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Science

Geomorphological analysis of drainage changes in the NE Apennines piedmont area: the case of the middle Tavo River bend (Abruzzo, Central Italy)

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ABSTRACT
This work presents a tectonic geomorphology analysis of a river bend in the middle Tavo River valley, in the piedmont area of the NE Apennines (Abruzzo Region), between the eastern slope of the chain (Gran Sasso Massif) and the Adriatic coast. The main map (1:15,000 scale) was obtained through a morphometric, geological, and geomorphological analysis, and was composed of four sections including orography and hydrography at basin scale, main map at local scale, geomorphological cross-section and longitudinal profiles, and morphoneotectonic analysis. This study provides a basis for the recognition of morphostructural and morphotectonic features that control the drainage evolution of the Tavo River. Specifically, the study is focused on the Tavo-Saline basin characterized by possible capture processes, and the evolution of the watershed with the Pescara basin. The results from this study can contribute to the understanding of the evolution of the NE Apennines piedmont area since the Middle Pleistocene.

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Morphotectonics; fluvial terraces; longitudinal profiles; drainage evolution; river bend; capture process

1. Introduction

Mountain chains and piedmont areas are largely affected by drainage-changes-related landscape evolution (Burbank & Anderson, 2011; Twidale, 2004). This is well-known since the beginning of the 1900s, and is particularly evident in the NE piedmont area of the Apennines chain, which experienced uplift and emersion from the marine environment during the Pleistocene (Bonarelli, 1932; Castiglioni, 1935; Demangeot, 1965; Mazzanti & Trevisan, 1978). The drainage network in these tectonically active regions is sensitive to both passive and active tectonic control due to folding and faulting (Giano, Gioia, & Schiattarella, 2014; Gioia, Schiattarella, & Giano, 2018; Maroukian et al., 2008; Valente et al., 2019; Vita-Finzi, 2012). The main river adaptations are evidenced by transverse drainage fluvial valley and related features, patterns change, lakes formation, etc. (see e.g. Schumm, Dumont, & Holbrook, 2002; Twidale, 2004). A set evident adaptation features is related to river bends and specifically, river captures/diversions. These elements can be found in several rivers, both worldwide (Ferrater et al., 2015; Giaconia et al., 2013; Lahiri & Sinha, 2012; Roy & Sahu, 2015; Val et al., 2013), and in the Adriatic piedmont domain (Bracone et al., 2012; Della Seta et al., 2008; Lupia Palmieri et al., 1995, 1998, 2001; Mayer, Menichetti, Nesci, & Savelli, 2003; Miccadei, Piacentini, Dal Pozzo, La Corte, & Sciarra, 2013; Miccadei, Piacentini, Gerbasi, & Daverio, 2012; Urbano, Piacentini, & Buccolini, 2017). Previous regional studies indicated that neotectonics has a strong influence on the morphological setting of Apennines piedmont sector mainly through drainage network evolution (Alvarez, 1999; Amato, Aucelli, Bracone, Cesarano, & Rosskopf, 2017; Aucelli, Cavinato, & Cinque, 1996; Coltorti & Farabollini, 2008; Currado & Fredi, 2000; Cyr & Granger, 2008; Del Monte, Di Bucci, & Trigari, 1996; Wegmann & Pazzaglia, 2009). However, the Abruzzo region is still poorly studied in terms of the understanding of river diversions/piracy (Della Seta et al., 2008; Demangeot, 1965; D'Alessandro, Miccadei, & Piacentini, 2008). Furthermore, more erodible lithologies rarely preserve evidence of active tectonic deformation. Therefore, the analysis of geomorphic features and drainage network system becomes a valuable tool for the reconstruction of morphostructural and morphoneotectonic features (Centamore, Ciccacci, Del Monte, Fredi, & Lupia Palmieri, 1996; Currado & Fredi, 2000; Doornkamp, 1986; D'Alessandro et al., 2008; Giano, Pescatore, Agosta, & Prosser, 2018; Miccadei, Mascioli, & Piacentini, 2011).

This work is focused on a detailed tectonic geomorphology analysis of a large river bend in the middle Tavo River valley, which is close to the southern drainage divide of the Pescara River, in the NE Abruzzo

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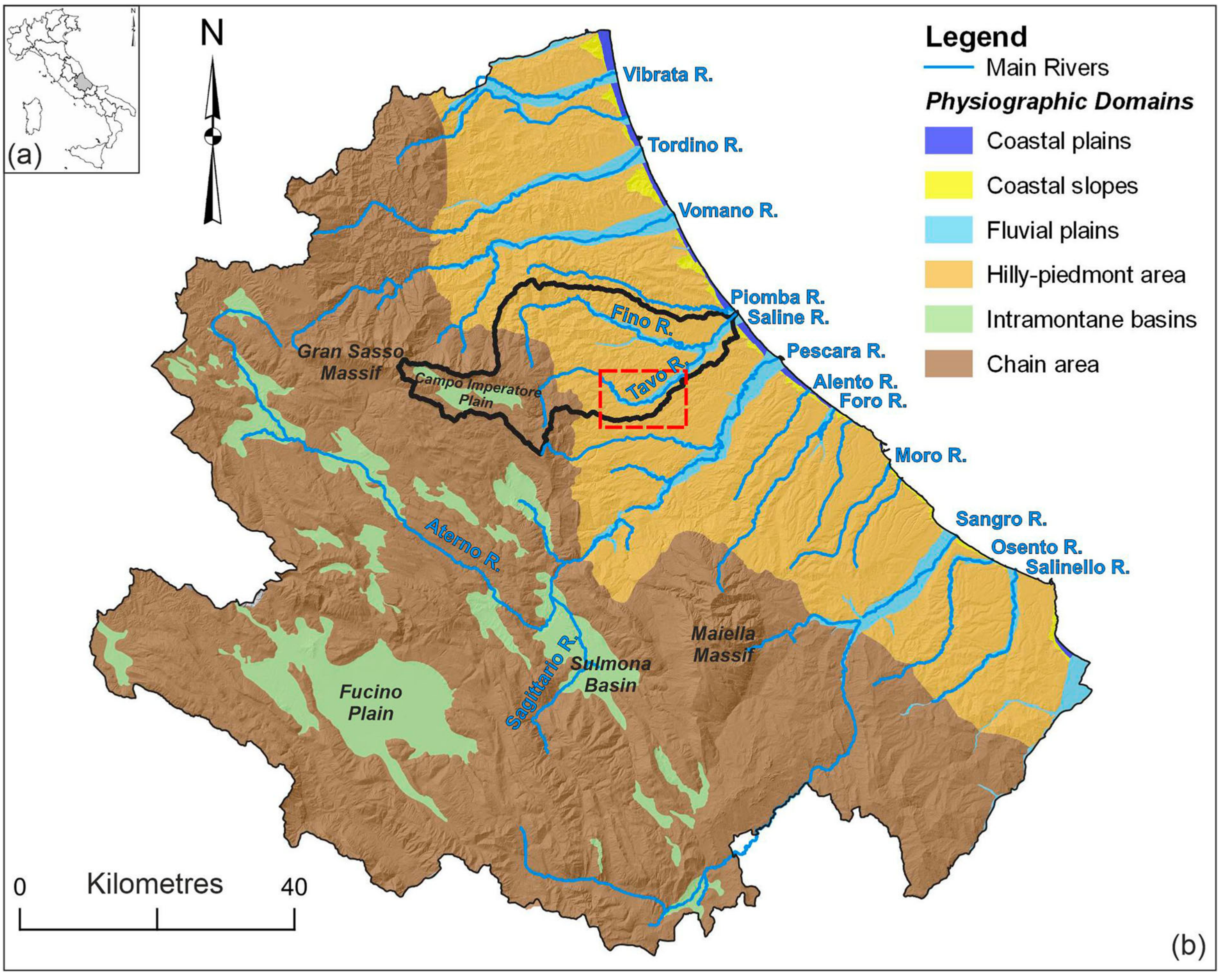

