River channel adjustments in Southern Italy over the past 150 years and implications for channel recovery

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Abstract

Multi-temporal GIS analysis of topographic maps and aerial photographs along with topographic and geomorphological surveys are used to assess evolutionary trends and key control factors of channel adjustments for five major rivers in southern Italy (the Trigno, Biferno, Volturno, Sinni and Crati rivers) to support assessment of channel recovery and river restoration.

Three distinct phases of channel adjustment are identified over the past 150 years primarily driven by human disturbances. Firstly, slight channel widening dominated from the last decades of the nineteenth century to the 1950s. Secondly, from the 1950s to the end of the 1990s, altered sediment fluxes induced by in-channel mining and channel works brought about moderate to very intense incision (up to 6–7 m) accompanied by strong chan- nel narrowing (up to 96%) and changes in channel configuration from multi-threaded to single-threaded pat- terns. Thirdly, the period from around 2000 to 2015 has been characterized by channel stabilization and local widening. Evolutionary trajectories of the rivers studied are quite similar to those reconstructed for other Italian rivers, particularly regarding the second phase of channel adjustments and ongoing transitions towards channel recovery in some reaches. Analyses of river dynamics, recovery potential and connectivity with sediment sources of the study reaches, framed in their catchment context, can be used as part of a wider interdisciplinary approach that views effective river restoration alongside sustainable and risk-reduced river management.

1. *Introduction*

The assessment of hydromorphological conditions of rivers is a fun- damental part of sustainable and efficient river management (e.g. Van der Nat et al., 2003; Downs and Gregory, 2004; Hupp and Rinaldi, 2007; Larsen et al., 2007; Gregory et al., 2008; Habersack and Piégay, 2008; Rinaldi et al., 2009, 2011, 2013; Surian et al., 2009a, b; Kondolf, 2011). The role of fluvial geomorphology in river management and res- toration is now well recognized in the European context, especially within the Water Framework Directive (WFD, European Commission, 2000). Most Italian (e.g. Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009b; Comiti et al., 2011; Ziliani and Surian, 2012 and references therein) and European rivers (e.g. Garcia-Ruiz et al., 1997; Bravard et al., 1999; Lach and Wyżga, 2002; Liébault and Piégay, 2002; Keesstra et al., 2005; Rovira et al., 2005; Kondolf et al., 2007; Wyżga, 2008; Gurnell et al., 2009; Kiss and Blanka, 2012; Rădoane et al., 2013) have experienced considerable channel changes over the past twocenturies. Human disturbance has been assessed as a key driver of chan- nel adjustments, as catchment scale (e.g. land use changes and torrent control works) and/or reach scale impacts (e.g. channelization, con- struction of dams, gravel mining, etc.) modify natural sediment and flow regimes (Liébault and Piégay, 2002; Surian and Rinaldi, 2003; Surian et al., 2009 a,b,c; Comiti et al., 2011; Preciso et al., 2012; Ziliani and Surian, 2012). These factors work alongside natural control factors (Rumsby and Macklin, 1996; Starkel, 2002; Amsler et al., 2005; Kiss and Blanka, 2012; Rădoane et al., 2013), especially climate change (Knox, 1993; Korhonen and Kuusisto, 2010). Climate change not only impacts upon the efficiency of land degradation processes (Dotterweich, 2008; Notebaert et al., 2011), it also induces land-cover changes which may facilitate or obstruct runoff and soil degradation (Liébault and Piégay, 2002; Starkel, 2002).

In many instances, fluvial response to human interventions is much faster and more intense than responses to natural influences (e.g. Leopold, 1973; Petts, 1979; Williams and Wolman, 1984; Knighton, 1991; Kondolf, 1997; Winterbottom, 2000; Marston et al., 2003; Rovira et al., 2005; Gregory, 2006; Ibisate et al., 2013; Segura-Beltrán and Sanchis-Ibor, 2013). In Italy, strong narrowing and moderate to very intense incision during the second half of the 20th century is interpreted to reflect human disturbances, especially in-channel mining (Rinaldi et al., 2005; Surian et al., 2009b; Comiti et al., 2011; Ziliani and Surian, 2012).

2. *Study area*

The selected rivers (namely Trigno, Biferno, Volturno, Sinni and Crati, Fig. 1A) are influenced by a typically Mediterranean to warm temperate climate that is characterized by alternating low-flow and high- flow conditions during spring–summer and autumn–winter, respectively. Some physiographic and hydrological features of these rivers are summarized in Table 1. The spatial hierarchical framework developed by Rinaldi et al. (2012), which takes into account the specific Italian context and complies with the Water Framework Directive requirements, was used to designate segments and reaches in relation to physiographic units and catchments.

The Trigno and Biferno rivers, mainly located in the Molise region, flow to the Adriatic Sea, cutting the Apennine chain transversally.Their catchments are underlain by limestones and marly limestones in the upper portions and by multi-colored clays and siliciclastic flysch de- posits in the middle and lower portions (Aucelli et al., 2001; Cesarano et al., 2011; Rosskopf and Scorpio, 2013). For both rivers, proceeding downstream, four physiographic units and four segments (1–4) are identified (Fig. 1B; Table 1). Segment 1 of the Trigno River crosses the mountain Apennine unit. It contains a confined, straight and single- threaded channel. In contrast, the first segment of the Biferno River crosses the Boiano intermontane plain and its channel has a meandering pattern. Segments 2 (Fig. 1B) cross the hilly Apennine areas and contain largely confined sinuous channels. Finally, segments 3 and 4 cross high plain and low plain areas and are characterized respectively by sinuous and meandering channel configurations.

The Volturno River flows across theMolise and Campania regions to the Tyrrhenian Sea. Limestone and flysch deposits mainly underlie its catchment. Its course has been divided into five segments (Fig. 1B; Table 1). In segment 1, the channel crosses the mountain Apennine unit and has a confined sinuous pattern. Segments 2 and 3 cross intermontane Apennine plain areas and contain sinuous or locally sinuous with alternate bars (segment 2) and sinuous or meandering channels (segment 3). Finally, segments 4 and 5 cross high plain and low plain areas and channels are sinuous or meandering.

The Sinni River flows across the Basilicata region to the Ionian Sea. Its course has been divided into five segments (Fig. 1C; Table 1). Segments 1, 2 and 4 cut the southern Apennine chain crossing mountainous to hilly landscapes consisting of carbonate, siliciclastic and crystalline-metamorphic rocks with narrow and confined channels that are sinuous and single-threaded. In segments 3 and 5, channels have a well-developed multi-threaded pattern and cross intermontane Apennine and high plain areas, respectively. Finally, segment 6 cuts across the flat low plain area and contains sinuous and sinuous with alternate bars channels.

The Crati River flows across the Calabria region to the Ionian Sea. Crystalline rocks and clastic deposits of Neogene and Quaternary age underlie its catchment. The Crati course has been divided into four segments (Fig. 1D; Table 1). Segment 1 incises the crystalline bedrock of the mountain Apennine unit with a sinuous confined channel. Segment 2, which goes through the tectonic depression of the Crati basin (Spina et al., 2011), is characterized by sinuous and sinuous with alternate bar channel morphologies. A confined sinuous channel characterizes segment 3 which crosses the hilly Apenninic area, whereas in segment 4, which crosses the Crati alluvial coastal plain, the channel is sinuous to straight and almost completely bordered by artificial levees.

3. Materials and methods

3.1. Selection of study reaches

River segments were divided into reaches defined as relatively homogeneous sections of river along which current boundary conditions are sufficiently uniform (Brierley and Fryirs, 2005). Subsequently, 20 study reaches were selected for more detailed study (Fig. 1B–D; Table 2) taking into account difficulties tied to river access, channel mobility and evidence of appreciable morphological changes over the past century, while excluding a priori confined segments and those bordered by artificial levees.

3.2. GIS analysis of maps and aerial photographs

Channel features were analyzed from topographic maps and aerial photographs dating from 1869 to 2012 (Table 3) using ArcGIS 10 soft- ware. Aerial photos and topographic maps were scanned at a resolution of 800 and 300 dpi, respectively, and rectified in a GIS environment using large-scale topographic maps as a base layer and 20 to 30 selected ground-control points, mostly located in the vicinity of the channels. First-order and second-order polynomial transformations were applied to historical and more recent maps, respectively. For each year consid- ered, channels were edited as polygons to obtain average channel width, pattern and related changes over time. Polygons defined includ- ed single channels and unvegetated or scarcely vegetated bars but ex- cluded vegetated islands. Average channel width was evaluated as the ratio between polygon area and length, using procedures outlined by Surian et al. (2009c). Channel width measurement errors (Table 3) were estimated using the method of Mount et al. (2003) which sums two independent errors. The first error is associated with bank-line digitization and depends on map scale and pixel dimensions of aerial photographs. It was calculated by multiplying pixel resolution by the mean of the maximum number between repeat left and right bank-line delineations, and estimated to range from 4–25 m. For the second error, related to distortions of recti- fied air photos, the ArcGIS software provided root mean square errors (RMSE) in the order of 1.5–6 m for aerial photographs and 15–25 m for historical maps.

3.3. Assessment of channel changes

Channel morphologies were determined based on criteria and threshold values listed by Rinaldi et al. (2012) and references therein. The following channel morphologies were identified: braided, wander- ing, sinuous with alternate bars, sinuous, meandering and straight. For current channel morphologies within study reaches, field surveys en- abled substantiation of stream mobility and provided insight into the ef- fects of recent flood events.

Regarding channel width changes, when comparing river reaches, a channel width variation index ΔW (%) was introduced. This index al- lows for percentage calculation of width variations for each reach and considered time interval through the following equation:

$$\Delta W\ (\%) = (W/W^{54} *100) - 100;$$

where W is the average channel width measured in different years (from 1869 to 2012) and W_{54} is the average channel width in 1954. W_{54} is a reference point as extracted from air photographs which are affected by lower estimation errors relative to topographic maps edited prior to 1954 (Table 3).

As for channel-bed elevation changes, quantitative evaluation refers to the period 1954–2013, since topographic data on channel-bed elevation for the period prior to 1954 are too scattered, and are useful only for qualitative estimation. Since long-term data on channel sec- tions were not available, evaluations on channel-bed elevation changes are based on data extracted from topographic maps acquired in 2013 surveying 35 channel cross sections. Topographic measurements were performed with a DGPS system (Trimble R6 GPS system) affected by horizontal (location) and vertical (elevation) errors of less than 2 cm and 3 cm, respectively.

Channel incision was estimated by calculating height differences of similar geomorphic surfaces of different age, for instance the floodplain surfaces active in 1954 and 2013, respectively. Channel incision was classified according to Rinaldi et al. (2012) using the following classes: negligible (≤ 0.5 m), limited or moderate (0.5–3 m), intense (3–6 m) or very intense (N 6 m).

