Segment 1, in the Main Map; reach immediately downstream the confluence with the Fersina River in Segment 2, in the Main Map.

4.3. Longitudinal profile and cross-sections

The Main Map also illustrates the longitudinal profile of the Adige River, which is characterized by the presence of several knickpoints, mostly located near the confluences with the main tributaries. Mean average slope is 0.3% in the segment between the Passirio River confluence and the village of Vilpiano/Vilpian (Segment 1). It decreases to 0.1% from Vilpiano to the confluence with the Isarco River (Segment 1,

Table 2. Analytical results of C14 dating.

ID	Source	Location	Segment	Elevation m a.s.l.	Depth m	Material	Facies	Radiocarbon Age (Years BP)	Calibrated age ±2σ (95.4%)	Software for calibration
1	Bargossi et al. (2010)	Lana	1	280	−5	Charcoal	Alluvial fan	1299 ± 17	665÷720 AD (67,2%) 741÷766 AD (37,7%)	Calib 7.0.4
2	Cucato M. private archive	Andriano	1	245.8	−3.3	Peat	Swamp	735 ± 32	1223÷1295 AD	Calib 7.04
3	Cucato M. private archive	Andriano	1	243	−2.10	Plant remains	Swamp	1148 ± 41	774 ÷ 980 AD	Calib 7.043
4	Avanzini et al. (2012)	Laghetti	1	208	−2.7	Plant remains	Fluvial – Debris flow	235± 45	1513÷1600 AD (15,5%) 1727÷1812 AD (36,9%) 1617÷1693AD (38,4%)	Calib 7.04
5	Avanzini et al. (2012)	Laghetti	1	197.8	−15	wood	Fluvial	1017± 30	970 ÷ 1046 AD (92.9%) 1090÷1121AD (6,0%) 1139÷1148 AD (1,1%)	Calib 7.04

Main Map). From here, it increases to 0.2% down to the village of Ora (Segment 1, Main Map). In the remaining segment from Ora to the end of the study area, the river profile shows an approximately constant slope, ranging from 0.08% to 0.09%. As discussed by Robl, Hergarten, and Stüwe (2008), such slopes are quite lower compared to nearby Alpine valleys. Along the longitudinal profile, a comparison of the pattern distribution before 1803, in 1803 and in 1856 is reported. Such comparison highlights that, before 1803, a higher number of meanders developed in both segments, but also that a multi-channels pattern had occurred for some time in reaches that in earlier and later times instead developed a single-thread meandering pattern (e.g. see Section 4.4). In 1803, meanders occurred only downstream of the Avisio confluence (Segment 2, Main Map), and multithread morphologies were located downstream of the main confluences. In 1856, the river was already channelized.

Eleven cross-sections show the differences in elevation between the paleo-channels, the swamps, as well as their lateral distribution. They also show a rather systematic presence of a fluvial ridge. It is worth noting that in several cases (e.g. sections B-B′, D-D′, E-E′, Main Map) there is a good overlapping between paleo-channels and fluvial ridges.

4.4. Geomorphological evolution of the Adige valley bottom

The Adige River and its tributaries have considerably changed their morphology over approximately the last 1000 years. Historical chronicles from Roman times and early Middle Age describe the course of the Adige as having several active channels and large wetland areas (Comiti, 2012). Anabranching and braided patterns were probably very common if not dominant in Segment 1 in those times, as revealed by the many detected multithread paleo-channels.

Up to the mid eighteenth century, multithread morphologies appear well developed in the whole segment from Merano to Egna/Neumarkt (see Segment 1 and longitudinal profile, Main Map). The channels position changed over time, as shown by the lateral shift from the right to the left side of the valley undergone by the reaches between Merano and Andriano/Andrian and between Ora and Magrè, both in Segment 1 (Main Map). Meandering prevailed instead in Segment 2 (Main Map), but some meandering paleo-channels were detected in many reaches of Segment 1 as well (e.g. from Andriano to the confluence with the Isarco River; from Egna to the end of the Segment 1, in the Main Map see also longitudinal profile).