Figure 1. (a) Location map of the study area in Central Italy; (b) physiographic domains of the Abruzzo Region. The black line indicates the Tavo-Fino-Saline River basin. The red-dashed box indicates the location of the study area.

area (Central Italy; Figure 1). The study area was investigated from a geographical and geomorphological standpoint since the first half of the 1900s (Bonarelli, 1932; Castiglioni, 1935; Demangeot, 1965), and this study provides a new contribution of field data to the understanding of drainage changes and landscape evolution.

We present a 1:15,000 scale tectonic geomorphology map of the Tavo River bend area supported by descriptions of the landforms and deposits. The main purpose of this paper is to apply mapping methods to evaluate the influence of neotectonics on the relief and drainage network evolution. The aim of this local paper is to provide context for further research and to contribute to the understanding of the formation of the Tavo River bend and evolution of the water divide between the Pescara and Tavo-Saline River basin.

2. Study area

The Tavo River is located in the piedmont-hilly area of the Abruzzo Region, and extends from the eastern slope of the chain down to the Adriatic coast. The Tavo River flows ~42 km from the Gran Sasso Massif into the junction with the Fino River. After the junction, the Saline River runs for another ~7 km to the Adriatic Sea. The Tavo-Fino-Saline basin covers a surface of ~615 km^2, of which ~410 km^2 are in the piedmont area (Figure 1). The middle part of the Tavo River features a significant river bend from NW-SE to SW-NE (Figure 2) and flows close to the drainage divide with the Nora River, which is a main tributary of the Pescara River.

The chain area shows a high-relief landscape, made-up of pre-orogenic carbonate sequences that pertain to different Meso–Cenozoic paleogeographic domains. The main tectonic features are represented by NW–SE to N–S-oriented (W-dipping) thrusts, which affected the chain and inner piedmont area from the Late Miocene to the Early Pliocene (Calamita, Satolli, Scisciani, Esestime, & Pace, 2011; Vezzani, Festa, & Ghisetti, 2010). The compressional tectonics was followed by strike-slip tectonics along mostly NW–SE to NNW–SSE-oriented faults (Late Pliocene-Early Pleistocene), largely masked by younger extensional tectonics since the Early-Middle Pleistocene (D'Alessandro, Miccadei, & Piacentini, 2003; Geurts, Whittaker, Gawthorpes, & Cowie, 2020). The Adriatic piedmont is characterized by a hilly landscape composed of sin- and late-orogenic deposits (i.e.

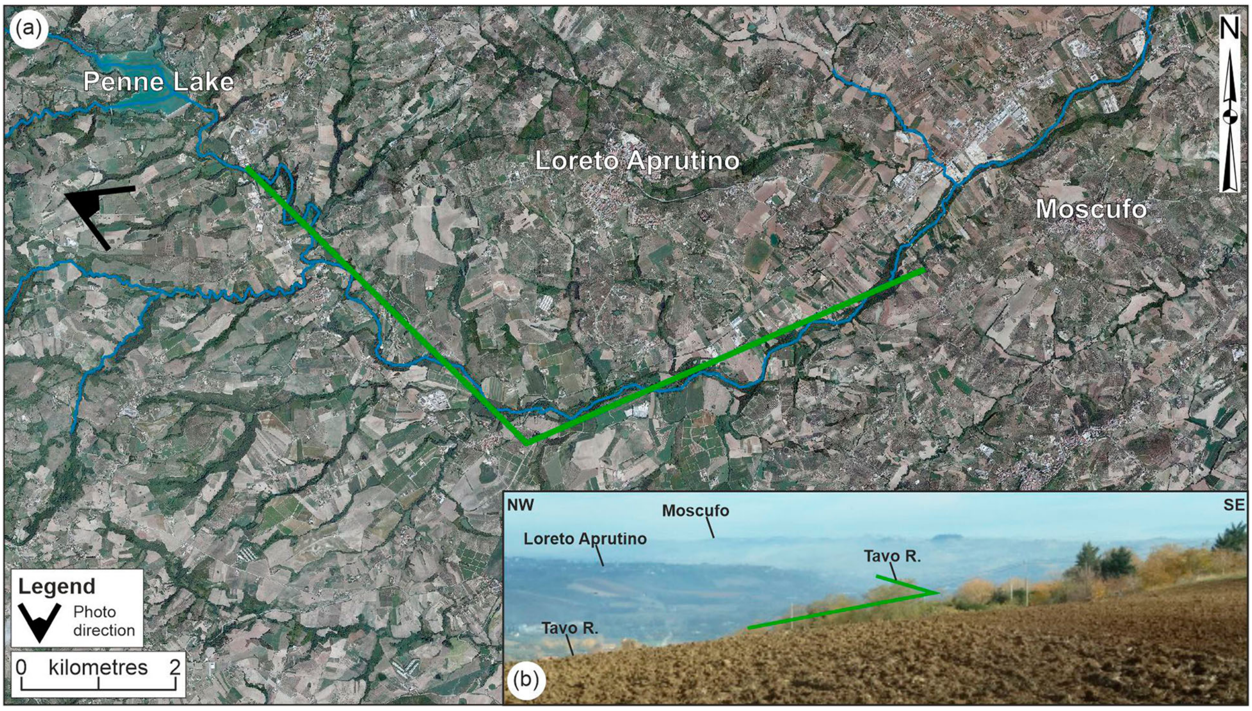

Figure 2. Significant river bend (green line) in the middle course of the Tavo River from NW-SE to SW-NE: (a) orthophoto images (Abruzzo Region, 2010); (b) landscape photo.

arenaceous pelitic turbiditic foredeep sequences), which are largely covered and unconformably overlaid by Pleistocene hemipelagic (i.e. clay, sand, conglomerate) sequences. Post-orogenic deposits mainly consist of slope, alluvial, and travertine deposits. The morphostructural setting is a result of the Pleistocene evolution of the Adriatic foredeep domain, as characterized by an uplifted slightly NE-dipping homoclinal setting.

