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Channel Changes and Controlling Factors over the Past 150 Years in the Basento River (Southern Italy)

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Abstract: Channel changes are receiving growing interest in relation to the relevant implications for river management and restoration. In this kind of analysis, purely qualitative approaches have been gradually replaced by quantitative approaches aimed at reconstructing the temporal variations in parameters (e.g., channel width and depth) to investigate not only the evolutionary trend of the river but also the possible cause-effect connections. This paper investigates the channel dynamics in the Basento River (Basilicata Region, Italy) over the past 150 years, when the river was heavily affected by human activities (e.g., hydraulic interventions and gravel mining) and climate changes. Channel adjustments were analysed with historical maps, aerial photos, and geomorphological surveys. The results show that the channel underwent a strong narrowing during the twentieth century, similar to many rivers in Italy, with the most intense phase from the 1950s to the 1990s (with the width varying from −30% to −80%). The morphology pattern remained almost completely unchanged, apart from a few reaches located in the hilly area that were affected by intense modifications before the 1940s. The causes of channel adjustments were identified as human disturbances (land use variations, channel interventions at the reach scale, sediment mining) from the end of the 1800s to present, as well as natural factors (changes in frequency, duration, and intensity of flood events), whose effects have intensified since the late 1990s.

Keywords: fluvial dynamics; channel narrowing; human disturbances; Basento River

1. Introduction

Fluvial dynamics, resulting from the interaction between water and sediment flow and the surrounding river system (e.g., topography, slopes, sediment, and vegetation availability), can undergo anthropogenic and natural conditioning [1].

Alteration of fluvial dynamics may lead to morphological adjustments (planimetric and altimetric), which can occur at the reach scale over short periods of time and limited spatial extents or over long time intervals (from tens to thousands of years) and involve the entire river system, depending on the intensity, extension, and type of disturbance [2].

Generally, the channel response to anthropogenic interventions is rapid and depends not only on the type of intervention but also on the spatial scale. Several studies have demonstrated how variations in land use [3–7], urbanization [8,9], channelization [10,11], dam construction [12–14], and sediment mining [15–18] alter flow and sediment regimes, leading to changes in river dynamics and morphology. Over the past 200 years, the morphological fluvial dynamics of most European and Italian rivers have been mainly modified by human impacts [19–23].

On the other hand, the influence of natural factors including climatic and hydrological variations [24–27], tectonic movements [28–30], volcanic phenomena [31–34], and sea level changes [35,36] can generally act on river systems, inducing morphological variations over both the long (e.g., [37,38]) and short term (e.g., [39]).

Reconstruction of the fluvial evolutionary dynamics highlights the effects of the influence (natural and anthropogenic) of geomorphological factors on the river system [11,40]. Over time, studies of river dynamics in Italy have received growing attention, as clearly shown by the bibliographical review conducted by [41] for the period 1963–2007. Until the 1990s, the approach was mainly qualitative and aimed to understand if and when channel changes occurred. More recently, a quantitative approach was increasingly conducted to reconstruct the variations in river parameters, such as channel width and depth, and to investigate both river evolutionary trends and some possible cause-effect ties [42].

To date, numerous studies have evaluated the morphological variations in river in central and northern Italy [43–51], while much fewer studies have focused on southern Italy [52–57]. This difference is perhaps related to the reduced interest and importance of rivers in southern Italy in terms of the size, length, and water discharge, and above all, the frequency of flood events and intensity of the effects, even though there have been several cases of great impacts. Most of these studies point out that three main phases of morphological "adjustment" have occurred: (i) Phase I lasted from the end of the 19th century to the middle of the 20th century when river incision was less intense and narrowing occurred due to effects related to the end of the "Little Ice Age" [58,59] and land use changes. ii) Phase II started in the 1950s, or 20 years later in cases such as for central and southern Italian rivers (e.g., [52,54,60], until the 1990s. This phase was characterized by a more intense anthropogenic impact, causing strong narrowing and incision of rivers. iii) Phase III began, on average, at the end of the 1990s, with delay or advances of 10 years in some cases and continues to the present; this phase is characterized by less intense channel adjustments and, in some cases, morphological recovery. For this last phase, several local differences have been noticed in both northern rivers and those in central and southern Italy, which do not exhibit clear temporal trends.

The morphological dynamic of the Basento River was investigated over the last century using qualitative analysis [61], considering the morphological changes in the river due to anthropogenic interventions between the 1950s and 1990s. Over time, the impacts of erosion phenomena in the mouth and coastal plain have been examined by several geomorphological studies [62–66].

This paper evaluates the fluvial dynamics of the Basento River over the last 150 years. In particular, the main aims are (1) to reconstruct the evolutionary trajectory of channel morphology; (2) to identify the links between channel changes and human and natural factors; and (3) to highlight the similarities and differences in the evolutionary trajectory with other Italian rivers. Channel adjustments were analysed in the Geographic Information System (GIS) environment using historical maps, aerial photos, and geomorphological surveys.

2. Study Area

2.1. Geographical Setting

The Basento River originates from Mount Arioso (1715 m a.s.l.) in the northern Lucanian Apennines, and it flows in the SW–NE direction in the first mountainous section up to Potenza; then, its flow direction changes to the NW–SE direction, flowing into the Gulf of Taranto (Ionian Sea). The river course is ca. 170 km, and it can be divided into three main sections: Upper, middle, and lower Basento (Figure 1). The upper Basento flows in the mountain area crossing the Apennines up to Campomaggiore; the middle Basento flows in hilly areas from Tricarico to Bernalda; finally, the lower Basento crosses the coastal plain and flows into the Ionian Sea near Metaponto.

This study focuses on the river section in the hilly and coastal plain areas from Ferrandina up to the river mouth (Figure 1). In this section, which coincides with the lower Basento and a part of the middle Basento, the flow length is ca. 73 km, and the channel morphology ranges from sinuous in the upper part to meandering. The river longitudinal profile shows a significant slope variation (Figure 2) that coincides with changes in the channel pattern. The channel slope is in the range of 0‰–2‰.

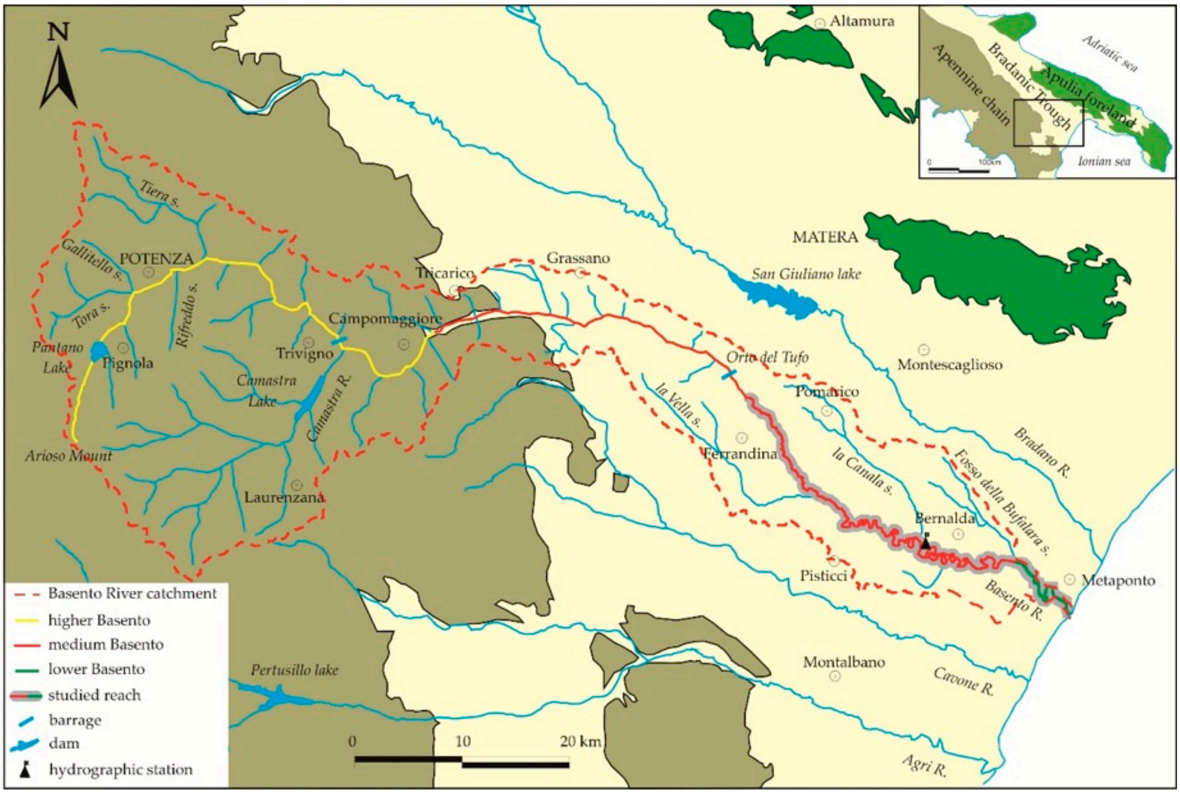

Figure 1. General setting of the study area.

