Reach-scale morphological adjustments and stages of channel evolution: the case of the Trebbia River (northern Italy)

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Abstract

A multitemporal series of aerial photos and cross-section topographic surveys have been used to analyze reach-scale channel evolution along a segment (length of about 22 km) of the lower Trebbia River (Northern Italy) with the aims to investigate the relations between channel width vs. bed-level adjustments and to identify spatio-temporal patterns of stages of channel evolution. Dendrochronology was used to determine the age of tree establishment of riparian and island forests during channel evolution.

We identified a first phase of major adjustments (1954 – 1992) following a series of disturbances, dominated by channel narrowing and bed incision. During the final stage of narrowing, woody vegetation establishment contributed to stabilize new floodplain or island surfaces. A period of partial morphological recovery occurred from 1992 and 2010, dominated by an inversion of trend of channel width. During the phase of partial recovery, a stage of widening combined with a continuation of bed incision was identified, and a last stage characterized by widening and initial aggradation was observed on the central portion of the study reaches. Suitability and differences of existing channel evolution models (CEMs) derived in other geographical contexts were discussed, and a specific conceptual model comprising four stages of channel evolution was developed for the lower Trebbia River.

Keywords

Channel changes; Channel adjustment; Dendrochronology; Channel evolution models; Trebbia River.

1. Introduction

Adjustments in alluvial channel morphology have important implications in terms of ecosystem functioning and hazards associated with river dynamics. Knowledge of past trajectories of morphological change is recognized as a fundamental step for correctly interpreting current channel conditions and for predicting likely future trends (Brierley et al., 2008; Dufour and Piégay, 2009). Furthermore, understanding how a river channel has adjusted to natural events or human alterations can provide a basic knowledge for assessing river susceptibility or sensitivity (e.g., Bledsoe et al., 2012; Downs et al., 2013), and prediction of likely future river conditions is fundamental for defining morphological recovery potential and therefore to set realistic targets for river management and restoration (Brierley et al., 2008).

Morphological channel changes associated with natural events and human factors, and mutual relations between channel width and bed-level adjustments, have been analyzed by several authors (e.g., Schumm et al., 1984; Simon, 1989; Simon and Thorne, 1996; Liébault and Piégay, 2002; Simon and Rinaldi, 2006). Various conceptual channel evolution models (CEMs) describing a sequence of stages of channel evolution were initially developed for incising, single-thread channels (e.g., Schumm et al., 1984; Simon and Hupp, 1986). Although they have been subsequently applied and verified in several areas (Simon and Thorne, 1996; Simon and Rinaldi, 2000, 2006), it has also been recognised that different or extended sequences of channel evolution can be observed, depending on various factors (e.g., Elliott et al., 1999; Thorne, 1999; Hawley et al., 2012; Cluer and Thorne, 2013).

An increasing number of studies have analyzed channel adjustments of Italian rivers recently (e.g., Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009;

Ziliani and Surian, 2012). Many of these studies have conducted multitemporal analyses of aerial photos, showing detailed trajectories of channel width and identifying progressive adjustments (e.g., Surian et al., 2009). After two historical phases of predominant channel narrowing and bed incision, a more recent inversion of trend (after the 1990s) consisting of widening and aggradation has been described for some rivers (Surian and Rinaldi, 2004; Rinaldi et al., 2009; Surian et al., 2009; Ziliani and Surian, 2012). However, this recent phase of partial recovery and the processes leading to the inversion of trend have not been completely clarified. This is partly related to the fact that only a few studies included extensive data on bed elevation changes (Rinaldi and Simon, 1998; Surian and Cisotto, 2007; Ziliani and Surian, 2012), preventing investigation of the relations between channel width and bed-level adjustments in more detail. Classification schemes of channel adjustments have been developed (e.g., Surian and Rinaldi, 2003), and some differences with existing channel evolution models have already been discussed (e.g., Rinaldi and Simon, 1998; Rinaldi, 2003). For example, CEMs were originally developed and mostly applied to incised single thread channels with predominantly cohesive banks, while many studies on Italian rivers concern braided or wandering, coarse-grained conditions.

The role of vegetation on the development of depositional surfaces during morphological recovery following disturbances has also been recognized as fundamental (e.g., Hupp and Simon, 1991; Hupp, 1992); however, few studies have focused on these aspects related to the evolution of Italian rivers (e.g., Hupp and Rinaldi, 2007; Comiti et al., 2011). A particular feature characterising the fluvial environment is the strict and reciprocal relationship that exists between the active geomorphic processes responsible for the variation of fluvial patterns and the biotic components of the landscape (Corenblit et al., 2014). In this sense, the riparian vegetation and investigations on its evolution may provide important information on river evolution (e.g., Hupp and Rinaldi, 2007). Moreover, detailed evolution models have been recently proposed, as for example the fluvial biogeomorphic succession (FBS) model of Corenblit et al. (2007) in which different stages of riparian vegetation succession are linked to fluvial landform adjustments through time. The characteristics of riparian vegetation may be considered indicative of the current stability of landforms, and for this reason the acquisition of data regarding the age of stabilization of fluvial surfaces (i.e., floodplain and islands) has been performed through a dendrochronological sampling to provide additional information on channel adjustments.

Braided rivers were common in Alpine regions of Italy during the last century, but they have undergone dramatic changes because of human activities. Few braided rivers still exist in northeastern Italy (for example the Tagliamento River) as well as in southeastern France, and there is a need to promote preservation of these morphologies because of the biodiversity sustained by the dynamic mosaic of terrestrial and aquatic habitats (Gurnell et al., 2009; Piégay et al., 2009; Belletti et al., 2013). Apenninic braided rivers are even more uncommon and have received less attention; therefore, studies that aim to understand past evolution and likely future trends of such morphologies are important.

The previous overview on Italian rivers provides a general background of scientific gaps and motivations associated with the present study on the Trebbia River. The Trebbia catchment is located on the northern Apennines and the river has an originally braided morphology (before recent adjustments) and still maintains a tendency toward braiding along some portion of its course (e.g., Bollati et al., 2012).

Previous studies on the alluvial portion of the Trebbia River allowed identification of the overall trajectories of morphological changes and the determination of their relation to the main human disturbances over the last 150–200 years (Rinaldi et al., 2005a; Pellegrini et al., 2008). This study permits the documentation of the evolution of an originally braided river, combining previous knowledge with the acquisition of new data that allowed for the investigation of channel width vs. bed-level adjustments in more detail.

Specific aims of this paper are (i) to investigate channel adjustment at different spatial scales, i.e., at segment vs. reach-scale, to identify whether a spatiotemporal sequence of stages of evolution can be recognised; (ii) to clarify interactions of channel width vs. bed-level changes during the various stages of channel evolution, including an assessment of the age of vegetation establishment during morphological recovery; and (iii) to make a synthetic review of existing CEMs derived in other geographical contexts, based on which we discuss suitability and differences and/or to develop a specific conceptual model of channel evolution.

2. Study area

2.1. General setting

The Trebbia catchment is located in the northern Apennines (Emilia Romagna, northern Italy) and covers an area of about 1070 km^2 (Fig. 1). The physiography of the catchment consists of largely mountainous and hilly areas (85% of the total), with a basin relief of about 1406 m; geology is characterized by sedimentary series, mainly marls and sandstones, and outcroppings of ophiolitic rocks in some areas of the catchment. The climate is characterized by a cold winter and a dry summer season; mean annual rainfall is 1440 mm/y, with most of the precipitation occurring during autumn and spring, with October and April being the rainiest months.

The Trebbia is one of the main tributaries of the Po River, with a total length of about 120 km; mean annual discharge along the medium portion of the river is estimated to be about 35 m^3/s (gauging station of San Salvatore, drainage area of 631 km^2; Fig. 1).

The spatial pattern of channel morphology is strongly controlled by the physiographic conditions of the valley, with frequent confined meanders in the upper reach, followed by prevailing partly confined reaches crossing the hilly areas, and then unconfined reaches with a tendency toward braiding along a wide alluvial fan included in the Po River plain. In this study we focussed on the latter unconfined river section, having a length of 22.125 km (Fig. 1A). According to the segmentation procedure defined by Rinaldi et al. (2013) and Gurnell et al. (2014), the investigated section was defined as a river segment that is a macroreach with similar conditions in terms of valley setting. The segment was then divided into seven reaches (Fig. 1B) with relatively homogeneous morphological characteristics and same channel typology (Table 1). The final reach (i.e., about the last 1000 m before the confluence with the Po River) has been excluded from the analysis because of significant artificial control on channel morphology (artificial levees) and because of some gaps in map and aerial photo coverage. Current channel morphology of the analyzed river segment is predominantly wandering, but with some narrower reaches (1 and 6) where channel pattern can be better described as sinuous with alternate bars (Rinaldi, 2003; Rinaldi et al., 2013) and other wider reaches with a marked tendency toward braiding (3 and 4). Channel slope ranges from about 0.2 to 0.4%; median diameter of bed sediments is in the range of 33 to 80 mm (Rinaldi et al., 2005a; Pellegrini et al., 2008; Surian et al., 2009).

