Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

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To cite this article: Antonella Marsico, Stefania Lisco, Valeria Lo Presti, Fabrizio Antonioli, Alessandro Amorosi, Marco Anzidei, Giacomo Deiana, Giovanni De Falco, Alessandro Fontana, Giorgio Fontolan, Massimo Moretti, Paolo E. Orrú, Enrico Serpelloni, Gianmaria Sannino, Antonio Vecchio & Giuseppe Mastronuzzi (2017) Flooding scenario for four Italian coastal plains using three relative sea level rise models, Journal of Maps, 13:2, 961-967, DOI: 10.1080/17445647.2017.1415989

To link to this article: https://doi.org/10.1080/17445647.2017.1415989

JOURNAL OF MAPS, 2017
VOL. 13, NO. 2, 961–967
https://doi.org/10.1080/17445647.2017.1415989

Science

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Flooding scenario for four Italian coastal plains using three relative sea level rise models

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ABSTRACT

The coastal areas of the central Mediterranean Sea are sensitive to climate change and the consequent relative sea level rise. Both phenomena may affect densely urbanized and populated areas, causing severe damages.

Our maps show the land-marine flooding projections as effects of the expected relative sea level rise for four Italian coastal plains using (i) IPCC AR5 estimations, based on the IPCC RCP 8.5 emission scenarios and (ii) the Rahmstorf 2007 model. Isostatic and tectonic data were added to the global projections to estimate the relative sea changes expected along the coastline by 2100, as well as sea-flooding. The northern Adriatic map shows the study area, extending for about 5500 km^2, and is presented at a scale of 1:300,000 with two inset maps at a scale of 1:150,000. The Oristano coastal plain is about 125 km^2; the map scale is at 1:60,000 with an inset map scale at 1:33,000. The Cagliari coastal study area extends for 61 km^2; the map scale is at 1:60,000 with two inset maps at 1:30,000. The Taranto area extends for 4.2 km^2 and is represented at a scale map of 1:30,000, while the three inset maps are at a scale of 1:10,000.

ARTICLE HISTORY
Received 7 June 2017
Accepted 7 December 2017

KEYWORDS
Relative sea level rise; Italian coastal plains; IPCC and Rahmstorf projections; flooding maps; 2100 scenarios

1. Introduction

Coastal areas are highly sensitive to dynamic processes determining relative sea level rise and landscape modifications (Bondesan et al., 1995; Karim & Mimura, 2011; Strauss et al., 2012). Instrumental and observational data show that global sea level is rising as a result on the sum of eustatic, glacio-hydro-isostatic, and tectonic (including volcanic) signals (Lambeck & Purcell, 2005). Therefore, scenarios of land flooding should take into account the role of vertical land movements (VLMs) (Anzidei et al., 2014; Anzidei et al. 2017; Aucelli et al., 2016; Lambeck et al., 2011; Rovere et al., 2012; Wöppelmann & Marcos, 2012), such as natural or anthropogenic land subsidence.

In Italy, the coastlines stretch for more than 7500 km and are characterized by valuable natural and historical sites. They host important urban and industrial installations and tourist activities implying that about 70% of the population lives in coastal areas (www.annuario.isprambiente.it) (Figure 1).

Previous studies all along the Italian coasts (Lambeck et al., 2011) identified 33 sites potentially prone to the marine flooding considering the sum of isostatic and tectonic VLMs and the expected sea level rise derived by the International Panel on Climate Change (IPCC, 2007). More recently, we focused our attention on sea level rise projections for the year 2100 (Church et al., 2010; Church et al., 2013; Rahmstorf, 2007) and estimated impacts for four areas of the Italian peninsula considering the IPCC AR5 reports 2013 for the maximum RCP-8.5 scenarios (www.ipcc.ch) of climate change (Figure 2), adjusted for the rates of VLMs (Antonioli et al., 2017).

In this paper, we present new detailed maps for four Italian coastal plains showing the present coastlines and their estimated future positions due to the extension of land flooding. These areas host industrial, military, and tourist facilities and have been chosen as case studies, representative of all the Italian coasts. Furthermore, these areas present different tectonic settings, being stable, slightly uplifting or subsiding, as well as different geomorphological elements, representative of the coastal landscape variability of the Italian region.

