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Article

Short-Term GIS Analysis for the Assessment of the Recent Active-Channel Planform Adjustments in a Widening, Highly Altered River: The Scrivia River, Italy

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Abstract: From the 1990s onwards several Italian rivers have experienced a recent phase characterized by active-channel widening and, generally, by bed-level stability or slight aggradation. However, its triggering factors and its diffusion, along with the relationship between active-channel planform dynamics and vertical adjustments, are still quite debated and only few studies are available. This research deals with the active-channel planform changes occurred along the Scrivia River floodplain reach (NW Italy) over the period 1999–2019 and it aims at investigating in detail the ongoing geomorphological processes under the river management perspective. The study is based on a quantitative multitemporal analysis of aerial photographs and satellite images performed in a GIS environment and supported by field surveys. The outcomes revealed a generalized trend of gentle active-channel widening together with widespread bank instability and several (26% of total banks) intense and localized bank retreats involving both the modern floodplain and the recent terrace. In the investigated 20-year period, the active-channel area has increased by 22.7% (from 613.6 to 753.0 ha), its mean width by 25% (from 151.5 to 189.3 m), whereas no relevant length variations have been noticed. These morphological dynamics have been more or less pronounced both at reach scale and over time. The extreme floods occurred in the investigated period can be considered the most important triggering factor of the active-channel planform changes, most probably together with an increase of the reach-scale unit stream power due to changes in the channel geometry occurred over the 20th century.

Keywords: channel changes; channel widening; controlling factors; river management; evolutionary trajectories; Italian rivers; Scrivia River

1. Introduction

The analysis of past and present fluvial landforms and geomorphological processes provides essential information to carry out sustainable and effective measures of both land planning and fluvial-environment management [1–8]. For many years, numerous researchers have been investigating riverbed changes over time in order to: (i) understand the ongoing dynamics, (ii) define the evolutionary trends, (iii) comprehend the fluvial response to the variation of driving forces and boundary conditions, and, last but not least, (iv) assess the role of anthropic interventions on fluvial dynamics [9–20]. Several studies reported in literature focus on riverbed adjustments occurred in historical time, that is over the past few centuries, at the so-called medium-term temporal scale [11,21]. However, aiming to precisely define the ongoing morphological dynamics, the most suited time span to consider for analyzing the riverbed adjustments ranges from the present-day to approximately 10–25 years ago [11,22,23].

Previous studies concerning the morphological evolution of Italian rivers outlined their main morphological tendencies over the last two centuries, that is substantially before the occurrence of the most intense and widespread anthropic interventions on fluvial systems. As reported by several authors [18,24–28], three evolutionary phases can be recognized: (i) the first one, from the last decades of the 19th century to the 1950s, is generally characterized by gentle narrowing and incision albeit, in some cases, no large-scale dominant processes are recognizable up to the beginning of the 20th century [18]; (ii) the second one, from the 1950s to the 1990s, presents the most relevant channel adjustments related to fast, severe and generalized narrowing and incision processes, coupled with a reduction in braiding degree and with an increase of sinuosity; (iii) the third one, from the 1990s onwards, shows a reversal trend since it is characterized by active-channel widening and by an overall slight aggradation or bed-level stability; however, this latter phase is documented only along some rivers [25,29,30].

The causes behind the 20th century channel changes are now widely documented [18,21] and have been recognized in the reduction of the sediment budget due to in-channel quarrying activity [19,31], occupation of areas of fluvial pertinence [21,32], channelization [19,33,34], land-use changes at catchment scale [16,30,35–38] and building of cross works such as weirs and dams [39–41]. On the contrary, the triggering factors of the most recent phase are still quite debated in the scientific literature [29,30] and according to previous research could be related to: (i) the end of the in-channel sediment mining for commercial purposes, which is dated back around the late 1980s–early 1990s [20,42,43], (ii) changes in the riverbed geometry resulting in an increase of unit stream power [44], and/or (iii) the occurrence of large flood events [21,24,25,29,30].

This study investigates in detail the active-channel planform adjustments occurred from 1999 to 2019 along the Scrivia River floodplain reach (northwestern Italy) by means of a multitemporal analysis of aerial photographs and satellite images performed in a GIS environment and supported by field surveys. This fluvial stem is characterized by a large geomorphological variety presenting a multi-thread, transitional, and single-thread channel pattern moving downstream-ward. As reported in previous studies [32,45], the examined reach experienced the aforementioned morphological evolutionary stages, including the most recent one. Furthermore, during the 20th century, and particularly between the 1960s and the 1980s, the study reach was severely affected by human pressures, mainly consisting of sediment removal, channelization and consecutive occupation of riverine areas.

Nowadays, the active channel is affected by intense and localized bank retreats and widespread bank instability processes. The current morphological dynamics are raising serious management issues in a densely cultivated and urbanized landscape as the Scrivia River floodplain is.

In this framework, this research aims to accurately characterize the ongoing morphological processes along such river and to identify the most probable triggering factors. The outcomes of this study are expected to increase the knowledge about the most recent evolutionary phase registered for the Italian rivers and to provide useful information under the river management perspective.

2. Study Area

The Scrivia River basin is located in the northwestern sector of Italy (Figure 1a), and it encompasses the territory of three important northern Italian regions: Liguria, Piemonte and Lombardia, spreading over about 1000 km^2. The main fluvial stem, i.e., the Scrivia River, has a length of about 90 km and rises in the upper part of the basin, within the territory of the Liguria region, at the confluence between the Laccio and Pentemina creeks. It flows approximately northward receiving all the major tributaries from the right side of the valley (i.e., Borbera River, Brevenna River, Vobbia River, Ossona River and Grue River) up to the confluence with the Po River, the most important and largest Italian watercourse.

The Scrivia River and its tributary Borbera River are among the best examples of braided rivers in north-western Italy.

The geologic setting of the Scrivia basin is characterized by the tectonic units involved both in the Alps and the Northern Apennines orogeny. The outcropping geologic formations belong to the Ligurian and Epiligurian Units and to the post-orogenic sedimentary successions of the Tertiary Piedmont Basin [46–50]. These geologic complexes overall consist of a wide range of sedimentary rocks such as shales, marls, marly limestones, mudstones, sandstones and conglomerates. The geologic setting is completed by deep marine marly clays of Pliocene age outcropping at the junction area between the hilly and mountainous part of the catchment and the floodplain. The latter is composed of fluvial deposits dated back to Quaternary.

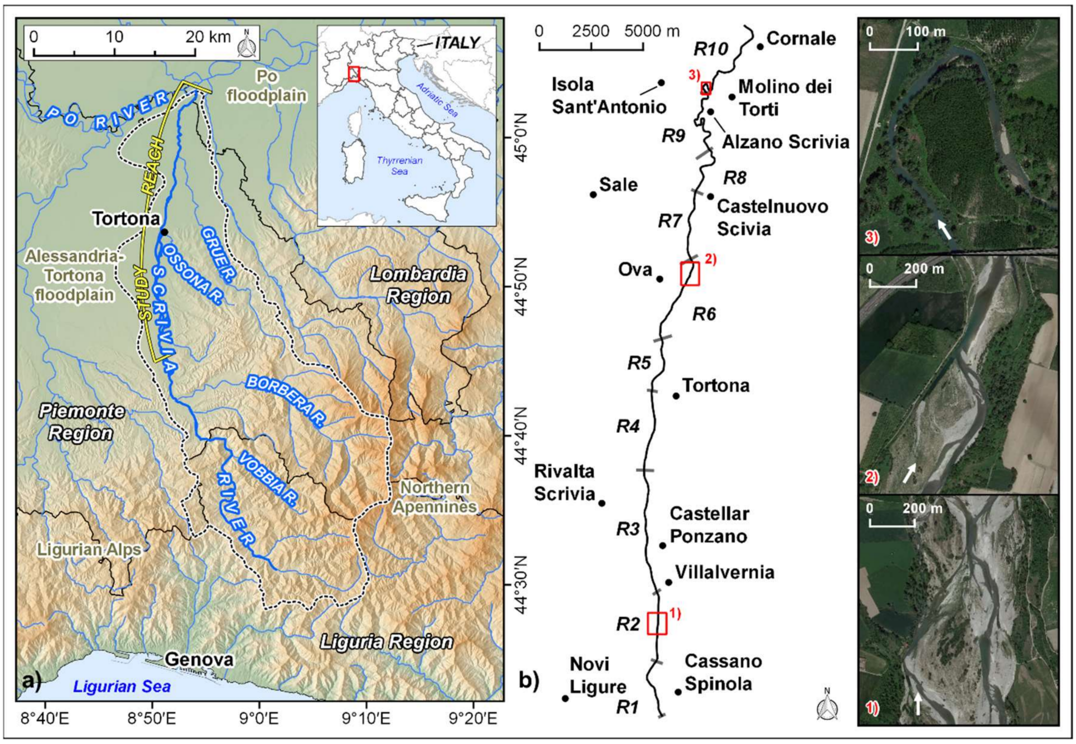

Figure 1. (**a**) Location of the study reach; (**b**) Delimitation of reaches characterized by homogeneous geomorphological features; the red frames highlight sites that are representative of the three major segments outlined along the study reach. See the text for explanation.

