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SCIENCE

Geomorphology of the floodplain at the confluence of the Aventino and Sangro rivers (Abruzzo, Central Italy)

Tommaso Piacentini[a], Tullio Urbano[a*], Marco Sciarra[a], Ileana Schipani[b] and Enrico Miccadei[a]

[a]*Laboratory of Tectonic geomorphology and GIS. Department of Engineering and Geology (INGEO), Università degli Studi 'G. d'Annunzio' Chieti-Pescara, Via dei Vestini 31, 66100, Chieti Scalo (CH), Italy;* [b]*CIRF Centro Italiano per la Riqualificazione Fluviale, Viale Garibaldi 44A, 30173, Mestre (VE), Italy*

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This paper presents a geomorphological map of the floodplain at the confluence of the Aventino and Sangro rivers (scale 1:10,000), located across the Adriatic piedmont of the Maiella Massif (Abruzzo Region, Central Italy). This area is in the lower reach of the Sangro–Aventino drainage basin, which in the mid-1900s was affected by the creation of four main artificial water reservoirs by damming of the basin's major rivers and the related network of spillway pipes for hydropower purposes. This, combined with climatic factors, induced a strong rearrangement of river channels and floodplains. The fluvial geomorphological features have been analyzed through a detailed-scale multi-temporal analysis based on geomorphological field mapping, topographic analysis, and a remote sensing analysis carried out on aerial photos, orthophotos and Lidar images. The map includes three sections: physiographic and geological setting; main geomorphological map; multi-temporal (1954–2009) and morphometric analysis of the floodplain. The mapping is focused on landforms and continental deposits, mainly linked to fluvial, slope and anthropogenic processes, and to 1954 and 2009 river channels planform analyses and the related morphometric parameters, in order to outline the changes in the river dynamics, strongly influenced by anthropogenic intervention. At a local scale, this type of map can contribute to the understanding of the causes, mechanisms and consequences of the changes in fluvial form and support river management. Finally, it may represent a tool for the assessment of natural hazards in landscapes characterized by intense and rapid geomorphological (fluvial) processes, as well as a tool for correct land management.

Keywords: geomorphological map; floodplain; channel adjustments; anthropogenic influences; Sangro and Aventino river basin; Central Italy

1. Introduction

In Italy, as in other countries within the Mediterranean region, the availability of natural resources and the need for road and rail connections has driven human civilization to utilize alluvial plains, turning farm land into a strategic area for land use, and modifying it for housing industrial parks,

*Corresponding author. Email: tullio.urbano@unich.it

mining areas, artificial water reservoirs and urban areas. As a consequence of human impacts, significant channel changes generally take place, such as vertical adjustment and changes in channel width and pattern (e.g. Kondolf, 1997; Petts, 1979; Petit, Poinsart, & Bravard, 1996). Evidence of such dynamics can be observed in Italian rivers which have been subjected to human disturbance and modification for a long time with most of them having experienced drastic channel adjustments (Surian & Rinaldi, 2003).

According to Dedkov and Mozzeherin (1992), these anthropic impacts are greater in Mediterranean streams than in any other climatic zone. During the twentieth century, the river morphology underwent a strong evolution resulting from human intervention and climatic factors (short-term climatic fluctuations) (Grove, 2001; Surian & Rinaldi, 2003). Furthermore, climate change could further affect the hydrology and morphology of river systems, where changes to the frequency and magnitude of flood flows present the greatest threat. The consequences of changes in flow include, in turn, changes in channel dimensions, gradient, channel pattern, sedimentation, bank erosion rates and channel migration rates (Ashmore & Church, 2001).

From a geomorphological perspective, many rivers are characterized by intense and dynamic geomorphic processes, such as flooding, episodic avulsion, channel adjustment and bank erosion, which can be considered as natural events vital to river and floodplain geomorphological (Leopold, Wolman, & Miller, 1964) and ecosystem processes (Thoms, 2003). Lowland river floodplain–channel interactions influence vegetation establishment. Subsequent sediment–vegetation feedback influences floodplain dynamics and topographic evolution (Hupp & Osterkamp, 1996; Marston et al., 1995; O'Connor, Jones, & Haluska, 2002; Richards, Brasington, & Hughes, 2002), as well as floodplain sediment storage. The sediment deposited on lowland river floodplains comprises one component of a river's multi-dimensional transfer and storage system. Longitudinal, lateral and vertical continuity, and connectivity of the floodplain and channels during various flood magnitudes over time account for the creation and maintenance of floodplain topography and biodiversity. Longitudinal continuity influences downstream sediment supply and floodplain processes (Stanford & Ward, 2001; Ward & Stanford, 1995). Lateral continuity transfers water and sediment from channels onto floodplains (Junk, Bayley, & Sparks, 1989). Thus, floodplain hydrology, including the magnitude and duration of overbank flows, is a critical factor in mitigation efforts (Bedford, 1996) or river restoration and management (Galat et al., 1998; Poff et al., 1997).

Italy and particularly the Abruzzo Region are particularly susceptible to natural hazards due to both their geological and geomorphological peculiarities, as well as to climate and weather conditions. Moreover, large-scale urbanization significantly increased after World War II. Over the last century rivers have undergone remarkable channel adjustments. These have been induced by a range of human interventions such as channelization, bank protection, mining, deforestation, river damming, water intake, but also by climatic factors (such as the short-term climate warming at the end of the Little Ice Age) that lead to drastic changes in discharge regimes, to a natural decrease in sediment supply from hill slopes and to a spontaneous re-colonization of flood plains by vegetation (Grabowski, Surian, & Gurnell, 2014; Grove, 2001; Surian et al., 2009).

Spatial planning in floodplain areas requires an insight into the geomorphology of river systems, in which a view of rivers as four-dimensional systems provides the basis for integrated risk-based planning. Several recent geomorphological cartography projects have considered in detail large sectors of alluvial environments, mostly concentrating in NE Italy (e.g. the Geomorphological Map of the Province of Venice, Bondesan, Meneghel, Rosselli, & Vitturi, 2004). In the new Geological Map of Italy (CARG Project, see Pasquarè & Venturini, 2004), geomorphological features are not generally represented in great detail, although in some of the sheets considering lowland areas the main alluvial landforms (i.e. paleochannels, terraces, crevasse splays and fluvial ridges) have been mapped in detail and could be used to derive an effective map of floodplain

morphology (e.g. Stefani, Vincenzi, & Cibin, 2003). Conversely, the new Geomorphological Map of Italy has only produced several sheets. However, it should be noticed that over the last few years several other local administrations, such as Provinces and Regions, have funded detailed geomorphological maps of alluvial plains, which have not been published.

