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# Subsidence and recent landscape evolution at Volturno Coastal Plain (Italy)

Ines Alberico, Fabio Matano *

*Consiglio Nazionale Delle Ricerche, Istituto Scienze Marine, 80132, Napoli, Italy*

A R T I C L E  I N F O

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A B S T R A C T

Alluvial plains along the coasts of the Mediterranean Sea are susceptible to subsidence due to natural sediment compaction, tectonic forces, urban growth and over-exploitation of groundwater resources. Subsidence process may largely affect coastal landscapes, especially in areas with compressible deposits in the subsoil. In this article, the historical changes of landscape (from 1600 to present) and the vertical ground movement (in the last 30 years) of Volturno Coastal Plain (VCP) were analyzed to shed light on the possible relations between the location of subsiding lands and the landscape changes in the last centuries mainly due to land reclamation works. To this aim, historical maps, satellite images, and radar interferometric vertical ground deformation datasets were acquired and integrated in a geographic information system. The historical cartography allowed to ouline the landscape changes of coastal plain features that took place mainly in the marshy and swampy areas and in the dune system before and after the reclamation works. Ground deformation trends have been assessed between 1992 and 2021 based on processing several radar satellite data with Synthetic Aperture Radar Differential Interferometry (DInSAR) techniques. Vector and grid analysis tools have been used to draw features of past landscapes, to continuously represent the vertical movement of soil and to compare the available data. Before the mid-1950s, anthropogenic activity was limited and not associated with active subsidence processes in the marshes and lacustrine areas. However, in recent decades, satellite radar interferometric data show that high subsidence areas in the middle and lower sectors of Volturno Coastal Plain (VCP) are locally enhanced by anthropogenic activity. It is noteworthy that the subsidence of VCP today is related to the cumulative effects of several processes that have developed at different temporal and spatial scales.

## 1. Introduction

Nowadays, most floodplains are affected by intense subsidence processes worldwide (Ericson et al., 2006; Wu et al., 2022) which cause increased coastal erosion (Hinkel et al., 2013), relative sea-level rise (Nicholls et al., 2021), coastal flood vulnerability (Hinkel et al., 2014), groundwater salinization (Schuerch et al., 2018), and risk of damage to urban infrastructures (Nicholls et al., 2008). Subsidence may lead to significant changes in coastal landscape over hundred to thousand years (Anzidei et al., 2014; Benjamin et al., 2017; Shirzaei et al., 2021).

Subsidence is a response to superficial and deep deformation induced by natural processes and anthropogenic factors at different spatio-temporal scales. Glacial isostatic adjustment and basin tectonics lead to a steady subsidence rate. Natural sediment compaction, swelling/shrinking of clay soils in vadose zone, organic matter oxidation, aquifer system and hydrocarbon reservoir compaction, and large earthquakes may cause highly variable coastal subsidence rates in space and time. Human effects (i.e. solid/fluid extraction and load-induced compaction) accelerate subsidence in coastal zones (Shirzaei et al., 2021).

Subsidence-related hazard is affecting an increasing number of densely populated coastal regions worldwide causing damage to the environment, infrastructure, and urban areas (Milliman and Haq, 1996; Nicholls et al., 2008; Erkens et al., 2015).

In the Mediterranean area, many coastal plains are affected by subsidence due to several natural and anthropogenic factors (Frihy et al., 2010; Teatini et al., 2011, 2012). Holocene coastal successions have been evidenced among the potential drivers of subsidence in the Mediterranean area (Higgins, 2015; Ruberti et al., 2017; Matano et al., 2018). The evolution of modern river deltas began at the end of the Last Glacial Maximum (LGM) by aggradation and progradation processes within incised valleys that were filled by fluvio-lacustrine, transitional, and marine deposits during the 6.5–2.0 ka BP. The natural compaction of the transitional deposits, composed of sands, silts, clays and peats, can result in subsidence of several millimeters over years, especially in the

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* Corresponding author.
*E-mail address:* fabio.matano@cnr.it (F. Matano).

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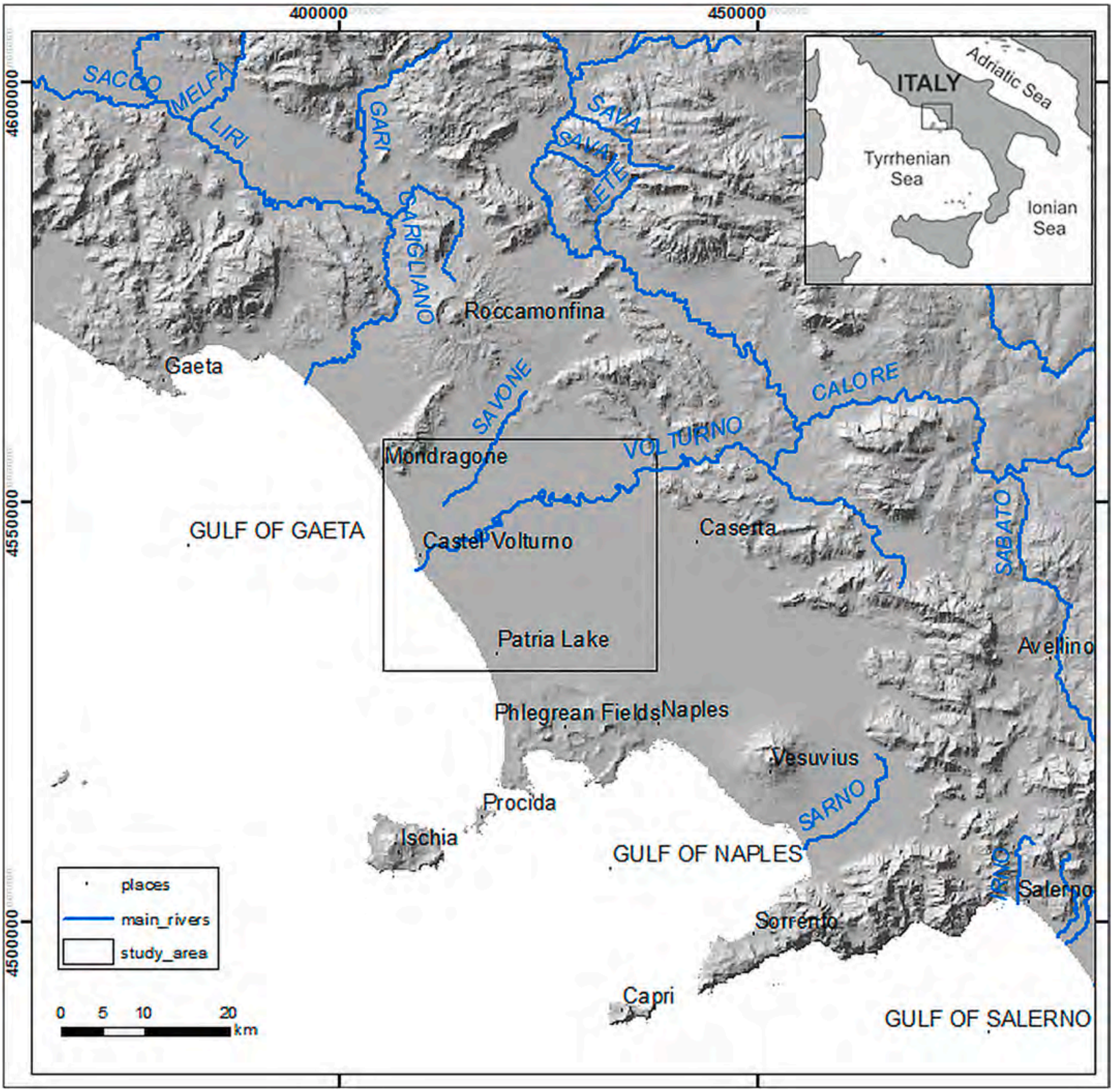

**Fig. 1.** Location of the study area in southern Italy.

presence of thick organic-rich layers (Meckel et al., 2006, 2007, 2008; Shi et al., 2007; Tornqvist et al., 2008; van Asselen, 2011).

The purpose of the present article is to assess the relations between the subsidence processes and landscape changes in the last centuries. The study area is the coastal plain of Volturno River (Campania Region) located along Tyrrhenian Sea coastline and north Campi Flegrei volcanic field (Fig. 1). The morphology of the Volturno coastal plain was deeply changed in the last century due to both short-term climatic changes and anthropic modifications (Alberico et al., 2017, 2018; Donadio et al., 2018), having experienced significant land reclamation since the early 1600s and intensive urbanization in the 1980s. These anthropogenic impacts pose difficulties in characterizing the most important natural subsidence processes due to tectonics, subsurface stratigraphy, and hydrogeological features of plain. In this article, several historical and technical topographic maps were utilized; they represent an important cultural source of information for investigating spatial-temporal evolution of social and environmental features (Herrault et al., 2008; Duan et al., 2017; Can et al., 2021), landscapes (Alberico et al., 2018; Piškinait and Veteikis, 2023 and reference therein), coastlines (Houser et al., 2008; Leyland and Darbya, 2008; del Pozo and Anfuso, 2008; Alberico et al., 2012; Alberico et al., 2018; Chrisben Sam and Gurugnanam, 2022) and urban growth (Cousins, 2001; Gimmi et al., 2016; Pinho and Oliveira, 2009; Lafreniere and Rivet, 2010; Alberico and Petrosino, 2014; Alberico et al., 2017; Brandolini, 2017; Rimal et al., 2020; Wang et al., 2015; Manniello et al., 2022). The historical data have been compared with satellite radar interferometric data giving an overall perspective on the spatial ground deformation in Volturno Coastal Plain over the last three decades, from 1992 to 2021. These data have been obtained by