The landscape of the Scrivia River catchment is strongly influenced by the transition between the Northern Apennines and the Quaternary floodplain of Alessandria and Tortona. Overall, 80% of the basin area is hilly and mountainous while the remainder corresponds to the floodplain. From a geomorphological point of view, two main sectors can be distinguished along the main valley: (i) the upper sector, extending approximately from the main water divide, which separates the Scrivia basin from the Ligurian coastal Tyrrhenian basins, up to the regional border between Piemonte and Liguria, and (ii) the lower one, which begins where the main valley spreads out up to the outlet of the Scrivia River. The former is bounded by mountain peaks exceeding elevations of 1000 m a.s.l. and culminating with the highest elevation of Mt. Ebro (1700 m a.s.l.), and it is characterized by narrow and deep-incised valleys, where competent rocks (e.g., marly limestones and conglomerates) outcrop, and by wide and gentle valleys, often characterized by alluvial fans, in case of hilly landscapes made up of soft rocks. In this section of the basin, the Plio-Quaternary tectonic evolution strongly affected both the hydrographic network (e.g., abrupt changes in direction) and the basin morphology (e.g., basin asymmetry) [48,51–55]. The lower sector includes the main floodplain, where the Scrivia River becomes unconfined, and presents a series of wide fluvial terraces. These are mainly located on the left-bank, suggesting that during the Quaternary age the main river moved toward E-NE carving its fluvial sediments [56,57].

In terms of land use, the mountainous portions of the basin are prevalently covered by woods while cultivated areas are rare and somewhat scattered. On the contrary, both the hilly sectors and the floodplains are occupied by extensive agricultural areas. In the last few decades, many agricultural lands have been replaced by urban areas. Urbanization was particularly severe along the valley floors, where many buildings, together with primary and secondary road infrastructures, were constructed.

The climate setting of the Scrivia River catchment is substantially characterized by rainy and cold winters alternated with warm and dry summers [58,59]. The average annual rainfall is around 900 mm [60]. Generally, precipitations are more abundant during the autumn season. However, inside the basin an increase of the mean annual precipitation with altitude is observed, with values reaching approximately 1500–1700 mm in the upper sections, near the main water divide. Here, the orographic effects brought by the Northern Apennines, and the peculiar atmospheric circulation affecting the Ligurian Sea, frequently produce abundant and sometimes very intense precipitations [61–69].

According to the stream gauge of Guazzora, located approximately 5 km upstream of the Po confluence, and considering the monitoring period 2001–2018, the Scrivia River shows an average daily discharge of 13.7 m^3/s and a mean annual maximum discharge of 306.6 m^3/s. Due to exceptional rainfall events that often affect the upper part of the basin, the Scrivia River is highly prone to floods. During the last century, 12 main floods events were recorded (i.e., 1931, 1934, 1935, 1945, 1951, 1953, 1960, 1963, 1970, 1977, 1982 and 1993) [70,71] while since the beginning of the 2000s several intense floods are documented (i.e., 2000, 2002, 2009, 2010, 2011, 2013 and October–November 2014) [45]. The largest peak discharges refer to the 1945 and 1951 events, when 1800–1900 m^3/s (uncertain record) and 1650 m^3/s were registered, respectively. The main floods occurred from 2002 to 2014 reached a maximum water level ranging between 7.25 and 8.24 m at the aforementioned stream gauge (Figure 2). Here, the daily hydrometric level was 18 times higher than 5 m, 7 higher than 6 m and 1 higher than 7 m, according to available data covering the period 2001–2018 (Figure 2).

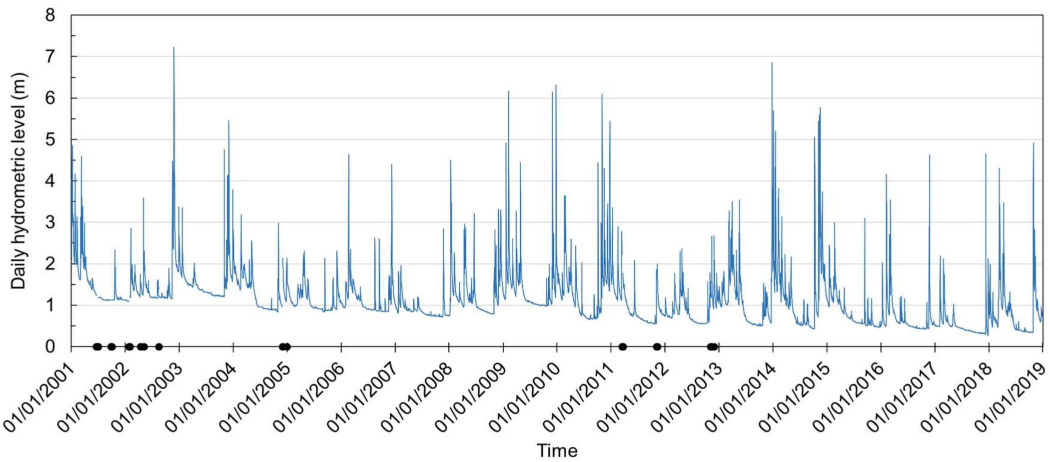

Figure 2. Mean daily hydrometric level measured at the Guazzora gauge station from 2001 to 2018. Black dots on x-axis highlight missing data in the time series. The 2011 extreme flood is not documented.

The study reach is situated north of Novi Ligure, from which the Scrivia riverbed becomes unconfined, down to the Po River and it is about 40 km long (Figure 1b). The active channel can be distinguished in three major sections presenting homogeneous landforms: (i) the upstream segment (12.5 km), with very wide, straight and multi-thread channel; (ii) the central segment (14.5 km), which is the most urbanized and that shows a transitional channel pattern; and (iii) the downstream segment (13 km), characterized by a narrow and deeply incised active channel presenting a variable degree of sinuosity.

Generally, banks are non-cohesive or multi-layered and only in the downstream-most few kilometres cohesive banks prevail. Sediment grain size ranges from approximately 30 cm in diameter down to sand and finer fractions. From the geomorphological point of view, the areas adjacent to the riverbed are generally classifiable as recent terrace or modern floodplain. The latter are generally delimited by the active channel bank and by a major scarp accounting for an ancient bank, often presenting old bank protections. These morphologies derive from the medium-term morphological evolution experienced by the active channel of the Scrivia River floodplain reach [45].