In our maps, eustatic, isostatic, and tectonic data are used to assess the expected effects of sea level rise

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Figure 1. The Italian coastal areas are characterized by important human settlements that are sensitive to sea level rise: (a) the Fondi Plain, near Latina (Latium, Italy) is one of the 33 areas of the Italian coastal zones prone to marine flooding (Lambeck et al., 2011) (Photo G. Mastronuzzi, 2005); (b) the Mouth of Carapelle river, near Foggia (Apulia, Italy) with damaged wetlands after the sea-storms occurred on February/March 2009 (Photo by M. Caldara, 2009).

according to Church et al. (2013) and Rahmstorf (2007) projections and include the rates of glacio-hydro-isostasy estimated by Lambeck et al. (2011). Our goal is to provide detailed maps (M1, M2, M3, and M4) of potential marine flooding scenarios at four densely urbanized and populated Italian coastal areas for the year 2100. The areas include the northern Adriatic and the coastal plains of Oristano, Cagliari, and Taranto (Figure 3).

2. Methods

This study is part of a more complex research study on land flooding due to sea level rise and VLMs for the year 2100 in the Italian region, as also reported in Antonioli et al. (2017) and Anzidei et al. (2017).

The authors used the AR5 RPC 8.5 scenario as the maximum of the IPCC projections (Church et al., 2013, 380 and 700 ppm CO_2 in atmospheric content) and the Rahmstorf (2007) model to account for the flooding expected in 2100. The IPCC scenario provides minimum and maximum values of sea level rise at 0.53 and 0.97 m, respectively, while the Rahmstorf (2007) scenario predicts a sea level rise of 1.4 m. To assess the relative sea level rise in the investigated areas, we used the methodology previously applied in the Vector Project (http://vector.conismamibi.it/) that takes into account the expected isostatic, tectonic, and eustatic-steric rates of sea level rise for each area. The extension of potentially flooded lands is projected on topography using high-resolution Digital Terrain Models (DTM). The LIDAR data (spatial resolution of 1 × 1 m, with vertical accuracy (v.a.) ± 0.1 m and 2 × 2 m, with v.a. ± 0.2 m), made available from various Agencies (Italian Ministry of the Environment, Autonomous Region of Sardinia), were used in all areas since they cover all the coastal zones and the inland throughout almost all of the study areas. For those lands not covered by the available LIDAR data, other DTMs such as TINITALY/01 with grid of 10 × 10 m in the Friuli Venezia Giulia (v.a. ± 1.2 m) and Veneto Regions (v.a. 1.8 m), Regional DTM 5 × 5 m in the Emilia Romagna Region

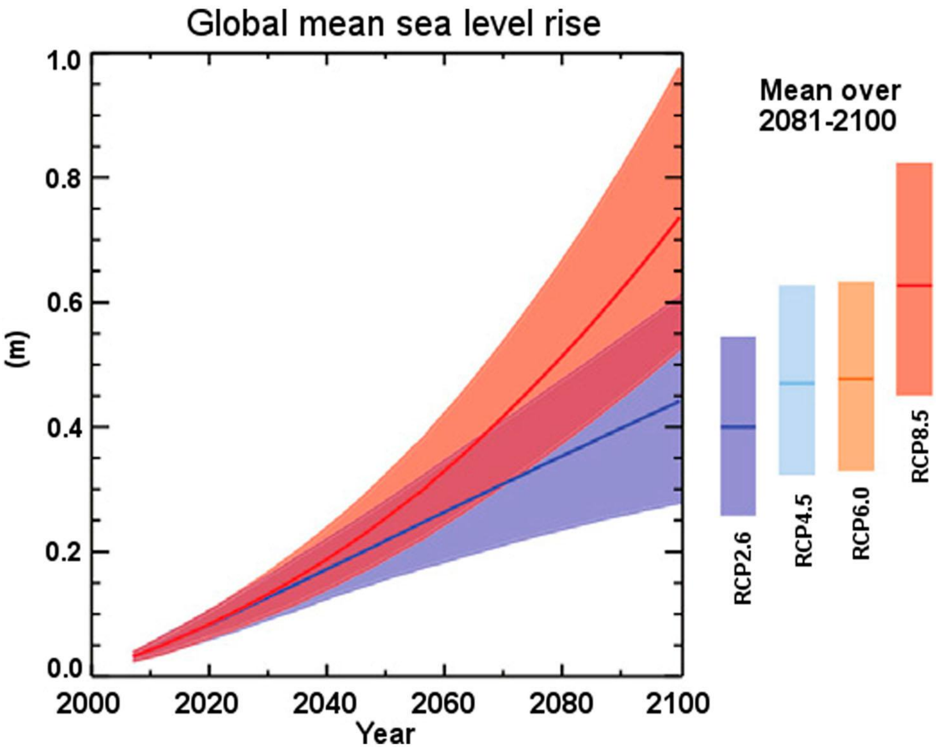

Figure 2. Sea level rise projections for 2100, as proposed by the IPCC 2013 report.