In this framework, geomorphological maps implemented within a geographic information system (GIS), as is the case in this work, can effectively be used as a tool to support natural risk assessment and other management fields (urban planning, land ecology, forestry and soil science) (Smith, Paron, & Griffiths, 2011). This work has been implemented within the Land Management Plan of the Site of Community Importance of *Lago di Serranella e colline di Guarenna* and *Lecceta di Casoli e Bosco di Colleforeste*, set up by Casoli Municipality in partnership with the *Terre del Sangro-Aventino* association and a wide research group including the Department of Engineering and Geology, 'G. d'Annunzio' University of Chieti-Pescara (Italy), and other universities and institutions.

As with many other Italian streams, the Aventino and Sangro rivers, located in the Adriatic piedmont of the Central Apennines (Italy), have undergone significant channel adjustments over the last 60 years, following the completion of the Casoli dam (1958) and the Serranella weir (1981) and intense gravel mining, with a subsequent dramatic change in the flow and sediment regime.

This explanatory note presents the geomorphological map of the Aventino–Sangro river junction (1:10,000 scale), located in the lower part of the Sangro–Aventino river basin. The mapped area is already represented in a 1:50,000-scale morphotectonic map of the Aventino–Lower Sangro valley (Miccadei, Piacentini, Dal Pozzo, La Corte, & Sciarra, 2013) following an extensive drainage basin scale geomorphological analysis in the central-eastern Apennines (see Miccadei, Piacentini, Gerbasi, & Daverio, 2012b; Miccadei et al., 2013; Piacentini, Sciarra, Miccadei, & Urbano, 2015; Santo et al., 2014).

This work is the result of a detailed geomorphological analysis mostly aimed at highlighting geomorphological features and processes that characterize the valley floor system of the Aventino–Sangro river junction area, and at quantifying the significant adjustments that have affected the river channels since 1954. The resulting map consists of three main sections:

(1) physiographic and geological setting;
(2) main geomorphological map and
(3) multi-temporal (1954–2009) and morphometric analysis of the floodplain.

2. The study area

The Aventino–Sangro river junction area is located in the southeastern part of the Abruzzo Region (Italy), across the Adriatic piedmont of the Maiella Massif (Central Apennines) (Figure 1(a)–(c)).

The Central Apennines are an arc-shaped and asymmetric mountain range marked by alternating > 2000 m high ridges and 500–1500 m deep valleys with a NW–SE to N–S trend, as well as by wide intermontane basins (e.g. Fucino Plain, Sulmona Basin). It is a Neogene fold-and-thrust belt consisting of a north-east migration of a chain-foredeep system toward the Adriatic foreland (Patacca & Scandone, 2007). Since the Late Pliocene, the thrust belt has been affected by regional uplift and extensional tectonics, inducing the displacement of the main ridges of the chain, the formation of tectonic valleys and intermontane basins, and the emergence of the western Adriatic area, with the subsequent evolution of the Apennine piedmont (Piacentini & Miccadei, 2014; and references therein).

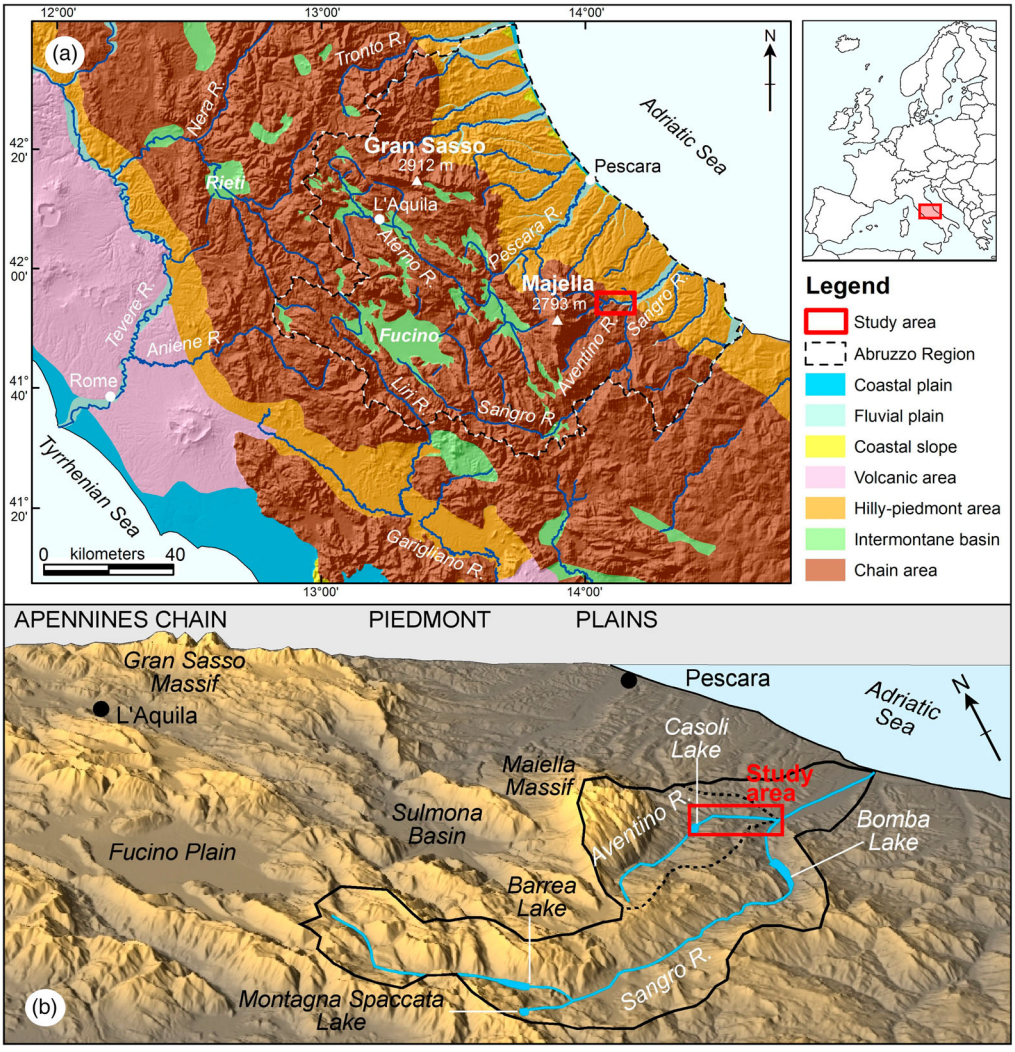

Figure 1. (a) Physiographic domains of Central Italy and (b) shaded relief of the southeastern Abruzzo Region (SRTM-90) with the main hydrographic elements characterizing the Aventino–Sangro river basin.

