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1 **IS AFFORESTATION A DRIVER OF CHANGE IN ITALIAN RIVERS WITHIN THE**
2 **ANTHROPOCENE ERA?**

3
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11
12 **Highlights**

- 13 • A multi-scale diachronous-synchronous approach is used
- 14 • Land-use changes at both reach and basin scales drove adjustment in Italian river
- 15 • Southern rivers do not undergo floodplain afforestation, although they narrowed
- 16 • Similarities and differences between Italian and French river evolutions are found
- 17 • Geomorphic diagnosis must consider land-use change effects on river adjustments

18
19 **Keywords:** Multi-scale and multi-temporal analysis, diachronous-synchronous approach,
20 evolutionary trajectories, land cover changes, vegetation encroachment, local controlling factors.

21
22 **Abstract**

23 For eight rivers situated from northern to southern Italy, the evolutionary trajectories since the
24 middle 19th century and the key controlling factors of channel adjustments were reconstructed
25 using a combined diachronous-synchronous approach, integrating data from catchment- to reach-

26 scale. The analysis takes advantage of multi-temporal GIS analysis of maps, aerial photographs, and
27 orthophotos, and data from literature, archives, and official surveys of population and agrarian
28 censuses. From the middle 19th century to the 1950s, both channel widening and narrowing were
29 observed. These processes were related to land use disturbances (e.g., afforestation versus
30 deforestation) acting at both reach and catchment scales. From the 1950s to 1970s, channel
31 narrowing in some rivers accelerated simultaneously with forest encroachment on fluvial corridors
32 and human abandonment of intense floodplain uses, before the action of any other factors. In
33 southern Italian rivers, channel adjustments were more intense and occurred later than in northern
34 ones, but they remained more active once adjustment ended. Mature floodplain forest establishment
35 is not always observed on these rivers, although they underwent a rural decline that can be
36 explained by drier climatic conditions, maybe exacerbated by dewatering due to channel incision.
37 This also means that upland afforestation and its effects on bedload delivery have been a more
38 critical driver in controlling narrowing than floodplain afforestation, as in this southern context we
39 do not observe floodplain afforestation during the period, but grazing expansion. When forest can
40 establish along the channel, as seen on the Volturno, narrowing is even more important. River
41 widening in the early 2000s–2010s did not compensate for longer term narrowing, demonstrating a
42 shift in river responsiveness that was partly due to upland and floodplain afforestation inducing
43 higher channel resistance to bank erosion and bedload deficit. Such morphological evolution was
44 also observed in southeastern France, but occurred a bit earlier, with stronger similarities with
45 northern Italy and the Apennines. These drivers of change must not be underestimated in
46 geomorphic diagnosis, even if they are more difficult to assess.

47

48 **1. Introduction**

49 A wide range of human activities (e.g. gravel mining, construction of dams and bank protection,
50 land-use changes) have been considered as the main drivers of channel change in European rivers

51 over the last few centuries (Comiti and Scorpio, 2019). These controlling factors have worked
52 alongside natural drivers such as climate change (Rumsby and Macklin, 1996; Gob et al., 2008) and
53 the occurrence of extreme floods (Arnaud-Fassetta et al., 1999; UribeArrea et al., 2003). Basin-
54 scale land-use modifications and changes in riparian vegetation composition have been recognized
55 to impact fluvial processes (Sidle and Sharma, 1996; Magilligan and McDowell, 1997; Liébault et
56 al., 2005; Nadal-Romero et al., 2012). In general terms, a decrease in vegetation cover along slopes
57 is associated with increases in sediment production, and vice versa (Liébault et al., 2005; Pisabarro
58 et al., 2019), while vegetation cover on channel banks and floodplains can amplify river corridor
59 roughness and resistance to erosion (Gurnell and Petts, 2002; Liébault and Piégay, 2002; Corenblit
60 et al., 2007; Gurnell et al., 2016).

61 Several studies in the Spanish Pyrenees (García-Ruiz et al., 1997; Beguería et al., 2006; García-
62 Ruiz, et al., 2010; Sanjuán et al. 2016) demonstrated hydrological and geomorphic effects of land-
63 use changes at a catchment scale. Experimental plots were used to demonstrate that deforestation,
64 the cultivation of steep slopes, overgrazing, and recurrent fires in the montane belt caused high
65 runoff rates and extreme soil erosion during the 18th and beginning of the 19th centuries. As a
66 consequence, channels presented a braided morphology, widespread bare bars, morphological
67 instability, and prevalent bedload transport. Conversely, depopulation of mountain areas and the
68 concentration of most human pressure in the valley bottoms, farmland abandonment, and decreases
69 in livestock pressure during recent decades (following World War II), have caused forest
70 recolonization, reduction of overland flow, and soil erosion, and consequently overall channel
71 narrowing and incision in secondary streams, with the formation of new terraces. The recent
72 development of new fluvial terraces resulting from reforestation has been reported in other
73 Mediterranean mountains, including the southern French Alps (Liébault and Piégay, 2001, 2002;
74 Piégay et al., 2004). In particular, most of those rivers underwent channel aggradation during the
75 19th century because the basins were subjected to deforestation, erosion, and frequent intense floods.

76 During the 20th century, channels narrowed progressively because of sediment starvation due to a
77 set of factors including the end of the Little Ice Age, torrent controls, and hillslope afforestation due
78 to grazing decline. From the 1950s to 1970s, channel narrowing accelerated, affecting a large part
79 of the hydrographic network, including branches further downstream from sediment sources. This
80 specific afforestation period is related to the development of hillslope forests and the associated
81 deficit in sediment propagation downstream, as shown by Liébault et al. (2005), but is also affected
82 by activities further downstream such as river margin afforestation and the abandonment of
83 intensive floodplain land-uses such as grazing and riparian forest exploitation, which occurred
84 synchronously with upland abandonment and afforestation (Liébault and Piégay, 2002; Taillefumier
85 and Piégay, 2003; Piégay et al., 2004; Liébault et al., 2005; Lallias-Tacon et al., 2017). Grazing
86 activities and agricultural practices on floodplains contributed to bank instability and erosion
87 (Magilligan and McDowell, 1997), while to the contrary, forested floodplains increased hydraulic
88 roughness conditions, potentially reducing channel shifting, floodplain areal erosion, and chute cut-
89 off frequency, thereby facilitating vegetation establishment on bars (Liébault and Piégay, 2002).

90 Local factors, especially vegetation development on the floodplains and gravel mining, were
91 considered key factors for explaining the narrowing process and metamorphosis from braided to
92 wandering/meandering patterns that occurred in the Magra river in the northern Apennines (Dufour
93 et al. 2015).

94 A detailed literature review shows that during the last 20 years, dozens of papers were published
95 analyzing channel adjustments in Italy over the last two centuries (Table 1). Most studies on Italian
96 rivers agree that modifications occurred in three phases, highlighting broad common trends (Fig. 1).
97 The so called “Phase 2” occurred between the 1950s and 1990s, and was characterized by very
98 intense channel narrowing, planform morphology simplification, and bed-level lowering. This
99 phase was widely recognized in all Italian rivers, and was essentially linked to the reduction of
100 sediment supply caused by anthropic factors such as gravel mining, dam closure, channelization,

101 bank protections, and other in-channel works (Table 1). Phase 2 corresponds with a period of huge
102 socio-economic modification of Italian society, new economic processes, and changes in population
103 growth following World War II. This context was characterized by the abandonment of mountain
104 areas and the displacement of both agricultural activities and populations to the valley bottoms and
105 coastal plains, and finally the development of mechanized agriculture.

106 After the 1980s/1990s, during the so called “Phase 3” (Fig. 1 and Table 1), most rivers underwent
107 an inversion trend, characterized by channel widening, local or widespread bed-level aggradation,
108 and channel planform shifting from a single thread to wandering or even multi-threaded
109 morphologies. Except for a few cases (e.g. the Mareit and Aurino rivers, Fig. 1 and Table 1), where
110 restoration operations were carried out, the occurrence of large floods were observed to be the most
111 common drivers of a rapid and abrupt channel recovery (Table 1). However, in some rivers, channel
112 recovery was instead associated with the cessation of sediment mining (e.g. the Tagliamento,
113 Trebbia, Biferno, and Volturno rivers described in Table 1).

114 In contrast to the second and third phases, “Phase 1” is less well described and understood. As
115 shown in Figure 1, no common temporal trend in the magnitude and distribution of channel
116 modifications is evident over the entire Italian peninsula. However, it seems that channel stability or
117 trends towards narrowing, and probably slight incision, prevail in the rivers in the northern and
118 central part of Italy (from Aurino to Paglia, Fig. 1), while rivers in southern Italy (from Trigno to
119 Crati, Fig. 1) show more variability or a slight prevalence for widening. These contrasting
120 conditions probably indicate that the rivers in central-northern Italy were previously affected by
121 more consistent in-channel human disturbance, which reduced sediment availability earlier (Scorpio
122 et al., 2015), as is described for some of the rivers (e.g. Mareta, Adige, Piave, Tagliamento, Scrivia,
123 Crati), where deliberate narrowing was caused by the construction of levees and groynes at the end
124 of the 19th century/beginning of the 20th century (Table 1). The general trend of narrowing,
125 especially in the rivers of northern Italy, may be temporarily inverted by the occurrence of extreme

126 flood events that caused remarkable channel widening (see the events affecting the Mareta between
127 the 1920s and 1940s, the Brenta in the 1960s, the Piave in the 1880s and 1960s, and the Magra in
128 the 1940s, Fig. 1).

129 Finally, there may also be differences in the definition of the evolutionary trajectories, which can be
130 attributed to variations in the accuracy of the maps and temporal variations in scanning, especially
131 in the time span before the 1950s. In particular, long time spans between consecutive maps do not
132 allow the evaluation of whether channel changes occurred consistently over specific periods, or
133 whether the changes showed accelerations and decelerations.

134 Overall, channel changes in Phase 1 are interpreted as being related to climate changes connected to
135 the end of the Little Ice Age (ca 1850–1880), to the modification of sediment supply coming from
136 slopes because of land-cover modification at the catchment scale, and to the application of soil-
137 erosion control measures on slopes and tributaries (Table 1). Deforestation and soil erosion are well
138 documented between the 19th century and the first decades of the 20th century, whereas increasing
139 afforestation and slope movement stabilizations are described since the 1930s/1950s (Table 1).

140 The literature overview of the Italian rivers demonstrated that many drivers have interacted over
141 space and time, as is the case in other rivers worldwide (Downs et al., 2013). In most cases, it is not
142 straightforward to establish a clear link between each individual factor and the observed channel
143 condition and its evolution (Dufour et al., 2015), and the role of land use changes at the catchment
144 and reach scales has been addressed only qualitatively in most Italian case studies (see the column
145 ‘Effects of Land use changes at catchment and/or reach scale’, Table 1). The effects of afforestation
146 at a catchment scale were quantified in a few papers (see Table 1: Comiti et al., 2011; Preciso et al.,
147 2012; Ziliani and Surian, 2012; Bollati et al., 2014; Magliulo and Pignone, 2016; Scorpio et al.,
148 2015; Scorpio and Roskopf, 2016; Fortugno et al., 2017; Marchese et al., 2017), although only six
149 out of 40 considered studies compared land use changes occurring in the corridor area with channel

150 adjustments (Aucelli et al., 2011; Comiti et al., 2011; Dufour et al., 2015; Surian et al., 2015; Picco
151 et al., 2017; Mandarino et al., 2019).

152 To fill this gap, multiple basins were analyzed, with eight rivers from the north to the south of Italy
153 being considered (Sesia, Stura di Lanzo, Stura di Demonte, Borbera, Nure, Volturno, Trigno, and
154 Fortore rivers). The study was based on a diachronous-synchronous approach carried out at
155 catchment and reach scales and compared channel adjustments and land use changes with the aim
156 of separating the influences of natural and human drivers.

157

158 **2. Study area**

159 Eight rivers situated within three distinct regions from the north to the south of Italy were analyzed
160 (Fig. 2). The Sesia, Stura di Lanzo, Stura di Demonte, and Borbera rivers are located in the
161 Piemonte Region, in the north-western part of Italy (Fig. 2A); the Nure is located in the Emilia-
162 Romagna Region, in northern Italy (Fig. 2A); and the Volturno, Trigno, and Fortore rivers fall in
163 southern Italy (Fig. 2B). From a physiographical point of view, the Sesia, Stura di Lanzo, and Stura
164 di Demonte drain from the Alps, the Borbera and Nure drain from the northern Apennines, and the
165 Volturno, Trigno, and Fortrose drain from the southern Apennines. These rivers were selected as
166 they are characterized by different climatic, geologic, and physiographic characteristics; different
167 fluvial system sizes and morphologies; and different socioeconomic contexts and degrees of human
168 impact. Some of the physiographic and hydrological features are summarized in Table 2.

169 The catchments of these rivers span a wide range of geological conditions. A prevalence of
170 metamorphic rocks, especially gneiss and serpentinite, characterize the Sesia, Stura di Lanzo, and
171 Stura di Demonte basins, with lower but relevant outcropping of igneous rock (granites) in the
172 Sesia, and sedimentary rocks, especially dolomites, in the Stura di Demonte. The Apennines basins
173 are composed of sedimentary rocks, with some differences between river systems. The Borbera,
174 Nure, and Fortore are underlain by sandstones and mudstones, with outcrops of clay and

175 conglomerates of marine and continental environments in the lower sector of the Fortore River. The
176 Volturno and the upper part of the Trigno catchment are mainly composed of limestone, marly
177 limestones, and flysch deposits. Multi-colored clays and siliciclastic flysch deposits prevail in the
178 middle and lower portions of the Trigno basin. The climate is temperate with rainfall peaks
179 concentrated in the spring and autumn in the Sesia, Stura di Lanzo, Stura di Demonte, Borbera, and
180 Nure basins; and Mediterranean to warm temperate, in the Volturno, Trigno, and Fortore. In
181 particular, the headwater portions of the southern Apennines basins present a temperate–warm
182 humid climate, while the medium and lower sectors are largely represented by a temperate–warm
183 humid climate with warm summers in the Volturno, and very hot and dry summers in the Trigno
184 and Fortore. As a consequence, discharges in the channels show low-flow conditions in spring–
185 summer seasons and high-flow in autumn–winter (Aucelli et al., 2007). The Sesia and Stura di
186 Lanzo have partly ice-fed basins (1% and 12% glaciated areas, respectively).

187 In the Sesia, Stura di Lanzo, Stura di Demonte, and Nure rivers, channel morphologies - from
188 upstream to downstream - shift from a single sinuous thread or a sinuous morphology with alternate
189 bars, to a multithreaded, wandering and/or braided morphology, before returning to a single-
190 threaded morphology (sinuous and meandering) in the lower plains. The Borbera features a braided
191 planform morphology.

192 In the Trigno and Fortore, wandering and sinuous channels alternating with bar morphologies
193 feature in the unconfined reaches and upper valleys, respectively, while, sinuous to meandering
194 patterns prevail in the confined reaches and lower/coastal segments. The Volturno presents a
195 prevalence of single-threaded patterns composed of sinuous morphologies with alternate bars in the
196 upper valley, and sinuous and meandering channels in the medium and lower valley.

197 Forty-three study reaches providing a total length of 165 km were selected (Fig. 2), taking into
198 account evidence of appreciable morphological changes over the past century, while excluding
199 reaches that were confined. For the Nure, Volturno (in the multi-threaded segment in 1954), Trigno,

200 and Fortore (upstream of the Occhito dam) rivers, most of the channel length was analyzed to
201 examine changes in propagation from upstream to downstream over time. To analyze the influence
202 of land-use changes within the river corridors on channel morphology, a further 22 reaches
203 presenting low direct human impacts (gravel mining, bank protection, damming upstream) until at
204 least the 1970s were further selected from the 43 reaches on the basis of the availability of maps
205 and aerial photos, and the technical constrains linked to the quality of the available material (Fig. 2
206 and Table 3). These reaches were compared with the aim of assessing the effects of catchment-scale
207 vs reach-scale controlling factors.

208 In all catchments, human activities took place mainly over the second half of the 20th century (Table
209 4). At the reach scale, the alpine rivers and most reaches in the Nure and Volturno experienced
210 human impacts consisting of gravel mining in the floodplains and the construction of in-channel
211 works since the late 1970s (Table 4). In the Trigno and Fortore, human pressures started in the
212 1980s, although they were more intense and widespread than in the other rivers (Table 4).

213

214 **3. Materials and methods**

215 A combined diachronous-synchronous approach integrating data from catchment to reach scale over
216 several time periods was used in this study (Downs and Piégay, 2019). Channel changes were
217 related to different drivers of change, on the bases of the temporal synchronicity and spatial
218 proximity.

219

220 **3.1. Channel planform changes**

221 Channel changes were estimated by means of a diachronic approach using a set of historical maps,
222 aerial photos, and orthophotos (Table 5). Measurement errors were estimated using the method
223 proposed by Mount et al. (2003). In accordance with previous similar studies in the same or other
224 areas (Winterbottom, 2000; Scorpio et al., 2015; Scorpio and Roskopf, 2016; Surian et al., 2009b),

225 the maximum error was estimated to be about 35 m for the historical maps and lower than 5 m for
226 the aerial photographs.

227 Channels were edited as polygons, including the low flow channels and bare alluvial sediments
228 classified as bars, while islands were excluded from the active channel areas. To remove size
229 effects, the active channel width was standardized by the root mean square of the basin area (W^*
230 sensu; Piégay et al., 2009). W^* is considered as a proxy for the sediment supply.

231 To allow the comparison of different river reaches, active channel width changes were calculated
232 with respect to the active channel width in 1954 (the oldest aerial photos available for all rivers)
233 using the following equation:

$$234 \quad \Delta W_{1954}(\%) = (1 - W/W_{1954}) * 100 \quad (1)$$

235 where W is the average active channel width measured in different years (from 1852 to 2016), and
236 W_{1954} is the average active channel width in 1954. W^* and ΔW_{1954} were computed for all the 43
237 analyzed reaches.

238 For the 22 selected reaches, the annual rates of channel width variation (expressed in m y^{-1}) were
239 evaluated for four periods: 1954–1970s; 1970s–1980s; 1980s–1998; 1998–2010s.

240

241 **3.2. Land cover changes**

242 Land use changes were evaluated at both reach and catchment scales. At the reach scale, analyses of
243 land use evolution were carried out for the 22 selected reaches, using a diachronic approach in
244 ArcGis and several sets of aerial photos and orthophotos representative of five periods (1954;
245 1970s; 1980s; 1990; 2010s; see Table 5 for more details).

246 To improve uniformity in the interpretation of aerial photos and orthophotos of different resolutions
247 and quality, nine land uses classes were mapped, following the methodology proposed by Dufour,
248 2005 and Dufour et al., 2015: active channel (wetted channel and unvegetated bars); sparse pioneer
249 vegetation (sparse pioneer vegetation on gravel bar); dense pioneer vegetation (dense pioneer

250 vegetation on the bars, islands, and incipient floodplains); shrub land (units dominated by shrub
251 species); grasslands (units dominated by meadow and herbal species); grasslands with trees and
252 shrubs (units dominated by meadow and herbal species with the presence of sparse trees and
253 shrubs); post- pioneer vegetation (units dominated by mature woodland, usually corresponding with
254 floodplains or recent terraces); agricultural areas; and human activity (roads, gravel mining,
255 housing).