(position accuracy 2 m from http://servizigis.regione.emilia-romagna.it/ctwmetadatiRER/metadatoISO.ejb?stato_IdMetadato=iOrg01iEnP1idMetadato76884), SRTM 30 × 30 m (≤10 m relative vertical height accuracy from https://www2.jpl.nasa.gov/srtm/statistics.html) in the Oristano inland were added to the highest resolution DTMs. Table 1 displays the period of the LIDAR survey (column 6) and the Agencies that produced the DTM (column 7).

We considered the long-term tectonic and isostatic rates in the investigated coastal areas in order to account for the VLMs (Table 1). For the northern Adriatic region, vertical tectonic movements rates were reported by Ferranti et al. (2006, 2010); and Antonioli et al. (2007, 2009, 2017). The rate ranges from −0.4 mm/yr between Trieste and Caorle (northern Adriatic 1, Table 1, columns 1 and 2) to about −0.95 mm/yr between Chioggia and Cesenatico (northern Adriatic 3, Table 1, columns 1 and 2). For the coastal area of Taranto, we considered the vertical tectonic rates derived from the MIS 5.5 coastal deposits (Amorosi et al., 2014; Negri et al., 2014), thereby obtaining a vertical movement rate of +0.14 mm/yr (Table 1, column 2). In the Oristano Plain, the similar MIS 5.5 deposit is at 7 m mean sea level (Ferranti et al., 2006), confirming the tectonic stability of the area (Table 1, column 2). For the area of Cagliari, the tectonic stability is inferred from the presence of deposits containing *Persististrombus latus* (= *Strombus bubonius*) and a survey carried out on marine deposits (Orrù, Antonioli, Hearty, & Radtke, 2011; Orrù et al., 2014). Isostatic rates are derived from Lambeck et al. (2011, Figure 3), with values ranging between −0.12 and −0.62 mm/yr (Table 1, column 4): the minimum isostatic values are found in the northern Adriatic, whereas the maximum are found in Sardinia.

The long-term VLMs were compared against instrumental data of GPS and tidal observations.

The current rates of the geodetic VLM derive from the results from several GPS networks operating in the Euro-Mediterranean area. Here, we considered the velocities of GPS sites located within 10 km from the coastlines, acquired for more than 2.5 years (Anzidei et al., 2014; Serpelloni et al., 2013). The geodetic vertical rates are not necessarily purely tectonic rates because the present-day VLM includes different anthropogenic (mostly induced subsidence) and natural processes. The latter includes geodynamic, tectonic, and volcanic processes that could be active simultaneously. The GPS data (Table 2) show a diffuse subsidence in the northern Adriatic area, reaching a maximum in the Venice lagoon, whereas, in both the Taranto and Cagliari Gulfs, the GPS velocity is close to zero. No data are available for the Oristano Gulf.

Current sea level trends derive form tidal data collected in the time span 1875–2013 from a set of both historical and modern stations located along the investigated areas (Table 3) (www.mareografico.it; www.pol.ac.uk). The sea level trend is a rise in all stations, ranging from 2.44 mm/yr (Venice, Punta della Salute, 1909–2000 series) to 10.7 mm/yr (Venice,