Previous researches testified that from the last decades of the 19th century to the 1950s some relevant active-channel migration processes occurred. Furthermore, no generalized planform changes were recorded at least until the 1920s [45]. Subsequently, from the 1950s to the late 1990s, active-channel narrowing, stabilization and incision were largely the dominant processes leading to consistent and fast morphological changes. For example, from Novi Ligure to Castelnuovo Scrivia, the comparison between the 1954 and the 1999 active channel revealed a mean narrowing greater than 100 m, with the largest localized width reduction ranging from 48% to 58%. By considering the whole study reach, in this period the mean channel width decreased from 259.2 m to 149.7 m (−42.2%) while the channel area from 1009.2 ha to 613.6 ha (−39.2%). Furthermore, a riverbed deepening of about 2.5 m and 4 m were documented in the middle segment near Tortona from 1970 to 1994 [57,70,71] and at the Po River confluence between 1954 and 1988 [70], respectively. Along the central sector of the study reach, these morphological adjustments led to a variation in channel type from multi-thread to transitional or single-thread channel pattern. These morphological dynamics are consistent with the morphological evolution documented for most of the Italian rivers and are strictly associated with the severe anthropic interventions that extensively affected the fluvial system in the second half of the 20th century and particularly from 1960s to 1980s [32,45]: sediment quarrying activity, channelization and occupation of riverine areas. As reported in a previous study, the occupation of riverine zones was promoted by the regulations concerning land ownership and riverbed morphological changes in force up to 1994 [32]. Since the late 1990s, it was observed an inversion of morphological tendencies which indicates a slight and generalized active-channel widening along with a reactivation of morphological processes.

At the present day, bank protections, mainly consisting of prisms of concrete used as ripraps (the so-called "prismate") and to a less extent of rock or concrete revetments, cover 52% of the banks along the study reach. The second reach is the less channelized reach. In contrast, from the third reach to the Po River, the extension of defenses ranges between 47% and 71% of total bank length, being always higher than 60% downstream the sixth reach. Furthermore, paleochannels and almost all the recent terraces close to the riverbed, namely most of the river corridor [72], are occupied by facilities and infrastructures along with cultivated fields that often spread up to the riverbanks.

3. Methods

This research is based on a multitemporal analysis of aerial photographs and satellite images performed in a GIS environment using GRASS GIS [73] and QGIS [74], and coupled with field surveys.

3.1. Data Sources

The multitemporal analysis is based on a set of seven different data sources consisting of orthophotos and Google Earth images spanning the period 1999–2019 (Table 1). The former were imported in a GIS environment from the Italian National Geoportal [75] and the Piemonte Region Geoportal [76] by means of the web map service function. The latter were imported through the Quick Map Service plug in. The orthophotos retrieved from the Italian National Geoportal are characterized by a positional accuracy ≤4 m. In order to check the positional accuracy of the other images, a number of control points were located on the reference map (i.e., the 2012 orthophoto) and on the one under assessment, and their deviation was computed [11]. In general, a positional error ≤5 m was estimated for measurements [11,18,45,77].

Table 1. List of cartographic data used in this research. The scale values marked with * indicate the scale range of data visualization. CGR: Compagnia Generale Riprese Aeree; AGEA: Agenzia per le Erogazioni in agricoltura.

Year	Datum	Data source	Scale	Resolution
1999	Orthophoto	National geoportal, CGR	1:10,000	1 m
2007	Orthophoto	National geoportal, CGR	1:10,000	0.5 m
2009	Orthophoto	Piemonte Region	1:5,000	0.4 m
2012	Orthophoto	National geoportal, AGEA	1:10,000	0.5 m
2015	Orthophoto	Piemonte Region, AGEA	–	0.4 m, 0.2 m
2016	Google Earth	Google Earth	1:1000–1:2500*	–
2019	Google Earth	Google Earth	1:1000–1:2500*	–

3.2. Photo Interpretation and Field Surveys

The essential datum for the assessment of channel planform features and changes over time is the active channel polygon. In this research, the active channel was manually digitized at each considered time through photographic interpretation. According to previous researches [11,21,45,78,79], the active channel was defined as that portion of surface constituted by wetted channels and adjacent bare or partially vegetated bars (Figure 3a). Considering the relevant difference in inundated channel dimensions that may exist among the investigated data sources, which mainly depends on the different discharge at the time aerial photographs and/or satellite images were acquired [79], the active channel represents the meaningful spatial unit to reflect the current geomorphic processes disregarding flow conditions [80]. In this study, the active channel polygon includes vegetated surfaces located between banks because of difficulties in distinguishing accurately between islands and bars covered by annual or biennial plants on past remotely sensed data [81]. Moreover, the low-flow channels were digitized as lines on each series of images. Both the polygons and lines were digitized at a scale larger than 1:2500.

A wide campaign of geomorphological field surveys was performed in 2016, 2017 and 2019 by using a common GNSS device, in order to carry out a detailed qualitative analysis of the current landforms that characterize the riverbed and its adjacent areas. This activity supported the GIS-based identification of the active channel and contributed to the ongoing geomorphological processes assessment.

3.3. GIS Analysis

The active-channel planform features and their changes over time were investigated for each considered year and each time step, respectively, both at reach scale and at the study reach as a whole.

The identified reaches show homogeneous geomorphological features, lengths that are generally minor than 5 km [22,82] and the extremities corresponding to man-made structures that have been stable over time, such as bridges and weirs. The definition of reaches derives from the active-channel segmentation already illustrated and used in previous researches [32,45], in order to obtain results comparable with existing data and thus to expand prior studies.

Firstly, the centerline was extracted from the active-channel polygon through an automated GIS procedure of polygon skeletonization, followed by a smoothing procedure aimed to obtain a sinuous line (Figure 3a). This line is defined as the line equidistant from banks [21,80].

Subsequently, the active channel area and length were measured both at reach scale and at the whole study reach scale. The mean active-channel width (MCW) was computed for each reach as the ratio between area and length, for each considered year. The comparison among these values allowed to outline the active-channel width changes over time. In particular, a percentage value of width variation (ΔW) was defined as "$MCW/MCW_{1999}*100$", where MCW_{1999} is the mean active-channel width measured in 1999, at reach scale [18,25]. Furthermore, a series of 25 m equally-spaced transects was located perpendicular to and along each channel centerline, and their portions overlapping the active-channel polygon were assumed to represent the active-channel width at site scale (Figure 3a). In order to appreciate the width variations in detail continuously along the whole study reach and to compare distinct dates, the lengths of consecutive transects, namely the channel width values, were progressively summed up (CUMW) and the longitudinal distances of transects were normalized [80].

The sinuosity index (SI) was computed at reach scale as the ratio between the channel centerline length and the straight line connecting the channel centerline extremities [83–85]. The braiding index (BI) derives from the ratio of the number of intersections between the aforementioned active-channel width transects and the low-flow channels, to the number of measurements, namely of transects [86–88].