256 The nine land-use units were mapped within the corridors of historical changes, and within the
257 areas composing the former active channels in previous years that were then abandoned in
258 following years (e.g., land mapped in 1976 within the polygons forming the active channel in 1954,
259 then abandoned in 1976). The historical corridors overlaying the active channels mapped since the
260 19th century were defined (when maps were available), especially from 1954 to the present.

261

262 At the catchment scale, land cover changes were analyzed using data sets from several sources
263 (Table 5), including data from the literature (Di Martino, 1996), official surveys of the National
264 Agrarian Census (<http://seriestoriche.istat.it/index.php?id=8>), interpretation of orthophotos and
265 maps available on regional websites (<http://geoportale.regione.emilia-romagna.it/it/contenuti/database-uso-del-suolo>; <http://www.geoportale.piemonte.it>), and Corine
266 land cover maps obtained from the Italian Ministry of Environment
267 (http://geoportale.isprambiente.it/tematiche_pt/suolo/). The collected sources allowed the
268 reconstruction of land use changes from 1836 to 2012 in the Volturno and Trigno catchments, from
269 1853 to 2012 in the Nure Catchment, from 1929 to 2012 in the Borbera and Fortore catchments, and
270 from 1960 to 2012 in the Sesia, Stura di Lanzo, and Stura di Demonte catchments. To confirm the
271 trends detected for each catchment and to increase the long-term data for the Stura di Lanzo, Stura
272 di Demonte, and Fortore basins, additional analyses at the province/regional level (Torino province
273 for the Stura di Lanzo, Cuneo province for the Stura di Demonte, and Molise region for the
274

275 Volturno, Trigno, and Fortore basins) were carried out for the period 1929 to 2012, using data from
276 the ISTAT website (<http://seriestoriche.istat.it/index.php?id=8>).

277 Land uses at the catchment scale were reclassified into the following main types: forested area,
278 pasture and meadow, ploughed land (including crops mainly characterized by cereals), cultivated
279 trees (including crops with cultivated trees), shrub cover, and other (including urban areas, sparsely
280 vegetated areas, bare rock patches, recently burnt areas, and river beds).

281

282 **3.3. Population and livestock densities**

283 Statistics on population and livestock densities can provide indicators of the anthropogenic pressure
284 on the environment at different scales (Taillefumier and Piégay, 2003). In Italy, 10-yearly
285 population censuses have been conducted regularly since 1861, with the exception of 1891 and
286 1941. Data on the population composition between 1861 and 2011 were imported from the website
287 ISTAT (<http://seriestoriche.istat.it/>; <http://seriestoriche.istat.it/index.php?id=8>) and used to derive
288 statistics and density trends in all analyzed catchments and the municipalities in which the 22
289 selected reaches are located.

290 Livestock composition trends were also derived from the ISTAT website, based on a number of
291 surveys between 1908 and 2010. Analysis were carried out at the province level (Torino Province
292 for the Stura di Lanzo River, Cuneo Province for the Stura de Monte River, Piacenza Province for
293 the Nure River) and the regional scale (Volturno, Trigno, and Fortore rivers). Data are referred to
294 1908, 1930, 1941, 1961, and 2010 for analyses at the province scale, and to 1908, 1930, 1941,
295 1961, 1970, 2000, and 2010 for the analyses at the regional scale.

296

297 **3.4. Climate trends and changes in the frequency of floods**

298 Climate changes over the last century were reconstructed from studies on precipitation and
299 temperature trends (Brunetti et al., 2000, 2004a, 2004b).

300 With the exception of the Stura di Lanzo River at the Lanzo gauging station (Arpa Piemonte, 2012),
301 data on discharge were either unavailable for the studied rivers, or the existing records showed a
302 number of gaps and were not therefore suitable for analysis.

303 The occurrences of flood events were reconstructed using data extracted from the AVI project
304 (<http://avi.gndci.cnr.it>) for the Volturno river, from various archives provided by the basin
305 authorities for the rivers Trigno, Biferno, and Fortore, and by the Consortium 'Bonifica della
306 Capitanata' for the Trigno and Fortore rivers.

307

308 **4. Results**

309 **4.1. Channel planform and width changes**

310 Analysis of the W^* distribution of all 43 reaches highlights several differences (Fig. 3A). Rivers in
311 the southern Apennines (Volturno, Trigno, and Fortore) and the Borbera and Lavaiana present a
312 high potential for sediment supply (Fig. 3A; W^* in all reaches and all years exceeds 1 and goes up
313 to 29.3 in the Fortore in 1954). The Nure and Lardana also show some W^* values higher than 1, but
314 the minimum values decrease to 0.24 in the Nure and 0.8 in the Lardana. The Alpine Rivers are
315 characterized by lower W^* , ranging between 0.08 and 0.19 in the Stura di Demonte, between 0.16
316 and 0.41 in the Stura di Lanzo, and between 0.17 and 0.31 in the Sesia (Fig. 3A).

317 Analysis of the changes in W^* over time reveals that before 1954, W^* was slightly lower than after
318 1954 in the Stura di Lanzo (from 0.42 to 0.35; Fig. 3B), Nure (from 1.3 to 1.01 on average; Fig. 3C)
319 and Trigno (from 20 to 19.5 on average; Fig. 3E) rivers, but was slightly higher in the Sesia (from
320 0.26 to 0.3; Fig. 3B), Stura di Demonte (from 0.16 to 0.19; Fig. 3B), Volturno (from 13.2 to 18.7 on
321 average; Fig. 3D), and Fortore (from 20.8 to 24.2 on average; Fig. 3F) rivers. This suggests a
322 decrease in sediment supply in the Nure and Stura di Lanzo and an increase in the Sesia, Stura di
323 Demonte, Volturno, and Fortore.

324 Between 1954 and the 1990s, W^* decreased in all rivers, with rivers in the southern Apennines
325 showing a sudden decrease between 1954 and the 1970s; while the decline in W^* in the other rivers
326 was more gradual and uniform over time (Figs. 3B and 3C). In the Borbera River, W^* decreased
327 from 11 to 9 between 1954 and the 1970s, and then oscillated between 9 and 8.5 until the present
328 day (Fig. 3B).

329 After the 1990s, W^* increased in all rivers except the Volturno and Sesia, where it continued to
330 decline (Fig. 3).

331 Further differences between rivers in northern and southern Italy are highlighted when all 43
332 reaches are considered (Figs. 4A and 4B). Before 1954, the active channel widths of all rivers were
333 within approximately $\pm 20\%$ of those in 1954 (Figs. 4A and 4B).

334 After 1954, active channel narrowing in southern Italy (Fig. 4B) exceeded -60% up to the
335 1980s/1990s. Maximum narrowing was reached in the Fortore in 1998 (-88% on average) and in
336 the Volturno in 2016 (-89% on average). In the northern Italian rivers, narrowing was lower than
337 -60% , with maximum values being attained in the 1990s or 2010s (up to -46% in the Sesia in
338 2015; -53% in the Stura di Lanzo in 2015; -55% in the Stura di Demonte in 1996; -26% in the
339 Borbera in 1996; -45% on average in the Nure in 1988; -65% in the Lardana in 1988; -59% in the
340 Lavaiana in 1998; Fig. 4A).

341 Trends of active channel width changes from upstream to downstream in the same river show a
342 general decrease in channel narrowing in the reaches closer to confluences or to the river mouth
343 (Fig. 4C). Reaches upstream do not present clear and unequivocal trends, especially in the Trigno
344 and Fortore rivers, while narrowing propagated downstream at a decadal time scale in the Nure
345 River (Fig. 4C).

346 In the 22 selected reaches, several differences in terms of the timing of peak periods and the
347 amounts of average annual active channel width variation are evident (Table 6). High rates of
348 narrowing are shown by the reaches Volt2 and Volt4 in the Volturno River (average annual rates

349 ranging from -4.0 to -4.6 m y^{-1} between 1954 and the 1980s), reaches in the Trigno River in the
350 southern Apennines (Tr5 and Tr9, with average annual rates up to -4.5 and -5 m y^{-1} respectively in
351 the 1980s–1990s), and the Stura di Lanzo (average annual rates up to -4.1 m y^{-1} between 1954 and
352 1970s), Stura di Demonte (average annual rates up to -3.5 between the 1970s and 1990s) and Sesia
353 (average annual rates up to -3.2 in the 1980s–1990s) in the Alps (Table 6). Rivers in the northern
354 Apennines (Borbera, Nure, Lardana, and Lavaiana) experienced maximum annual rates of
355 narrowing up to -2.0 m y^{-1} , but the average values were lower than -1 m y^{-1} . In the Nure
356 catchment, the upper reach (Nur1) and the reaches in its tributaries (Lar1 and Lav1) presented
357 similar trends over the entire investigated period, with maximum narrowing occurring between
358 1954 and the 1970s (Table 6). Reaches downstream (from Nur3 to Nur10, Table 6) show a peak
359 period of narrowing in the 1970s–1980s, with higher values in the reach Nur10 (-4.0 m y^{-1}). Trends
360 and rates in the Borbera river (Bor1, Table 6) are similar to those found in the Nure basin.
361 The Fortore river in the southern Apennines reached peak annual rates of narrowing (up to -1.5 m
362 y^{-1} , Table 6) in the periods 1954–1970s and 1980s–1990s.
363 In the Stura di Lanzo, Nure, Trigno, and Fortore rivers, some evidence for widening (between $+0.3$
364 m y^{-1} in the Fortore to $+7.8$ m y^{-1} in the Stura di Lanzo, Table 6) is observed, especially after the
365 1990s.

366

367 **4.2. Land cover changes at the reach scale**

368 Detailed maps allowing land use characterization in the landscape corridor before 1954 are
369 available for the Volturno in southern Italy and the rivers in the Piemonte Region (Sesia, Stura di
370 Lanzo, Stura di Demonte, and Borbera). In all these rivers, grasslands and semi-natural vegetation
371 (especially pioneer vegetation, shrub lands, and grasslands with trees) prevailed in the middle of the
372 19th century, with agricultural areas coming second. At that time, riparian forests were almost absent

373 in the Volturno and Sesia, while they were present in a juvenile and sparse phase with
374 discontinuous coverage in the Stura di Lanzo, Stura di Demonte, and Borbera.

375 After 1954, specific land use typologies are clearly recognizable in the corridor of the historical
376 channel changes of the 22 reaches (Fig. 5).

377 Post-pioneer vegetation encroachment started from the middle of the 20th century to approximately
378 the 1980s, in the Borbera, Lavaiana, Nure1, Nure3, and Volturno (Fig. 5). In 1954, the Sesia and
379 Stura di Demonte were already well forested (27% and 32% respectively), while the Lardana,
380 although presenting a low coverage of riparian forest (3%), was characterized by juvenile phases
381 presenting sparse (41%) and dense (16%) riparian vegetation, which developed into mature forest
382 over time, especially during the 1970s and 1990s (Fig. 5). In all the rivers mentioned above,
383 channel narrowing occurred with the absence of increasing human pressure (except for the Volturno
384 River) and the increase in post-pioneer vegetation, even though land uses changes did not present
385 the same temporal patterns, as river vegetation encroached earlier in some rivers (Sesia, Stura di
386 Lanzo, Stura di Demonte, Lardana) than in others (Borbera, Volturno, Nure). In the Volturno River
387 (Vol4 and Vol5), forest expansion was possibly limited by increases in agricultural areas and
388 human activities after the 1980s. After a first phase of channel narrowing contemporary with forest
389 expansion in the Stura di Lanzo (between 1954 and 1980s), widening abruptly took place as a
390 consequence of flood events between the 1980s and 1990s (Fig. 5).

391 The Nure River shows an upstream to downstream gradient in forest cover increase and channel
392 narrowing. Upstream channel changes occur sooner than those downstream (breaking points in
393 channel area change between 1954 and 1970s in Nur1, between the 1970s and 1980s in Nur3, Nur5,
394 and Nure6, and between the 1980s and 1990s in Nur10; breaking points in forest cover change
395 between 1954 and 1970s in Nur1 and Nur3, between 1970s and 1980s in Nur5 and Nur6, and
396 between the 1980s and 1990s in Nur10), denoting a clear downstream propagation probably related
397 to a decrease in sediment supply from upland sources. Overall, post-pioneer vegetation started to

398 become established in the 1970s, and human impacts, similar to the situation for the Volturno river,
399 increased after the 1980s (agricultural area changed from 22%–25% in 1954 to 25%–45% in the
400 2010s; human activities from 0% in 1954 to 4%–18% in the 2010s, Fig. 5).

401 The Trigno and Fortore rivers in southern Italy exhibit similar land use changes and configurations,
402 being mainly dominated by agricultural areas, grasslands, and human activities (Fig. 5). Between
403 1954 and the 2010s, agricultural areas (from 6%–23% in 1954 to 11%–32% in 2010s in the Trigno;
404 from 4%–33% in 1954 to 44%–53% in 2010s in the Fortore) and human activity (from 0 in 1954 to
405 10%–19% in the 2010s in the Trigno, from 0% in 1954 to 7%–23% in the 2010s in the Fortore)
406 showed increases coincident with the decrease in the active channel. Shrub lands, grasslands, and
407 grasslands with trees and shrubs showed relevant occurrences since 1954, especially in the Trigno.
408 In contrast to all the other rivers, riparian vegetation never particularly developed in the Trigno and
409 Fortore (maximum expansion 7%–22% in the 2010s in the Trigno; 8%–13% in the 2010s in the
410 Fortore), with it starting to only lightly increase since the 1990s, when human activities and
411 agricultural areas declined (Fig. 5).

412 Similar trends are noted in the progressive abandoned portions of the active channels (Fig. 6). The
413 areas abandoned by the active channel between 1954 and 1970 were mainly encroached by post-
414 pioneer vegetation (exceeding 40% of land uses) in the Sesia, Stura di Demonte, Borbera, and
415 Volturno rivers (Fig. 6A). In the Nure and Lardana, there was a prevalence of pioneer vegetation,
416 while grasslands with the presence of trees and shrubs were widespread in all reaches, but
417 particularly in the Lavaiana (Fig. 6A). The Trigno and Fortore rivers showed especially high levels
418 of grasslands and shrubs, and evidence of human activities and agricultural pressures (Fig. 6A).
419 Between the 1970s and 1980s, pioneer vegetation and secondary post-pioneer vegetation
420 encroached along all the rivers except for the Trigno and Fortore, where human activities prevailed
421 (Fig. 6B). Since the 1980s, riparian forests, pioneer vegetation, shrub lands, and grasslands with
422 trees and shrubs increased along all reaches (Figs. 6C and 6D). Between the 1980s and 1990s,

423 human impacts kept affecting rivers in southern Italy (Trigno and Fortore) and along some reaches
424 of the Nure (Fig. 6C). In some rivers (Stura di Lanzo between 1980s and 1990s and Trigno and
425 Fortore between 1990s and 2010s, Figs. 6C and 6D), previous land uses were substantially eroded
426 and vegetation was rejuvenated by flood events.

427 In summary, analyses of the land use changes in the corridors of the studied reaches between 1954
428 and the 2010s have highlighted similarities between the rivers in the Piemonte Region (northern
429 Italy), the Nure, Lardana, Lavaiana, and the Volturno River in southern Italy, especially concerning
430 contemporary afforestation and channel narrowing. For these rivers, phases of vegetation
431 encroachment do not present a synchronous pattern, as the Sesia and Stura di Demonte were already
432 forested in 1954, while in the other rivers, forest expansion started in the 1970s–1980s (e.g., the
433 Volturno, Borbera, Lardana, Lavaiana, and Nur1), or even later in some reaches of the Nure river.
434 In the Fortore and Trigno river (southern Italy), channel narrowing occurred with the increase in
435 human pressure and the permanence of grazing areas.

436

437 **4.3. Land cover changes at the catchment scale**

438 Historical land use changes play an important role in sediment balance, runoff, and the impacts of
439 rainfall on flow and sediment generation, and consequently on morphological channel evolution.
440 When evaluating channel changes through time, it is therefore important to determine whether land
441 uses were stationary or not, and to consider them in the understanding of channel changes.

442 Although the data is subject to uncertainty related to the comparisons of maps having different
443 sources and scales, some relevant trends are clearly evident.

444 The Borbera, Nure (in northern Italy), and Volturno (in southern Italy) rivers present similar general
445 trends, even considering the two sub-periods (before and after the 1960s, Table 7, column trends): a
446 substantial increase in forest areas, especially from the 1930s onwards (from 22% to 64% in the
447 Borbera, from 33% to 52% in the Nure, from 18% to 50% in the Volturno between 1929 and 2012;

448 Table 7); a slight decrease in pastures and meadows (from 12% to 2% in the Borbera, from 18% to
449 9% in the Nure, from 26% to 16% in the Volturno between 1929 and 2012; Table 7); large
450 decreases in ploughed lands, especially in the Volturno River (from 19% to 1% in the Borbera,
451 from 33% to 8% in the Nure, from 50% to 7% in the Volturno between 1929 and 2012; Table 7);
452 and marked extension of cultivated trees, particularly after the 1960s (from 6% to 20% in the
453 Borbera, from 0% to 28% in the Nure, from 5% to 23% in the Voltuno between 1929 and 2012;
454 Table 7). Forest cover increased before the 1960s/1970s in the Borbera and Nure basins, and
455 especially after the 1970s in the Volturno (Table 7). In all these basins, forests increased in the
456 upper parts while cultivated trees increased in the lower parts, at the expense of pastures, meadows,
457 and ploughed lands. Analysis suggests the occurrence of a natural regeneration of vegetation after
458 the 1930s, and modification of farming practices from extensive to intensive.

459 The Trigno and Fortore rivers present some similarities in both sub-periods (Table 7). Forest cover
460 does not present the most interesting change occurring in these basins, as they are characterized by
461 only slight increases, from 15% to 29% in the Trigno River and from 7% to 15% in the Fortore
462 between 1929 and 2012 (Table 7). Notable increases occurred in the cultivated trees between 1929
463 and 2012, from 5% to 22% in the Trigno and from 4% to 24% in the Fortore (Table 7). Most forest
464 and cultivated trees increases occurred after the 1970s in both catchments. Despite a decrease in
465 ploughed lands from 61% to 30% in the Trigno and from 77% to 55% in the Fortore, especially
466 after the 1970s, they still remain the most widespread land use to the present. In both basins, pasture
467 and meadows cover 10% of the total area until the 1970s, after which they almost disappear. The
468 overall analysis of the land use changes in Trigno and Fortore basins suggests a strong control of
469 agricultural use of the territories.