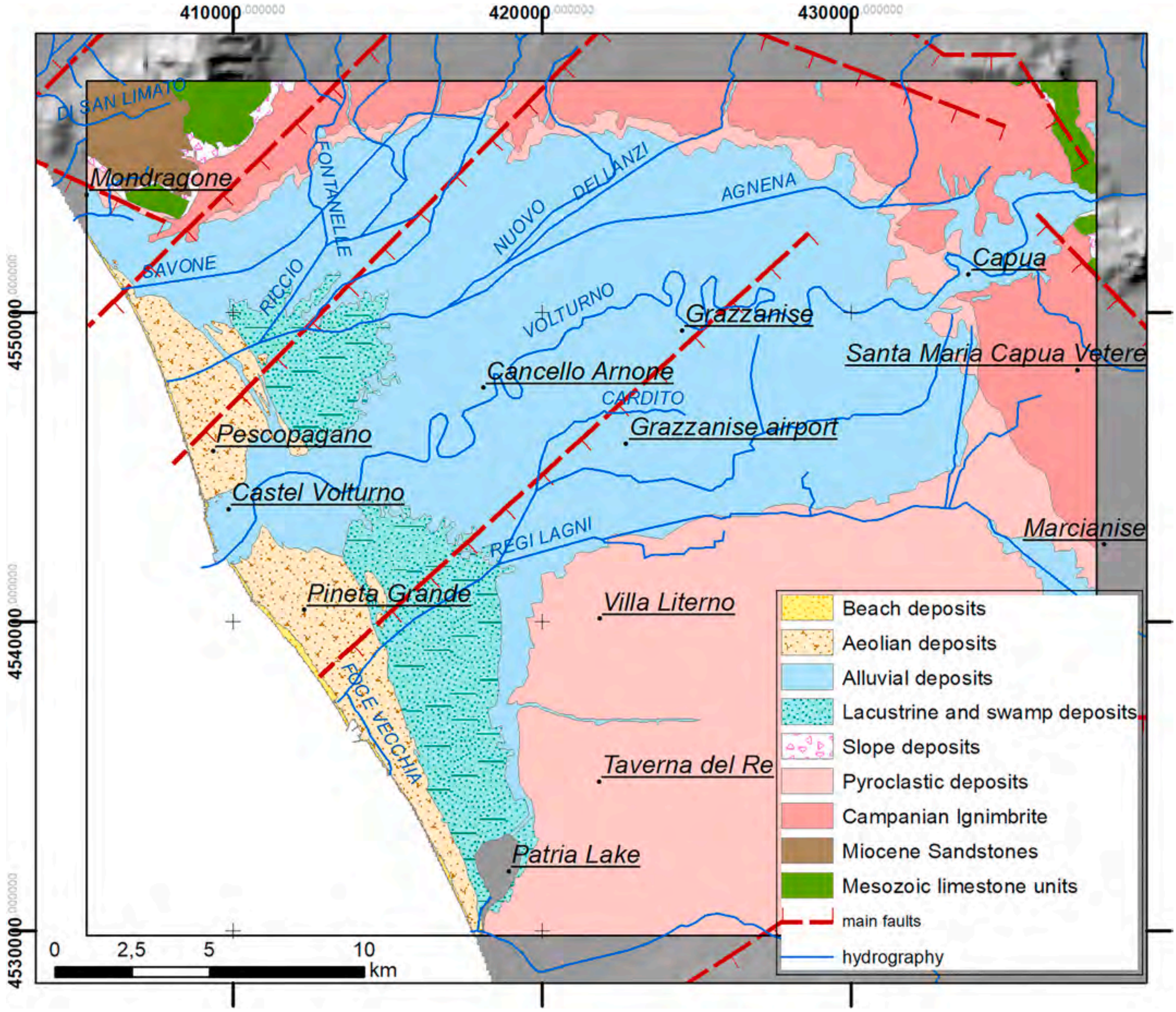

**Fig. 2.** Geological sketch map of the study area.

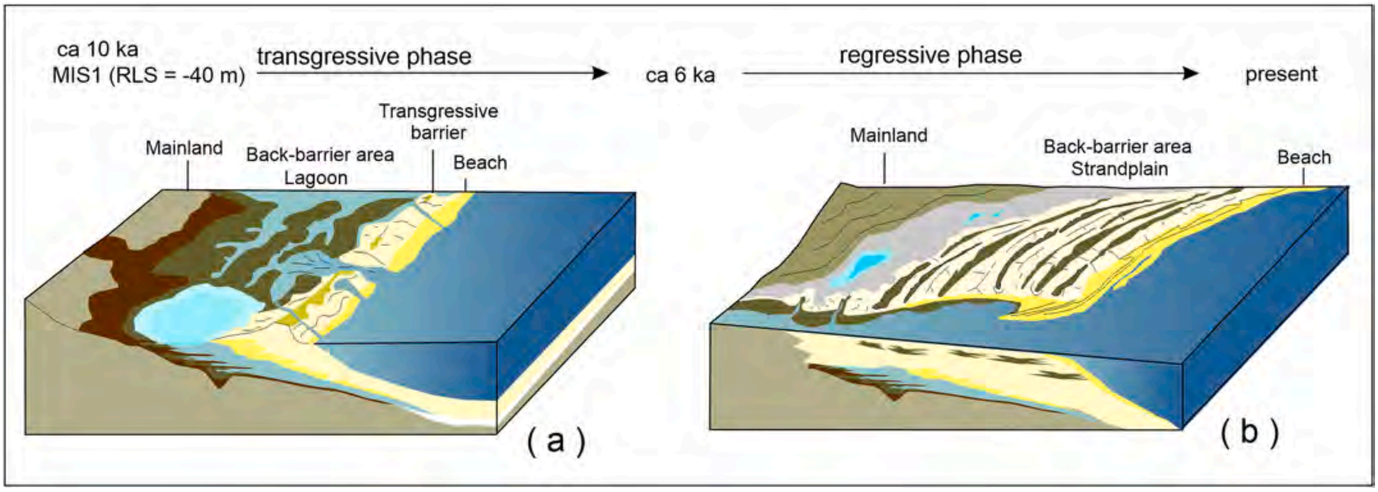

**Fig. 3.** Evolution of Volturno coastal plain since 10 ka BP.

**Table 1**
Historical maps and orthophotos employed to study the landscape changes at Volturno Coastal Plain. Date, scale and Root Mean Square Errors (RMSE) of georeferencing process are reported for each one.

| Historical maps | Date | Scale | RMSE | Data Source holder |
|---|---|---|---|---|
| Campaniae Felicis Typus | 1616 | Not available | No data | Alessandro Baratta |
| Provincia di Terra di Lavoro | 1714 | Not available | No data | Lorenzo Filippo de Rossi |
| Topographic and Hydrographic map of areas close to Naples | 1817–1819 | 1:25,000 | 30 | Italian Military Geographic Institute |
| Map of the Continental Provinces of the ex-kingdom of Naples | 1882 | About 100,000 | No data | Italian Military Geographic Institute |
| Map of the Kingdom of Naples | 1834–1860 | 1:20,000 | 20 | Italian Military Geographic Institute |
| Map of the Kingdom of Naples | 1838–1875 | 1:80,000 | 22 | Italian Military Geographic Institute |
| Map of Neapolitan Provinces | 1874–1882 | 1:250,000 | 50 | Italian Military Geographic Institute |
| Regional Technical Map (CTR) | 2019 | 1:5000 | 2 | Campania Region |
| Google Earth image | 2024 | Variable | 3 | Google |

**Table 2**
Satellite data. The main information related to the PSI data for the assessment of the VGDM rates is listed.

| Satellite (Orbit) | PS technique | Data Source | Time range |
|---|---|---|---|
| **SENTINEL 1 (Ascending)** | PSI, DS | EGMS (Copernicus-ESA) | Jan. 2016–Dec. 2021 |
| **SENTINEL 1 (Descending)** | PSI, DS | EGMS (Copernicus-ESA) | Jan. 2016–Dec. 2021 |
| **ENVISAT (Ascending)** | PSP | EPRS-E (MATTM) | Nov. 2002–Jul. 2010 |
| **ENVISAT (Descending)** | PSP | EPRS-E (MATTM) | Nov. 2002–Jun. 2010 |
| **RADARSAT (Ascending)** | PSI | TELLUS Project (Regione Campania) | Mar. 2003–Sep. 2007 |
| **RADARSAT (Descending)** | PSI | TELLUS Project (Regione Campania) | Mar. 2003–Aug. 2007 |
| **ERS-1/2 (Ascending)** | PSP | EPRS-E (MATTM) | Jun. 1992–Jan. 2001 |
| **ERS-1/2 (Descending)** | PSP | EPRS-E (MATTM) | Jun. 1992–Dec. 2001 |

space-borne Synthetic Aperture Radar Differential Interferometry (DInSAR) techniques applied to several radar satellite image datasets (ERS, ENVISAT, RADARSAT and Sentinel 1) with accurate spatial and temporal resolution (Matano et al., 2018; Matano, 2019).

## 2. Geological and geomorphological setting at a regional scale

In the northern Campania region (Fig. 1), the Volturno Coastal Plain (VCP) was formed during the Middle to Late Quaternary period through in-filling of a wide peri-Tyrrhenian tectonic depression (Fig. 2). The tectonic subsidence favoured deposition of more than 3000 m of Quaternary sediments (alluvial, palustrine, coastal) and volcanic products (Santangelo et al., 2010, 2017 Romano et al., 1994). The carbonate and volcanic substratum of VCP was displaced by the NE-SW, NW-SE and E-W trending faults (Mariani and Prato, 1988; Milia and Torrente, 2003; Milia et al., 2013; Ortolani and Aprile, 1978). Some of these lineaments correspond to normal faults that have been active since the Late Pleistocene with a vertical slip rate of 0.2–2.5 mm/yr (Cinque et al., 2000). VCP is confined seawards by a sandy beach-dune Holocene system and it is surrounded by calcareous-dolomitic ridges (bounded by NW-SE trending regional normal faults) in the northern and eastern inner sectors.

Up to the first part of Late Pleistocene, the plain was submerged because of the high subsidence rates related to the active faults. Sea level rise in the Last Interglacial period (130–115 ka BP) caused the coastline to reach the carbonate massifs at VCP margin (~20–25 km from the present-day coastline) (Romano et al., 1994).

In the second part of Late Pleistocene, the coastal plain was mostly covered by the pyroclastic materials of Campanian Ignimbrite (40 ka Giaccio et al., 2017) eruption of the Campi Flegrei caldera, the subsidence rates reduced, and sea level lowered during the Last Glacial Maximum (LGM) (Santangelo et al., 2010). The Campanian Ignimbrite deposits represents the substrate for the uppermost Pleistocene–Holocene sedimentation (Romano et al., 1994; Corrado et al., 2018; Budillon et al., 2022).

During LGM, the shoreline accordingly shifted towards the sea by forced regression of the paralic-shallow marine depositional systems; the entire plain emerged and a large, incised valley (15–20 km wide and up to 30 m deep along its central axis) was probably formed by the paleo-Volturno River (Amorosi et al., 2012; Sacchi et al., 2014). In particular, the Campanian Ignimbrite strata were incised by fluvial activity during the LGM, and the resulting valley was filled by fluvio-lacustrine, transitional, and coastal deposits of Holocene. When sea level rise let to a rapid flood in the lower sector of Volturno valley and shoreline retreats of several kilometers relative to the current shoreline (Fig. 3a) (Romano et al., 1994; Amorosi et al., 2012). A coastal progradation phase was established 6.5 ka BP when coastal aggradation formed a barrier-lagoon system (Fig. 3b), allowing formation of a wave-dominated deltaic system with flanking coastal plains, beach-dune ridges, and lagoonal-marsh areas. In this stage, the lagoons and swamps developed for several kilometers inland from the present coastline and their partially consolidated deposits are responsible for the major ground deformation today (Buffardi et al., 2021 and reference therein). This phase was mainly due to the decreasing rate of Late Holocene sea level rise and the increasing fluvial inputs associated with climatic and land-use changes during the Greek-Roman and Late Roman periods. Beach and lagoon environments were present along the present coastal zone until 2 ka BP (Romano et al., 1994; Barra et al., 1996; Santangelo et al., 2010; Amorosi et al., 2012, 2013; Sacchi et al., 2014).

Nowadays, the VCP geomorphological setting is characterized by a flat morphology with a slope up to 5° and an elevation varying from 0 m in the coastline to 40 m a.s.l. in north Capua (Fig. 1). The plain is bordered seaward by a 35-km long sandy beach, with multiple dune ridges located 3 km inland with a maximum height of 10 m a.s.l (Di Paola et al., 2021). The ridges are locally interrupted by the Volturno River, the Regi Lagni channel and the outfall of the Patria Lake (Aucelli et al., 2016). East the dune ridges, there is a wide lowland area (up to 2 m b.s.l.) with an extend of approximately 25 km$^2$ (Di Paola et al., 2021). This depression is remnant of the ancient barrier lagoon system (Romano et al., 1994; Barra et al., 1996; Amorosi et al., 2012, 2013), characterized by clayey and silty alluvial deposits, locally interspersed with peat layers (Ruberti and Vigliotti, 2017).

The VCP is currently characterized by dense agricultural fields, transport infrastructure and inhabited areas, both in the coastal areas (Castelvolturno and Mondragone towns) and in the inland areas (Capua, Grazzanise, Cancello Arnone, Villa LIterno). Most VCP marshes have been reclaimed since the 16th century to develop agricultural activity, while the urbanization along the coastal zone was at the expense of the beach-dune system since the mid-19th century (Ruberti and Vigliotti, 2017; Alberico et al., 2017, 2018). Human activities have often led to dramatic landscape changes, loss of coastal wetlands and accelerated coastal erosion (Cocco et al., 1992; Scorpio et al., 2015; Alberico et al., 2017, 2018; Ruberti et al., 2017; Donadio et al., 2018).

**Fig. 4.** *Provincia di Terra di Lavoro* map (Lorenzo Filippo de Rossi, 1714 - modified). The main rivers of Volturno Coastal Plain are in light blue. The main river of the Garigliano Plain is also represented.

## 3. Material and methods

This section explains the data, materials and methodologies adopted for analyzing the four-century landscape changes of VCP and the ongoing subsidence rate along with the spatial relationship between landscape evolution and subsidence.

