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Geomorphology of the Anthropocene in Mediterranean urban areas

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Abstract

Urban-geomorphology studies in historical cities provide a significant contribution towards the broad definition of the Anthropocene, perhaps even including its consideration as a new unit of geological time. Specific methodological approaches to recognize and map landforms in urban environments, where human-induced geomorphic processes have often overcome the natural ones, are proposed. This paper reports the results from, and comparison of, studies conducted in coastal historical cities facing the core of the Mediterranean Sea – that is, Genoa, Rome, Naples, Palermo (Italy) and Patras (Greece). Their settlements were facilitated by similar climatic and geographical contexts, with high grounds functional for defence, as well as by the availability of rocks useful as construction materials, which were excavated both in opencast and underground quarries. Over centuries, urbanization has also required the levelling of relief, which was performed by the excavation of heights, filling of depressions and by slope terracing. Consequently, highly modified hydrographic networks, whose streams were dammed, diverted, modified in a culvert or simply buried, characterize the selected cities. Their urban growth, which has been driven by maritime commercial activities, has determined anthropogenic coastal progradation through port and defence or waterfront works. Aggradation of artificial ground has also occurred as a consequence of repeated destruction because of both human and natural events, and subsequent reconstruction even over ruins, buried depressions and shallow cavities. As a result, the selected cities represent anthropogenic landscapes that have been predominately shaped by several human-driven processes, sometimes over centuries. Each landform represents the current result, often from multiple activities with opposing geomorphic effects. Beyond academic progress, we believe that detecting and mapping these landforms and processes should be compulsory, even in risk-assessment urban planning, because of the increase of both hazards and vulnerability as a result of climate-change-induced extreme events and extensive urbanization, respectively.

Keywords

Urban geomorphology, coastal city, geomorphological risk, anthropogenic landforms

I Introduction

From a geological point of view, including the debate of whether a new interval of geological time needs to be introduced – the Anthropocene – is broadly intended as the time in which human influence on Earth and its geological record have dominated over natural processes (Cooper et al., 2018; Crutzen, 2002; Steffen et al., 2007; Waters et al., 2016). In this context, research in urban geomorphology, which is a relatively recent topic and its theory and practice require continuous updates, insights and assessments, may address the definition of the Anthropocene (Brown et al., 2017; Cooke, 1976; Cooke et al., 1982; Rosenbaum et al., 2003; Tarolli et al., 2019). Methodological approaches to recognize and map landforms in urban environments are different to those used in natural environments, where geomorphological features are easier to identify (Del Monte et al., 2016; Ellison et al., 1993; Eyles, 1994; Mozzi et al., 2016; Teixeira Guerra, 2011). Geomorphological surveys in urban environments entail careful observations of urban topography, particularly at a medium–large scale (Coates, 1974, 1976). Insights from other sources, such as historical and geographical documents as well as archaeological and drill records, are essential in order to identify, map and date landforms, including those produced or modified by anthropogenic processes (Brandolini et al., 2018a; Del Monte et al., 2016; Luberti et al., 2019; Lucchetti and Giardino, 2015).

In Mediterranean and European cities, urbanization processes are particularly difficult to identify due to the stratification of urban expansion phases (Bathrellos, 2007; Zwoliński et al., 2018). These cities were often founded in ancient times, then expanded or decayed in the Middle Ages, and then progressively grew over centuries (Del Monte et al., 2013; Gisotti, 2016). Initially, the expansion was confined by the occurrence of topographic obstacles (watercourses, cliffs, heights, gorges, coastline, swamps, etc.). Subsequently, these elements of the landscape, considered unfavourable to the urban development and hardly surmountable in some historical periods, have been overcome through new construction techniques of modern structures and infrastructures, progressively more impactful and less adaptive (Donadio, 2017). In the 20th century, and particularly after the Second World War (WWII), the topography of many cities went through uncontrolled urban expansion/sprawl, which has been termed an “urban revolution” (Diao, 1996). In the Mediterranean, this was partly related to the development of tourism (Brandolini et al., 2017).

In the past, relationships between surface and subsoil were carefully considered to avoid damage due to unpredictable natural catastrophes, such as earthquakes, floods, storms, volcanic eruptions and landslides. In the last centuries, the increasing demand for land and the consequent decreasing supply of mainland have often triggered both uncontrolled expansion of the built-up area and the conurbation, also involving any available waterscape. These processes have increased the risk of present-day densely populated urban areas, which have developed in zones sparsely inhabited, until recently, but affected by high to extreme natural hazards (Del Monte et al., 2015; Hollis, 1975; McGranahan et al., 2007).

The growing interest is in how urban geomorphology can both aid in a better understanding of the effects of city development on geomorphological features, and their relationship to the increase in geo-hydrological risk also in relation to climate change (Berti et al., 2004; Brandolini et al., 2012; Del Monte et al., 2016; Lóczy and Sütő, 2011; Slaymaker et al., 2009) and contribute to the dissemination and preservation of cultural geo-heritage in urban areas (Pica et al., 2015, 2017, 2018; Reynard et al., 2017; Rodrigues et al., 2011; Zwoliński et al., 2017, 2018).

In the framework of these issues, the case studies of five Mediterranean coastal-city key sectors located at Genoa (Liguria, northwestern Italy), Rome (Lazio, central Italy) Naples (Campania, southern Italy), Palermo (Sicily, southern Italy) and Patras (southwestern Greece) are presented and compared (Figure 1). Even though they are far away from each other, the selected study areas feature a Mediterranean climate (Table 1), Csa/Csb Köppen–Geiger subtypes (Köppen, 1936; Kottek et al., 2006; Trewartha and Horn, 1980). They are classified as *coastal* or *fluvial hilly port cities* (Gisotti, 2016), generally showing almost the same exposure of the coast to sea wave action and similar morphology, with significant slope and terraced areas dissected by urban streams.

The main aims of this research are (1) to highlight the former geomorphological features that influenced the choice of early settlement and subsequent urban development; (2) to detect the new artificial landforms; (3) to evaluate the impacts of human intervention on geomorphological processes; and (4) to define the current geomorphological hazard and risk scenarios in the different study cases.

The final goal of this paper is to produce novel maps of anthropogenic landforms for each study area, with specific graphical devices devoted to the representation of man-made landforms (Figure 2) and following the experimental geomorphological classification (Campobasso et al., 2018) proposed by the Working Groups of the Italian Association of Physical Geography and Geomorphology (AIGeo) and the Italian Institute for the Environmental Protection and Research (ISPRA).

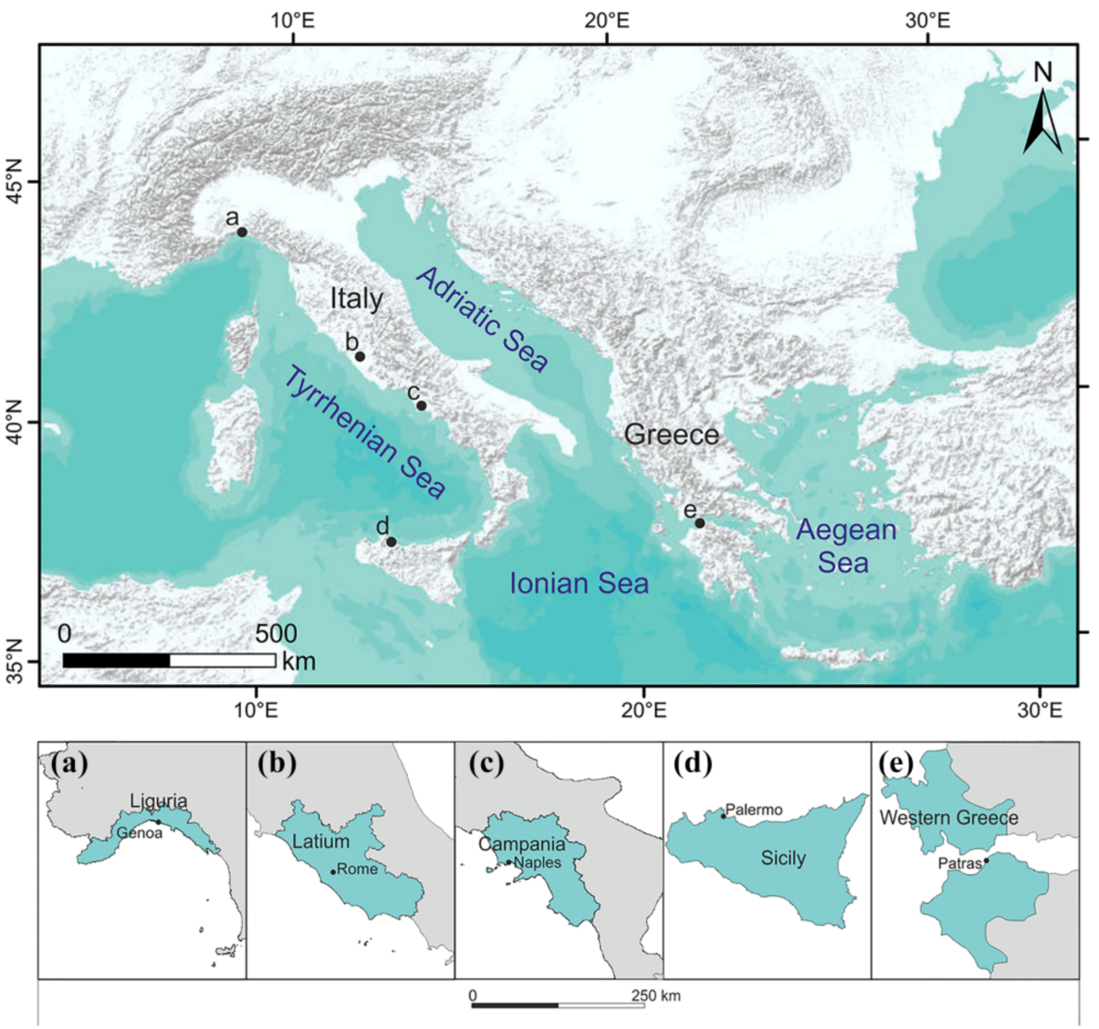

Figure 1. Location of the case study cities. (a) Genoa; (b) Rome; (c) Naples; (d) Palermo; (e) Patras.

Table 1. Basic climatic data of the five studied Mediterranean cities.

City	Mean annual rainfall (mm)	Mean annual temperature (°C)	Mean annual rainy days (> 1 mm)
Genoa	1268	15.8	101
Rome	798	15.3	77
Naples	866	18.0	86
Palermo	803	19.0	74
Patras	631	17.9	97

II Geographical setting of the case studies

1 Genoa

The Genoa historical centre faces the central Ligurian Sea (Figure 1). The natural morphological "amphitheatre", where the old historical town and port were built up, covers an area located between the two Genoa's main catchments (Figure 3): Polcevera Stream (west and Bisagno Stream (east). It is a roughly

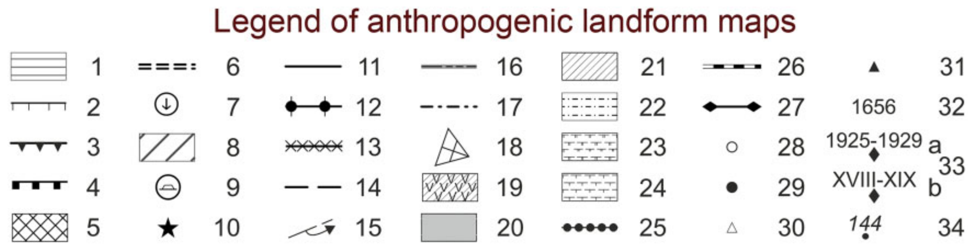

Figure 2. Legend for anthropogenic landform maps (Figures 3–7). Erosional landforms: 1: excavation area due to quarry activity and road, railway and building work; 2: edge of quarry scarp; 3: edge of scarp due to road, railway and building work; 4: edge of modified fluvial or marine terrace; 5: railway tunnel; 6: road tunnel; 7: lift tunnel/elevator shaft; 8: underground quarry/catacombs area; 9: underground cavity entrance (single quarry, air shelter, catacombs); 10: underground cistern; 11: poorly modified and/or natural riverbed; 12: culvert stream; 13: concrete riverbed; 14: eaves channel; 15: riverbed diversion; 16: underground aqueduct; 17: abandoned channel. Accumulation landforms: 18: modified alluvial fan; 19: filling material on valley, on slope and on anthropogenic excavation; 20: artificial hill; 21: marine embankment; 22: embankment due to railway, road, building work; 23: cultivated or well-preserved terrace; 24: abandoned or destroyed terrace; 25: retaining wall; 26: defence wall; 27: dam. Thickness (th) of filling materials: 28: th $\leq$ 5 m; 29: 5 m < th $\leq$ 10 m; 30: 10 m < th $\leq$ 20 m; 31: th > 20 m. Morphochronological data of main anthropogenic modifications: 32: date of morphogenetic event; 33: time span of morphogenetic event (a, years; b, centuries); 34: elevation m a.s.l.

triangular-shaped area surrounded by the 17th-century walls which started from the promontory of the lighthouse up to Mount Peralto (489 m above sea level (a.s.l.)); the eastern walls run along the eastern bank of the Bisagno Stream in order to protect the hill of Carignano, which is the eastern ridge of the historical centre (Brandolini et al., 2018a).