470 The Sesia, Stura di Lanzo, and Stura di Demonte rivers are tricky to compare with the other basins,
471 because numerical data are only available from 1960, and for these rivers, only data referring to the
472 second sub-period can be described.

473 The Sesia already presented very high forest coverage (46%, Table 7) in 1960, with this percentage
474 being comparable with the forests in the Nure and Borbera in the 1960s/1970s, and being higher
475 than that in the Volturno in the 1950s/1970s. In the Stura di Lanzo and Stura di Demonte rivers,
476 forested areas increased from 18% to 33% and from 24% to 28%, respectively.

477 Pasture and meadow largely decreased in all three rivers, (from 43% to 16% in the Sesia, from 68%
478 to 21% in the Stura di Lanzo, from 44% to 21% in the Stura di Demonte; Table 7).

479 Ploughed lands are negligible in the Sesia and Stura di Lanzo, while they showed a decrease from
480 22% to 13% in the Stura di Demonte. Agricultural areas occupied a very low percentage of the
481 basins.

482 In general, between 1960 and 2012, the Sesia, Stura di Lanzo, and Stura di Demonte land cover was
483 mainly characterized by increases in forest and shrub cover and a decrease in pastures and
484 meadows. Cultivated trees and ploughed land are not prevalent. Increased shrub cover is interpreted
485 as a transitional stage between pastures and meadows or cultivated plots to forest cover.

486 To compensate for the absence of data before 1960 in the Stura di Lanzo and Stura di Demonte
487 rivers, an analysis at the province scale was performed (Fig. 7A and Fig. 7B). The figures confirm
488 widespread pasture and meadow cover in 1929 that then declines over the 20th century, an increase
489 in forest cover only after the 1970s, while before it was constant. and a decrease in ploughed lands
490 in both provinces, which before 1960 were the most important land cover in the Cuneo Province
491 (Stura di Demonte). The increase in cultivated trees, especially after the 1970s (Fig. 7A and Fig.
492 7B), is not found in the studied area, maybe because the entire provinces include more plain areas.

493 Furthermore, trends in all the Molise regions (Volturno, Trigno, and Fortore rivers) confirm the
494 trends described for the singular rivers (Fig. 7C), and highlight the higher ploughed and agricultural
495 cover in southern Italy compared with the north (Fig. 7A and Fig. 7B).

496

497 **4.4. Evolution of population and livestock density**

498 Demographic changes in population and livestock were interpreted as indirect indicators of land use
499 change (Taillefumier and Piégay, 2003) and human pressure at basin and reach scales.

500 In 1861, the population density in the northern Italian river basins (Fig. 8A) was slightly lower
501 (from 56 inhabitants/km² in the Nure to 63 inhabitants/km² in the Stura di Demonte and Borbera
502 basins) than that in the southern Italian basins (Fig. 8B, between 78 inhabitants/km² in the Volturno
503 river and 88 inhabitants/km² in the Fortore river). An exception is represented by the Sesia (Fig.
504 8A), with 72 inhabitants per km². Between 1861 and the beginning of the 1950s, the population
505 slightly increased in most of the basins (e.g. up to 95 inhabitants/km² in the Fortore river, up 90 to
506 inhabitants/km² in the Sesia river and up to 71 inhabitants/km² in the Nure river), while it remained
507 fairly constant in the others. Differing from most catchments, the Borbera underwent a consistent
508 depopulation soon after the 1860s (Fig. 8A).

509 A rapid depopulation occurred in most of the basins between the 1950s/1960s and 1970s/1980s,
510 with a general migration of the inhabitants to the plain areas. Figures 8C and 8D show stronger
511 decreases in the mountain parts of the basins of all rivers. Depopulation had already started in the
512 1900s/1920s in some river basins of northern Italy, and started after the 1950s in those in southern
513 Italy. In the Trigno catchment, most of the population moved from the mountain to the coastal area
514 (Fig. 8D). However, the Stura di Lanzo and Stura di Demonte rivers showed a different pattern,
515 with increases in their populations.

516 After the 1980s, the population density was more stable in the basins of the northern Italian rivers
517 (Fig. 8A) and the Volturno river (Fig. 8B), whereas it continued to decrease in the Fortore and
518 Trigno river basins (Fig. 8B) and the mountain parts of the catchments of all the rivers (Figs. 8C
519 and 8D).

520 Analysis of the evolution of the demographic density of the population was also performed for the
521 neighboring municipalities of the 22 selected reaches (Fig. 8E and 8F). In all rivers where multiple

522 reaches were analyzed, the derived trends were very similar, and could be represented by a singular
523 trend, as indicated in Figures 8E and F.

524 The reaches in the Sesia, Stura di Lanzo, Stura di Demonte (Fig. 8E), and Volturno (Fig. 8F)
525 presented similar trends, with human density increasing since the 1860s. The period of stronger
526 population increase occurred in the 1950s/1960s in the rivers of northern Italy, and after the 1970s
527 in the Volturno.

528 The Nure, Trigno, and Fortore rivers have similar trends, characterized by a population increase
529 followed by a rapid decrease (Fig. 8E and 8F). The historical maximum density occurred in the
530 1920s in the Nure river (59 inhabitants/km²), and in the 1950s in the Trigno and Fortore rivers (85
531 inhabitants/km² in the Trigno reaches, 95 inhabitants/km² in the Fortore).

532 At the reach scale, the Borbera showed a different trend, with the population density reaching its
533 maximum in the 1910s/1920s (98 inhabitants/km²) and its minimum in the 1960s/1970s (77
534 inhabitants/km²).

535 Ovine (sheep) and caprine (goat) breeding is considered an extensive form of breeding that requires
536 little labor and is not wasteful of resources. It is traditionally characteristic of dry mountain areas,
537 where historic fluctuations in the livestock are often linked to economic and political events
538 (Taillefumier and Piégay, 2003).

539 Overall, the data show that ovine and caprine breeding in northern Italy never took a notable
540 diffusion during the study period (never higher than 0.10–0.15 head of cattle/ha). In these
541 territories, cattle were probably never of great importance, and bovine breeding involved more
542 intensive livestock production in barns. Cattle trends are comparable between the Torino and Cuneo
543 provinces (Stura di Lanzo and Stura di Demonte respectively; Figs. 9A and 9B). Bovine numbers
544 showed a particular increase after the 1960s, while ovine numbers showed notable decreases
545 between the 1940s and the end of the 1950s (Figs. 9A and 9B).

546 In Piacenza Province (Nure basin, Fig. 9C), the most widespread animal rearing concerned bovines.
547 Ovines decreased in numbers until the 1960s, after which they became of negligible relevance. In
548 southern Italy, different sources indicate a scattered decrease of breeding during the 19th century
549 (Barker, 1995), and the same trend is confirmed during the 20th century by data collected in this
550 study (Fig. 9D).

551 Ovine and caprine breeding have characterized the river basins of Southern Italy, although the
552 overall density trends show a fast period of decreasing density between the 1940s and 1950s (Fig.
553 9D). Bovine breeding increased in the southern river basins after the 1930s, but never became of
554 major importance (Fig. 9D).

555

556 **4.5. Trends in climate and flood frequency**

557 Analysis of the recent studies on precipitation and temperature trends over the last 200 years shows
558 that the Italian climate has become warmer and drier since the 1930s, especially in southern Italy
559 (Brunetti et al., 2000). Annual precipitation and the related number of wet days showed a
560 significant negative trend over all of Italy from 1880 to 2002 (Brunetti et al., 2004a). Some
561 important differences in climate modification over the Italian regions are highlighted. Temperature
562 showed a positive trend in all seasons in southern Italy, and especially in the autumn and winter in
563 northern Italy (Brunetti et al., 2004a), starting from the 1910s and 1920s. Temperatures rose rapidly
564 until the 1950s, and were then constant from 1950 to 1985, with only a slight drop in the period
565 1970–1980. After 1985, they began to rise again in all seasons. As a consequence, dry conditions
566 became stronger in the southern regions. Total precipitation showed no trend in the northern
567 regions, but a significant negative trend in southern regions, with the number of rainy days
568 decreasing in all regions, with the greatest decreases occurring from the 1930s to 1940s, and from
569 the 1960s to 1980s (Brunetti et al., 2004b). Significant positive trends in precipitation intensity were
570 registered in the northern part of Italy because of the strong decrease in the number of rainy days,

571 while in southern Italy, no significant changes in precipitation intensity were found, because both
572 total precipitation and the number of rainy days significantly decreased (Brunetti et al., 2004b). In
573 northern Italy, the increase in precipitation intensity caused an increase in heavy precipitation
574 events, while at the same time, droughts particularly affected the southern regions, causing
575 problems for agriculture during the summer.

576 Trends of flood discharge are continuous only for the studied reach in the Stura di Lanzo (station
577 Stura di Lanzo at Lanzo town Fig. 10A). The data show a notable increase in channel width during
578 the 2000s, which was concurrent with the occurrence of large floods (Fig. 10A). According to the
579 data extracted from the AVI project for the Volturno Rivers (Fig. 10B), a significant increase in the
580 frequency of flood events occurred during the 1990s, although these floods did not cause any
581 appreciable channel changes. The increase in channel width in the Fortore and Trigno rivers during
582 the 2000s is related to the occurrence of floods in 2003, 2009, and 2015 (Scorpio et al., 2016b). In
583 the Nure catchment, significant channel width changes were documented in 2015 because of a flood
584 event that occurred in September 2015 (Scorpio et al., 2018c).

585

586 **5. Discussion**

587

588 **5.1. A very clear regional difference in the narrowing process**

589 This study has revealed a variety of processes influencing channel responses during the last century.
590 The analysis allowed us to identify three main groups of rivers with similar cause-effect interactions
591 between channel behavior and controlling factors. The similarities and dissimilarities in the factors
592 controlling channel changes also varied over time. Overall, the evolutionary trajectories became
593 more similar over time, even between rivers located in different regional contexts, with the main
594 differences being related to the chronology of driver occurrences and associated channel changes.

595 In the Sesia, Stura di Demonte, and Stura di Lanzo rivers (Alpine rivers in the Piemonte region),
596 channel width declined with the encroachment of vegetation in the corridors and along the
597 hillslopes (Figure 11). In general, these rivers already presented higher percentages of forest cover
598 than the other rivers in the 1950s/1960s, at both reach and catchment scales, with this probably
599 being related to wetter and cooler climatic conditions and lower human impacts caused by the
600 earlier abandonment and depopulation of the mountain areas (which had already started in the 19th
601 century).

602 The Apennine rivers (Borbera, Nure, and Volturno) present a slight delay in afforestation and
603 vegetation recruitment compared with the Alpine rivers, with this being related to the extent of
604 human exploitation in the upper part of the basins until the middle of the 20th century (Figure 11),
605 and the considerable human pressure in the reaches. Data shows that the northern Apennine rivers
606 and the Volturno followed a similar trend, although with different timelines for the intensity of the
607 processes.

608 The Trigno and Fortore rivers in southern Italy present a different story (Figure 11). For these,
609 channel narrowing was particularly related to the decrease in high human pressure at the catchment
610 scale (especially before the 1950s, with ovine breeding and farming decline in the uplands),
611 whereas no afforestation occurred at the reach scale.

612 Narrowing seems to have occurred on most of the rivers before direct human impacts on channel
613 reaches, such as gravel mining and the construction of in-channel works (Italian and French rivers
614 between 1970s and 1990s), and therefore, land-use change must be taken into account in
615 geomorphic analysis to interpret channel changes in Italy, as is also the case in France and Spain
616 (Garcia-Ruiz et al., 1997; Liébault & Piégay, 2001, 2002; Piégay et al., 2004 ; Beguería et al., 2006;
617 García-Ruiz, et al., 2010; Sanjuán et al. 2016). Major land-use change has contributed to reductions
618 in sediment supply and an increase in floodplain resistance, leading to bed level incision and pattern
619 shifting to single-thread morphologies in downstream reaches and regressive erosion upstream.

620

621 **5.2. The initial 19th century widening**

622 Between the 19th century and the 1950s, active channel width changes occurred in all rivers,
623 although they were not associated with relevant planform morphology modification, as all reaches
624 maintained their original multithreaded pattern (braided or wandering). Because of the gap between
625 historical maps and the first aerial photos, accurate analysis of the timing of channel width changes
626 is not feasible within this period. Despite climate data indicating drier conditions in the rivers of
627 southern Italy, several similarities are found between rivers located in different geographical areas.
628 Overall, an evident trend of channel widening was found in the Sesia, Stura di Demonte, Volturno,
629 and Fortore (on average +20%), while narrowing was detected for the Stura di Lanzo and Nure (on
630 average -20%). In most basins, demographic pressure and economic needs induced farmers to
631 maximize production, cultivating as much land as they could. Ploughed lands were widespread at
632 the expense of forests and shrubs, despite unfavorable environments (Figure 11). Human pressures
633 active at the catchment scale, such as population growth, overgrazing, and deforestation for the
634 purpose of cultivation, increased runoff rates, soil erosion, and sediment supply to rivers. At the
635 reach scale, low resistance within floodplains due to the prevention of vegetation encroachment and
636 increased soil resistance through overgrazing resulted in channel widening. Most of the large active
637 channels observed during the first part of the 19th century in northern Italy and southeastern France
638 were the result of human pressures on uplands and river corridors. At that time, channels presented
639 multi-threaded morphologies, especially braided patterns, and were characterized by high rates of
640 bedload transport and low bank resistance. Because of this high pressure on land and its potential
641 effects on flow regime and bedload delivery, it is difficult to really assess the effects of the Little
642 Ice Age and its ending, as it is overwhelmed by other factors.
643 Limits on the available data make it difficult to isolate the causes of channel changes, although
644 overall, it is clear that human pressure along hillslopes had more impact on the southern rivers than

645 on the rivers of northern Italy, particularly in relation to the higher population density, higher
646 breeding of goats and sheep, and higher percentage of ploughed land in the catchments (Figure 11).
647 In the rivers experiencing widening, intense human activity was constant or increased between the
648 middle of the 19th century and the 1950s, whereas those rivers that experienced narrowing were
649 already impacted by rural population decline and the transformation of agricultural systems.
650 Between the 19th century and the 1950s, population density in the Volturno catchment exceeded 75
651 inhabitants/km², the forest cover had not yet started to increase considerably, and the hillslopes
652 were particularly exploited, with ploughed land reaching 50% of total cover (Figure 11). During
653 this period, factors controlling the Volturno dynamic were more comparable to those in other rivers
654 in southern areas than to northern ones. As for the other rivers in southern eastern Italy, the Fortore
655 underwent channel widening, while a specific trend is not clearly highlighted for the Trigno. Their
656 basins are characterized by many similarities in term of climate, average precipitation, orientation,
657 bedrock, mass-wasting processes, and general socio-economic contexts. In the Fortore, widening is
658 probably related to higher rates of sediment supply coming from slopes, which were caused by the
659 increased population density, especially in the mountain areas (Fig. 11), as also confirmed by the
660 higher percentage of ploughed lands in the catchment (Table 8 and Figure 11). In the Trigno,
661 mountains areas had already started suffering depopulation before the 1950s, owing to migration to
662 the coastal areas (Fig. 8D). The trends described for the channels find an indirect confirmation in
663 the evolution of the river mouths. Mouth trends show a significant shoreline retreat in the Trigno
664 (Aucelli and Roszkopf, 2000), which can be interpreted as an indication of a reduction in sediment
665 transport, probably related to the end of the Little Ice Age, and a moderate retreat coupled with
666 lateral migration in the Fortore (Scorpio and Roszkopf, 2016; Fig. 12), which can be interpreted as
667 an indication of significant sediment supply caused by higher human impact in the catchment.

668 In the Nure and Stura di Lanzo catchments, channel narrowing is chronologically linked to
669 afforestation along the hillslopes and the depopulation of the mountain areas that started before the
670 1950s.

671 In contrast to the good availability of data for investigating controlling factors at the catchment
672 scale, information on the possible human impacts on channels at the reach scale is scarcer for the
673 period before 1950. It is probable that positive trends in population density in the proximity of the
674 rivers (Figs. 8E, F, and Fig. 11) caused increases in direct human pressure, as shown for the
675 Volturno River, where maps in 1885 and 1909 display floodplains clearly colonized by semi-natural
676 and pioneer vegetation, while in 1954 they were occupied by arable cultivations reaching the
677 channel banks. Forested floodplains were very infrequent in the 1950s, except for the Sesia and the
678 Stura di Demonte rivers, where they represented 26% and 33% of land cover in the respective river
679 corridors (Figure 11).

680 Channel narrowing (on average -20%) was also documented for most rivers in southern France
681 (Liébault and Piégay, 2001, 2002; Taillefumier and Piégay, 2003; Piégay et al., 2004; Liébault et
682 al., 2005). Two phenomena were observed to complicate the chronology of changes: i)
683 depopulation occurred before upland and corridor afforestation (depopulation began in the 1830s, in
684 contrast to upland and corridor afforestation, which began in the 1930s–1950s), demonstrating that
685 a certain depopulation was needed before a noticeable effect on land use and then channel response
686 occurred. Such findings allow the disentangling of the end of the Little Ice Age effects (end of the
687 19th century) from land-use change effects (mid-20th century); ii) earlier afforestation was observed
688 in intra-mountain areas, and was interpreted as a political strategy to control erosion in the Sardes
689 kingdom (Upper Savoy) in the case of the Giffre river, or the combined effects of torrent works that
690 were built during between 1860 and 1920 in the French catchments, such as in the Ubaye river in
691 the southern French Alps.

692

693 **5.3. The mid-20th century big narrowing**

694 The data available after 1954 allow us to gain a full picture of the cause-effect relationships
695 between channel changes and influencing factors. This analysis allowed us to highlight differences
696 and similarities between rivers located in different regions. All channels suffered narrowing or an
697 acceleration in narrowing between the 1950s and 1990s. The rates for channel narrowing were
698 already elevated over the 1950s–1970s, when activities such as gravel mining and the construction
699 of in-channel works were not yet widespread (Figure 12).

700 Similar to the situation in Italy, in southern France, narrowing was documented in large rivers of the
701 piedmont and intra-montane valley between the 1950s and 1970s, as well as small mountain
702 streams, notably in the Prealps (Liébault and Piégay, 2001, 2002; Piégay et al., 2004; Liébault et al.,
703 2005). As explained in section 5.2, these rivers were already experiencing narrowing since the 19th
704 century, and between the 1950s and 1970s they suffered a new accelerated phase of narrowing (on
705 average –60% compared with the 1950s). Narrowing took place without any increase in direct
706 human impacts on channels or any relationship with a period of changes in the frequency and
707 magnitude of smaller floods (Liébault and Piégay, 2002). In France, narrowing was interpreted to
708 be a result of the interaction of human and climatic controls, with the former overwhelming the
709 latter. Sediment supply from the slopes showed a decrease in relation to the depopulation that had
710 already started in the 19th century, involving the abandonment of agricultural practices on the
711 hillslopes, afforestation, replacement of ploughed lands with open shrub land and meadows, and
712 decreases in livestock pressure (Taillefumier and Piégay, 2003). In the 1930s, some French rivers
713 (to the contrary to the 19th century, when floodplain forests were infrequent and arable areas were
714 interfaced with active channels) started to host forested riparian vegetation, or shrublands colonized
715 former grazed areas (Piégay et al., 2004). This was the case with the Ubaye River, where riparian
716 vegetation started to encroach from the early 1920s, and was well established in 1948 (Liébault and
717 Piégay, 2002).