2.2. Geological and Geomorphological Settings

The Basento catchment (1530 km^2) falls within the domain of the Apennine chain in the western part and within the Bradanic Trough in the eastern part. The first domain consists of tectonically superimposed flyschoid formations, with the oldest of Upper Cretaceous–Eocene age, while the most recent is referred to as the Upper Oligocene–Upper Miocene [67]. The latter domain corresponds to a narrow sedimentary basin with a NW–SE trend and is located between the southern Apennines and the Apulian foreland. This domain is filled with siliciclastic deposits belonging to the Bradanic Trough and is characterized by a Pliocene–Lower Pleistocene age [68,69]. The regressive units of the Bradanic Trough sedimentary cycle correspond to the more than 1000 m thick clayey “Argille Subappennine” Formation [69], ca. 50 m thick of the sandy “Sabbie di Monte Marano” and the conglomeratic “Conglomerato di Irsina” Formations [69].

In the Middle Pleistocene, the Bradanic Trough began to uplift, allowing both ancestral rivers, including the palaeo Bradano River, to cut deep valleys perpendicular to the coast [70]. The general mechanism of regression is complicated by glacio-eustatic sea level oscillations that occurred together with the uplift. This phenomenon is reflected by a complex system of coastal marine terraces [71–73] and several fluvial terraces [74]. Two levels of Holocene fluvial terraces have been identified in the Basento River [75]. The study area falls within the southeastern portion of the Bradanic Trough (Figure 3).

From a geomorphological perspective, the area is predominantly hilly and gradually slopes down towards the coastal plain [76]. Flatter areas can be found near the Ionian coast (Metaponto plain) and the river. The Basento catchment is characterized by a dendritic hydrographic network that develops from northwest to southeast.

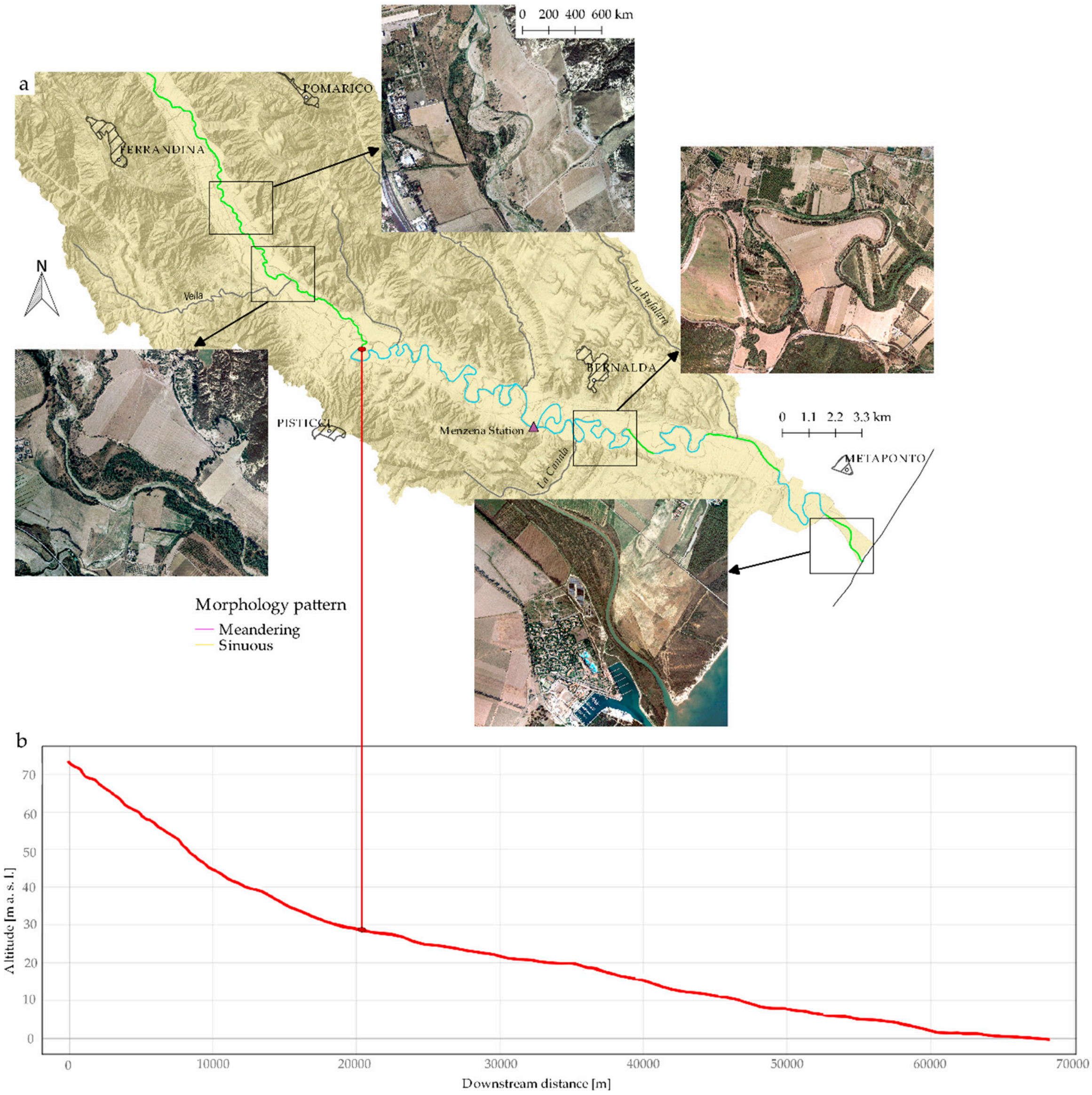

Figure 2. The study area: Examples of different channel patterns (**a**) and the longitudinal profile of the river (**b**).

From upstream to downstream, several large tributaries join the Basento River: Not far from Potenza, the Gallitello and Tora streams join the Basento River. The Pantano artificial lake is located in the Tora stream basin. Downstream, there are the Rifreddo (on the right bank) and the Tiera streams (on the left). At Trivigno, the river is blocked by a river weir, and at the right bank, it receives the contribution of the Camastra torrent where the homonymous dam is located. Near the coastal plain on the right bank, Basento receives the contributions from the Vella stream and finally the La Canala and La Bufalara streams.

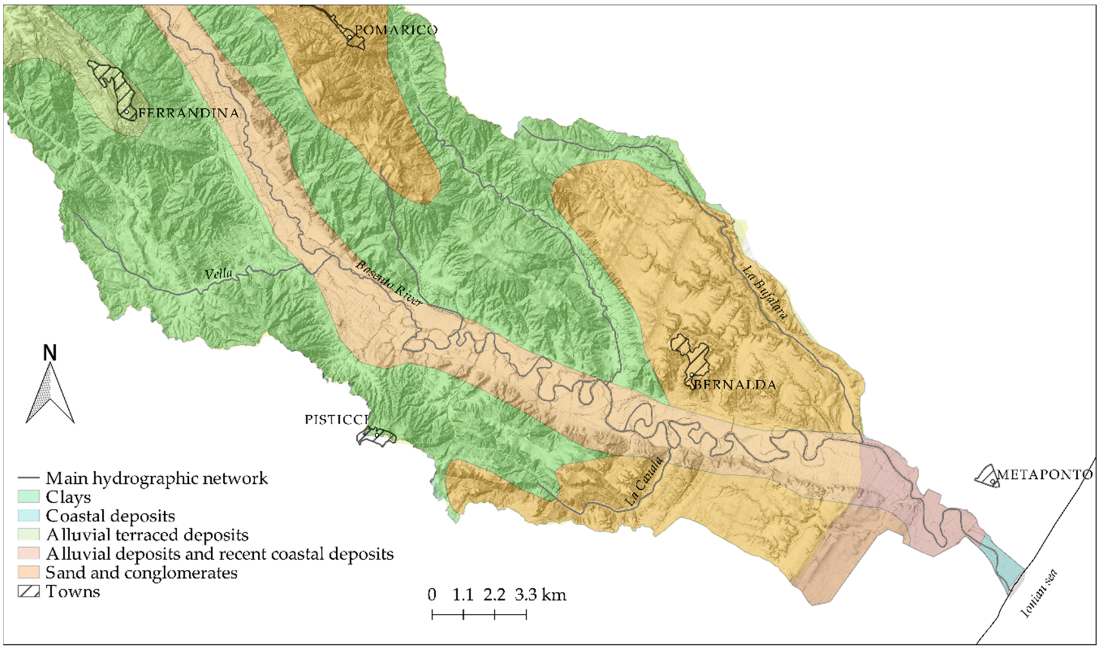

Figure 3. Lithological map of the lower valley of the Basento River from the town of Ferrandina to the Ionian coastline.