2.2. Human disturbances and impacts

Similar to other Italian rivers (Surian and Rinaldi, 2003; Surian et al., 2009), the Trebbia River and its catchment have been affected by the following human disturbances during the last centuries (Rinaldi et al., 2005b; Pellegrini et al., 2008): (i) construction of levees and other protection structures (nineteenth to twentieth centuries); (ii) reforestation in the drainage basin (nineteenth to twentieth centuries); (iii) construction of two dams in the upstream portions of some tributaries and three main weirs along the main channel (1950s to 1970s) (Fig. 1); (iv) intense sediment mining, started after World War II and with the maximum intensity between the 1960s and 1980s (Surian et al., 2009).

Land use change in the Trebbia catchment over the last 130 years has been documented by Duci (2011) using four different data sets; aggregation of data into five classes of land use allowed a comparison between such data sets (Table 2). The main result of this investigation is the progressive increase of forest cover, from 22% to 51% of the catchment area, respectively, in 1885 and 2006. The dams are located in the upper catchment but may have significantly affected the flow and sediment regime. Sediment mining has probably caused the most important alterations on channel morphology. Although quantitative data on extracted sediment volumes are lacking, segment-scale sediment exploitation has been very intensive during the period from the 1960s to the 1980s as a result of industrialization and urbanization of the area, which has been drastically limited by national legislation since the beginning of the 1990s.

3. Materials and methods

A multitemporal GIS analysis of planform changes was conducted, starting from historical maps dated 1885 and including a time sequence of 11 aerial photographs from 1954 to 2010 at various scales (Table 3). Older maps (1815, scale 1:100,000) were also used to qualitatively assess the channel morphology of that period but were not included in the quantitative analysis of changes because of the potential for significant error. The GIS analysis consisted of orthorectification and georeferencing of each image, digitalization of channel margins, and measurement of width of the channel and islands. Orthorectification was performed by using ERDAS Leica Geosystem 8.7. The maps and the aerial photographs were coregistered using maps at a 1:5000 scale as a base layer; for each aerial photo, a series of ground-control points were used, and root mean square errors (RMSE) deriving from orthorectification were estimated to be lower than the pixel size of the images. After delimiting and digitizing channel margins, a centerline of each year was automatically derived in GIS from the delimitation of the channel margins, and a series of cross sections orthogonal to the centerline were generated for each year. Then, channel width was measured for each of these cross sections as the sum of submerged channels and unvegetated or sparsely vegetated depositional bars. A spatial interval of 25 m between cross sections of measurement was used, which is relatively short spacing, on the order of one-tenth of the average channel width of 2010.

Limitations and errors related to georectification and digitizing of channel morphological features have been discussed by various authors (e.g., Gurnell, 1997; Winterbottom, 2000; Hughes et al., 2006). According to previous similar analyses using the same methodologies (e.g., Downward et al., 1994; Winterbottom, 2000; Liébault and Piégay, 2001; Rinaldi et al., 2009; Surian et al., 2009; Ziliani and Surian, 2012), a maximum error of 20 and 6 m, respectively, was estimated for our measurements on the historical map and aerial photographs.

Bed-level changes were investigated by a time series of four topographic surveys of cross sections (Fig. 1; Table 3). Previous studies (Rinaldi et al., 2005a; Pellegrini et al., 2008) have made use of the first available surveys (1974, 1992, and 2003) to assess the overall changes of longitudinal profiles. In this study, a new survey was done in 2009, consisting of a series of 18 cross sections overlapping the position of the previous cross sections of 2003. The survey was conducted using GPS equipment, consisting of two Topcon Hyper Pro antennas and a Topcon FC100 receiver; estimated planimetric and altimetric maximum error was about 2.5 and 4 cm, respectively.

For each cross section of the available surveys, the mean bed elevation was obtained as the average elevation of all the points of the channel bed starting from the bank toe (banks were excluded from this calculation). A weighted average elevation taking into account the distance between each pair of points was used, then the longitudinal profile of mean bed elevation was obtained for each year. In order to obtain a mean change of bed elevation along the longitudinal profile for each pair of years, the difference of the areas subtended by the longitudinal profiles of the two years was calculated for a given reach length.

A series of field surveys were performed to verify consistency of field evidence with the results of bed-level changes assessed by the longitudinal profiles and to gain additional information on present trends of adjustments. Interpretation of bed-level adjustments was supported by the application of specific field sheets (Rinaldi, 2008), and by using a series of evidence, including differences in elevation between homologous geomorphic surfaces (Rinaldi, 2003; Liébault et al., 2013).

Field work also included dendrochronological sample collection and analysis. Dendrochronology and botanical evidence have been widely used to analyze interactions of fluvial processes and hydrogeomorphic conditions in different morphogenetic contexts (e.g., Sigafoos, 1964; Hupp and Osterkamp, 1996; Hupp and Bornette, 2003; Pelfini et al., 2006; Garavaglia et al., 2010) and to date occurrence and rates of erosional or depositional processes supporting interpretation of the stage of adjustment in CEMs (Hupp and Simon, 1991; Hupp, 1992; Hupp and Rinaldi, 2007).

A more accurate reconstruction of channel changes was obtained by using a tree ring analysis with the aim of determining the age of tree establishment and therefore to date fluvial surfaces colonized by arboreal vegetation. This analysis can provide a field verification and detail on the determination of the period for vegetation establishment and colonization of in-channel and riparian surfaces in the context of channel evolution. Two dendrochronological surveys (2009 and 2010) were conducted, during which 92 *Populus nigra L.* distributed on eight sites along both channel banks and on islands were sampled for dating. The eight sampling sites are located along reaches 2 and 3 and were selected as representative of areas where morphological changes observed from aerial photographs were evident (Fig. 2). According to Liébault and Piégay (2001), the age of trees of the species that belong to the first stage in the ecological succession of riparian forests (e.g., *Populus nigra L.*) is an indicator of the date at which the geomorphic surfaces supporting these plants were formed. Corenblit et al. (2014) focused their attention on this species and in particular on its biogeomorphological life cycle (BLC), identifying four different stages of interactions (i.e., geomorphological, pioneer, biogeomorphological, and ecological) with the physical landscape processes, according to the tree age.

The oldest trees colonizing the investigated geomorphic surface were selected for tree ring analysis. Two cores were extracted from each tree by using an increment borer at the standard trunk height of 1.30 m (BH: breast height). For the dendrochronological investigations, tree-ring width was measured (accuracy of 0.01 mm) using the LINTAB and TSAP systems (Rinn, 1996), and core image analysis was performed by WinDENDRO software (Regent Instruments Inc., 2001). In order to reduce dating errors (Gutsell and Johnson, 2002; Koch, 2009), cross-dating of the dendrochronological series has been statistically processed by the COFECHA software (Holmes et al., 1986) and visually by the TSAP. The growth trend has been removed by indexing tree ring growth curves using Arstan (Cook, 1985) to improve observations on abrupt growth changes.

Given that the sampling height was 1.30 m, the colonization time gap (CTG) (Pierson, 2007) was considered, corresponding to the sum of the germination lag time (GLT, i.e., the time interval between stabilization of the new landform surface and germination of the sampled tree) and the growth time (BHGT, i.e., the interval between seedling germination and growth to sampling height).

Populus sp., and in particular *Populus nigra* L., is generally considered among the pioneer species, taking a short time to germinate on bars and new floodplain surfaces (Everitt, 1968; Gottesfeld and Johnson-Gottesfeld, 1990; Hupp and Simon, 1991;

Astrade and Bégin, 1997; Scott et al., 1997; Liébault and Piégay, 2001; Hupp and Rinaldi, 2007). As indicated by Corenblit et al. (2014) and according to the definition by Jones et al. (1994), *Populus nigra* L. may be defined as an engineer species that exerts a strong control over ecosystem function by creating or significantly modifying the habitat. Gutsell and Johnson (2002), working on *Populus tremuloides*, indicated this species to be early-successional (i.e., pioneer) characterized by high growth rates between the root collar and the first few meters, and calculated an average age correction of + 4/5 years in boreal forest (assuming GLT = 0). In our study, the definition of CGT presents some uncertainty as specific information for *Populus nigra* L. in the particular morphoclimatic context of the study area was not available in literature, and we defined a range rather than a fixed value. We assumed that most of the sampled pioneer trees germinated during the first growing season after a major flow event (GLT ranging from 0 to 1), and a BHGT of 2–3 years, resulting in a CGT ranging from 2 (MiCA, minimum corrected age) to 4 years (MaCA, maximum corrected age).