718 In Italy, it seems that Alpine Italian rivers also underwent afforestation at a catchment scale sooner
719 than the Apennine rivers, and this afforestation can be locally associated with torrential works that
720 were conducted during the first part of the 20th century, and in some catchments (Stura di Lanzo,
721 Stura di Demonte, Borbera), to the depopulation of mountain areas (Figure 11). Depopulation in
722 southern Italy (Volturno, Trigno, and Fortore rivers) took place only after 1950, some decades later
723 than in northern Italy and France. In all catchments in Italy, depopulation and the abandonment of
724 farmland and ploughed lands accelerated after World War II, causing less sediment production from
725 the slopes and the spontaneous colonization of pastures by shrub formations. In Italy, riparian
726 vegetation started to encroach on the river corridors at different times: before the 1950s in some
727 rivers of northern Italy (Sesia, Stura di Demonte, Lardana), and between the 1950s and 1980s in the
728 Stura di Lanzo, Borbera, Nure, and Volturno (Fig. 11). Riparian vegetation was characterized by
729 mature phases of post-pioneer vegetation in the Sesia (up to 73%), Borbera (up to 41%), and Stura
730 di Demonte (up to 42%), and by pioneer stages of forest growth composed of riparian forests,
731 sparse riparian vegetation, and grasslands with shrubs and trees in the Nure, Stura di Lanzo,
732 Lardana, and Lavaiana. The primary role of riparian forests and semi-natural vegetation in driving
733 channel narrowing between the 1950s and 1970s was also observed by Mandarino et al. (2019b) in
734 the Scrivia River, and by Dufour et al. (2015) in the Magra River (northern Apennines, see Fig. 2A
735 for location).

736 In the Nure River (northern Apennines), an upstream-to-downstream gradient in forest cover
737 increase and in-channel narrowing was found, similar to that shown by Liébault et al. (2005) with a
738 dendrochronological method. In light of these studies, the combination and comparison of such
739 studies between different rivers and along channel gradients is shown to be very valuable for
740 validating and establishing the importance of potential causes.

741 In both France and Italy, it became clearly evident that channel narrowing in some rivers (e.g. the
742 Drôme, Ain, and Ardèche rivers in France, and the rivers in northern Italy and the Volturno river in

743 southern Italy) occurred simultaneously with riparian vegetation encroachment on channel bars and
744 floodplains. Lallias-Tacon et al. (2017) asserted that long-term narrowing of the Bouinenc torrent
745 until 1975 resulted in a well-developed vegetated floodplain that was for the most part composed of
746 mature units. As confirmation, Liébault and Piégay (2002) presented the case of the Doubs River,
747 the channel of which remained stable from 1940 to 1996. The encroachment of riparian vegetation
748 onto the Doubs's floodplain was inhibited by the continuation of land exploitation and intense
749 livestock grazing.

750 In conclusion, controlling factors for channel narrowing between the 1950s and 1970s were referred
751 to overlaps between catchment-scale (depopulation and afforestation) and reach-scale factors
752 (riparian vegetation encroachment). At the reach scale, most intensive floodplain land uses were
753 abandoned (Liébault and Piégay, 2002), with the consequent rapid riparian forest expansion
754 occurring concurrently with the abandonment of agriculture and grazing in riparian zones.

755

756 Focusing in more detail on the rivers of southern Italy (Volturno, Trigno, and Fortore), it appears
757 clear that narrowing between the 1950s and 1970s was more intense (on average between –40% in
758 the Trigno and more than –50% in the Volturno and Fortore rivers, Fig. 4A and 4B) than in the
759 rivers of northern Italy (between about 20% in the Nure and 50% in the Lardana, Fig. 4A and 4B).
760 Channel narrowing was not supported by climate data (which highlighted a relatively wet climate
761 and higher flood frequency until the mid-1970s) (Scorpio et al. 2015), but by human impacts,
762 because as previously stated, southern Italy was impacted by a set of socio-economic
763 transformations between the 1950s and 1970s, transformations that had already occurred several
764 decades before in northern Italy. Narrowing in the south seems to be mainly linked to bedload
765 delivery decline, rather than increased bank resistance following reach afforestation. We may
766 expect that grazing also declined in the floodplain area, and that grass and shrub establishment may
767 have had a resistance effect. This first narrowing step was then exacerbated by local pressures (e.g.

768 gravel mining and the construction of in-channel works) inducing a second narrowing phase after
769 the 1970s–1980s (Figure 11). On the Magra River, Dufour et al. (2015) did not interpret any
770 downstream shift in change in a comparison of two reaches, and concluded that local factors were
771 the primary drivers of the narrowing (encroachment, not afforestation, and mining). They showed a
772 two-step evolution in the downstream reach, similar to that we observed in the Trigno and Fortore,
773 but not in their upstream reach. This fact may potentially allow the separation of local factors
774 (notably mining) from upstream ones, and allow discussion of upstream versus local control.
775 Because upstream and downstream land-use change results from the same drivers, they also have
776 the same chronology, and it is therefore difficult to distinguish the effect of each from the historical
777 data. In the case of France, the Doubs river was interesting in the sense that it showed that
778 narrowing did not occur on a reach that was not afforested, giving credit to a reach-scale
779 afforestation effect on narrowing. However, this observation is in contradiction with the southern
780 Italian cases.

781 Even if controlling factors at the catchment scale evolved similarly in the three rivers in
782 southern Italy (Volturno, Trigno, and Fortore), there were still some differences evident in the land
783 uses spreading in their fluvial corridors. Fluvial corridors were mainly affected by an increase in
784 grassland and grassland with scrubs and trees in the Trigno, and by grassland and agricultural areas
785 in the Fortore, denoting high human pressure (Figure 11). To the contrary, narrowing in the
786 Volturno river occurred with rates that were relatively much higher than those in the Fortore and
787 Trigno (Fig. 4B; Table 6), and together with the encroachment of mature riparian forest, similar to
788 the rivers in northern Italy (post-pioneer vegetation from 46% to 67%, Figure 11). This difference
789 in adjustment may be explained by the differences in vegetation encroachment, afforestation,
790 increasing floodplain resistance, and the induction of slightly more narrowing.

791 The difference between the Volturno and the Trigno and Fortore requires some interpretation. Two
792 factors seem to play noticeable roles. i) Wetter climatic conditions are observed for the Volturno

793 than for the Trigno and Fortore (Aucelli et al., 2007). Dry climates significantly slowed down forest
794 encroachment dynamics along these latter two rivers. No real afforestation occurred, because
795 conditions were too dry compared with the west side of the Apennines, and the dryness may even
796 be exacerbated by climate change as showed. ii) Channel bed lowering over the last decades in the
797 Trigno river was faster and more intense than in the other rivers, especially the Volturno (on
798 average exceeding 3 m). As a consequence, the former channel evolved rapidly into terraces,
799 without turning into floodplains. Differences in elevation did not allow the newly terraced surfaces
800 to be affected by periodic floods able to deposit fine sediments, and therefore soil did not become
801 well-developed, and the sparse riparian vegetation was composed of pioneer species adapted to the
802 marked circumstances of soil aridity. Similar evolutions are described in France for the Bès River
803 (Lallias-Tacon et al., 2017) and the Drome River at Luc-en-Diois (Liébault et al., 2005).
804 Conversely, data for the Volturno river indicate moderate incision that was able to maintain
805 hydrological connectivity between the channel and floodplain system. Current floodplains in the
806 Volturno river are located 1–2 m above the active channel, and present overbank deposits able to
807 preserve wet soil conditions favoring mesophytic woodland (Aucelli et al., 2011).

808

809 **5.4. Are these new ecosystems a proof of renaturation or of human disturbance?**

810 Narrowing was until recently considered to be a result of human disturbance and was interpreted as
811 a problem with the progressive disappearance of braided wide river systems. The perception of this
812 change is strongly discussed, because i) we understand that the 19th and even 18th century
813 conditions cannot be a pristine reference, and ii) the narrowing corresponds to a significant
814 renaturation of the valleys. Lallias-Tacon et al. (2017) analyzed the example of the Bouinenc
815 torrent, and explained that in long-term narrowing rivers, floodplains evolve with well-developed
816 forest composed of mature units. Similarly, high floristic diversity and good development in the
817 zonation of the riparian vegetation were observed in the Volturno river (Aucelli et al., 2011). For

818 this river, any floods able to cause appreciable channel widening and vegetation erosion were
819 recorded in the last decades (Fig. 10). Human disturbances can be considered in terms of incision
820 and floodplain disconnection, disrupting the recovery processes, as indicated earlier.

821 The Trigno River is characterized by being less species-rich, and is especially poor in woody
822 species in the floodplains, and although the herbaceous and pioneer communities in the channels
823 and onto the floodplain show high floristic richness (Aucelli et al., 2011). As described above, the
824 Trigno was affected by many erosion processes related to human pressure and recent flood events
825 that caused bank retreat and vegetation fragmentation. Lower woody species diversity and high
826 floristic richness in pioneer communities can also be considered to be an indication of channel
827 dynamics, as asserted by Dufour et al. (2015), who showed that higher activity rivers present lower
828 landscape diversity due to the domination of bar units with fewer vegetation units.

829 After the 1990s, all rivers widened as a consequence of flood events, except for the Volturno,
830 Borbera, and Sesia rivers, which presented with wider and more developed riparian forest. In most
831 cases, the widening processes after the 1990s do not counteract the 20th century narrowing. The
832 Volturno and Sesia have probably reached a new equilibrium, being less responsive and more
833 resistant to pulse disturbances than what they were during the 19th century.

834 The only exception is represented by the Borbera River, whose channel width and planform
835 morphology have remained almost constant since the 1970s (Figures 3B and 11). For the Borbera,
836 both local factors (land uses in the river corridor, human pressure in terms of the population density
837 near to the channel) and catchments factors controlling channel morphology have not changed over
838 the last few decades (Figure 11). In addition, immediately upstream of the study reach, the Borbera
839 presents confined or partly confined valley setting characteristics, with hillslopes frequently
840 affected by gravitational processes connected to the channel and able to provide a sediment supply,
841 showing that this river is still very responsive and one of the most active of the piedmont region and

842 even the western Alps (Bizzi et al. 2019); an Anthropocene river in a sensitive geological setting
843 exacerbated by human pressures.

844

845

846 **6. Conclusions**

847 This study compared channel evolutionary trajectories in eight rivers situated from the northern to
848 the southern part of Italy, and spanning a range of climatic, physiographic, geometric, and
849 socioeconomic characteristics. A combined diachronous-synchronous approach integrating data
850 from catchment to reach scale over several time periods was used.

851 Although there were some exceptions, most rivers demonstrated narrowing between the 19th
852 century and the end of the 20th century. Channel adjustments were more marked in southern than in
853 northern Italy. Human disturbances, with deforestation and maximization of cultivated lands during
854 the 19th century, rural system transformations, the construction of torrent works, in-channel works,
855 and gravel mining during the 20th century, have driven the channel dynamics. A clear synchronicity
856 between vegetation encroached on the floodplains and channel narrowing was found in the
857 Volturno in southern Italy and the rivers in the Alps and northern Apennines between the 1950s and
858 1970s. Post-pioneer vegetation encroachment did not present the same temporal patterns in all
859 rivers, as it commenced earlier in some rivers (Sesia, Stura di Lanzo, Stura di Demonte, Lardana)
860 than in others (Borbera, Volturno, Nure). Such morphological evolution was also observed in
861 southeastern France, but occurred a bit earlier, with strong similarities with northern Italy and the
862 Apennines. In the Nure River (northern Apennines), an upstream-to-downstream gradient in forest
863 cover increase and in-channel narrowing was observed.

864 This paper raises a question over how natural and in equilibrium with erosive conditions were the
865 channels in the 1950s. In fact, when aerial photos taken in the 1950s are examined, floodplains are
866 seen to be completely anthropized with arable lands and crops, while riparian forests that are known

867 to provide the most ecological benefits were very infrequent. Even the mid-19th century riverscapes
868 were human-driven by higher sediment delivery upstream and low channel resistance due to local
869 pressure, both of which maximized channel responsiveness.

870 This paper supports the idea that reconstruction of the evolutionary trajectory of fluvial systems and
871 their responses to past human and natural variability is a fundamental requirement for the correct
872 management of river corridors and the implementation of restoration projects, and although past
873 conditions will not be repeated exactly the same in the future (Brierley and Fryirs, 2016), it allows
874 assessment of future trends and provides information on their responsivity and sensitivity to
875 changes.

876 The findings of this study strengthen the need to perform analyses at catchment scales and to
877 seriously consider land-use changes both upstream and within valley corridors in the interpretation
878 of channel changes, because they definitely played a role prior to the intense channel mining,
879 damming, and rectification in the 1960s. As the chronology of the depopulation of mountainous
880 areas varies, as well as the river basin sensitivity to changes and vegetation adjustment, it seems
881 that there is a fairly complex mosaic of patterns along the Italian rivers. A potential north–south
882 gradient seems nevertheless accurate, with changes occurring much earlier in the north than in the
883 south, but also slighter changes occurring in the north, because the northern systems were less
884 sensitive to changes, both in terms of activation and deactivation.

885

886

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898

899 **Captions**

900 **Figure 1.** Chronology and intensity of the morphological changes in the Italian rivers. For
901 references see Table 1. Rivers are ordered from north to south.

902 **Figure 2.** Location maps of the studied rivers. Catchment limits and studied reaches in northern
903 Italy: Sesia, Stura di Lanzo, Stura di Demonte, Borbera, and Nure (A); and in southern Italy:
904 Volturno, Trigno, and Fortore (B).

905

906 **Figure 3.** Changes in W^* for all 43 analyzed reaches, all rivers, and all years (A). W^* changes from
907 1952 to 2010s in the Alpine rivers (Sesia, Stura di Lanzo, Stura di Monte, Borbera) and the two
908 tributaries of the Nure river (Lardana and Lavaiana) (B). W^* changes in all reaches of the Nure
909 river from 1877 to 2015 (C). W^* changes in all reaches of the Volturno river from 1885 to 2016
910 (D). W^* changes in all reaches of the Trigno river from 1878 to 2016 (E). W^* changes in all
911 reaches of the Fortore River from 1870 to 2015 (F).

912 **Figure 4.** Channel width variations over the past 170 years in the studied rivers in northern Italy
913 (A) and southern Italy (B), using the channel width variation $\Delta W_{1954}\%$ in respect to the channel

914 width in 1954. ΔW_{1954} % from upstream (reach 1) to downstream in the Nure, Volturno, Trigno, and
915 Fortore rivers (C).

916

917 **Figure 5.** Historical changes in land use trends in the corridors of the 22 reaches.

918

919 **Figure 6.** Land cover changes in the studied reaches between 1954 and the 1970s (A); 1970s and
920 1980s (B); 1980s and 1990s (C); and 1990s and 2010s (D). Negative values in C and D indicate
921 land uses eroded during flood events.

922

923 **Figure 7.** Land use changes between 1929 and 2012 in the Torino Province (Stura di Lanzo basin,
924 represents 13% of the province) (A); Cuneo Province (Stura di Demonte basin represents 21% of
925 the Province) (B); and between 1910 and 2012 in the Molise Region (Volturno, Trigno, and Fortore
926 river catchments represent 23%, 28%, and 7% of the territory of the region respectively) (C).

927

928 **Figure 8.** Evolution of the demographic population density in the studied catchments in northern
929 Italy (A); southern Italy (B); and the mountain catchments of the rivers in northern Italy (C).
930 Comparison of the demographic trends in all the Trigno catchment and the coastal area (D).
931 Evolution of the average demographic population density of the 22 selected reaches in northern
932 Italy (E); and southern Italy (F).

933

934 **Figure 9.** Demographic evolution of livestock in the: Torino province for the Stura di Lanzo basin
935 (catchment represents 13% of the province, A); Cuneo province for the Stura di Demonte basin
936 (catchment represents 21% of the province, B); Piacenza province for the Nure basin (catchment
937 represent 17% of the province, C); and Molise region for the Volturno, Trigno, and Fortore rivers
938 (catchments represent 23%, 28%, and 7% of the territory of the region, respectively, D).

939

940 **Figure 10.** Maximum annual discharge at the Lanzo gauging station and W^* trend in the Stura di
941 Lanzo river (A). Frequency of flood events from the 1910s to 2000s and comparison with W^*
942 within the Volturno river.

943

944 **Figure 11.** Evolutionary trajectories in comparison with the degree and timing of anthropic and
945 natural control factors at reach and catchment scales. key: GM = gravel mining; ICW = in-channel
946 work (groynes, bank protection, levees).

947 **Figure 12.** Shoreline changes in the Trigno and Fortore mouth areas between the 19th to the 1990s.
948 Modified from Aucelli and Roszkopf, 2000 and Scorpio and Roszkopf, 2016.