The Adriatic piedmont, linked to the chain area by an abrupt morphologic boundary, shows a *cuestas*, *mesas* and *plateaux* landscape (on Middle Pliocene to Early Pleistocene late-orogenic clay–sand–conglomerate marine sediments), sloping from ~1000 m a.s.l. along the chain front (Maiella Massif) to <100 m a.s.l. close to the coast. Here, the main rivers flow along wide floodplains, generally in a SW–NE direction, while the minor rivers are entrenched within narrow valleys and gorges. A complex sequence of post-orogenic Quaternary continental deposits, mostly consisting of slope, fluvial and beach sediments, overlie the Pliocene–Pleistocene marine sequences (ISPRA, 2010a, 2010b). Considering the alluvial environments, a Middle Pleistocene–Holocene staircase of terraces characterizes most of the valleys of the Adriatic piedmont and is related to the combination of climate, uplift and local tectonics (Buccolini et al., 2007, 2010; D'Alessandro et al., 2008; Fontana, 2012; Nesci, Savelli, & Troiani, 2012).

The study area is situated in the Sangro River Basin, with an area of 1560 km^2, and a mean elevation of about 970 m a.s.l. The Sangro River is 107 km long, and, like many rivers of the region, is a perennial and allogenic river originating from the Apennines range and flowing eastwards to the Adriatic Sea through the piedmont area. Its main tributary is the Aventino River, which flows for 45 km along the eastern side of the Maiella massif and then into the Sangro 20 km from the coast, draining an area of about 432 km^2 (D'Alessandro, Miccadei, & Piacentini, 2008).

The area is characterized by Mediterranean climate, with wet winters, dry summers, and periods of high snowmelt and rainfall (spring). Currently, annual precipitation ranges between 1000 mm in the mountains and 700 mm along the coastal sector (see upper slice of the Main Map).

Within the Sangro–Aventino basin, two dams (the Montagna Spaccata and Barrea lakes) in the chain area and two in the piedmont area (the Bomba and Casoli lakes) were built between 1949 and 1958 for hydropower purposes, altering the flow regimes (Capelli, Miccadei, & Raffi, 1997). For the study area, the most relevant hydrological element of anthropogenic origin is the Casoli Lake along the Aventino River (westernmost area of the Main Map). A minor weir (overflow dam) was built for industrial and agricultural purposes in 1981 in the lower part of the drainage basin, 0.5 km downstream of the Aventino–Sangro junction, forming the Serranella lake/marsh area (north-eastern part of the Main Map). Another significant hydrological element is the outfall channel of two spillway pipes used to carry pressurized water from the Bomba Lake and the Casoli Lake dams, respectively (the former along the Sangro River, about 10 km southwards), to the hydropower plant near the hamlet of Sant'Angelo (500 m southwards of the Selva di Altino village).

The mean annual water discharge of the Aventino River, immediately downstream of the Casoli Lake, was reduced from ~5.5 m^3/s (1937–1954 time series) to the current value of 0.5 m^3/s (limit for minimum environmental flows prescribed by law) by the river damming (whose effective value is occasionally even below the limit). Downstream, from this point to the junction with the Sangro River (eastern mapped area), the Aventino River receives water from minor tributaries (Verde, Avello, Laio, Rio Secco and Gogna streams) for an overall annual average discharge of ~4.5 m^3/s, and from the above-mentioned outfall channel (extremely variable discharge, up to a maximum flow regime of 42 m^3/s). Downstream of the Aventino–Sangro river junction, the hydraulic changes due to damming are slightly less evident and the mean annual water discharge of the Sangro River is reduced from ~27 m^3/sec (1937–1954 time series) to ~20 m^3/s (1977–2008 time series).

3. Methods

A detailed-scale geomorphological analysis allowed the creation of the large-scale map presented here (at 1:10,000 scale), as well as an outline of the main adjustments of the Aventino River over the last 60 years. The analysis is the result of mainly geological and geomorphological field mapping, air-photo and photogeology interpretation integrated with a multi-temporal and morphometric analysis of fluvial channels. It is supported by the creation of a digital elevation model (DEM) from 1:5000 scale Regional Technical Maps (Abruzzo Region, 2007), a key tool in the detection of low-relief landforms (Castiglioni, 1997) and a common analysis and representation method in alluvial geomorphology.

Air-photo interpretation was performed using 1:33,000 scale aerial photos (Abruzzo Region, 1987; IGMI, 1954a), 1:5000 scale orthophoto color images (Abruzzo Region, 2009), 1:25,000 scale topographic maps (IGMI, 1954b), and high resolution (1 m × 1 m) Ligh Detecting And Ranging (LiDAR) DEMs to support the mapping of the main landforms. The maps and photos were provided by the Struttura Speciale di Supporto Sistema Informativo Regionale of the

Abruzzo Region (or viewed on the webgis http://www.regione.abruzzo.it/xcartografia/), while the LiDAR DEMs were consulted through a Web Map Service (WMS) of the National Geoportal Maps (http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/servizi-LiDAR/LIDAR_ABRUZZO.map).

Geomorphological field mapping was carried out on a 1:5000 scale, investigating outcropping marine deposits, local marine bedrock lithology, continental deposits cover and different types of landforms (structural, slope, fluvial and anthropogenic). Particular attention was devoted to the analysis of floodplain and abandoned channels, and to the identification of the bankfull channels (Leopold, 1994). The mapping was performed according to the guidelines of the Geological Survey of Italy (ISPRA, 2007; SGN, 1994) and in accordance with the relevant literature concerning geomorphological mapping and fluvial geomorphology (e.g. Bondesan et al., 2004; GNGFG, 1994; Miccadei, Orrù, Piacentini, Mascioli, & Puliga, 2012a, 2012b; Piacentini et al., 2015; Rinaldi, Surian, Comiti, & Bussettini, 2013; Smith et al., 2011).

In order to provide quantitative data on channel planform adjustments, a multi-temporal analysis (1954 and 2009) was performed in a GIS on the basis of topographic maps, aerial photos/orthophotos and LiDAR images (for details see tables on the Main Map), supported by data obtained from field mapping. The Aventino River channel was sub-divided into homogeneous channel reaches, calculating, for each one, the following parameters (according to Rinaldi et al., 2013): (1) degree of confinement (Church, 1992); (2) index of confinement (Brierley & Fryirs, 2005); (3) average bankfull channel width (Surian, Ziliani, Cibien, Cisotto, & Baruffi, 2008); (4) braiding index (Egozi & Ashmore, 2008); (5) anabranching index (Nanson, 2013); (6) sinuosity index (Surian et al., 2009) and (7) channel morphology (Rinaldi et al., 2013).

Finally, the interpretation and combination of data from different analyses allowed us to produce an overall qualitative and quantitative geomorphological characterization of floodplains, and so evaluate adjustments to the river system from anthropogenic activity (weirs, dams, changes in the discharge regimes). The morphological effects on the Aventino River are summarized in a schematic geomorphological cross-section of the valley.