This area, which is about 8.5 km^2 wide, includes seven small and steep catchments, today barely identifiable due to urbanization, but effectively represented by the "Genova Zero" map (Barbieri, 1938). From a geological point of view, the area is characterized by marly limestones with thin interlayers of shales and blackish or greenish shales (Upper Cretaceous). Although the rock masses have been affected by several deformations, they show general bedding with dip direction towards the south-east and dip angle ranging between 30° and 60° (APAT, 2008). Stiff fissured clays (Pliocene) are situated in correspondence of the historical centre and old harbour area, within a graben structure with west-north-west–east-south-east direction. From 45 to 90–100 m a.s.l., along the slope and the divide with Polcevera and Bisagno valleys, the relict of some almost flat surfaces that cut Pliocene deposit, identifiable as Quaternary marine terraces, are observable (Brandolini et al., 1996). The climate of Genoa is dry with hot summers, relatively mild winters and heavy rainfalls mainly concentrated in autumn (Sacchini et al., 2012) (Table 1). Numerous flash flood events historically affected Genoa city (Brandolini et al., 2012; Faccini et al., 2015, 2016).

2 Rome

The territory of Rome faces the Tyrrhenian Sea (Figure 1). The climate is temperate, and autumn often has more rainy days than winter and spring (Table 1), whereas summer is generally dry and hot (Aeronautica Militare Servizio Meteorologico, 2009). The geological bedrock consists of marine clays and marls (Pliocene–Early Pleistocene), which underlie deposits of

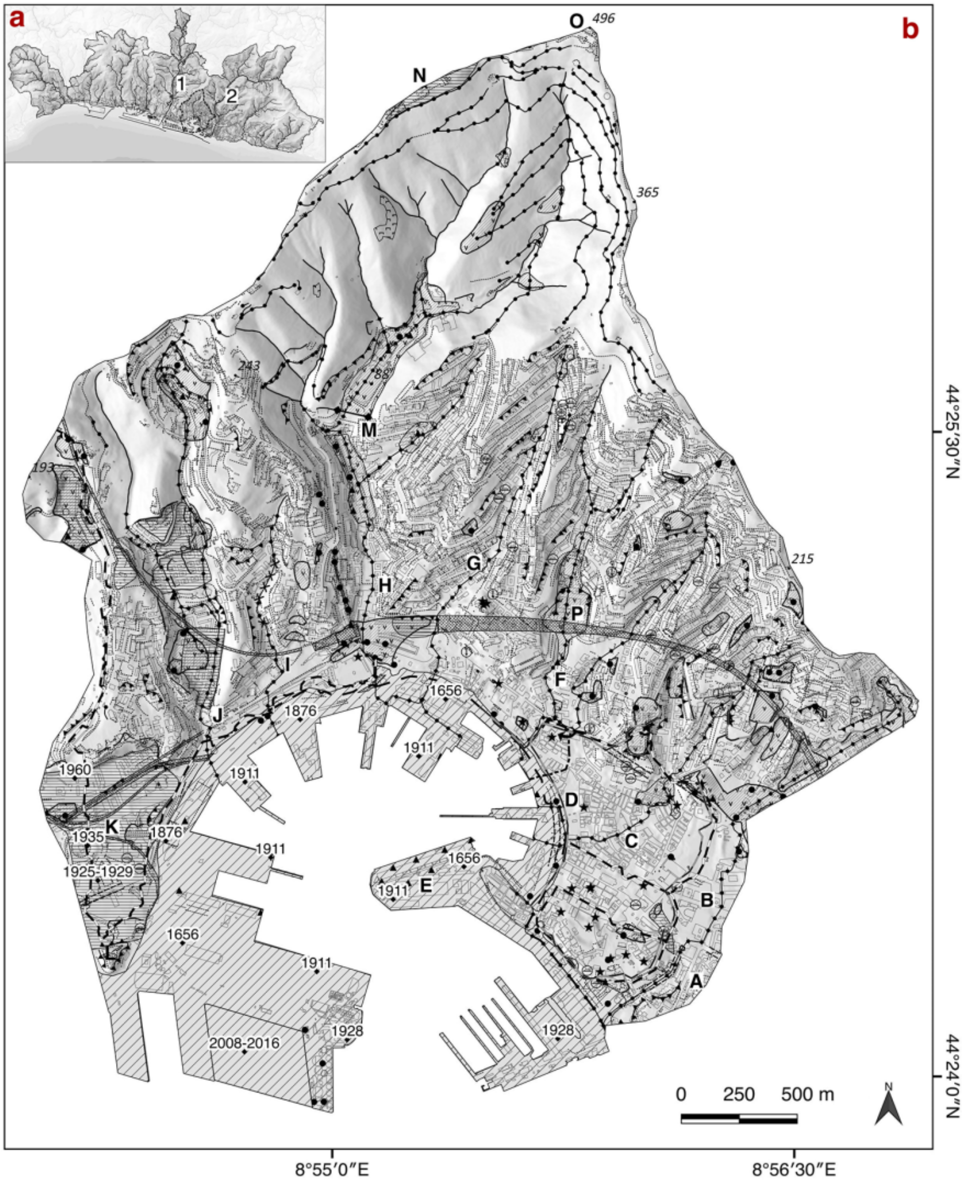

Figure 3. (a) Boundary of Genoa municipality with the location of the historical city area (dashed line) and of Polcevera (1) and Bisagno (2) streams. (b) Anthropogenic landforms map of Genoa (Liguria, northwestern Italy). For the legend, refer to Figure 2. Main toponyms cited in the text: A. Carignano Hill; B. Torbido Stream; C. S. Anna Stream; D. S. Giorgio Palace; E. Magazzini del Cotone; F. Carbonara Stream; G. S. Ugo Stream; H. Lagaccio Stream; I. S. Teodoro Stream; J. Dinegro Stream; K. S. Benigno promontory; L.Lanterna (lighthouse); M. Lagaccio dam; N. Forte Begato; O. Mt. Peralto; P. "Albergo dei Poveri" Palace.

coastal, lagoon, palustrine and fluvial environments. The continental sedimentary deposits are interdigitated with mainly pyroclastic deposits, erupted since Middle Pleistocene, due to the interaction between erosion processes, sea-level changes, tectonic displacements and

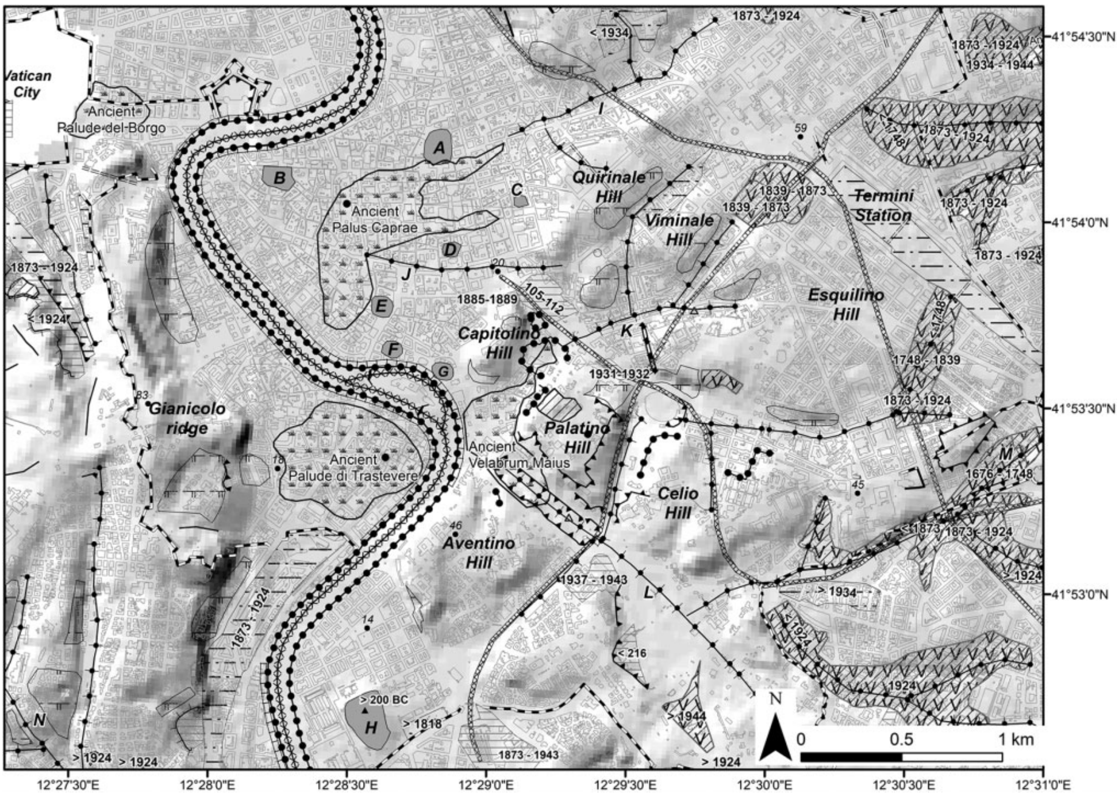

Figure 4. Anthropogenic landforms map of Rome (Latium, central Italy). For the legend, refer to Figure 2. Main toponyms of man-made hills and ancient streams cited in the text: A. Montecitorio; B. Monte Giordano; C. Monticello; D. Monte Cacco; E. Monte della Farina; F. Monte dei Cenci; G. Monte Savello; H. Monte Testaccio; I. Ancient Fosso Aquae Sallustianae; J. Ancient Fosso Petronia Amnis; K. Ancient Fosso Spinon; L. Ancient Fosso Nodicus; M. Ancient Fosso di Santa Croce; N. Ancient Fosso di Tiradiavoli.

volcanic activity. Since the last glacial age, the lowering of the base level of the Tiber River caused a fluvial deepening up to –50 m a.s.l. (Figure 4). The following fluvial deposition produced alluvial plains with deposits up to 60 m thick (Ascani et al., 2008; Belisario et al., 1999; Bellotti et al., 2011; Luberti et al., 2017 and references within; Lupia Palmieri et al., 1998).

The present-day physical landscape appears hilly, as a result of the volcanic plateau reshaped by fluvial processes. The area on the east side of the Tiber River hosts the largest part of a volcanic plateau. Fluvial deepening led to the development of numerous, elongated ridges in the interfluvial areas, flat at the summit, which still dominate the urban landscape of this eastern sector, which is that of the famous "Seven Hills" (Figure 4). To the west of the Tiber River, the alluvial plain ends at the foot of a tectonic ridge, which is affected by gravitational processes.

Over the past 3000 years, human activities have remodelled the topographic surface and become the most important modelling agent of relief. Many reliefs have been erased, whereas thick layers of anthropogenic deposits covered most of the natural landforms (Del Monte, 2017, 2018; Del Monte et al., 2013, 2016; Luberti, 2018; Luberti et al., 2018, 2019; Pica et al., 2017).