949

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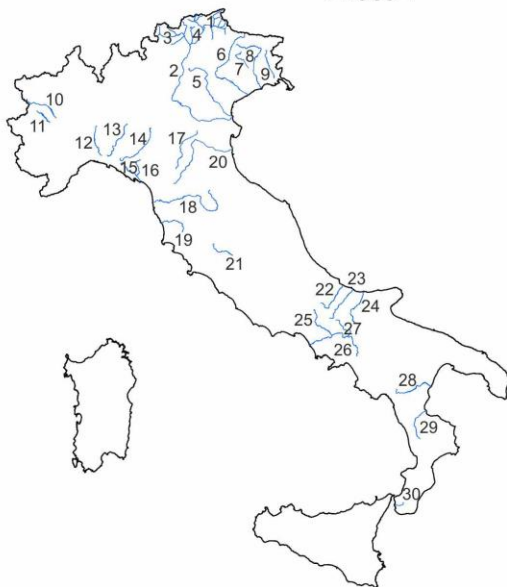
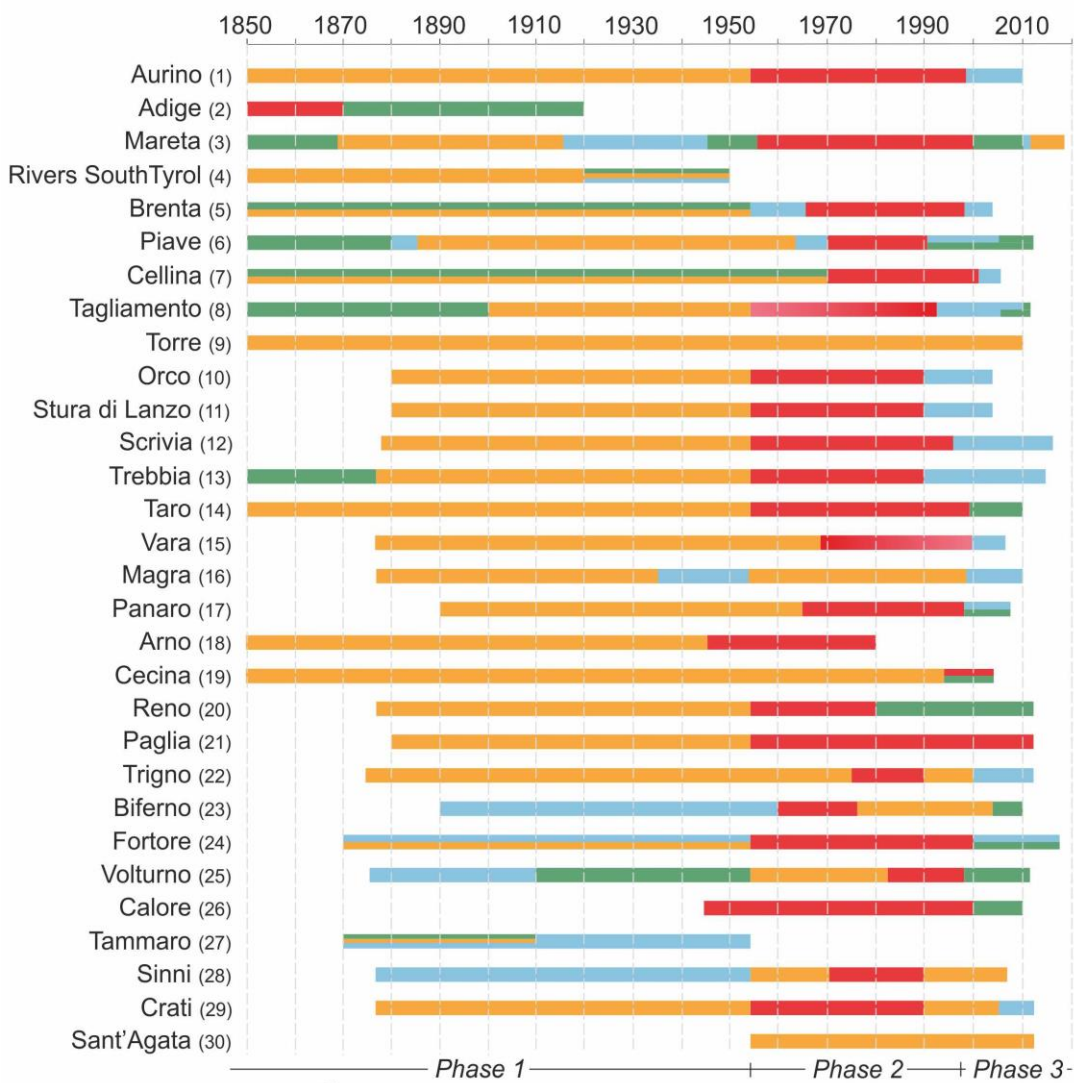
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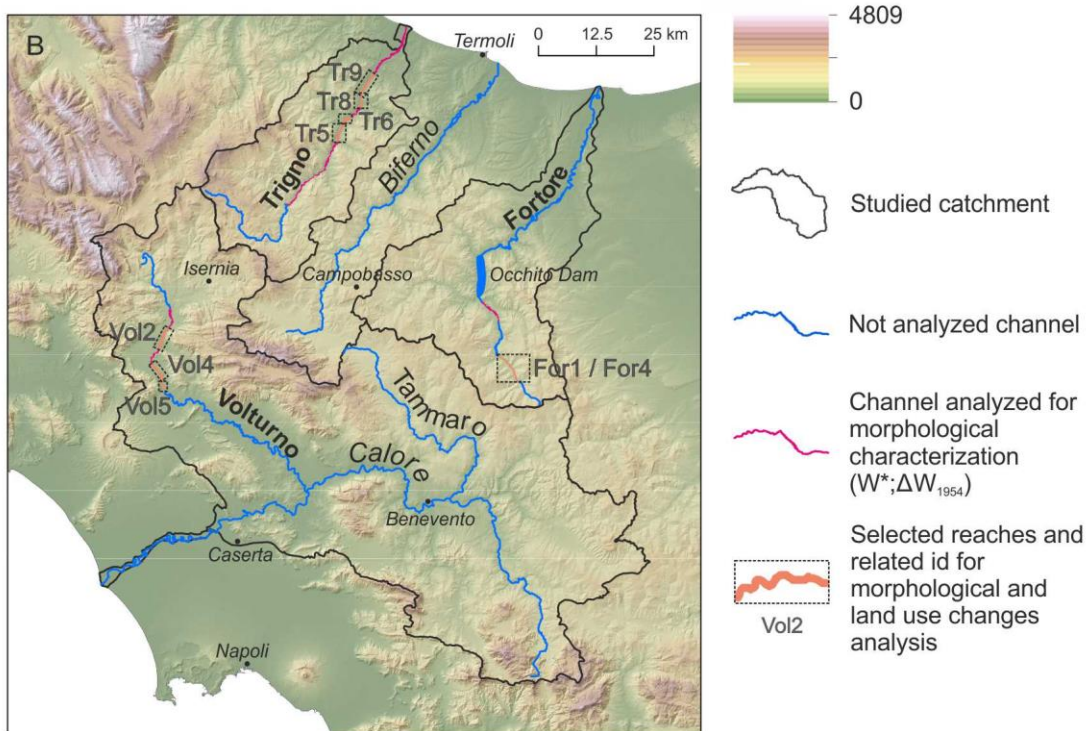
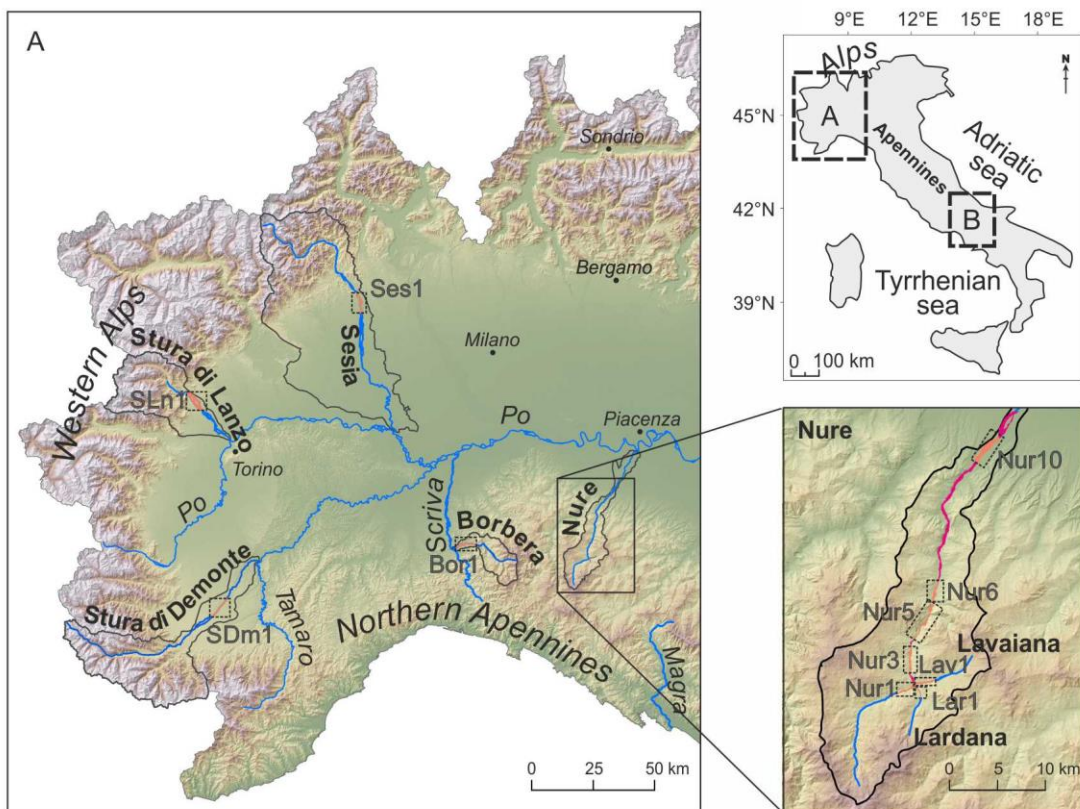
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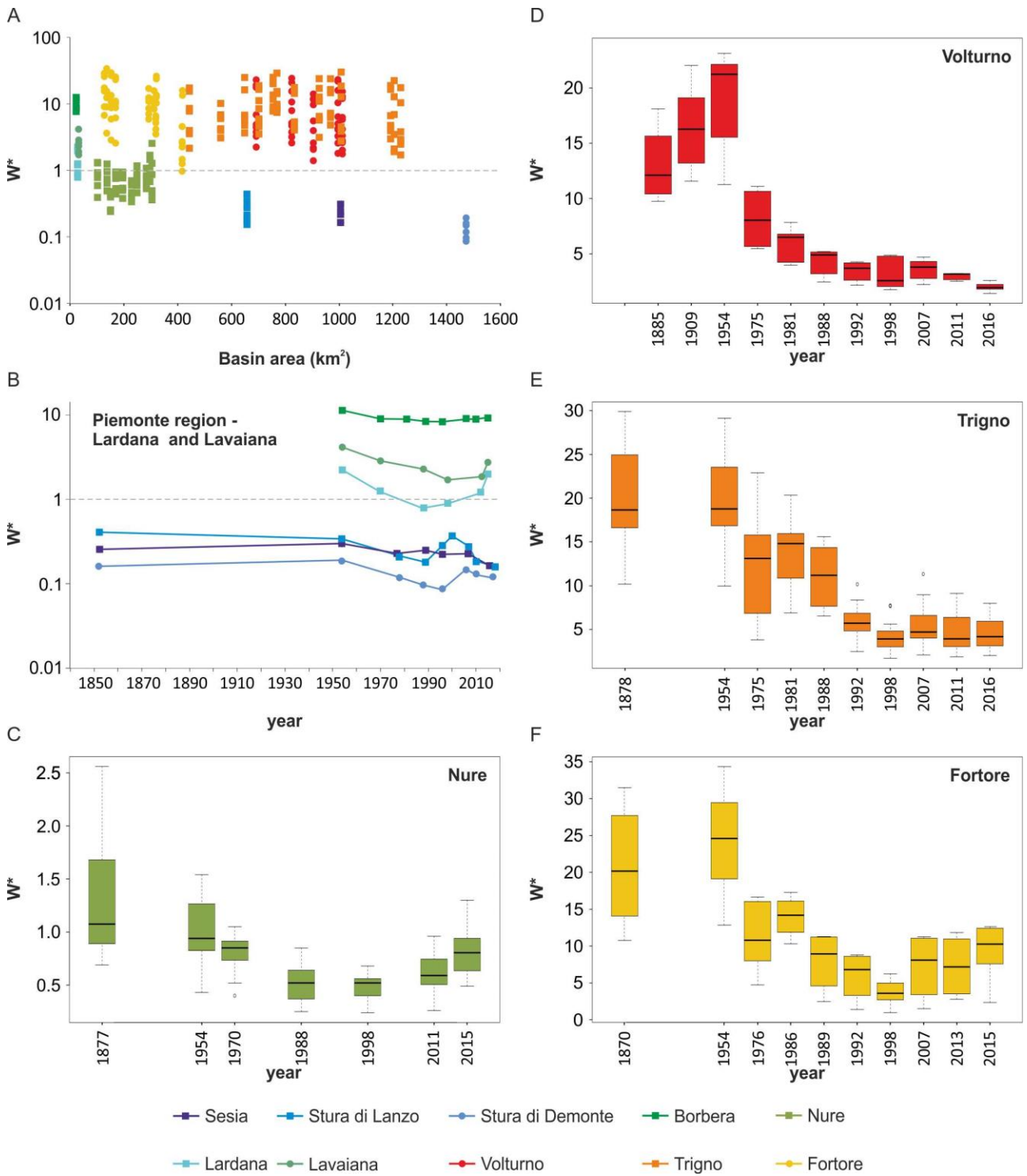


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1190 **Figure 3**



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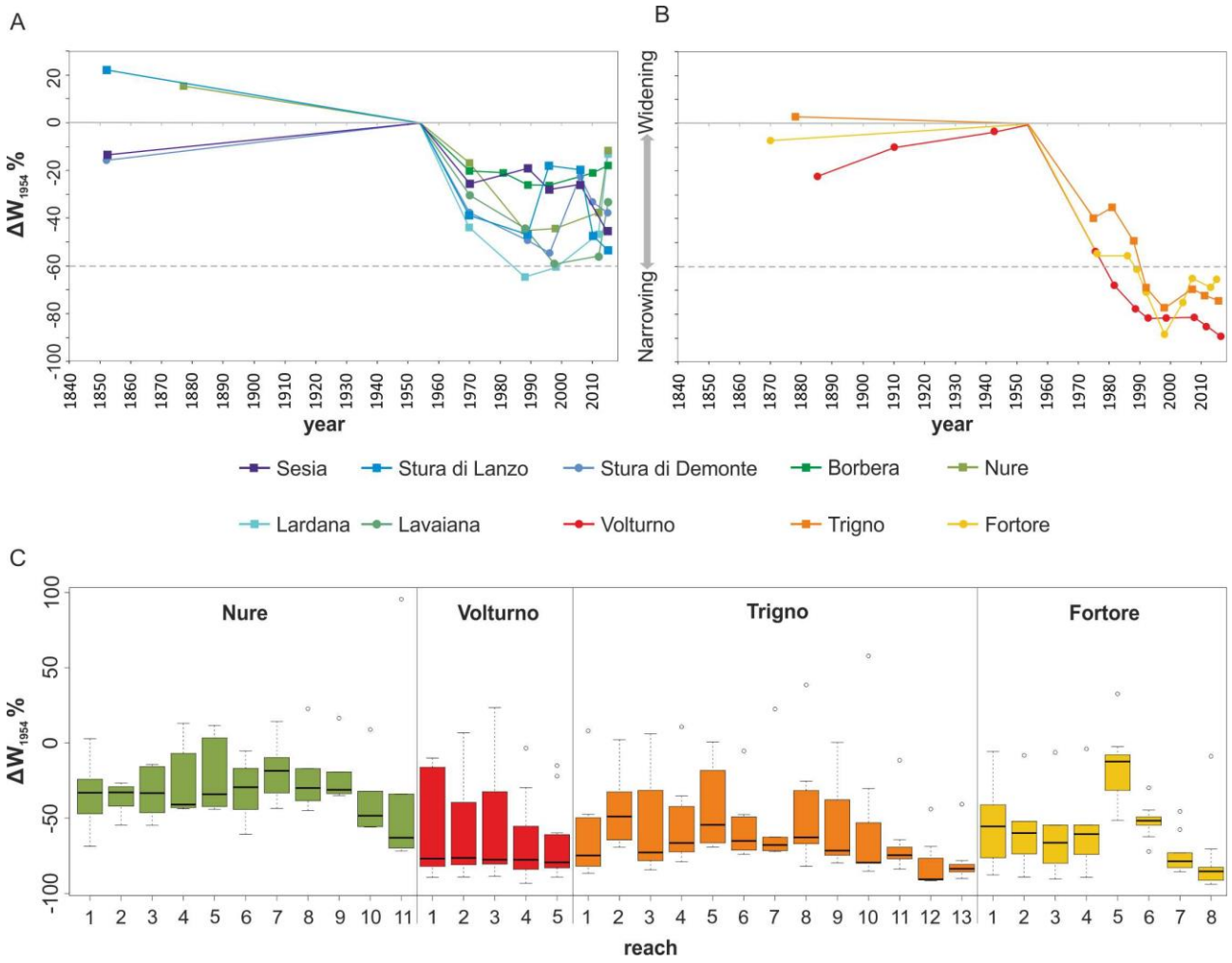
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1196 **Figure 4**



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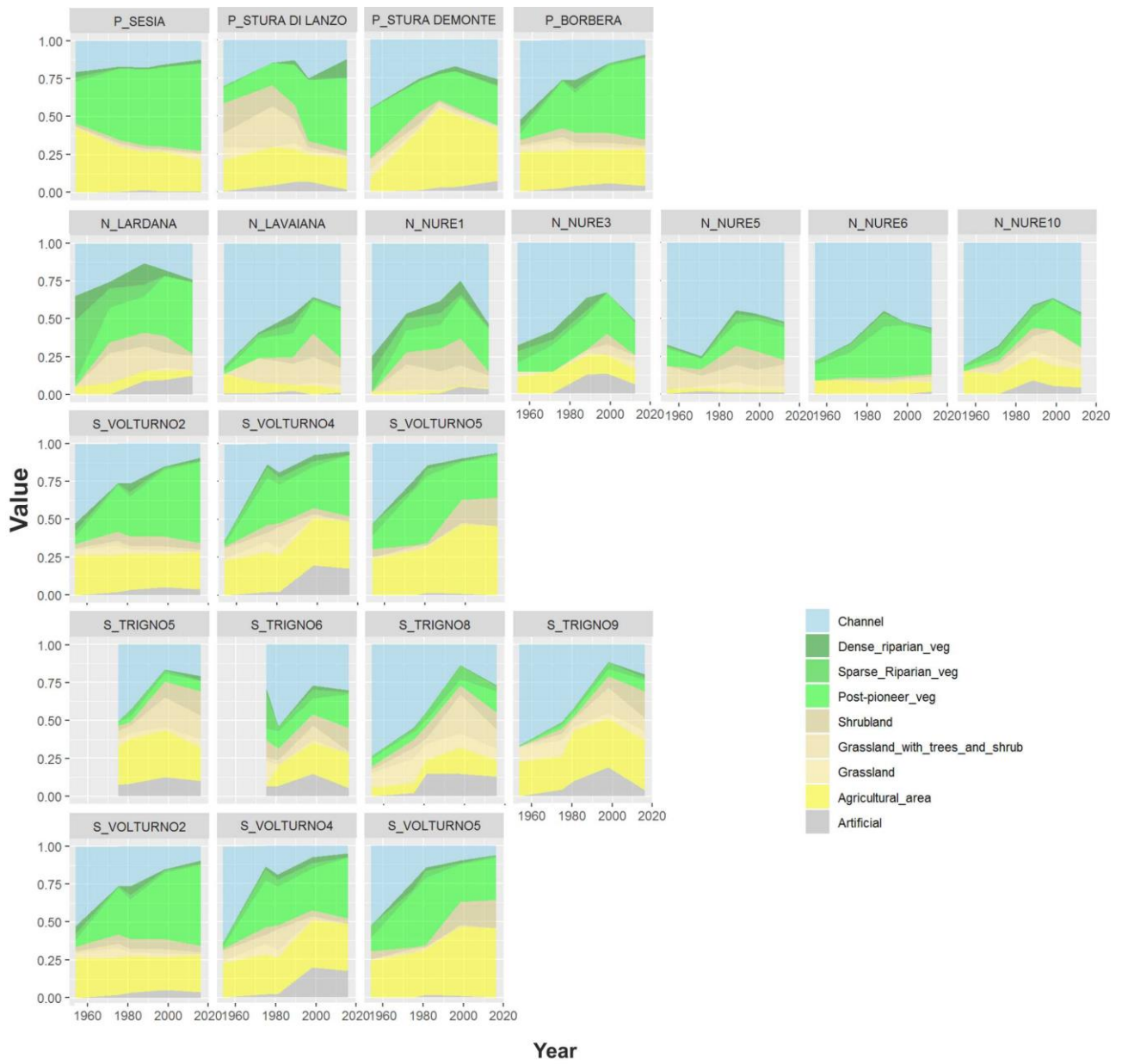
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1208 **Figure 5**