### *3.1. The dataset for diachronic landscape analysis*

Important information for evaluating the landscape changes at VCP since 1600 can be obtained from historical and topographic maps, orthophotos, and satellite images (Table 1). Small and large-scale maps have been used to have both an overview of the geographical elements shaping the study area and details of coastal landscape. Prior to spatial

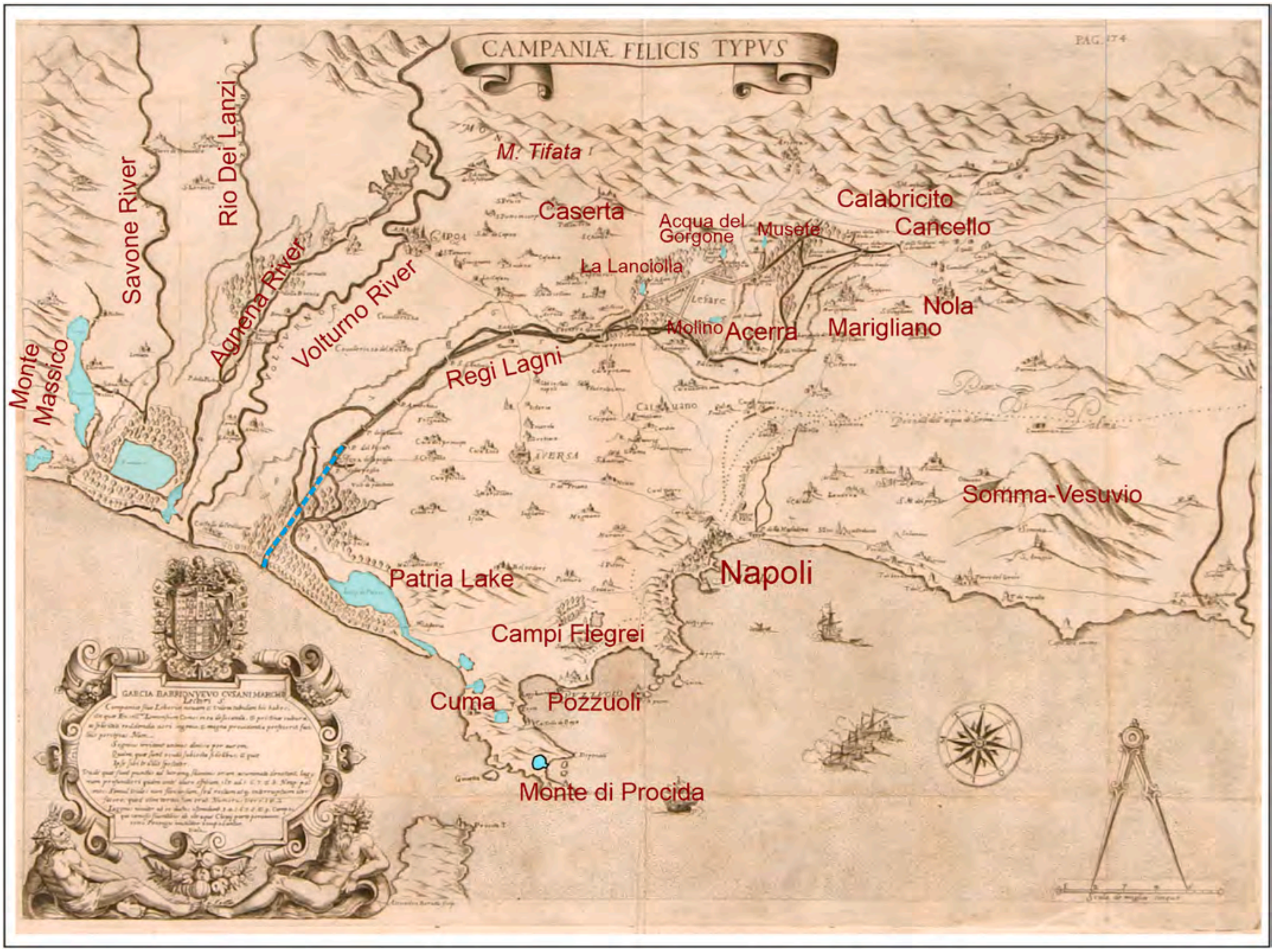

**Fig. 5.** *Campaniae Felicis Typus* map (Alessandro Baratta, 1616 – modified). The light blue line refers to the channel for draining Clanio river into the sea. The light blue areas represent the lakes or ponds.

analysis, the maps were georeferenced in the WGS 84 coordinate reference system by assigning to cartographic elements (e.g., road junctions, historical monuments and geodetic points) the geographic coordinates, WGS 84 system, of the same points (homologous points) on the modern technical maps (homologous points) of the Campania Region (Alberico et al., 2018). The 1616 and 1714 maps, not georeferenced due to a lack of homologous points with known geographic coordinates, were analyzed in this article for the first time providing relevant informations for the understanding of the evolution of the study area.

Automatic methods can extract single geographical elements such as streets, buildings or toponomy information from historical maps (Herrault et al., 2008; Duan et al., 2017; Garcia-Molsosa et al., 2020; Can et al., 2021; Groom et al., 2021; Schlegel, 2023). However, we used human-assisted digitization to outline man-made and natural elements (ponds, marshes, rivers, lakes, dunes, beaches, river mouths and coastlines) represented with different textures on the analyzed maps (Piškinait and Veteikis, 2023 and reference therein). In detail, we have outlined ponds, marshes, lake dunes, urban areas (polygonal elements), coastlines, rivers, channels and roads, (linear elements) where their location has been deduced from historical documents and recognized on historical maps. In conclusion, special attention was paid to all elements that had a direct impact on the evolution of subsidence processes or witnessed their short- and long-term effects.

### *3.2. DInSAR dataset for short-term vertical ground deformation*

Vertical Ground Deformation Movement (VGDM) was assessed for the last three decades by analyzing the available MultiTemporal Interferometric Synthetic Aperture Radar datasets (MT-InSAR) and Sentinel-1 satellite images in vertical polarizations of the European Ground Motion Service (EGMS).

In detail, datasets of ascending and descending orbit radar images acquired by the C-band sensors on-board ERS, ENVISAT and RADARSAT satellites have been used (Terranova et al., 2009; EPRS - MATTM, 2015). These data (Table 2) are available from 1992 to 2010 and they have been processed with different methods, such as Permanent Scatterers (PS; Ferretti et al., 2001) and Persistent Scatterers Pairs (PSP; Costantini et al., 2017). The coeval ascending and descending orbit radar images allowed for the evaluation of the vertical components of the ground deformation, based on the interpolation of PSI data point and trigonometric calculations (Vilardo et al., 2009; Matano et al., 2018; Matano, 2019). Then, 100-m spaced grid maps have been created for ERS, RADARSAT and ENVISAT datasets, showing the distribution of the vertical components of ground deformation velocity of the study area in 1992–2000, 2003–2007 and 2003–2010 time periods.

EGMS implemented by the European Space Agency processed synthetic aperture radar data of Sentinel-1 satellite constellations (Crosetto et al., 2021; Shahbazi et al., 2022) to provide Advanced Differential Interferometric SAR (A-DInSAR) data over the main part of Europe