3.4. Assessment of natural and human factors

To investigate relationship between channel changes and natural and human factors, we analyzed available data on climate trend, stream discharge, flood events, land cover changes and anthropic structures and interventions. With reference to climate change, recent studies on precipitation and temperature trends (Brunetti et al., 2000, 2001, 2002, 2004, 2012; Cotecchia et al., 2004; Izzo et al., 2004; Piccarreta

et al., 2004, 2012, 2013; Polemio and Casarano, 2004, 2008; Clarke and Rendell, 2006; Diodato, 2007; Federico et al., 2010; Caloiero et al., 2011; Capozzi and Budillon, 2013) were examined. Data on stream dis- charge were, unfortunately, unavailable for all studied rivers while available records showed a number of gaps and therefore were not suit- able for analysis. The occurrence of flood events over the past decades was evaluated using data extracted from the AVI project (http://avi.gndci.cnr.it).

Land cover characteristics and changes at catchment scale were an- alyzed using data sets from several sources. Data on forest cover refer- ring to the period 1840–2000 were extracted from Tichy (1962), DiMartino (1996) and D'Ippolito et al. (2013). The Corine land cover data of 2000 and 2006 were obtained from the Italian Ministry of Environment (http://www.pcn.minambiente.it/PCNDYN/catalogowms.jsp?lan=it). For the Molise region, a 1954 land use map was derived from photo-interpretation.

Through remote sensing GIS analysis, an inventory was carried out as to control works and mining sites at the reach scale and torrent control works at the catchment scale. This inventory was integrated with data on major hydraulic structures, channel and torrent control works acquired during field surveys and provided by basin authorities.

4. Results

4.1. Channel changes

The studied rivers have undergone significant channel changes over the past 150 years. Adjustment can be differentiated into three distinct phases. During the first phase, from the end of the 19th century to the 1950s, channel changes were less intense compared to those that oc- curred afterwards, with no common trend in channel width variation. Most of the Volturno, Biferno and Sinni reaches were affected by moderate widening while along the Crati and Trigno reaches narrowing prevailed. Furthermore, five reaches remained essentially stable showing very modest variations in width of +5% to −6% (Fig. 2B; Table 4). Overall data indicate a slight prevalence to widening. In this phase, modest river pattern changes occurred consisting, above all, in an increase of braided pattern at the expense of wandering morphology (Fig. 3).

No quantitative data on incision or aggradation are available to assess channel-bed elevation changes, but field surveys indicate that bed elevation changes were most likely very limited.

During the second phase, from the 1950s to the end of the 1990s, all study reaches underwent intense channel narrowing (Fig. 2; ΔW% Phase 2, Table 4) which reached a minimum of 58% in the Sinni River (Sn1) and a maximum of 96% in the Biferno River (Bf2). Average annual channel narrowing rates (W_aPhase 2, Table 4) range between 1.5 m/years (Vol6) and 21 m/years (Sn2). Narrowing rates reached maximum values in different sub-periods highlighting the singular behavior of each reach. Along the Biferno River, narrowing was more intense up until the 1970s while it reached maximum values along the Sinni, Trigno and Crati rivers (excluding reaches Tr4 and Cr5) from the 1970s onwards (Table 4). The Volturno reaches, instead, were alternatively characterized by peak values up until the 1980s (Vol1 and Vol4-Vol6) and after the 1980s (Vol2 and Vol3). Overall, the Trigno, Biferno, Volturno and Sinni rivers show increased narrowing downstream, conversely the Crati reaches show a net decrease in narrowing downstream (from 87% to 78%, Table 4). Channel pattern changes were equally intense in this period. Commencing with a wide prevalence of braided and wandering channel morphologies (75%, Fig. 3), the wandering pattern increased significantly up until the 1970s/1980s, then was almost entirely substituted by sinuous with alternate bars and sinuous patterns which constituted 80% of channel configurations in 1998. Only the Sinni River retained a braided pattern but with a strongly narrowed channel and reduced degree of braiding.ù

All rivers underwent channel incision from 1954 onwards. Along the Volturno and Crati rivers, within the upper reaches of the Trigno River (Tr1 and Tr2) and the Biferno and Sinni reaches Bf1, Sn1 and Sn2 (Figs. 4 and 5), incision was moderate. It was intense within reaches Tr3, Bf2 and Sn3 (Figs. 4 and 5) and very intense within reach Tr4 (Fig. 5). Reaches located downstream of major hydraulic structures show higher incision rates relative to those located upstream, as demonstrated for reaches Bf2, Sn2, Sn3 and Tr4 (Fig. 6). Regarding reach Tr4, channel incision caused rapid lowering of the water table with con- sequent effects on land use and riparian vegetation (Aucelli et al., 2011), and undermining of the San Salvo check-dam (Fig. 1, Table 5), which collapsed during the flood event in 2003 (Aucelli et al., 2004). Higher incision rates for reaches located closer to the coast (Tr4 and Sn3), likely reflect shoreline retreat of several hundreds of meters which occurred from the 1950s onwards (Cocco et al., 1978; Aucelli and Rosskopf, 2000; Vita et al., 2007; Rosskopf and Scorpio, 2013), causing knick- point initiation and retreat and the upstream migration of channel incision.

Remote sensing data and topographic measurements have highlighted that incision became more intense from the 1950s to the 1980s, at least in the Trigno, Biferno and Sinni rivers (Fig. 4). Along the Biferno River in particular, incision had already occurred for the most part by 1977 (Fig. 4B), concurrently with channel narrowing. Conversely, along the Volturno River, incision reached appreciable values (more than 0.5 m) from the 1980s onwards only (Aucelli et al., 2011), when most channel narrowing had already occurred. For the Crati River, data do not allow for definition of a period of major incision.

During the third phase, only modest channel width variations oc- curred. However, important differences were evident among rivers studied (Fig. 2). While the Volturno and Biferno rivers were essentially stable since 1998 (Fig. 2A), characterized by very limited narrowing or widening (Table 4), the Trigno and Crati rivers have been affected by appreciable widening (Fig. 2B; Table 4). Channel widening was accompanied by an increase of 25% of sinuous with alternate bars channels and an equal decrease of sinuous channels, as highlighted by reverse percentages (Fig. 3), while no data are available on channel-bed elevation changes. Along the Crati River, local channel widening in some cases led to the destruction of tens of meters of mature riparian forest (Fig. 6). The Trigno reaches, after widening until 2007, once again decreased in width from 2007 to 2011. All reaches located downstream of major hydraulic structures, namely Tr4, Bf2, Sn2 and Sn3, continued to undergo narrowing (Table 4) and specifically along the Sinni River a prevailing trend towards narrowing persisted at least until 2006.

4.2. Human disturbances and impacts

The studied rivers were affected by the following human distur- bances: i) forest cover changes; ii) hydraulic interventions at catchment and reach scale; and iii) sediment mining. Major deforestation took place in the Molise (Di Martino, 1996) and Basilicata (Tichy, 1962) be- tween 1836/1850 and 1929 (Fig. 7A). Forest expansion occurred after 1929, due to natural reforestation and reforestation measures. In Campania and Calabria, forests expanded in response to reforestation measures from the 1950s onwards (Tichy, 1962; D'Ippolito et al., 2013). According to Bevilacqua (2005), reforestation in southern Italy is also the result of natural re-expansion of forests subsequent to agricultural abandonment and displacement of agricultural activities to valley bottoms and alluvial coastal plains. The post-war trend of agricultural abandonment due to insufficient income is well document- ed for other countries of southern Europe (MacDonald et al., 2000).

Analysis of photographs confirms this trend in Molise from 1954 to 2006 (Fig. 7B). It highlights a notable increase of forest cover at the expense, above all, of farmland (in the case of the Volturno catchment leading even to an inversion of relative percentages, Fig. 7B) and, secondly, of grassland. Progressive increase of forest cover from the 1930s onwards is considered to have contributed to progressive stabilization of hillslopes and, hence, to reduction of sediment delivery to rivers. Torrent control works were carried out within all study catchments and reached their maximum intensity from the 1950s to the 1980s in the Trigno and Biferno watersheds and from the 1960s to 2000 within the Volturno, Sinni and Crati watersheds (Fig. 8). River control works (consisting mainly of levees, bank protections and groynes) were built within study reaches at the beginning of the 20th century and especially from the 1950s onwards (Fig. 8). In particular, within the Biferno, Trigno and Sinni study reaches, they were built primarily from the mid-1950s to the end of the 1980s/beginning of the 1990s. In the Biferno reaches, most control works were built in the 1960s, along with the Ponteliscione dam (Table 5) and the road which crosses the entire valley floor up to the coast, and integrated with others (Fig. 8) after the flood event in 2003 (Aucelli et al., 2004). As for the Crati River, main works consist of levees already built in the 1930s on the left bank and integrated mainly in the 1970s with others along the right bank. Finally, as for the Volturno River, control works were implemented relatively late, from 1976–1999 (Fig. 8). Furthermore, between 1942 and 2000 several major hydraulic structures (dams, check-dams and flood storage reservoirs, Fig. 1; Table 5) were built. Differences in peak periods of con trol works clearly highlight different needs in managing single rivers, from safeguarding of agricultural, industrial and building areas to construction and protection of new roads crossing the valley floors.

Regarding gravel mining activities, official data available for the Sinni and Trigno rivers (Cocco et al., 1978; Aucelli and Rosskopf, 2000) have highlighted maximum intensity during the 1960s and 1970s, with extracted volumes of at least 200,000 m3 along the Trigno River and even approximately 15,000,000 m3 along the Sinni River. From the end of the 1970s to the end of the 1990s, gravel extraction considerably decreased, reaching very modest volumes along the Trigno River (approximately 40,000 m3), but still important volumes (approximately 700,000 m3) along the Sinni River. As official data on extracted volumes are based on mining licenses, they most likely lead to a net underestimation of real volumes (Aucelli and Rosskopf, 2000).

Remote sensing analysis confirms that gravel mining activities commenced in the 1960s and reached peak values in the 1970s along the Trigno, Biferno and Sinni rivers and in the 1980s along the Crati and Volturno rivers (Fig. 9). Prior to the late 1970s/1980s, sediment mining occurred in channels and floodplain areas. From the 1990s on- wards, mining activities were essentially limited to terraced surfaces and significantly decreased due to legislative regulation enacted by regional institutions and basin authorities. In the case of the Trigno, Biferno and Sinni rivers, peak periods of mining in channels and flood- plain areas are consistent with those of river control works (Figs. 8 and 9) and construction of major hydraulic structures (Table 5) and roads. As for the Crati River, the mining peak is linked to the development of urban settlements and industrial areas on the valley floor from the 1960s onwards.

4.3. Natural factors

Over the last 200 years, climate change in the Mediterranean is related to the decline and end of the Little Ice Age (LIA, Orombelli, 2007) and the subsequent period of warming. Annual precipitation and related number of wet days show a significant negative trend all over Italy from 1880–2002 (Brunetti et al., 2004). In southern Italy, precipitation decreased by −56 mm/100 year, mainly in winter seasons (−35 mm/ 100 years). Overall wetter conditions up until the 1930s

(Brunetti et al., 2004; Cotecchia et al., 2004; Polemio and Casarano, 2004, 2008; Diodato, 2007) (Fig. 10B) favored alluvial fan deposition, delta and shoreline progradation (Aucelli and Rosskopf, 2000; Bellotti, 2000; Alberico et al., 2012; Rosskopf and Scorpio, 2013) and hillslope dynamics, above all landslide occurrence (Almagià, 1910). From the mid-1930s onwards (Fig. 10B), climate became progressively warmer and drier (Brunetti et al., 2000, 2004; Cotecchia et al., 2004; Polemio and Casarano, 2004, 2008; Diodato, 2007).