4. Geomorphological map overview

4.1. *Orographic and hydrographic setting*

The Aventino–Lower Sangro valley reaches its maximum altitude on the Majella Massif (2783 m a.s.l.), while to the east the topography slopes down with abrupt changes to the Aventino River Valley. Here, the Aventino River is dammed at a ~100 m deep gorge to form the Casoli Lake (250 m a.s.l.), located in the westernmost mapped area. Downstream of the ~800 m long gorge, the river flows from 210 m a.s.l. down to its junction with the Sangro River (~ 90 m a.s.l., easternmost mapped area). The longitudinal river gradient ranges from 10.6 m/km on the western side of the mapped area to 8.8 m/km in the central part, and to 11.5 m/km in the eastern sector (with local values of 14.06 m/km in the Guarenna-Selva di Altino bridge area). The overall valley floor is characterized by an alluvial plain with variable widths (from ~350 to > 1000 m) and is surrounded by hilly relief with irregular slopes (Figure 2).

The Aventino River drains the eastern slope of the Majella Massif, collecting various tributaries such as the Verde, Avello, Laio, Rio Secco and Gogna streams (Figure 2(c)). The latter, partially within the mapped area, shows a marked meandering pattern and flows into the Serranella Lake. The Aventino River, conversely, shows an anabranching channel superimposed on an ancient braided channel (see Section 5).

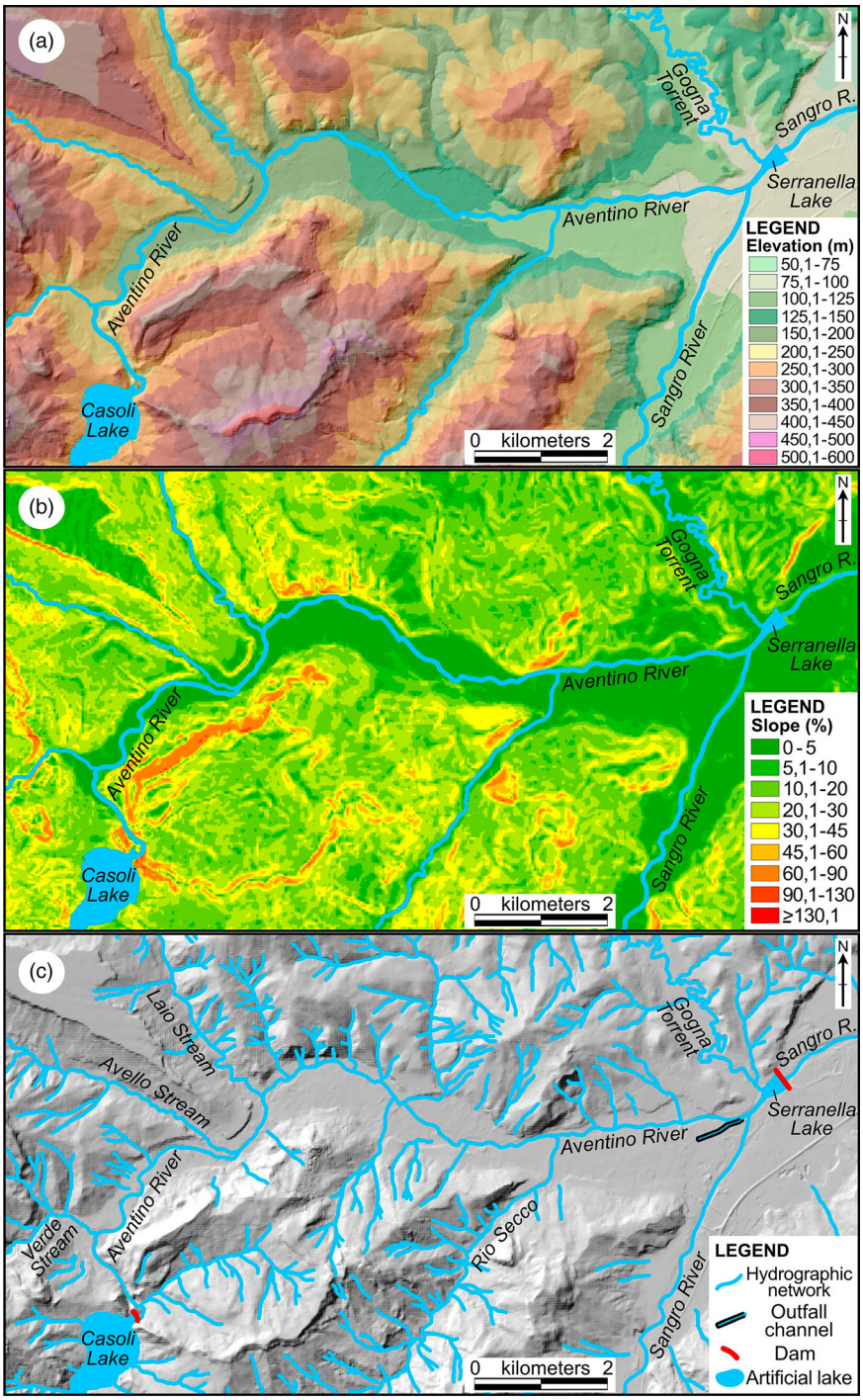

Figure 2. Physiographic features of the study area: (a) elevation map; (b) slope map and (c) shaded relief with main hydrographic features.

4.2. *Lithology*

The outcropping lithologies in the investigated area mainly consist of near-surface continental deposits (∼85%). These deposits lie on a marine bedrock made up of limestone and marly-limestone levels – topping a marly pelagic succession and chaotic clay assemblages pertaining to the Meso-Cenzoic Molise basin succession (Festa, Accotto, Coscarelli, Malerba, & Palazzin, 2014; Patacca & Scandone, 2007) – and of a clay–sandstone–conglomerate belonging to the Upper Pliocene–Lower Pleistocene marine succession of the *Formazione di Mutignano* of ISPRA (2010a, 2010b).

The continental deposits range in age from the Upper Pleistocene to the Holocene, and mainly consist of fluvial (∼50%) and backfill (∼5%) deposits, fully covering the valley bottoms; landslide deposits (∼15%); and slope and colluvial deposits (∼30%) are scattered along the valley slopes.

The outcropping lithologies have been classified based on their depositional environment according to the geological mapping guidelines issued by the Italian Geological Survey (SGN, 1992). The mapped lithology units (legend on the Main Map) are listed in the following subsections (the numbers in brackets refer to the map) and are also referred to the related units on the official Italian Geological Map of the area (ISPRA, 2010a, 2010b).

4.2.1. *Marine bedrock (units from 10 to 13):*

4.2.1.1. *Argille varicolori (13)*. This unit is made up of clay and marly-clayey deposits, with colors varying from red to brown, and from green to gray, moderately compact, in a chaotic setting characterized by a pervasive scaly cleavage. The maximum observed thickness is $<$ 100 m. These clays represent the oldest unit of the study area (Oligocene–Miocene) and are referred to as the *Argille Varicolori* auct. (Patacca & Scandone, 2007; Selli, 1962).