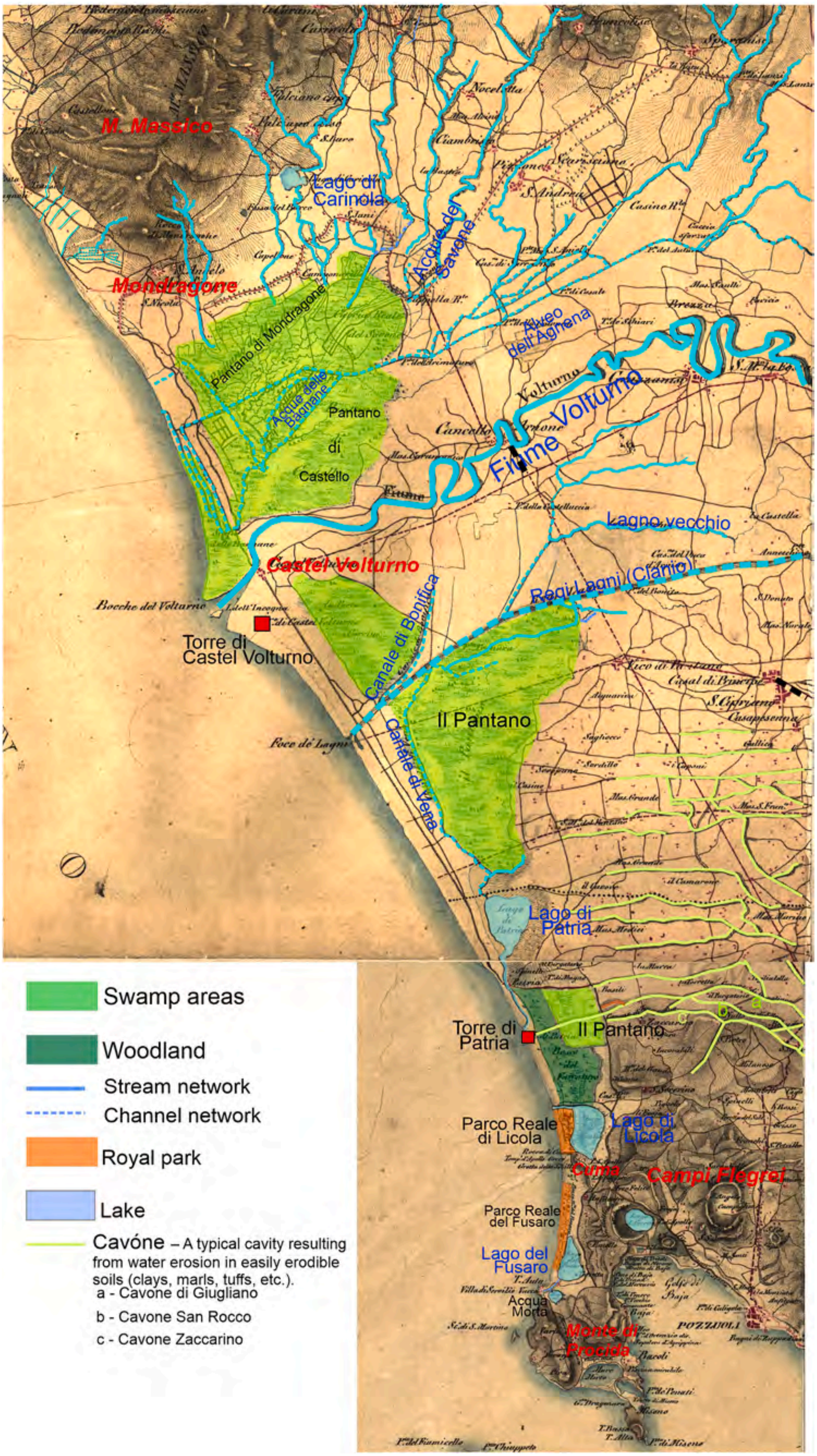

**Fig. 6.** Topographic map of 1822 at 1:100,000 scale, (Italian Geographic Military Institute).

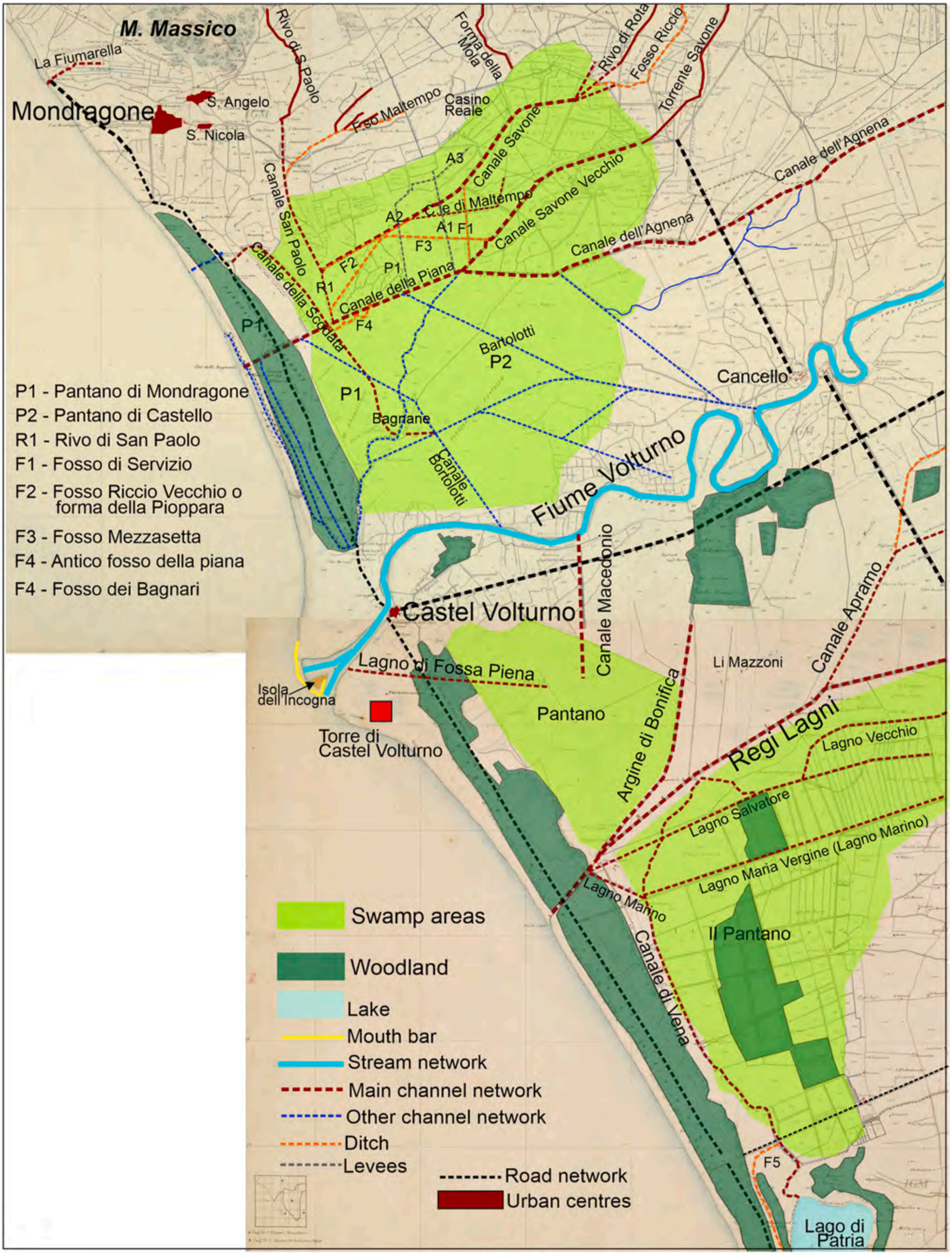

**Fig. 7.** Topographic map of 1834–1860, 1:20,000 scale (Italian Geographic Military Institute). The woodlands were outlined from Topographic and Hydrographic Map of the surrounding areas of Naples 1817–1819 at 1:25,000 scale.

**Fig. 8.** Map of the Kingdom of Naples 1839–1875. The names in green indicate marshy areas. Reliefs, volcanic areas (italicized) and other locations are in red. Lakes and Volturno River are in light blue, but minor rivers are shown with blue lines and channels are demonstrated with dashed blue lines. Black dashed lines indicate the main roads built since 1841. The red dashed line is the Domtiana Road (from Longobardo, 2004).

territory since 2015 to 2021. This service processes average velocities and deformation time series, derived by both Persistent Scatterers (Ferretti et al., 2001) and Distributed Scatterers (Berardino et al., 2002; Ferretti et al., 2011) techniques, by combining radar acquisitions of ascending and descending orbits. Four datasets from 2 b to 3 levels of EGMS interferometric products were used. Level 2 b products includes Line of Sight (LOS) measurements calibrated by a Global Navigation Satellite System reference network at full Sentinel-1 resolution; in this way the LOS data are absolute values being no longer relative to a local reference point. Contrary to the older dataset, is unnecessary to apply the trigonometric calculations to the Sentinel datasets because the vertical and horizontal components of ground deformation are already provided. Level 3 products (ortho) correspond to vertical component (vertical motion) and East-West component (horizontal motion) derived from level 2 b products at 100 × 100 m pixel due to the Copernicus DEM resolution. We have produced a 100-m spaced grid map based on the spatial interpolation of the Level 3 data point. All datasets (Table 2) were imported in a geographic information system to identify the places with active subsidence process. The total VGDM (expressed in mm) was calculated by multiplying the average annual rates for the relative time period expressed in years (Matano, 2019) between 1992 and 2021.

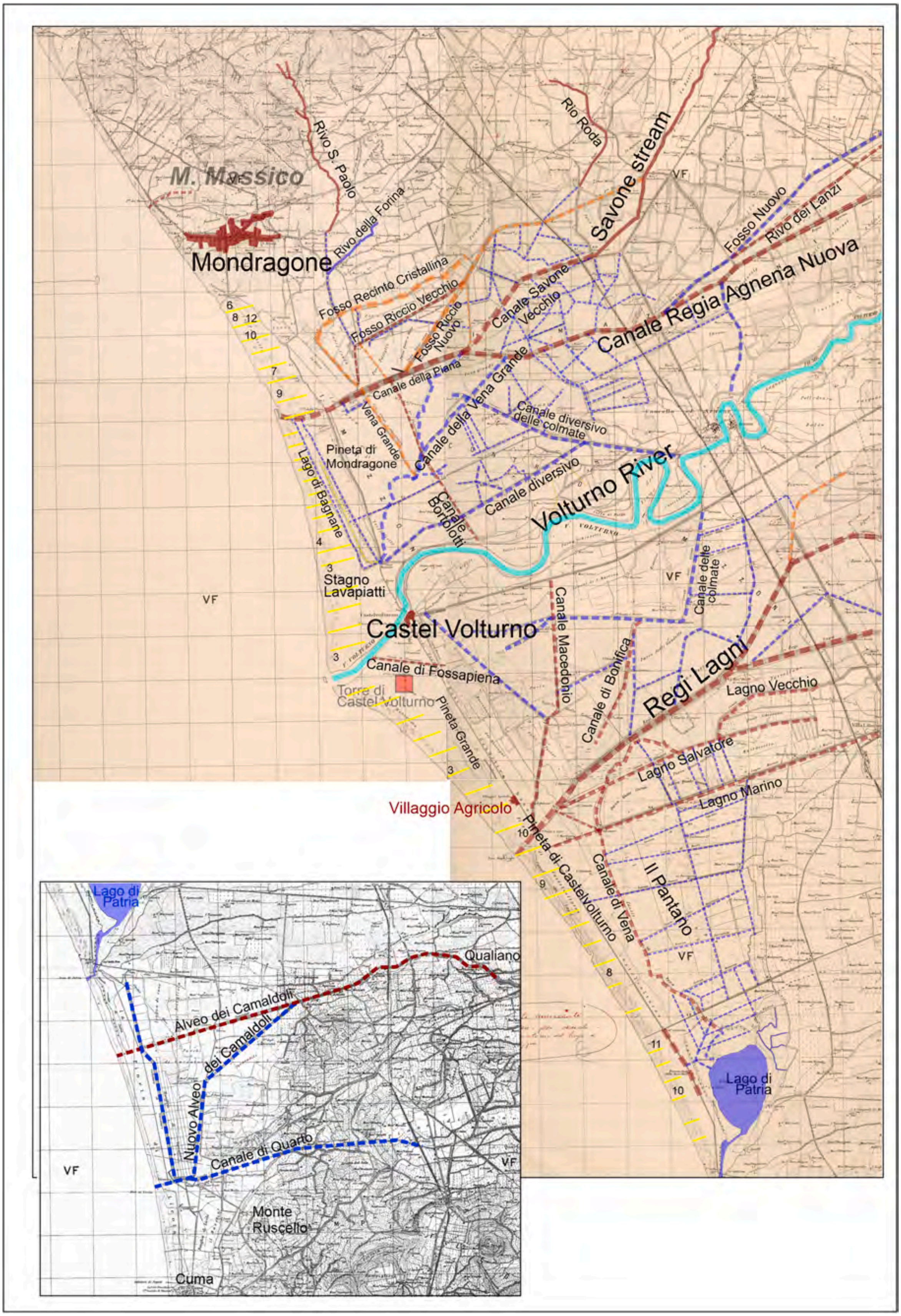

**Fig. 9.** Topographic map of 1936 at 1:20,000 scale (Italian Geographic Military Institute). Dark red dotted lines are the channels older than 1860, while the blue dotted lines are the channels built after 1860. Orange dotted lines represent ditches, while the yellow line indicates the dune system. The dark red polygons are the urban centers of Mondragone and Castel Volturno. The inset displays *Alveo dei Camaldoli*, the main river channel between Patria Lake and Cuma.

**Fig. 10.** The houses built on the north side of Volturno River (A) and the erosion on south side (photos from Cocco et al., 1994). The erosion is testified by the Faro (enclosed in the red circle) on the beach in photo A and in the sea in photo B.

**Fig. 11.** The accommodations of up to 12 floors in the Pineta Mare locality (A) and man-made structures (B) (photos from Cocco et al., 1994).

## 4. Results

### 4.1. Historical and recent human intervention to coastal landscapes

The earliest evidence of human presence in the VCP goes back to 9 BC when the Opians built a small nucleus of dwellings, named *Volturnum*, at the mouth of Volturno River. The fertility of soil in this plain was immediately recognized by the Romans (27 BC – 476) as they called it "*Campania Felix*" ("Happy or Lucky Campania" in English). The area was abandoned as a consequence of the invasion of Barbarians and probably to unfavorable cold climatic conditions (Büntgen et al., 2016; Margaritelli et al., 2016). This territory was dominated by different populations over time (Alberico et al., 2018 and reference therein), and living condition of the locals improved only during domination of the Bourbon dynasty (735–1860). The swamps and marshes prevented agricultural development in the lower part of the VCP until several reclamation plans were carried out over time (Afan de Rivera, 1847; Ciasca, 1928; Provincia di Caserta, 2012). The following subsections describe chronologically both the natural landscape evolution of the coastal area and the changes made by man during land reclamation and urbanization works. These actions have profoundly altered the territory and consequently the spatial distribution of subsiding areas.

#### 4.1.1. Human intervention and modification of the coastal landscape between 1400 and 1714

The map of 1714 shows the Volturno and Clanio, the largest rivers of the VCP, and two smaller rivers, i.e. Saone, later named Savone, and Cales, which should correspond to Regia Agnena in more recent maps (Fig. 4). In the coastal zone there were several lakes and ponds spanning from Monte di Procida to Monte Massico (Fig. 5).

The Clanio river (Regi Lagni since 16th century), which ended their course into the Patria Lake (Fig. 5), was modified to reclaim the territory between Nola and Volturno River mouth (Conti and Pignatelli Spinazzola, 2010).

An attempt to resolve the problem of Clanio water stagnation in the area nearby Patria Lake and in the plain north of Naples was made before the mid-15th century by the Aragonese kings and at the end of the 16th century by Viceroy Juan de Zuniga. However, the funds allocated by viceroys Fernando Ruiz de Castro and than by Francisco de Castro (1599–1603) allowed the reclamation of territory crossed by Clanio River by constructing new ditches, widening and rectifying Clanio river path and over all building an artificial channel at mouth of this river and the channels of Lagno Maria Vergine, Lagno Salvatore and Lagno Canale Vecchio (Fig. 5). The reclamation plan could be considered completed by the end of 1609 apart from few interventions made during the viceroyalty of Pedro Fernandez de Castro (1610–1616) (Conti and Pignatelli Spinazzola, 2010 and reference therein).

#### 4.1.2. A detail on coastal landscape in 1822

The historical map of 1822 plays a crucial role in the comprehension of the past environment of the study area, as it offers an overview of the coastal landscape between Monte Massico and Monte di Procida (Fig. 6).