4. Results

A first step of analysis consisted of integrating the existing knowledge with the addition of the most recent data on channel width (from aerial photos of 2010) and bed elevation (from cross sections of 2009). Channel width and bed elevation changes were aggregated at segment scale in order to visualize the overall changes that occurred along the entire study portion of the river. Although an exhaustive discussion of the causes of the various phases of adjustments is beyond the scope of this paper, Fig. 3 summarises channel adjustments and relevant human factors influencing channel morphology (Pellegrini et al., 2008). The two largest flood events that occurred in the period (1953 and 2000, with estimated peak discharge at San Salvatore of 3430 m^3/s and 2475 m^3/s, respectively) are also indicated on Fig. 3. Additional information on magnitude and sequence of floods during the period of investigation was not available because of the lack of a sufficiently long time series of maximum annual peak discharge within the catchment. The three phases (1, 2, and 3) indicated in Fig. 3 are those described in previous studies on the Trebbia River (Rinaldi et al., 2005a; Pellegrini et al., 2008), as well as on many other Italian rivers (Rinaldi et al., 2009; Surian et al., 2009; Ziliani and Surian, 2012). Specifically, phase 1 refers to a first period of narrowing, mainly attributed to land use changes at the catchment scale, to a partial reduction of lateral mobility by bank protection and artificial levees, and eventually to a reduction of sediment delivery related to the end of the Little Ice Age. Even with the relatively high error in the measurement of channel width from historical maps, the average change from 1885 to 1954 was about 130 m, therefore well above the margin of error. Phase 2 refers to the main phase of narrowing and incision starting from the 1950s and mainly associated with intensive sediment exploitation (Pellegrini et al., 2008). Phase 3 concerns the recent period (about the last 15 years) of inversion in the channel-width trend related to a partial recovery of channel morphology (i.e., an increase in channel width and a tendency toward braiding) mainly as a consequence of a drastic reduction in sediment removal.

The second part of the analysis focused on the period of major adjustments after the 1950s and the following period of partial recovery (i.e., phases previously indicated as 2 and 3). In this second part, we analysed change at the reach scale in order to determine in more detail whether the trends were similar to those observed at the segment scale, or if there were differences between reaches reflecting some spatiotemporal pattern of evolution.

Channel width measurements were aggregated for each of the seven morphological reaches previously defined; bed profiles were also integrated from different years along the same reaches. Results of this analysis are shown in Fig. 4 (bed elevation data were available for reaches 2 to 6 only). The analysis of the trajectories of change for the different reaches shows, as expected, a more variable range of situations accounting for some local conditions but still sharing common general characteristics. In regards to the trajectories of channel width (Fig. 4), we identified the time intervals of the two main phases (major adjustment and partial recovery phases) and classified the types of change (Table 4).

The phase of major adjustment was dominated by channel narrowing, with some short periods of limited widening (reaches 1, 2, and 6, for an interval of time < 10 years). The end of this phase ranges from 1990 (five out of seven cases) and 1996 (the remaining two cases). The partial recovery phase was characterized by dominant widening but often alternating with shorter periods of limited narrowing. The amount of change during the partial recovery phase was significantly lower than that of the major adjustment, ranging from about 10% (reaches 3 and 6) to 60% (reach 2), also as a consequence of the shorter time interval.

The low number of available data points did not allow for the reconstruction of the trajectories of bed-level change with the same detail as channel width. A synthesis of width and bed-level adjustments during the investigated period 1954–2010 for all the reaches is reported in Table 5. From this summary, no recognizable spatiotemporal patterns of change are evident (e.g., upstream or downstream migration of some process through time). Rather, the central portion (reaches 3, 4, 5) exhibits a quite similar pattern of changes, particularly in terms of bed elevation with bed aggradation following incision, whereas bed incision occurred for the entire period along reaches 2 and 6.

Bed incision is clearly the most common type of adjustment, but with the important consideration that in three out of five cases bed-level lowering did not continue during the last time interval (2003–2009) and was replaced by a slight aggradation or stability. Concerning the relations between channel width and bed elevation changes, a first qualitative result deriving from Table 5 is that the decreasing trends in bed elevation are prolonged for some years after narrowing converted to predominant widening. Therefore, bed aggradation or stability and channel widening do not entirely occur during the same interval of time, but there is a period when incision and widening occur together.

We assessed more quantitatively the relations between channel width vs. bed-level adjustments, and we investigated the existence of spatiotemporal patterns. We chose three periods (1974–1992, 1992–2003, 2003–2009) dictated by the availability of bed elevation data. For these three periods we selected the channel width data closest to the years with topographic surveys (1974, 1992, 2003, 2009). A maximum difference of 2 years exists between bed elevation and channel width data. The three selected periods are also meaningful in terms of trajectories of change, given that the first period (1974–1992) covers the second half of the major adjustments, and the following two intervals (1992–2003 and 2003–2009) are associated with the recent phase of partial recovery. Changes in channel width vs. bed elevation for the same time interval are plotted in Fig. 5, from which the following considerations can be drawn: (i) the period 1974–1992 is dominated by the associated incision–narrowing and by the high amounts of both processes; (ii) during the second period (1992–2003), a very clear association of widening and incision is apparent; and (iii) the final period (2003–2009) is characterized by the highest variability, but with an important shift toward aggradation (three out of five points).

Results of the dendrochronological analysis are summarized in Fig. 6, where the number of trees germinating in the time interval 1963–2000 are reported for the two reaches where samples were collected (Fig. 2). From the analysis of aerial photographs, these samples are localized on geomorphic surfaces that originated during channel narrowing in the interval 1980–1990. Determination of the year of tree germination allowed identification of the year of arboreal vegetation establishment on riparian and island surfaces in more detail and, therefore, the timing of stabilization of new floodplains and islands during the narrowing phase.

Correlation results among the annual ring width curves of the trees in the eight sampling areas are sufficiently good, showing an average COFECHA correlation index of 0.4966, with the highest values (0.546–0.747) associated with the 11 sampling areas located along the left channel bank ((d), (e), (i), and (j) in Fig. 2). The oldest sampled surface (the most southern, (a) in Fig. 2) is located along the outer bank of a meandering bend along reach 2. In this location, most of the trees populating the surface germinated between the late 1970s and the early 1990s with a peak in 1977 (MaCA) – 1979 (MiCA) (see details in Fig. 6). Other sites, located along reach 3 ((b)-(k) in Fig. 2) were all completely established in the first half of the 1990s. The peak of germination was reached in 1985 (MaCA) – 1987 (MiCA), suggesting a younger age for the corresponding surfaces. In detail, the trees on islands germinated between 1983 and 1992 (MiCAs), while the investigated surfaces located on the left bank were colonized mainly in the period 1984–1995 (MiCAs) and 1984–1991 (MiCAs) on the right bank. In summary, this data provides additional field evidence that the colonization of arboreal vegetation along the investigated reaches mainly occurred during (1977–1979) (reach 2) or after (1984–1986) (reach 3) the period of major channel narrowing (phase 2). Arboreal vegetation initially established on newly formed surfaces (floodplain and islands) during the final phase of incision and narrowing.

5. Discussion

Results of the analysis of channel changes along a river length of about 22 km and over a period of about 60 years show evidence of a temporal sequence of stages characterized by different combinations of width and bed-level adjustments. The following discussion is organized as follows: (i) the discussion of the results of this study is preceded by a synthetic review of existing CEMs developed in other geographical contexts, and on their applicability to Italian river systems based on previous studies; and (ii) results for the Trebbia River are discussed and set within a conceptual framework of channel evolution, reconsidering differences with existing CEMs previously identified.

5.1. Existing knowledge on CEMs and on their applicability to Italian rivers

Research conducted in various areas of the United States has shown a sequence of stages of channel evolution for river systems disturbed by channelization, base level lowering, or alterations to the flow and/or sediment regimes (Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989). This typical succession of stages has led to the development of a series of channel evolution models (CEMs) based on the concept of location-for-time substitution and shifts in dominant adjustment processes. These models describe a phase of initial bed incision, followed by bank instability and widening, and by a subsequent stage of downstream aggradation as degradation migrates upstream. Bed incision (degradation) is typically the first primary adjustment following the human disturbance, followed by channel widening because banks exceed critical height (depending on their composition) for bank failure. Then, downstream bed aggradation begins as a result of bank sediment delivery from upstream, and a new floodplain is progressively rebuilt during the recovery phase leading to the progressive establishment of an endpoint ‘quasi-equilibrium’ morphology.

The CEMs were initially developed for incising, single-thread channels and, although they have been subsequently applied and verified in several areas (Simon and Thorne, 1996; Simon and Rinaldi, 2000, 2006), it has also been recognised that different or extended sequences of channel evolution can be observed, depending on various factors. For example, Elliott et al. (1999) proposed a seven-stage evolution model to describe contemporary arroyos that formed in the late nineteenth and early twentieth centuries in many regions of the southwestern USA. Thorne (1999) proposed that an additional stage may be added to account for late-stage evolution from straight to meandering for some of the channels from which the original CEMs were developed. Hawley et al. (2012) have presented a novel five-stage CEM of semiarid stream response to altered hydrologic and sediment regimes associated with urbanization, which includes an evolutionary sequence of braided channel morphology. Finally, Cluer and Thorne (2013) have recently proposed a novel stream evolution model (SEM), including a precursor stage of possible multithread morphology prior to disturbance and introducing an evolutionary cycle framework within which streams may evolve through the common sequence, recover to a previous stage, lack some stages, or repeat part of the evolutionary cycle. This condition proximate to a morphological threshold is similar to the ‘alternative stable state’ concept developed for ecological systems (e.g., Beisner et al., 2003; Folke et al., 2004).