4.2.1.2. *Marly-limestone (12)*. This unit consists of gray-whitish, coarse-grained, bioclastic limestones and marly-limestone, arranged in decimeters-to-meters thick beds and interbedded with marly and calcilutite levels from light gray to dark gray (Figure 3(a)). Locally, detrital facies are rich in fossils, such as Mollusc (e.g. Ostreids), Bryozoa and *Lithothamnium*. The maximum outcropping thickness is ∼200 m. It is referred to as the *Formazione di Tufillo* auct. (Selli, 1962) and dates back to the Middle-Upper Miocene age.

4.2.1.3. *Claystone-sandstone (11)*. This unit is made up of alternating yellowish claystone and sandstone arranged in centimeters-to-decimeters thick beds, with rare turbiditic sandstone and calcarenite horizons up to 2 m thick.

The maximum observed thickness is up to 50 m. These rocks are referred to as the *Flysch di Agnone* auct. (Selli, 1962) and date back to the Upper Miocene–Lower Pliocene age.

4.2.1.4. *Clay (10)*. This unit consists of blue-gray clay and marly-clay interbedded with thin sand and clayey-sand levels (Figure 3(b)). Stratification is not clearly evident, but locally plane-parallel thin layers are present. The sand/clay ratio is $<<$ 1. The maximum observed thickness is $>$ 150 m. The unit is referred to as the *Formazione di Mutignano* (FMTa) of ISPRA (2010a, 2010b). The age is Upper Pliocene p.p.—Lower Pleistocene p.p.

4.2.2. *Continental deposits (near-surface deposits, units from 1 to 9)*

4.2.2.1. *Terraced fluvial deposits (9)*. This unit is made up of fluvial conglomerates, generally clast supported in a sandy matrix, with mostly calcareous pebbles and cobbles (size 5–10 cm),

Figure 3. Marine and continental deposits of the study area (numbers refer to the legend of the map): (a) marly-limestone bedrock, 12; (b) blue-gray clay deposits, 10; (c) strath contact between the bedrock (Clay deposits, 10) and the Terraced fluvial deposits, 9; chaotic assemblage of landslide material, 2; (e) colluvial deposits made up of a chaotic mixture of calcareous, well-rounded pebbles and cobbles in a silty matrix, 5 and (f) heterometric Fluvial channel gravels (4a) of the Sangro River with a detailed view of a lens made of coarse to medium sands.

and occasionally marly and cherty pebbles, from sub-rounded to well-rounded (Figure 3(c)). They are arranged in decimeters-to-meters thick layers and lenses, with cross bedding and imbricated structures; several decimeters-to-1 m thick lenses and layers of sands and silts are interbedded. Occasionally, lenses of clay, peats, calcareous concretions and paleosols are present. The thickness varies from a few meters to about 20 m. This unit is referable to the terraced fluvial–alluvial deposits of the Aventino and Sangro rivers (D'Alessandro et al., 2008; Miccadei et al., 2013), dating from the Middle-Upper Pleistocene age.

4.2.2.2. *Ancient landslide deposits (8)*. Ancient landslide deposits are made up of a chaotic assemblage of marly-limestone, calcarenite and conglomerate boulders, with very large subordinate blocks of marly-limestone deposits, in a sandy and clay matrix. The observed thickness is heterogeneous and ranges from a few to > 100 m.

4.2.2.3. *Fluvial plane deposits (7)*. This unit consists of sand and gravel, with lenses and levels of silt and clay, and calcareous concretions; gravel is made up of heterometric (size 1–30 cm) and polygenic (calcareous and cherty) clasts, with rounded and sub-rounded shapes, mainly matrix-supported. The thickness ranges from 1 to 5 m. This unit is referred to as the 'alluvial deposits'(olo_b) of ISPRA (2010a, 2010b) and dates back to the Holocene age.

4.2.2.4. *Scree slope deposits (6)*. This unit consists of loose to weakly cemented scree slope deposits, composed of angular and etherometric calcareous clasts, with a poor sandy matrix. Locally, metric and decametric marly-limestone blocks are present. The unit is referred to as the 'slope deposits' (olo_a) of ISPRA (2010a, 2010b) and dates back to the Holocene age. The observed thickness is 1–10 m.

4.2.2.5. *Eluvial-colluvial deposits (5)*. This unit consists of loose to moderately firm deposits in a chaotic assemblage, with silt, clay, sand and reworked soil sediments. Polygenic and heteometric clasts having sizes ranging from several centimeters to few decimeters are included. These deposits are referred to as the 'colluvial deposits'(olo_{b2}) of ISPRA (2010a, 2010b) and date from the Holocene. The observed thickness is variable, ranging from a few meters to 10 m.

4.2.2.6. *Fluvial deposits (4)*. This unit is made of gravel with small levels and lenses of coarse to medium sand; gravel is mainly made up of calcareous and heterometric clasts, with sub-rounded to sub-angular shapes, with a sandy matrix. The observed thickness is < 2 m. Based on the recent adjustment of the Aventino River, this unit has been divided into two similar subunits:

- present-day channel deposits (4a) (Figure 3(f)) and
- pre-dam channel deposits (4b).

These deposits are referred to as the 'alluvial deposits'(olo_b) of ISPRA (2010a, 2010b) and date back to the Holocene.

4.2.2.7. *Palustrine deposits (3)*. This unit is made up of inconsistent clay and silt rich in organic matter, with interbedded fine sand and peat levels, and subordinate lenses of heterometric fluvial gravel. These deposits are referred to as the 'palustrine deposits' (olo_e) of ISPRA (2010a, 2010b) and date back to the Holocene. The estimated thickness is < 2 m.

4.2.2.8. *Landslide deposits (2)*. This unit consists of a chaotic arrangement of polygenic clay and sand deposits, with marly-limestone and conglomerate boulders, and subordinate marly blocks (Figure 3(d)). The unit is referred to as the 'landslide deposits' (olo_{a1}) of ISPRA (2010a, 2010b) and dates from the Holocene. The thickness ranges from a few to 10 m.

4.2.2.9. *Backfill deposits (1)*. This unit is made up of chaotic and heterometric deposits constituted by gravel, sand, clay and fragments of waste material. In abandoned quarries, sand and clay with scattered pebble and cobble quarry waste are present. The unit is referred to as the 'backfill

deposits' (olo_h) of ISPRA (2010a, 2010b) and dates back to a very recent Holocene age (last century). The observed thickness is < 5 m.

4.3. *Geomorphology*

The study area is characterized by diverse landforms, heterogeneously distributed in relation to the morphological, hydrographic, and lithological setting and to climatic factors. The most recurrent features are fluvial landforms, slope landforms due to the action of gravity, and soil erosion landforms, sometimes controlled by the lithostructural characteristics of the area (legend on the Main Map). The geomorphological mapping was mainly aimed at providing a detailed overview of the recent evolution and present-day dynamics of the Aventino River valley floor system.