The present-day tectonic setting is dominated by extensional tectonics that is still active in the axial part of the chain, as suggested by historical and recent earthquakes (up to M 6.0; e.g. Gran Sasso Massif 1950; L'Aquila 2009; Amatrice 2016). The Adriatic piedmont is characterized by moderate seismicity (M 4-5; e.g. Atri 1563; Torrevecchia Teatina 1992, San Giuliano di Puglia, 2002) in a complex tectonic regime with strike-slip related earthquakes (Kastelic et al., 2013; Miccadei, Carabella, Paglia, & Piacentini, 2018; Valensise, Pantosti, & Basili, 2004). The Adriatic Sea is affected by subsidence, moderate compression, and strike-slip related seismicity (M 4-5; e.g. Abruzzo-Marche coast, 1987; Figure 3; Rovida, Locati, Camassi, Lolli, & Gasperini, 2016).

The geomorphological evolution of the piedmont began after the emersion around the end of Early Pleistocene as a result of a regional differential uplift with gentle NE tilting. This was related to compressional tectonic or late compression uplifting rebound or asthenosphere dynamics (Ascione, Cinque, Miccadei, Villani, & Berti, 2008; Centamore & Nisio, 2003; Dramis, 1993; D'Alessandro et al., 2003; Faccenna, Becker, Miller, Serpelloni, & Willett, 2014; Sembroni et al., 2020), and led to a sub-parallel (SW–NE) arrangement of the main valley incised across the emerged coastal plain by fluvial and slope processes (D'Alessandro et al., 2008; Miccadei, Mascioli, Piacentini, & Ricci, 2011; Piacentini, Galli, Marsala, & Miccadei, 2018).

Since the Middle Pleistocene, the uplift of this sector, along with Quaternary climatic fluctuations, forced alternating phases of fluvial incision and alluvial deposition (D'Agostino, Jackson, Dramis, & Funiciello, 2001; Miccadei, Piacentini, & Buccolini, 2017; Pizzi, 2003). This contributed strongly to defining the arrangement of the drainage network and induced strong selective erosion processes, while the control of tectonics on landforms is not clear. The evidence of drainage network arrangement and evolution is recorded by different orders of terraces (no less than four orders, named from T1 to T4, starting from the highest) along the major valleys (Capelli, Miccadei, & Raffi, 1997; Miccadei et al., 2012, 2013, 2018) and well-exposed in the mid-lower Tavo River valley.

3. Methods

The tectonic geomorphology analysis of the Tavo River bend was based on an integrated approach that incorporate the cartographic and morphometric analyses of orography and hydrography (at drainage basin scale), photogeological analysis, geological and geomorphological field mapping, and geomorphological profiles drawing (at local scale).

The Main Map presented in this paper includes four main sections:

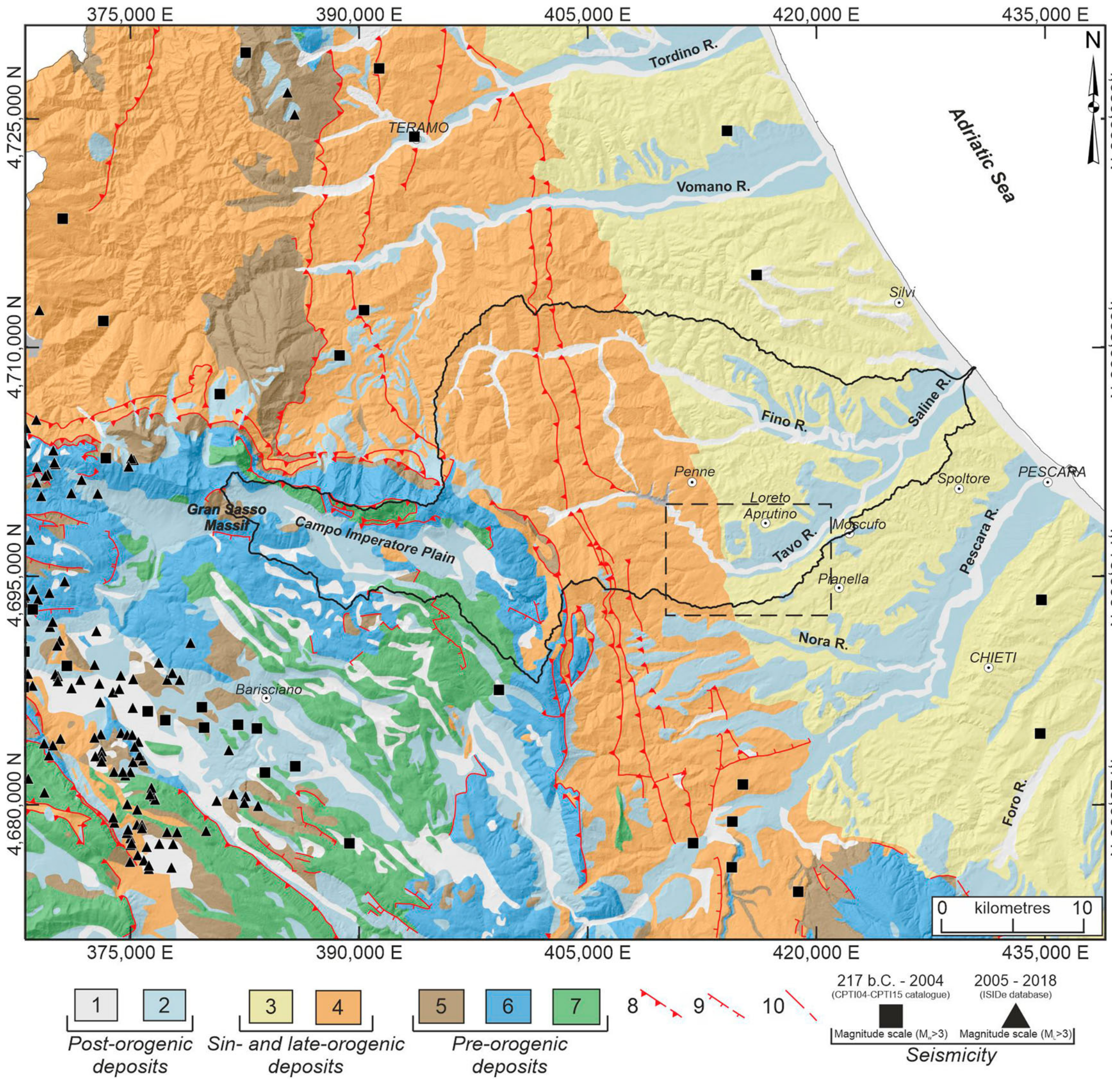

Figure 3. Geological sketch map of NE Abruzzo (modified from Carabella, Miccadei, Paglia, & Sciarra, 2019). Legend: post-orogenic deposits – (1) fluvial deposits (Holocene), (2) fluvial and alluvial fan deposits (Middle-Late Pleistocene); sin- and late-orogenic deposits – (3) hemipelagic sequences with conglomerate levels (Late Pliocene–Early Pleistocene), (4) turbiditic foredeep sequences (Late Miocene–Early Pliocene); pre-orogenic deposits – (5) carbonate ramp facies (Early Miocene- Early Pliocene), (6) slope and pelagic basin sequences (Cretaceous–Miocene), (7) carbonate platform sequences (Jurassic–Miocene); (8) major thrust (dashed if buried); (9) major normal fault (dashed if buried); (10) major fault with strike-slip or reverse component (dashed if buried); seismicity – CPTI04 (Gruppo di Lavoro, 2004)-CPTI15 (Rovida et al., 2016) catalogue (black square); ISIDe (ISIDe Working Group, 2007) database (black triangle). Black line: Tavo-Nora-Saline River basin; the black dashed box indicates the location of the study area.

