Quaternary Research

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--Manuscript Draft--

Manuscript Number:	QUA-17-179R3
Article Type:	Research Article
Keywords:	channel planform change; channel adjustments; channel migration; channel narrowing; Geographic Information System; GRASS GIS; QGIS; Scrivia River; Italian Rivers
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Published in Quaternary Research on 30 August 2018 Volume 91(2) (2019) 620–637

https://doi.org/10.1017/qua.2018.67

Channel planform changes on the Scrivia River floodplain reach in NW Italy from 1878 to 2016

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A detailed quantitative multitemporal analysis of historical maps, aerial photos and satellite images was performed to investigate the channel planform changes that occurred along the Scrivia River floodplain reach from 1878 to 2016. Various parameters concerning channel planform features (channel length, area, width, braiding, sinuosity, lateral migration, activity and stability) were computed through an innovative GIS-based procedure, starting from manually digitized active channel polygons. Three active channel morphological evolution stages were outlined: 1) from 1878 to the 1950s; 2) from the 1950s to the end of 1990s; 3) from the end of 1990s onwards. In the first period, generally, the river was able to migrate in its floodplain shaping the riverscape. Active channel narrowing and increasing channel stability characterize the second period. The most recent phase shows an inversion of morphological evolutionary trend. It is characterized by a slight generalized widening related to the reactivation of stabilized surfaces and to bank erosion processes. Particularly from the 1950s to the 1990s, in-channel sediment mining and channelization with consequent occupation of riverine areas strongly affected the Scrivia River. These factors, together with floods, are thought to be likely the most representative causes of such consistent and fast morphological changes.

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INTRODUCTION

Lateral erosion and deposition processes cause loss of land (from floodplain to active channel) and vice versa also stabilization of new surfaces (from active channel to floodplain). Thus, these dynamics are responsible for an important part of the sediment cycle (Kondolf, 1994; Sear et al., 2003). In agricultural and urbanized landscapes, fluvial lateral dynamics can cause conflicts with landowners and provoke damages to infrastructure and people (Piégay et al., 2005). However, on the other hand channelization (i.e. blocking geomorphological processes) means transforming "wonderful ecosystems into run-down hydraulic pipelines" (Sansoni, 1995), producing negative ecologic, geomorphologic and hydraulic effects (Piégay and Rinaldi, 2006).

Many authors around the world (Werritty and Ferguson, 1980; McEwen et al., 1989; Gurnell et al., 1994; Lajczak, 1995; Gurnell, 1997; Kondolf, 1997; Malavoi et al., 1998; Leys and Werritty, 1999; Shields Jr et al., 2000; Winterbottom, 2000; Liébault and Piégay, 2002; Rapp and Abbe, 2003; Piégay et al., 2005; Gordon and Meentemeyer, 2006; Hooke, 2008; Giardino and Lee, 2011; Nelson et al., 2013; Block, 2014; Das and Pal, 2016) studied river planform changes over time in order to define the evolutionary trends, to assess the triggering factors and to manage the fluvial environment, particularly of river systems highly impacted by humans. Research conducted on Planform changes in Italian rivers (Canuti et al., 1991; Dutto and Maraga, 1994; Castaldini and Piacente, 1995; Surian, 1999; Aucelli and Rosskopf, 2000; Marchetti, 2002; Rinaldi, 2003; Surian and Rinaldi, 2003; Rinaldi et al., 2005; Cencetti and Fredduzzi, 2008; Pellegrini et al., 2008; Rinaldi et al., 2008; Surian et al., 2009b; Turitto et al., 2010; Comiti et al., 2011; Ziliani and Surian, 2012; Magliulo et al., 2013; Bollati et al., 2014; Clerici et al., 2015; Ziliani and Surian, 2016; Cencetti et al., 2017) identified some morphological evolutionary phases from the 19th century onwards.

Two historical phases of predominant channel narrowing are registered: the former up to the 1950s and the latter from the 1950s to the 1990s. These phases are in turn accompanied by a reduction in braiding degree, by an increment of sinuosity and by an increasing active channel stabilization. The third and most recent stage, from the 1990s onwards, reveals a slight inversion of the morphodynamic trend of some Italian rivers.

Nowadays it is widely recognized that a detailed analysis of the river dynamics of the last two centuries yields valuable information to understand ongoing dynamics and potential future evolutionary trends, under a river management perspective (Rinaldi, 2006; Brierley et al., 2008; Dufour and Piégay, 2009).

This paper focuses on the active channel planform changes of the Scrivia River floodplain reach occurring between 1878 and 2016. The choice of this time interval is constrained by data availability and accuracy (Cencetti and Fredduzzi, 2008; Cortemiglia, 2011) to define the medium and short-term channel evolutionary trends and channel adjustments (Rinaldi et al., 2014). In fact, even if many rivers were subjected to human alterations prior to the 19th century (Petts et al., 1989; Billi et al., 1997; Winterbottom, 2000; Montgomery, 2008; Comiti, 2012), the most intense and widespread morphological adjustments of the historic period affected Italian floodplain rivers just in this time interval, and particularly after the 1950s (Winterbottom, 2000; Rinaldi et al., 2011, 2014).

In a heavily urbanized and cultivated zone such as the Scrivia floodplain, mainly fields, but also facilities and infrastructures, have often spread up to the edges of the river banks, increasing risks and modifying the fluvial environment. During recent years, the Scrivia River floodplain reach has been affected by intense bank erosion processes and by reactivation of lateral dynamics blocked for decades. These processes emphasized the ongoing difficult relationship between people and rivers, showing serious management issues.

The purpose of this research is to outline planform changes of the Scrivia River at a medium temporal scale (also called “management scale”, e. g. the last 100-150 years) (Rinaldi et al., 2014). Particularly, we examined the extent and the pattern of variations of the active channel of the Scrivia, at reach scale and for its entire floodplain extent. The aim is to understand its historical and recent active channel planform evolution, identifying its overall morphological variations and its current dynamics to inform effective and sustainable riverscape management.

STUDY AREA

The Scrivia River is one of the main right-bank tributaries of the Po River. It is about 90 km long and flows northward, with headwaters originating in the Ligurian-Piedmontese Apennines, in the hinterland of Genoa, very close to the Ligurian Sea (Fig. 1). In some reaches, it is together with its main tributary, the Borbera River, one of the most representative examples of braided rivers in the Northwestern parts of Italy. The Scrivia catchment spreads over about 1000 km², of which 80% consists of hilly and mountainous areas. The altitude ranges from 1700 m a.s.l of the highest peak (Mt. Ebro) to 67 m a.s.l. at the confluence with the Po River.

The main outcropping lithotypes are sedimentary rocks including marly limestones, mudstones, marls, sandstones and conglomerates belonging to Ligurian and Epiligurian Units and to the Tertiary Piedmont Basin (Molli et al., 2010; Federico et al., 2014; Barbero et al., 2017; Piana et al., 2017). At the interface between the Apennines and the Quaternary floodplain, a narrow belt of Pliocene sedimentary rocks locally crops out (Fig. 2). The topography of the mountainous part of the basin is heavily controlled by tectonics and lithology (Mandarino et al., 2015). Important geological structures and lineaments are present and conditioned the landscape evolution such as the pronounced asymmetry of the basin (Fannucci and Nosengo, 1977; Pellegrini et al., 2003; Capponi et al., 2009; Festa et al., 2015; Mandarino et al., 2015; Sacchini et al., 2016a). Furthermore, generally wide valleys and gentle slopes characterize areas with a clayey bedrock, whereas steep slopes and narrow valleys have formed on marly limestones and conglomerates. Steep slopes occur also in parts of the hilly zone located in Piemonte Region characterized by badland formation. At the outlet of the valley, the evident and extensive series of fluvial terraces, that spreads mostly on the left bank, reveals that during the Quaternary the Scrivia River migrated E-NE entrenching into its own sediments (Braga and Casnedi, 1976; Cortemiglia, 1998).

The Scrivia River has a mean daily discharge of 14.2 m^3 s^{-1} and a mean annual maximum discharge of 304 m^3 s^{-1}, recorded for the period 2001-2016 at the gauging station located 5.14 km upstream the Po confluence. The climate is characterized by hot and dry summers and cold and wet winters with rainfall concentrated mainly in autumn and showing its minimum in summer (Cortemiglia, 2012; Sacchini et al., 2012). At catchment scale the annual average rainfall is circa 900 mm (Autorità di Bacino del Fiume Po, 2001). However, a large difference in rainfall intensity and cumulate rainfall exists between the lower and upper part of the Scrivia River Basin, particularly considering the rain areas close to the Po-Ligurian drainage divide, near Genoa. These zones are influenced by the atmospheric circulation prevailing over the Ligurian Sea, called the Genoa Low (Sacchini et al., 2016b), causing exceptional precipitation followed by flood peaks.

The largest floods in the 20th century occurred in 1945 and 1951 with a peak discharge of circa 1800-1900 m^3 s^{-1} (this data is uncertain) and 1650 m^3 s^{-1} measured at the gauging station located 4 km upstream of the study reach. Other extreme floods are registered in 1931, 1934, 1935, 1953, 1960, 1963, 1970, 1977 and 1982 (Alpha Cygni, 1994; Tropeano et al., 1999). The most recent extreme floods occurred in 1993, 2000, 2002, 2010, 2011, 2013 and 2014.

The mountain areas are mainly covered by forest, with sparse cultivated patches. The valley floors are generally very urbanized and host much relevant road infrastructure. Hillslopes and floodplains are intensively cultivated. However, a growing urbanization has affected a consistent portion of agricultural land. In the mountainous part of the catchment there are four reservoirs located in tributary basins.

The study reach is located north of Serravalle Scrivia, from where the valley spreads out and the river becomes unconfined, down to the Po River, for a total length of 40 km. Here three main segments (Rinaldi et al., 2014) characterized by homogeneous geomorphological features can be recognized: the upstream section (12.5 km) shows a very wide, straight and multithread channel; the central section (14.5 km) presents a transitional channel pattern and is the most urbanized one; the downstream segment (13 km) is narrow, deep-incised and sinuous, with short consecutive meanders that give the way to wide curving river features in the last few kilometers (Fig. 3). Outcropping bedrock can be observed only at the upstream border of the study reach where the river erodes the edge of an old fluvial terrace and about 11 km downstream, where sedimentary rocks outcrop from sediments in the middle of the active channel. Sediment grain size ranges from a diameter of 30 cm down to sand and finer fractions.

Many facilities and much infrastructure are located in proximity of the channel and cultivated fields often spread up to the bank edges, occupying paleochannels and most of the river corridor (Piégay et al., 2005). Moreover, a diffuse presence of river management works, mainly bank protection structures, is located along the whole study reach. These structures are overall longitudinal defenses mainly constituted by prisms of concrete used as ripraps (the so-called “prismate”) and sporadically, by rock ripraps and revetments.

According to reports and historical sources, a consistent sediment mining activity also affected the Scrivia River in the second half of the 20th century, as already documented for many other Italian rivers (Conti et al., 1983; Farabollini et al., 2008; Colombo and Filippi, 2010). In-channel sediment extraction was particularly severe from the 1960s to the 1980s, and after the ban in the early 1990s it has been sometimes authorized as river maintenance intervention to prevent flooding or as remuneration for other kinds of hydraulic works (e.g. bank protection construction). Some works and unpublished studies (Alpha Cygni, 1994; Cortemiglia, 1998; Tropeano et al., 1999; Duci, 2011) document for that period a considerable narrowing of the active channel and from 1970 to 1994 a deepening of about 2.5 m of the middle segment near Tortona. This period was followed by a phase of stabilization or a slight reversal trend registered between Serravalle Scrivia and Castelnuovo Scrivia from 2000 onwards, involving both channel width and riverbed elevation. At the confluence, the Po active channel incision was about 4 meters between 1954 and 1988.