While an overall decrease in average annual precipitation occurred from the beginning of the 20th century to the 1970s, intervening periods were drier (1920s and 1940s) and wetter (1930s and 1950s to mid-1960s) (Aucelli and Rosskopf, 2000; Cotecchia et al., 2004; Izzo et al., 2004; Polemio and Casarano, 2004, 2008; Capozzi and Budillon, 2013). A decrease in annual and daily precipitation along with number of wet days intensified from the 1970s to the 1990s (Fig. 10B) causing severe to extreme dry conditions, especially during winter (Brunetti et al., 2001, 2002, 2004, 2012; Cotecchia et al., 2004; Izzo et al., 2004; Piccarreta et al., 2004, 2012, 2013; Polemio and Casarano, 2004, 2008; Clarke and Rendell, 2006; Federico et al., 2010; Caloiero et al., 2011; Capozzi and Budillon, 2013). Negative trends are also demonstrated by the maximum amounts of 24 h, 3-day and 5-day precipitations (Piccarreta et al., 2012), number of extreme events (Piccarreta et al., 2013), high-intensity events (Brunetti et al., 2012) and length of rainy periods (Brunetti et al., 2012). From 2000 to the 2010 decade, an overall inversion trend occurred in the study area, characterized by a slight increase in annual precipitations (Fig. 10B) and length of rainy periods (Izzo et al., 2004; Federico et al., 2010; Piccarreta et al., 2013).

Studies carried out in Basilicata and Calabria (Clarke and Rendell, 2006; Polemio and Petrucci, 2012) highlight significant change in the frequency of flood events after the 1970s (Fig. 10B). In Basilicata, the av- erage frequency increased from 0.7 yr−1 in 1955–1962 to 1.2 yr−1 in the mid-1970s, then once again decreased to 0.2 yr−1 until the mid- 1990s (Clarke and Rendell, 2006). In Calabria, flood frequency increased from 1880 to 1974 then slightly decreased from 1974 to 2007 (Polemio and Petrucci, 2012). Data extracted from the AVI project (http://avi. gndci.cnr.it) highlight higher frequencies for the Sinni and Volturno rivers around the 1950s and 1970s and once again during the 1990s for the Volturno River.

From 2000 onwards, several major flood events occurred along the studied rivers. The Trigno and Biferno rivers suffered two major flood events. The first one occurred in January 2003 (Aucelli et al., 2004) with major impact on channel segments 3 and 4. The second flood event closed a period of intense and frequent rainfall from November 2008 to April 2009 (Di Pilla and Cardillo, 2009) and was less damaging but also impacted upon the Volturno River. Larger flood events impacted upon the Crati River in 2008 and 2009 and upon the Sinni River on 16th November 2008 and 1st December 2013.

5. Discussion

5.1. Channel adjustments

Channel changes over the past 150 years occurred in three phases (phases 1–3, Fig. 10C). Although rivers had individual behavior as to magnitude and temporal distribution of channel modifications, their evolutionary trajectories display several similarities. During phase 1 (Fig. 10C), no common trend in channel width change is evident. However, a trend to channel widening appears to be slightly dominant com- pared to narrowing and involved mainly the Volturno, Biferno and Sinni rivers (Table 4). Channel widening is interpreted to reflect increased hillslope dynamics and sediment delivery to rivers connected with the latest pulsations of the Little Ice Age (Bravard, 1989) and due to huge deforestation which occurred from 1850 to the end of the 1920s. Instead, there was little direct human impact upon rivers in southern Italy during this period, as shown by Barker (1995) and Clarke and Rendell (2006) for the Biferno and Sinni rivers. An exception is the Crati River where extensive construction of levees along the left channel side induced channel narrowing during this phase.

During phase 2, all rivers studied underwent considerable channel narrowing and bed incision. These changes are not supported by climate data which highlight a relative wet climate and higher flood frequency (Fig. 10B) until the mid-1970s. This indicates that human disturbance largely prevailed over climatic influence. Meanwhile, a reduction in precipitation from the mid-1970s to the 1990s may have strengthened the effects of human disturbances.

Comparing specific evolutionary trajectories of selected rivers as to timing, magnitude and distribution of human disturbances, highlights a series of relationships:

(i) The role of human disturbance at the catchment scale, i.e. landcover changes and torrent control works, is evident for the Volturno River where gravel mining and river control works were concentrated from the late 1970s onwards, when narrowing had already partially occurred. It is less evident for other rivers where reach interventions commenced earlier.

(ii) River control works and in-channel mining are key driving factors for channel narrowing and channel-bed incision. They normally occurred more or less concurrently (Fig. 10) and, especially from the 1960s to the 1990s, together caused a decrease in sediment availability. For the Volturno River, the role of sediment mining was overall very modest (Fig. 9). Regarding the Crati River, channel adjustments occurred first under the prevailing control of river works, then the effect of in-channel mining was added.

(iii) Dams and check-dams have modified downstream sediment transfer, inducing greater rates of narrowing and incision of downstream reaches.

(iv) Major phases of narrowing and incision did not necessarily occur concurrently. For example, along the Volturno River incision became significant after most of the narrowing had occurred. At least in this case, incision appears to be a primary response to reach intervention, specifically control works.

(v) The reduction of sediment fluxes due to human disturbance also had its impact on river systems through huge shoreline retreat and consequent upstream migration of channel incision.

The third phase, covering approximately the period from 2000–2015, highlights a prevailing trend to channel stabilization or even widening (Fig. 10C). In particular, the Trigno and Crati rivers underwent some widening, largely within the range of variations that occurred previously. Following the construction of levees and groynes between the 1960s–1980s and further channel narrowing from the 1980s onwards, these rivers are currently characterized by narrow erodible corridors within which channels are able to shift laterally. Limited woody riparian vegetation favors bank erosion processes. The Volturno and Biferno rivers have been essentially stable since 1998, with only very slight localized widening. Recent construction of channel works and development of a wide, stable and continuous riparian forest (Aucelli et al., 2011) may be responsible for limited channel mobility. As for the Sinni River, the third phase is marked by a slight shift to more stable conditions in the Sn1 reach while in the reaches located respectively downstream of the Montecotugno dam and the Santa Lucia check-dam which trap the sediments flowing into them from upstream channel narrowing persisted.

The overall emerging trend towards channel stabilization and recovery is interpreted as the effect of the cessation of in-channel mining, implying higher in-channel sediment supply, coupled with some short-term effect of episodic larger floods, which have favored bank erosion and increased sediment mobility. Conversely, the individual behaviors of the single study reaches highlight differences in channel and sediment mobility and catchment conditions (Brierley and Fryirs, 2009; Fryirs et al., 2009).

5.2. Comparison of river evolutionary trajectories on national scale

Findings from this study indicate broad convergence in the timeframes of channel adjustments in southern and in central- northern Italy (see Surian et al., 2009b and references therein) over the last 150 years. However, some important differences are also evident. While rivers studied in southern Italy have shown an overall slight dominance of channel widening during the first phase, slight narrowing and low incision affected rivers in central-northern Italy. This contrast indicates that rivers in central-northern Italy were already affected by notable human disturbance that reduced sediment availability. In contrast, rivers in southern Italy were influenced primarily by climatic factors and deforestation that increased sediment availability at the time. The second adjustment phase was very similar throughout Italy. Rivers in southern and central-northern Italy underwent strong channel narrowing which lasted respectively up until the end of the 1990s and up until the end of the 1980s/beginning of the 1990s. Furthermore, all rivers suffered moderate to very intense channel-bed lowering. Sediment mining is considered to be the primary driver of channel adjustments of rivers in central-northern Italy during that period (Rinaldi et al., 2005; Surian et al., 2009b; Comiti et al., 2011; Ziliani and Surian, 2012). As for rivers in southern Italy, sediment mining was accompanied by extensive channel works.

As for the third phase, rivers in central-northern Italy have undergone channel widening (from 1% to 91%) combined with channel-bed stability or slight aggradation, driven primarily by reduction of in- channel mining and responses to large flood events (Surian et al., 2009b; Ziliani and Surian, 2012). In contrast, only some of the rivers in southern Italy show modest widening (up to +10%) while others are essentially stable or continue to narrow. The emerging trend to channel recovery seems to be favored first by in-channel mining cessation and second by the occurrence of larger flood events.

5.3. Implications for channel recovery

Analyses of evolutionary trajectories provide insight into degradational and recovery traits, guiding management actions that are compatible with channel adjustment trends in efforts to sustain channel recovery and achieve the best conditions possible (Brierley and Fryirs, 2005; Brierley et al., 2008; Dufour and Piegay, 2009; Rinaldi et al., 2013 and reference therein). Current hydromorphological conditions of the study reaches clearly highlight the need for mitigation of the different effects of channel adjustments and human interventions. They thus also indicate that the recovery of their past conditions is neither feasible nor worthwhile. Human disturbances have notably altered the study rivers over the past 150 years. Moreover, due to channel adjustments since 1954, very consistent portions of the original channel systems have turned into terraces that are now occupied by farmlands and other human activities. Furthermore, hydraulic interventions at the reach and catchment scale have greatly reduced longitudinal and lateral sediment connectivity with permanent effects on river dynamics and future chan- nel trends (e.g. Hooke, 2003; Fryirs et al., 2007).

In order to assess potential for channel recovery in the study reaches, their trajectories were analyzed adopting the procedure proposed by Surian et al. (2009a), building upon Brierley and Fryirs (2000) and Brierley and Fryirs (2005). This qualitative procedure classifies river reaches into four categories, i.e. river typologies (Table 6), from “A”, high recovery, to “D”, no recovery, by considering recent channel changes. It furthermore considers the overall assessment of the magnitude of channel adjustment and connectivity of river reaches with sediment sources (Table 6) and thus provides basic data needed for identifying intervention priorities and related measures.

Along the study reaches, magnitudes of channel adjustment range from moderate to very high (Table 6). Moderate magnitudes characterize the reaches Sn1, Cr3 and Cr4 which have been affected by moderate to high channel width changes and moderate bed-level changes associated with configuration changes. High magnitudes characterize the reaches Tr2 and Cr5 due to high channel width and moderate bed- level changes associated with configuration changes. All other reaches are characterized by very high magnitudes of channel changes, due to high to very high changes in width and moderate to very intense bed- level changes associated with configuration changes, except for the reach Sn2 which preserved its original pattern.

Regarding river typology (Table 6), the study reaches are classified as follows: the Trigno reaches Tr2 and Tr3 and the Crati reaches, except for Cr2, are assigned to category B (moderate recovery); the Trigno reaches Tr1 and Tr4, all Biferno and Volturno reaches and the Sinni and Crati reaches Sn1 and Cr2 are placed in category C (slight recovery or no significant changes in channel morphology); finally, reaches Sn2 and Sn3 are placed in category D (no channel recovery).

In order to ascertain the overall connectivity of single study reaches with sediment sources, we extended our analysis to the catchment scale and considered both upstream and lateral sediment sources, as shown below in summary.