(1) Orography and hydrography (in the upper right part);
(2) Main map (in the central upper part);
(3) Geomorphological cross-section and longitudinal profiles of fluvial terraces (in the central lower part);
(4) Morphoneotectonic analysis (in the lower part).

The morphometric and hydrographic analyses, as well as the mapping, were carried out with GIS (QGIS 2018, version 3.4 'Madeira'). Vector topographic data (1:25,000–1:10,000–1:5,000 scale) were retrieved from the Abruzzo Region (2007a, 2007b, 2007c). A 5 m cell Digital Terrain Model (DTM) was processed from the 1:5,000 scale map. The analysis was focused on the investigation of the detailed definition of the drainage network and main orographic features, such as elevation and slope (first derivate of elevation – Strahler, 1952). Basin boundaries and drainage lines, as hierarchized according to Strahler (1957), were automatically obtained from the DTM using QGIS and verified by means of 1:5,000 air-photos (Abruzzo Region, 2010). Their azimuthal orientations were derived by automatic GIS procedures. After a 100m-segmentation of the lines, allowing the actual distribution to be detected, they were analyzed using frequency-weighted rose diagrams (Belisario et al., 1999; Gioia et al., 2018; Miccadei et al., 2018). Finally, the drainage pattern types were also analyzed (Hack, 1973; Howard, 1967; Twidale, 2004).

Geological and geomorphological analyses were based on field mapping integrated with air-photo interpretation. In this process, field mapping was carried out at the 1:5,000 scale to investigate lithological features, superficial deposit cover, and the type and distribution of morphological field evidence of tectonics. Mapping was performed according to the guidelines of the Geological Survey of Italy and AIGeo (Italian Association of Physical Geography and Geomorphology) (ISPRA, 2007; ISPRA & AIGEO, 2018) and was also in accordance with the literature concerning morphotectonic mapping (Amato et al., 2018; Bianchi et al., 2013, 2015; Calista et al., 2016; Chelli, Segadelli, Vescovi, & Tellini, 2016; Giano et al., 2014; Miccadei et al., 2019). Air-photo interpretation was performed using 1:33,000 scale stereoscopic air-photos (Flight GAI 1954 and Flight Abruzzo Region 1981–1987; Abruzzo Region, 1987; IGMI, 1954) and 1:5,000 scale orthophoto color images (Abruzzo Region, 2010) to support the geomorphological investigation. Morphological field evidence of tectonics was classified according to their locations in the landscape (relative to ridges, slopes, valleys, and hydrography). Moreover, these elements were investigated by considering the connection with the passive or active role of tectonics. The connection and alignment of these elements along a specific direction can provide evidence for morphotectonic processes and suggest the passive or active role of tectonics in the landscape shaping (Della Seta et al., 2008; Gioia et al., 2018).

Field surveys and stratigraphic observations accurately constrained the distribution of terraced fluvial deposits. The various fluvial terrace levels were defined through morpho-lithostratigraphic transverse profiles and based on the heights of terrace surfaces (tread and strath, the latter when visible) above the bottom valley and the morphological continuity. The longitudinal distribution of any single terrace level was analyzed by plotting it on longitudinal profiles (Keller & Pinter, 2002; Merritts, Vincent, & Wohl, 2004). Local correlation, geochronological constraints (dating, paleosols, lithic industries; Agostini, Di Canzio, & Rossi, 2001; APAT, 2006; Carrara, 1998; ISPRA, 2010a; Marcolini et al., 2003), and correlation with the neighboring valleys (Parlagreco et al., 2011; Urbano et al., 2017) allowed us to infer the age of each fluvial terrace. The relationships between morphological field evidence of tectonics, their directions, and anomalies in the distributions of fluvial terraces (e.g. displacements and bumps in the longitudinal profile) are likely to provide evidence of morphoneotectonics, and relative geomorphological constraints in the timing of landscape evolution.

4. Results and discussion

The main features of the middle Tavo River basin are presented in the Main Map, which incorporates four sections, as described hereafter.

4.1. Orography and hydrography

The analysis of orography and hydrography was carried out at the drainage basin scale in the entire Tavo-Fino-Saline River basin, which features a major escarpment along the eastern front of the chain, then its elevation decreases gradually from the piedmont toward the coastal area. Three main orographic sectors can be identified as follows:

(1) Chain front sector: W mountain sector, which include the eastern slope of the Gran Sasso Massif, from ~3000 m to ~750 m a.s.l., is characterized by steep areas with slopes up to 60° with a SW sub-flat zone corresponding to the Campo Imperatore Plain.
(2) Piedmont sector: SW hilly sector, with elevations from 300–400 m to 750 m a.s.l.; this sector fringes into the eastern chain front with a rugged-to-gentle morphology, and is interrupted by deep and narrow incisions of the main watercourses.
(3) Eastern hilly coastal sector: NE hilly area with tabular relief and an elevation <300 m a.s.l., showing gentle slopes and some local steep-to-vertical scarps along the edge of the relief.

The Tavo-Fino-Saline River was hierarchized with streams ranging from the 1st to 7th order; and the azimuthal directions of each stream order are synthesized in Figure 4. The diagrams of the 1st and 2nd order streams show a sub-elliptical shape, with minor spikes in SW-NE, NW-SE, and E-W directions; starting from the 3rd order, the main trends are again NW-SE (3rd), SW-NE (4th), but also N-S (3rd, 5th), ESE-WNW and WSW-ENE (5th, 6th); the 7th order stream is SW-NE-oriented.

Furthermore, the types of drainage pattern of the entire basin were classified. The Tavo River basin, in its western part, is characterized by a parallel (Pa) and dendritic (D) drainage patterns; dendritic (D) patterns are predominant in both the central and lower parts, and are characterized by high-order streams. On the right valley side, an angular (Ag) pattern can be observed. A contorted pattern (Co) was observed at the confluence between the Fino and Tavo Rivers. The Fino River basin shows a trellis pattern (T) in the western sector (N-S- and E-W-oriented). To the east, pinnate-trellis (Pi-T) and dendritic (D) patterns were observed. Local centrifugal (Rf) patterns were caused by isolated reliefs. The Saline River basin shows a dendritic (D) to parallel (Pa) drainage pattern on both sides of the valley. In the study area, the dendritic (D) drainage pattern is predominant, with a large area showing angular (Ag) patterns, in the right valley side along the bend of the Tavo River, where the streams branch following two main directions (WSW-ENE and NW-SE; upper–right inset map).