METHODS

To assess the Scrivia River planform changes we performed a detailed historical analysis of riverbeds considering available cartographic documents and aerial photographs. This multitemporal analysis was carried out in a GIS environment using GRASS GIS (GRASS Development Team, 2017) and QGIS (QGIS Development Team, 2017). Our analysis consists of three phases: i) Georeferencing of images, ii) photograph interpretation and digitizing of morphological elements and, iii) vector and raster geoprocessing. Graphs were plotted using the Python library Matplotlib (Hunter, 2007). A large campaign of field surveys, conducted in 2016 and in 2017, allowed us to characterize the current morphologic conditions of the river, supporting and validating the photograph interpretation phase.

Data sources

In this study, we used ten different data sources to investigate channel planform changes that cover the period between 1878 and 2016. The oldest considered datum is the “Gran Carta d’Italia”, which is the first existing modern cartographic document covering the study area (Cortemiglia, 2011). This map of Italy, accomplished in 1903 (Cortemiglia, 2011), was produced by the Italian Institute for Military Geography and is composed by sheets of different scales (1:100,000, 1:50,000 and 1:25,000); we used the sheets 1:25,000 scale published in 1878 (“Villalvernia”, “Tortona” and “Castelnuovo S.”) and 1882 (“Casei Gerola”). We combined them to obtain a complete coverage of the area referring to this series as 1878 map. The other map we used is dated 1922 and represents the upgrade of the former 1878 map. From the 1950s onwards the availability of aerial photos grew considerably; there are many flights that cover partly or completely the Scrivia River floodplain reach. We selected the most representative to ensure consistent interpretations.

We used aerial photos approximately at 1:33,000 scale from the “GAI Flight”, the first aerialphotogrammetric survey covering Italy (1954/1955), and also aerial photos from the 1977 flight. From 1980 we used a series of orthophotos at 1:5,000 scale (1980) and at 1:10,000 scale (1988, 1999, 2007, 2012). Google Earth images (2016) represent the most recent available datum.

The QGIS plugin “Georeferencer” was used to rectify and georeference the oldest maps (1878) and the oldest aerial photos (1954) applying a “thin plate spline” transformation for the oldest maps and a second order polynomial transformation for the aerial photos. Both were resampled with a “nearest neighbor” resampling method. We used the 2012 orthophoto series as the base for the georeferencing procedure (UTM-WGS84). Ground Control Points were located for each processed image around the riverbed but not too far from it, to minimize the distortion in the area of interest (Hughes et al., 2006; Block, 2014; Clerici et al., 2015). To assess the positional accuracy, we calculated the root mean square error (RMSE) of each fixed location and the average RMSE of each image was maintained around one pixel width to minimize errors. Available aerial photos from the 1977 flight and orthophotos dated from 1980 were already georeferenced in the UTM-ED50 coordinate reference system. 1922 map and data sources from 1988 to 2012 were available from the National Geoportal Web Map Service, with a positional accuracy ≤ 4 m for the orthophotos. Google Earth images dated 2016 were visualized in QGIS at 1:2,500 scale through the “Quick Map Service” plugin. Working at a fixed scale allowed us to use always the same images whose date was checked directly in Google Earth. The positional accuracy of these “ready to use” data was checked referring to the orthophotos of 2012 by computing the RMSE of a series of control points located on well-defined locations, both on the reference map and the one under evaluation (Winterbottom, 2000). These procedures allowed us to obtain a positional error lower than 15 m for the maps and, generally, lower than 5 m for the images (Surian et al., 2009a). An orthorectification process of maps and aerial photos is not required because the analysis concerns only the floodplain reach of the Scrivia River, not considering slopes (Neteler and Mitasova, 2002; Block, 2014; Cencetti et al., 2017).

Photograph interpretation and digitizing

After the georeferencing procedure we performed a photograph interpretation phase in order to generate a consistent vector Geodatabase. Since the channel planform changes cannot be assessed by comparing inundated channel dimensions, because discharge may be very different in considered data sources (Nelson et al., 2013), we digitized manually the active channel polygon for each series of documents (maps and photos). Active channel is defined as that portion of surface constituted by wetted channels and adjacent bare or partially vegetated bars (Winterbottom, 2000; Surian et al., 2009a; Nelson et al., 2013; Cencetti et al., 2017). The active channel polygon reflects ongoing geomorphic processes (Block, 2014) independent of flow conditions at the time of the survey. Hence, we assume that the active channel polygon marks the boundaries of annual highwater, substantially coinciding with the bankfull channel (Wallick et al., 2006; Cencetti et al., 2017).

Its limits were defined as the boundary between water or bars and surfaces densely covered by stable vegetation; they were generally marked by an abrupt linear change in vegetation density or by a clear topographic break. However, sometimes it was very difficult to identify precise riverbed edges, in particular where steep banks could not be identified and where active vegetated bars blended into the modern floodplain (Rinaldi et al., 2015b). In these cases changes in vegetation coverage was used to locate the edges. In this research vegetated surfaces located within the active channel (i.e. entirely surrounded by base-flow channels or emergent sediments units) were incorporated into the active channel polygon due to the complexity of distinguishing between islands and bars covered by annual or biennial plants with a certain degree of accuracy (Rinaldi et al., 2015a). We also digitized wetted channels as lines considering, as far as possible, photos series not showing extreme events like floods or droughts, in order to compute the Braiding Index.

Finally, river management works, such as bank protection, bridges, weirs and embankments, were digitized on the 2016 images. Bank protection structures such as gabionades, ripraps and walls were classified as “longitudinal defenses”, whereas features like groynes were classified as “cross defenses”. Moreover, we characterized them as “certain” or “uncertain” according to their recognizable presence in the field and/or in the data.

Polygons and lines were digitized at 1:5,000 scale on maps and at 1:2,500 scale on photos. In this phase, we identified ten reaches, each generally no longer than 5 km (Rinaldi et al., 2014), with homogeneous geomorphological features to perform a more detailed analysis. Their limits were located at stable human cross works like weirs and bridges present on different time steps. Subsequently, the reaches were defined considering channel pattern and channel width variations, presence of ancient fluvial terraces, channel slope, tributaries and river management works. Channel slope was assessed qualitatively considering the active channel longitudinal profile at 10 m steps derived from a high-resolution Digital Terrain Model (5 m cell size) produced with LiDAR data surveyed in 2009 (property of the Piemonte Region).

GIS analysis

Starting from the preprocessed set of vector layers, we performed a detailed GIS analysis in order to assess the morphodynamic evolution of the river. Firstly, we automatically generated the channel centerline, defined as the line of points equidistant from the banks, smoothing the line extracted from Thiessen Polygons to obtain a sinuous line (Block, 2014; Cencetti et al., 2017). Channel width at different time steps was computed at reach scale by the ratio of the active channel area to its length. Moreover, we continuously located transects perpendicular and at a regular spacing along to the whole channel centerline, clipping the transects by the bankfull polygon. Since the direction of the overall planform course did not change significantly over time (except for the more downstream reach), the Sinuosity Index (SI) (Schumm, 1963; Brice, 1964; Malavoi and Bravard, 2010) was computed at reach scale dividing the channel centerline by the straight line merging the reach endpoints in order to compare the value in different years. To assess the degree of braiding, the

Braiding Index (BI) (Ashmore, 1991; Egozi and Ashmore, 2008) was computed automatically at reach scale. It is defined as the ratio of the total number of channels divided by bars intersecting transects, to the total number of transects used. Overlapping all active channel layers we identified the historical migration zone (hereafter abbreviated to HMZ), following (Rapp and Abbe, 2003).

To describe channel migration over time we applied the following parameters: Distance of Migration (Rapp and Abbe, 2003; Giardino and Lee, 2011; Block, 2014; Das and Pal, 2016), Rate of Migration (Shields Jr et al., 2000; Rapp and Abbe, 2003; Urban and Rhoads, 2003; Hooke, 2008; Giardino and Lee, 2011), Channel Activity (Downward et al., 1994; Nelson et al., 2013; Kuo et al., 2017) and Historical Channel Stability (Downward et al., 1994).

As illustrated in Figure 4, initially we defined polygons representing the space subjected to migration process, hereafter called migration polygons. We did this considering the portion of surface occurring between two consecutive channel centerlines (centerline migration polygons) and between two consecutive right or left bank edges (bank migration polygons) (Fig. 4b). Then we extracted the line equidistant to the two above-mentioned consecutive channel centerlines, hereafter called migration centerline, similarly to the procedure described before to get the channel centerline (Fig. 4c). Furthermore, we located transects at a 25 m regular interval, along and perpendicular to the migration centerline (Fig. 4d). These transects were clipped once by centerline migration polygons (Fig. 4e), once by left bank migration polygons and once by right (Fig. 4f), creating three transects layers. Transects length defines the distance of migration respectively for centerlines, left banks and right banks. These length values are referred to the progressive distance from the upstream limit to the outlet of the migration centerline, thus to the entire study reach. This procedure was performed for each couple of consecutive years. This approach allows analysis of both channel migration and channel width changes through channel migration itself. The latter element, particularly, has been rather innovative and likely constitutes the first time that bank migration is used to assess accurately at site-scale channel width variations over time.

In order to obtain a Migration Rate for each reach expressed in meters per year, we divided the centerline migration polygons total surface by the length of the oldest of the two channel centerlines and the number of years of the analyzed time interval (see Fig. 4). The same was done for the banks. We started from right and left bank migration polygons, dividing their surface respectively by the oldest right and left bank length and the number of years.

Channel Activity is a relevant indicator of channel stability over time; here it was defined overlaying two consecutive active channel positions (Fig. 5a) and identifying new active channel areas (erosion – from floodplain to active channel) as well as abandoned surfaces (deposition – from active channel to floodplain) (Fig. 5b). We computed the Channel Activity as the sum of eroded and abandoned surface areas per year (m^2 y^{-1}) as well as per year and per unit of longitudinal distance (m^2 y^{-1} m^{-1}) (Nelson et al., 2013). To identify the prevalent process, we calculated the balance between eroded and abandoned areas and the percentage of non-changed, e.g. stable, active channel surfaces as well as the percentage of changed active channel surfaces referring to the former active channel area. The latter is defined as the difference between abandoned and eroded areas divided by the oldest of the two compared channels surfaces. Channel Activity was computed along the whole study reach for each kilometer and at reach scale.

Finally, active channel polygons were converted to raster files and binarized: pixels were assigned the number of years dividing two consecutive active channels. No data pixels were treated as zero value. Through an overlay procedure, the Historical Channel Stability (Downward et al., 1994) was defined summing up all raster files of the analyzed period in order to create a map showing for each pixel the number of years of active channel occupancy. The accuracy of this parameter is strictly related to the number of overlapping data and to their respective survey dates (Downward et al., 1994); the more data are available and the closer the survey dates are, the higher the precision.

In recent years, GIS analysis has substantially improved this kind of analysis. Nevertheless, the procedures for computing considered parameters and indices are very time consuming and error prone. In order to address this aspect we developed a set of GRASS GIS shell scripts to conduct the analysis. Some of the scripts can be executed automatically, some of them in a semi-automatic way.

RESULTS

The analyzed maps, aerial photos and satellite images show consistent planform changes that occurred along the Scrivia River between 1878 and 2016. Processes of active channel lateral migration, narrowing, widening and variation of channel pattern took place at different rates in space and time, shaping new riverscapes. In order to perform a detailed analysis, the study reach was split in 10 reaches, whose features are described in Table 1. From the upstream end to the outlet the channel pattern changes from multithread to transitional and finally to single-thread channel. The upstream three reaches present a wide active channel with maximum widths of 404 m and 325 m respectively for the second and the third reaches. These reaches are characterized by wide bare bars or bars that are partially covered by vegetation that divide some flow channels resulting in a braided pattern. From the 4th reach downstream, the active channel loses its braiding degree and narrows, thus, showing transitional features. The four downstream reaches are characterized by almost parallel banks that delimit a single flow channel. Bars, although quite large, are evident and alternate in the 7th and in the 8th reaches and almost disappear in the two downstream meandering reaches of about 40 m width. The mean length of the study reach over the time period considered is 39,464 m. A maximum value of 40,626 m is registered in 1954 and a minimum of 35,228 m in 1878. The most consistent channel length variability is recorded from 1878 to 1954 in the downstream reaches. Thereafter the parameter was overall quite stable with variations smaller than 1 km.