Along the Trigno River, downstream sediment transfer is limited by some weirs located in segment 2 (Tr1, Tr2), and two major hydraulic structures (Fig. 1), the Chiauci dam and the San Salvo check-dam. The first permanently traps the sediments collected in segment 1 (coming from approximately 25% of the Trigno catchment), while the second impacts on segment 4 and especially on Tr4 located immediately downstream. River control works are largely obsolete and have only little influence on lateral connectivity. Lateral sediment sources are provided in segments 2 and 3 (Tr1–Tr3) by landslide affected hillslopes and minor tributaries, while most of the major tributaries are stabilized with gabions and weirs. Within segment 4 (Tr4), instead, slopes and tributaries are largely detached from the main channel due to the interposed alluvial plain. The overall connectivity of the study reaches with sediment sources is evaluated moderate for Tr1, moderate-high for Tr2 and Tr3, and low for Tr4 (Table 6).

Segment 1 of the Biferno River crosses an intermontane plain in which sediments are largely stored in a permanent manner. In segment 2, downstream sediment flux is partially intercepted by some check-dams (Fig. 1) and is definitely blocked by the Ponteliscione dam (with a drainage area equal to ca. 85% of the Biferno catchment) located upstream of Bf2. Some lateral sediment source is provided by unstable hillslopes bordering the main channel, affected by diffuse landslides and erosion by surface water, while major tributaries are largely stabilized or separated from the main channel by pocket plains. The overall connectivity of reaches Bf1 and Bf2 with sediment sources is evaluated low-moderate and very low, respectively (Table 6).

Longitudinal connectivity along the Volturno River is disrupted by some weirs present in segment 1 and various check-dams and a storage reservoir (Fig. 1) located in segments 2 (Vol1, Vol2, Vol3) and 3 (Vol4, Vol5, Vol6) which are responsible for limited sediment transfer especially to Vol3 and Vol4. In segment 2, the main channel receives sediments supplied from some major tributaries, while minor tributaries and hillslopes are largely disconnected in both segment 2 and segment 3 due to interposed alluvial fans and plains. The overall connectivity of the Volturno reaches with sediment sources (Table 6) is evaluated as low for Vol3 and Vol4, low-moderate for Vol1, Vol5 and Vol6 and moderate for Vol2.

Downstream sediment flux along the Sinni River is intercepted by some major hydraulic structures (Fig. 1): the Cogliandrino and Monte Cotugno dams that store the sediments coming from approximately 9.5% and 68% of the catchment, respectively, and the Santa Lucia check-dam located immediately upstream of reach Sn3. Lateral connectivity is very limited in segment 2, while segment 3 (Sn1) receives important lateral sediment sources by some major tributaries. Downstream of the Monte Cotugno dam, segment 4 receives the sediments delivered by the Sarmento River, the largest tributary of the Sinni River. However, the sediment transfer downstream to segment 5 (Sn2) is limited as the Sinni River crosses a narrow, confined valley section that blocks the transfer of part of these sediments. Moreover, lateral sediment sources are very limited in segments 5 (Sn2) and 6 (Sn3) as the main channel is decoupled from tributaries and hillslopes. The overall connectivity of the Sinni reaches with sediment sources is progressively decreasing downstream and considered moderate for Sn1, low for Sn2 and very low for Sn3 (Table 6).

The longitudinal connectivity along the Crati River is only marginally disturbed by weirs located in segment 1 and first kilometers of segment 2. Consequently, the study reaches are characterized by a huge down- stream sediment flux, sustained by lateral sediment inputs thanks to the presence of a connected floodplain and a number of tributaries. The overall connectivity of the Crati reaches with sediment sources is considered high (Table 6).

In synthesis, the overall connectivity with sediment sources of the reaches that are located immediately downstream of dams or check dams and receive little or no lateral sediment inputs (Tr4, Bf2, Vol3, Vol4, Sn2, Sn3) is low or very low. It is low-moderate or moderate for the reaches that are only marginally impacted by hydraulic and crossing structures and receive lateral sediment inputs by tributaries, while hillslopes are largely decoupled from the main channel (Tr1, Bf1, Vol1, Vol2, Vol5, Vol6 and Sn1). It is moderate-high or high for the reaches that are only marginally impacted by hydraulic and crossing structures, with main channels quite well connected to the hillslopes and tributaries and bank protection structures no longer in contact with the river banks (Tr2 and Tr3, Cr1–Cr5).

The results obtained on river typology and connectivity can be used to define a catchment-based prioritization of the study reaches for river rehabilitation (Brierley and Fryirs, 2000), aimed at the identification of reaches whose recovery potential maximizes the likelihood of success. In this light, the first priority is attributed to the study reaches placed in category B and characterized by a moderate-high or high connectivity which represent connected reaches with relative high recovery potential where even minimally invasive interventions will facilitate channel recovery. The study reaches placed in category C with respectively low- moderate to moderate or very low to low connectivity are partially isolated and isolated reaches with some potential of rehabilitation whose recovery most likely will require major structural interventions. Finally, the reaches placed in category D are highly degraded reaches characterized by low or very low connectivity and scarce to no recovery potential. For these reaches it is important to minimize off-site impacts to avoid further channel degradation and to sustain the preservation and improvement of the present riparian and aquatic ecosystems.

These results highlight that the maintenance of channel recovery will depend on future interventions and that river management needs to be performed at the catchment scale (Brierley and Fryirs, 2005, 2009; Hillman and Brierley, 2005). The overall good ecological conditions of the study reaches strongly encourage interventions to sustain channel dynamics and recovery. In fact, most of them fall within protected areas, namely Special Protection Areas (SPAs) or Sites of Com- munity Importance (SCIs). As such, they are subject to a series of constraints aimed at safeguarding their ecological integrity. Furthermore, the overall low to moderate levels of hydraulic risk (as specified in the hydrogeological setting plans developed by basin authorities) mainly refer to the presence of cultivated areas, hydraulic and river-crossing structures, and do not pose particular constraints upon risk management. Exceptions include the reaches Cr1 and Cr2 which cross an industrial settlement and are associated with a very high level of hydraulic risk.

To promote and maintain channel recovery, which strictly depends on sediment yield and fluxes, a range of interventions with the principal objective of improving lateral and longitudinal continuity of river processes and reduction or cessation of channel incision are required. In this light, the designation of reaches as an erodible river corridor (Piégay et al., 2005) which allows the river to erode in the future, is fundamental in all reaches characterized by a low level of hydraulic risk. Major human disturbance, especially sediment mining, should be banned. Definition of functional mobility corridor can positively influence not only the natural recovery of the channel system but also the development, preservation and expansion of river habitats and ecosystems (Habersack and Piégay, 2008). For instance, as highlighted by Scorpio et al. (2014) for some rivers in southern Italy, the presence of the Eurasian otter, a semi-aquatic top predator which acts as an umbrella and keystone species, closely depends on the moderate to very good morphological quality of the river and is inhibited in reaches where channel incision has been intense to very intense and disconnectivity is evident.

Specific potentials and limitations of such measures (distribution and amount of on-going bank erosion, degree of conflicting human activities, costs, propriety rights, ecological benefits, etc.) should be assessed as part of an advanced programming phase. For the partially isolated and isolated reaches with some potential of rehabilitation, specific reach-scale interventions such as the removal of levees, bank protections and groynes aimed at improving channel-floodplain connectivity, lateral channel and sediment mobility, can be proposed. Such interventions are particularly suitable for the Volturno reaches Vol1–Vol4 which are bordered by several bank protections and groynes that are obsolete or simply protecting agricultural lands of low value. Regarding the isolated reaches with some potential of rehabilitation and the highly degraded reaches, interventions that provide for sediment transfer from dams and check-dams to downstream reaches will help to avoid further channel degradation and sustain some future channel recovery. For these reaches, interventions aimed at the improvement of the ecological and hydrological functionality of the riparian zones are highly recommended.

Finally, concerning interventions at the catchment scale, it would be useful to remove torrent works (weirs, etc.) and eliminate features in selected minor tributaries with low anthropic pressure to promote sediment delivery to the study rivers. Such measures, once potentials and limitations have been investigated in detail, would provide fundamental support for reach scale interventions which alone may not represent a long-term solution for sediment increase.

6. Conclusions

This study reconstructed the history of channel modifications and evolutionary trajectories of some rivers in southern Italy over the past 150 years. These rivers have undergone considerable channel adjustments that are quite similar to those that occurred in other rivers in central-northern Italy, especially channel narrowing and channel-bed lowering which were primarily driven by human interventions at the reach scale and consequent alteration of sediment fluxes.

Concerning river restoration prospects, knowledge of evolutionary trajectories and current hydromorphological conditions is deemed fundamental when promoting channel dynamics and recovery. The potential for channel recovery, the connectivity conditions and the prioritization of the study reaches are the basis of a range of measures proposed in this paper for river rehabilitation, possibly within the framework of a more promising integrated reach to catchment scale strategy.

Assessment of evolutionary trajectories and potential of channel recovery can support and therefore be encompassed in a broader interdisciplinary approach required for effective river restoration in the framework of sustainable and risk-reduced river management. The results of this study can support work by basin authorities for risk management and regional institutions such as ARPA (Regional Environmental Protection Agency) to comply with the WFD and define ecological quality assessment.