Various studies on channel evolution of Italian rivers included some consideration on the suitability of CEMs for such systems. Rinaldi and Simon (1998) observed that channel adjustments in the Arno River system (Tuscany, central Italy) differ from similar unstable fluvial systems altered by human disturbances because channel widening following degradation and subsequent aggradation in downstream reaches have been limited because of an extensive presence of bank protection. Surian and Rinaldi (2003) developed a classification scheme grouping the observed channel changes into a series of main categories of adjustment. Similarly, Rinaldi (2003) proposed a regional classification scheme of channel adjustments that occurred in Tuscan fluvial systems and discussed some significant differences from CEMs, including (i) lack of an aggradational phase and of a spatial distribution of dominant processes and trends; and (ii) channel narrowing rather than widening. These variations were attributed to a series of possible factors and differences, such as (i) geological bed controls; (ii) channel morphologies, bed and bank materials; and (iii) diverse human disturbances. Subsequent studies (Surian and Rinaldi, 2004; Rinaldi et al., 2008, 2009; Surian et al., 2009) have reported an additional stage for a series of rivers in northern Italy consisting of widening and slight aggradation that occurred after 1990. This new stage could be related to a delayed response to the cessation of the intensive sediment exploitation of the previous period (Rinaldi et al., 2009) and/or to a change of channel geometry and an increase of unit stream power (Ziliani and Surian, 2012).

5.2. A conceptual framework of channel evolution of the Trebbia River

Based on the trajectories of morphological adjustments, in this section we propose a more detailed sequence of stages of channel evolution over the last 60 years, i.e., covering the period of phases 2 and 3 described in previous studies on the Trebbia and other Italian rivers (Pellegrini et al., 2008; Rinaldi et al., 2009; Surian et al., 2009).

Before this study, very few cases included sufficient bed-elevation data to allow investigation in more detail on relations between width and bed-level adjustments and consequently the application of a CEM. In the following part we summarize the results obtained for the Trebbia River and discuss them in the context of an evolutionary framework in relation to possible causes and factors.

From the results of the study of the Trebbia River changes, there is evidence of a partially cyclic evolutionary trend, with a sequence of four stages of evolution and shifts in dominant adjustment processes but without a return to the initial stage (Fig. 7). Compared to other CEMs where the evolutionary sequence starts from a stable, ‘undisturbed’ condition, such an initial stage is more problematic to identify in the case of most Italian rivers. Previous works generally report a first phase of incision and narrowing generally started at the end of the nineteenth century and continued up to the 1950s, which has been interpreted as result of afforestation, bank protection, and eventually a reduction of sediment delivery related to the end of the Little Ice Age. Therefore, the beginning of the 1950s (stage I) cannot be considered as the initial, ‘undisturbed’ condition, but rather as the start of a new evolutionary cycle overlapping a previous degradational phase. The main disturbances causing the start of this new degradational phase (stage II) can be considered a combination of the drastic increase of sediment removal after World War II and the construction of dams upstream. Data on the Trebbia River clearly show that bed incision and channel narrowing act simultaneously, at least during the period of available bed level data (1974–1992) (Fig. 5).

Existing information on the Trebbia River, as well as on other Italian rivers, suggests that it is not possible to determine whether incision and narrowing started contemporarily or whether one of the two adjustments favoured the other. For example, in the case of French rivers, narrowing usually occurred slightly before the incision as it was also associated with afforestation of the river corridors (about 1930s to the late 1960s) in areas that were actively used for grazing; whereas incision reached a peak in the 1970s in relation to intense mining activity (Liébault and Piégay, 2001, 2002). In small tributaries of these rivers, channel narrowing occurred in association with formation of terraces from a decrease of sediment supply with a clear downstream progressing pattern (Liébault et al., 2005).

Channel narrowing represents an apparent difference compared to CEMs applied in the USA, as they predict a phase of channel widening. A series of reasons can explain this difference: (i) channel widening of CEMs refers to the overall cross section, while narrowing of Italian rivers is referred to the channel width intended as low water channels and unvegetated bars, delimitated by the margins of the new terraces generated by incision (Rinaldi, 2003); (ii) bank instability related to bed incision, which is indicated as the cause of widening, is a dominant factor in single-thread, mostly cohesive channels of CEMs. This process is less important in wide, coarse-grained, transitional, or braided channels, where reduction of bedload (induced by sediment removal) and fast colonization and encroachment of abandoned surfaces by vegetation are more relevant factors.

Dendrochronological data support the evidence that vegetation has a primary role during the late narrowing stage. Island and riparian forests along new floodplain surfaces were established mostly during the period 1985–1990, i.e., during the phase of maximum narrowing, and have played an important role in starting the recovering phase. This time interval during which the greater number of trees along reaches 2 and 3 germinated may be considered corresponding to the geomorphological and pioneer stages of the BLC of *Populus nigra* L., as indicated by Corenblit et al. (2014), when the survival of trees is strictly linked to their location in respect to the active channels. An important human factor during this phase of maximum narrowing could also be the promulgation of a national law (1985), which prohibits the cutting of vegetation along riparian corridors, and therefore promoting vegetation encroachment that otherwise, in previous decades, would be partially removed by local owners of agricultural lands and inhabitants for domestic use.

The results from the Trebbia River clearly show that after incision and narrowing there was a following phase (1992–2003) (stage III) during which a slight incision was associated to the start of widening (Fig. 5). The association between incision and widening has been rarely observed in other Italian case studies. For example, Rinaldi et al. (2009) observed along the Magra River that there is good correspondence between the reversal of temporal trends in channel width and bed elevation such that an increase in channel width is usually associated with a phase of aggradation and vice versa. The reversal of the channel width trend from narrowing to widening has been so far attributed to a lagged response to the end of the intensive sediment removal (end of the 1980s). Although this could represent an indirect cause, the actual mechanism triggering the start of widening has not been explained.

Widening in some CEMs becomes a dominant process characterizing the stage after incision because the banks exceed a critical height for mass failure. In the case of the Trebbia, as previously noted, bank instability does not appear to represent a dominant process in controlling channel width because of different bank material (mainly coarse-grained) and the wider channel morphology. In this case, the reason for the start of a widening phase is not completely known, but a possible hypothesis is that relatively frequent flows — which would normally spill over the floodplain — are constrained within the incised and narrow channel. Therefore, the noticeable change of channel geometry during the phase of narrowing has produced an increase of unit stream power in the reach (Ziliani and Surian, 2012).

The encroachment by arboreal vegetation may have further promoted concentration of flow in the new channel bed, by increasing roughness along the new surfaces, and therefore increasing stream power per unit channel width. Therefore, high unit stream power may be responsible for an increasing erosive action and therefore starts to promote lateral erosion by fluvial sediment entrainment. Once lateral erosion starts, the introduction of wood in the channel may be an additional mechanism, besides sediment supply, to explain a further tendency to lateral shifting.

This stage may also correspond to the biogeomorphological stage of the BLC (2-15 year-old trees) (Corenblit et al., 2014), which is characterized by the strong growth increase in stem and roots systems. This is immediately followed by the ecological stage (15-30 years-old trees) when mature trees are located on stabilized floodplains and islands and their future depends on the persistence of the geomorphic surface in response to a disturbance regime, as for example channel migration (Corenblit et al., 2014). Some of the riparian community may be destroyed (as visually observed in the local situation along the Trebbia River during the multitemporal surveys) or survive, transforming into a hardwood terrestrial formation.

Available data on the late stage of evolution (2003–2009) (stage IV) along the Trebbia River are still limited, but they support the idea that in some reaches a possible reversal of bed-level trend has started to occur, i.e., from incision to slight aggradation or stability, although for some other reaches incision is still occurring (Fig. 5). The reversal of bed-level trend is clearly attributable to the start of widening during the previous stage, and the consequent increase in sediment delivery.

Ziliani and Surian (2012) attributed a major role to bank erosion in the recovery of the Tagliamento River, while catchment-scale processes were not considered as playing a significant role. Furthermore, as for the previous stage, widening also promotes introduction of wood derived from the new forested riparian areas therefore favouring further lateral erosion and bed-level recovery.

Unlike CEMs, no clear evidence of a temporal pattern of adjustments is observed. This can be related to the different human disturbances affecting the Trebbia River and other Italian rivers. Sediment removal may be the dominant type of disturbance along the study reaches during the twentieth century, which trigger or accelerate bed incision. Sediment mining has been extensively and simultaneously carried out at many points along the main alluvial channels and tributaries of the fluvial systems. Incision at the points of extraction is a direct result of sediment mining in situ, while upstream and downstream migrating effects (Kondolf, 1994; Rinaldi et al., 2005b) produced bed degradation along the reaches between the pits. The adjustments mostly occurred longitudinally in synchronism along the rivers affected by mining.