Sinuosity Index and Braiding Index changes over time are plotted in Figure 6. Relevant differences in SI between reaches 1 to 7 and 8 to 10 are noticeable over the entire analyzed period. The BI evolutionary trend reveals a general decrease until 1999. Subsequently, a comparable reversal trend is noticed for most of the reaches upstream of Tortona, whereas downstream of Tortona up to Castelnuovo Scrivia a smaller inversion of BI tendency is detected from 2007 onwards. In the last ca. 13 km the BI was quite stable, close to 1.

As illustrated in Figure 7, significant channel width variations affected the Scrivia River over the last 138 years. Particularly, narrowing occurred in all reaches from the upstream end of the study area down to Castelnuovo Scrivia. In contrast, the last 10 km have always been the most stable showing only small fluctuations over time. Today any reach shows a smaller channel width than its mean channel width computed over the time period considered in this research. In 1922 only the 2nd and the 10th reaches show a consistent widening by comparison to 1878 and no general trend can be identified. Thereafter, from the first half of the 20th century to the end of the 1990s, almost all reaches show a narrowing trend becoming more and more representative due to measurements of channel width on aerial photos (from the 1950s). Comparing 1954 to 1999 active channel width, from the upstream end of the study reach to Castelnuovo Scrivia, mean narrowing of more than 100 m is measured with peaks of width reduction of 240 m (-58%), 178 m (-48%), 142 m (-56%) and 149 m (-52%) respectively in reaches 1, 4, 5 and 7. Compared to 2016 the decrease is generally minor with peaks of 128 m (-35%), 88 m (-35%) and 136 m (-48%) for reaches 4, 5 and 7. Seven of ten reaches show their maximum value of narrowing rate (from 3 m y^{-1} to 12 m y^{-1}) between 1954 and 1999, six of them from 1954 to 1988. This is generally the period of the main narrowing. Seven of ten reaches show their minimum mean channel width in 1999 and two in 1988. Nonetheless, referring to the total active channel, the mean channel width decreases almost linearly from 1922 onwards (Fig. 8).

In comparison with 1954, in 1999 channel width was 240 m (58%) smaller in the 1st reach, about 100 m (27%) smaller in the 2nd and in the 3rd and 177 m (48%) smaller in the 4th reach. From Tortona to Castelnuovo Scrivia the narrowing ranges between about 120 m and 150 m (about 50%) measuring both 1988 and 1999 width. Channel width changes from a mean value of 288 m measured in 1954 to 149 m in 1999. Just downstream of Castelnuovo Scrivia, after a narrowing of

58 % documented in 1999 a restoration of previous values occurred. In the last two reaches a widening is registered until 1980 followed by a width decrease in 1988 and by slightly fluctuating values until 2016. Generally, from 1999 onwards an enlargement is registered for the entire Scrivia River floodplain reach (Fig. 8). Comparing the width at reach scale between 1999 and 2016 peaks of 31%, 48% and 142% are registered for the 2nd, the 5th and the 8th reaches respectively.

This evolutionary trend is reproduced by the active channel area analysis Fig. 8, which reveals a loss in surface of 425.3 ha (36%), from initially 1174.3 ha in 1878 to 749 ha in 2016. In 1988 and 1999 the lowest active channel areas are documented. Today the total channel surface is 24.65% smaller than in 1954 upstream of Tortona, 34.55% smaller between Tortona and Castelnuovo Scrivia and 6.67% wider up to the Po River.

Annual channel activity was generally higher between 1922 and 1954 and later in the periods 1977-1980, 1980-1988 and finally 2012-2016. Net channel change (Fig. 9) reveals that most of active channel area was abandoned between 1922 and 1999; opposite results are recorded between 1977 and 1980. From 1999 onwards, the conversion from floodplain to active channel prevails, with peaks from the 2nd to the 6th reaches. The percentage of both unaltered and altered active channel surfaces denotes the same tendency (Fig. 10). Channel activity analysis at kilometric scale reveals the same trend providing more spatial detail.

Lateral migration along the entire study reach was assessed in detail continuously and at reach scale (Figs. 11 and 12). With regard to the distance of migration, Figure 11a illustrates the channel centerline magnitude and direction of migration plotted against progressive distance. The period 1954-1977 is chosen as an example. In Figure 11b, right and left bank edge lateral shifts are shown. This composed plot allows the distinction of channel centerline shifts related to the entire active channel migration from those associated with narrowing or widening processes. If a peak referred to the centerline corresponds to two specular peaks for banks (one negative and one positive), the active channel is shifted while maintaining its width. In contrast, if it corresponds to only one peak, or to two peaks both above or below zero, it implies that the indicated shift is accompanied by changes in width. Analyzing all considered periods, the most relevant channel lateral migrations occurred up to 1977. Between 1878 and 1922 shifts of hundreds of meters were noticed. Later, distance of migration values decrease and the advancement of both banks implies a channel narrowing. From the period 1999-2007 onwards, the mean centerline shift was about 10 m with maximum values no higher than 100 m. In the latest period, a few peaks are shown.

Figure 11c shows the cumulative migration curves for each period analyzed. Between 1878 and 1922, the curve shows frequent and pronounced steps, indicating abrupt channel migration. Close to 100% progressive distance, the most relevant increase is noticed. From the period 1954-1977 onwards, lateral shifts have become less relevant and pronounced. Considering a larger scale for trend visibility (Fig. 11c), the cumulate curves reveal that most of channel shifts occurred in periods 1954-1977 and 1988-1999. Other periods show lower values without relevant changes in slope. A general variation in trend is noticed downstream the 70% of progressive distance, where the reduction of steepness implies more stable conditions.

Distance of migration plots (Fig. 11a and 11b) show that the percentage of measurements (e.g. of clipped transects – see Fig. 4) that does not represent centerline lateral migration grows over time (Fig. 11d) (minimum of 3.3% between 1922 and 1954; maximum of 63.3% in the latest interval). The net bank migration, defined for each measurement along the migration centerline as the sum of left and right bank migration values (negative or positive values for advances or retreats respectively, for each bank), was also computed for each time step (Fig. 11e). We assumed that values between -5 m and 5 m correspond to no width changes. Thereby we take into account errors associated with image-to-map rectification and bank edge location identification. In contrast, values lower than -5 m and higher than 5 m imply that migration of banks is related to active channel narrowing (negative values) or widening (positive values). The histogram (Fig. 11e) reporting changes in active channel width related to the lateral migration of bank edges shows a great number of records identifying narrowing or widening up to 1977. Thereafter, stability increased considerably up to 48% in the latest period.

Mean migration rate for the entire Scrivia River ranges between 5.7 meters per year in 1878-1922 and 1.7 m y^{-1} in 1954-1977. At reach scale (Fig. 12) mean migration rate varies between 1.8 m y^{-1} and 5 m y^{-1} as mean value, and between 1.3 m y^{-1} and 2.8 m y^{-1} as median value. The parameter fluctuates over time. The maximum peak of 35 m y^{-1} is registered between 1878 and 1922 in the 10th reach. Sometimes left bank, right bank and channel centerline migration rates do not coincide and present very different values over time, as shown in upstream reaches. Five of nine periods show a migration rate lower than or near 3 m y^{-1} for all reaches. The overlapping of partial migration zones with the overall HMZ allowed the definition of trends already outlined by other parameters both at reach scale and for the entire study reach (Fig. 8). This can underline i) a reduction in lateral migration and ii) a moderate lateral migration performed by a narrower channel. Indeed, a narrower channel that shifts moderately into the floodplain involves a lower amount of surface in comparison with a larger channel. The period of active channel occupancy of the Scrivia floodplain surface over 138 years reveals that upstream of Tortona the channel was generally more stable (Fig. 13). Downstream the floodplain is progressively younger and the 9th and 10th reaches show more than 90% of surface belonging to the lowest class of channel occupancy. Considering channel occupancy classes between 1977 and 2016 most of surfaces are in the lowest and in the highest classes.

DISCUSSION

The results show that relevant planform changes affected the Scrivia River floodplain reach over the last 138 years, from 1878 to 2016. Furthermore, computed hydromorphological parameters outline well-recognizable trends in active channel morphological evolution. Hence, they allow identification of a sequence of channel adjustments stages.

In 1878 the Scrivia flowed approximatively northward according to the actual direction up to Castelnuovo Scrivia, thereafter a completely different path is documented. Where meanders developed in the 20th century the riverbed was quite straight and flowing northwestward up to the Po. At that time, two bottlenecks already existed close to Tortona and Castelnuovo Scrivia respectively, due to the presence of bridges and of the town itself. Between 1878 and 1922 an avulsion occurred. According to historical sources, in 1887 an intense Po River flood created a new channel southward, close to Alzano Scrivia. This avulsion process caused the disruption of a little village called Rotta dei Torti, already damaged by previous events. The Scrivia River was shortened and at the turn of the 19th and 20th Centuries it joined the Po River 3.6 km upstream of the present day location (Sacco, 1927). Later the Po abandoned its new channel which became subsequently the Scrivia active channel and thus, the confluence shifted northeastward. Evidence of these events is recognizable on maps and aerial photos and was visible in the field up to few years ago. Moreover, the relevant difference in radius of meander curvature upstream (narrow meanders) and downstream (soft and wide bends) of Alzano Scrivia is likely due to these events. These events are also at the origin of the consistent channel length and sinuosity increase recorded in that period. Considering the study reach from the upstream end to Castelnuovo Scrivia, in the period from 1922 to 1999 a general trend of consistent narrowing and of progressive decrease of channel lateral mobility is registered. A relevant increase in channel stability is noticed. Nonetheless, banks became gradually closer due to the above-mentioned narrowing process and this avoided a generalized lowering of channel centerline migration rate. Furthermore, the reduction in HMZ occupancy by both active channel and partial HMZ of consecutive time steps confirms narrowing and stabilization respectively.

Downstream of Castelnuovo Scrivia towards the Po River different dynamics are registered. Meandering occurred up to 1977 with lateral shifts and cut-offs. Channel width decreased significantly in reach 8 up to 1954 and after that a lower reduction is registered until 1977. The last two reaches show low fluctuations around the mean value of about 50 m, except for the 10th reach in 1922 whose width is influenced by previously described dynamics. From 1977 up to 1999, a slight increase in channel width was followed by narrowing and a lack of channel-bend evolution.

The well-recognizable disruption of morphological trends in 1977 and between 1977 and 1980 is due to the flood of the 7th and 8th of October 1977, which was one of the most relevant recent floods and triggered diffuse bank erosion processes along the whole study reach.

Since the 2000s trends have changed. A morphological restoration is recorded collectively by all considered parameters. This reversal trend was triggered by some relevant floods, in particular the consecutive events that occurred from 2010 to 2014. These events reactivated geomorphological processes modelling bars, wetted channels, and banks. In particular, between 2012 and 2016, numerous and locally very intense bank retreat processes are registered. However, in recent years (i.e. since the 2000s) no avulsions or cutoff occurred and cumulative curves of centerline migration register generally a gradual shift with only a few steps related to locally intense bank retreat processes.