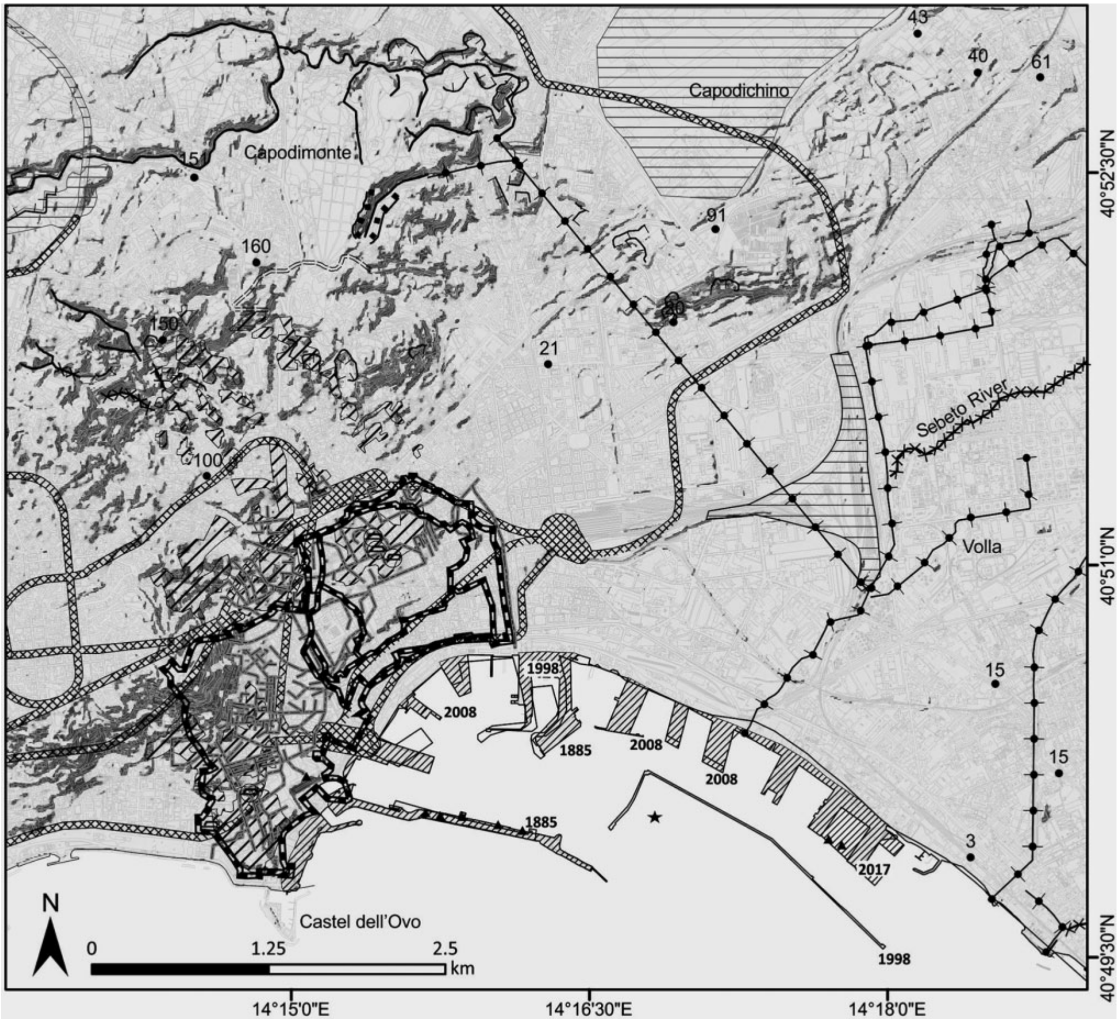

Figure 5. Anthropogenic landforms map of Naples (Campania, southern Italy). For the legend, refer to Figure 2.

3 Naples

The city faces the Tyrrhenian Sea and along the coastal belt exposed to western storms (Figure 1). The microclimate is subtropical, weakly continental and sub-humid–humid (Table 1) (Aeronautica Militare Servizio Meteorologico, 2009; Mazzarella, 2017). The Greeks founded Naples (Napoli) in the 8th century BCE; its etymology derives from the colony Neapolis (Νεάπολις), meaning new city. The Roman port (Di Donato et al., 2018; Russo Ermolli et al., 2014) was discovered during metro-line excavation near the modern port. The total metro length reaches 23 km.

The study area is 52 km^2 (Figure 5). The city is along the margin of a 12-km-large caldera between the active volcanic areas of the Phlegraean Fields (west) and Mount Somma-Vesuvius (south-east). The landscape is modelled on Late Quaternary pyroclastics (De Vivo et al., 2001; Monti et al., 2011). The city skeleton is mainly formed by the Neapolitan Yellow

Tuff (NYT; ~15 ka BP) (Deino et al., 2004) and other tuffs of local vents (Scarpati et al., 2013, 2015) underlying incoherent pyroclastics and Holocene deposits (Di Girolamo et al., 1984).

From 2700 years BP until the 1970s, the NYT was used as geomaterial for constructions (Morra et al., 2010). The underground down to 45 m below ground level (b.g.l.) shows caves and channels used as aqueducts from Roman times until the 19th century and as an anti-bomb shelter during WWII. Two river basins of about 1000 km^2 fall in the study area. The Arena di Sant'Antonio Stream (west) and the Sebeto River (east) cross the periphery plains; these urban rivers were engineered as a culvert or tunnel (De Pippo et al., 1998). The drainage network is subdendritic and is a third-order stream, sensu Strahler (1957). The network is 25 km long, 15 km of which are bridged and 5 km culverted. The drainage density is 0.48 km^{-1}.

The 1900s embankments, waterfront redesign and building of new neighbourhoods in the 1960s–1970s transformed the city: two large natural landforms vanished to build the railway station of Piazza Garibaldi (east) and the Capodichino Airport (north). Intense rainfalls occurred in the last decades (Braca et al., 2002), triggering flash floods and landslides. Similar flooding occurred from Roman times, as testified by alluvial deposits covering the ruins, to the end of the 1800s (Cinque et al., 2011). Considering the current waterscape, the poorly preserved hydrographic network and medium-to-high seismicity, the overall geomorphological hazard results range from high to extreme degrees (De Pippo et al., 2008).

4 Palermo

Palermo (*Pan-ormos*, Greek *Παν-όρμος*), with a maximum height of about 100 m a.s.l. (36 m a.s.l. the old town), is located on the northern coast of Sicily, southern Tyrrhenian Sea (Figure 1). The climate is characterized by high temperatures with hot-dry summers and rainy winters and autumns (SIAS, 2002; Table 1). Phoenicians founded the city in the 7th century BCE on a rocky spur flat at the top and isolated by two streams (Papireto and Kemonia), on which a large and easily defended port was built (Coroneo, 2011; Di Matteo, 2002). Deforestation has occurred ever since the beginning of the Roman occupation. The consequent increase in erosion processes and river transport over time produced a partial filling and a gradual downsizing of the port. In the Arab period (9th–11th centuries), the city continued expansion outside the old town, beyond the Papireto and Kemonia streams. Currently, the large plain on which Palermo stands is an almost entirely artificial construction.

This plain, Conca d'Oro, is bounded by broad scarps hundreds of metres tall passing inland, and lies on a depression of tectonic origin consisting of lowered faulted blocks. The blocks sunk below the sea level and were sealed by coastal and neritic clastic deposits (Marsala synthem; ISPRA, 2013a, 2013b) during the Calabrian age, and uplifted subsequently from the Middle Pleistocene. Along the plain of Conca d'Oro outcrops the Marsala synthem consisting of bioclastic calcarenites with a very slight dip towards the sea and lying on Mesozoic carbonates or Cenozoic clays (Floridia, 1956). Meso-Cenozoic rocks also crop out along the surrounding mountain area, which is sensitive to mass movement (mostly rockfall) and its related risk (Cafiso and Cappadonia, 2019). On the plain, a stair-step flight of uplifted coastal terraces, which were produced during Middle–Late Pleistocene marine highstands, develops from 0 m up to about 150 m a.s.l. Wide abandoned coastal cliffs derived from original fault scarps and bordered by broad talus slopes link the marine terrace surfaces to the mountain areas (Di Maggio et al., 2017).

Few rivers flow through the plain of Conca d'Oro. The main one is the Oreto River, which is about 20 km long and flows along the south

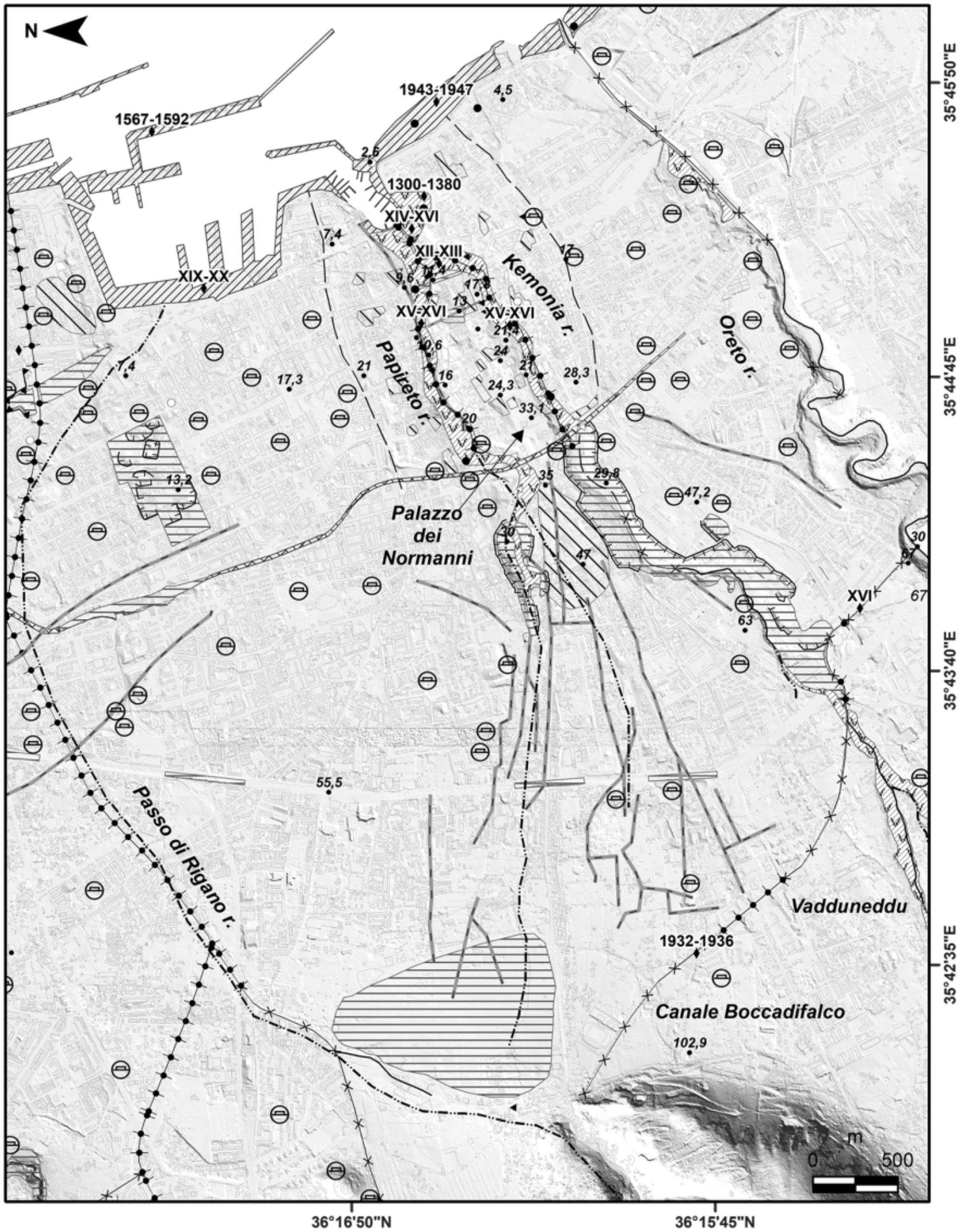

Figure 6. Anthropogenic landforms map of Palermo (Sicily, southern Italy). For the legend, refer to Figure 2.

margin of the city. Further north, the Rio Lisciardone (today, Passo di Rigano channel) is about 12 km long and flows to the port. Between these rivers, two other short streams (Kemonia and Papireto) flowed in the past.

5 Patras

Patras is located in Northern Peloponnese, at the foothills of Panachaiko Mountain (Figure 1). Glafkos and Milichos rivers form the broad boundary of the city to the west and east,

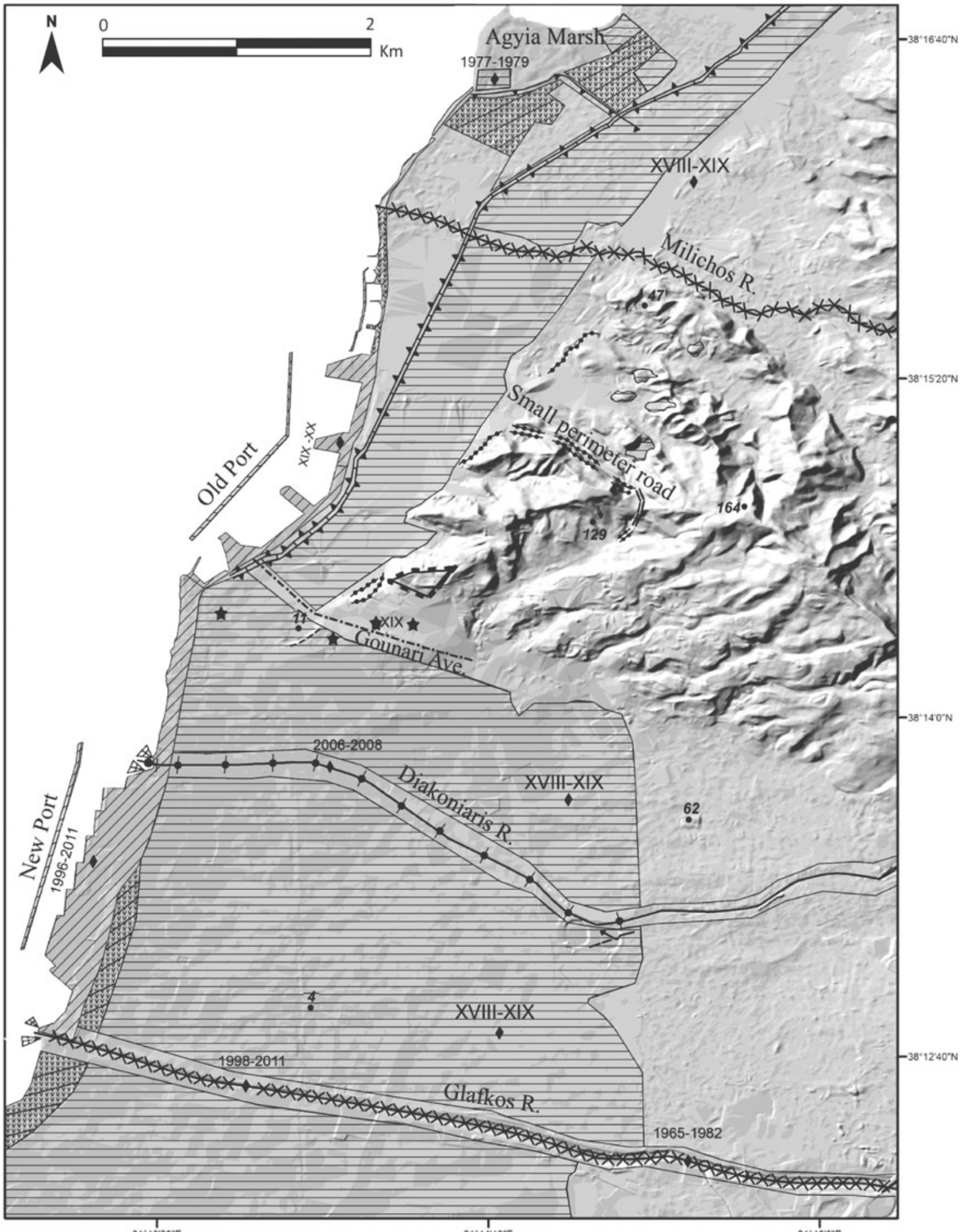

Figure 7. Anthropogenic landforms map of Patras (western Greece). For the legend, refer to Figure 2.