4.3.1. *Structural landforms*

Mapped structural landforms, mostly recognized across the Aventino River valley watersheds, include straight ridges and structure-controlled saddles. These landforms are mainly due to selective erosion on, respectively, harder (marly-limestone) and softer ('Argille varicolori' and clay) bedrock units, also affected by joints and a small faults network, linking the complex structural setting of the area and surface processes (see also D'Alessandro et al., 2008).

4.3.2. *Slope gravity landforms*

These landforms mainly consist of a large number of landslides, both active and inactive, and of two large ancient landslides, now partly covered by scree slopes and colluvial deposits.

Mapped slope gravity landforms include degradational scarps, gravity trenches or fissures, reverse slopes in the landslides, small landslides, soil creep, earthflow and complex landslides with related scarps (Figure 4(a) and 4(b)).

In detail, the north-eastern slope of Colle Foreste is characterized by active or quiescent earthflows and complex landslides, involving claystone-sandstone, marly-limestone and 'Argille varicolori' deposits.

Along the southern valley side (NE slope of the Casoli ridge) and the northern valley side (NW part of the map), the occurrence of an irregular topography marked by steep slopes, reverse slopes, concave complex slopes and downslope concave arched scarps on the top of the ridges is a clear morphological expression of two ancient landslides (Figure 4(a)). The landslides involved a large volume of marly-limestone and claystone-sandstone lithologies (thickness 2–300 m) that constitute the ridge, and were characterized by very complex failure dynamics, with a compound rotational and translational slide in the upper part of the slope evolving into a flow in the lower part.

Concerning its state of activity, the landslide now appears to be inactive, as also suggested by the presence of a large amount of scree slope deposits in the upper part of the landslide and of colluvial deposits in the lower one.

4.3.3. *Fluvial and soil erosion landforms*

The mapped fluvial and soil erosion landforms include fluvial erosion scarps, terrace scarps, riverbank retreats, entrenched fluvial segments, river beds with a trend to down-cutting, gullies, badland areas, swampy depressions, alluvial fans, V-shaped valleys, concave valleys, flat-bottom valleys and hanging valleys (Figure 4(c)–(f)). These landforms characterize the alluvial

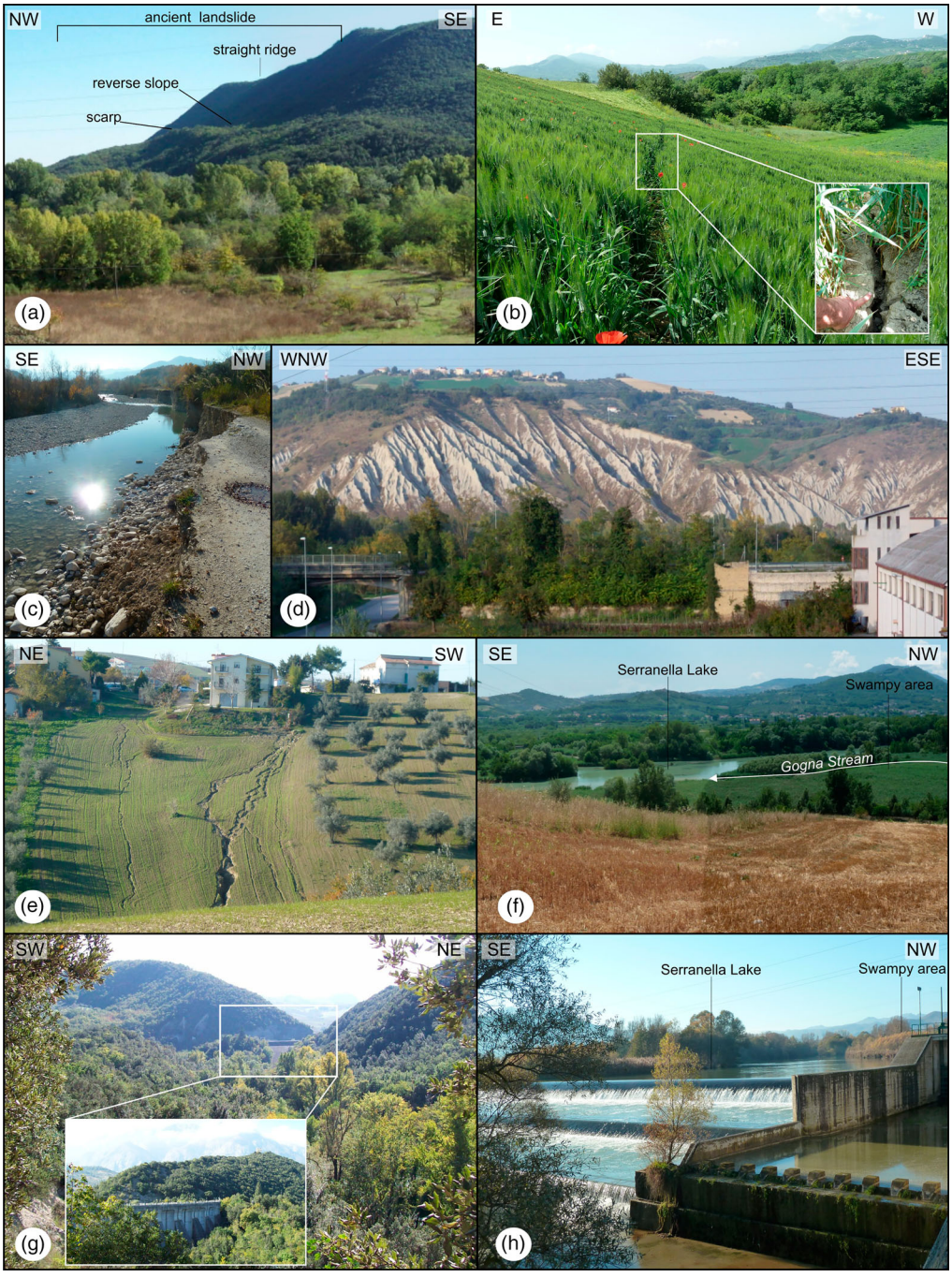

Figure 4. Geomorphological features of the study area; (a) complex ancient landslide; (b) gravity fissure; (c) the fluvial erosion scarp on a secondary road marks a riverbank retreat; (d) badlands area along the Aventino River valley; (e) gully erosion in agricultural areas; (f) swampy area; (g) the Casoli Lake dam on the Aventino River in the area of a deep gorge and (h) river weir (overflow dam) on the Sangro River forming the Serranella Lake (easternmost part of the study area).

plains of the Aventino, Sangro and Gogna rivers, or they are locally entrenched into the main valley slopes.