Aerial photographic analysis highlights that already before the 1950s the lateral migration of the Scrivia was controlled by bank protections. Initially groynes and, from the 1970s and 1980s onwards, prisms of concrete used as ripraps, heavily conditioned lateral dynamics stabilizing riverine areas. Generally, this active channel stabilization, together with narrowing, led to a gradual disconnection between riverbed and adjacent areas. It means that the active floodplain changed into recent terrace and that parts of the active channel changed into modern floodplain. This kind of morphological evolution is usually related to an incision process (Hupp, 1999; Simon and Darby, 1999; Hupp and Rinaldi, 2007) that, indeed, affected the Scrivia River in the second half of the 20th century, certainly promoted by an intense sediment mining activity. Consequently, riverine areas were colonized for agriculture, to create quarries or to locate facilities and infrastructure, increasing the level of river related risk. Nowadays the main critical issues are near Tortona, where industrial areas, highways and dumps are located close to the bank edge. Elsewhere agriculture spread up to the riverbed. Especially in the second half in the 20th century a diffuse and almost always illegal practice of farmers occupying the terrain left by rivers is documented ("Speciale Parco dello Scrivia", 1987; Ente Riserve Naturali Garzaia di Valenza e Garzaia di Bosco Marengo, 1988;

Mandarino, 1995). These facts are the reason for a growing protest from the 1970s to the end of the 1980s. Supported by two municipalities, the protest led to the institution of limited areas to preserve fluvial, i.e. state-owned, plots of land.

These morphological adjustments led to a variation in channel type generally from multithread to transitional or single-thread pattern for some reaches. It occurred just where sediment mining activity, bridge-associated check dams, facilities and infrastructure were concentrated, e.g. mainly in the central part of the study reach. Furthermore, channelization caused a decrease in sinuosity downstream of Castelnuovo Scrivia.

Recent widening, triggered by floods and underlined by the presence of diffuse high and steep retreating banks along the River (particularly downstream the 7th reach) can be interpreted as a morphological response to alterations and to riverbed narrowing and lowering. Nowadays the River is widening where it is possible involving both the recent terrace and the modern floodplain formed in-channel during the recent decades of channel incision and narrowing. Bank protection structures are often undercut at their base or they are already collapsed. For this reason, in approximately the last 10-15 years, further bank protections were built locally in order to stabilize some natural banks or to restore ancient defenses. This is the origin of the channel widening and the increase in activity noticed between 2007 and 2012 in reaches 8 and 9. Today 52 % of the Scrivia River banks are protected. The least channelized reach is the second reach. Here a high diversity of fluvial forms can be observed. This reach, indeed, assumes a great naturalistic relevance and has been recognized as one of the Natura 2000 European Network sites. From the 3rd reach up to the Po River high percentages of protected banks are registered ranging between 47% to 71% of total banks (sum of left and right) length, always higher than 60% downstream of the 6th reach.

CONCLUSIONS

This study highlights channel planform changes that occurred along the Scrivia River floodplain reach over the last 138 years, from 1878 to 2016. A detailed multitemporal analysis of historical maps, aerial photos and satellite images was performed in a GIS environment and supported by field surveys. This multitemporal analysis allowed: i) quantitative and accurate definition of the medium and short term evolutionary trends (Winterbottom, 2000) and ii) assessment of ongoing dynamics (Rinaldi et al., 2014). Various parameters concerning channel planform features were computed both automatically and semi-automatically through a FOSS GIS-based procedure.

Three well-defined periods of active channel evolution in the Scrivia River have been outlined: 1) from 1878 to the 1950s; 2) from the 1950s to the end of 1990s; 3) from the end of 1990s onwards. In the first period the river was generally able to migrate in its floodplain shaping the riverscape and even if people acted to gain land and to use the river resource, we cannot exclude that those morphological variations were due to natural processes. Since groynes are documented already in the 1954 aerial photos, it is likely that in the last part of the first period already a diffuse bank stabilization process started. Active channel narrowing, progressive blocking of lateral dynamics and resulting increase in channel stability characterize the second period. Narrowing affected consistently all reaches between Cassano Spinola and Castelnuovo Scrivia, whereas a reduction in braiding degree is registered in some reaches. Downstream of Castelnuovo Scrivia meandering processes were blocked from the 1970s onwards. In this stage, particularly between the 1960s and the 1980s, the Scrivia River was heavily affected by human alterations consisting mainly of severe in-channel sediment mining activity, channelization works, and consecutive occupation of old channels and of areas of fluvial pertinence left out of fluvial dynamics. The most recent period shows a reversal of the evolutionary trend. This is characterized by reactivation of stabilized surfaces and by diffuse bank erosion processes that caused local channel widening and reactivation of lateral dynamics blocked for decades.

The outlined active channel planform evolution generally follows the morphological trends displayed by most of Italian and European rivers for the same period, as reported in detail by

Pellegrini et al. (2008) and Cencetti et al. (2017). Considering the morphological response of rivers to human disturbance (Surian and Rinaldi, 2003) it is evident that the morphological evolution of the Scrivia River over the last 138 years has been heavily influenced by documented human activities. Sediment mining, channelization and consequent occupation of riverine areas are certainly a relevant cause of such consistent and fast morphological changes. Floods also played an important role in triggering the main processes and in distributing morphological responses to human alterations along the entire riverbed (Kondolf, 1994). In particular, the extreme floods that occurred in 1977 and from 2010 to 2014 represent relevant factors in the morphological evolution of the Scrivia River.

In order to understand the triggering factors of morphological changes further research is planned to investigate accurately variations in i) driving forces and ii) boundary conditions over the considered time period (Thorne, 1997; Rinaldi et al., 2014). In particular, the systematic work of collecting data about historical in-channel alterations from historical sources is ongoing. Furthermore, available riverbed elevation data are being processed in order to investigate bed level variations. The difficulty in finding information concerning climate and land-use changes at basin scale substantially slows the analysis of these factors. Next steps are also intended to investigate in detail the most recent riverbed changes, whose triggering factors are still quite debated in scientific literature (Bollati et al., 2014; Clerici et al., 2015).

As documented by (Ziliani and Surian, 2012; Bollati et al., 2014) for other Italian rivers that experienced similar trends, the present day evolution phase represents a partial recovery of morphological processes, e.g. the Scrivia River response to severe channel alterations. However, after decades of stability, narrowing and blocked dynamics it seems unthinkable for people that the river can move in its floodplain where, in the meantime, agriculture, facilities and infrastructure have often spread up to the bank edges. For cultural, historical and economic reasons, people bordering the river ask for new but “old school” interventions, such as new bank protections and/or dredging activities, to stabilize the ongoing dynamics. In this light the complaints of neighboring people and local governments stating: “the river has always been there”, have to be questioned. As documented in this research it is obviously not the case. Our findings are of potential great importance especially in terms of river management. Moreover, our results might be considered also in urban planning processes and be disseminated widely in order to raise the people’s awareness about rivers. Finally, if people understand river dynamics the execution of sustainable and effective river management strategies aiming to mitigate risks and restore the fluvial environment is much easier. This is particularly relevant especially in regard to the European Water Framework Directive (WFD) and the European Flood Directive (FD) (European Commission, 2000, 2007; Hooke, 2008).

ACKNOWLEDGMENTS

The authors thank Luisa Pellegrini (University of Pavia) who provided numerous information, maps and aerial photos concerning the Scrivia River. Furthermore, they sincerely thank the Senior Editor Lewis Owen, the Guest Editor David Bridgland and two anonymous reviewers for their detailed and helpful comments and suggestions that substantially improved the manuscript.

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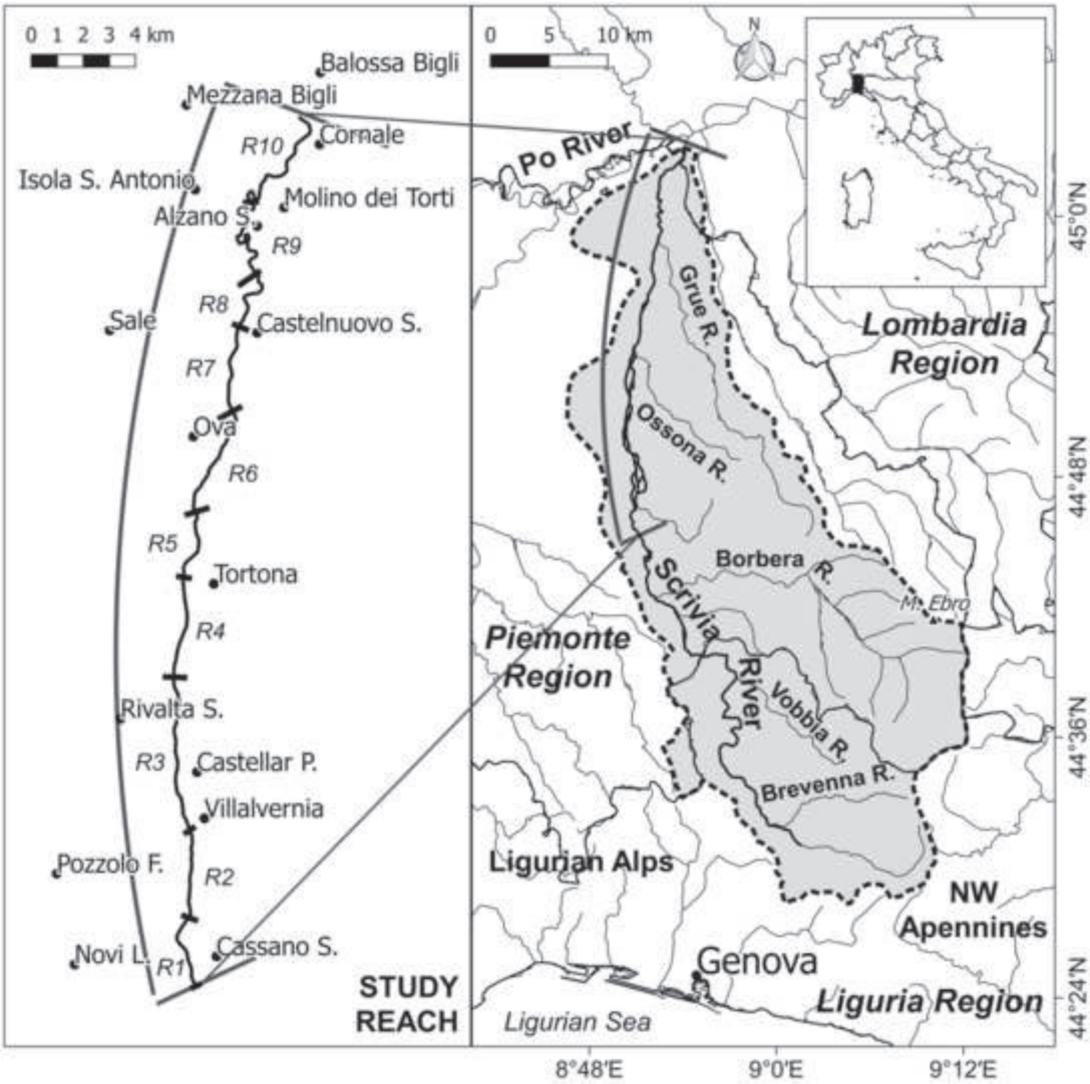
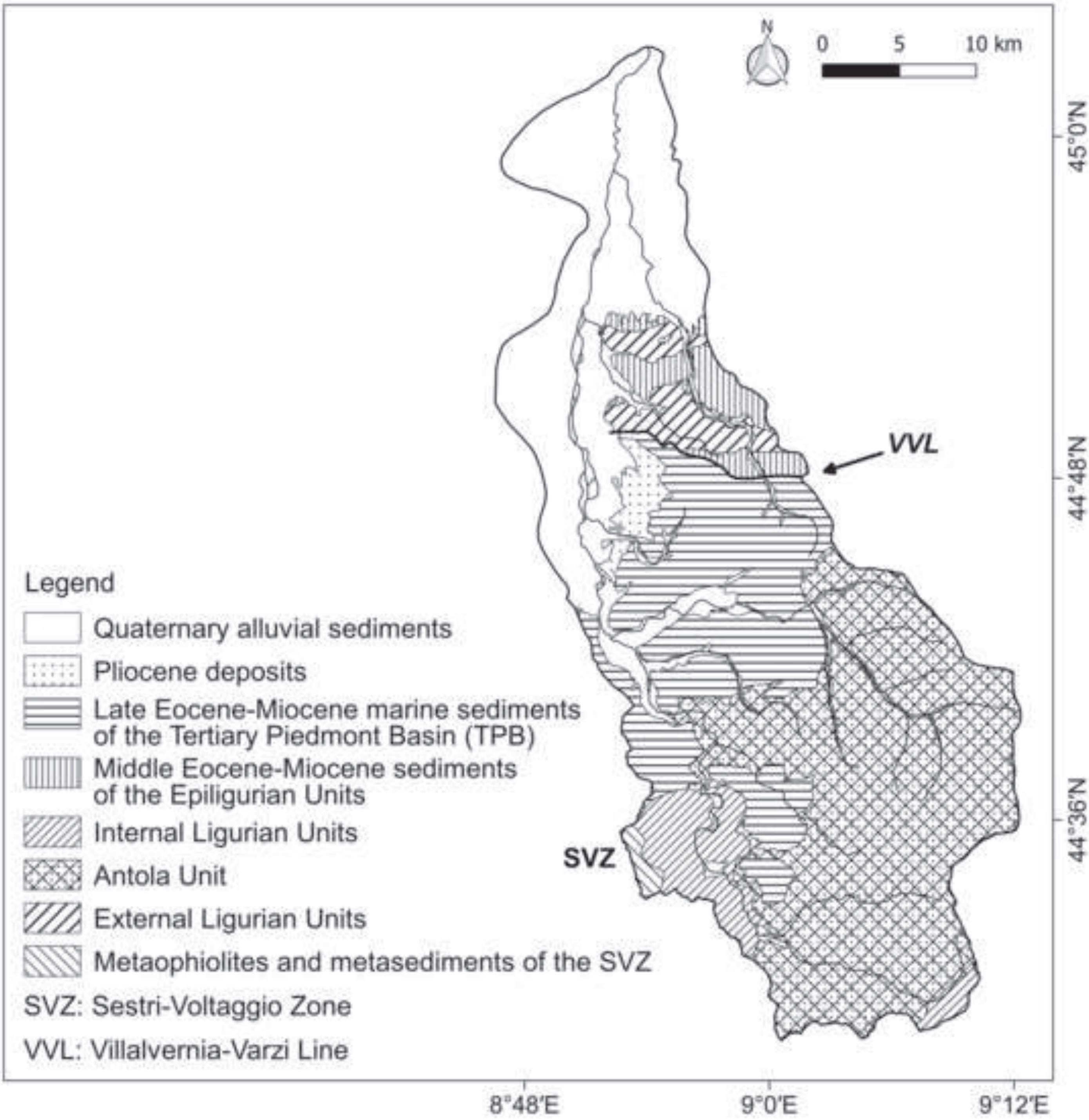
Table