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Figures and tables

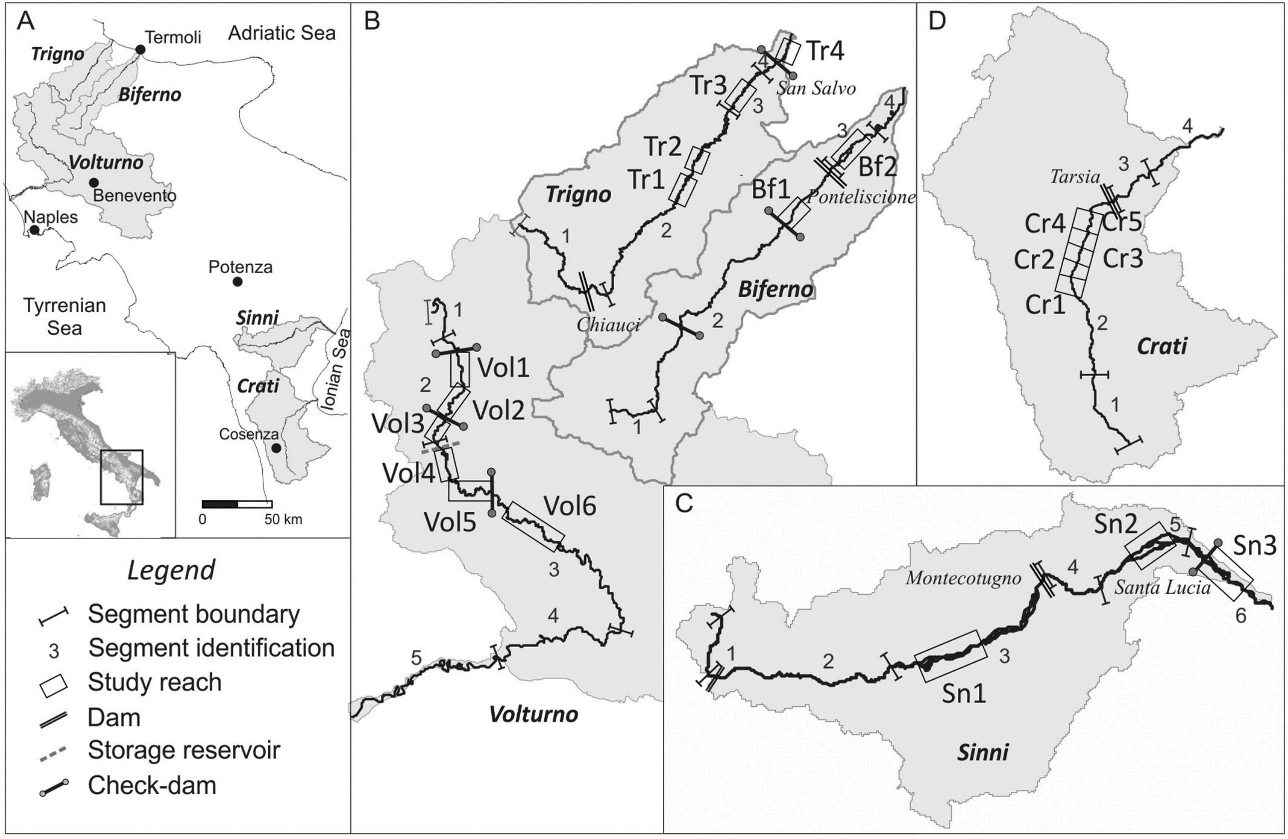
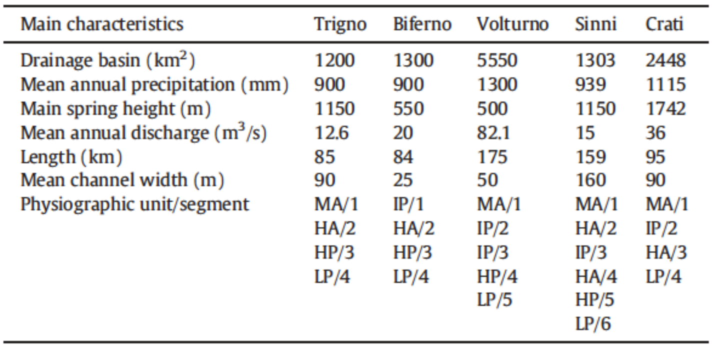


Fig. 1. (A) Location and catchment limits of studied rivers. Location of river segments, study reaches and main hydraulic structures: Trigno, Biferno and Volturno rivers (B), Sinni River (C) and Crati River (D).

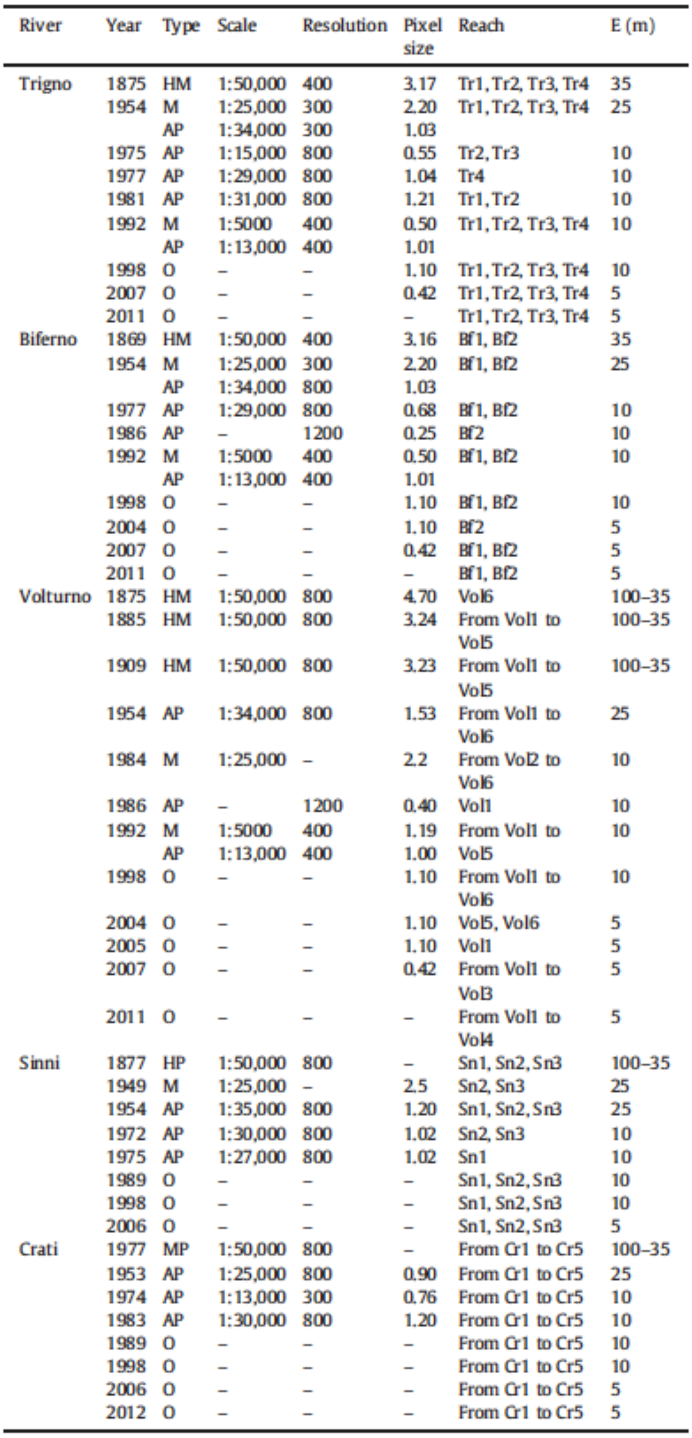


Main characteristics	Trigno	Biferno	Volturno	Sinni	Crati
Drainage basin (km^2)	1200	1300	5550	1303	2448
Mean annual precipitation (mm)	900	900	1300	939	1115
Main spring height (m)	1150	550	500	1150	1742
Mean annual discharge (m^3/s)	12.6	20	82.1	15	36
Length (km)	85	84	175	159	95
Mean channel width (m)	90	25	50	160	90
Physiographic unit/segment	MA/1 HA/2 HP/3 LP/4	IP/1 HA/2 HP/3 LP/4	MA/1 IP/2 IP/3 HP/4 LP/5	MA/1 HA/2 IP/3 HA/4 HP/5 LP/6	MA/1 IP/2 HA/3 LP/4

Table 1 - Main physiographic and hydrological characteristics of studied rivers. Code for physiographic unit: MA = Mountain Apenninic area; HA = Hilly Apennine area; IP =Intermontane Apenninic Plain; HP= High Plain; LP = Low Plain. 1–6 = segment ID

River	Reach	Length (km)	Channel pattern	Slope (%)	Physiographic unit/Segment
Trigno	Tr1	3.4	SAB	0.59	HA/2
	Tr2	4.6	W	0.85	HA/2
	Tr3	3.5	SAB	0.66	HP/3
	Tr4	2.3	S	0.26	LP/4
Biferno	Bf1	4.9	S	0.61	HA/2
	Bf2	7.6	S	0.41	HP/3
Volturno	Vol1	5.1	S	0.51	IP/2
	Vol2	4.6	SAB	0.46	IP/2
	Vol3	2.3	S	0.43	IP/2
	Vol4	4.6	SAB	0.45	IP/2
	Vol5	11.5	M	0.15	IP/3
	Vol6	17.9	S	0.10	IP/3
Sinni	Sn1	6.0	B	0.60	IP/3
	Sn2	3.8	B	0.65	HP/5
	Sn3	3.3	SAB	0.42	LP/6
Crati	Cr1	2.0	SAB	0.30	IP/2
	Cr2	2.9	S	0.20	IP/2
	Cr3	2.0	SAB	0.20	IP/2
	Cr4	3.8	S	0.10	IP/2
	Cr5	3.4	SAB	0.59	IP/2

Table 2 – Main morphological features of studied reaches. Channel patterns: braided (B),wandering (W), sinuous with alternate bars (SAB), sinuous (S), meandering (M). For codes of physiographic units and segments ID, see Table 1.



River	Year	Type	Scale	Resolution	Pixel size	Reach	E (m)
Trigno	1875	HM	1:50,000	400	3.17	Tr1, Tr2, Tr3, Tr4	35
	1954	M	1:25,000	300	2.20	Tr1, Tr2, Tr3, Tr4	25
		AP	1:34,000	300	1.03		
	1975	AP	1:15,000	800	0.55	Tr2, Tr3	10
	1977	AP	1:29,000	800	1.04	Tr4	10
	1981	AP	1:31,000	800	1.21	Tr1, Tr2	10
	1992	M	1:5000	400	0.50	Tr1, Tr2, Tr3, Tr4	10
		AP	1:13,000	400	1.01		
	1998	O	–	–	1.10	Tr1, Tr2, Tr3, Tr4	10
	2007	O	–	–	0.42	Tr1, Tr2, Tr3, Tr4	5
	2011	O	–	–	–	Tr1, Tr2, Tr3, Tr4	5
Biferno	1869	HM	1:50,000	400	3.16	Bf1, Bf2	35
	1954	M	1:25,000	300	2.20	Bf1, Bf2	25
		AP	1:34,000	800	1.03		
	1977	AP	1:29,000	800	0.68	Bf1, Bf2	10
	1986	AP	–	1200	0.25	Bf2	10
	1992	M	1:5000	400	0.50	Bf1, Bf2	10
		AP	1:13,000	400	1.01		
	1998	O	–	–	1.10	Bf1, Bf2	10
	2004	O	–	–	1.10	Bf2	5
	2007	O	–	–	0.42	Bf1, Bf2	5
	2011	O	–	–	–	Bf1, Bf2	5
Volturno	1875	HM	1:50,000	800	4.70	Vol6	100–35
	1885	HM	1:50,000	800	3.24	From Vol1 to Vol5	100–35
	1909	HM	1:50,000	800	3.23	From Vol1 to Vol5	100–35
	1954	AP	1:34,000	800	1.53	From Vol1 to Vol6	25
	1984	M	1:25,000	–	2.2	From Vol2 to Vol6	10
	1986	AP	–	1200	0.40	Vol1	10
	1992	M	1:5000	400	1.19	From Vol1 to	10
		AP	1:13,000	400	1.00	Vol5	
	1998	O	–	–	1.10	From Vol1 to Vol6	10
	2004	O	–	–	1.10	Vol5, Vol6	5
	2005	O	–	–	1.10	Vol1	5
	2007	O	–	–	0.42	From Vol1 to Vol3	5
	2011	O	–	–	–	From Vol1 to Vol4	5
Sinni	1877	HP	1:50,000	800	–	Sn1, Sn2, Sn3	100–35
	1949	M	1:25,000	–	2.5	Sn2, Sn3	25
	1954	AP	1:35,000	800	1.20	Sn1, Sn2, Sn3	25
	1972	AP	1:30,000	800	1.02	Sn2, Sn3	10
	1975	AP	1:27,000	800	1.02	Sn1	10
	1989	O	–	–	–	Sn1, Sn2, Sn3	10
	1998	O	–	–	–	Sn1, Sn2, Sn3	10
	2006	O	–	–	–	Sn1, Sn2, Sn3	5
Crati	1977	MP	1:50,000	800	–	From Cr1 to Cr5	100–35
	1953	AP	1:25,000	800	0.90	From Cr1 to Cr5	25
	1974	AP	1:13,000	300	0.76	From Cr1 to Cr5	10
	1983	AP	1:30,000	800	1.20	From Cr1 to Cr5	10
	1989	O	–	–	–	From Cr1 to Cr5	10
	1998	O	–	–	–	From Cr1 to Cr5	10
	2006	O	–	–	–	From Cr1 to Cr5	5
	2012	O	–	–	–	From Cr1 to Cr5	5