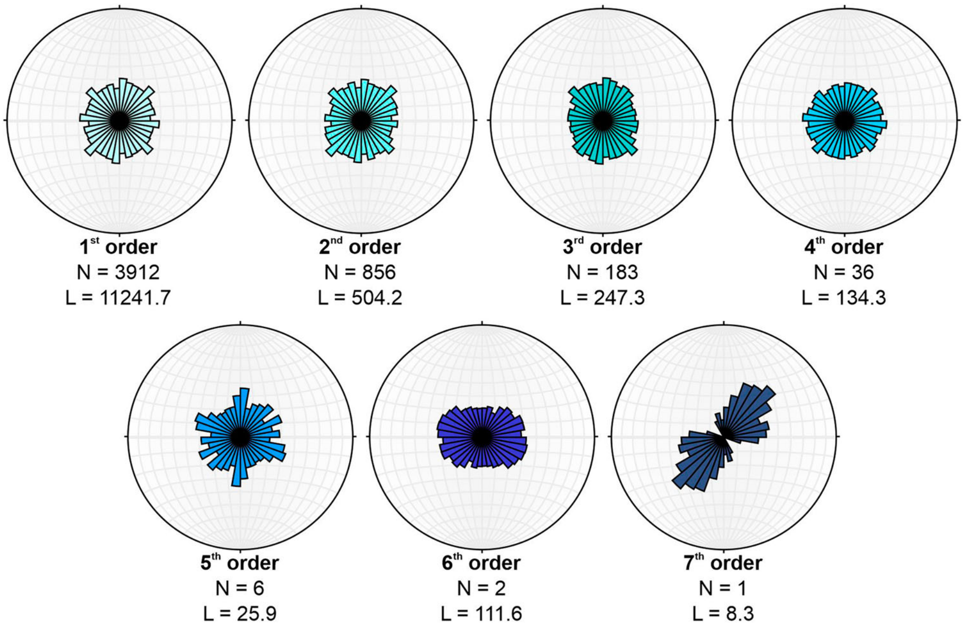

Figure 4. Frequency-weighted rose diagram with the azimuthal direction of each stream order of the Tavo-Fino-Saline River. N: number of the streams for each order; L: total length of the streams (Km) for each order. The rose diagrams are normalized by area with respect to the stereonet.

4.2. Main map

On the Main Map, the distribution of bedrock lithology, cover deposits, and evidence of tectonics are represented. Outcropping lithologies were classified in marine and continental deposits (APAT, 2006; ISPRA, 2010a, 2010b). They are listed in the following paragraphs, from the oldest to the youngest (numbers refer to the map and its relative legend).

4.2.1. Marine deposits (bedrock) (from 13 to 11)

The bedrock includes three main units of marine deposits (Figure 5) as follows:

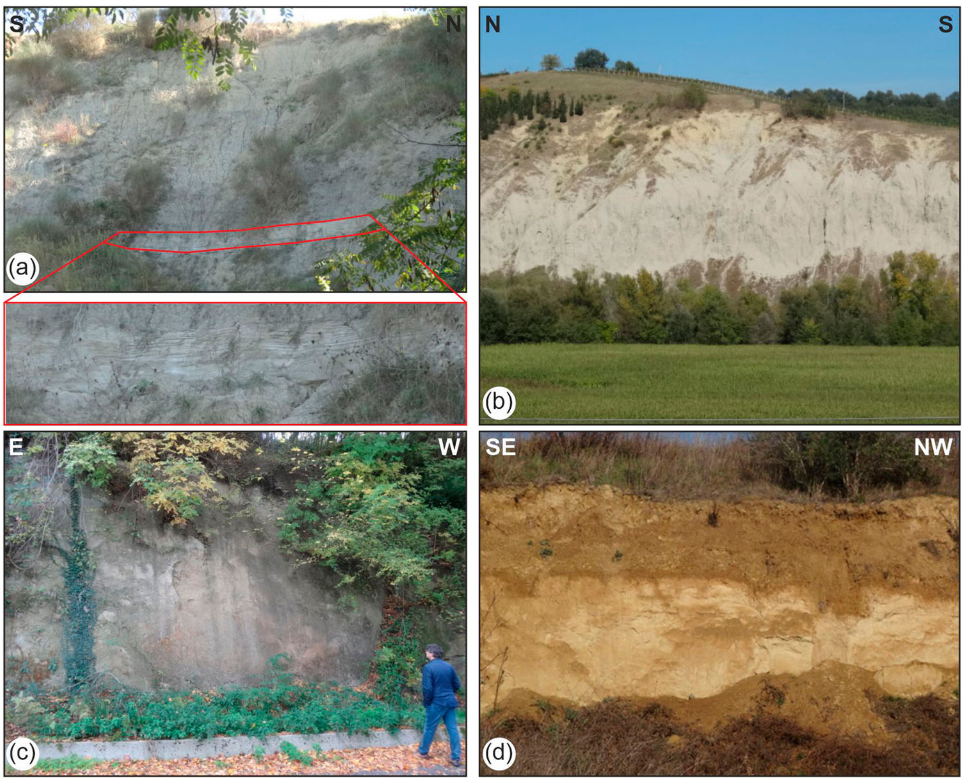

Figure 5. Marine deposits of the study area (the units numbers refer to the legend of the map); (a) pelitic-arenaceous unit (13) at St. Pellegrino; in the box, a detail of a parallel laminated sandy level; (b) badlands in the pelitic-arenaceous unit (13), near St. Pellegrino; (c) arenaceous unit (12) along a secondary valley near St. Pellegrino; (d) pelitic unit (11) at Re Martello.

- The pelitic-arenaceous unit (13) is composed of turbiditic layers, with fine sand or coarse silt at the base and pelite at top, in medium layers, which largely outcrop in the western part of the map, on the slopes of the ridges along the right Tavo River valley side.
- The arenaceous unit (12) is made-up of massive to fine arenaceous banks, with pelitic intercalations, which outcrop along the steep slopes located in the upper part of the right valley side.
- The pelitic unit (11) is characterized by massive clays and silty clays, and laminated pelites layers, with arenaceous interbedding, in medium layers, which compose the bedrock of the central-eastern part of the area that is exposed on the slopes of the secondary valleys along both the valley sides. In the eastern part, a higher arenaceous component is present with less pelitic fraction and no internal structures.

4.2.2. Continental deposits (near-surface cover deposits) (from 10 to 1)

The continental deposits comprise eight units of Pleistocene to Holocene fluvial deposits (10–3), eluvial-colluvial (2), and landslide (1) deposits. The deposits (listed and described in the legend of the map) mainly consist of calcareous gravels and conglomerate with sandy levels (Figure 6). The age is constrained by the geomorphological correlation with isotopic dating (U/Th, C^{14}) of travertines, alluvial deposits and paleosols, attributions of archaeological findings, and lithic industries (see the table in the map).