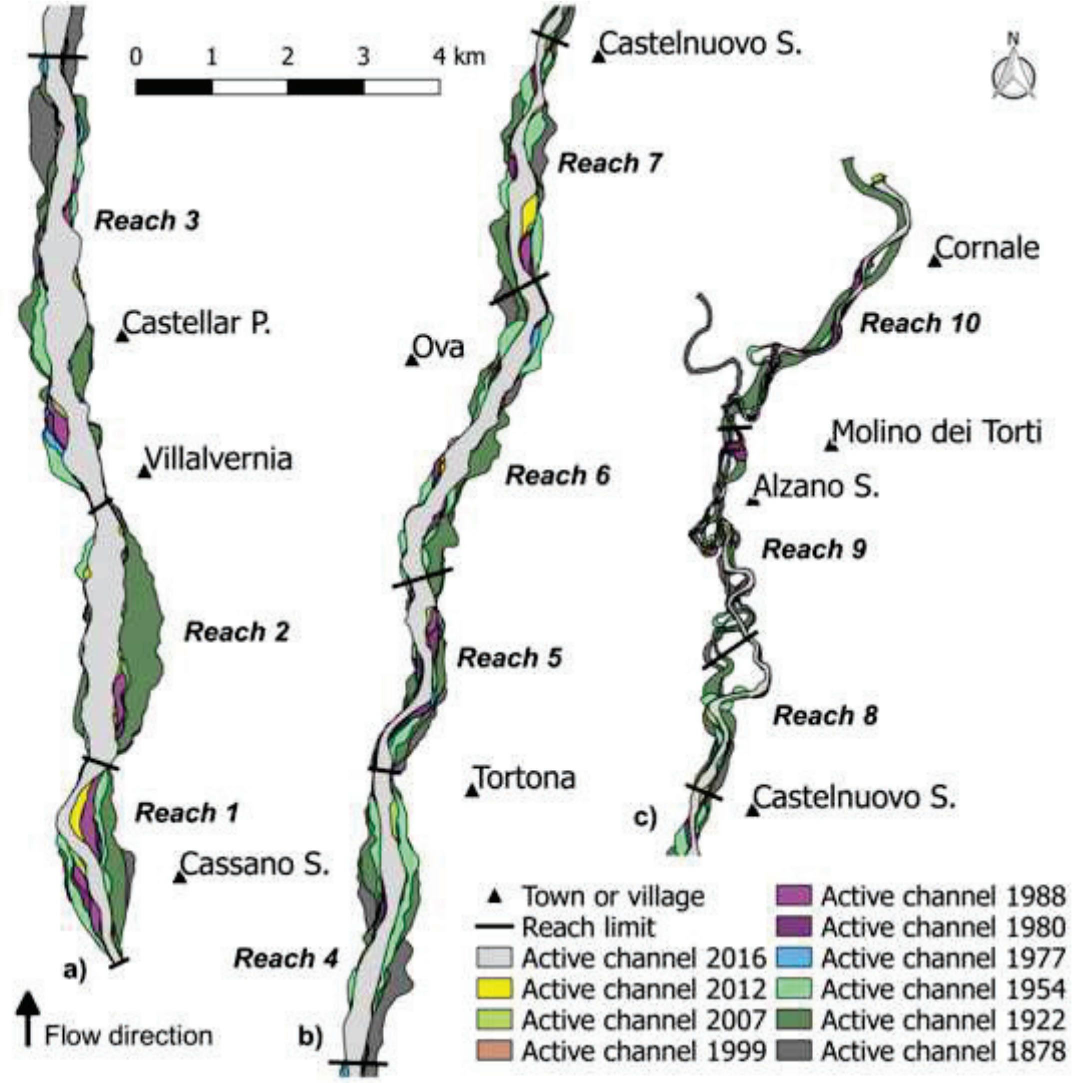
Reach number	Length (m)	Upstream limit (m)	Downstream limit (m)	Average width (m)	Area (ha)	Sinuosity Index*	Braiding Index*	Channel type**
1	2967	0	2967	158	46.95	1.1	1.2	W
2	3427	2967	6394	404	138.64	1.0	2.8	B
3	6095	6394	12489	325	198.19	1.0	1.9	B
4	3939	12489	16428	241	95.28	1.0	1.5	W
5	2790	16428	19218	166	46.39	1.1	1.3	W
6	4388	19218	23606	241	106.17	1.1	1.4	W
7	3435	23606	27041	149	51.42	1.0	1.2	SAB
8	2748	27041	29789	80	22.22	1.4	1.1	SAB
9	4648	29789	34437	41	19.18	1.6	1.0	M
10	5448	34437	39885	45	24.57	2.0	1.0	M

*Sinuosity Index and Braiding Index are dimensionless parameters.

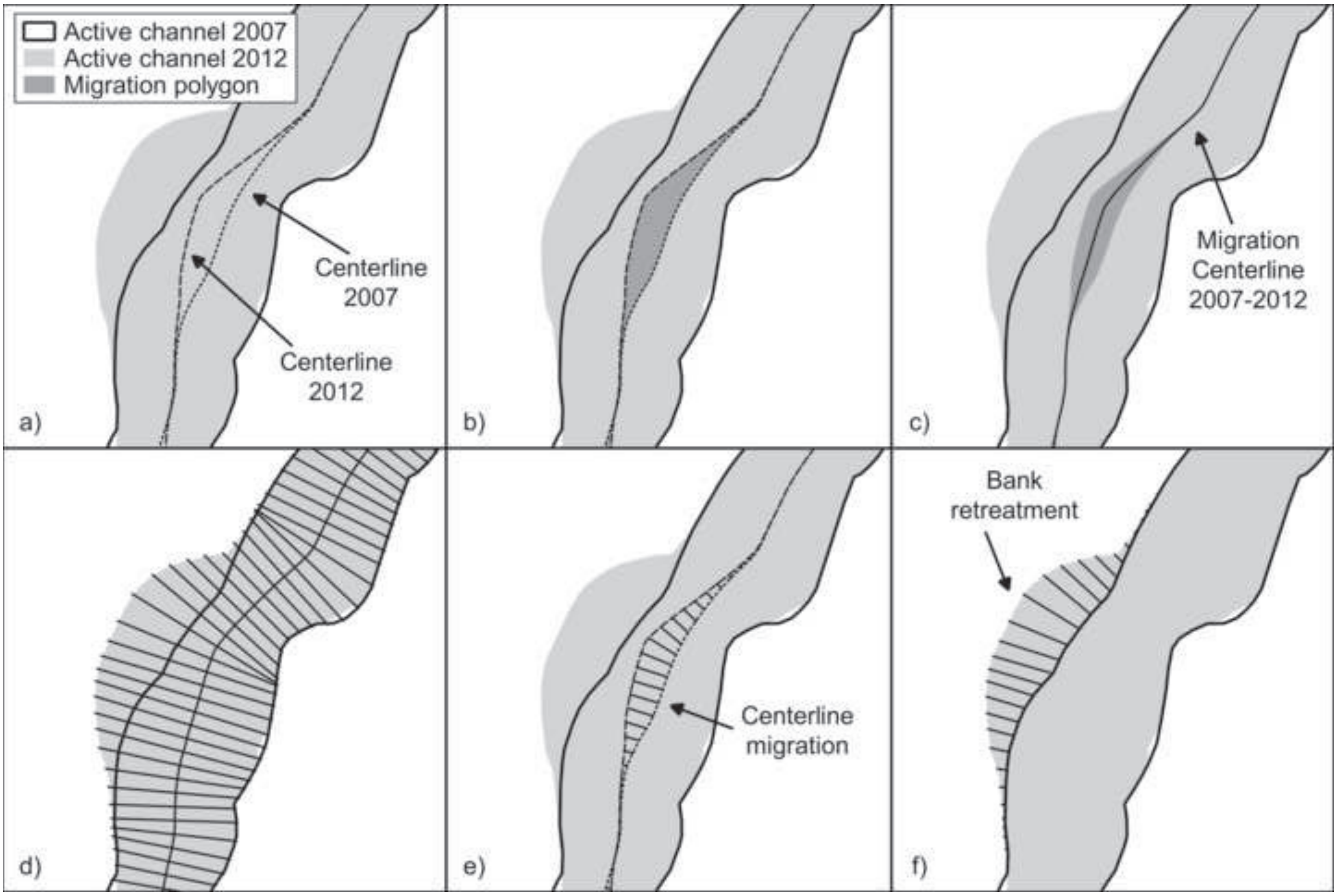
** Channel type: Wandering (W); Braided (B); Sinuous with alternate bars (SAB); Meandering (M).