Table 3 - Characteristics of materials used: topographic maps (HM=historicalmaps: ≤1926; M=more recent maps: ≥1942), aerial photographs (AP) and orthophotos (O). E=error estimated for channel width evaluation

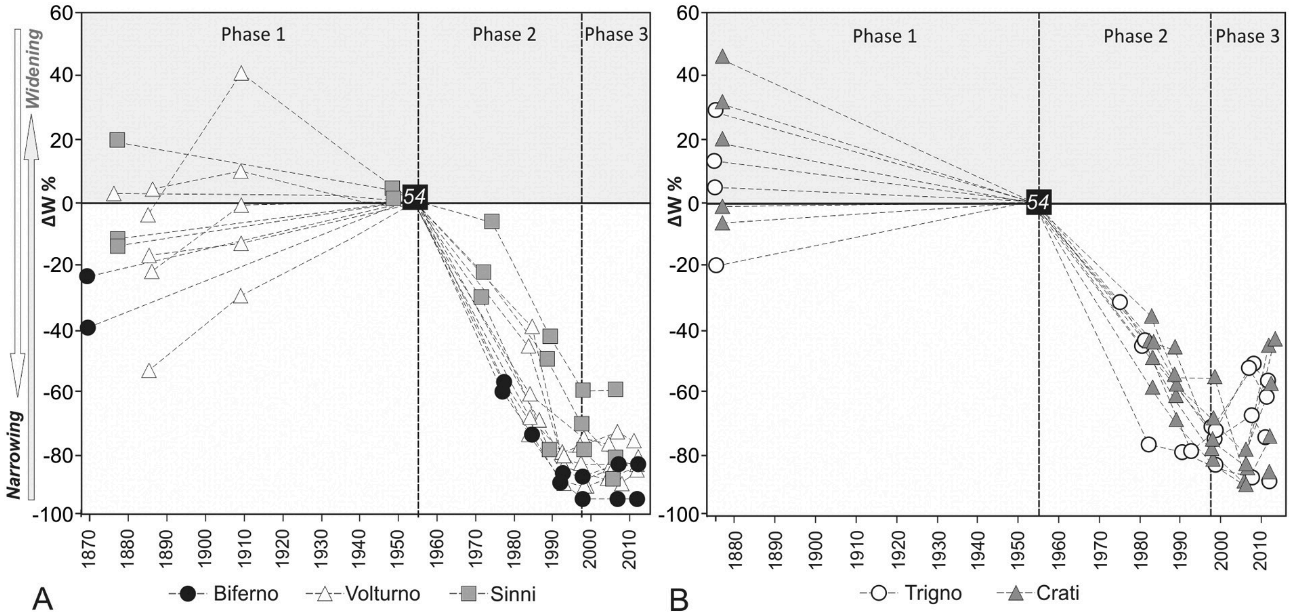


Fig. 2. Channel width variations of the 20 study reaches over the past 150 years calculated by using the channel width variation index ΔW%. (A) Biferno, Volturno and Sinni rivers. (B) Trigno and Crati rivers.

River	Reach	ΔW (%)			W_aPhase 2 ($m\ yr^{-1}$)	$W_a$max Phase 2 ($m\ yr^{-1}$)	W_a Phase 3 ($m\ yr^{-1}$)	Wa1954-Present ($m\ yr^{-1}$)
		Phase 1	Phase 2	Phase 3				
Trigno	Tr1	+14	−75	−75	−4.6	−5.5 (1981–1992)	0.0	−3.6
	Tr2	+5	−72	−62	−5.5	−11.6 (1981–1992)	+2.5	−3.6
	Tr3	+30	−72	−58	−4.5	−6.2 (1975–1992)	+3.0	−2.8
	Tr4	−20	−85	−90	−6.2	−9.7 (1954–1977)	−1.3	−5.1
Biferno	Bf1	−33	−89|	−84	−4.1	−5.0 (1954–1977)	+1.1	−3.2
	Bf2	−23	−96	−96	−7.8	− 9.4 (1954–1992)	−0.2	−6.5
Volturno	Vol1	−17	−83	−84	−5.5	−6.3 (1954–1986)	−0.3	−4.2
	Vol2	−40	−76	−76	−4.9	−12 (1984–1992)	+0.1	−4.8
	Vol3	−20	−85	−83	−3.5	−9.6 (1984–1992)	+0.2	−3.1
	Vol4	−53	−88	−82	−7.4	−8.9 (1954–1984)	+1.6	−6.4
	Vol5	+4	−89	−87	−3.5	−3.9 (1954–1984)	+0.8	−3.0
	Vol6	+3	−75	−77	−1.5	−1.8 (1954–1984)	−0.3	−1.3
Sinni	Sn1	+10	−58	−60	−5.8	−11.0 (1975–1989)	−0.9	−5.0
	Sn2	−12	−70	−82	−21.0	−29.0 (1989–1998)	−20.0	−20.8
	Sn3	−13	−79	−87	−9.4	−15.0 (1972–1989)	−5.4	−8.8
Crati	Cr1	+20	−87	−73	−6.9	−9.5 (1975–1989)	+9.5	−5.4
	Cr2	−6	−87	−84	−5.2	–	+1.4	−4.5
	Cr3	+45	−82	−43	−2.5	–	+10.4	−1.2
	Cr4	+53	−80	−44	−2.5	−5.3 (1989–1998)	+9.8	−1.2
	Cr5	−3	−78	−57	−2.9	−3.1 (1954–1974)	+7.0	−1.9

Table 4 - Channel width variations, ΔW(%),within the study reaches during the three phases calculated with respect to the channel width in 1954 (W54). Phase 1: negative and positive values indicate widening and narrowing, respectively; phase 2: negative values = narrowing; phase 3: higher or lower negative values with respect to values of phase 2 indicate narrowing and widening, respectively.Wa=average annual channel width variation.Wamax Phase 2=maximumWa value and related period for the second phase. For the Crati River,Wa Phase 2 andWamax Phase 2 include data up to 2006.

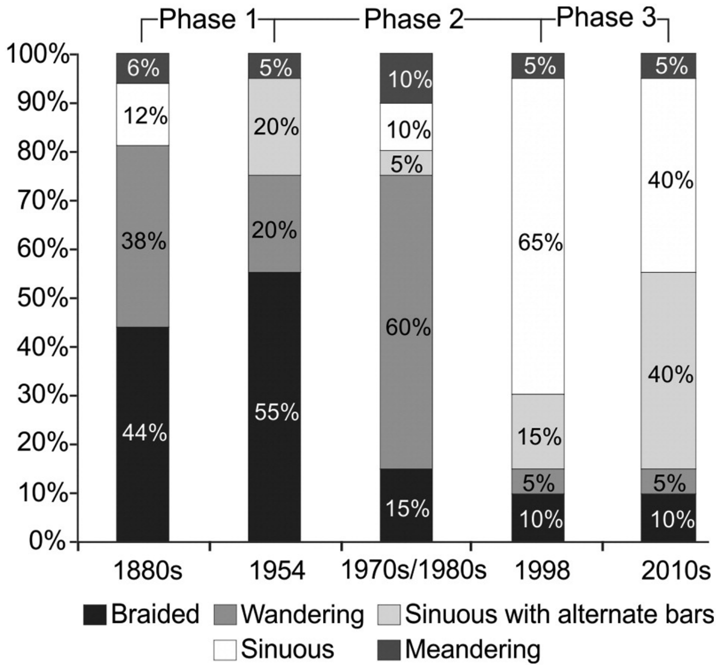


Fig. 3. Pattern distribution (in %) during all three phases.

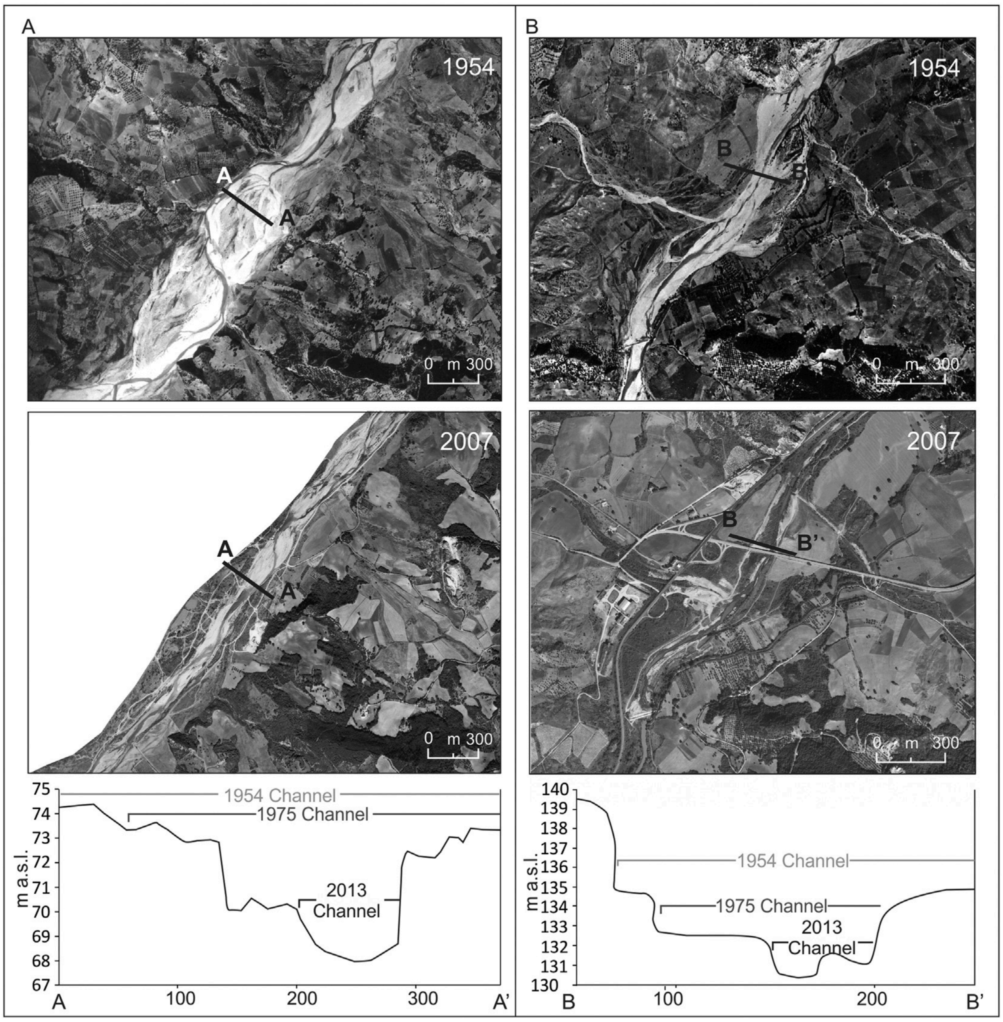


Fig. 4. Cross-sections showing channel incision in the Trigno and Biferno reaches Tr3 (A–A′) and Bf1 (B–B′) over the period 1954–2013.