respectively (Figure 7). The climate is characterized by a dry summer and a mild, rainy winter (Table 1). The bedrock is the Olonou–Pindou geotectonic zone. Tectonically, the area is characterized by two groups of faults, with north-east–south-west and north-west–south-east directions (Tsiambaos et al., 1997) and by high seismicity.

The history of the city spans over 4000 years; the first settlement indications come from the prehistoric age when Patras was an important commerce centre. One of the most important

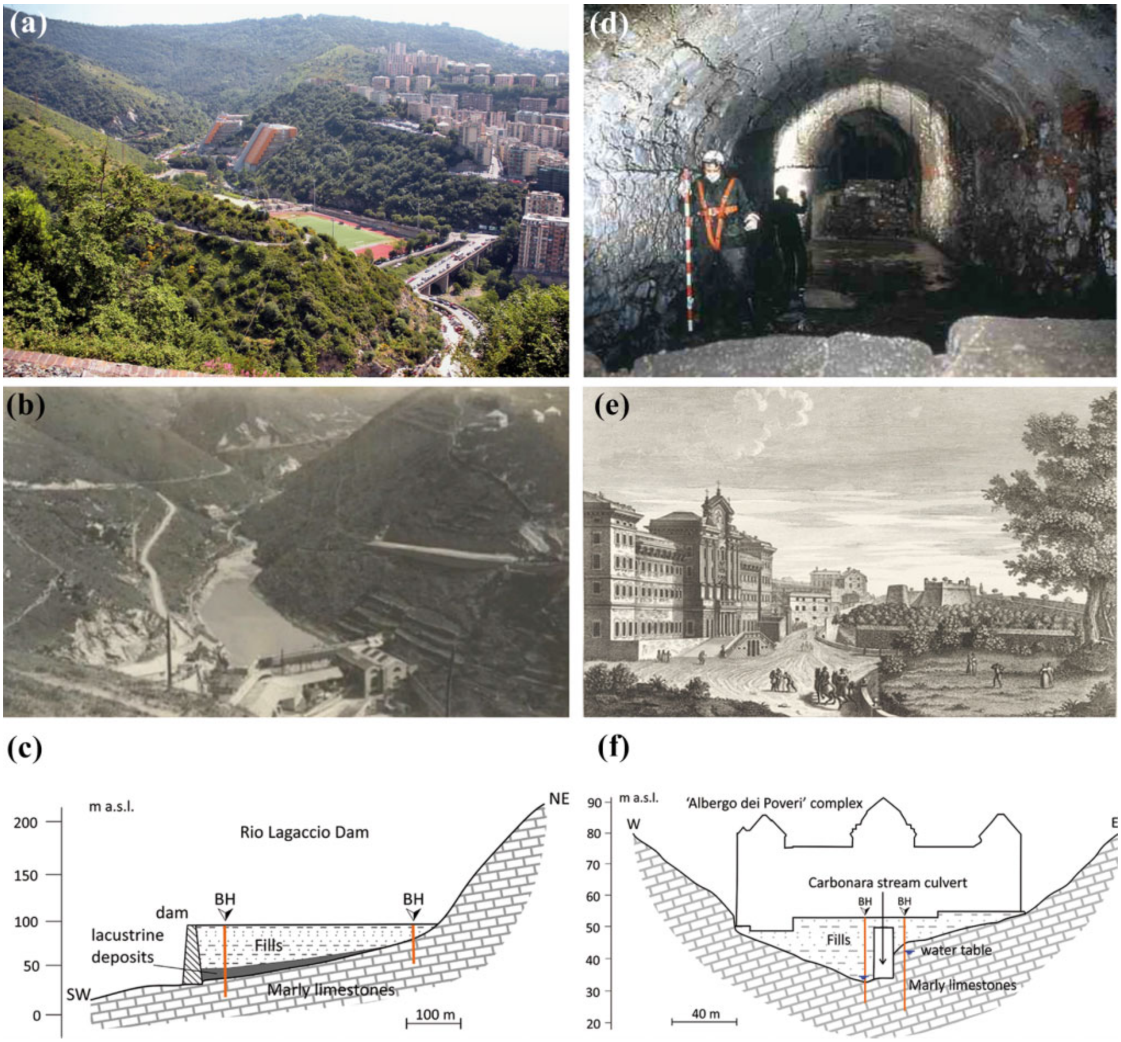

Figure 8. Genoa: (a) Lagaccio Stream valley – the present-day situation, with the sports facilities on the fills; (b) Lagaccio Dam lake in the 1960s; (c) Lagaccio Valley geomorphological longitudinal section; (d) Carbonara culvert stream under the building complex of "Albergo dei Poveri"; (e) engraving of the "Albergo dei Poveri", dating back to the XIX century; (f) Carbonara Valley geomorphological cross-section.
BH: boreholes.

features of the city of Patras is its port, which has been heavily modified during the years. It is a part of Patras Gulf, which is a microtidal sea, dominated by locally generated waves from strongly bimodal wind patterns (Alevizos and Stamatopoulos, 2016; Piper et al., 1982). The first indications of maritime and coastal activities during the prehistoric ages have been located in the area of Aygia in the north-east of the city. During the Frank occupation in the 13th century, Patras Port was moved to the northern side of the city, so that it lays in a beeline from the city's castle, where extension works took place in 1930. In 1956, the port was further extended northwards.

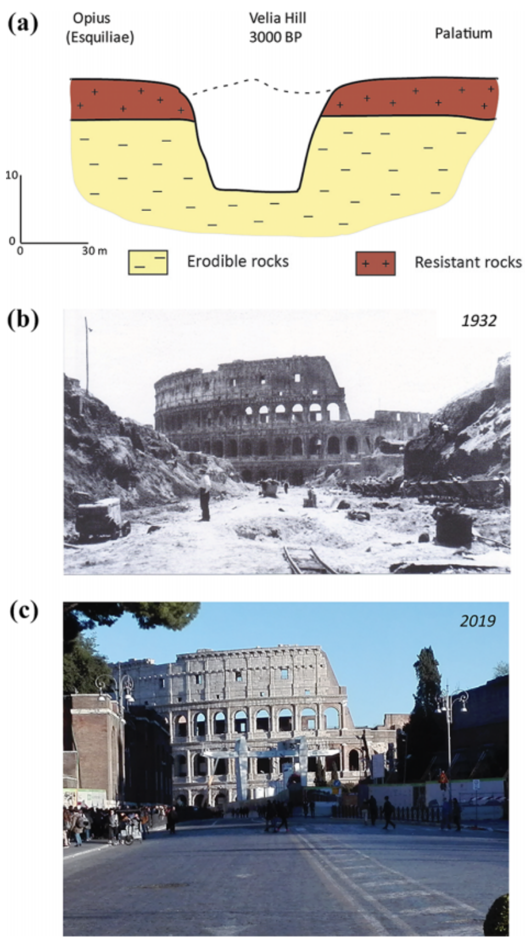

Figure 9. Rome: the Velia hill, whose original form had already been partially transformed in the Nero and Flavi Emperors age, was finally demolished for the construction of a large boulevard next to the Colosseum (Via dei Fori Imperiali). (a) Cross-section between the Opius-Esquiliae (on the left) and the Palatium (on the right). (b) Demolition of the Velia hill (Source: Insolera, 1985). (c) The absence of the Velia hill from the physical landscape of the city. The Velia hill was one of the seven heights corresponding to the putative Seven Hills of the Romulus age.

The drainage network of the study area mainly consists of three rivers: the Diakoniaris and the aforementioned Glafkos and Milichos. In the past, catastrophic floods from these rivers determined heavy damage to infrastructures and even casualties. The Diakoniaris is one of the most catastrophic overflowing rivers in Greece, with recurring floods in winter. Presently, the banks of the Diakoniaris from the coastal area up to 1 km upstream are covered by the main avenue (Despiniadou and Athanasopoulou, 2006). Land use changes following the development of Patras city have led to the canalization of Glafkos River in the 1970s and Diakoniaris River in the 2000s. The city underwent fast and continuous expansion in the mid-1800s, and even greater development in the 1950s, with a high influx of people that, as a result, developed rural areas, merging them with the city.

III Materials and methods

Each of the large-scale geomorphological maps of urban centres, particularly devoted to representing anthropogenic landforms, collects and summarizes the results obtained by (1) a preliminary collection and analysis of existing information from the scientific and technical literature; (2) a multi-temporal comparison of photographs and topographic maps of various ages; and (3) a detailed campaign of field observations and surveys. The research started by reviewing the existing geological and geomorphological information of the five areas. Geological maps were available from both the Geological Survey of Italy and the municipality city-plan services. Other very useful information came from borehole databases of the public authorities, which allowed both precise interpretations of the nature of bedrock and shallow deposits, and a quantitative assessment of the thickness of the man-made deposits. The original stratigraphic logs have been reinterpreted by classifying them according to the different thicknesses of the filling materials, and by identifying the presence of cavities and artefacts.

Significant geomorphological information was collected from the basin plan for the reduction of geo-hydrological risk, the municipal urban plans of each of the cities and the scientific literature. Among the numerous articles consulted, the geological and geomorphological observations by Limoncelli and Marini (1969) and by Rovereto (1938) and historical urban evolution by Barbieri (1938) deserve particular mention for the Genoa case study. With regard to Rome, a great amount of geognostic data and spatial information was provided by the two geologic monographs by Ventriglia (1971, 2002), whereas geomorphological information on the city before the modern urbanization was extracted by several historical papers and books, starting from Brocchi (1820). For Naples, a large amount of historical and recent maps were collected in the archive of the Authority of the Port System of the Central Tyrrhenian Sea. Within the Palermo city, the main man-made changes have been reconstructed thanks to data from Columba (1910) and Todaro (2002, 2004). With regard to the Patras municipality, the "Memories of Maps", by Alexopoulou and Stamatiou (2014), was particularly significant.

The multi-temporal comparison of georeferenced maps, aiming at the reconstruction of the geomorphological landscape pre-dating the main urbanization (19th century), was mainly focused on the identification and mapping of ancient and recent excavation and backfilling activities, historical cavities and quarries, modifications to the hydrographic network, landfills at the seaside, aqueducts and historical walls. A comprehensive list of all of the sources that were consulted and used (e.g. topographic, thematic and historical maps, aerial photos, satellite images, borehole databases and basic elevation types) is reported in Table 2.

The aerial photos allowed authors to improve geomorphological interpretation of the area between the 1930s and 1990s. Further analysis of the recent and present landscape was performed using Google Earth Pro, including images up to 2018.

The detailed on-site geomorphological survey performed in urban environments allowed the following activities:

- geomorphological observations, aimed at identifying and mapping the areas affected by excavations and landfills, as a comparison with the results obtained by the interpretation of stratigraphic logs;
- identification of other anthropogenic landforms, as areas (e.g. quarries), linear features (e.g. retaining walls, artificial scarps) and points (e.g. cisterns, tunnel entrances).