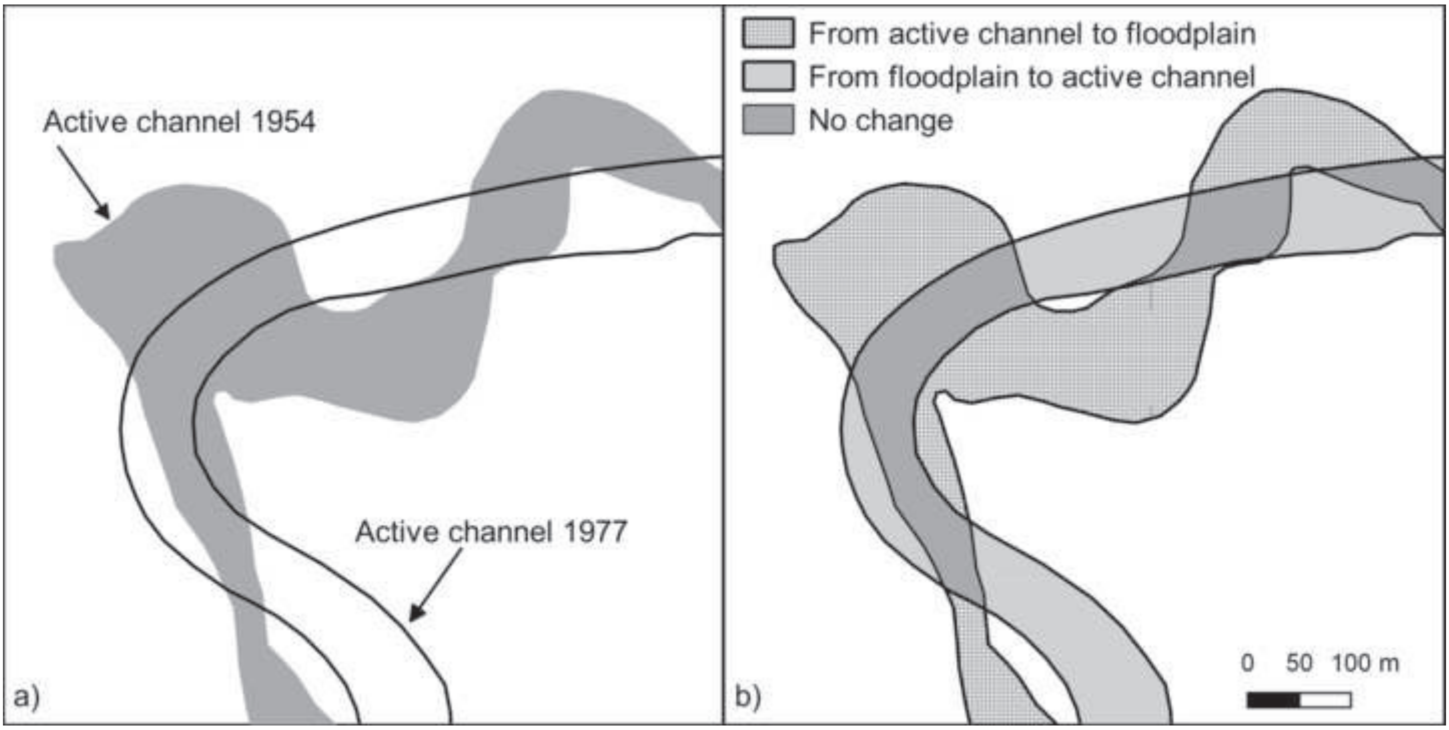

0 1 2 3 4 km
Balossa Bigli
Mezzana Bigli
Cornale
R10
Isola S. Antonio
Molino dei Torti
Alzano S.
R9
R8
Sale
Castelnuovo S.
R7
Ova
R6
R5
Tortona
R4
Rivalta S.
R3
Castellar P.
Villalvernia
Pozzolo F.
R2
Cassano S.
Novi L.
R1
STUDY REACH
0 5 10 km
N
Po River
Grue R.
Ossona R.
Borbera R.
M. Ebro
Scrivia River
Vobbia R.
Brevenna R.
Lombardia Region
Piemonte Region
Ligurian Alps
NW Apennines
Genova
Liguria Region
Ligurian Sea
45°0'N
44°48'N
44°36'N
44°24'N
8°48'E
9°0'E
9°12'E

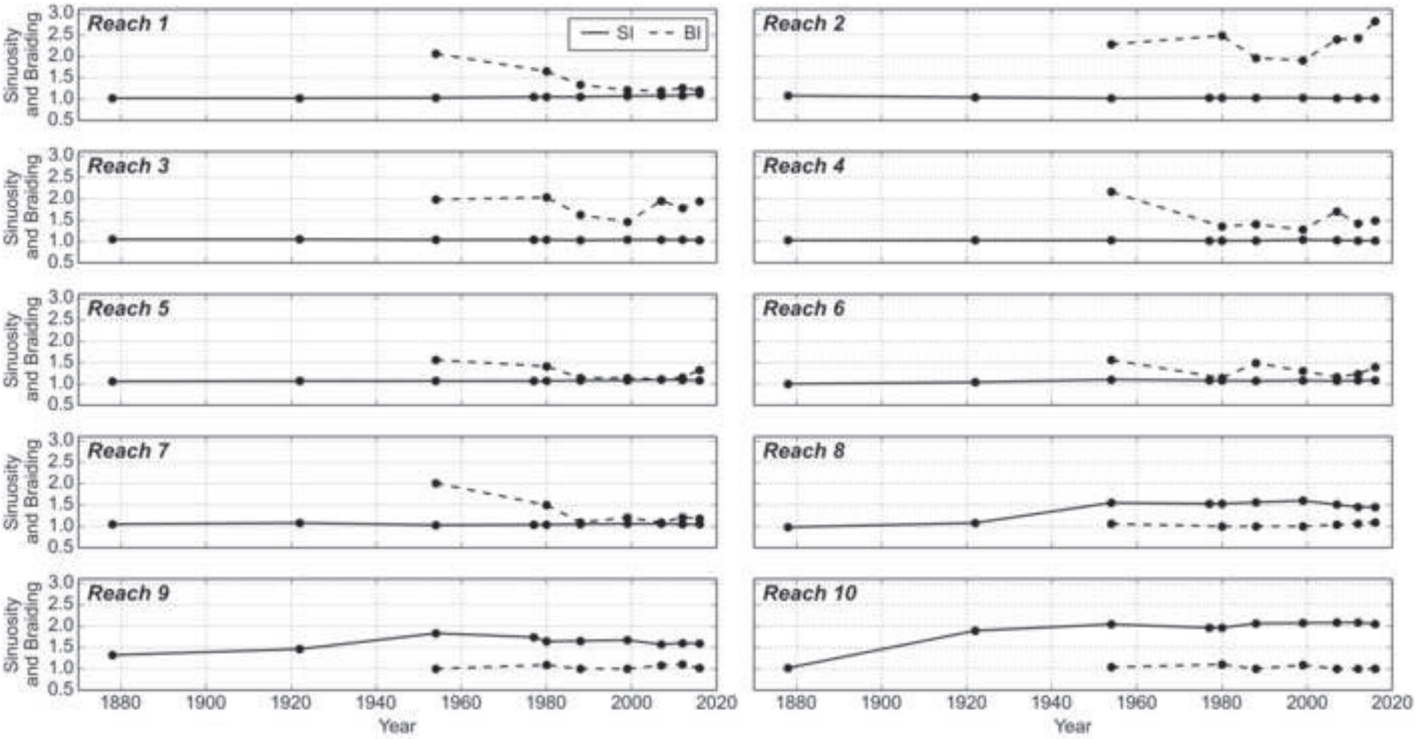

N
0
5
10 km
45°0'N
44°48'N
44°36'N
VVL
SVZ
Legend
Quaternary alluvial sediments
Pliocene deposits
Late Eocene-Miocene marine sediments of the Tertiary Piedmont Basin (TPB)
Middle Eocene-Miocene sediments of the Epiligurian Units
Internal Ligurian Units
Antola Unit
External Ligurian Units
Metaophiolites and metasediments of the SVZ
SVZ: Sestri-Voltaggio Zone
VVL: Villalvernia-Varzi Line
8°48'E
9°0'E
9°12'E

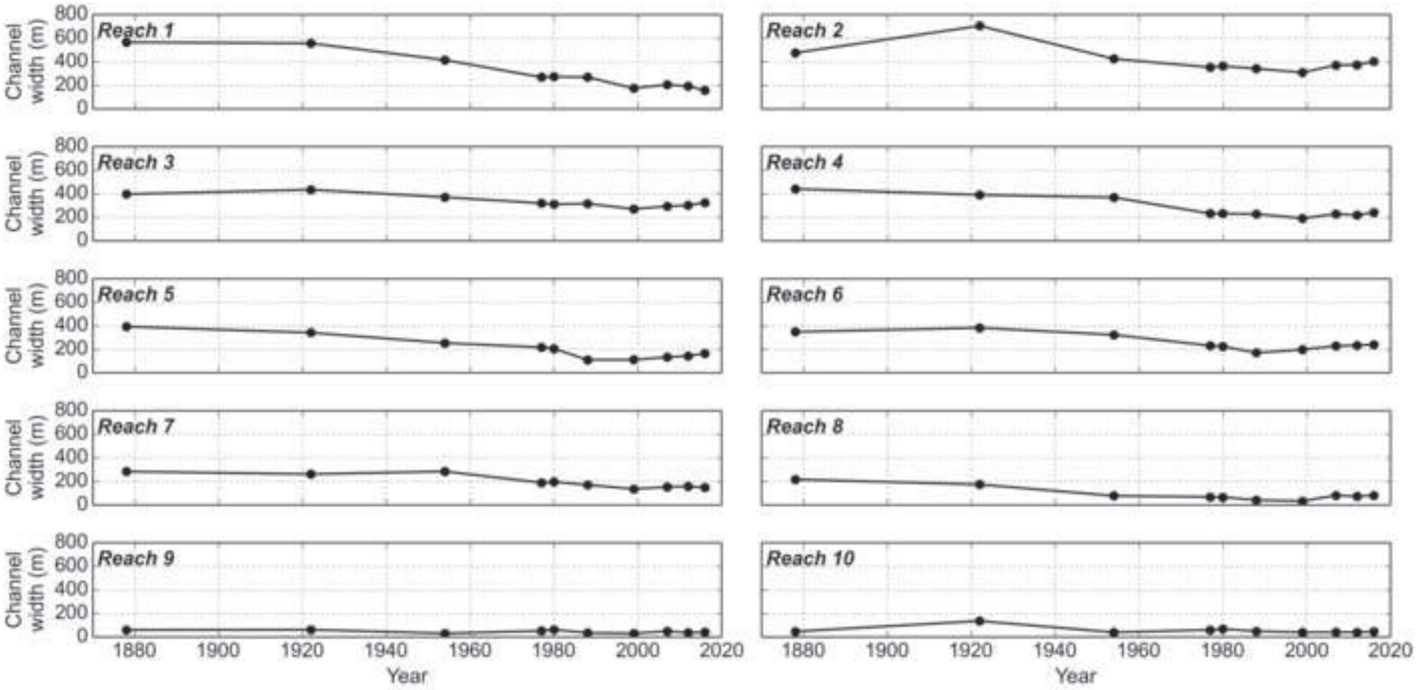

0 1 2 3 4 km
N
Castelnuovo S.
Reach 3
Castellar P.
Villalvernia
Reach 2
Reach 1
Cassano S.
a)
Flow direction
Reach 7
Ova
Reach 6
Reach 5
Tortona
Reach 4
b)
Cornale
Reach 10
Molino dei Torti
Alzano S.
Reach 9
Reach 8
Castelnuovo S.
c)
▲ Town or village
— Reach limit
Active channel 2016
Active channel 2012
Active channel 2007
Active channel 1999
Active channel 1988
Active channel 1980
Active channel 1977
Active channel 1954
Active channel 1922
Active channel 1878