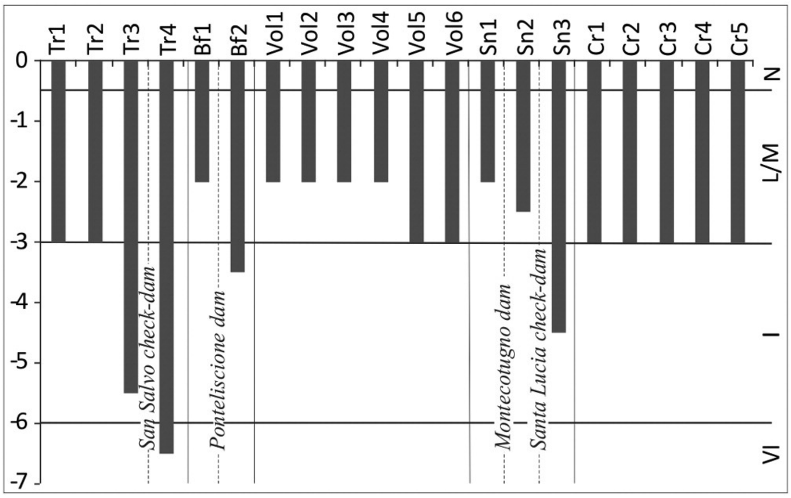
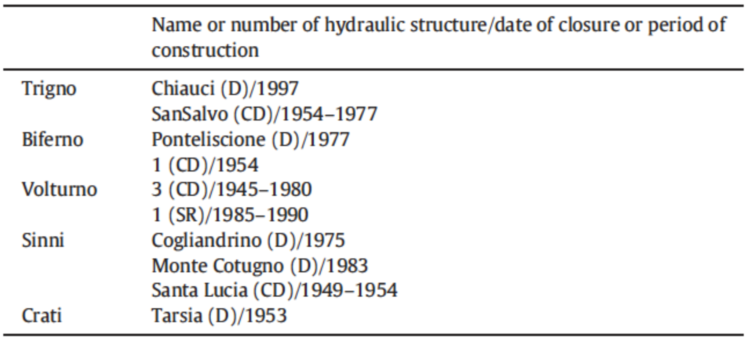


Fig. 5. Amount of channel incision of study reaches from 1954 to 2013. N=negligible; L/M = low or moderate; I = intense; VI= very intense.

Fig. 6. Comparison of a portion of the Crati reach Cr5 showing consistent channel widening from 2003 (A) to 2012 (B).



	Name or number of hydraulic structure/date of closure or period of construction
Trigno	Chiauci (D)/1997 SanSalvo (CD)/1954–1977
Biferno	Ponteliscione (D)/1977 1 (CD)/1954
Volturno	3 (CD)/1945–1980 1 (SR)/1985–1990
Sinni	Cogliandrino (D)/1975 Monte Cotugno (D)/1983 Santa Lucia (CD)/1949–1954
Crati	Tarsia (D)/1953

Table 5 - Hydraulic structures and relative dates of closure or periods of construction: D=dam; CD = check-dam; SR= storage reservoir.

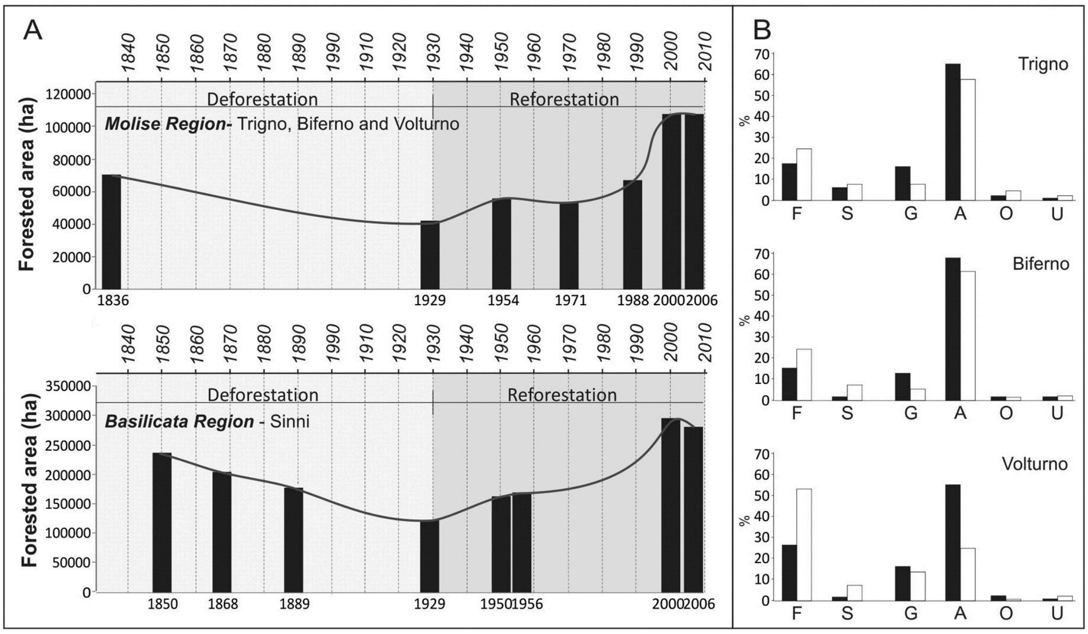


Fig. 7. (A) Forest cover variations from 1836/1850 to 2006 in theMolise and Basilicata regions. (B) Comparison of land cover (in %) in 1954 (in black) and 2006 (in white) in the Biferno catchment and in the portions of the Trigno and Volturno catchments falling within theMolise region; F=forests; S=shrubs; G=grasslands; A=agricultural areas; O=open spaces; U = urbanized areas.

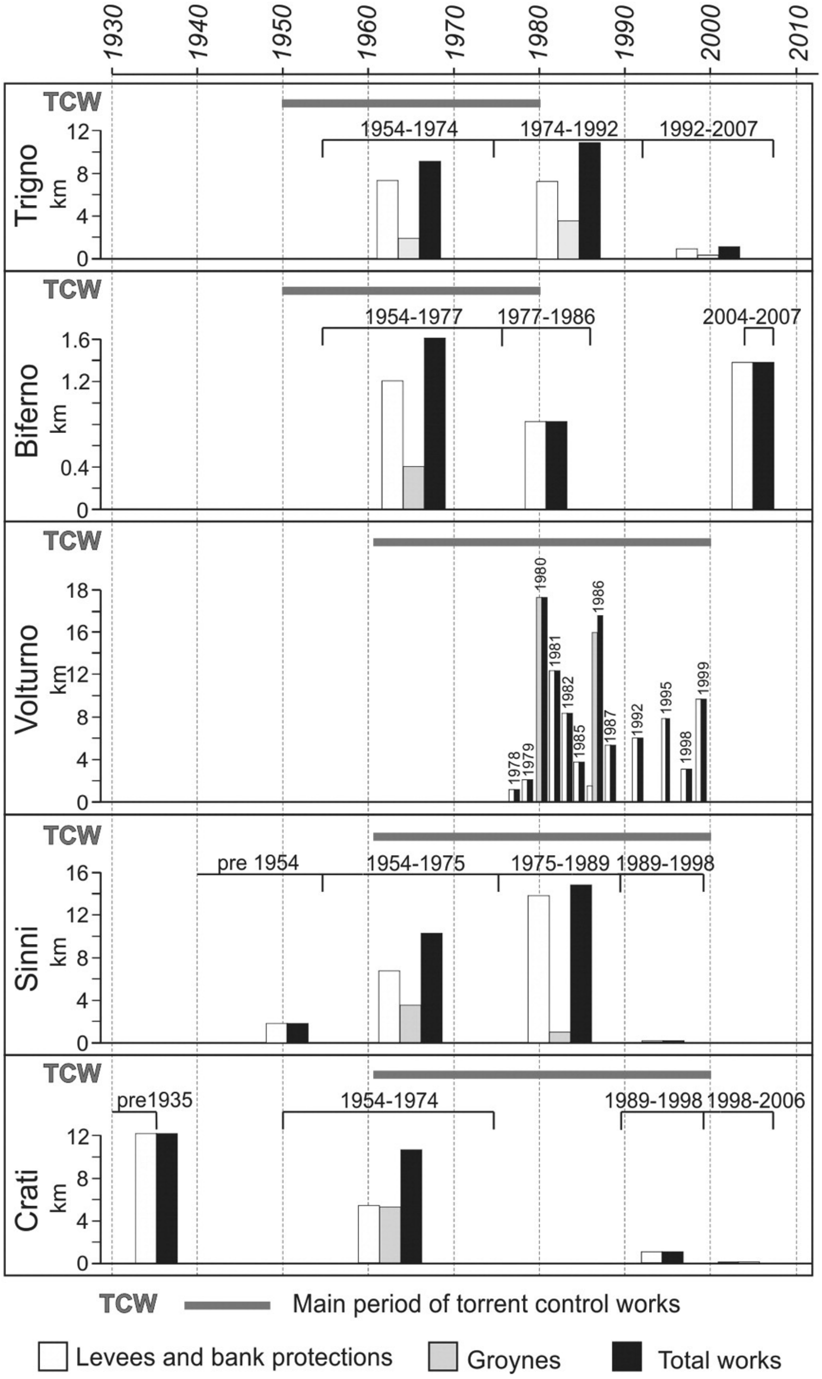


Fig. 8. Peak period of torrent control works in the catchments and length (in km) of river banks with control works constructed during various periods within the study reaches.