All collected data were georeferenced and processed using a Geographic Information System (both ArcMap v. 10.2.2 and QuantumGIS v. 2.18). Classification and mapping of the anthropogenic landforms refer, with the integration of some new items, to the official guidelines of the geomorphological legend published by ISPRA, in collaboration with the National Working Groups of AIGeo, following a morphoevolutive dynamic approach (Campobasso et al., 2018; Mastronuzzi et al., 2017). Each anthropogenic (man-made) landform was classified according to its morphogenetic process (filling or excavation) and its activity (Chelli et al., 2018; Del Monte et al., 2016; Rosenbaum et al., 2003), considering the adopted original cartographic scale (1:5000), which is consistent with the necessity to map the exceptional variety of landforms of the urban landscape (Figure 2).

IV Results

1 Drainage network changes

Through the centuries, following progressive urban sprawl, almost all of the five city drainage networks have been strongly modified, mostly causing a reduction of flow sections. The river catchments of the studied areas have surface areas ranging from less than 10 to about 50 km^2, depending on the physical geography of the territory. The only fluvial basin of considerable size is that of the Tiber River, which is upstream of Rome and occupies an area greater than 17,000 km^2.

Table 2. Comparative list of cartographical-aerial photo materials and data sources consulted/used for the realization of anthropogenic landform maps.

City	Base maps	Historical maps	Aerial photos, orthophotos, satellite images	Thematic maps, boreholes database	Basic elevation types
Genoa	• CTR Liguria 2007 – scale 1:5000	• Napoleonic Cadastre 1805–1814 • Carta degli Stati Sardi di Terraferma 1815–1827 – scale 1:9450 • Municipality map by Ignazio Porro 1836 – scale 1:2000 • Municipality map by Poggi (1898) • IGMI 1878, 1939 – scale 1:25000	• IGMI 1936 • GAI 1954 • Regione Liguria 1973, 2007	• Barbieri 1938 • Basin Master Plan for geo-hydrological risk mitigation • Municipality Plan	• 5 m cell size DTM, interpolated from CTR 2007 – scale 1:5000
Rome	• CTR Lazio 1990 – scale 1:10000 • CTR Lazio 2002 – scale 1:5000	• Nolli 1748 – scale 1:2910 • Moltke 1852 – scale 1:25000 • Direzione del Censo 1866 – scale 1:4000 • IGMI 1873 – scale 1:25000 • IGMI 1907, 1924 – scale 1:5000	• Nistri 1919 • SARA Nistri 1934 • MAPRW RAF 1943, 1944 • GAI 1954 • Regione Lazio 1980s	• Lanciani 1893–1901 – scale 1:1000 • Ventriglia 1971 – scale 1:20000 • Ventriglia 2002 – scale 1:20000 • Corazza and Marra 1995 – scale 1:10000 • Marra and Rosa 1995 – scale 1:10000 • Funiciello and Giordano 2008 – scale 1:10000	• 5 m cell size DTM, interpolated from CTRN 2002 elevation data – scale 1:5000
Naples	• CTR Campania 2004 – scale 1:10000 • CTP Napoli 1998 – scale 1:5000	• Carafa 1775 – scale 1:3808 • IGMI 1955 – scale 1:25000 Map of Naples by Theti (1560) in Valerio and Bellucci (1998) • Maps of neighbourhoods of Naples (1830) in Valerio and Pane (1987) • Map of the city of Naples from Municipality of Naples (1872–1880) • Topographical maps of the Municipality Mapping Service of Naples (1975) updated to 1985 • Photographic archive of CNVVF	• RAF USAAF 1943 • Telespazio spa – QuickBird 2002, 2003, 2004 • Orthophotos – scale 1:10000, pixel size 50 cm by the Agency for Disbursements in Agriculture Resolution (2012) • LIDAR (2009) surveyed by Nuova Avioriprese in the project Cecosca (Cave Satellite Center)	• Comune di Napoli 1967,1972, 2000 • Variant to the General Plan of Naples 1999, 2005 • CARG F°446-447 Napoli 2015 • Authority of the Port System of the Central Tyrrhenian Sea 2018	• 1 m cell size DTM, interpolated from LIDAR volo Città Metropolitana di Napoli 2009–2012 – pixel size 0.25 m
Palermo	• ARTA Lotto 1 "Cart2000" – scale 1:2000 • CTR Sicilia 2007–2008 – scale 1:10000	• ITM 1885 – scale 1:5000 • Columba 1913 – scale 1:7875 • NISTRI 1935 – scale 1:5000 • IRTA 1956 – scale 1:5000 • IGMI 1912, 1937, 1970 • SAS 1973,1994 – scale 1:25000 • CTR 1994, 2005 – scale 1:10000	• ARTA Ortofotocarta digitale IT 2000 – scale 1:10000 • ARTA Ortofoto ATA 2007–2008, pixel size 0.25 m	• Cusimano et al. 1995 – scale 1:25000 • Calvi et al. 1998 – scale 1:50000	• 2 m cell size DTM, interpolated from LIDAR volo ATA 2007–2008 – pixel size 0.25 m
Patras	• NASA EarthDATA/EOSDIS No.: ASTGTM2_N38E021	• HMGS online database • Special publication of Patras municipality, "Memories of Maps" (Alexopoulou and Stamatiou, 2014) • Map of HMGS. Patras, 1989	HMGS database aerial photos • 1979 – scale 15000 • 2002 – scale 20000 • 1960 – scale 15000 • 1965 – scale 8000 • 2002 – scale 20000	• Patras Municipality thematic layers of neighbourhoods, infrastructure and road network, 2008	• 30 m cell size DEM ASTER Global

ARTA: Assessorato Territorio e Ambiente Regione Siciliana; CARG: Carta Geologica d'Italia; CNVVF: Corpo Nazionale dei Vigili del Fuoco; CTP: Carta Tecnica Provinciale; CTR: Carta Tecnica Regionale; CTRL: Carta Tecnica Regionale Regione Lazio; CTRN: Carta Tecnica Regionale Numerica; DEM: digital elevation model; DTM: digital terrain model; GAI: Gruppo Aereo Italiano; HMGS: Hellenic Military Geographical Service; IGMI: Istituto Geografico Militare Italiano; IRTA: Istituto Rilievi Terrestri Aerei di Milano; ITI: Istituto topografico italiano; LIDAR: Light Detection and Ranging; MAPRW-RAF: Mediterranean Allied Photo Reconnaissance Wing, British Royal Air Force; RAF-USAAF: British Royal Air Force, US Army Air Forces; SARA: Società per Azioni Rilevamenti Aerofotogrammetrici; SAS: Società Aerofotogrammetrica Siciliana.

Table 3. Drainage network modifications.

City	A (km^2)	D_L (km)	R_L (km)	R_E (km)	R_C (km)	D_R (km^{-1})	D_A (km^{-1})	D_C (km^{-1})	D (km^{-1})
GENOA	6.98	23.7	7.29	0.22	16.18	1.05	0.03	2.32	3.40
ROME	19.66	30.74	1.07	6.07	23.60	0.05	0.31	1.20	1.56
NAPLES	52.01	25.02	4.97	5.20	14.80	0.10	0.10	0.28	0.48
PALERMO	47.03	21.00	7.65	9.00	4.35	0.16	0.19	0.09	0.44
PATRAS	58.94	16.25	3.50	9.20	3.87	0.06	0.16	0.06	0.28

A: study area; D_L: drainage network length; R_L: natural river length; R_E: concrete riverbed length; R_C: culvert riverbed; D_R: drainage density of natural rivers; D_A: drainage density of artificial rivers; D_C: drainage density of culvert streams; D: total drainage density of the fluvial network.

The average length of the urban hydrographic network is about 20–25 km, of which just a small portion, ranging 1 km (Rome) and 7 km (Genoa, Patras), is included in a natural or slightly modified environment. A significant part of watercourses (5–10 km) has a concrete riverbed (except for Genoa, where the fluvial network is carved into the bedrock). In all the study cases, many natural streams of the original hydrographic network became culverts (4–24 km) and all these changes have modified the drainage density of the fluvial system (Table 3). Many streams became artificial channels and culverts, in order to reclaim swampy deposits or to obtain flat surfaces suitable for urbanization (Figure 8).

In Rome, the marshy land in the Murcia Valley was reclaimed in the first millennium BCE, to build the well-known Cloaca Maxima, an underground pipe system still in operation (Figures 4 and 9). In Genoa, the hydrographic network, except the upper parts of the Lagaccio Stream catchment, is now totally hidden by buildings and roads that have been built there since the Middle Ages (Figure 3). Presently, none of the watercourses are visible in the historic centre of Naples: the mouths of main streams (Arenella Valley, Arenaccia Valley, Sebeto River, Volla River) have been modified as culverts or artificial channels since the Middle Ages (Figures 5 and 10). Underwater pipelines currently flow along the seabed of the eastern sector of the port or offshore.

In the old town of Palermo, anthropogenic deposits gradually filled the stretches further downriver of the Kemonia and Papireto valleys, whose stream beds have been turned into artificial channels and culverts since the 14th century (Figures 6 and 11). Today, during heavy rains, flooding along the built-up areas above the culverts shows that sections of the drainage tunnels are insufficient. In Patras, the Glafkos, Milichos and Diakoniaris watercourses currently show concrete riverbeds and culverts, and their channelling has led to the narrowing of the flow sections (Figures 7 and 12). Urbanization has also caused the diversions of rivers, as in the case of the St. Gerolamo Stream in Genoa, which, in the 13th century, was artificially captured and diverted into the Carbonara Stream.

A relevant human intervention was performed in the southern part of Rome centre, in the area that in ancient times was drained by a eastern tributary of the Tiber River within the ancient walls, the Nodicus River. This stream underwent many anthropogenic modifications and diversions during the centuries, and its original path is known only downstream of the Basilica of St. Giovanni (Luberti et al., 2018).

In the north-west hilly part of Naples city, the Sebeto-Volla and Torrente Cavone watercourses delimit the south-east and south-west airport area, at an average altitude of 80 m a.s.l.; the main stem and the hydrographic network were gradually diverted eastwards,

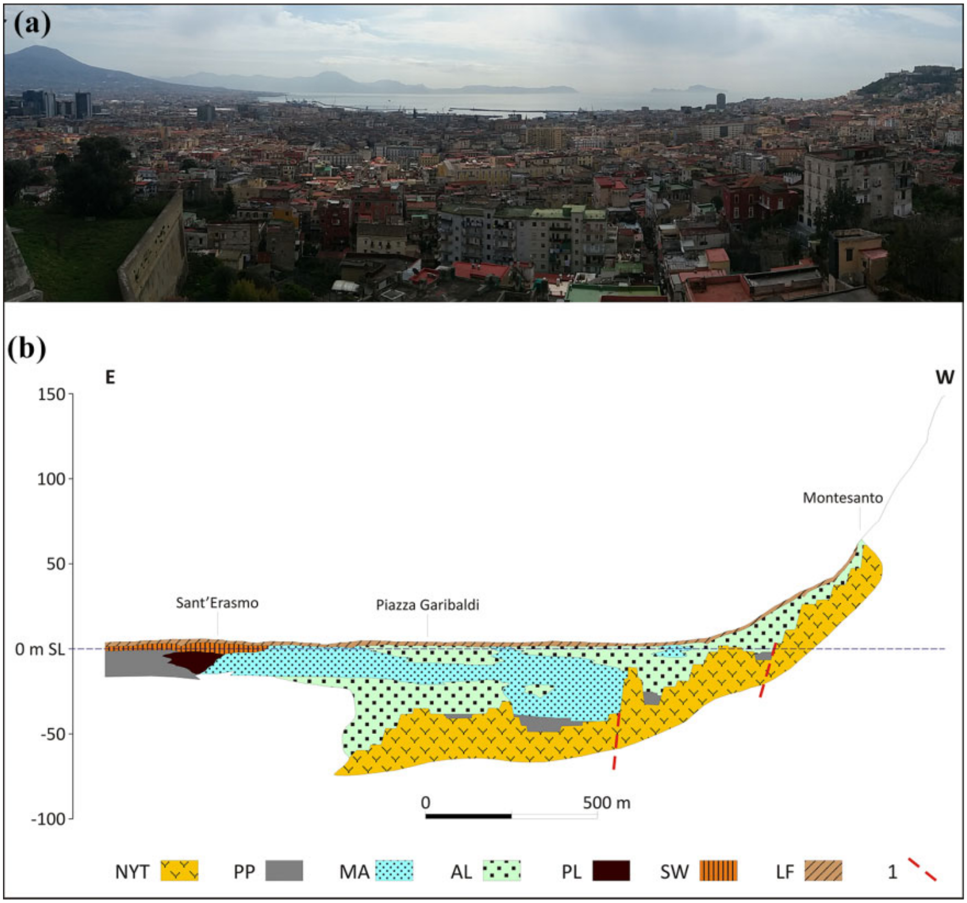

Figure 10. Naples: (a) East–west view of the city from the hilly area to the minor coastal plain and port; (b) geomorphological cross-section of downtown.
NYT: Neapolitan Yellow Tuff; PP: pyroclastics; MA: marine deposits; AL: alluvial deposits; PL: peat levels; SW: swamp deposits; LF: landfill; 1: concealed or presumed fault.

especially during the Viceroyal and Bourbon periods.