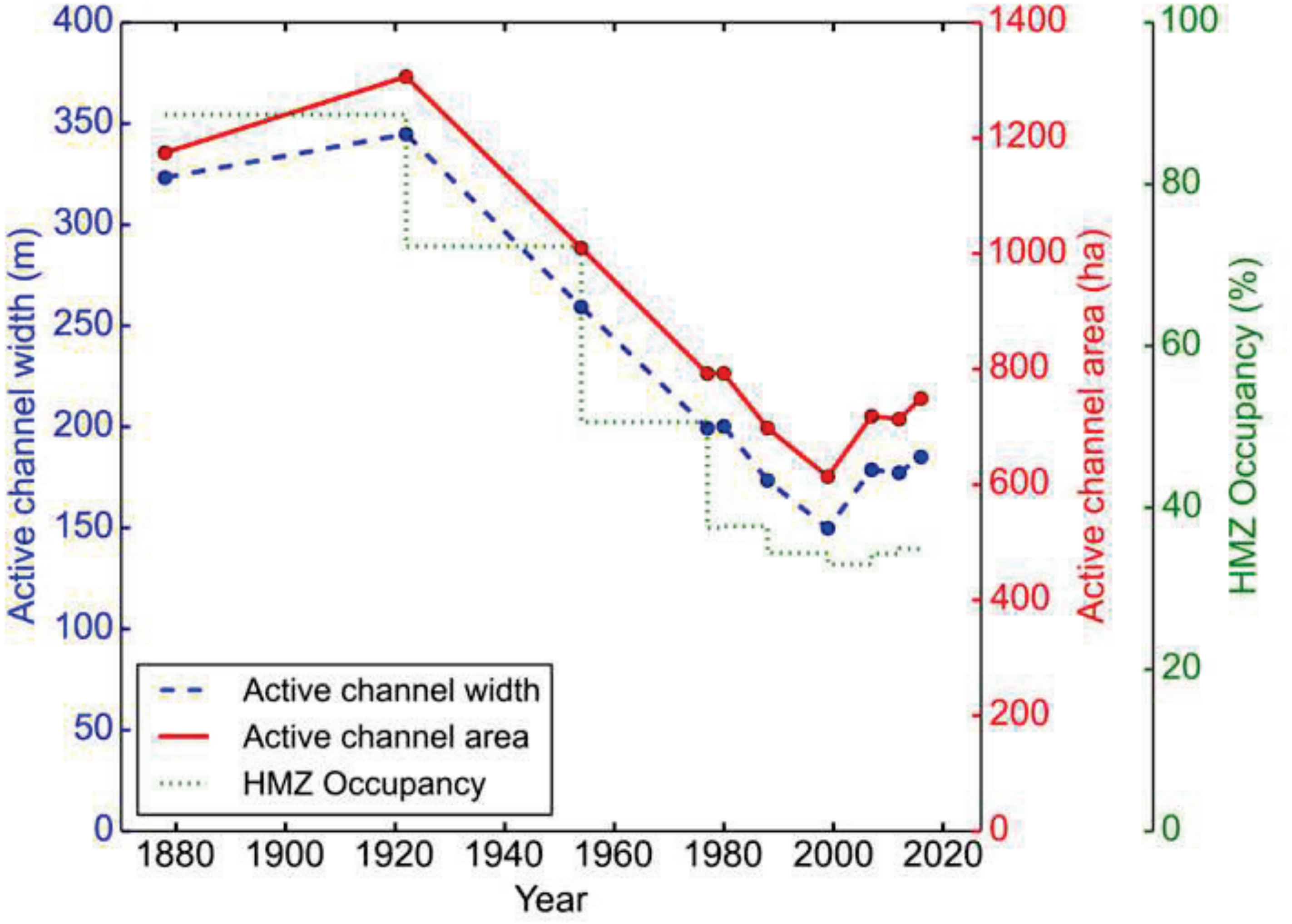
Figure

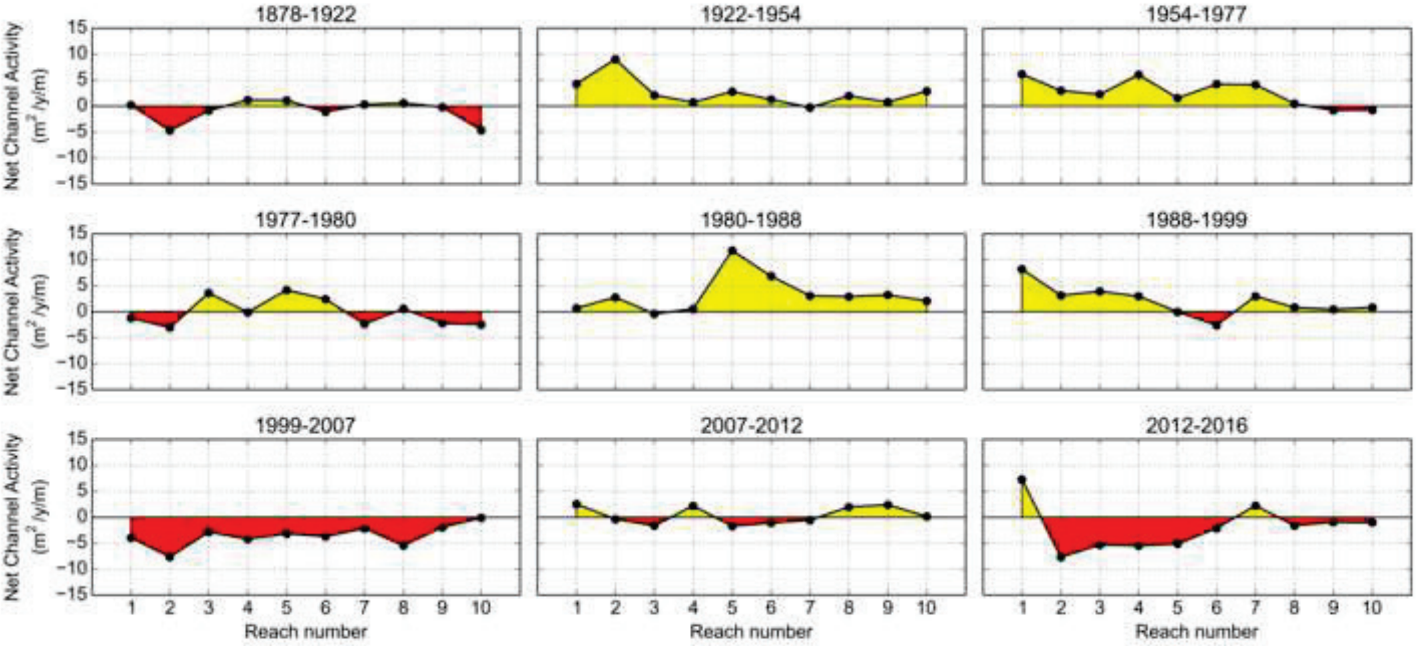

Active channel 2007
Active channel 2012
Migration polygon
Centerline 2007
Centerline 2012
a)
b)
Migration Centerline 2007-2012
c)
d)
Centerline migration
e)
Bank retreatment
f)

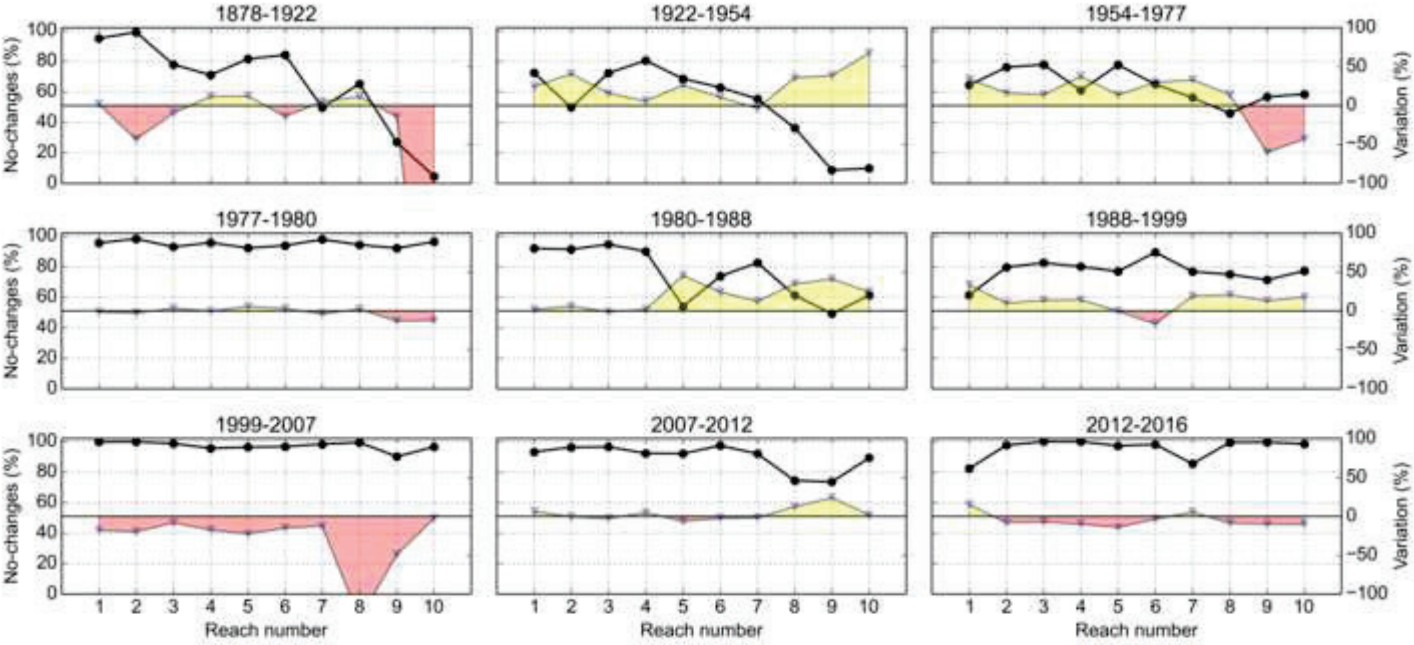

Active channel 1954
Active channel 1977
a)
b)
From active channel to floodplain
From floodplain to active channel
No change
0 50 100 m