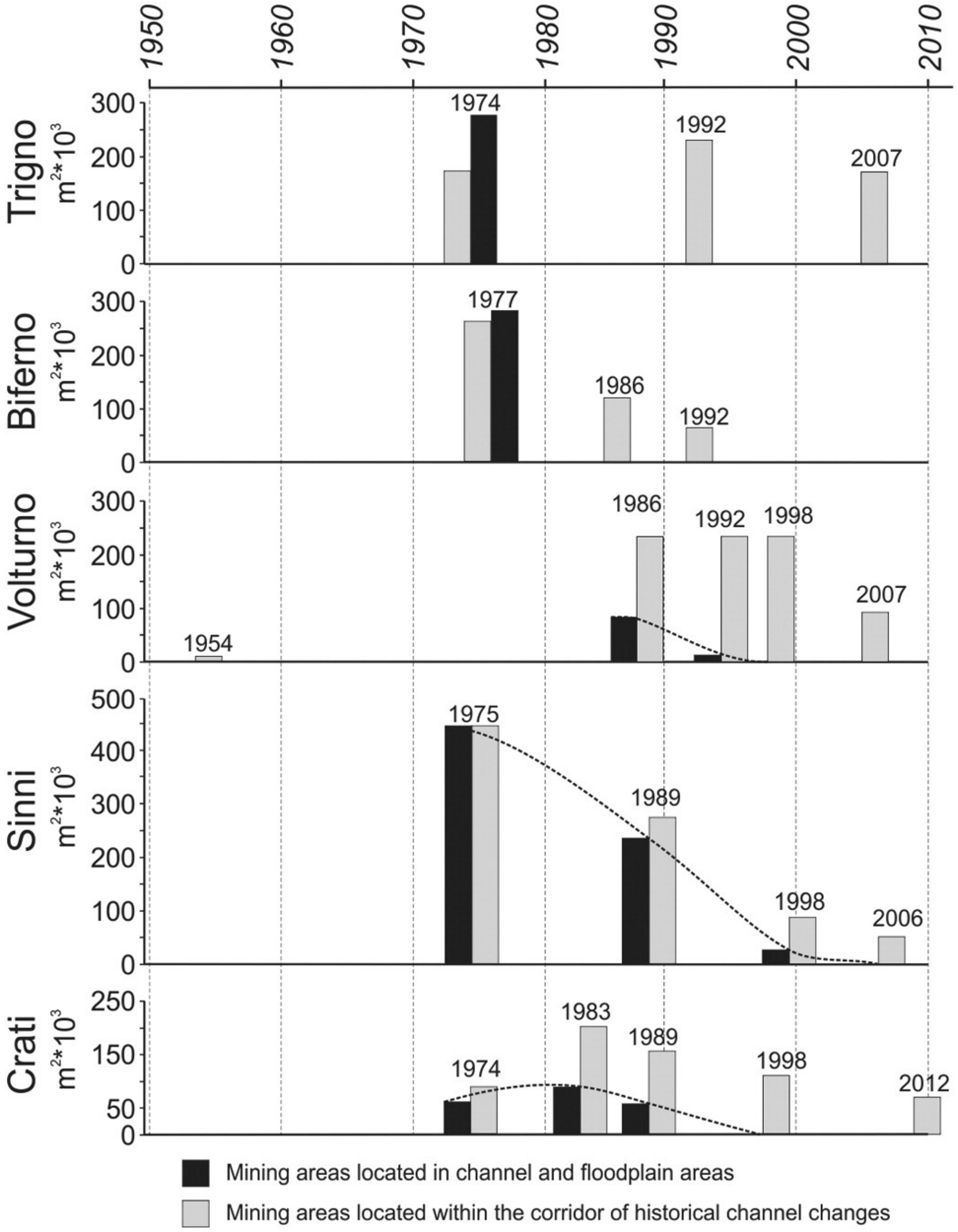


Fig. 9. Extent of mining areas in the study reaches during various periods.

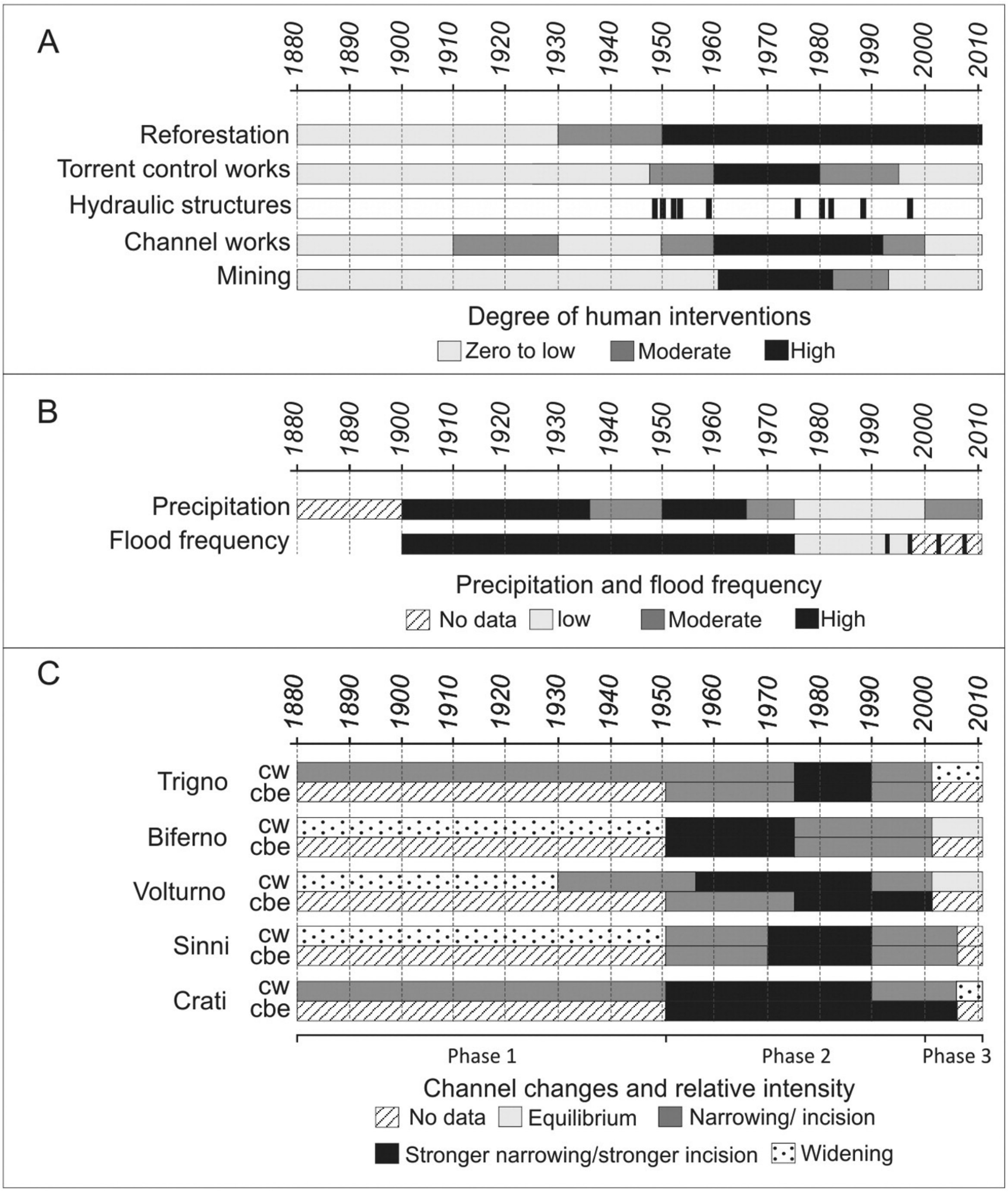
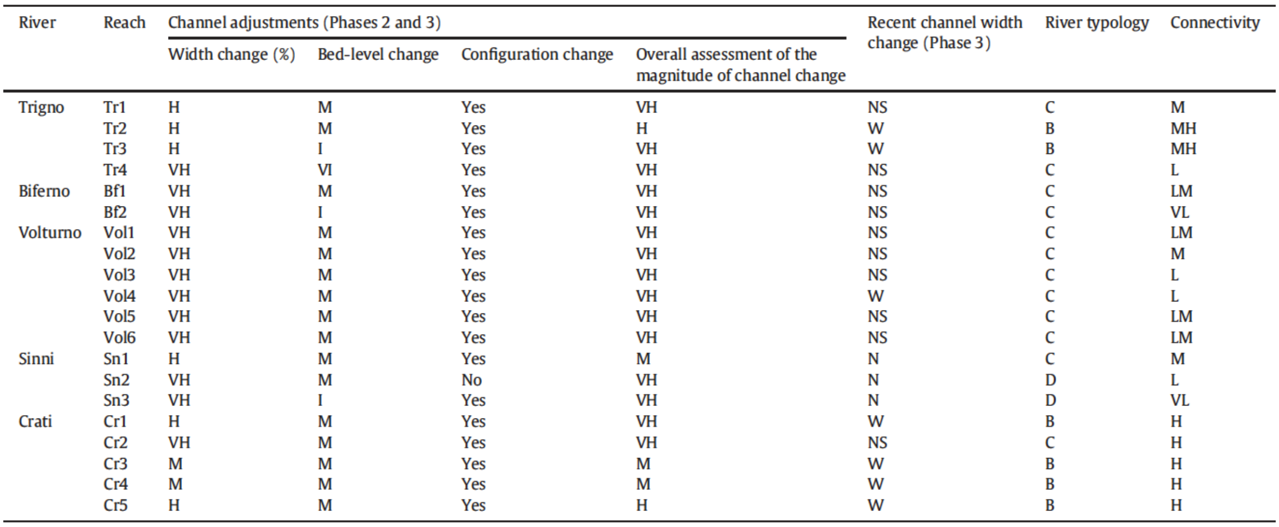


Fig. 10. (A) Types and degree of human interventions. (B)Degree of precipitation and flood frequency over time. (C) Intensity of channel changes (cw=channel width, cbe=channel-bed elevation).



River	Reach	Channel adjustments (Phases 2 and 3)				Recent channel width change (Phase 3)	River typology	Connectivity
		Width change (%)	Bed-level change	Configuration change	Overall assessment of the magnitude of channel change			
Trigno	Tr1	H	M	Yes	VH	NS	C	M
	Tr2	H	M	Yes	H	W	B	MH
	Tr3	H	I	Yes	VH	W	B	MH
	Tr4	VH	VI	Yes	VH	NS	C	L
Biferno	Bf1	VH	M	Yes	VH	NS	C	LM
	Bf2	VH	I	Yes	VH	NS	C	VL
Volturno	Vol1	VH	M	Yes	VH	NS	C	LM
	Vol2	VH	M	Yes	VH	NS	C	M
	Vol3	VH	M	Yes	VH	NS	C	L
	Vol4	VH	M	Yes	VH	W	C	L
	Vol5	VH	M	Yes	VH	NS	C	LM
	Vol6	VH	M	Yes	VH	NS	C	LM
Sinni	Sn1	H	M	Yes	M	N	C	M
	Sn2	VH	M	No	VH	N	D	L
	Sn3	VH	I	Yes	VH	N	D	VL
Crati	Cr1	H	M	Yes	VH	W	B	H
	Cr2	VH	M	Yes	VH	NS	C	H
	Cr3	M	M	Yes	M	W	B	H
	Cr4	M	M	Yes	M	W	B	H
	Cr5	H	M	Yes	H	W	B	H

Table 6
Channel adjustments in the selected river reaches, river typology and connectivity with sediment sources. Width change: moderate (M) b50%; high (H) 50–75%; very high (VH) N 75%. Bed-level change: moderate (M)=2–3m; intense (I) N3–6m; very intense (VI) N6 m. Overall magnitude of channel change. Moderate (M): moderate width and bed-level changes associated with configuration change (Yes); high width changes and moderate bed-level changes without configuration change (No). High (H): width changes are relative high and bed level changes are moderate (M), normally associated with configuration change (Yes). Very high (VH): high to very high width changes and moderate to very intense bed-level changes, normally associated with configuration change (Yes). Recent channel width change (Phase 3): NS = no significant change; N = narrowing; W = widening. River typology, based on recent channel changes: B = moderate widening and equilibrium; C = slight widening, or no changes, and equilibrium; D = narrowing and, eventually, incision. Connectivity with upstream and lateral sediment sources: VL = very low; L = low; LM = low-moderate; M = moderate; MH= moderate-high; H = high.