A specific focus was devoted to terraced deposits. Their arrangement is summarized in the transversal morpho-lithostratigraphic scheme, which graphically shows their distributions on the valley sides at different elevations above the present valley bottom, up to the watershed (e.g. C.le Fiorano gravels (10) and Loreto Aprutino gravels (9)).

4.2.3. Morphological field evidence of tectonics

Deduced from the geomorphological features of ridges, slopes, valleys, and hydrography, the morphological field evidence of tectonics was classified and described in detail (Figure 7).

The landforms, as related to ridges, characterize the right watershed of the Tavo River. This area is dominated by the main straight ridges, also with altimetric and planimetric discontinuities, with directions from WNW-ESE to WSW-ENE and then to SW-NE, and by several saddles (Figure 7(a)). Secondary ridges, which develop in E-W and SW-NE directions, are perpendicular to the main ones, especially in the western part. In central and eastern sectors, the orientations of these ridges are parallel (WSW-ENE and SW-NE) or oblique (WNW-ESE and NW-SE) to the main ones. The secondary ridges, placed on the left valley side, are arranged in three preferential orientations: (i) E-W, represented by the main asymmetrical ridge; (ii) from SW-NE to SSW-NNE, characterized by symmetrical ridges of small extension; and (iii) NW-SE-oriented, represented by minor ridges at lower elevations.

The slope landforms were mostly found on the right valley side, including structural scarps, counter slopes, and triangular facets. Fluvial terraces and erosion scarps were found especially on the left valley side; on the right valley side, they were found only at higher elevations and along the watershed of the basin (see the morpho-lithostratigraphic profile in the map). In general, these landforms correspond to the summit depositional surfaces of the fluvial terraces (Figure 7(c)).

The valley landforms are widespread in the minor tributary valleys of the Tavo River. These landforms refer to valleys with different morphology (V-shaped, concave, and flat bottom) and symmetry (symmetrical and asymmetrical valleys; Figure 7(d)). Hanging and beheaded valleys are also present. Generally, in each secondary valley, there is a morphological transition from concave valleys in the highest part, flowing on superficial colluvial deposits, to V-shaped valleys in the lower part, as carved in the bedrock. All major streams consist of a flat-bottom valley in their final segment.

The main hydrography feature of the study area is the Tavo River bend, from NW-SE to SW-NE direction. In the western sector, minor river bends are from WSW-ENE to WNW-ESE, and several counterflow confluences are present. In the central sector, bends are mostly from SSE-NNW to SSW-NNE and from SSE-NNW to E-W, and several 90° confluences are present. In the eastern sector, the secondary streams show bends from NNW-SSW to NW-SE and NW-SE to N-S, with the Tavo River tributaries showing both 90° and counterflow confluence.

4.3. Geomorphological cross-sections and longitudinal profiles of fluvial terraces

Lithological and stratigraphical information were summarized in cross-sections and longitudinal profile of the Tavo River valley, together with the field evidence of tectonics (whose analysis was extended to the entire area surrounding the Tavo bend; lower-left on the map). The terraced deposits were plotted according to the height above the present valley, defined for each fill and strath terrace level. Furthermore, we outlined a possible stratigraphic correlation (see the table in the map) that partially revised previous attributions (APAT, 2006; ISPRA, 2010a, 2010b; Urbano et al., 2017). This was done by comparing the heights above the valley bottom of fluvial terraces among the Tavo-Saline basin and neighboring basins (Nora and Pescara R.) and their time constraints. These attributions require a more detailed analysis with further