A summary of the stages of channel evolution observed along the Trebbia River are shown in Fig. 7. Periodic oscillations and partial reversals of temporal trends can be related to the occurrence of high magnitude floods or to periods within which a relatively high frequency of significant flow events occurred. Notably cyclic evolution does not imply that the river will recover its initial morphology, but rather a cyclic sequence of combinations of width and bed-level adjustments occurs. In fact, existing data on the Trebbia and other Italian rivers show that the amount of widening and aggradation of the current stages of evolution is still a minor amount of the incision and narrowing that has occurred from the 1950s to the beginning of the 1990s. In the case of the Trebbia River, channel widening ranges from about 10% to 60% of the amount of previous narrowing. Not enough data on bed-level changes exist, but the available information suggests that aggradation is still a relatively small part of the previous incision. However a complete recovery of channel width could temporarily occur during intense flood events. For example, this has been observed along the Orco River where a very large flood (the largest recorded in the twentieth century) occurred in October 2000 (Pellegrini et al., 2008; Surian et al., 2009) and more recently along the Magra River during a flood (25/10/2011) with a return period of 100–200 years (Nardi and Rinaldi, 2014). In these cases, channel width can be comparable to the 1950s; however, a partial colonization of vegetation on the new channel bed could again decrease the channel width over the years following the flood.

6. Conclusions

This paper presents a study on channel evolution of a 22-km alluvial segment of the Trebbia River (northern Italy), a very interesting fluvial system not only from a scientific point of view but also for cultural and educational opportunities (Bollati et al., 2012). The focus is on reach-scale dynamics over the last 60 years. Multitemporal analysis of aerial photos allowed reconstruction of detailed trajectories of change in channel width. Topographic cross sections allowed definition of the main bed-level changes with a lower temporal frequency. These analyses then allowed the investigation of reach-scale patterns of channel width and bed-level adjustments and identification of a sequence of stages of channel evolution. Tree-ring data analysis provided additional information on channel evolution and on the life cycle of riparian community during the 1980s to 2010s time interval.

Some main conclusions can be summarized as follows:

- A sequence of stages of channel adjustment can be identified. The first part of an evolutionary cycle represents the main response to disturbances (i.e., sediment mining and upstream dams are the most relevant), dominated by narrowing and incision. A second part represents the partial recovery phase, dominated by widening.
- We observed channel incision combined with widening, which was not yet well documented for other Italian rivers. We also observed slight aggradation or bed stability combined with widening, but higher uncertainty exists on this combination of processes, although they have been observed in other Italian case studies with similar characteristics.
- Observed changes can be set in an evolutionary framework of existing CEMs, as similar shifts of dominant processes are observed, but with some difference that can be related to various factors. A conceptual model of channel evolution specific for the Trebbia River better represents these specific features and could be applied to a wider range of Italian rivers with similar characteristics

in terms of valley setting, channel morphology, and types and chronology of human disturbances. Additional data are needed to confirm some aspects of and to verify extension of this sequence to other Italian rivers, as well as to understand the extent of recovery phases in the future.

- Finally, these findings can be relevant in terms of river management. A channel evolution model based on the knowledge of past trajectories of morphological change can provide important information on possible future trends and therefore on morphological potential and possible endpoint targets for river management or restoration. Historical range of variability is a useful tool. However, this historical range should be used in combination with channel evolution models in order to set the current evolution in the most recent evolutionary framework. Historical conditions cannot be used often as a reference of possible future changes because previous catchment/floodplain conditions have completely changed and these changes may be irreversible. Therefore, identification of the most recent evolutionary cycle can provide a much more realistic range of morphological conditions that can be potentially reached in the future, assuming that no other controlling variables change.

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Figure captions

Fig. 1. Study area. (A) Trebbia River catchment and river segment investigated in this study; BR = Brugneto dam, BO = Boschi dam, SS = San Salvatore, w = weir. (B) Delineation of homogeneous reaches from aerial photos of 2010 (continuous line), dashed line = cross section, PC = Piacenza, RI = Rivalta, RV = Rivergaro.

Fig. 2. Aerial photographs (1954, 1985, 2010) showing the evidence of narrowing of the portion with dendrochronological analysis and location of samplings. In the 2010 photograph the 11 dendrochronological sampling areas are indicated, by lowercase letters, inside the white circles.

Fig. 3. Trends of width and bed-level adjustments at the segment scale with human impacts and main flood events. Human disturbances: horizontal bars indicate temporal interval and relative intensity of the different impacts. Numbers 1, 2, and 3 refer to the phases of channel evolution identified in previous studies (Pellegrini et al., 2008; Surian et al., 2009).

Fig. 4. Trends of adjustments at reach-scale over the last 60 years.

Fig. 5. Channel width vs. bed-level adjustments associated to the three periods of analysis. A: Bed aggradation; I: bed incision; N: channel narrowing; W: channel widening.

Fig. 6. Dendrochronological data: number of trees vs. time. (A) Reach 2; (B) reach 3. The black dot corresponds to the MiCA (minimum corrected age; correction factor +2 years). The horizontal bar indicates the time interval between the real measured age of trees (on the right) and the MaCA (maximum corrected age; correction factor +4 years).

Fig. 7. Conceptual framework of channel evolution for the lower Trebbia River. (A) Four stages of channel evolution. (B) Stages of channel evolution associated with the trends of width and bed-level adjustment at segment-scale showed in Fig. 3.

Table 1
Main characteristics of the morphological reaches

Reach	Length (m)	Typology	Distinctive morphological characteristics
1	2850	Sinuous with alternate bars	Relatively narrow, prevailing single-thread, alternate side bars
2	3500	Wandering	Increasing width, local braiding
3	3625	Wandering	Increasing width, braiding and islands
4	4225	Wandering	Decreasing braiding
5	3050	Wandering	Decreasing width, local braiding
6	2700	Sinuous with alternate bars	Relatively narrow, prevailing single-thread, alternate side bars, local braiding
7	2175	Wandering	Increasing width, highly sinuous baseflow

Table 2

Land use changes in the Trebbia catchment over the last 130 years (from Duci, 2011). Land use data derive from Regione Emilia Romagna (1885 and 1976) and from Corine land cover (1994 and 2003)

Land use classes	1885	1976	1994	2003
Forest (%)	22	37	43	51
Meadow (%)	59	12	9	6
Cultivated (%)	14	42	44	36
Uncultivated (%)	5	9	4	7

Table 3
Summary of data sources used for the analysis of channel adjustments. Type of aerial photos: C: coloured; B/W: black-white

Historical maps (scale)	1815 (1:100,000), 1885 (1:25,000)
Aerial photos (scale)	1954 (B/W - 1:35,000), 1976 (C - 1:13,000), 1980 (B/W - 1:7,500), 1985 (B/W - 1:35,000), 1990 (B/W - 1:34,000), 1996 (B/W - 1:40,000), 2000 (C - 1:40,000), 2002 (C - 1:30,000), 2003 (B/W - 1:5,000), 2006 (C - 1:12,000), 2010 (C - 1:8,000)
Topographic surveys (number of cross-sections)	1974 (9), 1992 (14), 2003 (18), 2009 (18)
Field surveys	2008, 2009, 2010
Dendrochronological data	2009, 2010

Table 4

Summary of channel width adjustments. ΔW: change in channel width; N and n: narrowing; W and w: widening; I and i: incision; A and a: aggradation (capital letter for major phases, i.e. >10 years long)

	Period of major adjustment			Period of secondary adjustments		
Reach	Time	ΔW (m)	Adjustments	Time	ΔW (m)	Adjustments
1	1954-1990	-147,4	N-w-n	1990-2010	59,3	W
2	1954-1990	-183,8	N-w-N	1990-2010	109,2	W-n-w
3	1954-1996	-770,5	N	1996-2010	74,7	w-n-w
4	1954-1990	-516,6	N	1990-2010	142,2	W
5	1954-1990	-292,0	N	1990-2010	68,8	W-n
6	1954-1996	-377,6	N-w-N	1996-2010	34,6	W
7	1954-1990	-459,6	N	1990-2010	60,4	W-n-w

Table_5_rev2

Table 5
Summary of phases of channel width and bed-level adjustments. N and n: narrowing; W and w: widening; I and i: incision; A and a: aggradation (capital letter for major phases, i.e. >10 years long).

<table>
<tr><th>Reach</th><th colspan="13">Width and bed-level adjustments</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">N</td><td colspan="2">w</td><td>n</td><td colspan="8">W</td></tr>
<tr><td colspan="13">n.a.</td></tr>
<tr><td rowspan="2">2</td><td colspan="2">N</td><td>w</td><td colspan="2">N</td><td colspan="4">W</td><td>n</td><td colspan="3">w</td></tr>
<tr><td></td><td colspan="11">I</td><td></td></tr>
<tr><td rowspan="2">3</td><td colspan="7">N</td><td colspan="2">w</td><td>n</td><td colspan="3">w</td></tr>
<tr><td></td><td colspan="9">I</td><td colspan="2">a</td><td></td></tr>
<tr><td rowspan="2">4</td><td colspan="5">N</td><td colspan="8">W</td></tr>
<tr><td></td><td colspan="9">I</td><td colspan="2">a</td><td></td></tr>
<tr><td rowspan="2">5</td><td colspan="5">N</td><td colspan="4">W</td><td colspan="4">n</td></tr>
<tr><td></td><td colspan="9">I</td><td colspan="2">a</td><td></td></tr>
<tr><td rowspan="2">6</td><td colspan="2">N</td><td>w</td><td colspan="4">N</td><td colspan="6">W</td></tr>
<tr><td></td><td colspan="11">I</td><td></td></tr>
<tr><td rowspan="2">7</td><td colspan="5">N</td><td colspan="3">W</td><td>n</td><td colspan="4">w</td></tr>
<tr><td colspan="13">n.a.</td></tr>
<tr><td></td><td>1954</td><td>1974</td><td>1976</td><td>1980</td><td>1985</td><td>1990</td><td>1993</td><td>1996</td><td>2000</td><td>2002</td><td>2003</td><td>2006</td><td>2009
2010</td></tr>
</table>