The channels of the Aventino and Sangro rivers are laterally confined by fluvial erosion scarps on fluvial deposits, with scarps ranging from a few decimeters (south-westernmost study area) to ~5 m (Sangro–Aventino junction area). Generally, these scarps are weathered or strongly reshaped by human intervention. Within this lateral boundary (related to the pre-dam bankfull stage), the streams are entrenched and the bankfull level is indicated by further scarps (riverbank) delimiting the present-day bankfull channel. This break is marked by a system of fresh scarps with local variable heights ranging from 1 to 7–8 m (Figure 4(c)). In terms of channel evolution stages, this channel morphology highlights an overall incision of the streams and the subsequent narrowing of the present-day bankfull channel.

Recognized fluvial landforms and related processes outline a recent and rapid evolution, as in the obvious case of the lower Aventino channel, dominated by intense down-cutting processes (also evidenced by the outcrop of the bedrock along the channel; Figure 5), or – in the case of riverbank retreat – due to meander migration and the subsequent lateral (sideways) erosion by the Gogna Torrent, which caused a loss of agricultural land.

Badlands, gullies and V-shaped valleys are widespread along the slopes on clay and colluvium (Figure 4(d) and (e)). Fluvial terraces are widespread all along the left valley slopes, with elevations above the present valley floor ranging from 25 to about 20 m, highlighting various phases of valley floor dissection. At the mouth of the tributary valley of the main rivers, fluvial plains are sometimes covered by alluvial fans of different sizes, the largest of which is

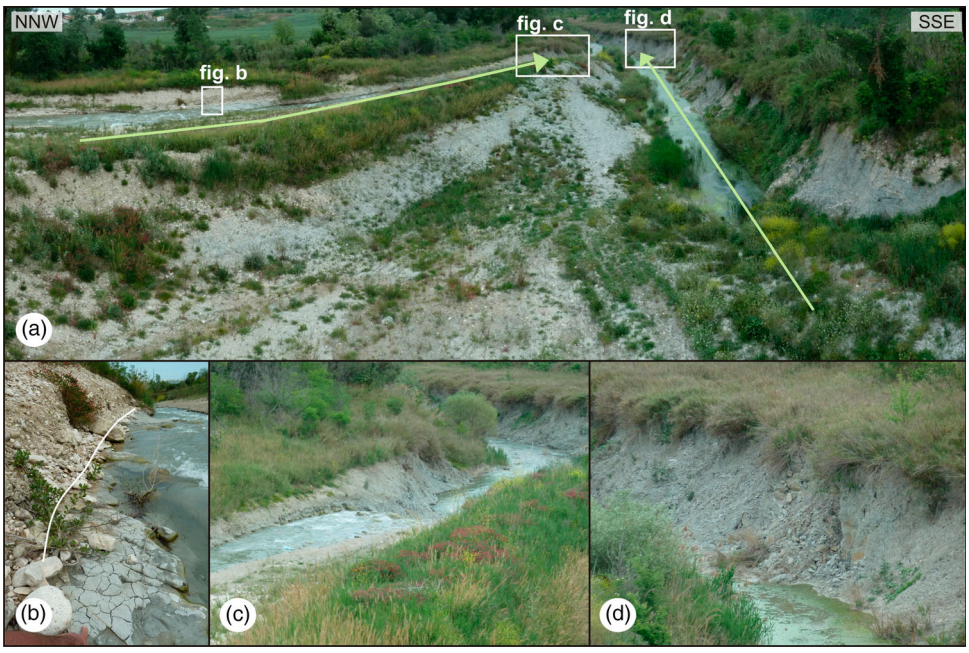

Figure 5. The Aventino River at the Guarenna-Selva di Altino bridge (eastern part of the map area); (a) two main channels with trend to down-cutting: the original watercourse (right channel) is now obstructed and has been redirected onto the left channel by human intervention in order to reduce fluvial erosion in the bridge area; (b) strath contact between the fluvial deposits and the clay bedrock showing a down-cutting process; (c) knick point indicating a rapid base-level adjustment and (d) river bank failure affecting the clay marine deposits, underlining fluvial sediments (pre-dam bankfull deposits).

located at the Aventino River-Rio Secco Stream confluence. Generally, alluvial fans show low values of radial slope ($\leq 0.5^{\circ}$) and are dissected by fluvial channel incisions or gullies, lacking any evidence of recent dynamics. A large swampy area includes the Serranella Lake (Figure 4(f)).

4.3.4. *Polygenetic landforms*

Mapped polygenetic landforms result from the action of several morphogenetic processes, on both the marine bedrock and the continental deposits cover, and include structural scarps affected by debris falls and polygenetic scarps. The former can be recognized on the summit areas and slopes of the ridges made up of marly-limestone units. Polygenetic scarps, originally carved by fluvial erosion and reshaped by human activity, are widespread along the whole valley floor of the study area and are related to floodplain deposit excavations and to the creation of embankments along the edges of the rivers.

4.3.5. *Anthropogenic landforms*

Mapped anthropogenic landforms include scarps, dams, river weirs, quarries and artificial lakes.

The most relevant anthropogenic landform is the dam which forms the Casoli Lake, located in the westernmost part of the study area (Figure 4(g)). This concrete arch-gravity dam was built in 1958 by damming the Aventino River gorge at the Torretta Ridge, a hilly form with a NW–SE trend, made up of marly-limestones.

A minor weir (overflow dam) was built in 1981 in the lower part of the drainage basin, 0.5 km downstream of the Aventino–Sangro junction, producing the Serranella lake/swampy area (Figure 4(h)). Another significant anthropogenic element located immediately upstream of the Aventino–Sangro junction is the outfall channel of two spillway pipes of the Casoli Lake and the Bomba Lake dams, respectively.

Other anthropogenic landforms that characterize the floodplain of the easternmost mapped area and of the industrial park areas are structures for bank protection.

5. Multi-temporal (1954–2009) and morphometric analysis of the floodplain

Channel adjustments on the Aventino River over the last 60 years, following the completion of the Casoli dam (1958) and the Serranella weir (1981), were outlined and documented by means of multi-temporal air-photo interpretation, and calibrated during field mapping. Both activities were aimed at providing a detailed description of the recent evolution and present-day dynamics of the valley floor.

In order to provide quantitative data on channel planform changes, a multi-temporal analysis (1954 and 2009) was performed in a GIS by sub-dividing the Aventino River into homogeneous reaches and calculating seven morphometric parameters (tables on the Main Map lower slice).

The analysis of the floodplain in 1954, before the building of the dams, highlights a homogeneous river morphology (Figure 6(a) and 6(b)). The fluvial pattern is braided, marked by numerous well-developed fluvial bars. The bankfull channel width ranges from ~50 m (gorge area) to ~340 m (Aventino–Sangro river confluence). Considering the identified channel reaches, braiding indexes are always greater than 1.7 (except for the gorge area), while the sinuosity index never exceeds 1.26. The degree of confinement ranges from 87% to 0%, with a mean value of 40% (see table on the Main Map lower slice).