In the 16th century, a stretch of the Kemonia Stream in Palermo was diverted and channelled (Badami Channel) towards the Oreto River. After a severe flood in 1931 (Fabiani, 1931), the construction of the Boccadifalco Channel beheaded the two streams in their upstream sections, and their original tributaries (Vadduneddu Stream and Vallone Paradiso River, respectively) were diverted towards the artificial Badami Channel and then the Oreto River.

In Patras city, Diakoniaris River also turned a culvert up to 1 km upstream and diverted. Its covered riverbank now serves as one of the main road axes of Patras, called E. Venizelos Avenue, connecting to the new Port of Patras.

In order to quantify the main changes, the size modifications of the hydrographic networks and river catchments within the Palermo old town are shown in Table 4, as a representative example of the cases studied here. These data display the general shortening of the city streams due to rectification processes that have transformed meandering channels into straight

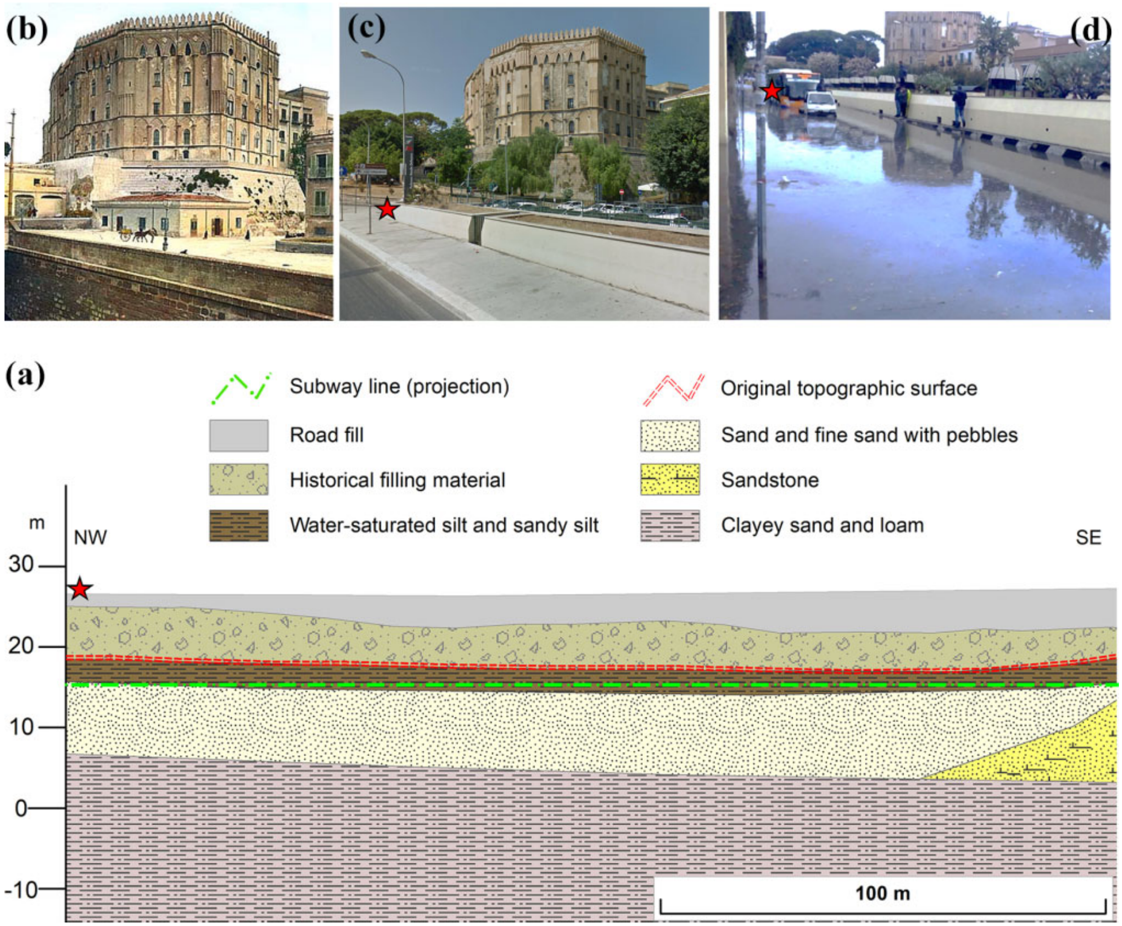

Figure 11. Palermo: (a) geomorphological cross-section of "Palazzo dei Normanni" area; (b) historical image of "Palazzo dei Normanni"; (c) current set-up via Google Street View (2018); (d) the area during a flood event (image available at: http://palermo.mobilita.org). The red star indicates the same side of the street.

riverbeds. The most significant changes in Oreto River and Kemonia Stream are produced by the man-made diversion processes that also led to the widening of some river catchments to the detriment of others. Excluding these latter processes, Oreto River has actually undergone a shortening of about 0.5 km in its final stretch.

2 Coastline changes

Urban sprawl has strongly modified the former asset of the coastlines of all the compared study areas, mainly by anthropogenic progradation of the shoreline. The coastal landscapes, following the construction of port infrastructures over centuries, have undergone major changes with the disappearance of former beaches and rocky coasts, creating a complete techno-coast landscape (De Pippo et al., 2008, 2009). Coastal retreat phenomena, due to the impact on river mouths and, consequently, on the transport and deposition of sediments, were particularly important along the littoral of Rome (Tiber River mouth) and Patras (Milichos mouth).

The current techno-coasts derive from progressive expansion phases of harbours by the

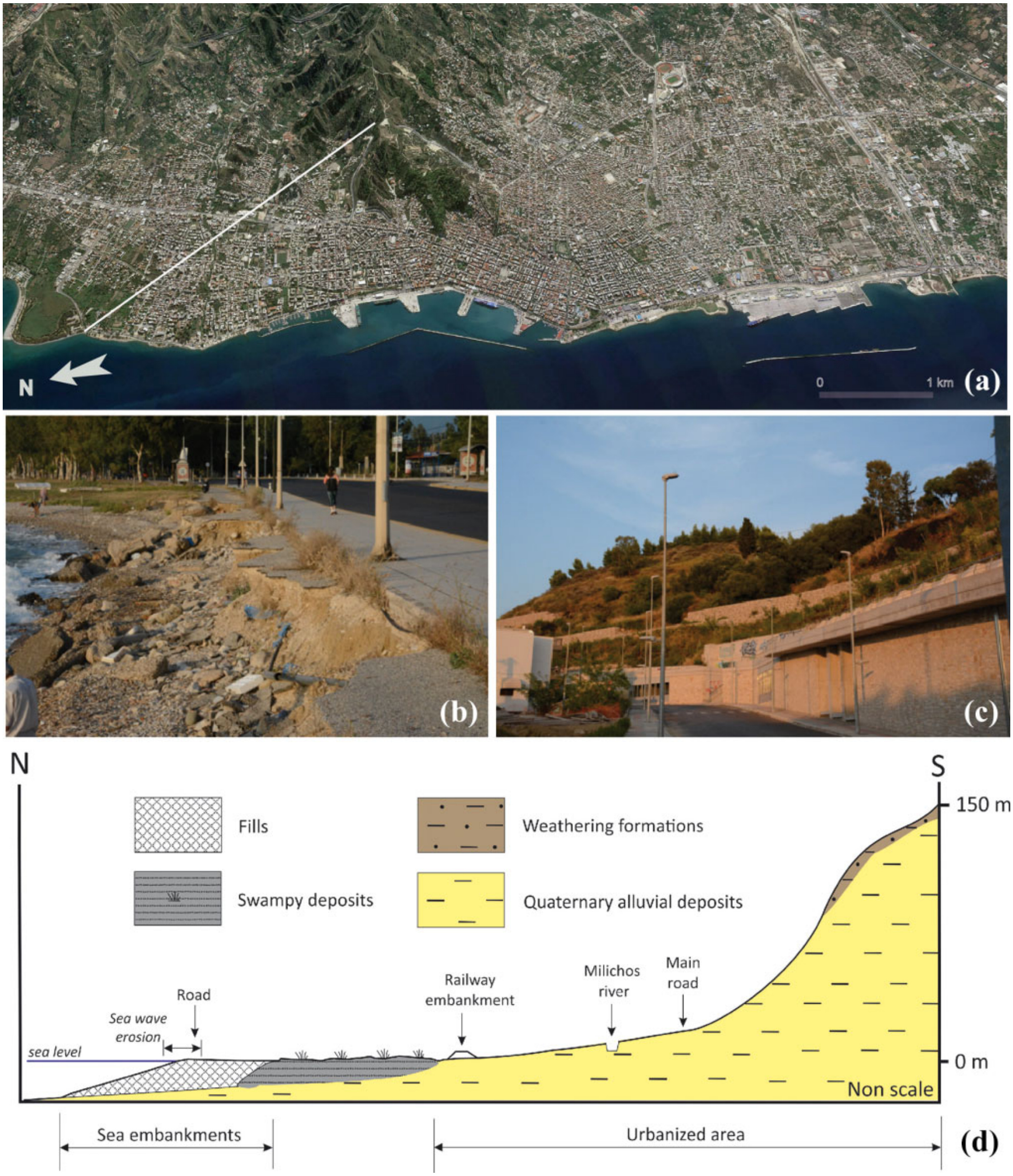

Figure 12. Patras: (a) north–south aerial view of Patras downtown with the location of geomorphological cross-section shown in D (white line); (b) debris filled the coastal area near Milichos River, which is affected by sea-wave erosion; (c) modified slope by excavation and retaining wall for the construction of western part of the small-perimeter Patras road; (d) geomorphological cross-section sketch.

Table 4. Main changes in the hydrographic networks and catchments along the studied area of Palermo (see Figure 6).

	Riverbed length (km)			Drainage catchment area (km^2)		
River	Original length	Current length	Length change	Original area	Current area	Area change
Passo di Rigano	10.90	10.48	–0.42	9.95	9.89	–0.06
Papireto	5.44	1.52	–3.91	5.08	3.69	–1.39
Kemonia	11.11	1.85	–9.25	9.59	3.95	–5.63
Oreto	8.08	17.63	9.54	10.09	17.11	7.02

construction of sea embankments. The old port of Genoa area, developed since the Middle Ages, gradually entailed an advancement of the shoreline up to the bathymetric of about 15 m. The oldest archaeological port find is a quay built with blocks of marl limestone attributed to the 12th century in the eastern sector of the bay. In the 17th century, large landfills were created along the western sector of the bay with the construction of the "New Pier", and in the central area with the creation of a new sea embankment where the S. Giorgio Palace and the "Magazzini del Cotone" were built. At the beginning of the 20th century, further expansions almost closed off the east side of the former bay (Figure 2).

The coastal changes of Rome started in ancient times with the ports at the Tiber River mouth. These changes were recently partially overlapped by the construction of the largest airport in the city in the area of the ancient imperial port.

In the study area of Naples, coastal morphology changes also concern the two-stage port expansion (Figure 5). The first was made during the Roman age, from the river mouth towards the south-west and the east, following the coast (Figures 5 and 10). The second, from the Middle Ages to the 20th century, expanded both eastwards and into the sea, reaching out southward with wide reclamations and docks.

The most distinct coastal changes of Palermo concern the port area (Figure 6), along a coastal sector about 25 km long. During the second half of the 16th century, the South and North quays were built leading to the progressive filling of the old port. As a result of increased traffic, new quays were built and the already existent ones were extended between the 19th and 20th century. The port was rebuilt after WWII and large coast stretches were covered by war rubble and filling material.

The coastal zone of the city of Patras has a history of intensive human uses, starting from the first construction of a port during the 1800s until today, while the city has two ports and accommodating infrastructure on the coast (Figure 7). The erosional processes on the coastal area of Patras were more evident since the 1960s, when they increased as a result of the extensive urbanization and modifications of main rivers, which were encased and shrunk, significantly reducing sediment supply to the coast.

The coastal zone of these Mediterranean cities, largely modified by man-made landforms, is mainly exposed to sea storm surge and sea wave erosion hazards, which are increasing as a result of climate change; the high number of vulnerable elements, both in terms of buildings (often strategic) and infrastructures, consequently results in high-level coastal risk.

Concerning the artificial progradation of the coastline due to the construction of harbour quays, it can be estimated that for Genoa, which is the major port in Italy, a mean progradation rate (sea embankment) of 2.1 m per year occurred from the 19th century up to today. On the other hand, the rocky cliffs have been affected by significant retreat, as in the exemplary case of the Lantern Promontory of Genoa: in the last century, due to intense excavations for urban growth (e.g. quarry, road and buildings), an anthropogenic mean erosion rate of about 3 m per year, versus an average natural rate of retreat estimated for flysch rocky cliff of 5 cm per year, has been evaluated (Lucchetti et al., 2014).