2.3. Climate and Hydrological Settings

The climate is strongly conditioned by the basin topography, considerably changing from the mountain area to the coast. In general, the climate is Mediterranean (with hot summers and mild winters) on the coast and continental in the mountains [77]. The pluviometric trend is generally of a maritime type, characterized by a maximum, which occurs between November and January, depending on the location, and a minimum that typical occurs in July or August [61].

The pluviometric data indicate an average annual rainfall of ca. 766 mm, with an irregular seasonal rainfall distribution. In general, extreme events are frequent and abundant between October and March, sharply decreasing in the following months [78,79].

The hydrological regime presents a seasonal pattern that is very similar to the rainfall regime, showing a significant relationship between rainfall and river flow, whose variations follow pluviometric tendency with a variable delay from zero to two months. The pluviometric regime was characterized by a maximum, which occurs between November and January (autumn/winter), and a minimum, which is typically in July or August (summer) [61] (typical of a Mediterranean-type stream) with an average annual flow of 12.2 m^3/s at the Menzena station (24 km from the river mouth). The most intense flood events in the Basento River most frequently occur in the period between October and March [80].

River flow varies considerably throughout the year. In general, the peak flow rate during the winter season varies from 10 to 20 times the monthly average. Occasional heavy rain over erodible substrate, resulting from agricultural activity often causes extensive damages with important and dangerous consequences. The most significant floods can submerge the entire alluvial plan in the meandering section of the river. Moreover, the passage of these floods is often destructive for the agricultural fields and the infrastructures therein since river defence works are absent [61].

2.4. Human Interventions

Beginning in the middle of the 20th century, the entire river basin was affected by a series of hydraulic interventions, such as dams, weirs, flood retention basins and flow diversions.

In the 1950s, the Basento River was affected by channelization aimed at rectifying some meandering reaches (from Pisticci to the coast). These operations were intensified in the 1970s. The most recent intervention was carried out in the 1990s at the Menzena station (just upstream of the La Canala stream entry), consisting of a floodway (with consequent cutting of artificial meanders) to divert river flow during a major flood event.

The land use in the Basento catchment, after the 1930s, as in the other main river catchment in the Basilicata region, was characterized by expansion of the forested area, following the shift of agricultural activities to the valley floor and the coastal plains [81]. This tendency, which is highlighted and analysed in Section 4.3, stopped in the 1950s, when most of the areas once occupied by forests were replaced by agriculture (in most parts) and urbanized areas.

Another important intervention was represented by mining (see Section 4.3 for more details) that was carried out along the river section from Calciano to Ferrandina, mostly in the 1960s/1970s, slowing down in only the late 1990s.

3. Data and Methods

3.1. Data and Cartometric Analysis

The river changes over the past 150 years were analysed using six historical maps at a 1:50,000 scale (Istituto Geografico Militare, 1873, 1945), black and white aerial photos mosaic at a variable average scale between 1:34,000 (1953) and 1:30,000 (1972), and three orthophotos from 1997, 2012, and 2013 [82,83] (Table 1). In addition, the 2013 *Carta Tecnica Regionale* (CTR) map and the digital terrain model (2013) at a resolution of 5 m [84] were also used to support the following digital analysis.

Table 1. Main data used for the evaluation of river changes over the past 150 years: Hm—historical map; Aph—aerial photo; O—orthophoto; bw—black & white photo; c—colour photo.

Data Availability							
Year	**1873**	**1943**	**1954**	**1972**	**1997**	**2012**	**2013**
Type	Hm	Hm	Aph (bw)	Aph (bw)	O (bw)	O (c)	O (c)
Scale	1:50,000	1:50,000	1:34,000	1:30,000	1:10,000	1:5000	1:5000

The geometric distortion of all historical maps was analysed before they were georeferenced to verify whether their different reference systems (RSs) and cartographic representations (RS of Bessel oriented over Monte Mario with Bonne and Sanson–Flamsteed cartographic representations) might influence the subsequent GIS analysis. The software used for this analysis was Map-Analyst [84–86]. Geometric analysis results demonstrated that all historic maps had notable differences between the nominal scale (1:50,000) and calculated scale (1:100,000 on average), although this does not determine that the maps are "distorted". Rather, it is possible that maps were probably derived from smaller-scale maps and then detailed with field surveys. It was therefore considered appropriate, once the geometrical–planimetric accuracy was verified, to carry out the geometric rectification (standard georeferencing) using the CTR map from 2013 at the 1:5000 scale as a reference.

For all other aerial photographs, the 2013 orthophoto was used for georeferencing due to its strong resemblance to aerial photos. Geometric rectification was conducted via GIS software (QuantumGIS 2.18 version) and the WGS 84 Universal Transverse Mercator-UTM 33 N reference system. Using the polynomial second-order transformation, the root mean square error (RMSE) values, calculated as the difference between the known ground control point coordinates (reference map) and the digitized pixel coordinates (source), were between 1 and 4 m for the data after the 1950s and 15–25 m for the historical maps.

3.2. River Reach Delineation

The study area was divided into sixteen reaches according to the method presented in [2], which involved four steps: (1) identification of the physiographic units (hilly and coastal plain units) and river segments defined by the limits of the physiographic unit within which these units are located and by other possible strong hydrological variations, such as large tributaries and/or confinement discontinuities; (2) definition of the confinement degree used to distinguish the river reach in areas not confined, semi-confined, and confined by natural factors, such as valley slopes, landslide deposits, tributary fans, and ancient river terraces [87]; (3) definition of channel morphology using the sinuosity index (SI) and braiding index (BI); (4) final delineation of the river reaches.

The first segmentation step was conducted for the entire Basento River (from the source to the mouth), as required by the method. The first segment spans from the source to ca. Trivigno, while the second segment spans from Trivigno to Tricarico (Figure 1), and the third segment begins in Tricarico. Since the analysis presented in this manuscript focuses on only the areas from (a part of) the 3rd to the 5th segments, the characterization of the reaches was carried out only in the latter segments. Three reaches belong to the 3rd segment, and ten belong to the 4th segment, all are located in the hilly area, while the 5th segment, which is located in the coastal plain, consists of three reaches (Figure 4).

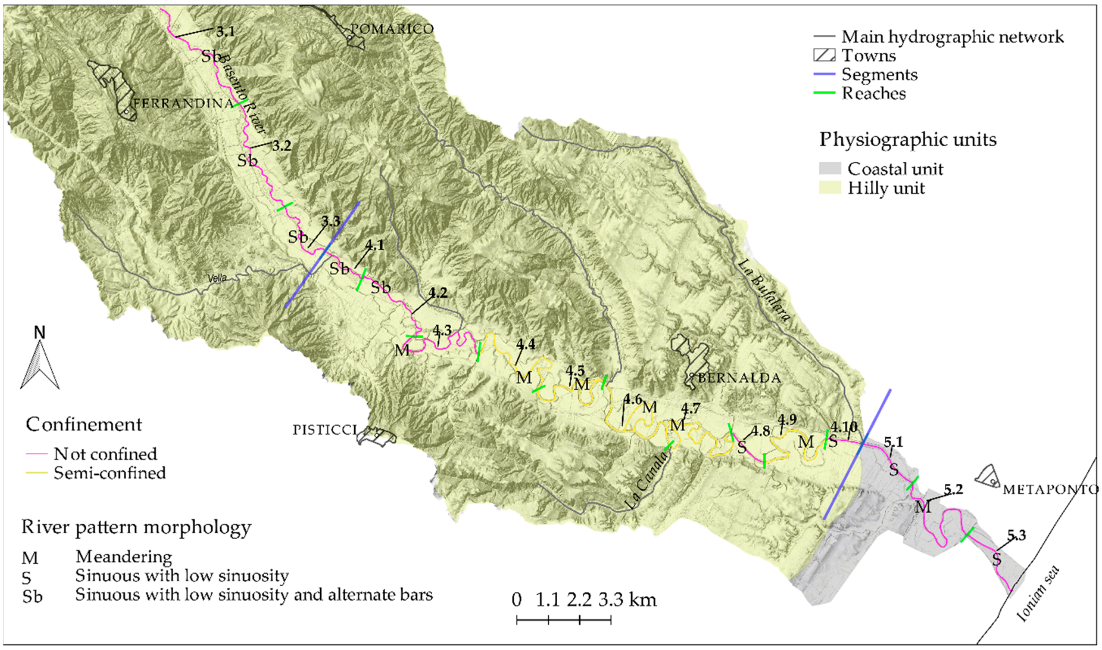

Figure 4. Delineation of the Basento River reaches. In the figure, the reaches are numbered using two dot-separated numbers: The first number is related to the segment, and the second is related to the progressive reach number. The 3rd segment comprises three sinuous reaches with bars (1–3), the 4th consists of ten reaches with some meandering and others non-confined or semi-confined sinuous; finally, in the 5th and last segment, the three reaches are all not confined, two of them are sinuous, and only one is meandering.

3.3. Fluvial Parameter Analysis

The analysis of the morphological river features required the adoption of the following:

- GIS analysis and photo interpretation;
- Geomorphological field surveys.