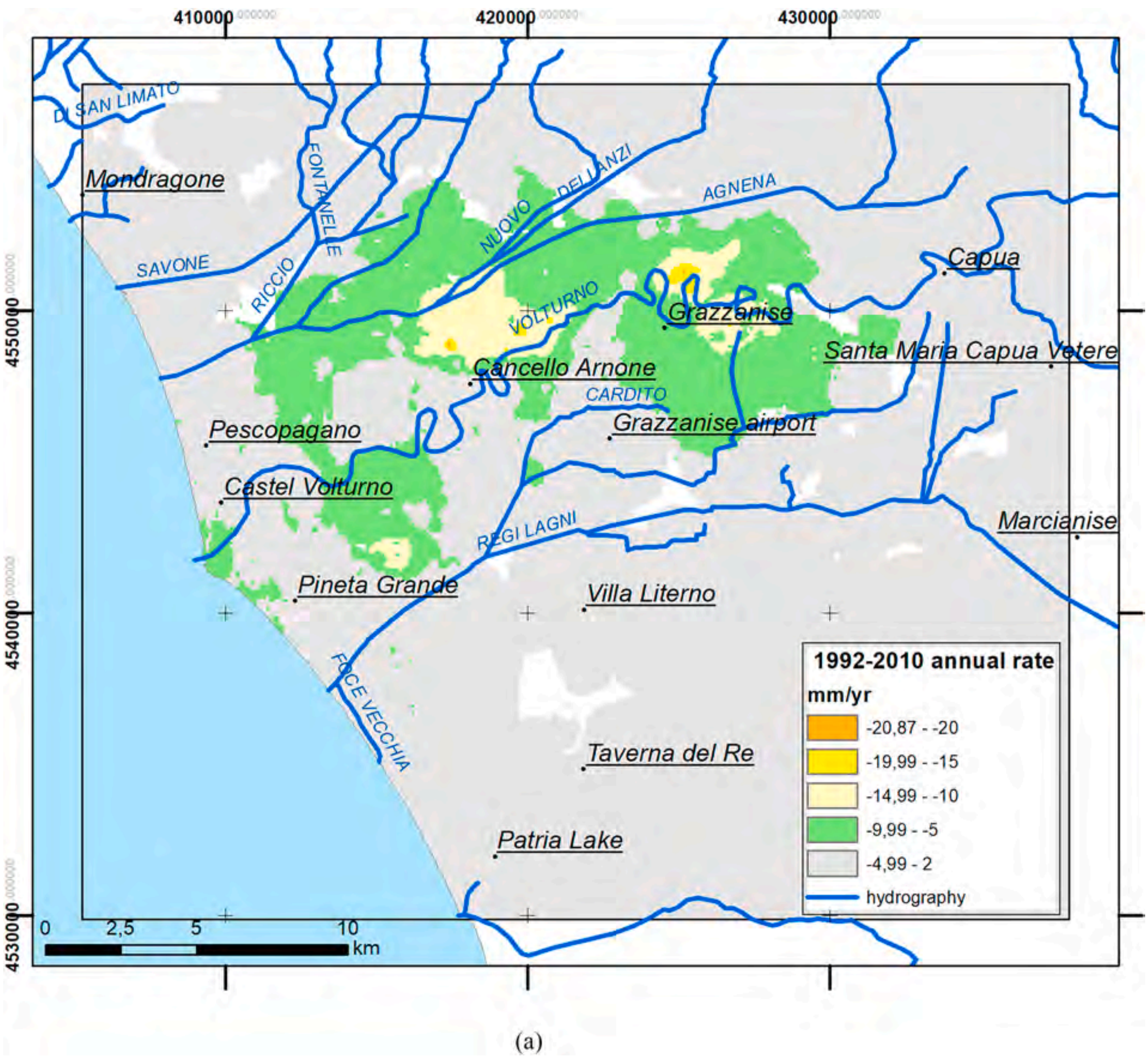

**Fig. 12.** A 100-m resolution map of annual subsidence rate (a) and cumulative vertical ground deformation (b) derived from DInSAR datasets during 1992–2011 (mod. by Matano et al., 2018) .

It shows the marshy areas, which extend several kilometres inland, the watercourses and the channels built to reclaim marshes. The incisions named “*covone*”, caused by runoff over easily erodible volcanic soils, characterize the area close to Campi Flegrei. These incisions usually stop suddenly in areas with less erodible soils (i.e. tuff or ignimbrite) or flow into the main channels and only in some cases reach the sea. In this map, it is also possible to observe Patria Lake, Licola Lake and other small waterbodies, e.g. *Acqua Morta* that will be infilled during further reclamation works, and some woodlands and two Royal Parks that made the study area an enjoyable place.

### 4.1.3. Human intervention and modification of the coastal landscape between 1839 and 1875

In the topographical map of 1839–1875, the Regia Agnena River and the Savone stream, ended their path between the *Pantano di Mondragone* and the *Pantano di Castello* (Figs. 7 and 8). From Savone stream to Carinola mountains, several minor streams ended their courses approximately 9 km from the sea (Savarese, 1856) in the lowlands (Fig. 8). These conditions favoured the formation of large swamp areas that from the coastal area extended for several kilometers inland (Fig. 7). The marshy areas are indicated by the toponyms reported with green text in Fig. 8; they covered approximately an area of about 340 km$^2$ on this map. Furthermore, the presence of high “sandbars” generated by the sea along the coastline led to accumulation of Savone stream water, Volturno river flood and rainfall in the back-dune sectors of the coastal plain forming wide ponds in the lowlands (Savarese, 1856).

A large pond in the Bagnane locality, bordered by the coastal dune, was located in the countryside between the Canale della Piana and the Volturno River. This latter was characterized by a mouth bar and a small island, called Isola dell’Incogna (Fig. 7).

To reclaim the VPC, some interventions were made on the north bank (i and ii) and on the south bank (iii) of Volturno River:

i. The Regia Agnena was connected to sea through *Canale della Piana* (Fig. 7) and several channels were built to convey waters from lowlands between Volturno River and Savone stream (Savarese, 1856).
ii. A new channel named *Fosso Riccio* was built to drain the area between Savone stream and the Monti di Carinola (Fig. 7) by

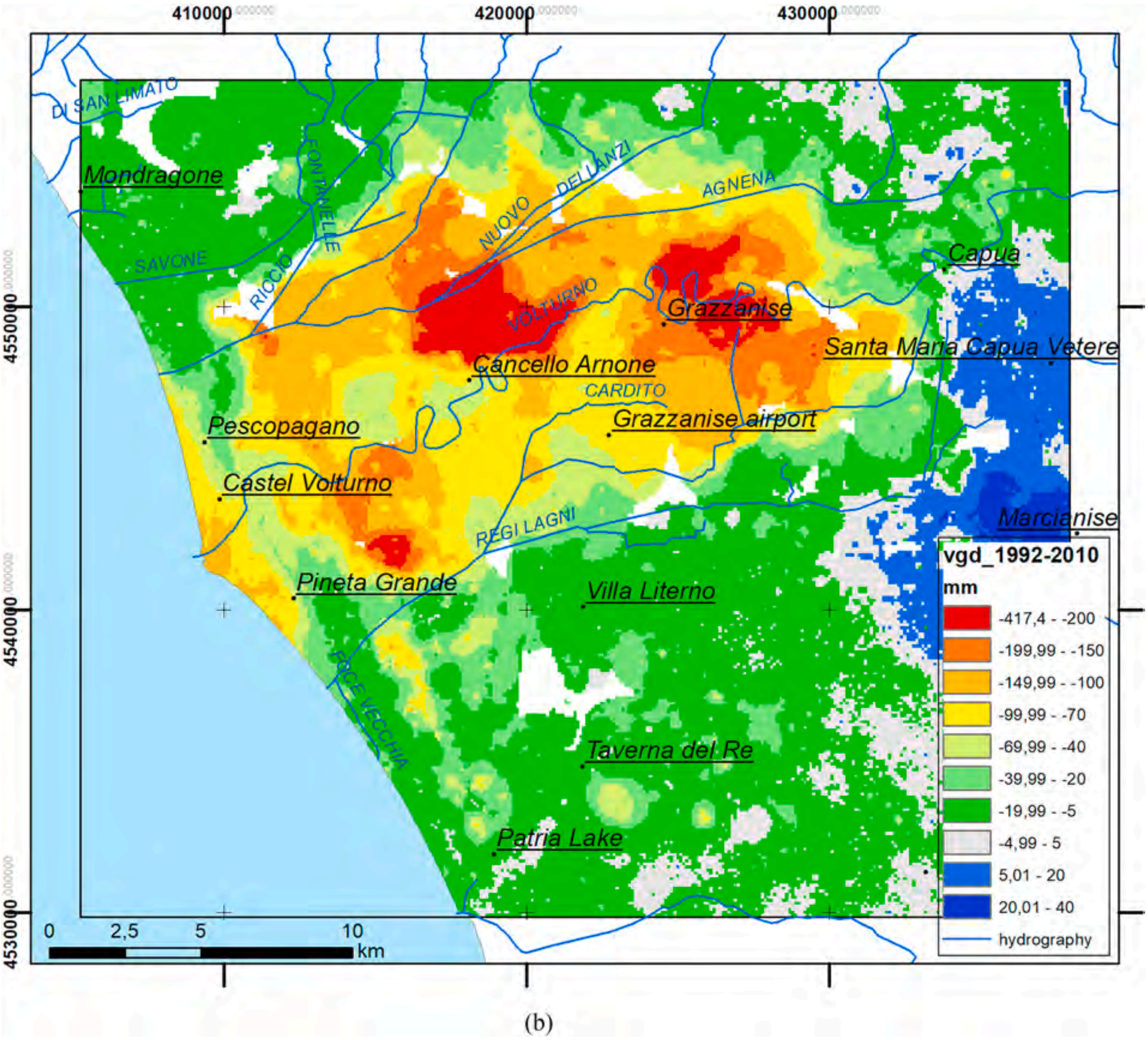

**Fig. 12.** (*continued*).

conveying the water of *Rivo Rota, Forma della Mola* and *Rivo di S. Paolo* into the sea through ditch of *Canale della Piana* (Fig. 7).

iii. Apramo channel was built to collect the river's overflowing waters after the dangerous flood events of 1812 and 1815 (Fig. 7).

Once the reclamation through land drainage was completed, the lowlands were filled with the river sediment. Starting from the northern costal area:

i. The lowlands between the mountains of Carinola and Regia Agnena were infilled with the sediments of Savone stream (Fig. 8). In order to improve the infilling work, ditches and channels were also built (Fig. 7).
ii. The countryside between the Volturno River and the Canale della Piana was infilled by *Bartolotti and* Canale *de' Militari* diversion *channel of Volturno River built betwwen* 1842 and 1845. *Furthermore, Lagno di Fossa Piena* and *Canale Macedonio* diversion channels near Castel Volturno were restored (Fig. 7).

The south side of Volturno River was divided, by the construction of last part of the Regi Lagni, into two zones (Fig. 7):

i. in the zone between Volturno River and Regi Langi, Vena channel was built to direct Volturno River flood into the Patria Lake and infill this sector with the sediment load (Fig. 7).
ii. in the zone between Regi Lagni and Patria Lake, the presence of Regi Lagni banks avoided the use of the sediment load of the Volturno River to reclaim the lowlands. In this area, the alluvial material of small streams flowing down from surrounding hills were used (Fig. 7).
iii. Southward, to infill the area between Lago Patria and Cuma, hosting the *Licola Lake* and minor marshes (Fig. 7), the alluvial material of small streams of sourrounding hills was used. Among these, the *Alveo de' Camaldoli* channel (Fig. 9), was used to carry the alluvial material through the Qualiano valley to the plain. Finally, the pond of Acqua Morta (Fig. 8), near Lake Fusaro, was manually filled as all the other ponds in the area.

### 4.1.4. *Human intervention and landscape changes since the middle of 1900*

The map of 1936 (scale: 1:25,000) shows a denser channel network and dune system with heights ranging between 6 and 12 m a.s.l. (Fig. 9). The mouth bar of Volturno River is absent and only a small portion of the *Incogna Island* remained. The settlements of Caste Volturno and Mondragone were still limited in size.