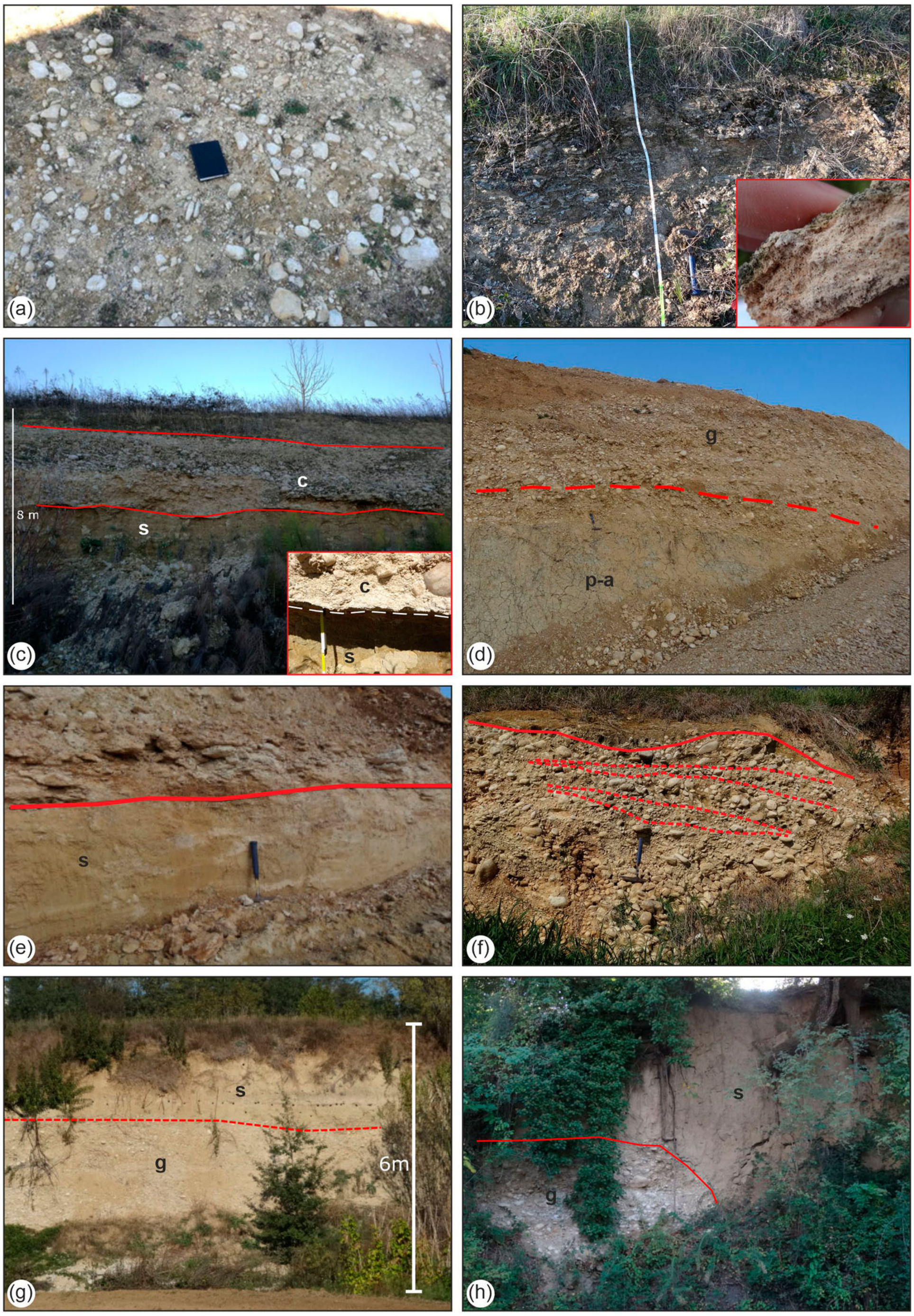

Figure 6. Continental deposits of the study area (the units numbers refer to the legend of the map); (a) gravels in sandy matrix belonging to the C.le Fiorano gravels (10); (b) outcropping of a calcareous concretion inside the C.le Fiorano gravels (10); in the red box, a detail of the calcareous concretion; (c) conglomerate layer inside the Paterno sands (8); in the box, detail of the contact between conglomerates and sands; (d) coarse gravels of the Farina gravels (7) which unconformably overlay the pelitic-arenaceous unit (13); (e) parallel laminated fine sands in the upper part of the Farina gravels (7); (f) alternation of medium to coarse gravels of the Re Martello gravels (6); in the upper part a calcareous concretion; (g) contact between gravels (lower part) and sands (upper part) inside the Cartiera sands and gravels (5); (h) St. Pellegrino sands and gravels (4): detail of the lenticular nature of the gravels.

investigations and comparisons specifically on the main valleys of the Adriatic piedmont.

In the longitudinal profile, terraces treads show a general downstream convergent geometry, although four anomalies (displacements and perturbations of the terraces geometry) were detected, outlining the active role of some main lineaments defined as morphoneotectonic elements:

- A1: lack of the highest terrace orders (T0-A, T0-B, T1, and T2) in correspondence to the Tavo River bend and upward downstream displacement of the corresponding terrace treads. A1 was found related to an NW-SE-oriented morphoneotectonic element, which have controlled the emplacement of the NE-SE segment of the Tavo River.

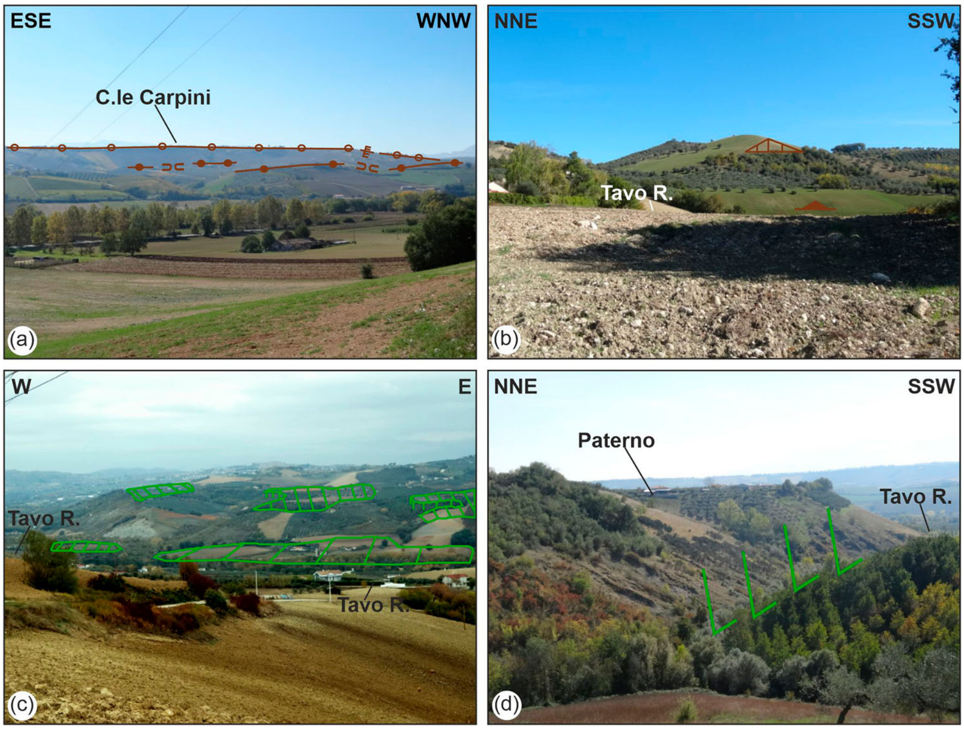

Figure 7. Geomorphological features of the study area (symbols of morphological field evidence of tectonics are portrayed as in the main map); (a) right side watershed near C.le Carpini with a principal asymmetric ridge and secondary symmetric ridges, parallel to the first one; (b) triangular facet and counter slope near St. Pellegrino; (c) fluvial surfaces and scarps at different heights (watershed, slopes and valley bottom) along the right Tavo River side; (d) right asymmetric valley of a stream near Paterno.

- A2: terrace treads related to T0-B, T1, and T2 are displaced. This anomaly was possibly connected to WNW-ESE-oriented morphoneotectonic elements, which have controlled the emplacement of the minor (hanging) valleys and main beheaded valleys at the watershed.
- A3: the downstream gradient of T1-T2-T3 terraced surfaces decreases; this anomaly was found connected to a major NW-SE beheaded valley along the Tavo-Pescara divide; it was possibly linked to an NW-SE morphoneotectonic element.
- A4: T1 is considerably shifted upwards (~+20 m downstream), while the other terraces show comparable treads elevations; T3 is absent. A4 corresponds to the junction of Tavo (SW-NE straight asymmetric valley) and Fino (WNW-ESE straight asymmetric valley) rivers. This anomaly is likely to be linked to a WNW-ESE-oriented morphoneotectonic element, occurring possibly after the deposition of T1 and before the emplacement of other terraces.

Furthermore, a longitudinal profile was extended to the Nora River valley to analyze the relationship between terraced deposits above the watershed. Here, the ancient fluvial terraces (T0-A and T0-B) of the Nora River valley can be correlated with the heights of corresponding terraces of the Tavo River valley, well over the watershed, outlining a possible connection between the ancient drainage of the Nora and Tavo River; lower terraces were entrenched and not directly correlated, which outlines the emplacement of the Tavo bend, with a capture process.

5. Conclusions

The Tavo River bend area is an example of drainage change by capture in the Apennine piedmont. Its geomorphological features were investigated through the mapping of field evidence of tectonics and fluvial terraces, obtaining the main map, the geomorphological sections and longitudinal terraces profiles, and the schemes presented in this work. This paper provides a methodological approach to evaluate the morphoneotectonic processes of the study area; moreover, it could provide clues regarding the possible influence of morphoneotectonic elements in the relief and drainage network evolution.