Figure_1_rev2

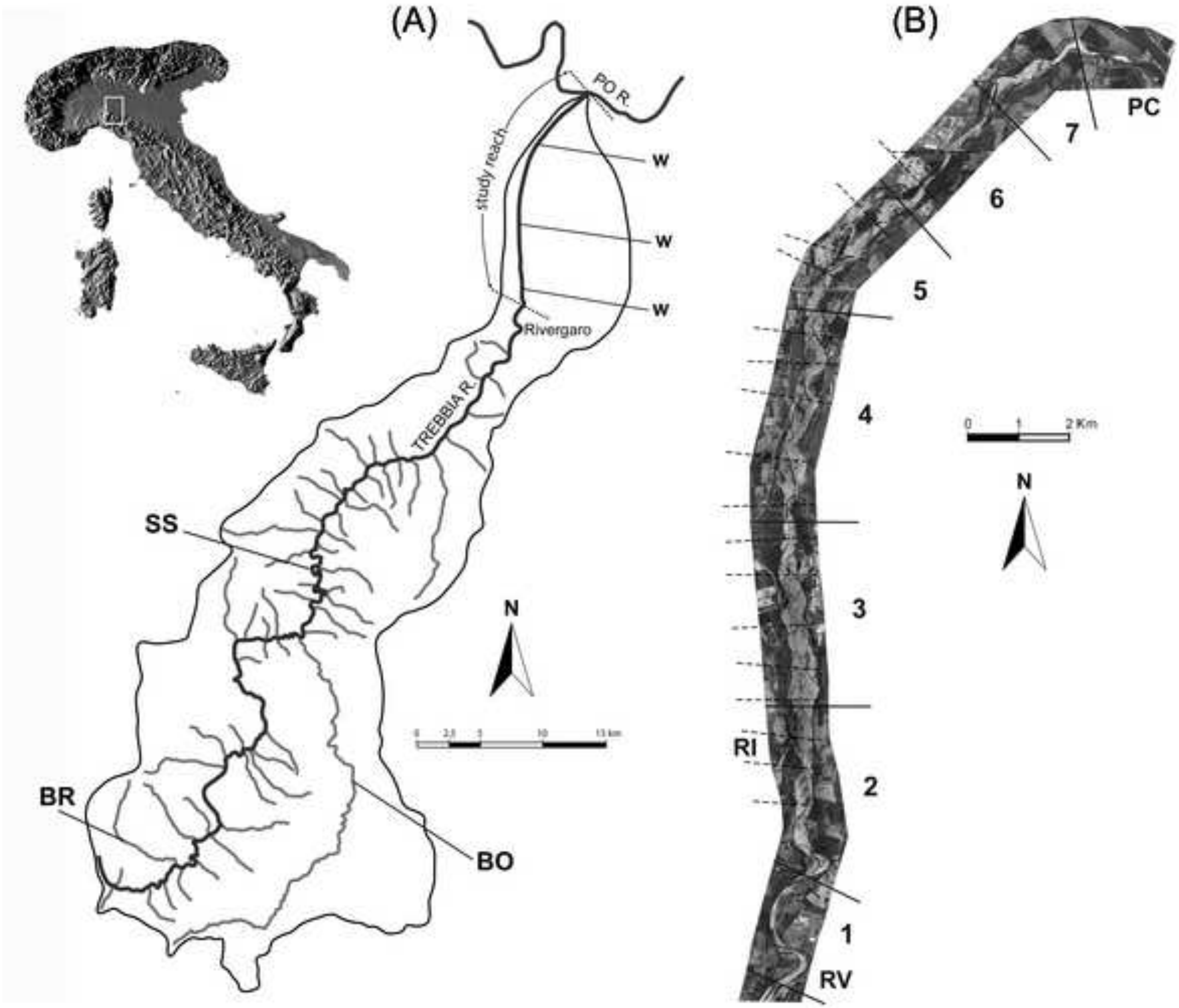

Figure_2

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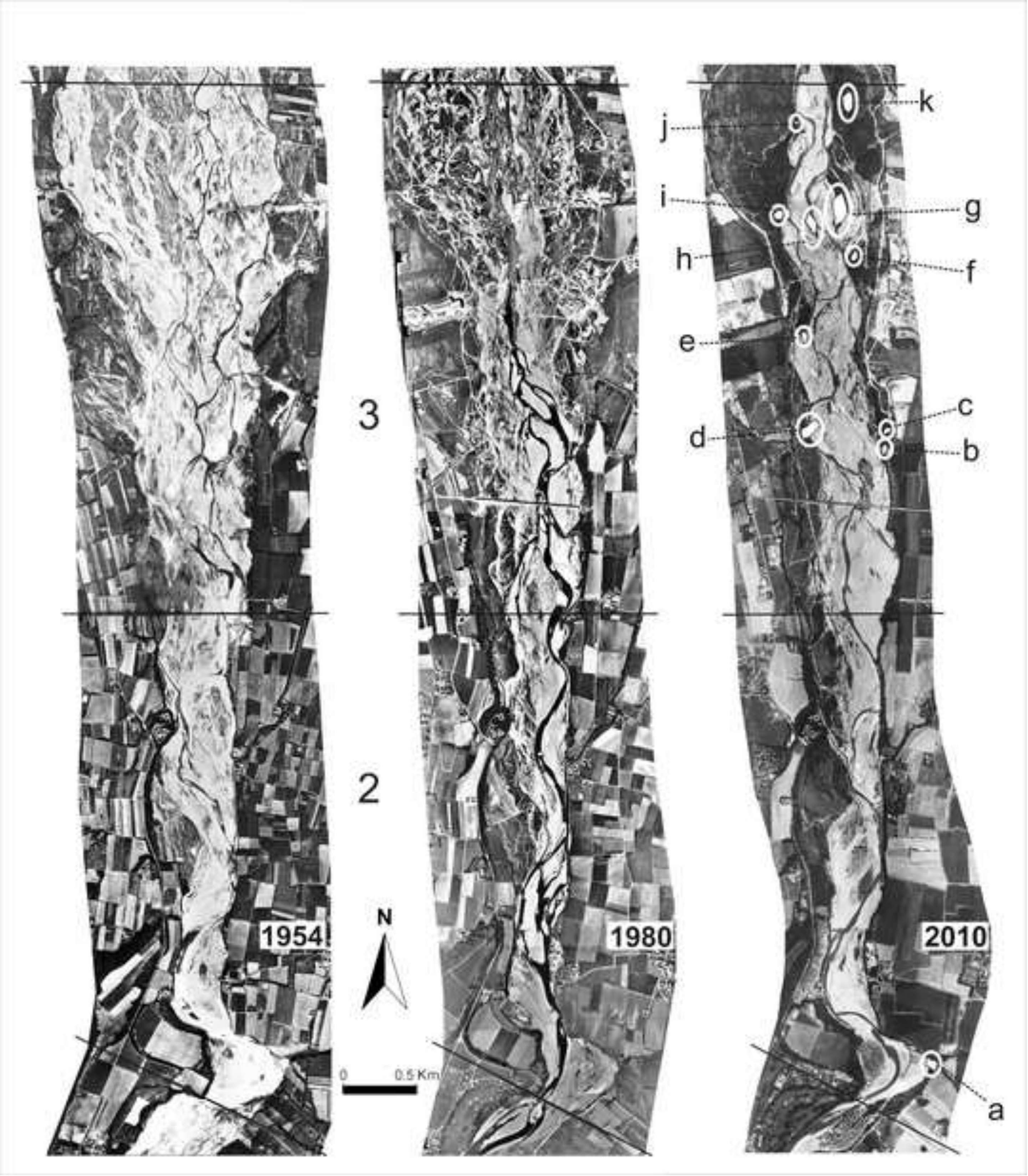