The human impact became intensive between the late sixties and

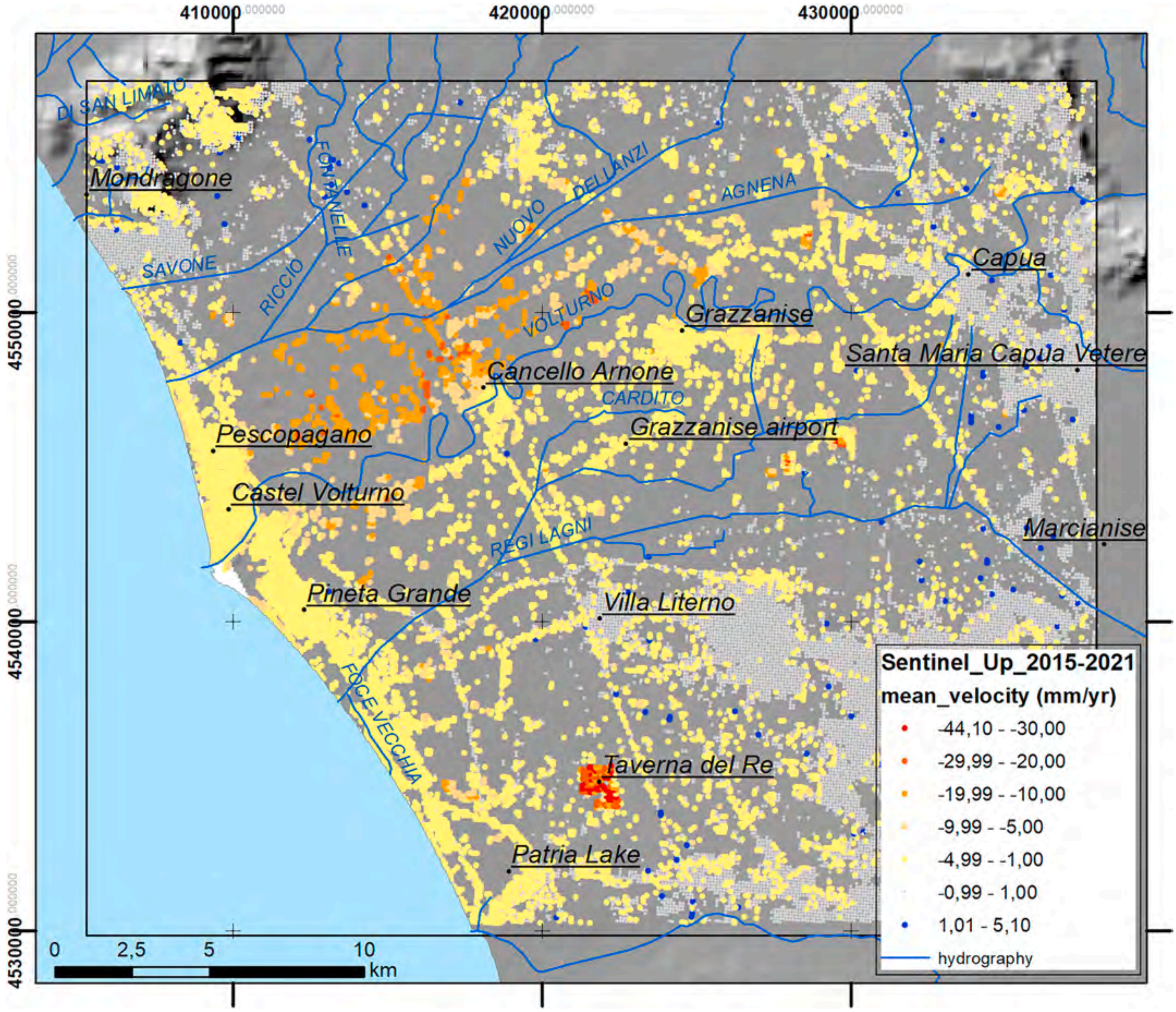

**Fig. 13.** Sentinel 1 mean annual vertical component velocity (mm/yr) field during 2015–2021 (EMGS Copernicus service).

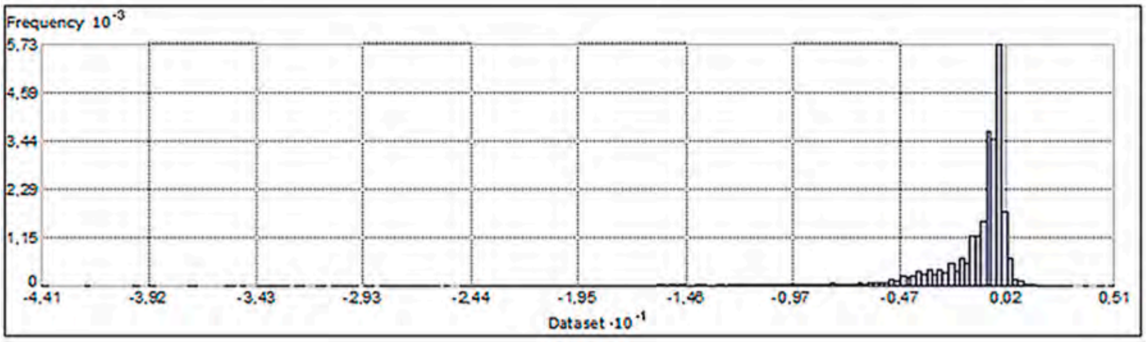

**Fig. 14.** Distribution of mean velocity values of Sentinel 1 data points (EMGS Copernicus service).

early eighties (Frallicciardi and Carisano, 2013; Alberico et al., 2018). The construction of ~5.000 tourist accomodations, in an area of ~3 km$^2$ (Cocco et al., 1994) on the north side of Volturno River (Fig. 10A), contributed to the sediment compactation. The south side has remained almost natural (Fig. 10B). Human intervention is even more significant in the Pineta Mare area, south of Volturno estuary. Briefly, tourist accomodations were built on large dune belts (Fig. 11A). A small harbour was built in an unused terminal section of the canal of the Regi

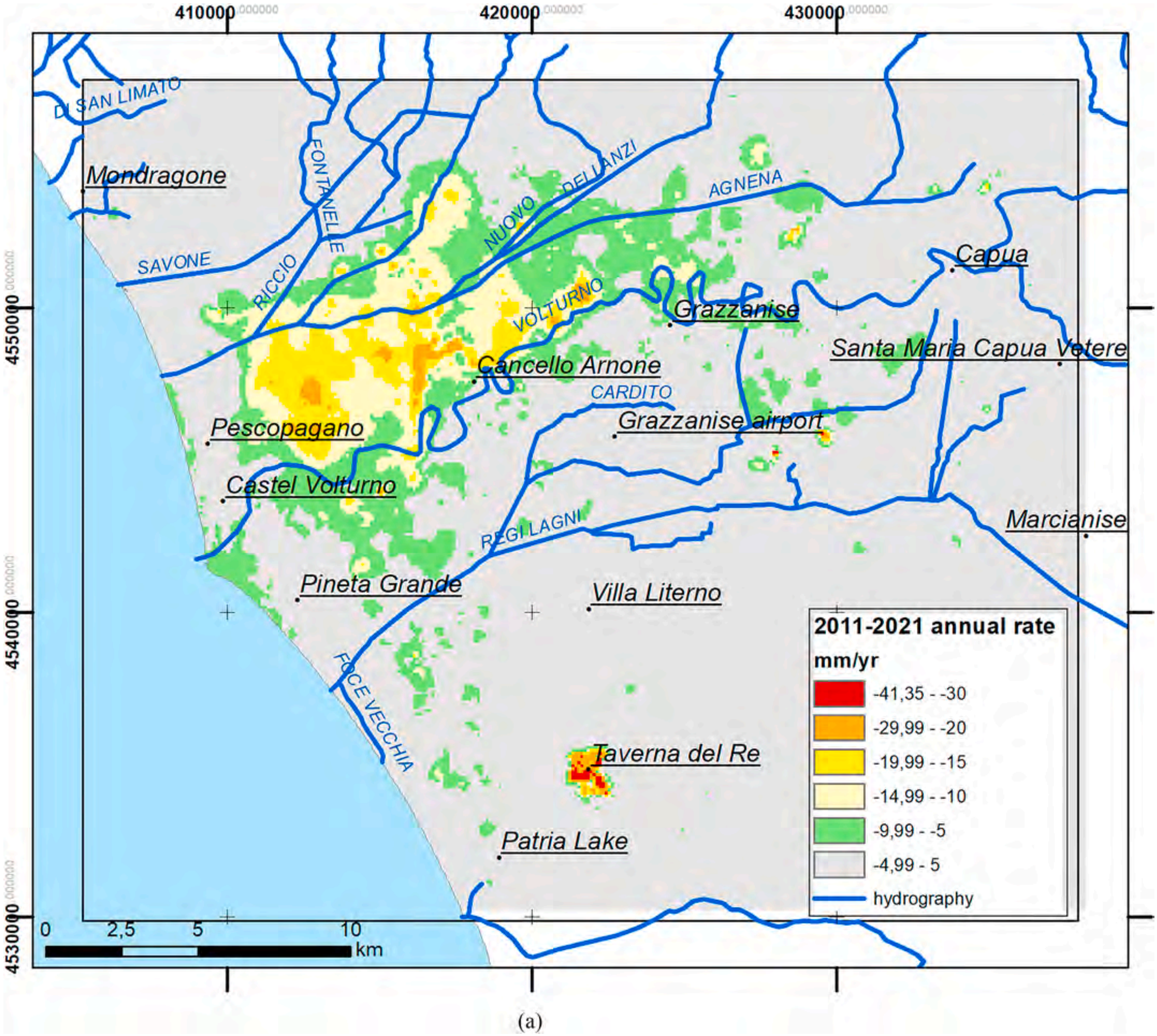

**Fig. 15.** A 100-m resolution map of annual rate (a) and cumulatitive vertical ground deformation (b) derived from DInSAR datasets during 2012–2021.

Lagni and abandoned after the construction of a new marina between 1978 and 1979. In this time interval, a residential complex and fourteen transversal groynes were built (Fig. 11B). Urbanization rate decreased in the following years, and most houses were abandoned by the late 1990s as a result of severe local touristic decline.

### 4.2. Subsidence rates and map

Matano et al. (2018) reported similar negative vertical velocity patterns in VCP over 1992–2000, 2003–2007 and 2003–2010 by analyzing ERS, RADARSAT and ENVISAT datasets, respectively. Spatial distribution of subsidence rate from 1992 to 2010 (Fig. 12) revelas VGD obtained from the average annual vertical velocity of the three satellite datasets (Matano et al., 2018). Only 10% of the investigated area was characterized by positive values (from 0 to +40 mm), 89% of the study area was characterized by negative values (up to −420 mm) and ~26% showed no significant evidence of subsidence or uplift (values between +10 and −10 mm). A large area (about 215 km$^2$) at central VCP demonstrated −50 to −420 mm subsidence (Fig. 12). The most negative values (below −200 mm) have appeared along Volturno River and around the towns of Grazzanise and Cancello Arnone. From −50 to −200 mm of subsidence was recorded in the back-dune depressions, near Villa Literno and the surroundings. The subsidence in the Volturno River mouth was moderate (−50 to −150 mm), while the dune ridge system was substantially stable. New data refferred to 2015–2021, obtained by Sentinel 1 dataset of vertical velocities (EMGS “Level 3” data points), show a different spatial subsidence compared to the previous periods, but a large-extent subsidence trend is always observed across the coastal plain (Fig. 13). Vertical velocity values range from +5.1 to –44.1 mm/yr. Statistical distribution of mean vertical velocity is shown in Fig. 14. The mean and median values are −1.63 and −0.6 mm/yr, respectively. 75% of the values are between −1.6 and – 0.2 mm/yr.