The analysis of the floodplain in 2009 shows significant planform changes marked by a segmentation of river morphology (also reflected in the identification of new sub-reaches, see table

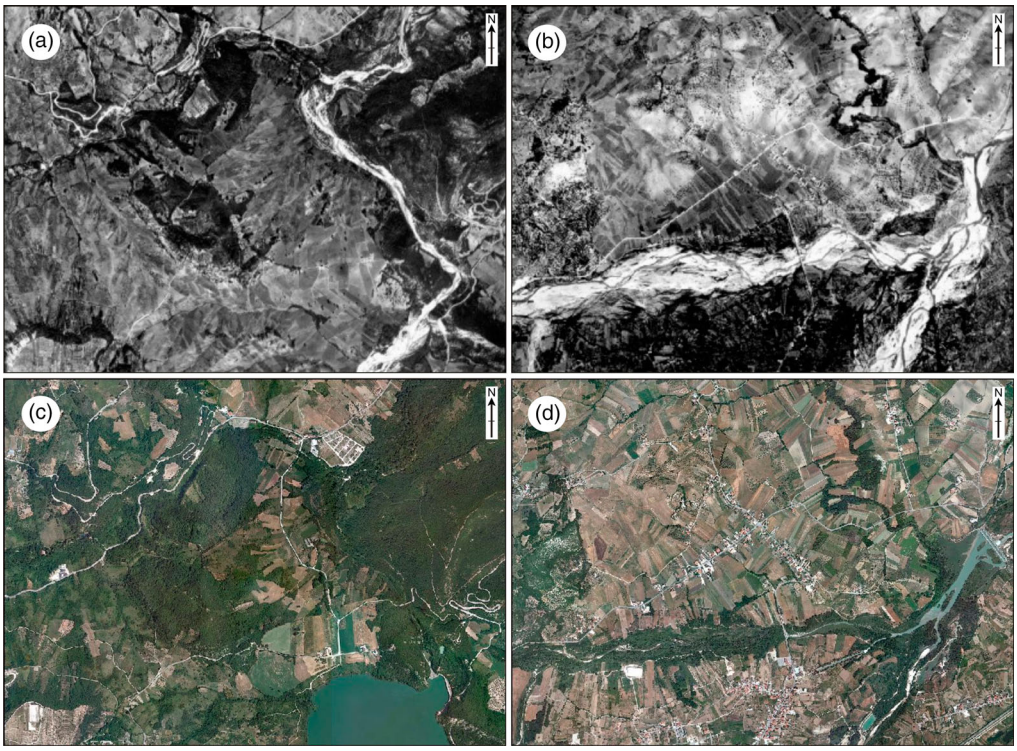

Figure 6. 1954 and 2009 aerial photos of the Aventino River between Casoli Lake and Serranella Lake document changes in river morphology: (a) 1954 and (c) 2009 images of the Casoli area; (b) 1954 and (d) 2009 images of the Serranella Lake area. (1954 air-photos provided by *Istituto Geografico Militare Italiano* IGMI, Authorization number: 6826/17.03.2015; 2009 air-photos provided by *Terre del Sangro-Aventino* Association and *Struttura Speciale di Supporto Sistema Informativo Regione Abruzzo*.)

on the Main Map lower slice) and by an overall increase in vegetation cover (Figure 6(c) and 6(d)). The fluvial pattern varies depending on the reaches and sub-reaches. Most of these show an anabranching pattern or an intermediate configuration between braided and meandering (wandering). Straight channels are also present. The bankfull channel width has considerably decreased and ranges from ~20 m (gorge area) to ~65 m (Aventino–Sangro river confluence). The braiding index never exceeds 1.8, while the anabranching index varies from 1.6 to 2.1. The sinuosity index depends on the reaches and takes on values ranging from 1.04 to 1.19. The degree of confinement is lower and ranges from 37.2% to 0%, with a mean value of 6.7%.

6. Conclusion

The 1:10,000 scale geomorphological map of the Aventino–Sangro river confluence (Central Italy) has been presented. The study allowed for the geomorphological characterization of the area, with special consideration given to fluvial landforms and the related processes.

The overall analysis highlights the recent and major transformations of the valley floor due to channel adjustments, mainly related to the construction of the Casoli dam (1958) and the Serranella weir (1981) and possibly to short-term climatic factors. Two main types of channel adjustment have been documented: (a) incision, which is commonly of the order of 3–4 m, but in some cases is more than 5 m and (b) narrowing, with a significant bankfull channel width reduction of

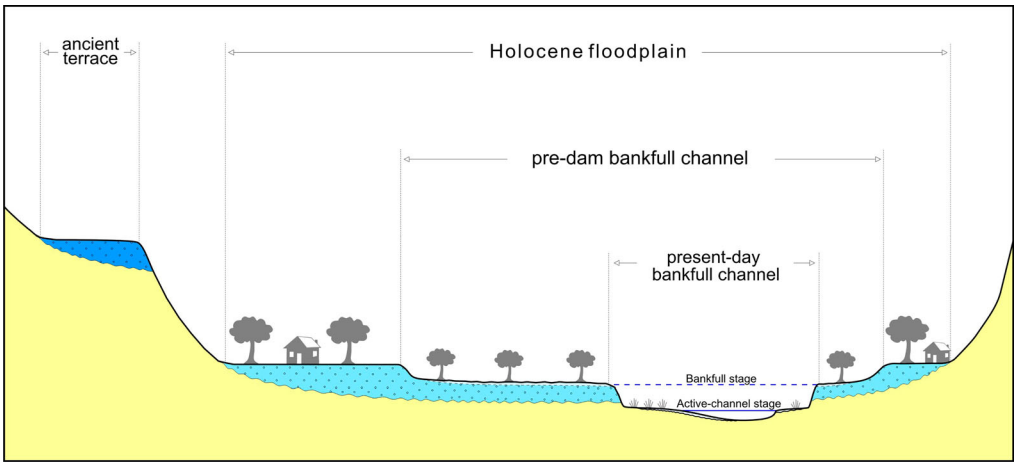

Figure 7. Schematic geomorphological cross-section of the present-day Aventino River floodplain.

up to 50% or more. In some reaches, these adjustments have led to changes in the channel pattern, particularly from braided to wandering, anabranching or straight.

The river channels have shown very similar evolutionary trends and magnitudes of adjustments, which have been primarily induced by human intervention (damming) and the related dramatic reduction in water and sediment supply. The morphological effects on the Aventino River are summarized in a schematic geomorphological cross-section of the valley (Figure 7).

In conclusion, as evaluation- and management-oriented approaches require the study of the fluvial geomorphological changes at a local scale (considering not only the change in the shape of the river and its floodplain, but also changes in the processes taking place in the river, which are dynamic, vary in magnitude, direction and time and depend on the characteristics of the system), the detailed mapping contributes to a comprehensive understanding of the mechanism, causes and consequences of landform changes in order to support flood hazard assessment and land management (urban planning, land ecology, forestry and soil science).

Software

The map presented in this work has been managed and produced using Esri ArcGIS 10.1.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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