However, starting from the end of the Middle Age, land reclamation works were locally carried out, and maps from the eighteenth and nineteenth century show a dominant sinuous to a meandering pattern, with only a few multi-thread reaches left (Scorpio et al., 2018). At the beginning of the nineteenth century (1803 in the Main Map), immediately before the massive channelization, the Adige River thus presented more stable morphologies, being characterized by a prevalence of sinuous, sinuous with alternate bars and meandering planform in the all study area (73% out the total analyzed length, Scorpio et al., 2018). Wandering, braided and anabranching morphologies only occurred immediately downstream the confluences with the main tributaries (e.g. Passirio, Valsura, Isarco, Noce, Avisio rivers, see also the longitudinal profile in the Main Map). A reach showing an anabranching pattern also developed between Gargazzone and Vilpiano (Segment 1, Main Map), while a braided channel was located between Bronzolo/Branzoll and Ora (Segment 1, Main Map). The latter is a remnant of the more extended multithread morphology active in the previous centuries.

Overall, planform morphologies ranged from braided/anabranching to meandering and sinuous, thus representing an example of the longitudinal shift from multithread to single – thread morphologies (Scorpio et al., 2018), already observed also in other river systems (Beechie & Imaki, 2014; Beechie, Liermann, Pollock, Baker, & Davies, 2006; Church, 2002). The sequence is usually interrupted by the confluence with a tributary, and restarts again immediately downstream (Benda, Andras, Miller, & Bigelow, 2004; Rice & Church, 1998; Scorpio et al., 2018).

Besides longitudinal channel pattern shifts, temporal shifts may not have been infrequent. An example is represented by the reach immediately downstream the village of Andriano (Segment 1, Main Map), in which two meanders developed up to 1760s. In 1803, the same reach showed a braided planform with many islands. The former meanders were cut off and abandoned. The pattern shifting is very likely related to the occurrence of large flood events in the late eighteenth century, associated to the characteristic climate conditions of the Little Ice Age.

The analysis has highlighted the important influence of tributaries and of their fans on the Adige geomorphological dynamics. Most fans have been capable to influence the Adige morphology, especially up to the beginning of the nineteenth century. Such influence goes beyond the rather trivial geometrical confinement directly associated by the presence of the fans: indeed the historical morphodynamic corridor of the Adige in the last 1000 years (light blue color in the Main Map) finds its way beneath the fans and also beneath the swampy areas which occur in 'morphodynamically shadowed' areas adjacent to consecutive fans on the same valley side, which could not be occupied by the river channel unless very unfrequently.

The most relevant morphological changes in the Adige valley are associated to the channelization carried out during the nineteenth century. Starting from the middle nineteenth century, the Adige underwent narrowing up to – 70% of the 1803 channel width and straightening, with consequent intense reduction of the number of bars, islands and secondary channels (Scorpio et al., 2018). Some wandering and anabranching reaches still persisted in Gargazzone area (Segment 1, Main Map), while artificial meander cut-offs had been already executed between Trento and Calliano (Segment 2, Main Map). The present channel is totally channelized by a straight to slightly sinuous morphology.

Afterwards, sediment supply to the Adige River was reduced during the late 1800s due to the construction of several retention check dams in its main tributaries, and more markedly around the early-mid twentieth century for the construction of reservoirs for hydropower production and flood protection.

Therefore, from the mid-nineteenth century, the effectiveness of natural factors in determining changes to the Adige River was highly reduced by the anthropic interventions. Channelization works prevented the geomorphological effects caused by the occurrence of extreme floods, which, as already shown in Marchese, Scorpio, Fuller, McColl, and Comiti (2017) and Scorpio et al. (2018), strongly increased in frequency in the late nineteenth century. Not even the extreme 1882 flood (recurrence interval >100 years in the Adige River) had any remarkable effect on the Adige channel morphology.