Both of these survey methods had the goal of analysing and measuring river features, such as river banks, channel width, and morphological pattern, to reconstruct the fluvial dynamics from 1873 to 2013.

At the river reach scale, we mapped:

- Channel area (Ra) (i.e., the area including low-flow channels, bars, and islands) according to the definition reported in [88], was digitized considering the channel margins (including canals and bars) that coincided with the full riverbed (full banks or bankfull) associated with the maximum flow that could be contained within the river without flood occurrence. For the historical maps, it was not possible to exactly identify the bankfull limit (riverbed with full banks), which was defined and then compared with other more recent riverbed limits.

- The margin of the central bars and fluvial islands (island area (Ia)) for the computation of the total riverbed area (of each reach) and the subsequent calculation of the average channel width.
- River axis (Rx) (which is the riverbed midline or centreline) defined using the "Fluvial Corridor" tool [89] in ArcGIS 10 software.

From the abovementioned vectorised data, other reach parameters were derived, such as the following:

- The average riverbed width from the ratio between Ra (subtracting Ia) and Rx reach length, according to the procedure presented in [88].
- The SI was calculated as the ratio between the reach length and Rx [2]. For only some reaches, the 1873 map was needed to define BI (defined as the number of active channels separated by bars, which was used in particular for multichannel rivers).

Land use was digitalized by photointerpretation for the years 1953, 1973, 1988, 1996, 2000, and 2013. The first hierarchical level and its three classes, characterized in the "CORINE Land Cover" maps, were used as references to distinguish (i) agricultural areas; (ii) forests and semi-natural areas; and (iii) urbanized areas.

Information about river mining was collected from the Regional Geological Service office, who acquired several pieces of information regarding the main periods and reaches that have been affected by river channelization with the cooperation from the Regional Civil Protection. These latter parameters were later verified by photointerpretation.

The information on the Basento River levees (localization and extension) was obtained via the levee system map reported in table D "Inventory map of intersections, settlements, and riverbed works" of the current Hydrological Plan [90].

Geomorphological field surveys on the 16 river reaches were carried out between March and November 2017. The sites that were homogeneously distributed along the studied reaches were selected to verify the river features, such as channel confinement, morphology, and artificial structures (e.g., levee).

To determine the links between climate, aims, and river changes, information about the main flood events that occurred over the last 150 years [80] was collected. Moreover, rainfall data were extracted from the literature, particularly the positive and negative rainfall trends [77], the recurrence of drought periods [91], and finally the frequency of the most intense rainy events [92–95], which could explain some major river changes due to flood events.

4. Results

4.1. Channel Width Variations

The channel width changes from 1873 to 2013 (Figure 5) indicate a general progressive reduction in channel width (e.g., reaches 3.3, 4.1 and 5.3 varied from 94 m, 64 m, and 108 m in 1873 to 41 m, 30 m, and 37 m in 2013, respectively). The exceptions are reaches 3.1 and 3.2, in which the most recent widths (2013) are greater than those of 1873 (from 45 m and 86 m to 78 m and 108 m in 2013, respectively).

Furthermore, important variations were recorded in 1953 and 1996. From 1943 to 1953, several reaches (3.1 to 4.2) showed intense reversing trends (widening) despite the occurrence of narrowing in the other reaches. Since 1953, most of the reaches underwent intense channel narrowing (e.g., the widths of reaches 4.9 and 5.1 changed from 32 m and 34 m in 1955 to 14 m and 19 m in 1972, respectively). Since 1996, some reaches have shown a slight narrowing trend, while others exhibited a slight widening trend. For example, reach 4.3 underwent narrowing from 1873 that continued until 2013, ranging from 38 m in 1873 to 30 m in 1955, then 12 m in 1996, and finally 10 m in 2013.

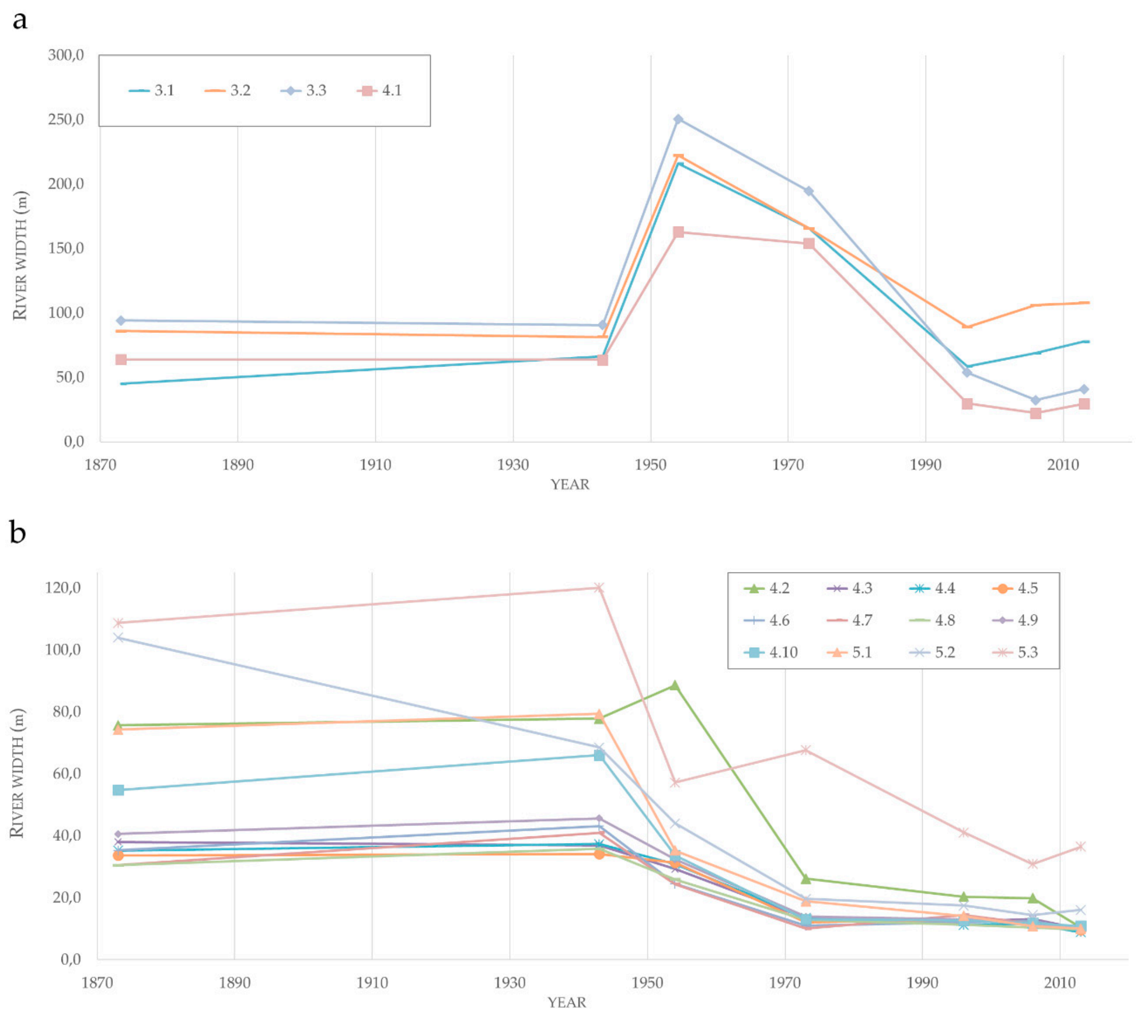

Figure 5. The temporal trend of the channel width (from 1873 to 2013) in the sixteen reaches of the Basento River divided into two graphs to facilitate trend visualization. Graph (**a**) shows reaches from 3.1 and 4.1, corresponding to the river section called "Basento Up" in the discussion section, while graph (**b**) shows reaches 4.2–5.3, which are grouped as "Basento Dw" (Section 5).

Figure 6 shows average width variation rates (ΔW/y) for each river adjustment phase obtained from the ratio between the river width difference observed at each phase time limit and the time span of each phase. During phase 1, most reaches exhibited a stable trend (without variation), except for a few reaches that showed enlargements (reaches 3.1, 4.7, and 4.10 with enlargement percentages up to 50%) and reverse trends (reach 5.2 with enlargement percentages up to −34%). In phase 2, for the narrowing reaches (ca. 70%), the percent of width (ΔW%) ranged between −8% and −56% (related to the width in 1943), with maximum and minimum rates equal to −6 m/year and −0.30 m/year, respectively (from 1943 to 1953). The reaches that exhibited widening tendencies during the same phase were all located between Ferrandina and Pisticci and reached enlargement up to +225% (ΔW%) with maximum rates up to 16 m/year. During phase 3, the maximum and minimum variation percentages of −82% and −28%, respectively, occurred with decreasing variation rates ranging between 0.3 and 15 m/year.