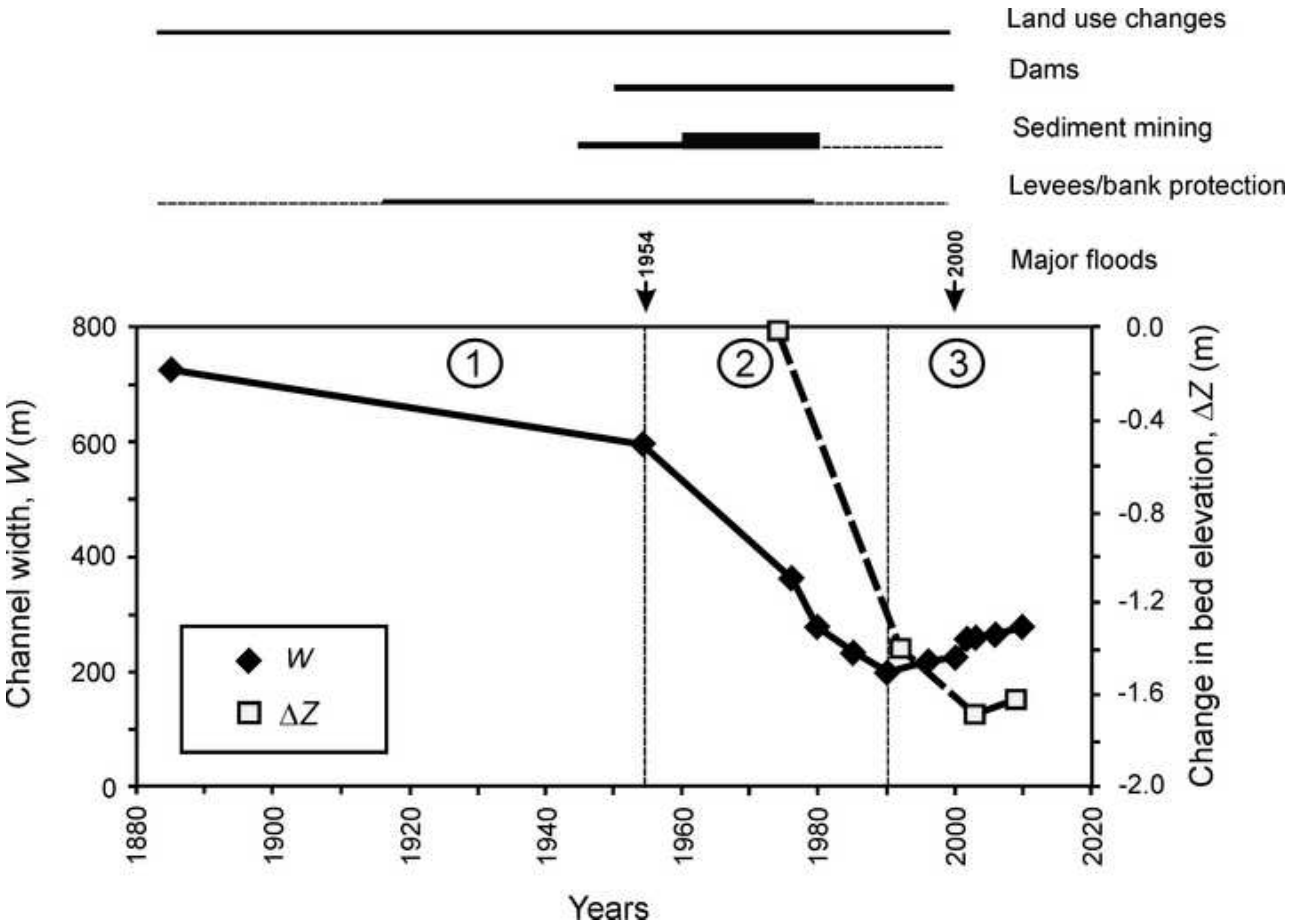
Land use changes
Dams
Sediment mining
Levees/bank protection
Major floods
1954
2000
①
②
③
W
ΔZ
800
600
400
200
0
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
1880
1900
1920
1940
1960
1980
2000
2020
Channel width, W (m)
Change in bed elevation, ΔZ (m)
Years

Figure_4

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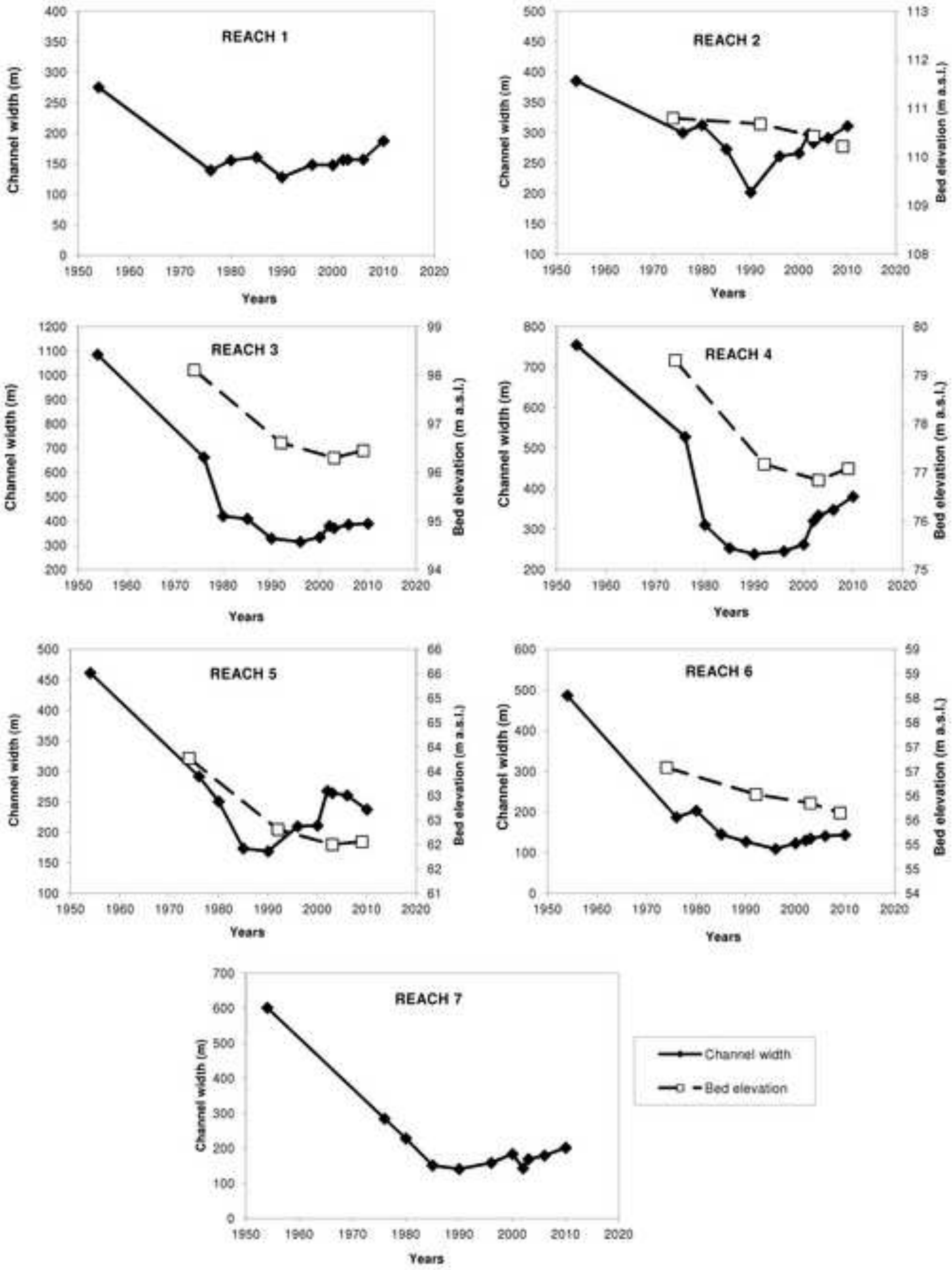
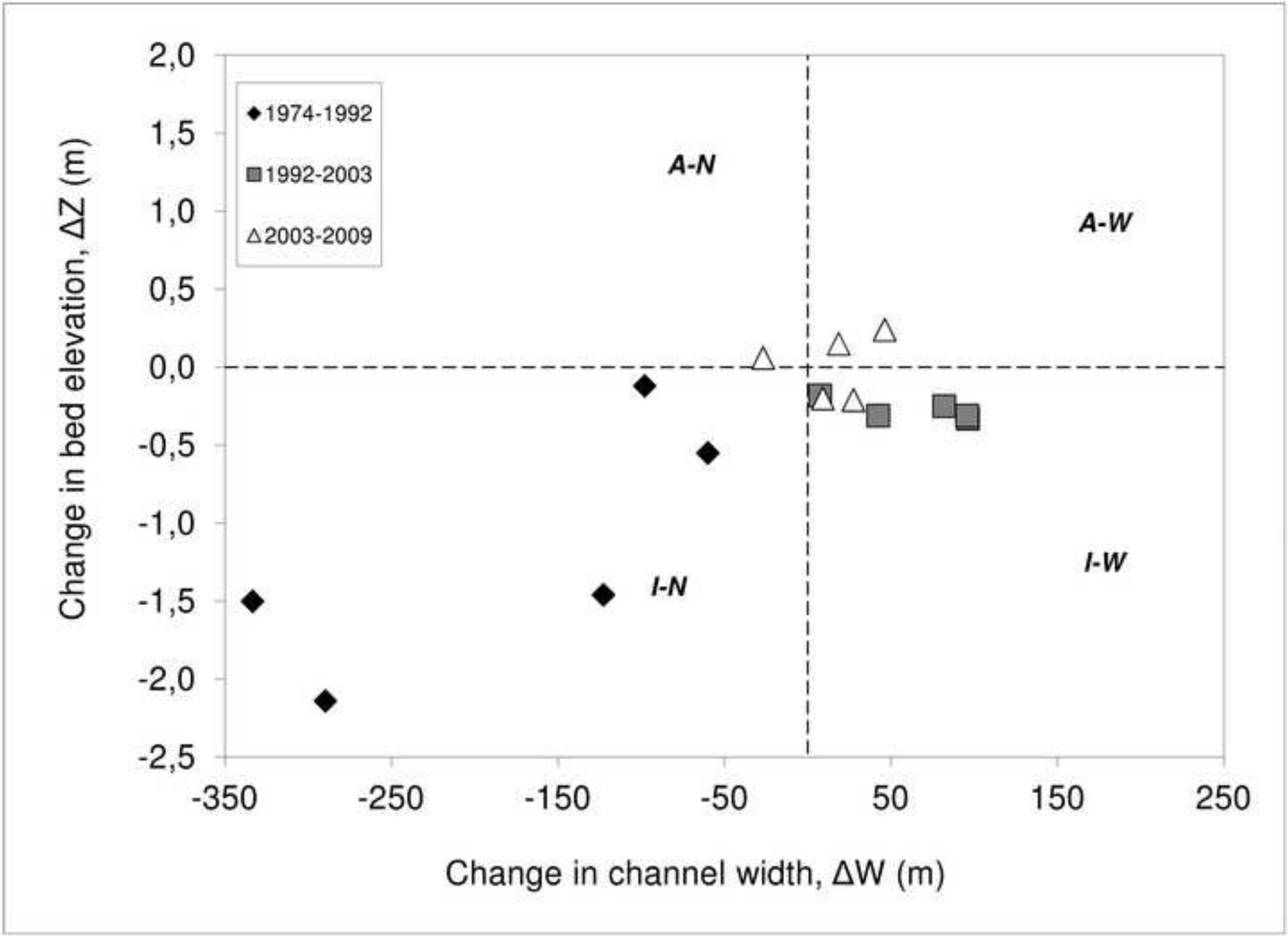