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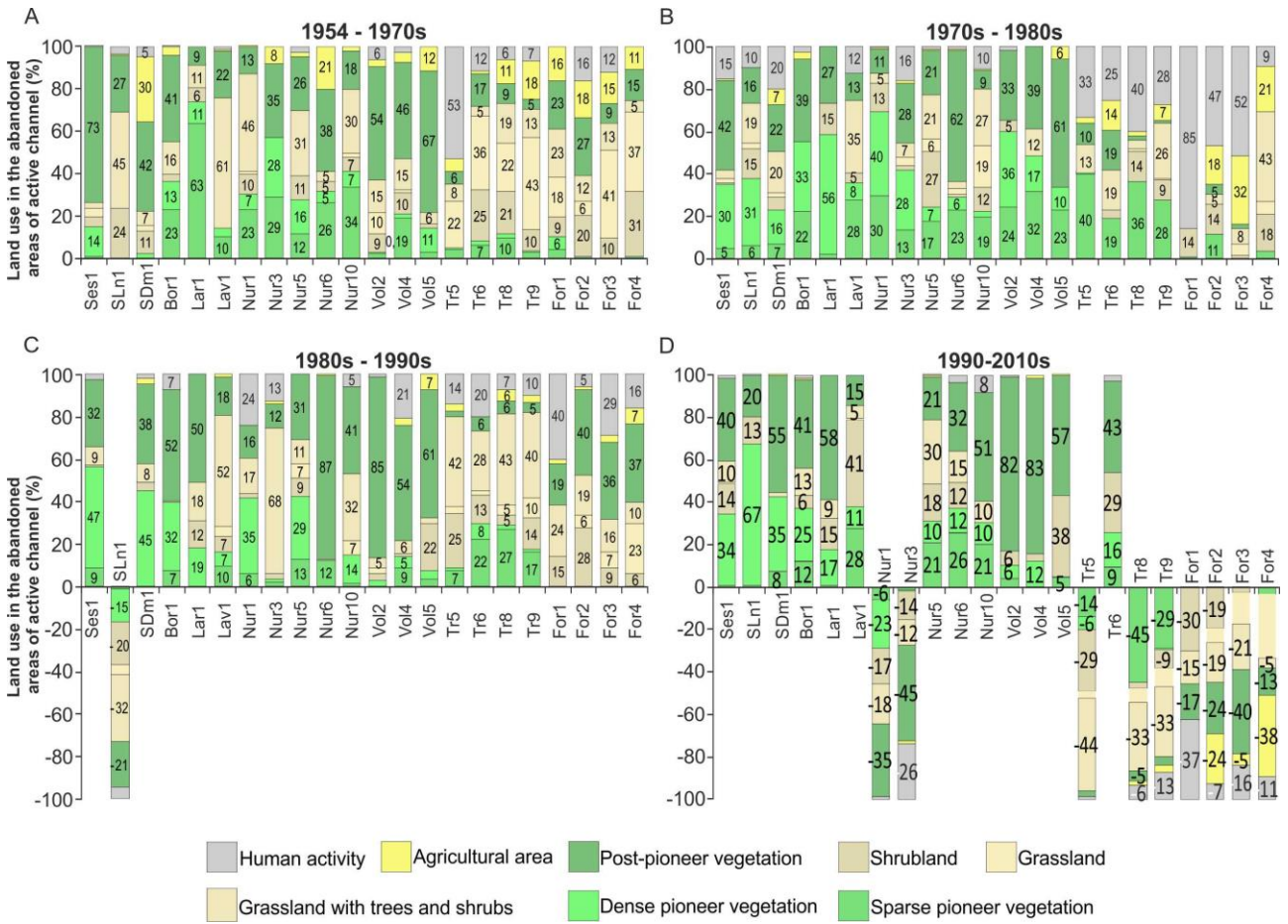
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1217 **Figure 6**



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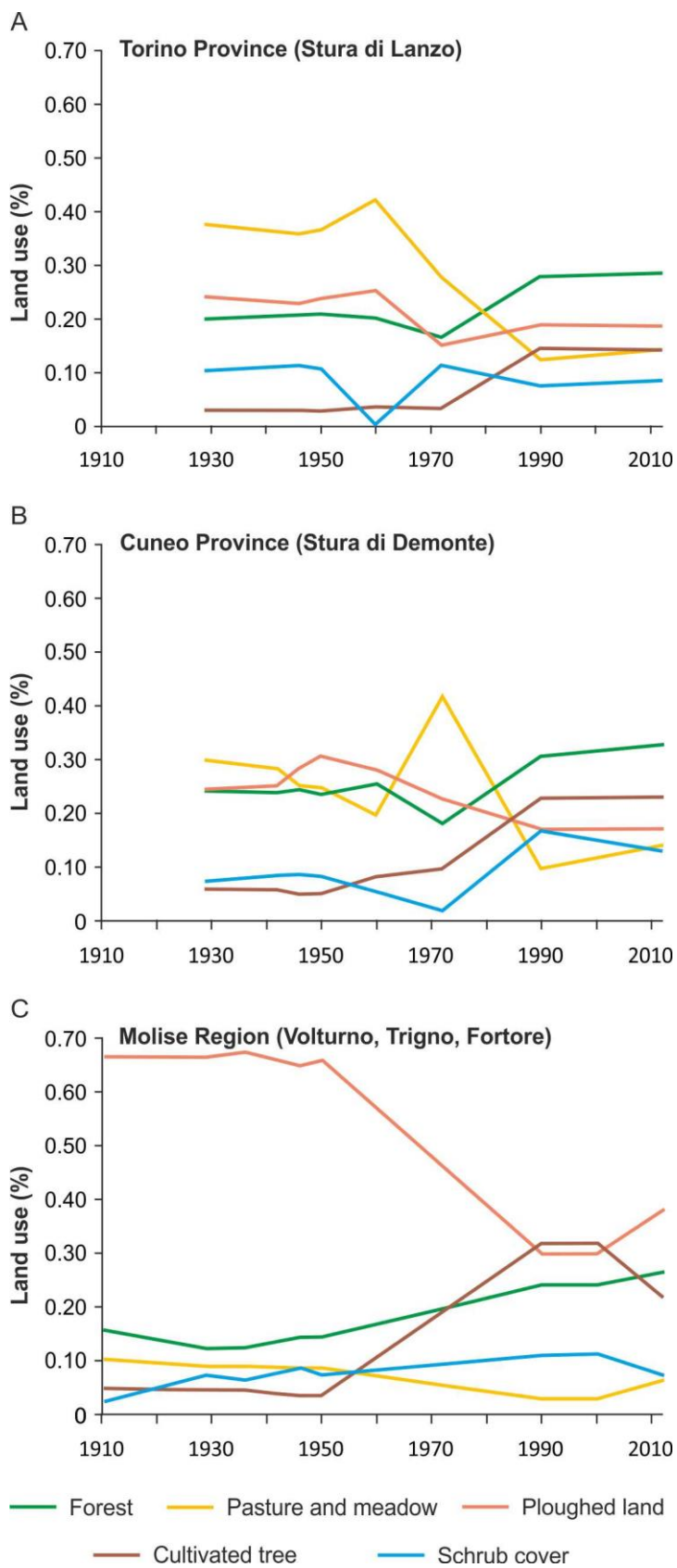
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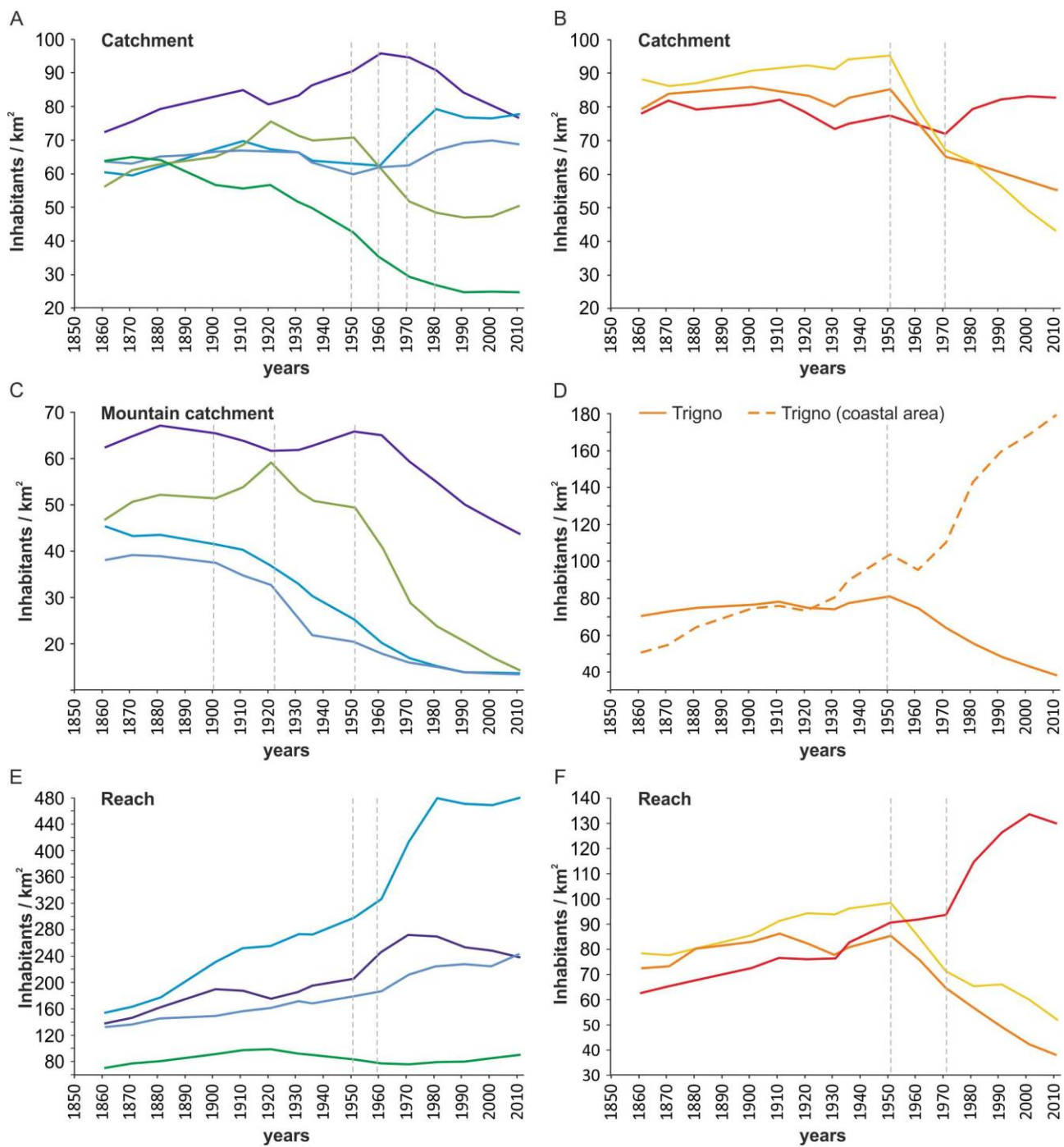
1230 **Figure 7**



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1233 **Figure 8**



1234 — Sesia — Stura di Lanzo — Stura di Demonte — Borbera — Nure — Volturno — Trigno — Fortore

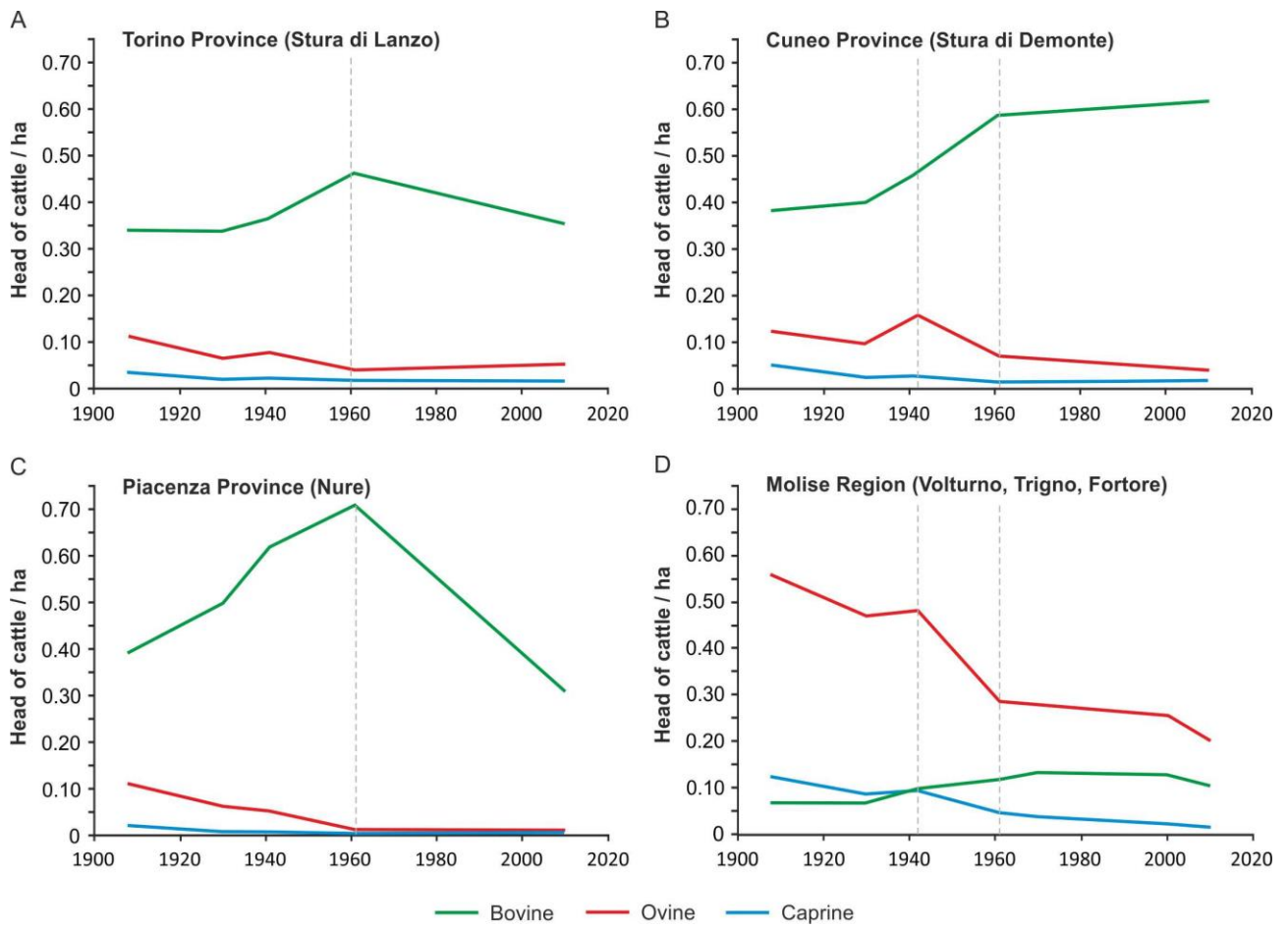
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1239 **Figure 9**



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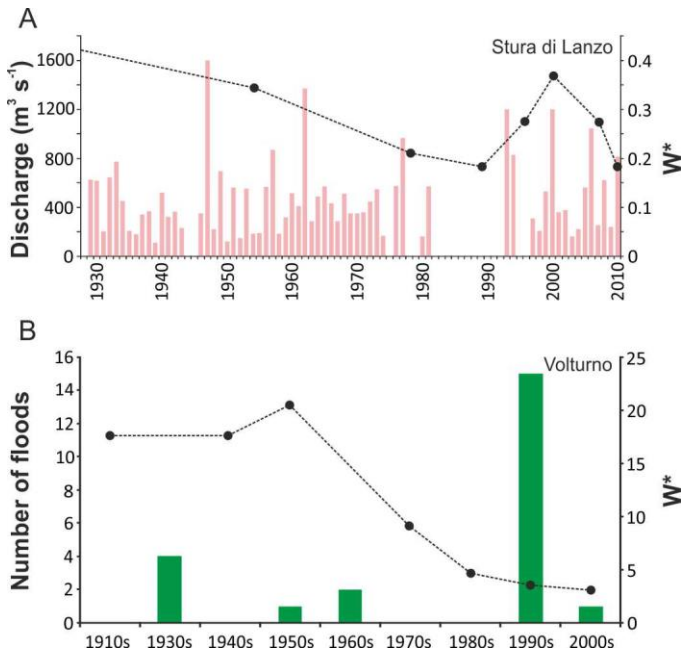
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1252 **Figure 10**