Finally, phase 4, which predominantly exhibited narrowing, showed low rates (less than one metre per year). Only two reaches located near Ferrandina (3.1 and 3.2) were characterized by a widening tendency with a percentage variation (ΔW%) of +33% and rates slightly greater than 1 m/year.

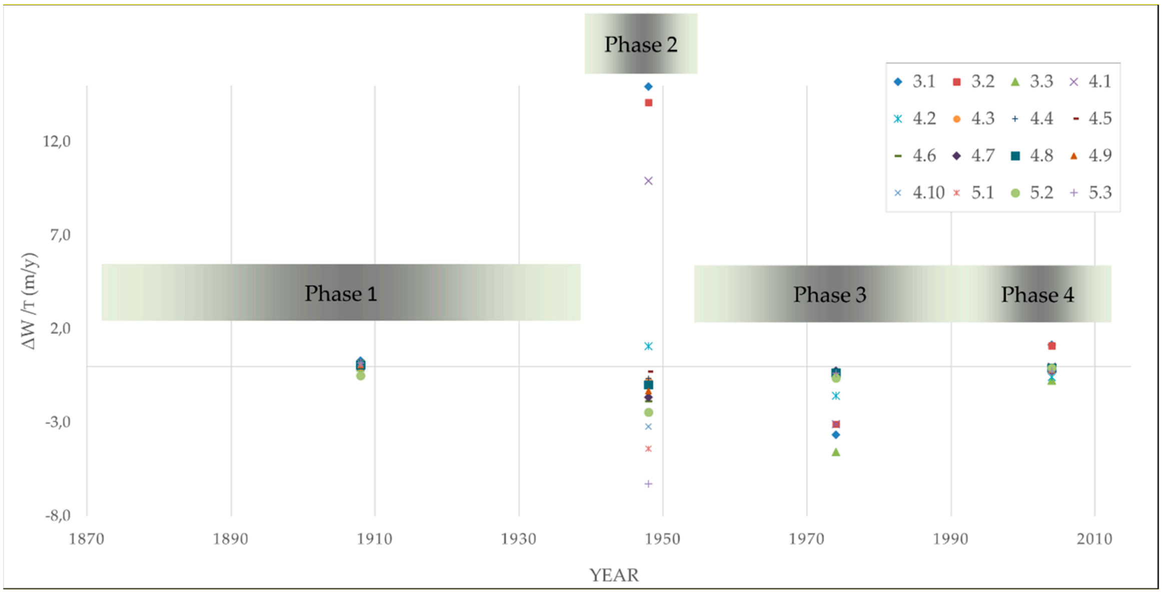

Figure 6. Average width variation rates (ΔW/y) during four river adjustment phases.

4.2. Changes in Channel Pattern

Sinuous and meandering single channel patterns were the main patterns observed in the studied section of the Basento River from 1873 to 2013, except for reaches 3.2, 3.3, and 4.2 which showed the braided with multichannel pattern in 1873 for which the BI [2] was calibrated. Figure 7 shows the temporal variations in the SI [2] for each reach. Several reaches of the 5th and 4th segments were characterized by a meandering pattern (SI ≥ 1.5), while the other reaches, belonging to the 3rd segment, were characterized by a sinuous pattern (SI ≤ 1.5). However, there were some exceptions because some reaches showed changes in the pattern morphology over short time periods, passing from sinuous to meandering and vice versa, or from braided to sinuous and vice versa.

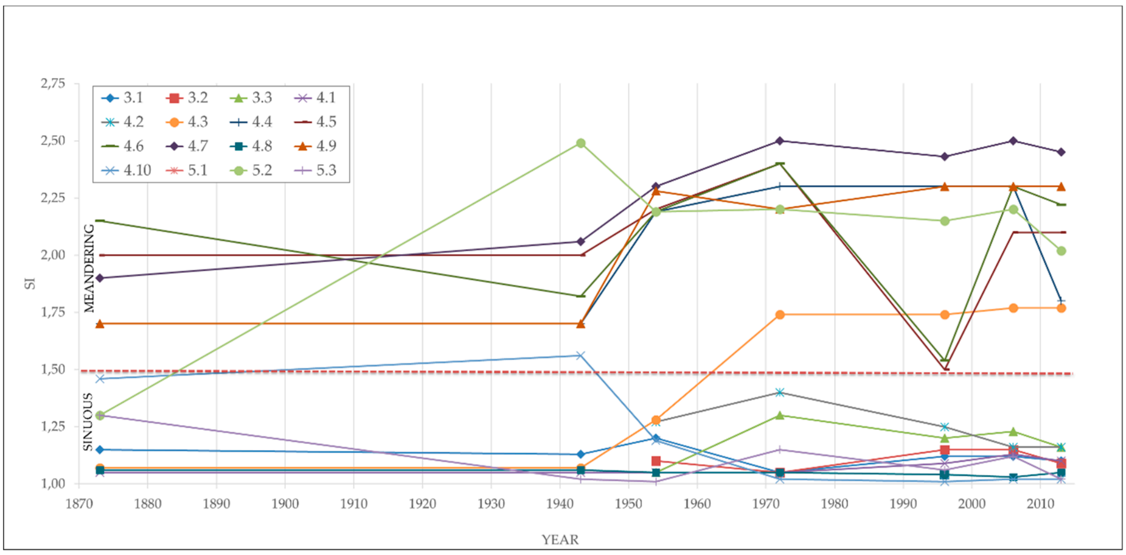

Figure 7. Morphological variation pattern based on the sinuosity index (SI) from 1873 to 2013.

Table 2 reports the morphology pattern for each reach between 1873 and 2013. This analysis revealed the morphological pattern variations between “contiguous typologies” [2], which represent similar morphological configurations (for example, a single riverbed channel that changes from meandering to sinuous), and in some cases, variations between “not-contiguous typologies” or rather variations between very different pattern morphologies (for example, from multiple channels to a single channel) [2].

Reaches 3.2, 3.3, and 2.2 revealed intense variations between non-contiguous pattern morphologies (braided to sinuous and vice versa) since in 1873, when they were characterized by braided patterns. Later, this configuration changed to a sinuous single-channel pattern.

In several reaches, channel pattern did not change from 1873 until 2013 (e.g., reaches 4.4–4.7, 4.10, 4.9, 5.1, and 5.3) or underwent limited variations between contiguous morphological pattern, passing from meandering to sinuous and vice versa only during short time periods (e.g., reaches 4.3, 4.8, and 5.2).

Table 2. Summary of the morphological pattern changes from 1873 to the present highlighting at the top of the table the four morphological adjustment phases occurred over time. Sinuous (S), tortuous (M), sinuous with alternating bars (Sb), braided (B). Sinuous (S), meandering (M), sinuous with alternating bars (Sb), braided (B).

	Phase 1→Phase 2→Phase 3→Phase 4					
Reach	Pattern Morphology					Variation Class
	1873	1943	1954	1996	2013	
3.1	S	S	S b	S b	S b	Unchanged morphological configuration
3.2	B	B	S b	S b	S b	Intense morphological configuration change (non-contiguous types) from 1943 to 1954
3.3	B	B	S b	S b	S b	Intense morphological configuration change (non-contiguous types) from 1943 to 1954
4.1	S	S	S b	S b	S b	Unchanged morphological configuration
4.2	B	B	S b	S b	S b	Intense morphological configuration change (non-contiguous types) from 1943 to 1954
4.3	S	S	S b	M	M	Limited or moderate morphological configuration variation (contiguous types) from 1954 to 1996
4.4	M	M	M	M	M	Unchanged morphological configuration
4.5	M	M	M	M	M	Unchanged morphological configuration
4.6	M	M	M	M	M	Unchanged morphological configuration
4.7	M	M	M	M	M	Unchanged morphological configuration
4.8	S	S	M	S	S	Limited or moderate morphological configuration variation (contiguous types) form 1954 to1996
4.9	M	M	M	M	M	Unchanged morphological configuration
4.10	S	M	S	S	S	Unchanged morphological configuration (slightly changed in 1943)
5.1	S	S	S	S	S	Unchanged morphological configuration
5.2	S	M	M	M	M	Limited or moderate morphological configuration variation (contiguous types) from 1873 to 1943
5.3	S	S	S	S	S	Unchanged morphological configuration

4.3. Analysis of Human Influence on the Basento River System

4.3.1. Land Use Change

Land use variation maps were extracted at the alluvial plain scale using the aerial photos and the orthophotos available for the period from 1953–2013 (Figure 8). This analysis was not applied to the historical maps (1873, 1945) since such maps do not provide reliable land cover information.

Agricultural areas progressively increased (from 50% to 75%) between the 1950s and the end of the 1980s, with a simultaneous contraction in the forested and semi-natural area (almost equal to the increase in agricultural fields) ranging from 49% in 1953 to 19% in 1988. Between 1973 and 1988, the extensions of the agricultural and forest areas showed peaks of expansion and contraction, respectively. In less than 15 years, the agricultural areas increased and occupied 75% of the flood plain, while the forested areas decreased to 19%. The land use maps suggested a main trend of progressive increases in urbanized areas accompanied by progressive decreases in forested areas.