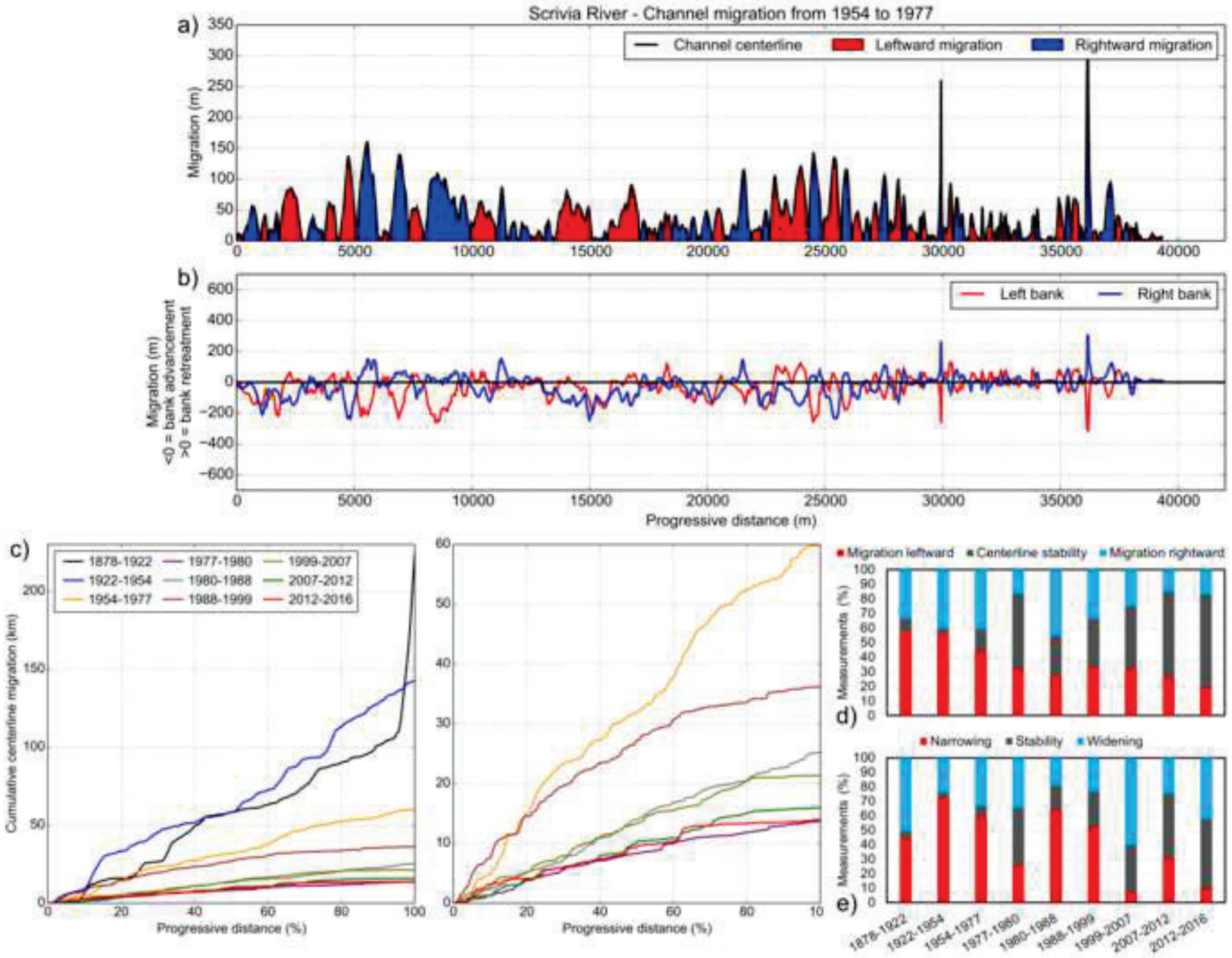

Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Reach 7
Reach 8
Reach 9
Reach 10
SI
BI
Sinuosity and Braiding
3.0
2.5
2.0
1.5
1.0
0.5
1880
1900
1920
1940
1960
1980
2000
2020
Year

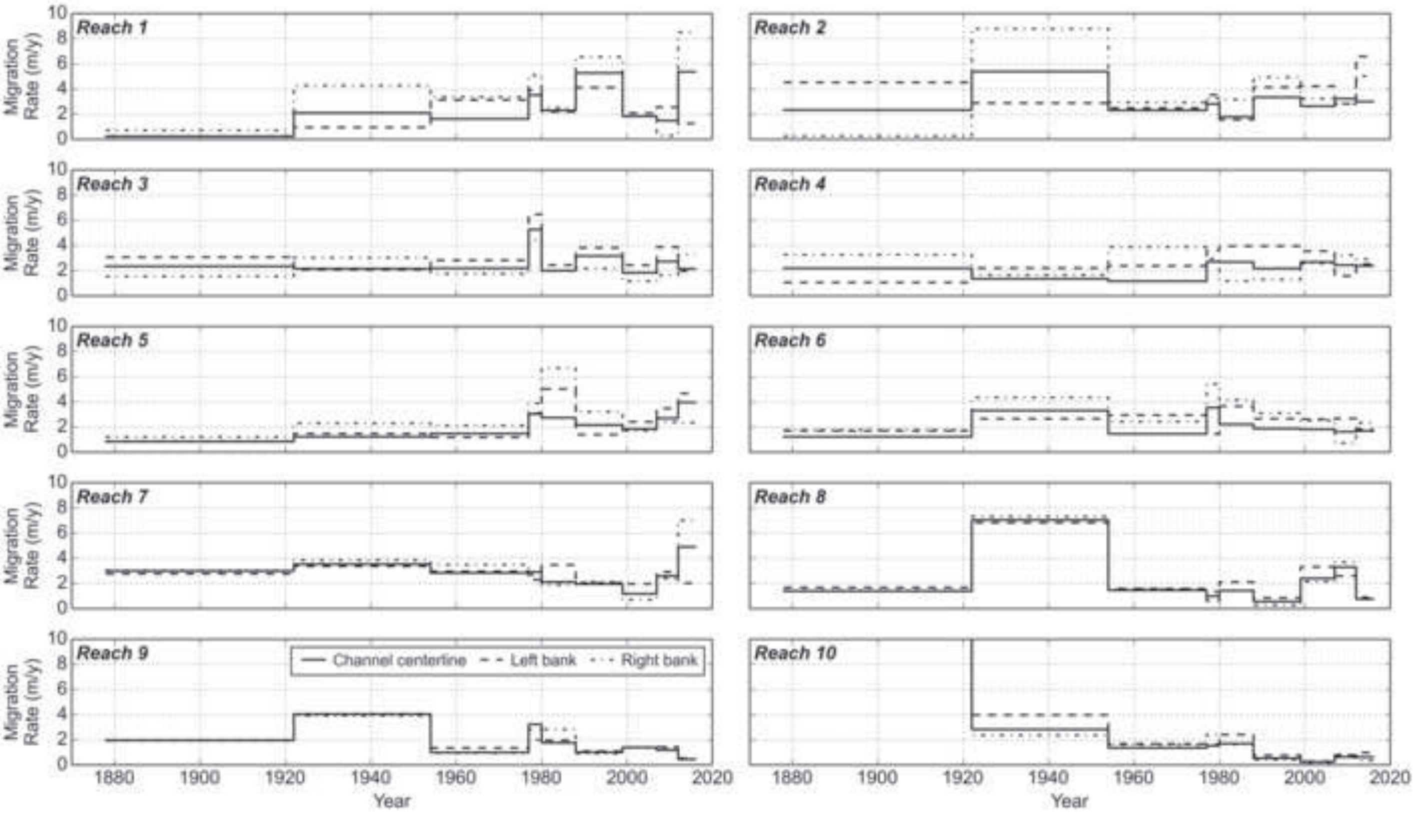

Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Reach 7
Reach 8
Reach 9
Reach 10
Channel width (m)
0
200
400
600
800
1880
1900
1920
1940
1960
1980
2000
2020
Year

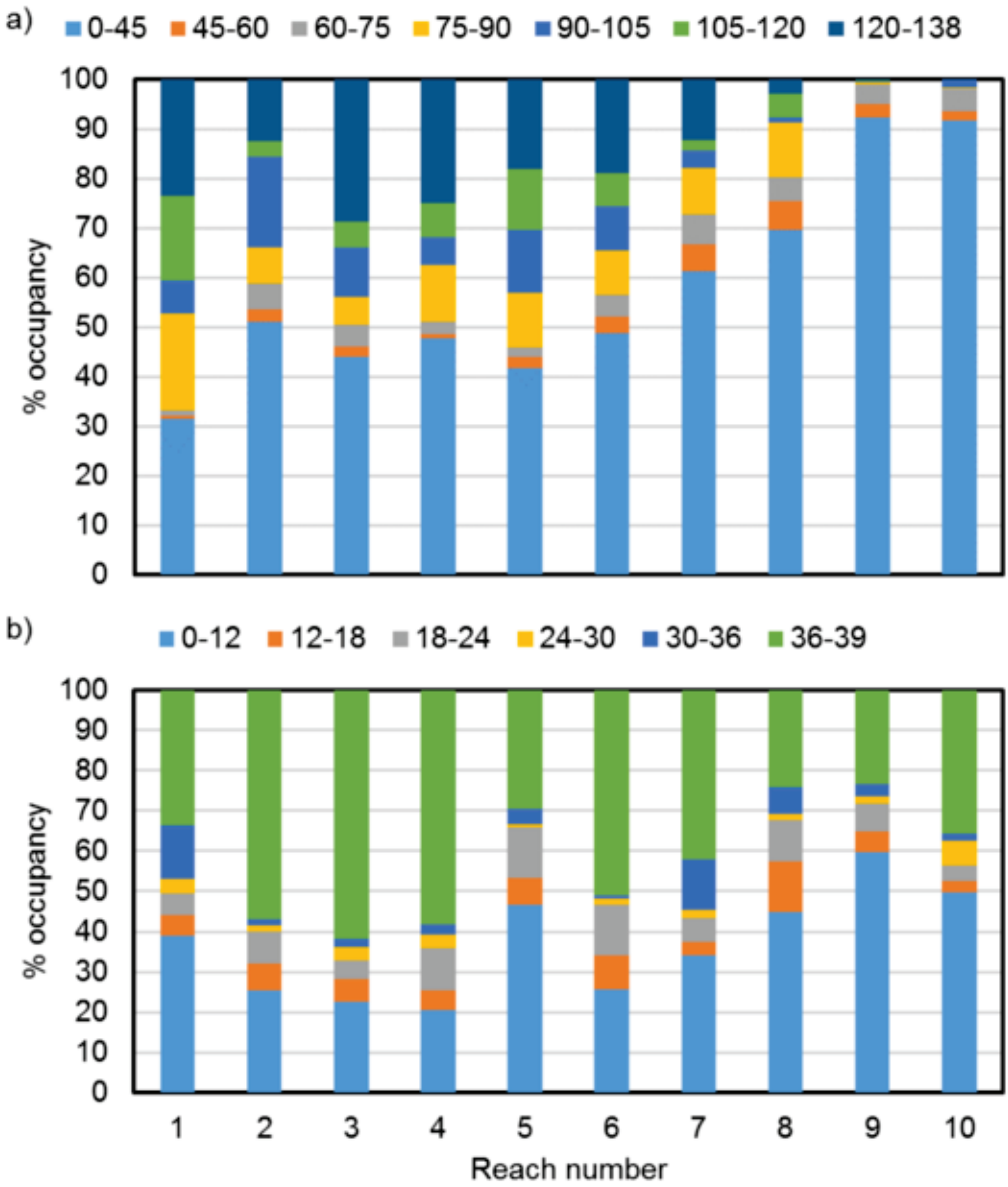

400
350
300
250
200
150
100
50
0
Active channel width (m)
1400
1200
1000
800
600
400
200
0
Active channel area (ha)
100
80
60
40
20
0
HMZ Occupancy (%)
1880
1900
1920
1940
1960
1980
2000
2020
Year
Active channel width
Active channel area
HMZ Occupancy


1878-1922
1922-1954
1954-1977
1977-1980
1980-1988
1988-1999
1999-2007
2007-2012
2012-2016
Net Channel Activity (m^2/y/m)
15
10
5
0
-5
-10
-15
1
2
3
4
5
6
7
8
9
10
Reach number


1878-1922
1922-1954
1954-1977
1977-1980
1980-1988
1988-1999
1999-2007
2007-2012
2012-2016
No-changes (%)
Variation (%)
Reach number
0
20
40
60
80
100
−100
−50
0
50
100
1
2
3
4
5
6
7
8
9
10


Scrivia River - Channel migration from 1954 to 1977
a)
Channel centerline
Leftward migration
Rightward migration
Migration (m)
0
50
100
150
200
250
300
350
0
5000
10000
15000
20000
25000
30000
35000
40000
b)
Left bank
Right bank
Migration (m)
<0 = bank advancement
>0 = bank retreatment
600
400
200
0
−200
−400
−600
Progressive distance (m)
c)
1878-1922
1922-1954
1954-1977
1977-1980
1980-1988
1988-1999
1999-2007
2007-2012
2012-2016
Cumulative centerline migration (km)
Progressive distance (%)
0
20
40
60
80
100
50
150
200
10
30
Migration leftward
Centerline stability
Migration rightward
Measurements (%)
d)
Narrowing
Stability
Widening
e)
1878-1922
1922-1954
1954-1977
1977-1980
1980-1988
1988-1999
1999-2007
2007-2012
2012-2016


Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Reach 7
Reach 8
Reach 9
Reach 10
Migration Rate (m/y)
0
2
4
6
8
10
Channel centerline
Left bank
Right bank
1880
1900
1920
1940
1960
1980
2000
2020
Year


a)
0-45
45-60
60-75
75-90
90-105
105-120
120-138
% occupancy
0
10
20
30
40
50
60
70
80
90
100
b)
0-12
12-18
18-24
24-30
30-36
36-39
% occupancy
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
Reach number