3 Excavations and filling on slopes and valleys, and on fluvial and coastal plains

The surface changes mainly consist of a number of excavations and fillings owing to the progressive urbanization of the five study cities. The most noticeable and significant excavation areas are the opencast quarries, currently mostly inactive, affecting the plain or hilly areas on which the cities are located. These quarries, from which building and ornamental materials were extracted, involve the presence of large and small topographic depressions consisting of quarry faces, benches and flats. Many of them have historical origins. The quarry activities began in the 8th (Naples) and 7th century BCE (Palermo), with maximum development in the 6th century BCE (Rome – construction of the Servian Walls) or in the Middle Ages (Genoa – beginning of the city structuring), and continued uninterrupted until the 18th–19th centuries (Genoa, Palermo) or the 1926–1970 time span (Naples). The numerous quarries are found in the areas adjacent to the old towns. Currently, they fall into the areas of urban expansion (Genoa, Naples, Palermo, Rome), covering an average surface of 0.001–0.002 km^2 (Naples) or 0.1–1 km^2 (Palermo) and showing a depth from 2 to 10 m. The largest opencast quarry is located at Genoa, at the end of the Promontory of San Benigno, which has produced 12,000,000 m^3 of extracted rock. Generally, the quarried materials were resistant and easy to work (marly limestones, Genoa; NYT and grey volcanic stone, Naples; calcarenites, Palermo; lithic volcanic blocks and sedimentary units, Rome). Today, many quarries are occupied by parks and private or public gardens (Palermo) and buildings (Naples, Palermo, Rome) or have been used for the city's road expansion (Genoa, Rome). In Patras, active opencast quarries are located along the inland hilly areas, 1–3 km away from the city. The largest of them occupy an area of about 0.1 km^2.

In all the selected cities, other major excavations also involve railway lines, railway stations, an airport area (Naples) and long sections of the main roads where deep underpasses and high walls were built. Their making led to deep excavations along plains, steep slopes and the outlet of the valleys, often accompanied by infilling works. These interventions have produced large flat areas, the removal of hills (Rome) (Figure 9), the reprofiling of slopes (Genoa, Naples, Rome), the construction of small, medium (Palermo, Patras) and large retaining walls up to 30 m high (Genoa) and the deforestation of many parcels of land (Patras).

The main accumulation landforms in the study cities concern the infilling of ancient valleys, coastal areas and quarries. In particular, the most important infilling affected Genoa and Rome. In Genoa, the main accumulations, involving up to about 1,000,000 m^3 of materials, affected valley bottoms and an ancient artificial lake, where flat areas up to 80,000 m^2 large were created to accommodate buildings, a hospital and recreational and sports centres (Figure 8). In Rome, land-reclamation works of many marsh areas were performed also by filling intervention, deposits from demolitions and urbanization activities repositioned in suburban valleys, and the accumulation of old ruins and flood deposits used as foundations for new buildings produced layers of anthropogenic deposits up to more than 20 m thick.

The anthropogenic changes have often caused, in turn, an increase in natural erosion processes, as landslides and run-off if the slopes have been increased. The highest rates of erosion processes often occur in anthropogenic deposits, which are also affected by piping and differential settlement, and may also involve the amplification of earthquake damage on buildings (Del Monte, 2018). Since ancient times, in the analysed urban areas, the processes of anthropogenic erosion and deposition have been more significant than the natural ones.

For example, in the city of Rome, the processes of river deposition, following the fluvial incision of the last glacial age, created a mass of deposits with a maximum thickness of 60 m in about 12,000 years, which corresponds to a deposition rate of 5 mm per year (Del Monte et al., 2016). The deposition rates have rapidly increased during the Anthropocene since ancient times: to build the Testaccio Hill, which was a dumping area next to the ancient fluvial port, the anthropogenic deposits were placed at a rate of 100 mm per year (40 m in about 400 years). Starting from the 19th century, some 20- or 30-m-deep valleys were filled, in just one year (Luberti, 2018; Luberti et al., 2019; Pica et al., 2017). As for the erosion processes, in the city of Rome the valleys were deepened in recent geologic times, at an average rate of less than 0.5 mm per year, while the erosive capacity due to human activities produced, already at the time of Trajan Emperor (2000 years BP), an erosion rate exceeding 5 m per year (Del Monte, 2018).

4 Anthropogenic underground cavities

In the five cities, hundreds of underground cavities in the urban centre and periphery are present, in general, in the first 40 m b.g.l. They were cut in different lithostratigraphic sequences, ranging from incoherent to stiff or cemented sedimentary, volcanic and transitional deposits and sometimes landfills. Overall, these cavities form intricate networks, measuring kilometres of length, and huge volumes of voids superimposed at various depths, together with underground utilities and sewers, lending the cities a kind of macro-scale porosity.

The anthropogenic landforms show simple or complex, horizontal, vertical or slanting, regular or very articulated shapes and dimensions. In the urban centres, they were excavated by hand, and often mechanically re-dug or widened between the Middle Bronze Age and recent times and for different purposes, which repeatedly changed over time.

Horizontal road tunnels cut hills or substratum, bypasses along flat areas connect different city districts, as well as recently segments of metro and railway tunnels. Vertical wells, both private and public, were drilled for lift shafts for more than 40 m of length. Sloping tunnels or railways were built especially for the hilly metro and the three funiculars of Naples and Genoa.

Particularly in Genoa, long roads and rail tunnels were excavated during the 16th–17th centuries. Most cavities were quarried during the Graeco–Roman period (about 2500 years BP) until the second half of 1800 in Naples, both to extract tuff bricks in order to build structures and walls over the ground, and to build mainly linear underground aqueducts.

Similar to Naples and Palermo, in Rome, a peculiar underground artificial waterscape exists, due to freshwater springs, aqueducts, fountains and an increasing demand for thermal baths. Amongst these, Palermo has many interconnected small cavities forming the Arab-origin aqueduct network. Some large cavities, previously catacombs, crypts or underground quarries, were equipped as air-raid shelters during the WWII in Rome, Naples and Palermo. Due to the landscape morphology abruptly changing from hilly to flat, Patras is mainly characterized by road tunnels cut throughout the mountain feet. In most of these cities, metropolitan tunnels were excavated from the second half of the 1950s and, in some districts, they are not yet completed.

In summary, subway tunnels, parking areas and many cavities are scattered below buildings and streets, drawing an intricate web of voids at different depths. Particularly in Rome, Palermo and Naples – especially in Naples, where there are over 10^6 m^3 of caves, about one-third of which are still unexplored (Clemente, 2018) – the risk of sudden sinking during and after severe thunderstorms, due to piping or a rapid change of groundwater level, as well as leaks from aqueducts and sewers (Nisio, 2008), in densely urbanized areas is high, and has even caused fatalities.

V Discussion

1 Human fingerprint on the selected cities

In the selected Mediterranean cities, urbanization has resulted in the increasing abundance and prominence of anthropogenic landforms, namely those created as a direct and commonly deliberate effect of human activities (Del Monte, 2018; Evans, 1997; Jefferson et al., 2013; Szabó, 2010). Over the past 3000 years, anthropogenic modelling processes have also widely modified natural landforms, creating vanished or modified natural landforms. Results from this study highlight the extent of such modifications, eventually confirming that humans represent now the most powerful global geomorphological agent, forcing Earth-system processes in landscape evolution (Cooper et al., 2018). The magnitude of man-made changes to deposits and landforms over time are significant factors in the characterization of the Anthropocene as a new epoch of geological time (Brown et al., 2017; Goudie, 2018). However, a better comprehension of such changes is required for the correct utilization and transformation of landforms in the process of urbanization (Diao, 1996), useful for planning and management of urban sprawls, including the evaluation of the resource potential and suitability of land (Cooke, 1976; Cooke et al., 1982; Pica et al., 2015).

Historical analysis shows that the first ancient settlements of the selected cities rose along strategic areas that were mainly stable, such as hill grounds with a flat top. The subsequent building expansion in alluvial plains and along stepped slopes created widespread situations of flooding and landslide risk. These situations have worsened with artificial ground modifications (e.g. underground cave excavations, valley filling). The preservation of the cultural and architectural heritage makes it difficult to eliminate these risks, unlike modern cities where urban development is planned and takes place in a previous territory less modified by man. The comparative analysis proved that each city was adjusted to the natural relief and, in turn, the relief was re-shaped due to the local needs of construction and planning (Bathrellos, 2007).

To highlight the former morphological features that suggested the choice of settlement sites, to detect the artificial landforms, to evaluate the impacts of human activities on geomorphological processes and to define the current geological risk scenarios, new graphic solutions for the representation of peculiar artificial ground have been tested. Hence, based on the official guidelines, the "Geomorphological map of Italy" (Campobasso et al., 2018) and considering the several types of artificial landforms (Li et al., 2017; McMillan and Powell, 1999; Pica et al., 2018; Rosenbaum et al., 2003), a very articulated legend has been developed.

The most similar modifications that were observed in the study areas concern the hydrographic networks. Almost all the drainage systems have been narrowed, channelled, culvert and in many cases diverted, causing a reduction in run-off sections. As a result, flooding events have been more frequent in recent decades, with a current increase in geo-hydrological risk scenarios, which, nevertheless, historically affected Genoa (Bixio et al., 2017; Lanza, 2003), Rome (Aldrete, 2007; Berti et al., 2004), Naples, Palermo (Cusimano et al.,

1989) and Patras (Alevizos and Stamatopoulos, 2016; Despiniadou and Athanasopoulou, 2006). The reduction of infiltration and the increase of the run-off due to the soil sealing have also enhanced the hazardous conditions (Brandolini et al., 2017). In the current context of climate change, outstanding rainfall events caused the recurrence of flash floods, usually centred in small areas, as happened recently in Genoa (Faccini et al., 2015), Palermo and Patras (Stamatopoulos and Alevizos, 2018). Despite a number of intervention works on the hydrographic networks to reduce the hydraulic risk (Todaro, 2002), which have quickly changed riverbeds and relative river catchments (see the Palermo case, Table 4), the urbanization in old alluvial plains and along filling or culvert watercourses has not removed this risk in the cities studied.

Climate change is also inducing sea-level rise, which implies more erosion and flooding events that increase the risk in coastal areas (Antonioli et al., 2017; Reimann et al., 2018) where human activities have already altered natural morphodynamics. Along the littoral, some natural landforms vanished, such as the former marine terrace of S. Benigno Promontory in Genoa, the dunes and swamps at Ostia in Rome, and the rocky cliff and swamp areas in Naples, Palermo and Patras. The development of the ports has modified the coastal landscapes, with significant works built both in ancient times (e.g. the Claudius port at Ostia and Old Port in Genoa) and in the modern age. The marine embankments built in Genoa, Palermo and Naples during the 20th century and in Patras in the last two decades, which caused anthropogenic progradation of the coastline (Marriner and Morhange, 2006), completely erased the former beaches and rocky coasts, and when impacting on the river mouth, as in the case of the Tiber River (Rome), also caused coastal erosional phenomena (Bellotti et al., 2011).

Anthropogenic excavation and filling both in fluvial valleys and in the coastal plains are mainly related to urbanization activities that require the levelling of the topography. The deposition of thick strata of man-made deposits resulted in anthropogenic aggradation. In historical Mediterranean centres, this ground-elevation increase is often tied to the historical habit to rebuild over the ruins deriving from the collapse of ancient buildings as a result of anthropogenic or natural events – for example, wars, earthquakes, fires, floods (Ventriglia, 1971).

Engineering and geomorphological care are tied to large volumes of anthropogenic deposits and the related negative effects in terms of hazard (e.g. subsurface erosion, piping, subsidence, seismic amplification) and risk (e.g. damage and collapse of buildings and road pavements, even in concurrence with underground cavities). The recognition and localization of "disappeared valleys" from the current landscape facilitate the reconstruction of the natural hydrographic network and locally enable the detection of the basal surface of the artificial deposits, even if there is a scarcity of boreholes (Del Monte et al., 2016; Luberti, 2018; Luberti et al., 2019).

Stepped slopes, which are characterized by an alternation of horizontal surfaces, obtained partly by excavation and partly by infilling, and vertical sections, generally provided with a retaining wall, are widespread. These landforms have been modelled, starting from medium-inclined slopes, in order to produce flat areas at different elevations for construction, as well as for multiple uses, including the "terraced urban landscape" of Genoa (Brandolini et al., 2018a). The correct interpretation of such anthropogenic changes to natural slopes contributes to the evaluation of geo-hazards (e.g. landslides triggering, creeps, gully erosion, piping) and the appropriate reduction strategies.

As for the aforementioned interventions that led to the elimination of natural depressions from the physical landscape, new additional valley-shaped artificial depressions also exist.

The Via dei Fori Imperiali in Rome, which appears, at first glance, to be of fluvial genesis (Del Monte et al., 2016), and the "i Cavoni" depression in Naples are examples.