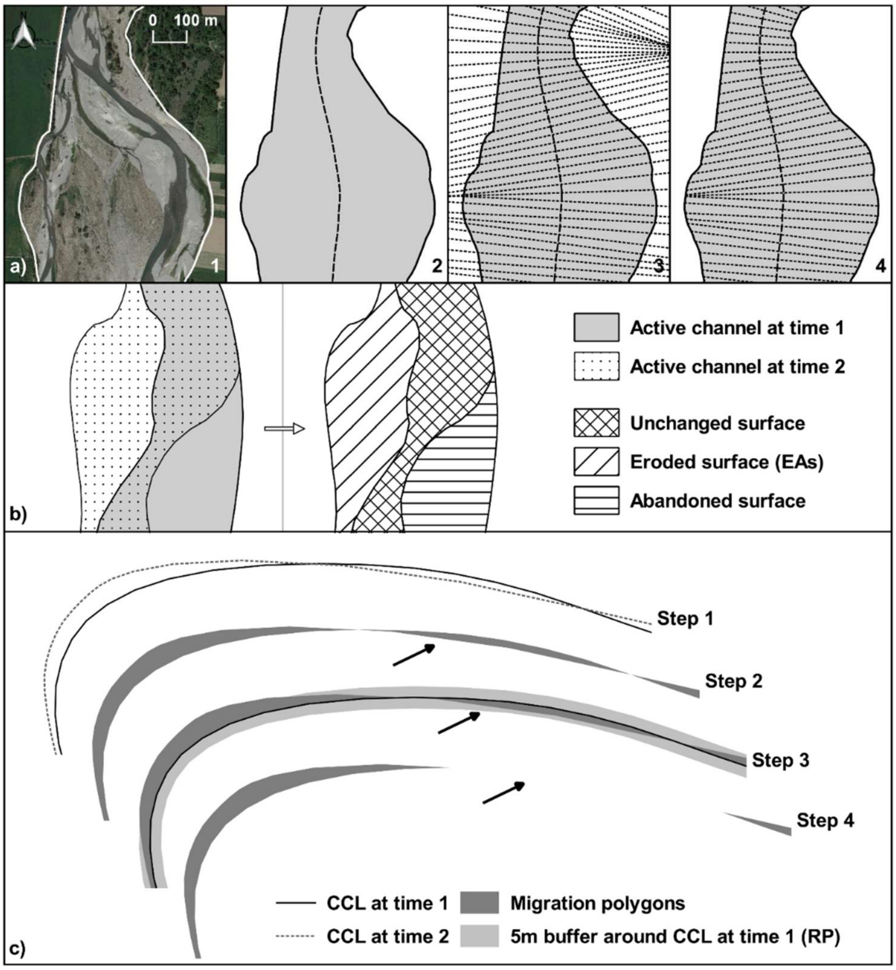

Figure 3. (**a**) Active channel definition and consecutive steps to evaluate channel width at site scale; see the text for explanation; (**b**) Polygons for the computation of NCA, PUS, PES and PDS. The superimposition of two active channel polygons resulted into three distinct layers representing (i) the areas belonging to the active channel at both times (i.e., unchanged surface); (ii) the areas converted from floodplain to active channel (i.e., eroded surface–EAs); (iii) the areas converted from active channel to floodplain (i.e., abandoned surface); (**c**) Procedure adopted in defining migration polygons; the arrow indicates a migration polygon included within the RP and thus not considered for the computation of MR; see the text for explanation.

In order to describe the prevalent riverbed planform change over time in terms of surface conversion from active channel to floodplain and vice-versa, the net channel activity (NCA) and the percentage of unchanged active-channel surface (PUS) were computed for each couple of consecutive years (Figure 3b), following procedures described in literature [32,45,79,89,90]. The same parameters were also computed together with the percentage of eroded (PES) and abandoned (PDS) surface by considering the comparison between the 1999 and the 2019 active channel (Figure 3b). Furthermore, the portions of 2019 banks presenting noticeable and ongoing retreat processes were mapped. The migration rate (MR), referred to the channel centerline horizontal displacement, was calculated as the ratio of the total area of polygons formed between the two considered active-channel centerlines (CCPs) to half of the sum of the aforementioned centerlines lengths [3,40,91,92] (Figure 3c). In order to consider only actual changes in channel-centerline position, rather than changes mainly related to both the active-channel digitization and the centerline extraction procedure, a 5-m-buffer was extracted around the oldest centerline, generating a reference polygon (RP) (Figure 3c). CCPs totally included within the RP were not considered for the computation of MR since they were intended to be false channel centerline migrations accounting for positional errors associated with the active-channel digitization and/or the channel centerline extraction procedure [93] (Figure 3c).

Eventually, the analysis focused on the relationship between recent planform adjustments and land-use and land-cover (LULC) of the involved areas. The superimposition of the 1999 and 2019 active channel polygons allowed to extract those surfaces that, on the one hand, constitute the active channel in 2019 and, on the other hand, were not included in the 1999 active channel, hereafter called eroded areas (EAs). Thus, the EAs represent surfaces that have been eroded either progressively or impulsively at any moment during the considered time span. Considering the 1999 orthophotos as a base, the EAs were classified into three major LULC classes: seminatural area, agricultural area and urban area, whose extension was calculated at reach scale. Moreover, the 1922 and 1954 active channel polygons, collected from previous researches [32,45], were taken into account to investigate the recent planform adjustments with respect to the past riverbeds. In particular, the EAs overlaying historical active channels were extracted and their total surface was computed at reach scale. Most of GIS procedures implemented to compute the geomorphic parameters were performed in GRASS GIS [73] by using chained command lines within the shell.

4. Results

The comparison of the active-channel polygon locations registered in the considered period allowed to outline the channel planform changes occurred between 1999 and 2019 along the Scrivia river floodplain reach, identifying different rates both in space and time.

The study reach is currently 39,770 m long, which is the minimum length over the time span investigated. The maximum length of 40,509 m dates back to 1999, revealing that no relevant length variations occurred. The present-day active channel spreads over an area of 753 ha, against the value of 613.6 ha measured in 1999, thus resulting 22.7% higher. This value was 718.3 ha in 2007 and 712.7 ha in 2009; afterwards a progressive increase was documented: 713 ha in 2012, 746.7 ha in 2015 and 749 ha in 2016.

The current morphological features of the identified reaches are summarized in Table 2. In the upper part of the study reach the active channel shows a multithread pattern, subsequently it changes to a transitional pattern in the central part and finally to single-thread pattern in the lower one. The highest values of channel width are documented in reaches 2 and 3, which are characterized by bare or partially vegetated wide bars dividing low-flow channels. The transitional channel pattern reaches present an active channel width around 150 m or 240 m and are substantially located at the main urban and industrial settlements. The downstream-most four reaches show a single flow channel within almost parallel sinuous banks. Alternate bars characterize the seventh and the eighth reaches whereas they almost completely disappear in the ninth and tenth ones. Along the downstream-most 10 km, the active-channel width is about 40 m, resulting 89.9% less than the widest reach width.

Table 2. Morphological features of identified reaches (referred to the 2019 active channel). W, wandering; B, braided; SAB, sinuous with alternate bars; M, meandering; S, sinuous.

Reach	Length (m)	Area (ha)	Mean width (m)	Sinuosity Index [1]	Braiding Index [1]	Channel type
1	2962	46.7	157	1.1	1.2	W
2	3394	141.7	417	1.0	2.3	B
3	6072	198.8	327	1.0	1.8	B
4	3938	95.5	242	1.0	1.4	W
5	2777	46.8	168	1.1	1.1	W
6	4363	107.4	246	1.1	1.2	W
7	3420	51.3	150	1.0	1.1	SAB

Table 2. *Cont.*

Reach	Length (m)	Area (ha)	Mean width (m)	Sinuosity Index [1]	Braiding Index [1]	Channel type
8	2728	20.9	76	1.3	1.1	SAB
9	4683	18.9	40	1.7	1.0	M
10	5433	24.9	45	1.4	1.0	S

[1] Sinuosity and braiding index are dimensionless parameters.

From 1999 to the present day no relevant changes in the SI are documented, except for a slight reduction in reaches 8 and 9 (Figure 4). The BI presents an increase up to 2009 followed by a reduction in reaches 2, 3 and 4, whereas it shows smaller fluctuations in reaches 1, 5 and 6. Moreover, a further common phase of slight BI increase was measured in 2015 and 2016 in reaches 2 to 6, followed again by a reduction up to 2019 in all reaches. In reaches 7 to 10, no relevant changes were measured, and BI remained quite constant, usually slight above 1 or equal to 1 (Figure 4).