4.5. Implications for present-day management of the Adige River

Reconstruction of the recent geomorphological evolution of floodplains or valley bottoms are advocated as key factors for planning restoration and management actions (Rinaldi, Simoncini, & Piégay, 2009; Surian et al., 2009), and thus the knowledge gained on the Adige river valley should be utilized for such a purpose. The mapped historical river corridor indicates that almost the entire Adige valley bottom has been subjected to channel dynamics and fluvial reworking over the last 1000 years, and which, in the hypothetical absence of the present channelization work, it could be expected to be partially re-occupied in the future. Recent trends in river management are often based on the concept of 'giving more room to the river', a strategy which has potential to fulfill both environmental quality and flood protection needs (Rijke, van Herk, Zevenbergen, & Ashley, 2012; Roth & Warner, 2007). However, the present high socio-economic value of the intensive land uses of the valley bottom (orchards, vineyards, manufacturing, transportation infrastructures) makes any large scale removal or lateral shifts of channelization works unthinkable. Nonetheless, the need and the possibility to plan and implement realistic, smaller scale river rehabilitation interventions of the Adige River is increasingly being considered by local managing authorities and can benefit from the outcomes of the present geomorphological reconstruction.

At a European level, river restoration is mainly guided by principles of the Water Framework Directive (EC 2000/60), which include that of historical 'reference conditions', viewed as those characterizing water bodies in historical times under almost negligible anthropic pressure, and assumed as a proxy for their best natural state. Such conditions have been too often viewed as static and our analysis provides further support to the advocated need of embracing a more dynamical reference concept when planning river restoration (Dufour & Piégay, 2009; Rinaldi, Surian, et al., 2015). A more sustainable and scientifically based approach consists in the rehabilitation of a continuous, erodible river corridor, set within unerodible levees. This might allow channel morphology to change over time even within the same reach, as it happened in the past under the influence of climatic conditions (Little Ice Age) and by the occurrence of large flood events. The historical river corridor mapped in this study as well as the detected previous channel patterns could then serve to identify and prioritize self-sustaining rehabilitation interventions, able to resume at least partly the river capacity to establish more diverse channel patterns – although simplified with respect to pre-channelization times – through moderate channel widening accompanied with sediment reintroduction.

5. Conclusions

The Main Map illustrates the transformations of the valley bottom and specifically changes in channel position and pattern over the last 1000 years. It includes paleo-channels dating up to the thirteenth century and a number of paleo-swamps, reclaimed during the nineteenth century. The Main Map shows remarkable changes in channel morphology, particularly from braided or meandering morphologies to straight.

Between the mid-nineteenth century and beginning of the twentieth century, due to extensive channelization works, the Adige River underwent the most considerable channel changes, consisting in channel narrowing up to – 70% of the initial value accompanied by a strong reduction in sinuosity as well as in the number of secondary channels, bars and islands (Scorpio et al., 2018). Similarly to the Adige, the terminal reaches of the main tributaries were also channelized.

A key outcome of the Main Map is the historical river corridor derived from the envelope of the areas that underwent channel dynamics over the last centuries. The Main Map can thus offer a valid support for developing sound, integrated river management plans aiming at combining an increase in the ecological quality of river corridors with flood risk mitigation, through the implementation of successful river restoration measures. Indeed, such measures require an accurate knowledge of past river dynamics (Brierley, Fryirs, Boulton, & Cullum, 2008; Rinaldi, Surian, et al., 2015), otherwise, the risk of failure is very high (Gurnell et al., 2016).

Software

ESRI's ArcGIS 10.4 was used to geo-reference the historical maps, to derive cross-section, longitudinal profile, to create the geomorphologic layers and the hillshades from DEMs. The final map was obtained combining the layers produced by using Corel Draw X6.

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