From the end of the 1980s to 2013, the trends reversed, in fact, agricultural areas exhibited a slight contraction from 75% to 71%. The forested areas exhibited a slight re-expansion (from 19% at the end of the 1980s to 20% in 2013). Urbanized areas expanded significantly from 1% in 1953 to 10% in 2013. From the end of the 1980s to 2013, urbanized areas showed the most intense expansion.

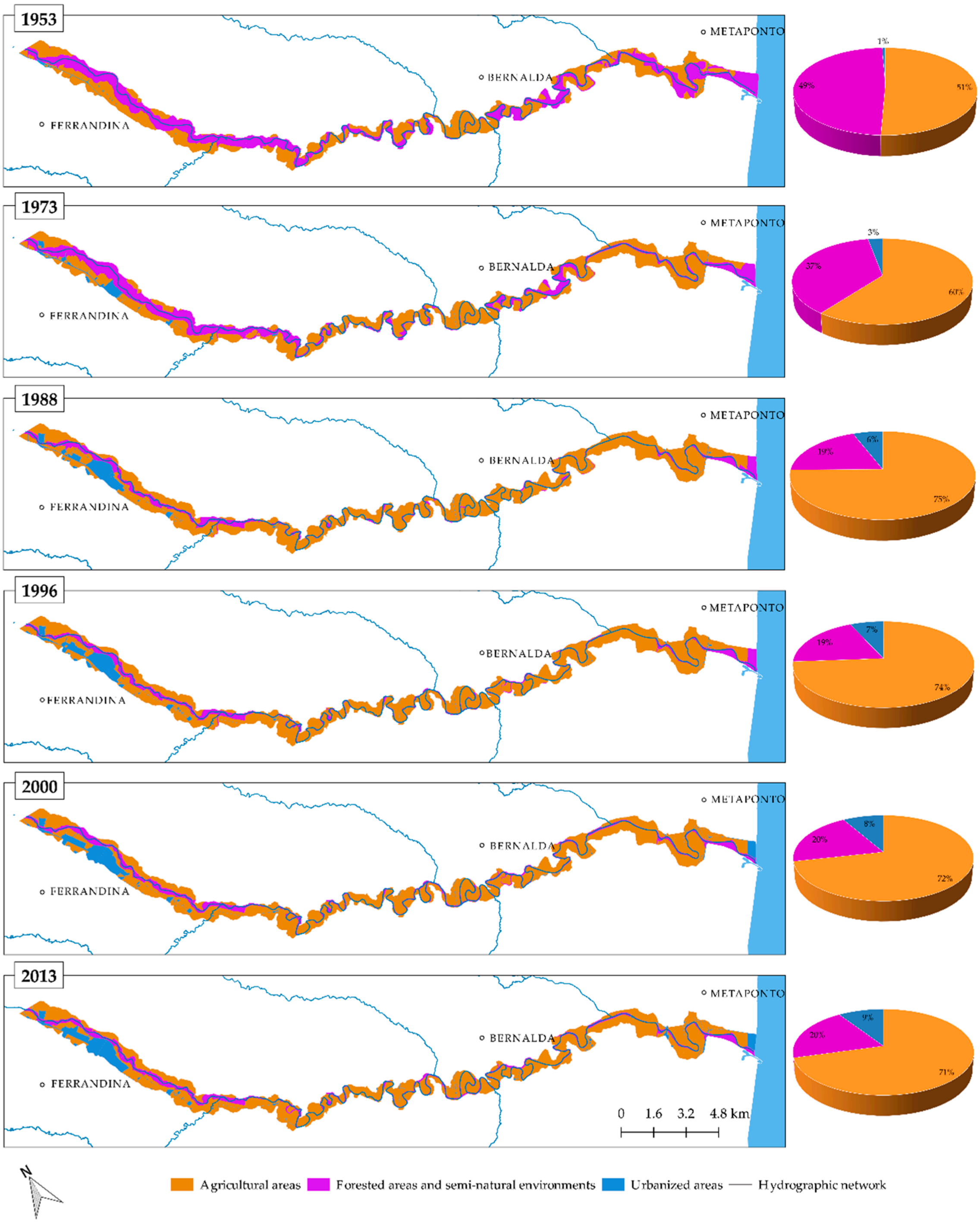

Figure 8. Land use variation maps in the alluvial plain of the Basento River terminal sector (from Ferrandina to the river mouth) with the side pie charts indicating the land use percentages.

4.3.2. Reach Scale Human Interventions

The studied section of the Basento River was affected by channelization mostly from the 1950s to 2013 (Figure 9). Between the 1950s and 1970s, the first intervention was carried out, with consequent meandering artificial cut-offs near Pisticci [61]. Then, other similar interventions were established in other meanders, all prior to the 1990s (Figure 9).

Moreover, levees were constructed in several sections of the river (consisting of beaten and/or entrenched levees, caged, or masonry banks) (Figure 10). In the investigated reaches, embankments were built mostly from the 1950s to the end of the 1990s. Beaten banks were mostly built downstream of Pisticci along the meandering section of the Basento River. The features of beaten bank varied locally: In some places, the beaten banks were 2 m high and 3 m away from the riverbed, while in other areas, the beaten banks were lower (just over one metre) but entrenched with ditches ca. 1 m deep. Despite local defence differences, all of the banks seem to have the same function (as reported by some local farmers), namely, river flood defence blocking, and limiting flood waves. Some local farmers have also reported that over time, due to the lack of maintenance, the banks became unsuitable for flood defence, often causing inundation of agricultural fields.

Although such interventions, both meander cut-off and levee constructions, were carried to mitigate flood risk, they had some effects on channel processes. Specifically, meander cut-off likely increased flow competence, decreasing sedimentation, and, therefore, bar formation. The effects of levees are less straightforward, but a decrease of overall lateral migration is likely to be expected and, locally, bank erosion is hindered.

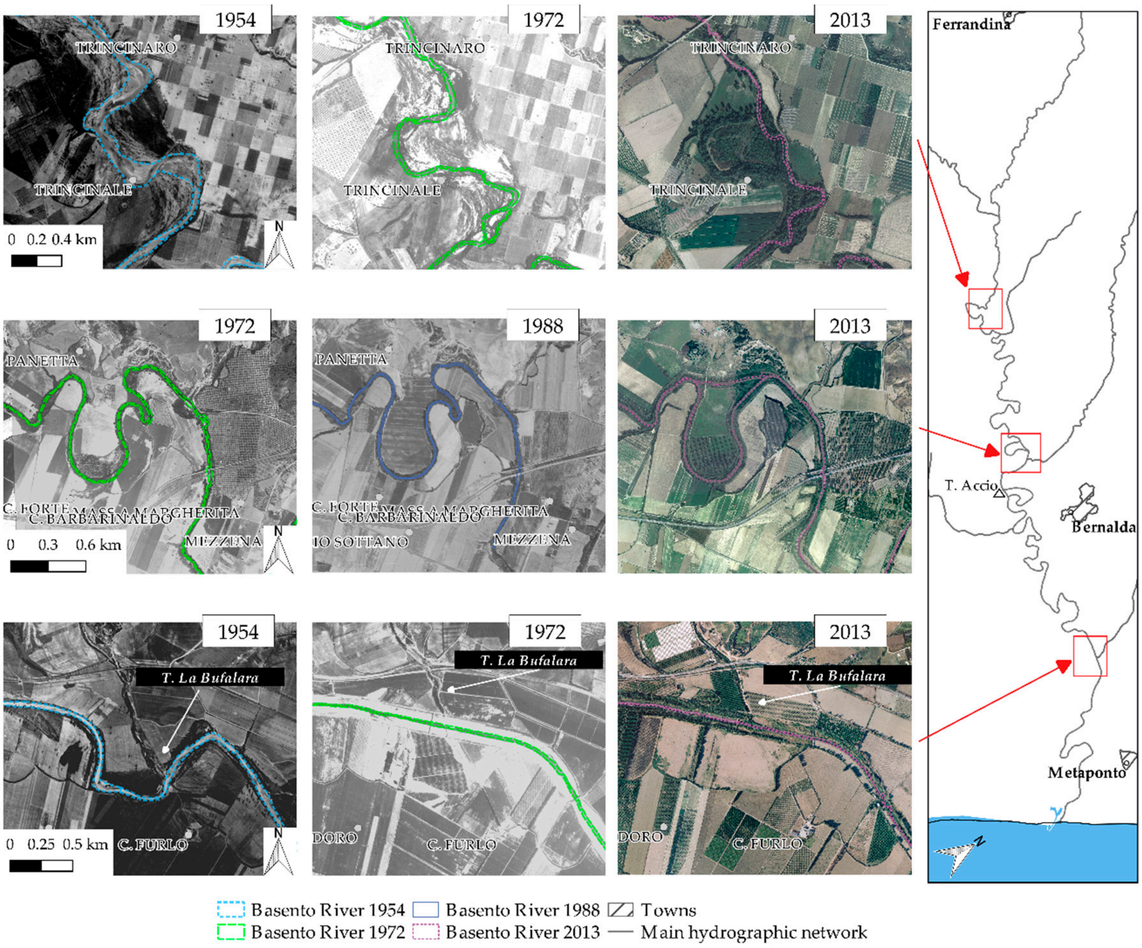

Figure 9. Examples of channelization with consequent artificial meander cut-offs from the 1950s to 1970s downstream of Pisticci.