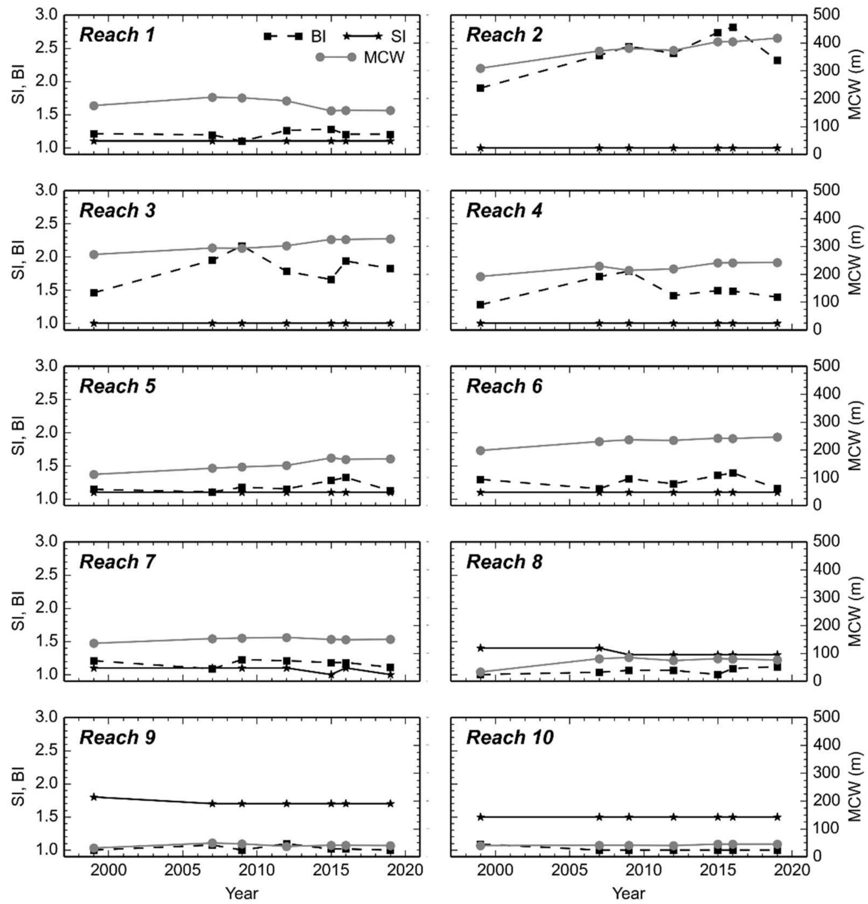

Figure 4. Variation of sinuosity index (SI), braiding index (BI) and mean active-channel width (MCW) over time at reach scale. SI and BI are dimensionless parameters.

A progressive active-channel widening affected the Scrivia River floodplain reach over the last 20 years, except for reach 1 (Figure 4). The highest MCW values are documented in 2019 in reaches 2 (471 m), 3 (327 m), 4 (242 m) and 6 (246 m). The same reaches showed the largest MCW values already in 1999. In contrast, the lowest values characterize the reaches 9 and 10, where MCW has fluctuated around 40 m for the whole considered time span. Referring to the whole study reach, the MCW increased by 25% in the period 1999–2019, namely from 151.5 to 189.3 m.

The reach-scale comparison of the percentage differences between the 1999 MCW and each subsequent MCW (ΔW) revealed some temporal trends (Figure 5a). A generalized channel widening (i.e., increasing trend) occurred up to 2007 and 2009 in all reaches and in seven out of ten reaches, respectively. Moreover, a further MCW increase is observed in the period 2012-2015, followed by no MCW changes up to 2019. The active channel widening measured between 1999 and 2019 amounts to 20–50% in reaches 2 to 5 and to 10–29% in reaches 6 to 10, with an outlier of 130% recorded in reach 8. The first reach experienced a narrowing (i.e., decreasing trend) of 10.3%. The highest ΔW values were noticed in reaches 5 in 2015 (52.7%), 8 in 2009 (157.6%) and 9 in 2007 (58.1%); in contrast, both reaches 8 and 9 experienced a ΔW reduction from 2009 to 2012. These variations are overall clearly noticeable at the scale of the whole study reach (Figure 5b). In fact, the CUMW at the outlet shows a relevant gap between 1999 and the other measurements, which represents the above-illustrated increase in channel width occurred after 1999. Furthermore, without considering the 1999 CUMW values, two distinct groups of CUMW curves are particularly noticeable (Figure 5b). The former shows CUMW maximum values ranging from 283.5 to 286.4 km and the latter from 296.7 to 299.4 km. They refer to the periods 2007–2012 and 2015–2019, respectively. The evident gap among these two groups of curves highlights that from 2007 to 2019 the riverbed experienced the largest increase in active-channel width between 2012 and 2015. The all CUMW curves follow overall the same trend, highlighting that no large and generalized channel width variations occurred along extensive portions of the study reach. Conversely, abrupt changes in steepness allowed for the identification of intense local-scale channel narrowing processes, for example at 5% of progressive distance, and channel widening processes, at 25%, 46% and 62%.

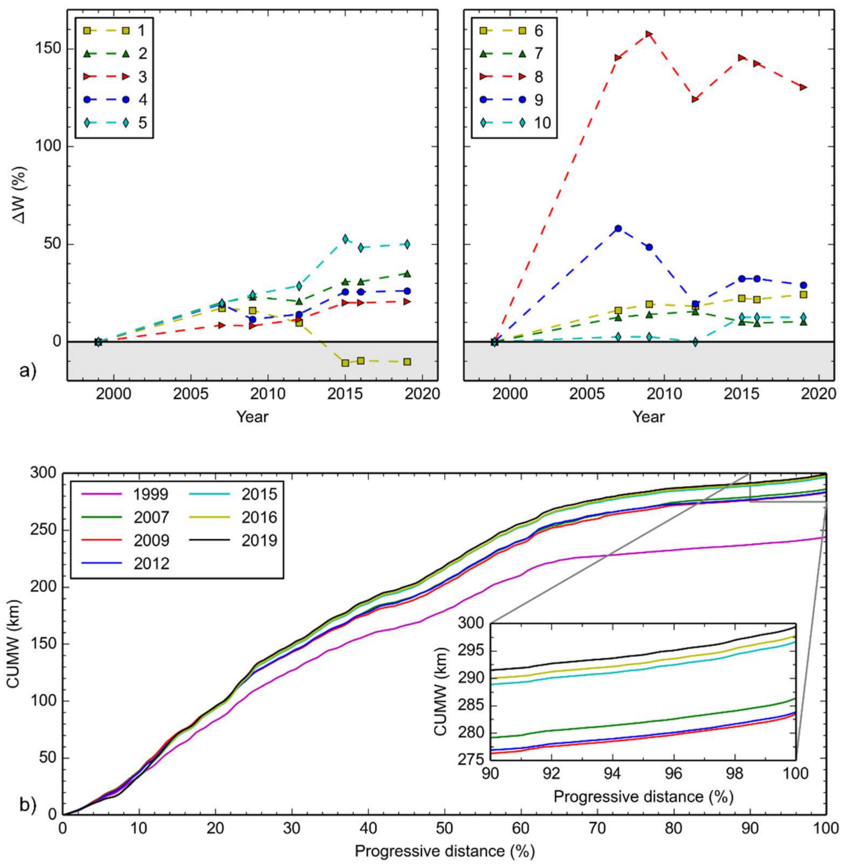

Figure 5. Active channel width changes; (**a**) Variations expressed by using the ΔW% parameter for reaches 1 to 5 and 6 to 10; increasing (decreasing) trend indicates widening (narrowing); (**b**) Cumulative active-channel width (CUMW) plotted against progressive distance. Steep slopes represent abrupt active channel width increase; moderate slopes indicate river stretches with a wide active channel; gentle slopes represent river stretches with a narrow active channel.

The balance between newly-formed and abandoned active-channel area highlights that the conversion from floodplain to active channel surface generally prevailed over the considered time period (Figure 6a). In particular, this morphological dynamic is rather evident from 1999 to 2007 and from 2012 to 2015. The reaches 2, 3, 5 and 6 experienced an almost complete (reaches 2, 3 and 5) or complete (reach 6) conversion of surfaces involved in lateral dynamics from floodplain to active channel. In contrast, the first reach shows counter-trend values which highlight a greater transformation of active channel surface into floodplain. Eventually, the tenth reach presents NCA values close to zero, suggesting the absence of a dominant process.