The main conclusions of the study outline that:

- from the analysis of the fluvial terraces (e.g. remnants of the oldest fluvial terraces, T0-A and T0-B, on the top of the hilly reliefs and across the watershed) is possible to outline an ancient landscape and drainage different from the present one (i.e. the upper Nora River flowing into the lower Tavo River) and subsequent drainage change with the capture of the upper Nora River (now flowing in the Pescar River) and emplacement of the upper Tavo River along the NW-SE direction (Figure 8);

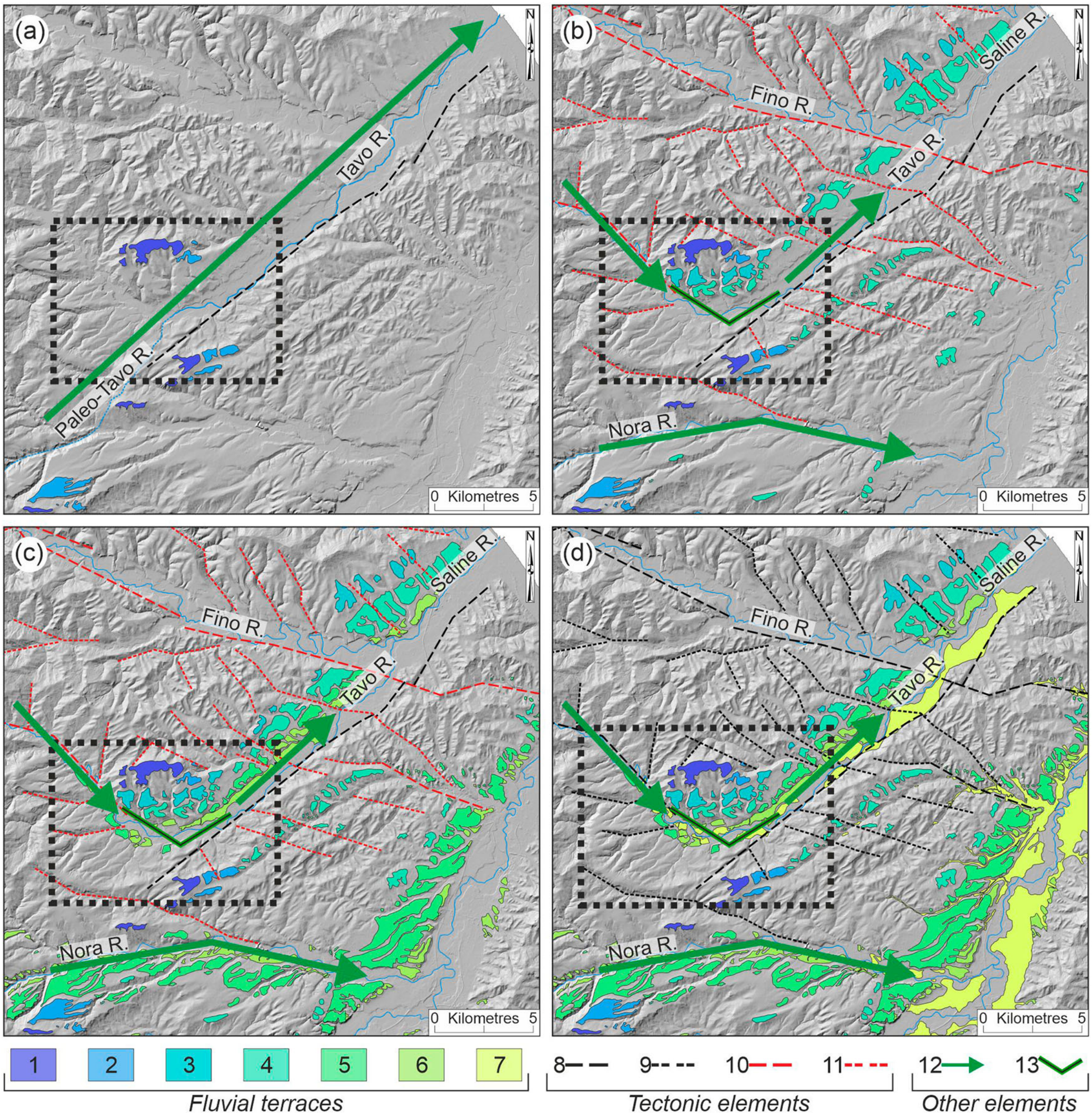

Figure 8. Main phases of the evolution of the Tavo River drainage network: (a) paleo-drainage network setting (Middle Pleistocene); (b) deposition of T1-T2 fluvial terraces (Middle – late Middle Pleistocene) independently in the Tavo R. and Nora R. basin; (d) deposition of T3-T4 fluvial terraces (Upper Pleistocene); deposition of T5 fluvial terrace (Holocene). Legend: fluvial terraces – (1) T0-A; (2) T0-B; (3) T1; (4) T2; (5) T3; (6) T4; (7) T5; tectonic elements – (8) principal tectonic element with passive influence; (9) secondary tectonic element with passive influence; (10) principal tectonic element with active influence; (11) secondary tectonic element with active influence; other elements: (12) drainage system; (13) Tavo River bend. Black dotted box indicates the location of the study area.

- combining the drainage network main orientation and the angular pattern distribution (mainly NW-SE, WNW-ESE and WSW-ENE) with the elongation of the main field evidence of tectonics (mainly NW-SE and WNW-ESE) and their correlation with terraces anomalies (lower part of the map), it is possible to provide a contribution to infer the neotectonic structures (mainly NW-SE- and WNW-ESE-oriented), their role, and relative timing in landscape evolution.

Finally, a preliminary hypothesis on the landscape evolution of the Tavo River bend can be summarized as follows:

- Initial SW-NE flow direction (Paleo-Tavo River, which combines the upper Nora and lower Tavo River) from the front of the chain to the piedmont area, evidenced by T0-A and T0-B terraces over the watershed (Middle Pleistocene; Figure 8(a));
- Capture of the upper Paleo-Tavo by the Nora River and formation of both Tavo and Nora River bends are evidenced by the deposition of T1-T2 terraces entrenched in the new Tavo and Nora River valleys (Middle and late Middle Pleistocene); these features are controlled by possible neotectonic elements, evidenced by the terraces anomalies, oriented toward NW–SE (A1, A3) and WNW–ESE (A2, A4; Figure 8(b));
- Landscape shaping and dominant angular pattern emplacement are controlled by NW-SE- and WNW-ESE-oriented morphoneotectonic features, as evidenced by the deposition of T3-T4 fluvial

terraces (Upper Pleistocene) and anomalies (A3, A4) in the T3-T4 longitudinal profiles (Figure 8(c));

- Emplacement of the recent alluvial plain and deposition of T5 (Holocene) along the Tavo-Saline River valley are not affected by the anomalies. They are also not actively influenced by the tectonic lineaments anymore (Figure 8(d)).

This study could represent a scientific basis and provide data for future analysis, aimed to better constrain, in space and time, the main phases of the evolution of the Tavo River and to provide a significant contribution to the understanding of Middle Pleistocene-to-present landscape evolution of the NE Apennines piedmont area.

Software

The vector/raster data and main map were managed using QGIS 3.4 Madeira®, with final editing performed using Corel Draw 2019®.

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