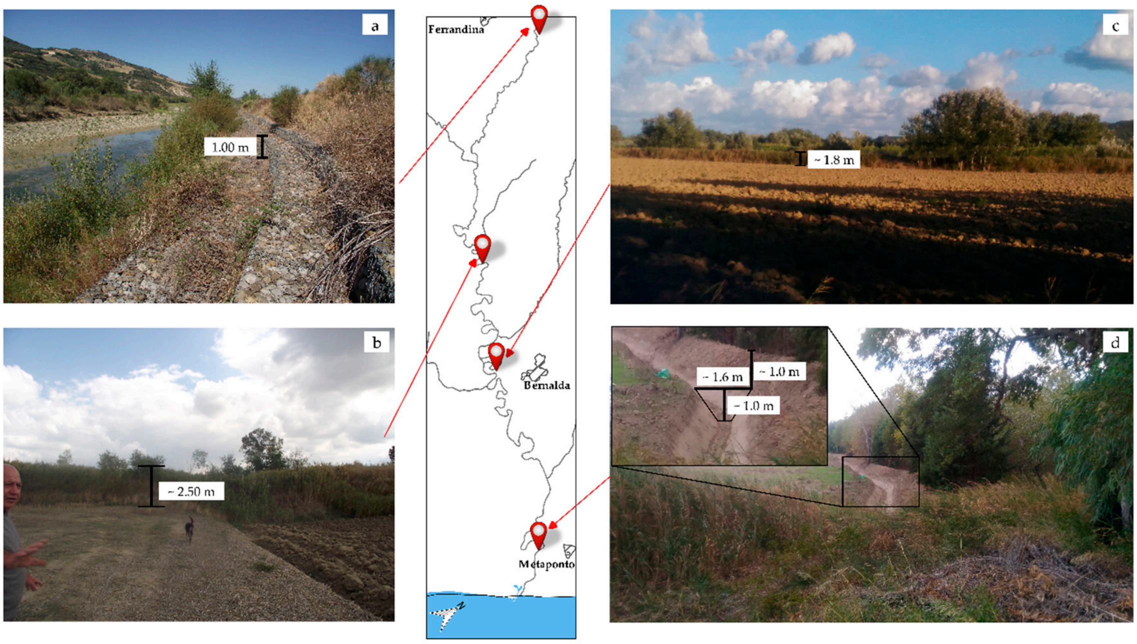

Figure 10. Examples of levees along the studied section of the Basento River. (**a**) Caged banks, (**b**) beaten levees ca. 2.5 m high, (**c**) beaten levees ca. 1.5 m high, (**d**) beaten and entrenched levees, with a deep trench up to a maximum of ca. 1.5 m and levees high of ca. 2.5 m from the bottom of the trench.

4.3.3. Sediment Mining

According to official sources [96], sediment mining was carried out along the river section from Calciano to Ferrandina (Figure 1), mostly in the 1960s/1970s, with a sharp slowdown in the late 1990s. Between the 1960s and the 1980s, five mining companies operated along the abovementioned reach. Information about the activity periods and methods are lacking, but according to the infrastructure and soil defence department of the Basilicata Region [97], it is likely that each company extracted between 25,000 and 30,000 m^3/year, resulting in a maximum of 150,000 m^3/year over the entire length of ca. 50 km (3000 m^3/km).

From the 1980s to the early 1990s, extraction permits were issued by the Basilicata Region, but at the end of the 1990s, due to law 183/1989, precise restrictions and extraction activity suspensions were issued. Regional law art. 24 n. 5 of 4 March 2016 allowed small (volumes less than 10,000 m^3) and punctual interventions aimed at mitigating erosive processes along reaches.

4.4. Flood Events and Precipitation Patterns

Over the last 150 years, several high-intensity flood events have occurred in the Basilicata Region [80], but these events have particularly affected the Basento River, as mentioned below, highlighting the events that occurred from 1923 to the end of the 1990s and the other events that occurred from 2000 to recent years (Figure 11).

Among the most intense events that affected the Basento River before the Second World War were the events that occurred in September 1929 and February 1931 [80]. In both cases, there was damage to the road infrastructure and inundation in the countryside due to the flooding of the river. In November 1946, another event occurred in the basin that caused flooding and inundated the Metaponto Plain [80]. The November 1959 flood event, which mainly affected the Ionian coast, was particularly intense, with a peak located in Pisticci. In both the provinces of Potenza and Matera, damage was considerable (building collapses, road interruptions), with 2000 displaced people and 11 deaths. The consequences were so dramatic that these events required the intervention of the army and navy.

In the 1960s, the most intense event was that in the autumn of 1963, during which the town of Craco (near Pisticci) was affected by a vast landslide that required evacuation of the entire town. In the following years, until the end of the 1990s, other intense events (including events in 1972 and 1985) were recorded; however, these events did not lead to consequences comparable to those mentioned above [80].

Flood events from 2000 to 2016 were better documented due to the greater availability of pluviometric data [80]. Among the most recent flood events, those in March 2011 and December 2013 were particularly intense (with return periods of over 50 years and 100 years, respectively) [98]. In each event, Basento flooding impacted the countryside above Pisticci and Bernalda, causing interruptions to the main roads. During the first event, the flood damage along the coast was enhanced by storms. The emergency situations during both events made the intervention by the army and the civil protection necessary, and the government declared a "natural disaster state". In December 2013, flooding waters submerged many parts of the town of Metaponto and its archaeological park.

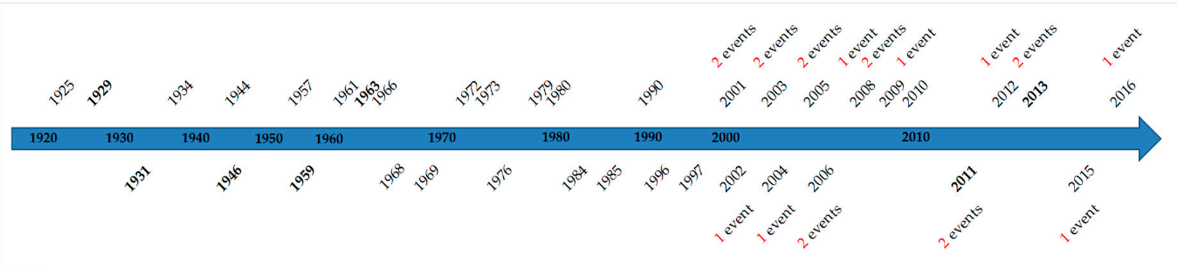

Figure 11. Time sequence of the main important hydrological events recorded in Basilicata in the period between 1921 and 2016. The graph has been taken from [82] and modified, including the most recent flood events.

From 1923 to 2000, the total annual rainfall decreased by ca. 156 mm, particularly during the winter season, [93]. Furthermore, the annual precipitation decrease became more significant over the last 30 years (from the 1980s to 2000) [91]. Over the same period, Piccarreta [92] calculated the standardized precipitation index (SPI) [99] at different time scales (12, 24, and 48 months) to evaluate and quantify drought periods, considering the rainfall trends. This index showed a greater frequency of drought periods starting in 1975. Additionally, the maximum rainfall evaluation amounts over 24 h, 3 days, and 5 days and the decline in extreme events [92] confirmed the negative trend. In contrast, from 2000 to 2010, the reverse trend was observed, with a slight increase in annual precipitation and the length of rainy periods [92].

Some studies [93,95] pointed out significant changes in the frequency of the most intense rain events after the 1970s. Since 2000, several flood events (caused by 150–200 mm of precipitation) have occurred in the Basento River [80], with an average frequency of ca. 0.8 years^{-1}, which is higher than the frequency recorded in the mid-1990s and that from 1955–1962. The most intense events recorded from 2000 to the present occurred in March 2011 and December 2013, with recurrence intervals ranging from 50 to more than 100 years [80].

5. Discussion

The combination of morphological changes with the different human and climatic factors provided insights into the evolutionary trajectory of the Basento River over the last 150 years. Figure 12 shows the channel changes over the last 150 years and possible controlling factors. The 16 study reaches were divided into two groups, an upstream (Up) and downstream (Dw) group, based on the morphological similarities and channel changes. The reaches ranging from 3.1 to 4.1 constitute the group called "Basento Up", while the reaches ranging from 4.2 to 5.3 constitute the "Basento Dw" group.

Although some reaches revealed individual behaviours regarding the magnitude and temporal distribution of channel modifications, the evolutionary trajectories displayed similarities among several reaches.