A relationship between subsidence and vertical velocity below −20 mm/yr was observed around Cancello Arnone, along the Volturno River

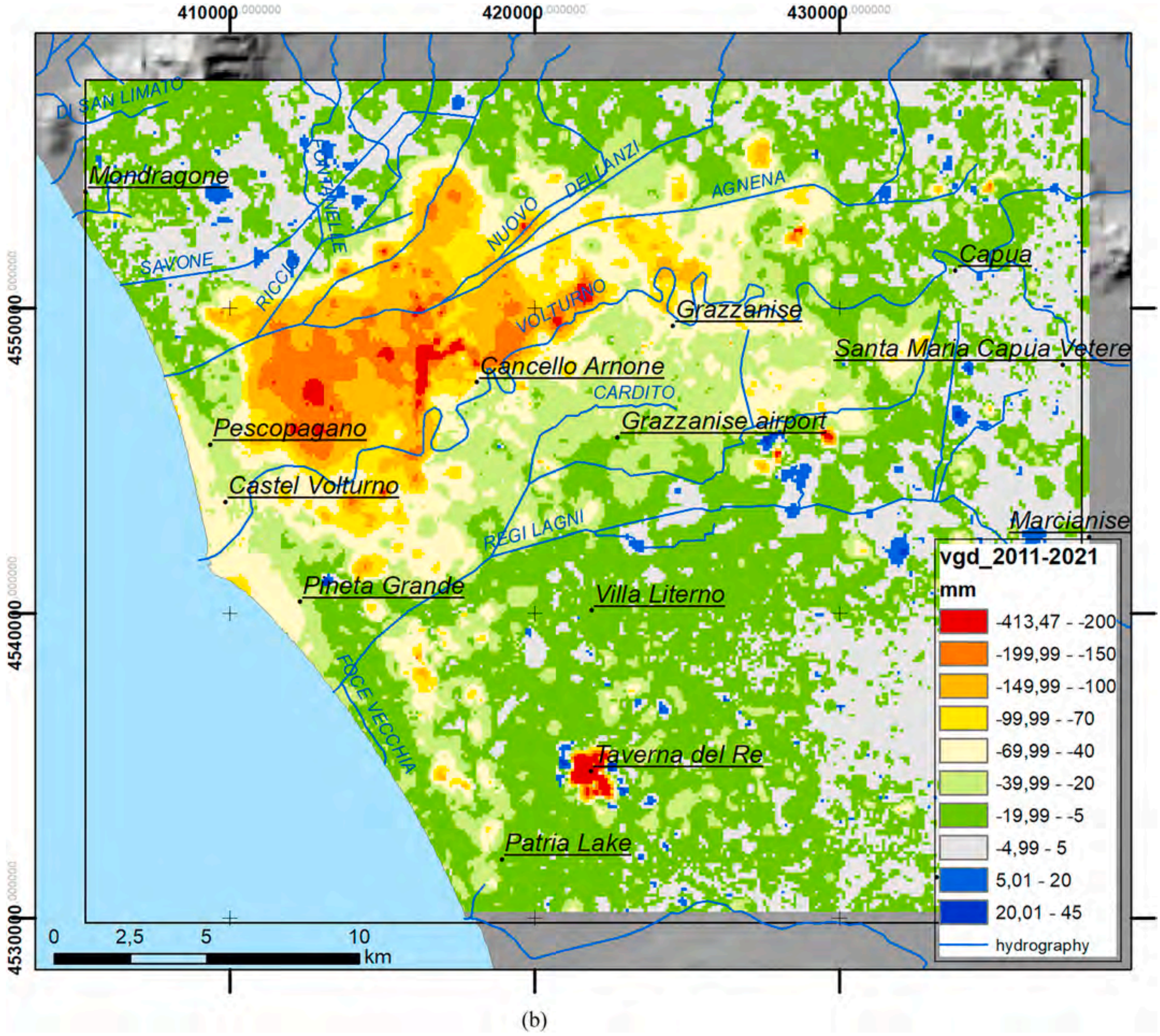

**Fig. 15.** (*continued*).

and in *Taverna del Re* locality (Fig. 13). Volturno River mouth showed moderate negative velocity (−5 to −10 mm/yr), while positive values (up to +5 mm/yr) are scattered across the plain.

The dataset with an average spatial density of 28.9 points/km$^2$ (26,123 points in 903.33 km$^2$) helps obtain representative regional ground deformation analysis irrespective of presence of missing data in small areas. Most EMGS Level 3 vertical data points occur nearman-made structures such as roads, railways and buildings.

The vertical ground deformation raster map derived by the interpolation of EMGS Level 3 vertical data points is shown in Fig. 15, being partially different from those in Fig. 12. The subsidence significantly affects central sector of the study area with values lower than −100 mm. In Taverna del Re locality, the largest temporary storage site for waste bales (“ecoballe” in Italian) in Campania was opened in 2001 with a concrete lay-by of about 130 ha that keeps about 6.5 millions of tons of waste covered by a high-density polyethylene tarp. This site shows very high negative vertical deformation (under −200 mm) due to progressive compaction of waste materials and the underlying soils. Moderately negative deformation (up to −100 mm/yr) was recorded in Volturno River mouth and from Patria Lake to *Pineta Grande* back-dune strip, but positive deformation (up to +45 mm) were measured in very small sectors scattered throughout the plain.

The overall cumulative vertical ground deformation obtained from DInSAR dataset (1992–2021) is shown in Fig. 16. In the last 30 years, moderate to very strong subsidence (between −100 and −615 mm) is recorded from Castel Volturno to Capua and between Savone and Regi Lagni watercourses. The highest negative deformation (lower than −400 mm) is measured in a narrow strip between Cancello Arnone and Grazzanise on the north bank of Volturno River. The Volturno River mouth, Taverna del Re locality and the back-dune area from Patria Lake to Pineta Grande show moderate to high negative deformation (−100 to −400 mm) although the area around the Grazzanise airport experienced moderate deformation (from −70 to −150 mm). In the eastern border of the plain, positive deformation (up to +40 mm) are observed between Santa Maria Capua Vetere and Marcianise.

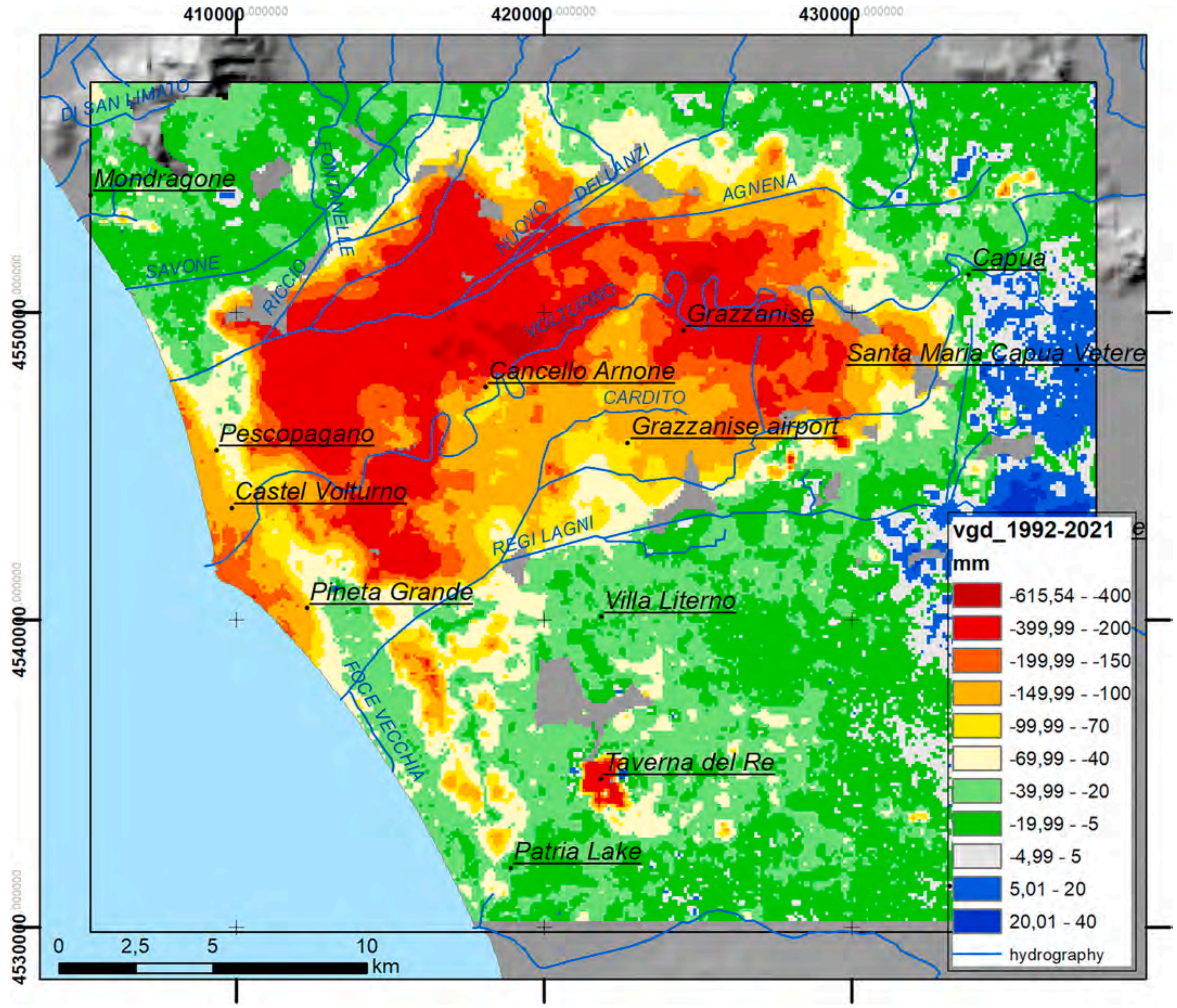

**Fig. 16.** Cumulated vertical ground deformation derived from DInSAR datasets during 1992–2021.

## 5. Discussion

The coastal plains along the western flank of Apennine chain formed within semigraben structures originated by the extensional tectonic regime induced by Tyrrhenian Sea opening during Pliocene/Lower Pleistocene (Patacca et al., 1990; Casciello et al., 2006; Sacchi et al., 2014). In VCP, the tectonic subsidence was related to the extensional faults bordering the Volturno plain with an average vertical slip rate of 1.35 mm/yr since Pleistocene (Cinque et al., 2000). This tectonic setting created favourable conditions for high sedimentation rates during Late Pleistocene – Holocene. The VCP was repeatedly invaded by the sea (Brancaccio et al., 1991, 1995), depending on the intensity of subsidence, sedimentation rates and eustatic sea-level oscillations, and was strongly aggraded after the highly explosive eruption of the Campanian Ignimbrite (40 ka BP; Giaccio et al., 2017), whose deposits represents the substrate for the uppermost Pleistocene-Holocene sedimentation (Romano et al., 1994; Corrado et al., 2018; Mastrocicco et al., 2019). After LGM, sea-level rise rapidly flooded the lower part of the Volturno valley (Romano et al., 1994; Amorosi et al., 2012; Ruberti et al., 2018). Since 6.5 ka BP, a phase of coastal progradation formed the present alluvial plain that is bordered seaward by sandy beach-dune system and a backdune lowland sector with an elevation between −2 b s.l. And 0 m a.s.l., that is the remnant of a retrodunal depression mainly infilled by clay and silty deposits, locally interbedded with peat layers (Amorosi et al., 2012).

This tectonic and stratigraphic setting, combined with the landscape morphology, created favourable conditions for the establishment of the long-lasting subsidence that characterises large VCP sectors. It is reasonable to state that subsidence is mainly due to the natural lithostatic compaction of fluvial and palustrine deposits formed during progradation phases occurred after 6.5 ka. These organic-rich deposits and clays filled the paleovalley incised by Volturno river during eustatic low sea level at LGM. Previous studies showed that subsidence is greater when there are thicker peat layers in the subsoil, typical of marsh and swamps (Bruno et al., 2020; Ruberti et al., 2017, 2018, 2022).