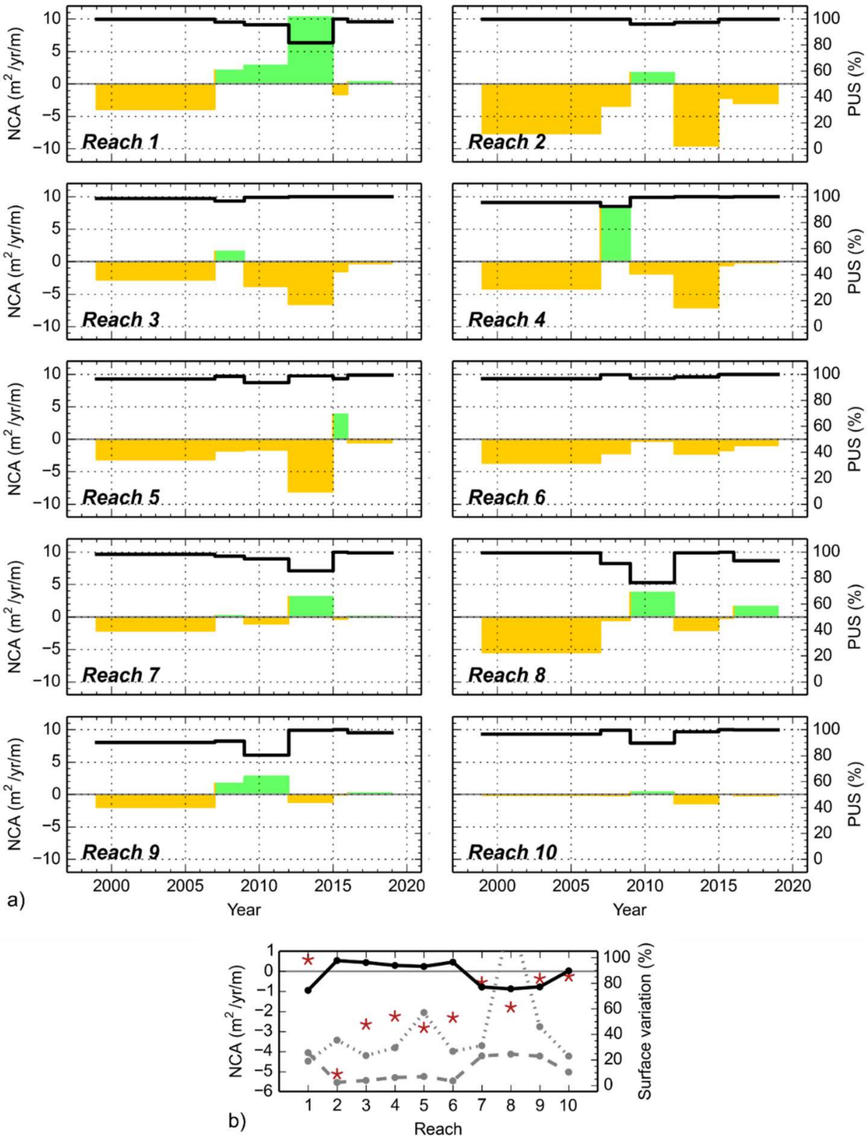

Figure 6. (**a**) Net channel activity (NCA) and percentage of channel unchanged area (PUS) for each consecutive time step. The green (yellow) highlights, keyed to the left *y*-axis, represent prevailing changes from active channel (floodplain) to floodplain (active channel). The black line is keyed to the right *y*-axis and represents the percentage of unchanged active-channel surface referring to the oldest riverbed of each time step; (**b**) NCA (red asterisks), PUS (black line), percentage of channel area converted into floodplain (PDS) (dashed grey line) and percentage of newly-formed channel area (PES) (dotted grey line) referred to the 1999 active channel, derived from the comparison between the 1999 and the 2019 active channels at reach scale. The outlier measured in reach 8 is 132.9%.

The PUS parameter highlights an overall planform stability over the period 1999-2019 (Figure 6a). In fact, values close to 100% are almost always documented for each investigated time step. In detail, PUS shows the minimum values of 81.7% in reach 1 while it ranges between 92.6% and 96.8% in reaches 2 to 6, and from 76.4% to 89.8% in reaches 7 to 10.

The comparison between the 1999 and 2019 active channel polygons reveals that along the vast majority of investigated reaches, the process of conversion from floodplain to active channel prevailed (Figure 6b). The lowest value is observed in reach 2 while similar values can be noticed for reaches 3 to 6 and 7 to 10, respectively. The highest degree of planform stability (>90%) is observed in reaches 2 to 6 and 10, whereas reaches 1 and 7 to 9 show a PUS ranging from 74.4% and 77.1%. Furthermore, the PES is always higher than the PDS, except in reach 1, with differences ranging from some percentage points to several tens.

The reach-scale MR referred to each considered period ranges from 0.1 to 7.2 m/year (Figure 7). The highest variations over time were documented in reaches 1, 5 and 7, which present a MR range of 6.6, 5.3 and 6.2 m/year, respectively. The other reaches showed a range between 2.1 and 3.8 m/year, while reaches 9 and 10 are characterized by the lowest range values 1.1 and 1, respectively. The highest MR values can be observed from 2007 to 2016. Taking into account the whole period 1999–2019, the reach-scale MR ranges from 0.25 m/year to 1.9 m/year, in reaches 10 and 7, respectively. Furthermore, values between 1.5 m/year and 1.9 m/year have been measured in reaches 1 to 5, 7 and 8, whereas between 0.25 m/year and 0.9 m/year in reaches 6, 9 and 10.

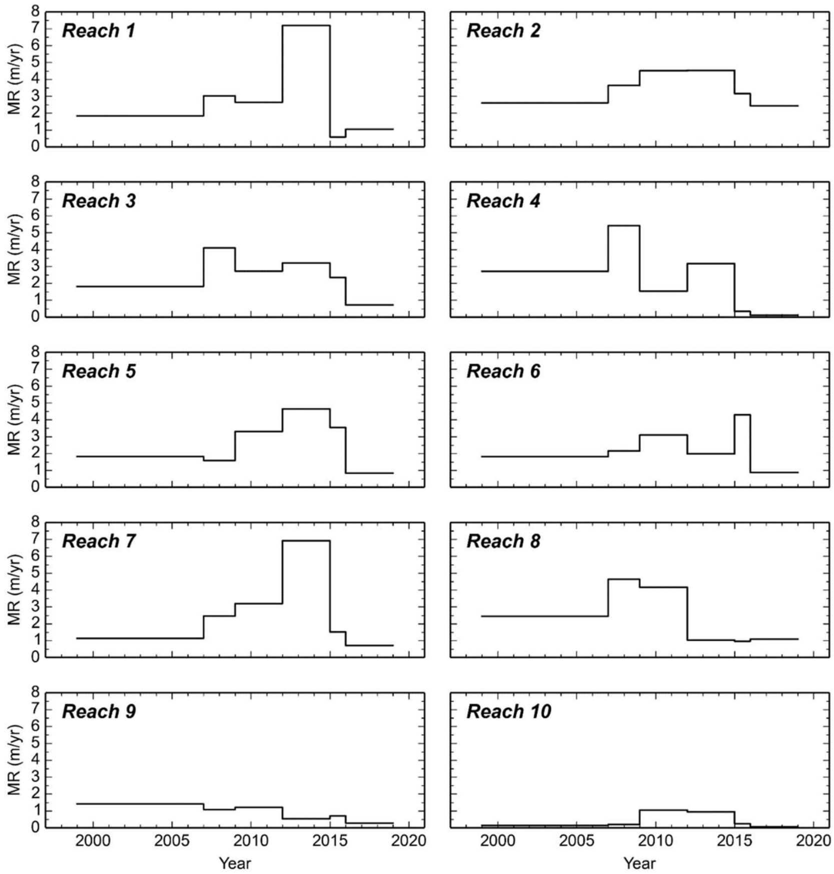

Figure 7. Reach-scale variations over time of the migration rate (MR) referred to the active-channel centerline.

As concerns the relationship between bank retreat processes and LULC of the involved plots of land, Figure 8a depicts the LULC classes distribution of the EAs at reach scale. Most of EAs are NAT, and, in particular, four out of ten and seven out of ten reaches, located mainly in the upper and middle part of the study reach, present values >90% and >75%, respectively. The highest percentages of AGR is registered in reaches 1, 3, 6, and 8 to 10. Substantially, urban areas are not involved in bank retreat processes, except for very small areas in reaches 5 and 6.

Considering the 1922 and 1954 active channel as reference point, it is evident that most of EAs are included within these ancient riverbeds (Figure 8b). Referring to both years, this observation is particularly evident for reaches 1 to 7. The overlapping values range from 51.7% to 87.9% in nine out of ten reaches, and from 51.4% to 90.4% in eight out of ten reaches with respect to 1922 and 1954, respectively. The lowest values referred to both the 1922 and 1954 channels are registered in the downstream-most three reaches, especially in the ninth and tenth. At the whole study reach scale, 70.5% of EAs is located within the 1922 active channel and 67.7% within the 1954 active channel.