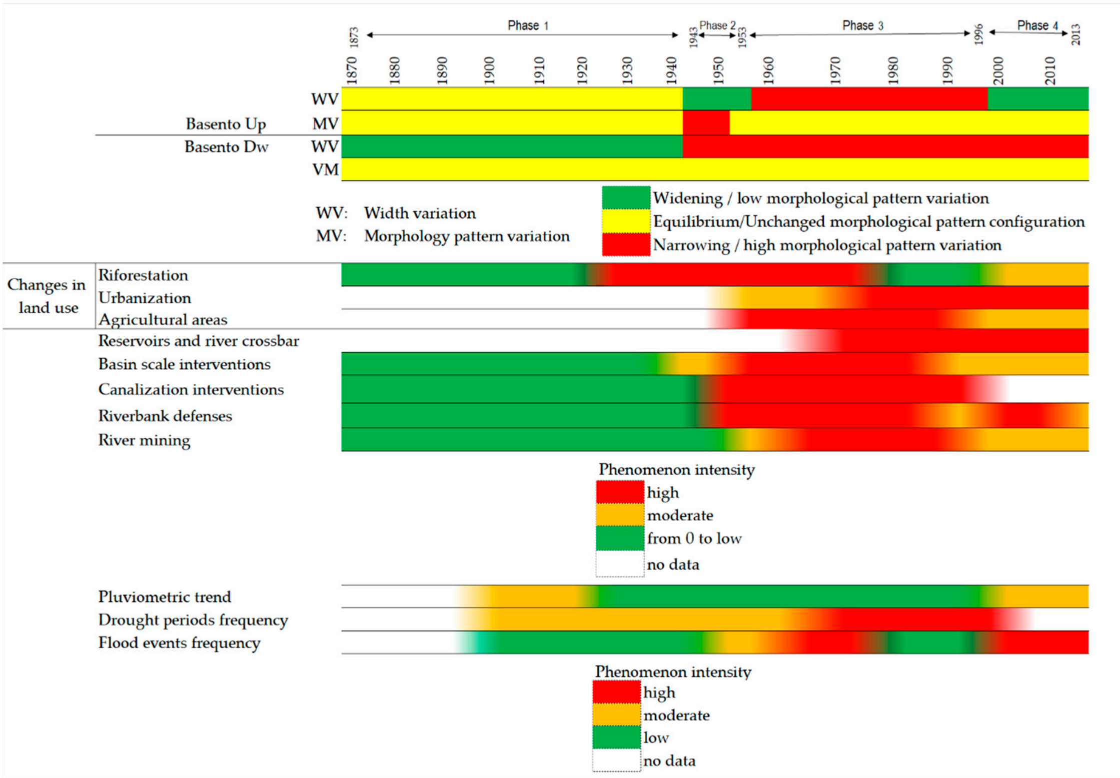

Figure 12. Evolutionary trajectory of channel morphology and controlling factors over the last 150 years including channel changes (channel width and pattern) averaged at the two reach-group scale: "Basento Up" (reaches 3.1–4.2) and "Basento Dw" (reaches 4.3–5.3); different colours are used to show the intensities of single controlling factors.

During phase 1 (1873–1943), both reach groups showed substantial stability in their width variations and morphological patterns, probably due to the very low anthropogenic impacts.

During phase 2 (1943–1953), the reaches in the "Basento Up" group underwent intense widening, probably due to the two main flood events that occurred in 1946 and 1959 (Section 4.4). During the same period, the river morphology pattern changed from a braided multichannel pattern to a sinuous single-channel (with alternating bars) pattern, likely in response to a decrease in sediment supply braced by a period during which forested areas increased (Section 4.3.1). The "Basento Dw" reach group underwent an inverse tendency of narrowing, which could have been favoured by the earlier channelization.

During phase 3 (1953–1996), both reaches underwent considerable channel narrowing. In phase 3, the intense narrowing could be explained by a combination of several human factors (land cover changes, channelization, and in-channel mining). This interpretation is supported by climate data that highlight a decrease in annual rainfall, more intense rainfall from the 1980s to 2000, and a higher drought period frequency starting in 1975, exacerbating the anthropogenic impacts on fluvial dynamics.

The major role of sediment mining became evident at the end of the 1990s, when mining stopped determining the inversion trend in "Basento Up" group (widening) (phase 4, 1996–2013). This trend was not evident in the reaches in the "Basento Dw" group, which underwent progressive river narrowing.

For reaches in which a widening trend was notified, the cause was not only the stop of river mining, but this tendency seemed to coincide temporally with a slight increase in annual precipitation and an increasing frequency of large flood events, sharpening the river widening trend. According to the latest studies since 2000, several flood events have occurred in the Basento River, with an average frequency of ca. 0.8 years^{-1}. Among these events, the most intense events that were recorded from 2000 to the present occurred in March 2011 and December 2013, with recurrence intervals ranging from

50 to more than 100 years [98]. In contrast, the narrowing tendency in the "Basento Dw" group can be interpreted to reflect increased agricultural activity, which implies new channelization.

Findings from this study indicate broad convergence of the channel adjustments in the Basento River with those in other Italian rivers [41–60] over the last 150 years. Nevertheless, there are some significant differences. First, four overall evolutionary phases were identified for the Basento River, not three, because the period from 1870 to 1955 was divided into two distinct phases (i.e., 1870–1945 and 1945–1955) according to the trends shown by the two main reach groups. The first period was characterized by a substantial equilibrium. The second phase demonstrated a simultaneous narrowing and widening trend, unlike what occurred in the other Italian rivers, where a narrowing trend was observed since the beginning of the 1900s. In the Basento River, a distinct narrowing phase appeared around the mid-1940s (phase 2), becoming more intense only later (beginning of the 1950s), probably due to milder and later anthropogenic pressure.

Until the end of the 1990s, variations in land use, channelization and sediment mining deeply controlled the channel dynamics. Later (from the late 1990s onward), the slight increase in annual precipitation and high frequency of the most intense flood events seemed to be the most important factors that caused slight channel widening in some reaches. Therefore, the climate seems to be a major driving factor in the recent evolution of the Basento River, unlike in other Italian rivers where the role of climate was not as evident.

We recognize that this study has some limitations and future research, on the Basento River or rivers that have undergone similar disturbances and trajectories, should fill some gaps. As for this specific case study, human interventions at the catchment scale and their effects on flow and sediment regime should be investigated more in detail. More in general, new approaches are needed for sound understanding of fluvial systems affected by cumulative human impacts [95], including the climate changes.

6. Conclusions

In this study, we analysed the evolutionary trajectory of the Basento River over the last 150 years (1870–2013). The changes in channel morphology were documented and compared with human and natural factors that occurred in the past. Channel adjustments, i.e., channel width and morphological pattern variations, occurred in four phases; two of them were strongly conditioned by changes in land use, channelization, and sediment mining (up to the end of the 1990s). The river channels revealed, with some exceptions, narrowing tendencies and some pattern variations. From 1873 to the end of the 1990s, reverse tendencies (i.e., dominant channel widening) occurred in two distinct periods from 1943 to 1953 and from the end of the 1990s to 2013 in all reaches except for a few. In each case, this reverse trend seemed to be controlled by climatic factors: Intense flood events (as has been indicated in literature) at the end of the 1940s and 1950s and at the end of the 1990s due to an increase in annual precipitation and increased frequency of large flood events [96]. The reaches with sinuous morphology exhibited increased sensitivity to changes in comparison to meandering reaches.

A comparison with the adjustment trends observed in other Italian rivers provided excellent compliance with the most important evolutionary phases. Human factors mostly influenced the river dynamics during the 20th century, especially from the second half of the 1900s, while climatic factors, although slightly less intense, determined the new phase of river recovery since the end of the 1990s.

If the current climatic trend, with an ever-increasing in number of high-intensity flood events, continues, it will determine the continuation of the last phase of morphological recovery in the Basento River. This trend could cause considerable damage and problems along the sections of the river that are in close contact with agricultural fields and industrial areas. It would be appropriate to consider possible actions for risk mitigation that comprise analyses of both morphological dynamics and hazard and flood risk.

Risk mitigation actions include the preservation of current river conditions (e.g., avoiding an increase in risk through the definition and adoption of danger and risk bands), improvements to the current river conditions, and the reduction in the vulnerability of the elements exposed via river band delimitation, which will allow the natural planimetric dynamics of the water course and the prevention of new construction [2]. The hydromorphological assessment proposed in [2] is a useful tool for detecting morphological dynamics, in terms of both morphological dynamic hazards and flood hazard. According to the different reach scenarios obtained along the river, this assessment could foresee prevention measures to be adopted (structural and non-structural interventions). Hydromorphological analysis allows both characterization of reaches or critical areas in terms of morphological dynamics and identification of reaches for which hydraulic modelling must consider morphological dynamics for flood hazard zonation.

Finally, it would be useful to monitor the dynamic evolution of the Basento River to verify new possible dynamic trends and their impacts in the surrounding areas.

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