Anthropogenically constructed landforms were also produced. In Rome, some of them date back to ancient times, and were subsequently levelled; others are still observable, such as the aforementioned Monte Testaccio, a hill made of waste materials. This hill, which lies in the Tiber River plain, is also an example of "vertical inversion of the relief"(Del Monte, 2018).

Worked grounds due to quarrying areas are widespread in the studied historical cities. Quarries were generally located near the ancient city walls to shorten transport and delivery times, reducing output costs. Most of these quarries were gradually incorporated into the urban fabric. In some cases, the abandoned quarry scarps are affected by gravitational phenomena, inducing landslide risk in urban areas, such as in the case of the slopes surrounding the Genoa historical centre (Brandolini et al., 2018a). The same risk is connected with anthropogenic scarps related to urban planning, as in Viale Tiziano in Rome (Amanti et al., 2012).

Underground quarries are widespread in Naples, Palermo and Rome. Extracting underground material made it possible to avoid soil loss, which is useful for agriculture, to take better-quality rock levels and to be able to work even in adverse weather conditions (Todaro, 2002, 2004). On the contrary, the existence of large underground quarries predisposes towards sinkhole-risk conditions (Parise, 2012), which may also be related to other artificial cavities, depending especially on their dimensions and depths from the ground level. Anthropogenic cavities vary much more than other landforms in terms of geometric types (point: e.g. cisterns; linear: e.g. tunnels), dimensions (from meters up to hundreds of meters), depths (from a few meters up to many tens of meters b.g.l.), human uses (e.g. motorways, catacombs, water aqueducts and tanks) and ages (from many centuries BCE to a few years). This implies that their characterization requires great attention in the evaluation of the potential hazard eventually connected with each cavity, especially in areas affected by morphotectonic, seismic and volcanic activity, as in the case of Naples and Patras (De Pippo et al., 2008; Despiniadou and Athanasopoulou, 2006).

Overall, it should be highlighted that in all the studied cities the anthropogenic activities have led to erosional and depositional rates up to several orders of magnitude greater than rates due to natural processes, as shown in the Results section. Moreover, some activities were conducted in contrast to natural processes – for example, terracing on stable slopes naturally affected by gravitational processes (Brandolini, 2017; Brandolini et al., 2018b). Further human activities and related landforms appear to bear no relationship to natural processes yielding similar landforms, in the same area. In Rome and Naples, quarrying activities output dense networks of anthropogenic cavities (Clemente, 2018) in volcanic rocks that are not affected by karstic processes.

Despite the intensity of anthropogenic activities, it should be emphasized that in historical urban centres multiple activities were conducted in the same site over centuries. Each landform resulting from any single activity was often modified or erased by subsequent works, each of them building a new often-temporary anthropogenic landform. As an example, in the Forum area of Rome, land reclamation works were carried out in the Archaic age, then urbanization spread across the available flat spaces. The excavation of a natural hill was later necessary to provide space for the Emperor Trajan Forum. In medieval centuries, the area was abandoned, and ruins and Tiber River flood deposits resulted in both natural and anthropogenic aggradation. Since the 19th century, archaeological digs started to induce human erosion, and this was enhanced in the 20th century when the construction of a parade road brought the demolition of medieval buildings and the erosion of both anthropogenic and natural deposits – that is, the Velia hill (Del Monte et al., 2016).

2 Anthropogenic landscape modification and its relationship with the Anthropocene

Conversely, modern towns face fewer human activities, both in terms of number and type of events, than historical ones. Some recently developed centres were morphologically transformed in just one single stage.

In New York City (USA), extensive levelling for urbanization purposes, both erasing relief and filling valleys, has only been carried out since the 19th century in Lower Manhattan, even though archaeological investigations have shown that anthropogenic layers were deposited since the 17th century. The archaeological data and the related anthropogenic deposits of 5 m mean thickness, resulting from investigations both in the Lower and Upper East Side of Manhattan, which was urbanized in the late 19th century (New York Public Library, 2019; Schuldenrein and Aiuvalasit, 2011; Yamin and Schuldenrein, 2007), provide rates of anthropogenic aggradation of 25 and 290 mm per year, respectively. By contrast, the urban Central Park, which is 3.2 km^2 wide, represents an area in which glacial landforms carved into the outcropping schist units have been substantially preserved from anthropogenic geomorphic processes.

In San Francisco, along the Bay Area, between 1938 and 1987 the eastern coastline was quite stable. From then to 1993 there was a huge expansion of the waterfront and port areas through concrete and landfill, with a coastline progradation from about 400 to over 1000 m between the mouth of Islais Creek and Lash Lighter Basin. From 1993 to 2000, an alternation of retreating and progradation of the non-engineered shoreline, within 10 m, occurred at India Basin; after 2000, the south coast seems more stable (Google Earth Pro data; BCDC, 2015).

In Sydney, Australia, the urbanization of the historical centre close to the port occurred during the 19th century. Land reclamation works and subsequent levelling determined the anthropogenic filling of deposits 3–6 m thick (Casey and Lowe Pty Ltd, 2015), thus providing an aggradation rate of up to 0.058 m per year. Conversely, the construction of the east offshore runway of the airport was performed in just two years during the 1990s (Google Earth Pro data), determining a progradation rate of 1550 m per year.

Pulau Ujong (Singapore) has undergone significant urban works in the last five decades, including coastal reclamation (Yong et al., 1991; Zhang et al., 2017). In particular, both the Tuas industrial area and the eastward extension of the Changi airport were constructed with progradation rates of about 290 m per year (National University of Singapore Libraries, 2019).

In Dubai (UAE), during the 21st century, great economic growth has resulted in both extensive and intensive urbanization (Nassar et al., 2014). From 2001 to 2009, the coast has been developed offshore, with circular artificial peninsula-island systems, including Palm Jumeirah and Palm Jebel Ali. The two palm-shaped systems have diameters of 5 and 7 km, and their construction took four and six years, respectively (Google Earth Pro data). These data provide rates of anthropogenic progradation of about 1.2 km per year.

Table 5 summarizes the aforementioned data, given just as representative examples, and compares them with those of two of the present study's historical Mediterranean cities. These data show that in quantitative terms – that is, rates of anthropogenic erosion, aggradation and progradation – major geomorphologic modifications (>10 m/yr) have ooccured, starting from the second half of the 20th century. Considering

Table 5. Match between two of the Mediterranean historical cities and some representative extra-European modern towns, in terms of intensity and rate of anthropogenic processes. Intensity is measured as a vertical increase (aggradation) or decrease (erosion) of the ground elevation, and horizontal development (progradation) or erosion (retreating) of the coastline. Climate refers to the classification of Köppen-Geiger as updated by Kottek et al. (2006).

Coastal city (Country)	Climate	Sector	Time span (yrs) Years BCE/CE	Aggradation (a) Progradation (p) Erosion (e) (m)	Rate of erosion (e) Aggradation (a) Progradation (p) (m/yr)	Reference for data or source
Genoa (Italy)	Csb	Old Port area	140 1876–2016 CE	300 (p)	2.1 (p)	Brandolini et al. (2018a)
		San Benigno Promontory	35 1925–1960 CE	250 (e)	7.1 (e)	
Rome (Italy)	Csa	Testaccio Hill, via di Monte Testaccio	400 150 BCE–250 CE	40 (a)	0.1 (a)	Del Monte et al. (2016)
		Trajan Forum, via dei Fori Imperiali	5 107–112 CE	25 (e)	5 (e)	Del Monte (2018)
New York City (USA)	Cfa	Lower Manhattan, Collect Pond	200 1650–1850 CE	5 (e) 5 (a)	0.025 (e) 0.025 (a)	Yamin and Schuldenrein (2007)
		Upper East Side of Manhattan (2nd Avenue, 90th–97th Street)	17 1879–1896 CE	5 (a)	0.29 (a)	Schuldenrein and Aiuvalasit (2011) New York Public Library website
San Francisco (USA)	Csb	Islais Creek Mouth, Bay Area Lash Lighter Basin, Pier 96	6 1987–1993 CE	414 (p) 1038 (p)	69 (p) 173 (p)	Google Earth Pro BCDC (2015)
Sydney (Australia)	Cfa	Circular Quay (George Street/Pitt Street)	103 1803–1906 CE	6 (a)	0.058 (a)	Casey and Lowe Pty Ltd (2015)
		Kingsford Smith Airport, east offshore runway 34R	2 1992–1994 CE	3100 (p)	1550 (p)	Google Earth Pro
Pulau Ujong (Singapore)	Af	Tuas Quay industrial area	43 1974–2017 CE	12,000 (p)	280 (p)	Yong et al. (1991) Zhang et al. (2017)
		Changi Airport extension	11 1992–2003 CE	3250 (p)	295 (p)	National University of Singapore Libraries webGIS
Dubai (UAE)	BWh	Palm Jebel Ali peninsula-island system	6 2003–2009 CE	7000 (p)	1166 (p)	Nassar et al. (2014) Google Earth Pro
		Palm Jumairah peninsula-island system	4 2001–2005 CE	5000 (p)	1250 (p)	

Af: equatorial rainforest; BWh: arid hot desert; Csa: warm temperate – dry and hot summer; Csb: warm temperate – dry and warm summer; Cfa: warm temperate – fully humid, hot summer.

that pre-industrial historical centres account for a total area, based on 1900 CE for a precautionary estimation, that ranges from 1% to 17% of the 2000 CE urbanized land, worldwide (Luberti, 2018), we suggest that the proposal to refer the lower limit of the Anthropocene as a geologic time unit to the mid-20th century is consistent, even with the geomorphological evidence. We agree with this time limit, although humans have influenced natural processes with different degrees of intensity both spatially and temporally, determining a diachronous lower boundary given by both anthropogenic deposits and landforms (Brown et al., 2017).

Despite some outstanding values concerning very recent works – for example, the Sydney and Singapore airport runways and the palm-shaped artificial systems in Dubai – the difference between ancient and modern cities stands not in the intensity of processes – for example, the rates of anthropogenic aggradation in Rome are not so different from those resulting in Manhattan and in Sydney. Instead, the actual difference lies in the number and type of events in the same site that brought about the landforms that we presently observe. The landscape that we perceive in the Roman Forum area is the result of innumerable small as well as huge events, as summarized previously, that have occurred over millennia. Conversely, the landscape of Dubai's palm-shaped systems is the result of just a huge single-project human-induced movement of sand put in place over a few years.

VI Conclusions

The selected ancient Mediterranean coastal cities exhibit anthropogenic landscapes that have predominately been shaped over centuries by several human-driven processes, since about 3000 years BP, and especially during the last centuries. Based on surveys, analyses, interpretation and comparison of the various man-made landforms, four main categories of morphological modifications have been detected: (1) drainage network changes; (2) coastline changes; (3) excavations and filling on slopes/valleys and fluvial/coastal plain; and (4) artificial underground caves. These process categories, their spatial and temporal variabilities and related landforms together outline aspects of "Geomorphology of the Anthropocene" (sensu Brown et al., 2017) and enforce the arguments (Zalasiewicz et al., 2019) in favour of the Anthropocene as a geologic time unit.

Topographic changes have been driven in relation to climate and geological features, including resources and reserves, as well as defensive and military purposes. Such expansion was initially confined by the presence of watercourses and topographic obstacles. The increasing demand for territory that is useful for urban development has brought about several types of anthropogenic processes, including land reclamation works, especially along the coasts, and levelling of the topographic surface, erasing former relief and filling depressions.

As a result, local sedimentation processes have been overwhelmed by anthropogenic progradation and aggradation, whose growth rates are often higher than those of the natural deposits. Each landform represents the current output frequently given by multiple activities, which may have acted with opposite geomorphic effects (e.g. erosion vs. construction). The hydrologic cycle is altered by urbanization, and the soil's geo-mechanical characteristics are compromised by the diffusion of thick layers of anthropogenic deposits upon which building and urban infrastructures are often founded. Moreover, additional loads provided by such construction works lower the resistance of underlying natural and, together with the presence of underground cavities, predispose situations of subsidence/sinkhole risk.

In conclusion, the impact and extent of human-driven geomorphological processes has enhanced the related risk levels due to an increase in both hazards and vulnerability. In urban centres, hazards are strongly connected with human activity, which often occurs without any prior assessment of its compatibility with pre-existing natural processes. In addition, hazard levels have been enhanced by the increase over time of climate-change-induced extreme events. In urban areas, vulnerability is firmly related to extensive urbanization, which has resulted in the subtraction of land that is functional for natural dynamics. The response to the risk-assessment results should include the prioritization of effective risk-mitigation measures, which should be identified through interdisciplinary studies.

Beyond academic progress, in the context of the need for a novel approach towards sustainable development, we believe that detecting and mapping both natural and anthropogenic processes and their interplay, together with related erosional and depositional landforms, should be obligatory, even in risk-assessment urban planning.

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