These wide marsh and swamp areas in the VCP have been highlighted through the analysis of historical documents and cartographies edited during the 18th-20th centuries and documented by the reclamation plans and works made since the 15th century (see section 4.1). In the present work, we have observed the spatial correspondence of these

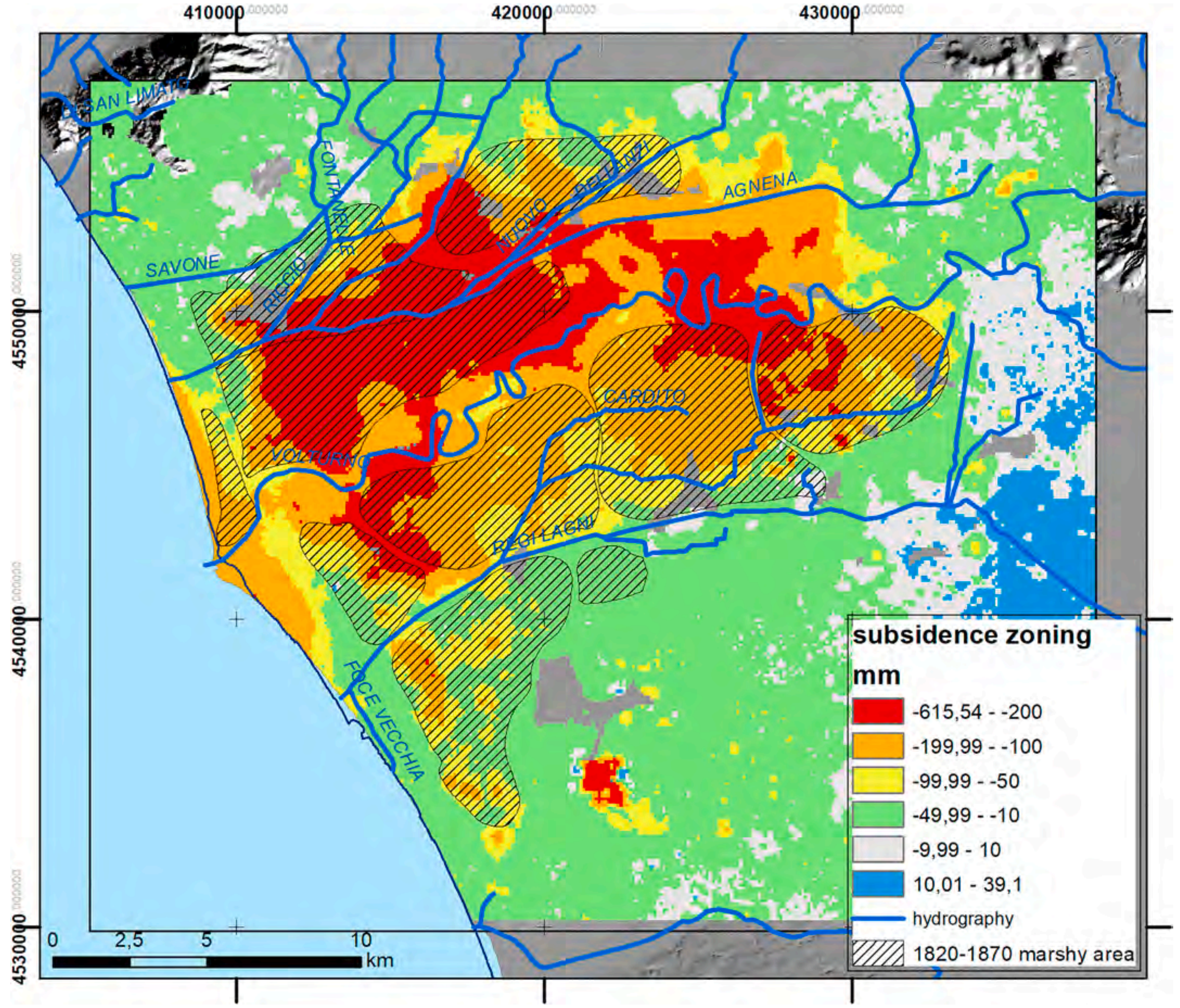

**Fig. 17.** Subsidence zoning from 1992 to 2021 and the nineteenth century marshy areas.

sectors with areas affected by recent subsidence recognized by the MT-InSAR data from 1992 to 2021 (Fig. 17) (see section 4.2). The wide presence of marshs and swamps in the Volturno coastal plain was also by the Kingdom of Naples.

Indeed, historical documents and maps (Figs. 4–10) have made it possible to identify: i) the extension of marshy and swampy areas in the back-dune depression areas, where some rivers and streams ended their course far from the sea, and ii) the timing of reclamation works partly responsible for the different degree of sediment compaction.

Since middle of 1400, the zones close to Clanio River was reclaimed, the works ended in 1603 with the building of an artificial mouth conneting the river to the sea. Land reclamation was ongoing on the south side of Volturno River until the early decades of 1800s. During the late eighteen and nineteen centuries, the land between Volturno River and Monti di Carinola was reclaimed. Only in the late nineteenth century, the lowland between Regi Lagni and Cuma was also reclaimed together with the Licola Lake, minor marshes and ponds. The different historical periods of land reclamation (the fifteenth to nineteenth centuries on the south side and since the seventeenth century on the north side) probably influenced the subsidence rates on the two sectors of the plain.

Nine different zones were recognized by considering the natural and anthropic landscape elements within the VCP and subsidence data from the last decades (Fig. 18): i) a slight uplift zone partly encompassing the plain and the outer slopes of Campi Flegrei caldera; ii) a stable coastal dune ridge; iii) a slightly subsiding zone in the outer plain and mountain slopes; iv) a variously subsiding zone formed by the post 1800 river mouth and beaches; v) a variously subsiding zone formed by the main river course and abandoned meanders; vi) a subsiding plain; vii) highly subsiding lowlands; vii) a highly subsiding waste disposal site; xix) a very highly subsiding plain.

Strong subsidence has been a key characteristic of the area between coastline and the middle VCP over time. Matano et al. (2018) reported that deformation spatially overlaps with the Volturno palaeovalleys in this are, where the very thick Holocene sedimentary sequence is responsible for the highest subsidence rates due to the presence of non-cohesive clayey silt, clay and peat with a medium to high degree of compressibility (Buffardi et al., 2021).

The subsidence rate in the plain is related to both primary and secondary (or creep) consolidation processes of the soft, compressible subsoil. The former derives from changing effective stresses (e.g., from

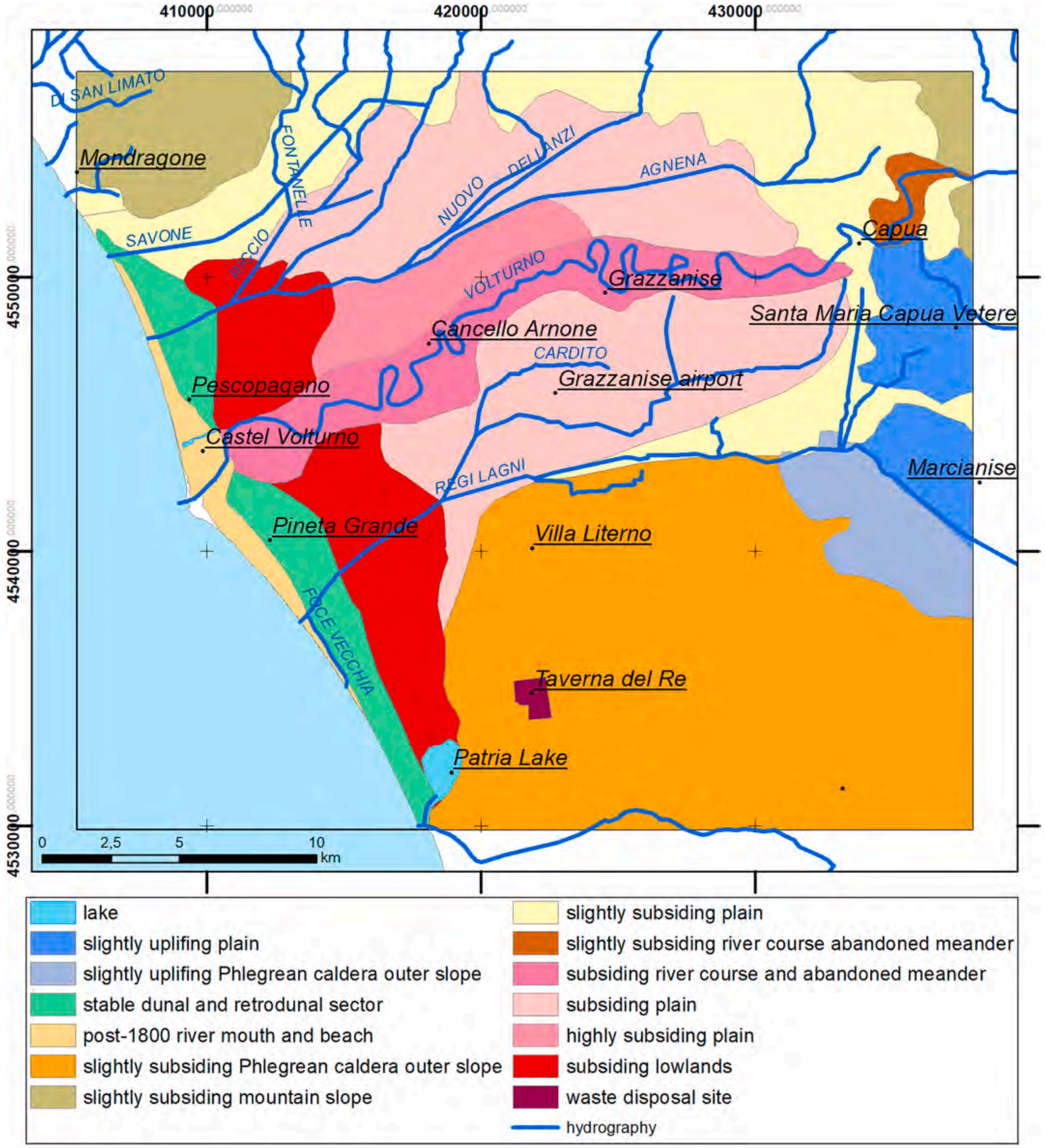

**Fig. 18.** Subsidence and morphological zoning in Volturno Coastal Plain.

load of livestocks, warehouses and buildings) and/or changing pore water pressures under constant total stresses (e.g., due to variation in groundwater extraction). The latter is, however, continuous soil deformation under constant effective stresses of lithostatic load. It is worth mentioning that if the subsidence induced by a primary consolidation process is over, the secondary consolidation processes may still continue to deform ground surface. According to Buffardi et al. (2021), the presence of organic matter increases secondary compression coefficient.

Anthropogenic activity such as groundwater expliotation and urbanization can locally intensify primary consolidation processes (Matano et al., 2018), but stratigraphy, and in our case study specifically the thickness of organic-rich Holocene deposits, plays a key role in secondary consolidation and variability of subsidence rates. In some sectors of VCP, industrial and intensive agricultural activities hinders water balance which may have a greater impact on the subsidence rates (Vilardo et al., 2009; Aucelli et al., 2016). Also the urbanization had an intensive impact on the coastal sector between the late 1960s and early 1980s with construction of approximately 5000 tourist accomodations on the north side of Volturno River (Cocco et al., 1994; Alberico et al., 2017).

A unique aquifer-scale groundwater circulation can be considered in the study area, characterized by a porous multi-layered aquifer system formed by volcaniclastic and alluvial deposits. The area is recharged by the lateral groundwater fluxes from carbonate aquifers in the eastern border of Campanian plain (Allocca et al., 2007; Coda et al., 2019), that locally increase soil pore pressure and partially explain the local uplift in the Marcianise-Caivano sector. The E-W trending active fault in the southern border of the study area might also contribute to the ground uplift (Matano et al., 2018).

## 6. Conclusion

Data derived from literature and historical maps, recent satellite images and satellite radar interferometric data from the last 30 years were analyzed to investigate the relationships between landscape evolution and subsidence processes in a wide coastal plain on the Tyrrhenian Sea margin of Southern Italy. The main findings indicate that the effects of subsidence observed today are related to numerous processes in VCP that have developed at different temporal and spatial scales.

Firstly, Tyrrhenian Sea opening resulted in an extensional tectonic regime in the study area which contributed to slow and homogeneous subsidence since over 1 Ma.

During LGM sea-level oscillations, the Volturno paleo-river eroded the Campanian Ignimbrite substratum and made a large, incised paleo-valley, filled with thick alluvial, lacustrine and coastal deposits of the uppermost Pleistocene-Holocene. Since 6.5 ka BP, coastal progradation formed the present alluvial plain, bordered by a 35-km long sandy beach-dune system on the seaward and a wide retrodunal swampy area since 2 ka BP.

The historical maps and documents mainly showed wide marsh and swamp areas in the back-dune sector of VCP since the fifteenth century. Several rivers and streams drained in this area and favoured the swamps and marshes until the late to ninteenth century due to the presence of large subsiding sub-sectors.

The current differences between subsidence of both sides of Volturno River can be related to the asymmetry of the incised valley which resulted in thicker clay and peat materials on the north bank. Between Agnena and Volturno River, swamps (named “Pantani” or “Mazzoni” in ancient Italian) are widespread and the maximum subsidence is recorded by radar satellite interferometric data. The different historical periods of land reclamation (the fifteenth to nineteenth centuries on the south side and since the seventeenth century on the north side) have also influenced the subsidence asymmetry.

Finally, anthropogenic activities such as urban growth, groudwater extraction for agricultural and breeding activities, and construction of big waste dumps have had only local effects on recent subsidence trends.

## CRediT authorship contribution statement

**Ines Alberico:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Fabio Matano:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization.

## Data availability

Research data are available upon request. To request the data, contact the corresponding author.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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