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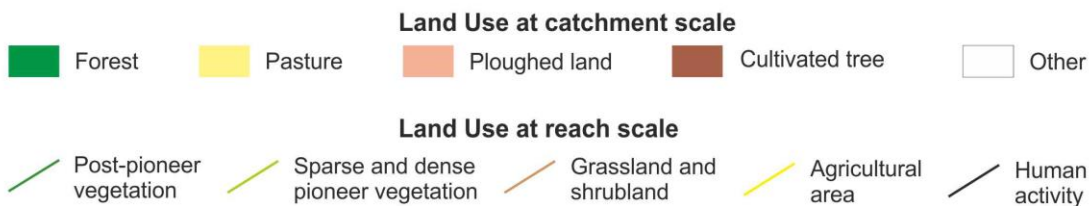
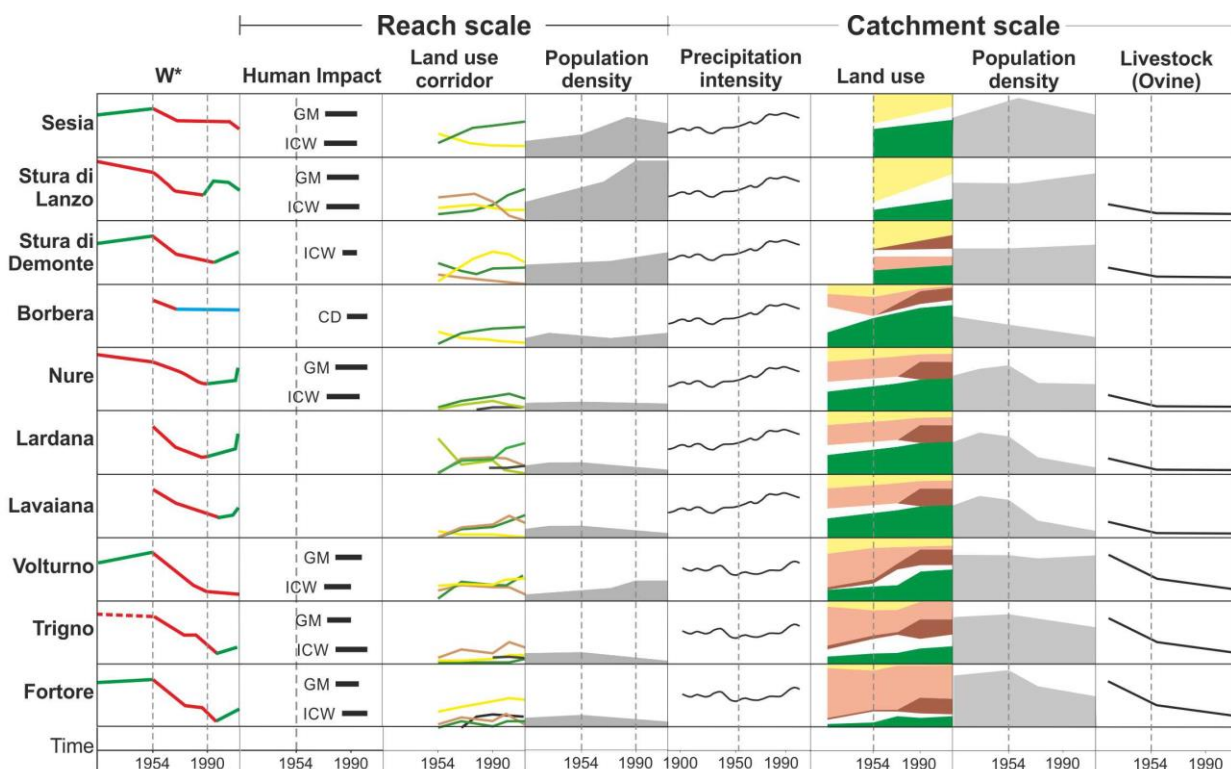
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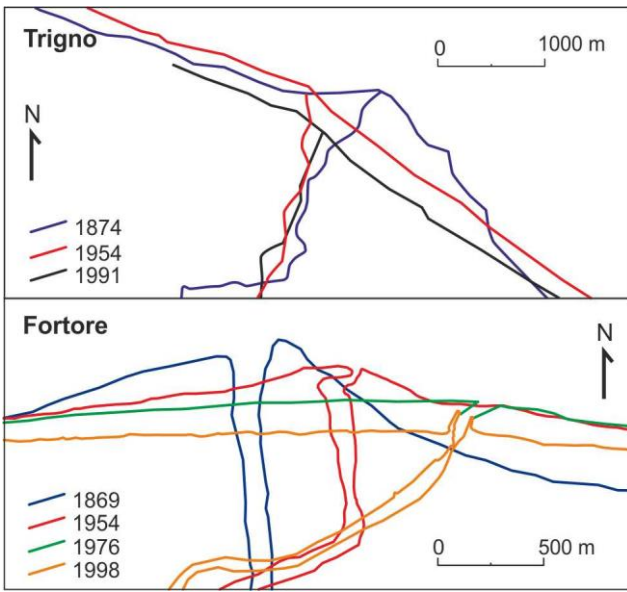
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1281 **Figure 12**



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Literature overview on morphological channel changes and related controlling factors over the last century in Italian rivers

River / ID Fig.1	Period	Channel adjustments	Main Controlling Factors	Effects of Land use changes at catchment and / or reach scale	Reference
Po	Pleistoc. - present	Narrowing	Climatic fluctuations during the Late Pleistocene. Increasing anthropogenic activities, during the Holocene	-	Marchetti, 2002
Ahr/Aurino (1)	1820-2011	1820 - 2003: Narrowing up to 65% Incision 2-4m After restoration in 2003: widening and aggradation	Climatic changes: end Little Ice Age; 1960s - 1980s: gravel mining 1970s: dam and check dam construction 2003: restoration interventions	Qualitative analysis of forest decrease at catchment scale (1850s-1940s)	Campana et al., 2014
Adige/Etsch (2)	1803-1917	Narrowing up to 87%; Incision; Patter simplification	Channelization	-	Scorpio et al., 2018a Scorpio et al., 2018b
Mareta (3)	1805-2017	1850 - 1870s: stability 1870s - 1917: narrowing 1917 -1945: widening 1945- 1954: stability 1954- 1990s: Intense narrowing 1990s- 2009: stability 2009-2011: widening 2011 - 2017: narrowing	1850- 1917: end Little Ice Age; levees construction; corridor management 1917 - 1945: flood events 1945- 1990s: gravel mining; check dam construction 2009: river restoration operation	-	Scorpio et al., in progress
Rivers in South Tyrol region (4)	1850s-1954	1850-1917: narrowing, pattern shifting from multithread/transitional to single-thread. 1917-1950: narrowing, stability or slight tendency toward widening	1850-1917: retreat of glaciers and decrease in sediment supply. 1917-1950: steady glacial cover or glacier advance determining unvaried channel widths or some widening.	Modification of forest cover at catchment scale between 1850 and 1976. Forest cover quite stable: average increase = 6% ; maximum increase = 16%.	Marchese et al., 2017
Brenta (5)	1805-2011	19 th century - 1990s: narrowing (-54% ; - 62%) 1990s -2003: widening (20%) Incision: 5m in the braided reach; up to 7-8m in single-thread reach	Degradation: Dam operation and gravel mining Recovery: suspension of gravel mining	Qualitative information on intense reforestation since the 1950s	Rinaldi et al., 2005 Surian and Cisotto, 2007 Surian et al., 2009a Surian et al., 2009b Moretto et al., 2014
Piave (6)	1805-2006	1900s- 1960s (Phase 1): narrowing 1970s-1990s (Phase 2): narrowing and incision up to 2m 1990s- 2006 (Phase 3): widening and possible aggradation	19 th century: deforestation; end Little Ice Age; Phase1: land use variation at catchment scale; groyne built in the 1940s; dams during 1930s-1950s Phase 2: gravel mining Phase 3: large flood events	Analysis of forests cover at catchment scale. Forest reached minimum extent between the 18 th and the 19 th century. Reforestation on hillslopes: since World War I and especially after the 1950s. * Analysis of vegetation cover type evolution and structure in the river corridor of studied sub-reaches	Surian et al., 1999 Surian et al., 2009a Surian et al., 2009b * Comiti et al., 2011 * Picco et al., 2017
Cellina (7)	1805 - 2002	19 th century - 1970s: stability 1970s- 1990s: narrowing (-54%) Since 2000s: widening (+ 5%)	Dam operation and gravel mining (since 1970s) Widening: after large floods	-	Surian et al., 2009a Surian et al., 2009b
Tagliamento (8)	1805-2012	1805- 1890s (Phase 1): stability/slight narrowing 1890s -1950s (Phase 1): narrowing (- 33%) 1950s-1990s (Phase 2): narrowing (- 56%) 1990s-2012 (Phase 3): widening and slight aggradation (0.2 m) Incision 0.5-3m (especially phase 2)	Phase 1: groyne, afforestation Phase 2: gravel mining; bank protections Phase 3: decrease of mining activity and bank protection	Modification at catchment scale over the last 180 years. Increase of forest cover from 21% in 1828 to 72% in 2006. * In the corridor area vegetation is mapped in 3 categories: herbaceous vegetation and low shrubs/trees; high shrubs and trees of low-medium height and tall trees	Rinaldi et al., 2005 Surian et al., 2009a Surian et al., 2009b Ziliani and Surian, 2012 * Surian et al., 2015
Torre (9)	1805-2000s	19 th century - 2000s: Narrowing (-76%) ; incision (- 3m)	1920s - 1930s: torrent control works 1950s - 1970s: gravel mining	-	Surian et al., 2009a Surian et al., 2009b
Main rivers in Piemonte region	Last decades	Narrowing -50%; Incision exceeding 1m	-	-	Bizzi et al., 2018

Orco (10)	1881-2000s	1881- 1950s (Phase 1): narrowing (-33%) 1950s- 1990s (Phase 2): narrowing (-44%) 1990s-2000s (Phase 3): widening (+133%) Incision, especially 1961-1975 (1-2 m on average; 3-4 m max)	Phase 1: management of corridors; use of secondary channels for irrigation; construction of road infrastructures. Phase 2: gravel mining; channel works Phase 3: large floods	-	Pellegrini et al., 2008 Turitto et al., 2008 Surian et al., 2009a
Stura di Lanzo (11)	1881-2000s	1881- 1950s (Phase 1): slight narrowing (-36%) 1950s-1990s (Phase 2): narrowing (-68%) 1990s - 2000s (Phase 3): widening (+98%) 1936-1975: incision 2-5m	Phase 1: management of corridors; use of secondary channels for irrigation; construction of road infrastructures. Phase 2: gravel mining; channel works Phase 3: large floods	-	Pellegrini et al., 2008 Surian et al., 2009a
Scrvia (12)	1878-2017	1878 - 1950s (Phase 1): avulsions, lateral migration 1950s -1990s (Phase 2): narrowing or channel banks stability 1990s - 2016 (Phase 3): slight widening, reactivation of bank-erosion processes.	Phase 1: river corridor management; natural processes; groynes construction and partial bank-stabilization in the last part of the first period. Phase 2: sediment mining and channelization Phase 3: floods	* In the historical migration zone, analysis of land use modification between 1954 to 2017, mapping of: active channel, semi-natural areas (woodlands, shrubs, herbaceous vegetation), agricultural and artificial areas.	Mandarino et al., 2019a * Mandarino et al., 2019b
Trebbia (13)	1880-2014	1880-1954 (Phase 1): narrowing (-19%) 1954-2000s (Phase 2): narrowing (-58%) and incision (1-2m) 2000s-2014 (Phase 3): partial recovery of channel morphology; widening (+15%)	Phase 1: land use changes at the catchment scale, bank protection; artificial levees; end Little Ice age Phase 2: sediment mining Phase 3: reduction in sediment removal	Modification of land cover at catchment scale (between 1885 and 2006). Increase of forest cover from 22% to 51%; decrease of meadow from 59% to 6%.	Pellegrini et al., 2008 Surian et al., 2009a Bollati et al., 2014
Taro (14)	1828-2011	Channel narrowing up to -75%; incision; decrease of braiding (- 43%), increase in channel length (13%) and sinuosity (29%); while in the last years morphological stability with possible slight narrowing.	Construction of 10 bridges and bank protections. Subtraction of riverbed areas for agricultural and industrial purposes. 1950s - 1980s: gravel mining	Before 1828: deforestation and agriculture expansion.	Clerici et al., 2015
Rivers in Tuscany	1954 - 1998	Average narrowing 50%; maximum narrowing (-75%) Incision between 2 and 9m (especially between 1945 -1980)	19th century - 20th century: reforestation at catchment scale 1950s - 1998: sediment mining; dam construction	Reforestation of large upland areas favored by a series of land management laws, for stabilization of slopes, and by the construction of a large number of weirs along mountain streams (more than 2700 weirs were built in the Arno River basin).	Rinaldi, 2003
Vara (15)	1877-2006	1877-1950s/1971 (Phase 1): narrowing (-62% - 68%) 1950s/1971- 1995 (Phase 2): narrowing (-32%-38%) 1995 - 2006 (Phase 3): widening (+2; +7%) Incision between 2 and 4 m	Phase 1: construction of check-dams along tributaries, and construction of groynes Phase 2: sediment mining Phase 3: intense floods	-	Rinaldi et al., 2005 Rinaldi et al., 2008 Rinaldi et al., 2009 Surian et al., 2009a
Magra (16)	1877-2010	1877- 1937 (Phase 1): narrowing 1937-1954 (Phase 1): widening (+5%; +10%) 1954 - 1995 (Phase 2): narrowing (-53%; - 58%) 1999- 2010 (Phase 3): widening (+2; +13%) Incision between 5 and 8m	Phase 1: construction of check-dams along tributaries, and construction of groynes (widening between 1937 and 1954 related to some large floods). Phase 2: sediment mining Phase 3: intense floods	*Analysis of the current vegetation and analysis of effects on channels dynamic of land cover changes in the historical corridor. Trends of 6 classes: active channel, pioneer vegetation, shrub, woodland, meadow and arable land, and human activity.	Rinaldi et al., 2008 Rinaldi et al., 2009 Surian et al., 2009a Nardi and Rinaldi, 2015 * Dufour et al., 2015
Panaro (17)	1890-2007	1890-1969 (Phase 1): narrowing (-41%; -68%) 1969- 1997/2007 (Phase 2): narrowing (-31%;-59%) 1997 - 2007 (Phase 3): narrowing/stability Incision: 4-10m	Phase 1: levees; afforestation at catchment scale; torrent control works Phase 2: check dams; sediment mining;	-	Rinaldi et al., 2008 Surian et al., 2009a
Arno (18)	1954-1980s	1844 - 1945 (Phase 1): incision between 0.5 and 2m 1945 - 1980s (Phase 2): incision between 1 and 3m.	Phase 1: land cover changes at basin scale, afforestation; construction of weirs along tributaries. Phase 2: dam construction, sediment mining	-	Rinaldi and Simon, 1998 Rinaldi et al., 2005
Cecina (19)	1883 - 2004	1883- 1994: narrowing (-81%--89%) 1994 - 2004: narrowing or stability Incision: 1-3m	-	-	Rinaldi et al., 2008 Surian et al., 2009a
Reno (20)	1860-2003	End 19 th - 1950s (Phase 1): narrowing 1950s-1970s (Phase 2): narrowing; incision 1970s -2012: no evidence of relevant changes Total narrowing 75-85%	Phase 1: reforestation; check dams; reservoir construction on some tributaries. Phase 2: gravel mining; reforestation; check dams. Most of the torrent control works consist of check dams	Land use modification at catchment scale in 1830, 1959, 2000. Four classes: crops, and agricultural surface; pastures and grasslands; forested areas; urban areas	Preciso et al, 2012

		Incision 1 and 8m	that were constructed mainly from the 1950s to the 1970s.	The reduction of sediment supply from the headwater is ascribed to: land use changes, cropland abandonment, natural and artificial reforestation, soil erosion-control measures on slopes.	
Paglia (21)	1883- 2013	1883- 1954 (Phase 1): narrowing 64% 1954 - 2012 (Phase 2): narrowing 70% Incision: 5 order of terraces in the 130 years	Gravel mining	-	Colica et al., 2018
Trigno (22)	1875- 2011	1875 - 1950s (Phase 1): narrowing (up to 30%) 1950s - 2007 (Phase 2): narrowing (-75%; -85%) 2007 - 2011 (Phase 3): widening (up to +15%) Incision: 3- 9m increasing downstream bridges and check dams	Phase 1: deforestation at catchment scale; end of Little Ice Age. Phase 2: gravel mining; groyne Phase 3: flood events; cessation of sediment removal	Analysis of land use changes at catchment scale in 1836/1850, 1950, 2000, 2006. Deforestation took place between 1836/1850 and 1929. Forest expansion occurred after 1929, due to natural reforestation; especially starting from the 1950s onwards reforestation due to agricultural abandonment and displacement of agricultural activities to valley bottoms and alluvial coastal plains. * In the studied reach analysis of the modification of the land use in the abandoned portion of the channel active in 1954, considering six land cover types: roads and mine sites; agricultural areas; broad-leaved forest; shrub and herbaceous vegetation; open spaces with little or no vegetation; river channels. Analysis of current floristic pattern in the recent terraces, floodplain and channel banks.	Aucelli and Roskopf, 2000 * Aucelli et al., 2011 Scorpio et al., 2015 Scorpio et al., 2016a
Biferno (23)		1869 - 1950s (Phase 1): widening (up +33%) 1950s - 1998 (Phase 2): narrowing (up to -96%) 1998- 2011 (Phase 3): stability Incision: 3.5m especially between 1950s and 1980s.	Phase 1: land cover modification at catchment scale; end of Little Ice Age. Phase 2: gravel mining; dam closure in 1977; bank protections Phase 3: cessation of sediment removal	Same analysis than as for the Trigno River	* Aucelli et al., 2011 Roskopf and Scorpio, 2013 Scorpio et al., 2015
Fortore (24)	1869- 2015	1869-1950s (Phase 1): widening prevailed in the reaches upstream reaches the dam and narrowing in those downstream. 1950s - 1990s (Phase 2): narrowing of up to 81% in upstream reaches the dam and 98% in downstream reaches. Incision from 1 to 5m 2000 - 2015 (Phase 3): widening and aggradation in the reaches upstream the dam and stabilization those downstream.	Phase 1: Deforestation and climate amelioration at the end of the LIA. Phase 2: gravel mining, channel works, the closure of the Occhito dam in 1966. Phase 3: large flood upstream the dam	Analysis of land cover changes at catchment scale (1800s, 1954, 1992, 2012). From 1800s to 1929 deforestation. Differences in deforestation in the upstream and downstream sectors of the catchment, caused different influences on the channel trends in the upper and lower sectors of the river. From 1929 to 1990, moderate reforestation, accompanied by a decline of cropland especially between 1929 and 1971.	Scorpio and Roskopf, 2016
Volturno (25)	1875- 2011	1875 - 1950s (Phase 1): widening (up to +40%) 1950s - 1998 (Phase 2): narrowing (up to -89%) 1998- 2011 (Phase 3): stability Incision between 2 and 3m	Phase 1: land cover changes at catchment scale; torrent work; end of the LIA. Phase 2: bank protections, groyne, gravel mining. Phase 3: cessation of sediment removal and bank protection construction	Same analysis than as for the Trigno River	* Aucelli et al., 2011 Scorpio et al., 2015 Scorpio et al., 2016a
Calore (26)	1954- 1998	1950s - 2004: average narrowing -66%, maximum narrowing - 86% Incision up to 4m Pattern morphology shifting from transitional to single-thread	Damming and channelization in the main tributaries; reduction of discharges due to water withdrawals and sediment mining from the riverbed	-	Magliulo et al., 2013 Scorpio et al., 2016a
Tammaro (27)	1870- 1955	1870 - 1909: any common trends; slight prevalence of widening. Any changes in planform morphology mainly single thread. 1909 - 1955: homogeneous widening and changes from a single thread to transitional patterns	1870 - 1909: unmechanized agriculture coupled with a strong emigration which drastically decreased the population density. 1909 - 1955: climate variability, ploughing, increase of population density. Increase of mechanization techniques in agricultural practice and inducing increase of soil erosion. Human activities such as sediment mining, channelization, are not documented.	Analysis at catchment scale (Benevento province scale): In 1920s: 65 % of territory consisted of arable lands, 15 % of forests, 10 % of permanent crops (mainly olive groves and fruit trees), and 10 % of pastures and open spaces with little or no vegetation. In 1951, arable lands composed more than 73 % of the territory.	Magliulo et al, 2016
Sinni	1877-	1877 - 1950s (Phase 1): widening (+12%)	Phase 1: land cover modification at catchment scale; end	Analysis of land use changes at catchment scale in	Cencetti and Fredduzzi, 2008

(28)	2006	1950s - 1998 (Phase 2): narrowing (-58%; -79%) 1998 - 2006 (Phase 3): narrowing (-60%; -87%) Incision -2; -4.5 m increasing downstream check-dams and dams	of Little Ice Age. Phase 2: gravel mining; dam closure and check dam construction Phase 3: sediment deficit downstream dams and check dams	between 1850 and 2006. Deforestation took place between 1850 and 1929, while forest expansion occurred starting from 1929.	Scorpio et al. 2015
Crati (29)	1877- 2012	1877- 1950s (Phase 1): narrowing 1950s - 2006 (Phase 2): narrowing (-78%; -87%) 2006 - 2012 (Phase 3): widening Incision -3m	Phase 1: deforestation at catchment scale; end of Little Ice Age; channel works Phase 2: bank protections; gravel mining Phase 3: flood event	-	Scorpio et al. 2015
Fiumara Sant'Agata (30)	1955- 2012	Narrowing 48% Incision between 1.3 m and 2.1 m; aggradation upstream check dams	Land cover changes; check dams construction	Land-use modification at catchment scale between 1955 and 2012. Forested areas, shrublands and agricultural areas increased by 43%, 25% and 12.5%, respectively. Open spaces areas and pasture lands decreased by 70% and 84%.	Fortugno et al., 2017

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1302 Numbers in the "river/ ID Fig.1" column, refer to rivers represented in Fig. 1. The asterisk symbol (*), in the column "Effects of Land use changes
1303 at catchment and /or reach scale", and bolded references indicates papers that analyzed land cover vegetation changes in the river corridor in relation
1304 with channel adjustments.