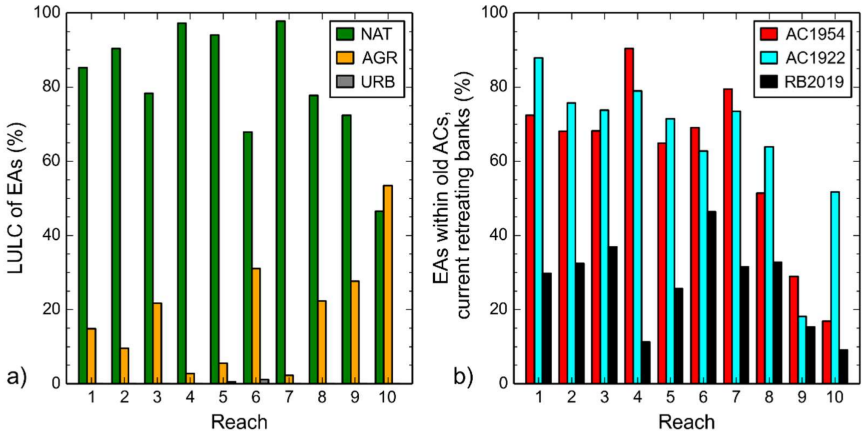

Figure 8. (**a**) 1999 LULC percentage area of 1999-2019 EAs at reach scale; NAT, seminatural area; AGR, agricultural area; URB, urban area; (**b**) Percentage of EAs belonging to the 1922 (AC1922) and 1954 (AC1954) active channel, and percentage length of the present-day retreating banks (RB2019).

Lastly, bank retreat processes currently affect 26.8% of banks along the whole Scrivia River floodplain reach. Vertical or sub-vertical high retreating banks are mainly located in reach 6 and subsequently in reaches 1 to 3, 5, 7 and 8 (Figure 8b). It is interesting to note that seven out of ten reaches register more than 25% of retreating banks and that anyway all reaches are in some measure affected by bank retreat.

As for field surveys, this activity allowed for bank mapping where it was difficult to pinpoint precise riverbed edges by using remotely-sensed data. Furthermore, it provided an overall overview on current landforms and detailed insights on specific features concerning bed-level changes and channel reworking (e.g., retreating banks, exposed roots along the bank toe, undermined man-made structures, sediment-covered vegetation and lobate bars).

5. Discussion

The results of this study indicate a generalized active-channel widening along the Scrivia River floodplain from 1999 to 2019. This dynamic has resulted more or less pronounced at reach scale. According to the computed morphological parameters, four evolutionary phases can be identified, each one characterized by well-defined geomorphological changes affecting the active channel.

The first phase (from 1999 to 2007–2009 depending on the considered reaches) presents a prevailing and generalized trend of active channel widening. During the second phase (from 2007–2009 to 2012) no overall morphological tendencies are documented, since active-channel planform stability, widening or narrowing have been only registered along distinct reaches. The third phase (from 2012 to 2015) is characterized by a further prevalence of active-channel widening. In this period, according to local people witnesses and official reports, large bank erosion processes were triggered by the intense floods occurred both in December 2013 and October-November 2014 [94–96]. Finally, the fourth phase (from 2015 to 2019) shows generalized active-channel stability and very slight widening, usually affecting only some reaches.

However, it should be noted that the first reach shows generally countertrend values indicating a progressive active channel narrowing occurred after 2009 and overall from 2012 to 2015, as illustrated by MCW, ΔW and NCA (Figures 4, 5a and 6a). This is associated with the stabilization of a large surface in the downstream-most part of the reach. Nonetheless, bank retreats are also documented along this reach. The channel planform dynamics outlined by NCA, PES and MR in reaches 8 and 9 between 2007 and 2012 come from channelization works [32,45] (Figures 6 and 7). The highest degree of channel activity has been observed in reach 2 that, in fact, presents widespread bank erosions and that experienced a progressive increase of the active channel width as well. On the contrary, the reaches 9 and 10 can be overall considered the most stable over the investigated time span (Figures 6a and 7). The generalized prevalence of the floodplain-to-channel conversion process in the period 1999-2019 is well-recognizable considering the high and low values of PES and PDS, respectively (Figure 6b). The homogeneous trends of CUMW curves, along with the overall progressive increase of CUMW values over time, highlight that the channel widening has been related to both locally-intense and widely-moderate bank retreats, rather than to very severe ones along the whole study reach.

The simultaneous analysis of ΔWs, PUSs and MRs (Figures 5a, 6a and 7) suggests that the channel centerline migration is substantially related to the variations in active-channel width. These morphological changes consist of narrowing along reach 1 and widening along the remaining ones, particularly along reaches 5 and 8. Thus, these outcomes suggest that no real lateral-migration processes involving the entire active channel occurred over the last 20 years. Furthermore, neither the slight reduction of the active-channel length accounts for real riverbed horizontal displacements as it is associated (i) to the Po River migration southward, (ii) to channel centerline strengthening, related to a very gentle reduction of sinuosity caused by channel widening, and (iii) to possible changes in the centerline shape related to the centerline-extraction GIS procedure.

It is interesting to note that the investigated period corresponds to a new geomorphological evolutionary phase of the Scrivia River floodplain reach. Such new phase is characterized by a reactivation of morphological processes together with an increase in channel width. This represents a reversal trend with respect to the dominant processes documented before the late 1990s. In fact, according to previous researches [32,45], from the 1950s to the end of the 1990s, the Scrivia River floodplain reach experienced a phase of severe narrowing and progressive stabilization of the active channel that resulted into a channel type variation along some reaches. The recent channel widening is largely included within the range of variations that occurred previously and is not associated with channel type changes, as demonstrated by the stable SI and by slightly-fluctuating BI values.

Numerous studies have documented this new and recent phase of channel widening along several Italian rivers just from the 1990s onwards [21,24,25,29,30,42,43]. However, the triggering factors of this phase are still quite debated; moreover, a high uncertainty regarding its diffusion and the combination between active-channel widening and channel incision, aggradation or bed stability still exists.

Along the Magra River and the Vara River the good correspondence detected between changes in channel width and bed-level, before the 2011 extreme flood, led to associate channel widening with aggradation and viceversa [30,42,43]. In these cases, the bed-level increase was attributed to the cessation of in-channel quarrying, generally dated back to the middle 1980s–early 1990s, thus implying a major in-channel sediment supply [20,25,30]. The severe widening recently experienced by the Orco River and the Stura di Lanzo River was attributed to the extreme flood occurred in 2000 [24]. In the same way, the increase in channel width reported for the Paglia River [21] and for the Taro River [29] was mainly due to floods. A moderate widening, accompanied by a very slight aggradation, was reported for the Tagliamento River, even if some fluctuations of short-term widening rates were measured [44]. Here, a reach-scale increase of unit stream power due to relevant changes in channel geometry, mainly resulting from past disturbances, has been demonstrated to have played a crucial role in triggering recent dynamics [44]. Channel widening combined with both incision and aggradation was also detected along the Trebbia River, where the increase of unit stream power at reach-scale has been thought to be at the origin of an increase in the erosive action and thus in lateral erosion [30]. As for some rivers of the southern Italy, the Trigno and Crati experienced moderate channel widening that was interpreted as the result of the interruption of in-channel sediment removal together with the occurrence of some floods. In contrast, the Biferno and Volturno rivers resulted essentially stable since 1998 and only affected by very slight and localized widening [25]. Finally, no reversal trend was reported about the Panaro River [97] and the Torre River [98], along which narrowing still seems ongoing.