Figure_5


◆1974-1992
■1992-2003
△2003-2009
A-N
A-W
I-N
I-W
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-2,5
-350
-250
-150
-50
50
150
250
Change in bed elevation, ΔZ (m)
Change in channel width, ΔW (m)

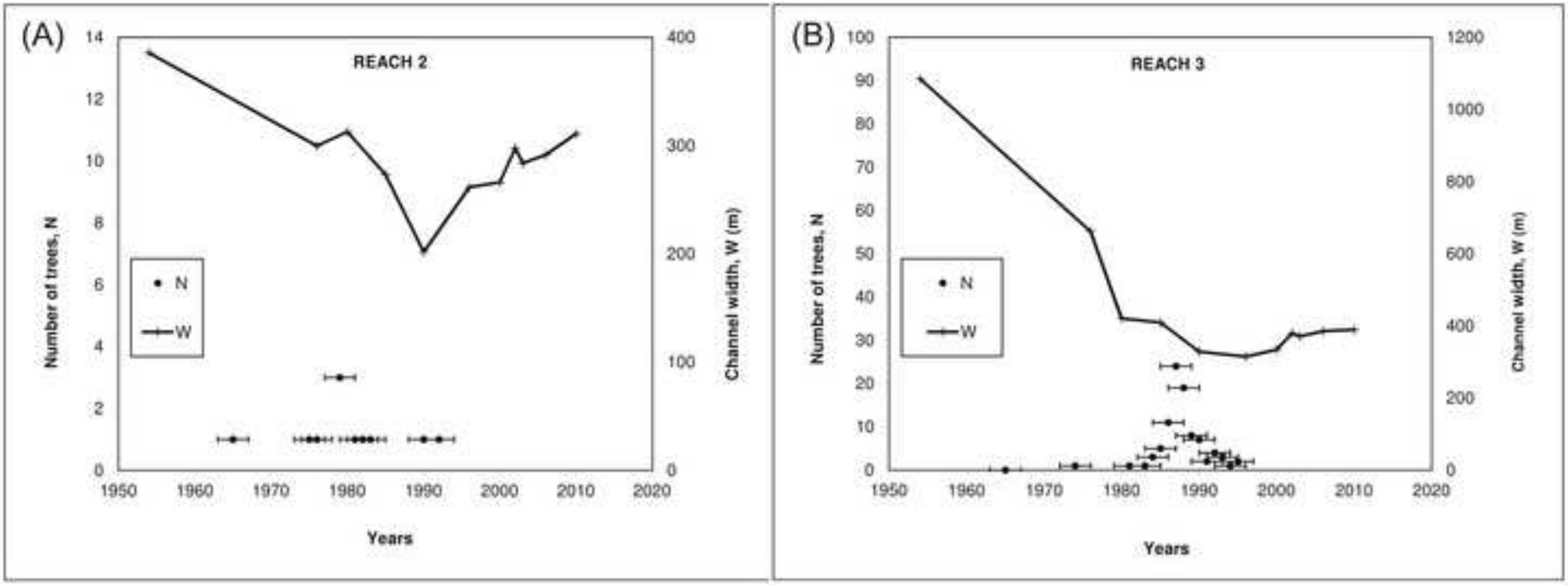
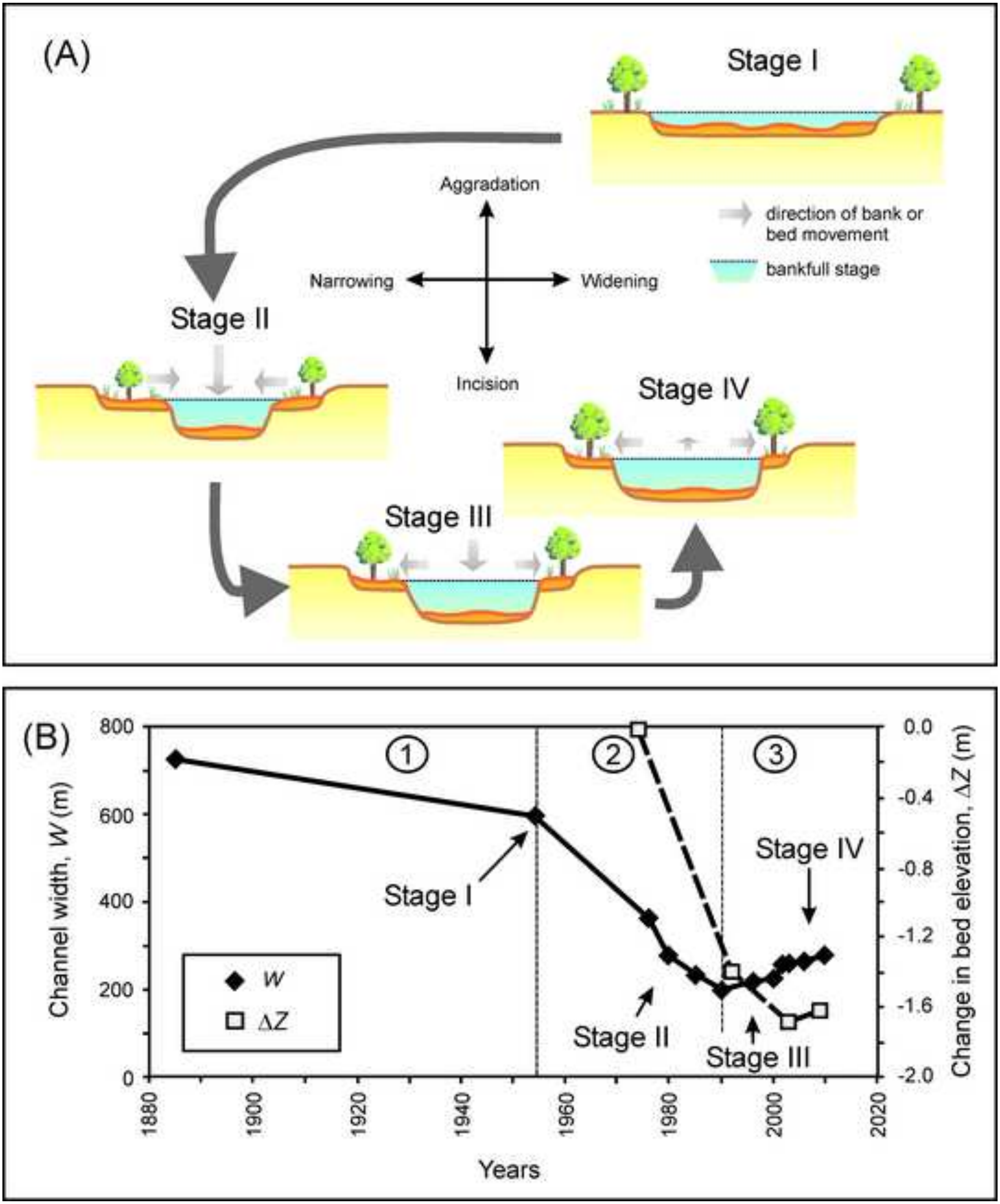

(A)
REACH 2
Number of trees, N
Channel width, W (m)
Years
N
W
0
2
4
6
8
10
12
14
0
100
200
300
400
1950
1960
1970
1980
1990
2000
2010
2020
(B)
REACH 3
Number of trees, N
Channel width, W (m)
Years
N
W
0
10
20
30
40
50
60
70
80
90
100
0
200
400
600
800
1000
1200
1950
1960
1970
1980
1990
2000
2010
2020

Figure_7_rev2



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