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1310 **Table 2**

1311 Main physiographic characteristics of the studied rivers

Main characteristics	Sesia	Stura di Lanzo	Sura de Monte	Borbera	Nure	Volturno	Trigno	Fortore
Location	Western Alps	Western Alps	Western Alps	Northern Apennines	Northern Apennines	Southern Apennines	Sothern Apennines	Southern Apennines
Drainage area (km ²)	3038	928	1472	212	430	5550	1200	1614
Max/ Min basin elevation (m)	4464 / 96	3676 / 205	3268 / 194	1711 / 43	1773 / x	2175/0	1735/0	1128 / 0
Main substrate rocks	Met and Int	Met	Met and Sed	Sed	Sed	Sed	Sed	Sed
Channel length (km)	140	80	115	38	75	175	85	110
Mean annual precipitation (mm)	1013	792	704	556	1150	1300	550	700
Mean annual discharge (m ³ /s)	70	26	47	6.4	15	82.1	12.6	13.5

1312 Legend for main substrate rocks codes: metamorphic (Met); intrusive igneous (Int); sedimentary
1313 (Sed)

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1332 **Table 3**

1333 Morphological characteristics of the selected 22 reaches

	Reach	River	Length (km)	Max elevation (m)	Min elevation (m)	Slope m/m	Pattern / average width (m) in 1954	Pattern / average width (m) in 2010s	
Alps	Ses1	Sesia	5	259	235	0.005	W / 308	SAB / 167	
	SLn1	Stura di Lanzo	7	417	346	0.010	W / 224	W / 104	
	SDm1	Stura di Demonte	6.4	358	348	0.002	B / 282	W / 175	
Northern Apennines	Bor1	Borbera	6.4	319	248	0.011	B / 238	B / 196	
	Lar1	Lardana	1.6	540	498	0.025	W / 62	W / 54	
	Lav1	Lavaiana	2.3	547	498	0.021	B / 129	B / 86	
	Nur1	Nure	2.4	536	467	0.028	W / 127	W / 131	
	Nur3	Nure	2.8	473	446	0.010	B / 156	W / 134	
	Nur5	Nure	4.9	420	373	0.010	W / 135	W / 139	
	Nur6	Nure	2.3	373	349	0.010	B / 182	W / 151	
	Nur10	Nure	3.9	187	155	0.008	B / 454	B / 235	
	Southern Apennines	Vol2	Volturno	6.2	200	175	0.004	B / 325	SAB / 35
		Vol4	Volturno	4.3	154	138	0.004	B / 366	SAB / 25
Vol5		Volturno	3.7	138	130	0.002	SAB / 248	S / 27	
Tr5		Trigno	4.3	178	142	0.008	B / 353	W / 114	
Tr6		Trigno	2.5	142	117	0.010	B / 415	W / 108	
Tr8		Trigno	2.8	105	86	0.007	B / 268	SAB / 90	
Tr9		Trigno	5.4	86	54	0.006	B / 372	SAB / 105	
For1		Fortore	1.1	390	377	0.012	B / 204	SAB / 66	
For2		Fortore	2.4	377	353	0.010	B / 243	W / 90	
For3		Fortore	2.3	353	333	0.009	B / 220	SAB / 67	
For4	Fortore	3.1	333	308	0.008	B / 188	SAB / 85		

1334 Legend for pattern codes: braided (B); wandering (W); sinuous with alternate bars (SAB); sinuous
1335 (S).

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Table 4

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Human impacts and period of construction/activity in the selected catchments (upstream the studied reaches) and reaches.

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River	Catchment scale				Reach scale							
	Alteration of longitudinal continuity		Alteration of lateral continuity	Mining GM	Reach	Human impacts in the reach Period and frequency/location						
	TW	D - CD	ICW									
Sesia		CD			Ses1	ICW (since 1970s, 10 - 20%) GM (since 1970s, FP)						
Stura di Lanzo		CD			SLn1	ICW (since mid 1970s, 14 ÷ 25%) GM (since mid 1970s, FP)						
Stura di Demonte		CD			SDm1	ICW (mid- 1980s, 14%)						
Borbera	Since 1960s	CD (1960s)	-	Mid-1980s	Bor1	CD (since late 1980s)						
Northern Apennines	Nure	Since 1977	CD (Since 1977)	Mid 1800 - 1990s	1980s - 1990s	Lar1	-					
						Lav1	-					
						Nur1	ICW (1980s, < 5%)					
						Nur3	GM (1980s - 1990s, FP)					
						Nur5	ICW (since 1950s, < 5%)					
						Nur6	ICW (1970s, 20%)					
						Nur10	ICW (since 1950s, 20 ÷ 50%) GM (1980s - 1990s)					
						Vol2	ICM (1970s - 1990s, 13 ÷ 30%) GM (1980s - 1990s, FP/C)					
						Vol4	ICM (since 1970s, 30%)					
						Vol5	ICM (since 1970s, 37%)					
Southern Apennines	Trigno	1950s - 1970s	D (1997)	1960s - 1990s	1960s - 2000s	Tr5	ICM (since mid - 1980s, 85%) GM (mid 1970s - 2000s, FP)					
						Tr6	ICW (1980s, 14%)					
						Tr8	ICW (1980s, 35%) GM (1980s, FP)					
						Tr9	ICW (1980s, 50%) GM (1980s, FP and C)					
						For1	GM (1980s)					
						For2	ICW (1970s-1980s, 15 ÷ 30%) GM (1980s, FP/C)					
						For3	ICW (mid 1980s-early 1990s, 60%) GM (mid- 1980s)					
						For4	GM (late 1980s - 1990s)					
						Fortore	1950s - 1990s	CD (1970s-1990s)	1960- 1990s	1970s - 1980s		

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codes: TW = Torrent control work; D = dam; CD= check dam; ICW= in-channel work (groynes, bank protection, levee); GM = gravel mining. FP = floodplain; C = channel. In column "Human impacts in the reach", the symbol % indicates the percentage of banks stabilized by bank protections.

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Table 5

Characteristics of materials used for studying channel evolution and land cover changes at catchment and reach scales.

Area	River /Catchment	Year	Type	Scale	Source	Analysis
Piemonte Region - Northern Italy	Ses; StdiLan; StDem	1852	HM	1: 50,000	Piemonte Region	CW
	all reaches	1954	AP	1: 25,000	IGM	CW; RLU
	all catchments	1960	Shp	-	Piemonte Region	BLC
	StDem; Borb	1970	AP	1: 25,000	Piemonte Region	CW; RLU
	Ses	1977	AP	1: 13,000	Piemonte Region	CW; RLU
	StdiLan	1978	AP	1: 13,000	Piemonte Region	CW; RLU
	StDem; Borb	1981	AP	1: 25,000	Piemonte Region	CW
	StdiLan	1988	O	-	Ministero Ambiente	CW; RLU
	Ses; StDem; Borb	1989	O	-	Ministero Ambiente	CW; RLU
	all catchments	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	1996	O	-	Ministero Ambiente	CW; RLU
	Borb	2006	O	-	Piemonte Region	CW
	Ses; StdiLan	2007	O	-	Piemonte Region	CW
	StdiLan; StDem; Borb	2010	O	-	Piemonte Region	CW
	all catchments	2012	Shp	-	Min. Ambiente	BLC
	StDem; Borb	2015	O	-	Google Earth	CW; RLU
	Ses	2016	O	-	Google Earth	CW; RLU
	StdiLan	2018	O	-	Google Earth	CW; RLU
Nure catchement Including Lardana and Lavaiana rivers	Nure catchment	1853	Shp	-	Emilia Romagna Region	BLC
	Nure (from r6 to r11)	1877	HM	1: 50,000	IGM	CW
	Nure catchment	1929	C	-	ISTAT	BLC
	all reaches	1954	AP	1: 25,000	IGM	CW; RLU
	all reaches	1970	AP	1: 28,000	IGM	CW; RLU
	Nure catchment	1976	Shp	-	Emilia Romagna Region	BLC
	all reaches	1988	O	-	Ministero Ambiente	CW; RLU
	Nure catchment	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	1998	O	-	Ministero Ambiente	CW; RLU
	Nure catchment	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	2011	O	-	Emilia Romagna Region	CW; RLU
	Nure catchment	2012	Shp	-	Ministero Ambiente	BLC
all reaches	2015	O	-	Google Earth	CW	
Southern Italy	all reaches	1836	L	-	Di Martino, 1996	BLC
	Fort	1870	HM	1: 50,000	IGM	CW
	Trig	1878	HM	1: 50,000	IGM	CW
	Vol	1885	HM	1: 50,000	IGM	CW
	Vol	1909	HM	1: 50,000	IGM	CW
	All catchments	1929	C	-	ISTAT	BLC
	Vol	1942-46	HM	1: 25,000	IGM	CW
	Vol; Trig; Fort	1954	AP	1: 34,000	IGM	CW; RLU; BLC
	All catchments	1970	C	-	ISTAT	BLC
	Vol; Trig	1975	AP	1: 15,000	IGM	CW; RLU
	Fort	1976	AP	-	IGM	CW; RLU
	Vol; Trig	1981	AP	1: 31,000	IGM	CW; RLU
	Fort	1984	Shp	-	Campania Region	BLC
	Fort	1986	AP	1: 31,000	IGM	CW; RLU
	Vol; Trig	1988	O	-	Ministero Ambiente	CW
	Fort	1989	O	-	Ministero Ambiente	CW; RLU
	all reaches	1992	AP	1: 13,000	Molise Region	CW
	all reaches	1998	O	-	Ministero Ambiente	CW; RLU
	all catchments	2000	Shp	-	Ministero Ambiente	BLC
	Fort	2004	O	-	Campania Region	CW
	all reaches	2007	O	-	Molise Region	CW
	all reaches	2011	O	-	Google Earth	CW
	all catchments	2012	Shp	-	Ministero Ambiente	BLC
	Fort	2013	O	-	Google Earth	CW
Fort	2015	O	-	Google Earth	CW; RLU	
Vol; Trig	2016	O	-	Google Earth	CW; RLU	

1374 Codes for reaches: Ses = Sesia; StdiLan= Stura di Lanzo; StDem = Stura di Demonte; Borb =
1375 Borbera; Vol = Volturno; Trig = Trigno; Fort = Fortore. Codes for Type: HM= historical maps;
1376 AP= aerial photographs; O = orthophotos; C = census data; L= literature data; Shp = shapfile.
1377 Codes for Analysis: CW = channel width; BLC = basin scale land cover; RLU = reach scale land
1378 use in the 22 selected reaches.

1379 IGM: Istituto geografico Militare

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1413 **Table 6**1414 Rates of average annual channel width variation expressed in m y^{-1} .

		Annual channel width variation (m y^{-1})				
		Reach	1954 - 1970s	1970s -1980s	1980s - 1990s	1990s -2010s
Alps	Ses1		-2.0	-1.1	-3.2	-2.3
	SLn1		-4.1	-2.7	+7.8	-3.5
	SDm1		-1.7	-3.4	-3.5	-0.9
Northern Apennines	Bor1		-0.9	-0.7	-2.0	-0.7
	Lar1		-0.2	-0.2	-0.1	-0.1
	Lav1		-0.5	-0.3	-0.2	-0.1
	Nur1		-0.9	-0.5	-0.3	+1.1
	Nur3		-0.5	-0.8	-0.2	+0.9
	Nur5		-0.3	-2.0	-0.2	-0.7
	Nur6		-0.5	-0.8	-0.0	-0.2
	Nur10		-1.7	-4.0	-0.4	-0.7
	Volt2		-4.1	-4.2	-0.9	-1.4
	Volt4		-4.0	-4.6	-1.5	-0.7
Southern Apennines	Volt5		-1.7	-1.9	-0.5	-0.3
	Tr5		-1.3	-3.5	-4.5	+1.1
	Tr6		-2.3	-0.2	-1.4	-0.3
	Tr8		-1.2	-2.6	-1.9	+0.9
	Tr9		-3.0	-4.5	-5.0	+1.4
	For1		-0.3	-0.2	-0.7	+0.3
	For2		-1.3	-0.8	-1.5	+1.0
	For3		-1.5	-0.4	-1.2	+0.3
	For4		-0.9	-0.3	-0.5	+0.8

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1416 Annual rates of channel width variation within the 22 studied reaches, during the four periods (1954
1417 - 1970s; 1970s- 1980s; 1980s- 1990s; 1990s- 2010s. Negative and positive values indicate
1418 narrowing and widening, respectively Bold numbers indicate the peak period for channel
1419 narrowing. Legend of background colors: white = narrowing $< -1 \text{ m y}^{-1}$; pink = narrowing $-1 \div 2 \text{ m}$
1420 y^{-1} ; narrowing $> 2 \text{ m y}^{-1}$; green = widening. For reach Id abbreviation see Table 3.

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1429 **Table 7**

1430 Land cover changes and main trends at catchments scale

River	Land use	1836	1853	1929	1954	1960	1970/ 76	1984	1990	2000	2012	Trends	
												1	2
Sesia	Forest	-	-	-	-	0.46	-	-	0.52	-	0.54		
	Pasture/ meadow	-	-	-	-	0.43	-	-	0.16	-	0.16		
	Ploughed land	-	-	-	-	0.01	-	-	0.00	-	0.00		
	Cultivated trees	-	-	-	-	0.01	-	-	0.04	-	0.04		
	Schrub cover	-	-	-	-	0.00	-	-	0.17	-	0.16		
Stura di Lanzo	Forest	-	-	-	-	0.18	-	-	0.33	-	0.33		
	Pasture/ meadow	-	-	-	-	0.68	-	-	0.16	-	0.21		
	Ploughed land	-	-	-	-	0.02	-	-	0.00	-	0.00		
	Cultivated trees	-	-	-	-	0.01	-	-	0.05	-	0.05		
	Schrub cover	-	-	-	-	0.00	-	-	0.14	-	0.17		
	Other	-	-	-	-	0.12	-	-	0.32	-	0.25		
Stura di Demonte	Forest	-	-	-	-	0.24	-	-	0.25	-	0.28		
	Pasture/ meadow	-	-	-	-	0.44	-	-	0.15	-	0.21		
	Ploughed land	-	-	-	-	0.22	-	-	0.13	-	0.13		
	Cultivated trees	-	-	-	-	0.01	-	-	0.09	-	0.08		
	Schrub cover	-	-	-	-	0.00	-	-	0.14	-	0.12		
	Other	-	-	-	-	0.09	-	-	0.24	-	0.16		
Borbera	Forest	-	-	0.22	-	0.48	-	-	0.66	-	0.64		
	Pasture/ meadow	-	-	0.12	-	0.18	-	-	0.05	-	0.02		
	Ploughed land	-	-	0.19	-	0.33	-	-	0.01	-	0.01		
	Cultivated trees	-	-	0.06	-	0.00	-	-	0.21	-	0.20		
	Other	-	-	0.41	-	0.01	-	-	0.08	-	0.12		
Nure	Forest	-	0.27	0.33	-	-	0.45	-	0.51	0.53	0.52		
	Pasture/ meadow	-	0.65	0.18	-	-	0.11	-	0.08	0.08	0.09		
	Ploughed land	-	0.03	0.33	-	-	0.36	-	0.08	0.08	0.08		
	Cultivated trees	-	0.01	0.00	-	-	0.01	-	0.29	0.27	0.28		
	Other	-	0.05	0.16	-	-	0.07	-	0.03	0.03	0.04		
Volturno	Forest	0.23	-	0.18	0.26	-	0.25	-	-	0.48	0.50		
	Pasture/ meadow/Schrub	0.16	-	0.26	0.17	-	0.37	-	-	0.15	0.16		
	Ploughed land	0.56	-	0.50	0.50	-	0.23	-	-	0.06	0.07		
	Cultivated trees	0.04	-	0.05	0.05	-	0.06	-	-	0.26	0.23		
	Other	-	-	0.01	0.02	-	0.10	-	-	0.06	0.03		
Trigno	Forest	0.25	-	0.15	0.18	-	0.16	-	-	0.27	0.29		
	Pasture/ meadow	0.24	-	0.09	0.17	-	0.15	-	-	0.01	0.01		
	Ploughed land	0.46	-	0.61	0.58	-	0.35	-	-	0.20	0.30		
	Cultivated trees	0.04	-	0.05	0.05	-	0.03	-	-	0.31	0.22		
	Schrub cover	-	-	0.05	0.00	-	0.17	-	-	0.17	0.17		
	Other	-	-	0.06	0.02	-	0.14	-	-	0.04	0.02		
Fortore	Forest	-	-	0.07	-	-	0.09	0.18	-	0.14	0.15		
	Pastures/ meadow	-	-	0.05	-	-	0.09	0.02	-	0.02	0.01		
	Ploughed land	-	-	0.77	-	-	0.47	0.71	-	0.53	0.55		
	Cultivated trees	-	-	0.04	-	-	0.03	0.04	-	0.25	0.24		
	Schrub cover	-	-	0.04	-	-	0.24	0.04	-	0.05	0.04		
	Other	-	-	0.02	-	-	0.09	0.03	-	0.01	0.02		

1431

1432 In the column "Trends": 1 = trends before 1960s / 1970s; 2= trend after 1960s / 1970s. Full arrows
 1433 indicate clear trends; dashed arrows or lines indicate less intense or constant trends. respectively.

1434 Legend of colors: green = forest; yellow = pasture and meadow; pink = ploughed land; brown =
 1435 Cultivated trees.

1436