As for the Scrivia River, the most recent geomorphological phase is mainly related to the sequence of major floods that occurred after 1999, particularly frequent between 2010 and 2014 (Figure 2). The outlined evolutionary trends of the investigated parameters and, thus, the four distinct stages identified in the time frame 1999–2019, substantially follow the aforementioned flood sequence. The documented variations in active-channel width and maximum CUMW over time, the lowest NCAs registered up to 2007 and between 2012 and 2015, and the highest MRs measured from 2007 to 2016 can be considered as the active-channel geomorphic response to the occurred high-magnitude floods. According to the outcomes of similar researches, the recent channel widening may have been also promoted by an increase in erosive action due to a growth of reach-scale unit stream power referred to the noticeable change in channel geometry occurred during the 20th century [30,44]. The active-channel widening registered along the Scrivia River floodplain reach is associated with two distinct processes of lateral erosion: (i) the collapse of banks exceeding a critical height for their stability, often promoted by the collapse of undermined bank defenses (Figure 9a,b); (ii) the re-appropriation of riverbed lands abandoned before 1999 due to incision and progressively colonized by vegetation (Figure 9c,d). The former was generally observed in single-thread and transitional channel reaches, while the latter mainly affected transitional and multithread channel reaches. These two distinct processes of lateral erosion seem to be associated with active-channel incision and aggradation, respectively. The LULC of EAs reflects these processes at reach-scale. In fact, the former mainly involves AGR/URB lands, which generally correspond to the recent terrace, while the latter mainly affects NAT areas, which are generally newly-formed in-channel modern floodplains (Figure 8a).

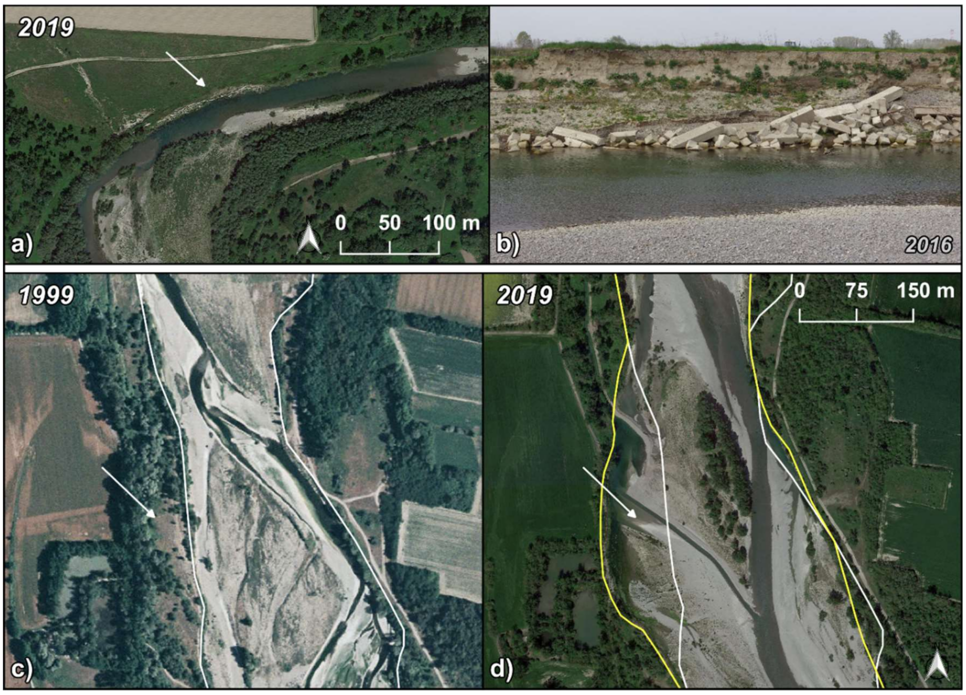

Figure 9. Examples of active channel widening associated with distinct lateral-erosion processes; see the text for explanation. (**a**, **b**) High and steep bank presenting a collapsed defense structure; the arrow in (**a**) indicates the location of (**b**) (photo by A. Mandarino); (**c**, **d**) The arrow in (**c**) indicates the in-channel modern floodplain formed before 1999 that has been eroded over the last twenty years (**d**); the white and yellow lines correspond to the 1999 and 2019 banks, respectively.

Bank erosion has led to an impulsive and currently-localized growth of in-channel sediment supply and thus of aggradation [99]. This is well testified by in-channel forms such as lobate bars, steep downstream front of bars and by in-channel vegetation slightly covered by sediments. However, evidences of incision such as exposed roots along the bank toe or undermined in-channel structures can be also recognized, particularly along the downstream-most reaches. Nevertheless, further studies could better define the bed-level changes associated with the documented planform dynamics. As highlighted in previous studies on other Italian rivers that experienced similar morphological changes [30,44], the ongoing evolutionary stage accounts for a partial recovery of morphological processes, namely the response of the Scrivia River to severe riverbed alterations [45].

In agricultural and urban landscapes such as the Scrivia River floodplain, bank erosion usually causes loss of lands, damage to structures and facilities as well as conflicts with landowners and among stakeholders. Moreover, historically prevails the notion that bank erosion is deleterious, which has often led to widespread traditional management interventions aimed to arrest such process [33]. However, bank erosion represents an essential component of the natural evolution of water bodies and floodplains [17,72,100]. It is now widely-known that an active water course, in terms of geomorphological processes, promotes the functioning of the entire fluvial ecosystem, and thus the diversification of habitats, the maintenance of biodiversity and the supply of a wide spectrum of resources and, in general, of ecosystem services [33,101–104].

In light of the previous observations, considering that more than a quarter of banks is affected by retreating processes and that a much higher value represents unstable banks, non-traditional strategies for bank erosion management could be implemented along the study reach, especially in areas presenting few elements at risk or where cultivated areas are close to the riverbank edge [25,32,72,91,105]. Within the study reach, the adoption of interventions to sustain the active-channel dynamics and the morphological recovery should be also encouraged by the presence of protected areas characterized by a high naturalistic value, namely two Sites of Community Importance belonging to the Natura 2000 European network along with a Regional Park (located approximatively in reaches 1 to 4, 7 and 8). Furthermore, this approach would be useful (i) to improve the low geomorphological quality, recently surveyed for the implementation of the Water Framework Directive [106,107] and (ii) to mitigate the river-related risks according to the Flood Directive [108]. In this regard, the definition of an erodible corridor [109,110] could represent an effective measure that, however, would require relevant changes in terms of both near-riverbed land property regulations and in people awareness on fluvial dynamics [32]. Undoubtedly, each type of river management strategies must be accurately analyzed and planned at large scale, analyzing in detail both specific benefits and drawbacks [17,25,111,112].

6. Conclusions

This research has outlined in detail the ongoing planform dynamics characterizing the Scrivia River floodplain reach by means of a quantitative multitemporal analysis of aerial photographs and satellite images covering the last twenty years. This analysis was performed in a GIS environment and was supported by field surveys. The use of chained command lines within the GRASS GIS shell allowed for the automatic computation of several morphological parameters that would have required many repetitive, time-consuming and error-inducing GIS procedures using manual methods.

After decades of active-channel narrowing and blocked lateral dynamics, the period 1999–2019 highlights a partial morphological recovery consisting of reactivation of channel dynamics and of generalized trend of gentle active-channel widening, often showing intense and localized bank retreats involving both the modern floodplain and the recent terrace developed over the 20th century. The sequence of extreme floods occurred in this period was identified as the triggering factor, most probably together with an increase of the reach-scale unit stream power related to changes in the channel geometry. Currently, the magnitude and the frequency of floods are considered the driving factors regulating the intensity of riverbed adjustments [44]. The observed active-channel planform changes are substantially in agreement with the morphological dynamics documented during the same period along numerous Italian rivers that have been affected by severe anthropic pressures and that experienced intense narrowing and incision processes over the 20th century.

The knowledge of the current riverbed morphological dynamics is essential to carry out effective and sustainable river management measures. Thus, the results of this study are of great relevance and can support decision-making processes concerning the implementation of the EU Water Framework Directive [107] and the Flood Directive [108]. Furthermore, these outcomes provide new insights about the recent phase of active-channel changes with respect to the morphological dynamic of Italian rivers. In anthropogenic landscapes like the Scrivia River floodplain, bank erosion causes loss of lands, damage to structures and facilities along with conflicts with landowners and among stakeholders. However, it should be noted that bank erosion is a natural process representing the essence of the natural evolution of unconfined fluvial systems. In view of the above, the current morphological phase of the Scrivia River and not only of this, together with the growing frequency of extreme and damage-inducing floods over the last years, can be regarded as a relevant opportunity to pursue non-traditional river management strategies aimed to both the restoration of the fluvial environment and the mitigation of river-related risks.

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