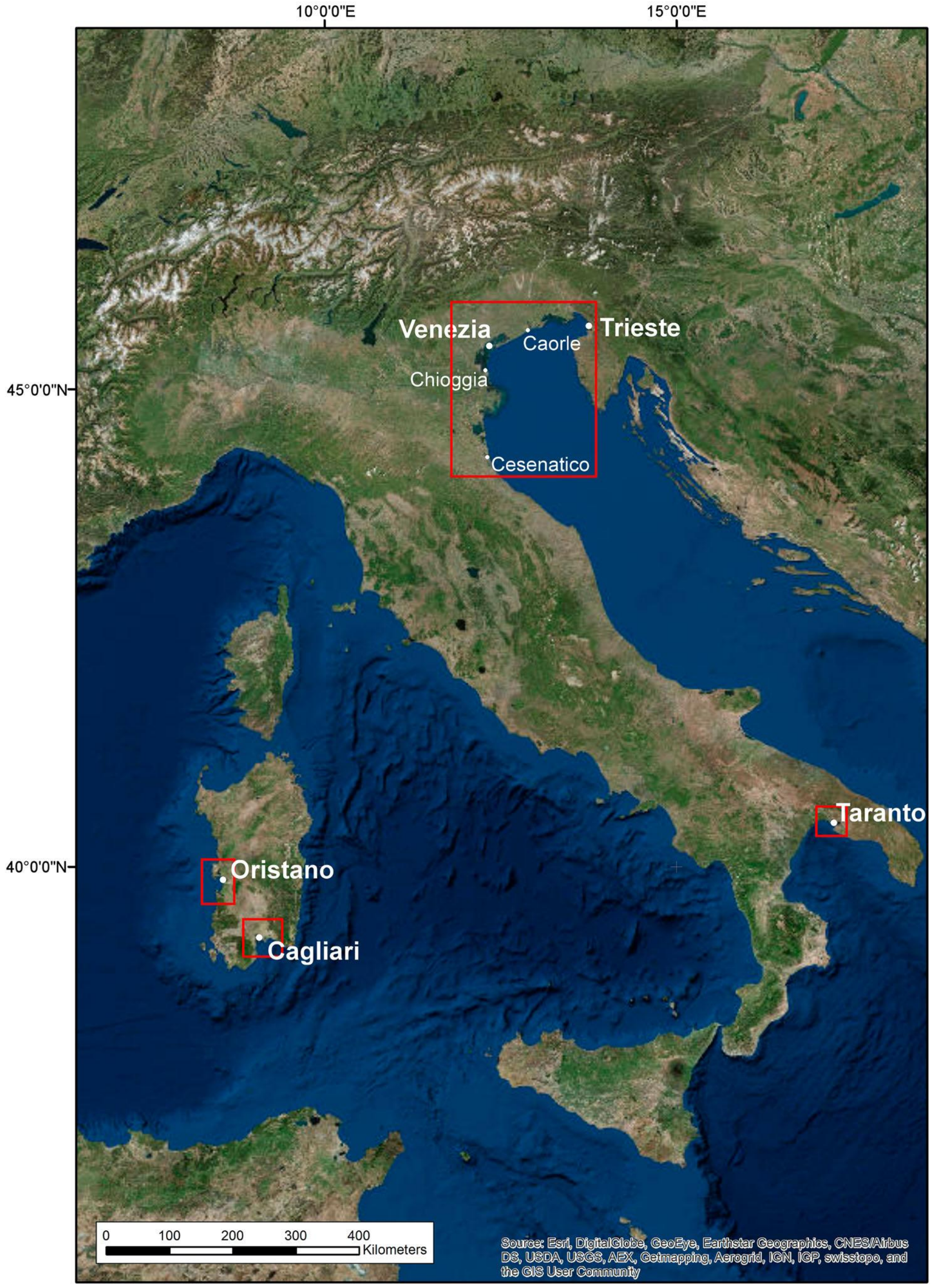

Figure 3. The four Italian areas investigated in this study, characterized by coastal plains and geo-diversity.

ISPRA network, 2000–2013 series) (Antonioli et al., 2017). Even though, the more recent values are not representative for the long-term trends due to sea level variability, both the tidal data and the cGPS data confirm a trend of land subsidence, in agreement with the geological data shown in Antonioli et al., 2017.

In the proposed reconstruction, we did not considered any possible response of the coastal sedimentary environments to the sea level change. At present, in the proposed cases, a general retreat and/or stability of the shoreline is always recognizable with the exception of some tracts of the Po river delta. It is reasonable that a fast sea level rise will produce a diffuse erosion in the transitional environments as result of the mass and energy balance related to the climatic changes. Its entity is not quantifiable, despite modeling approaches (i.e.: Davidson-Arnott, 2005; Lorenzo-Trueba & Ashton, 2014). The response of coastal systems to future climate and fluvial regime changes in terms of sediment discharge is also questionable; rainfall changes should influence the sedimentary budget at the river mouth and along shore. We can hypothesize that the combination of sea level rise and possible decrease of rains will produce a negative sedimentary budget and an important shoreline retreat. It will likely include the landward migration of the coastal erosion, increasing significantly the risk of flooding, especially in case of extreme events.

Table 1. (1) The investigated areas: the northern Adriatic area is distinguished according to the different tectonic and isostatic rates here presented. (2) Long-term tectonic rates and (3) relative references. (4) Isostatic rates and (5) reference. (6) Period of LIDAR survey and (7) the Agency that produced the DTM used in this study.

(1) Area	(2) Tectonic vertical movement (mm/yr)	(3) References	(4) Isostatic rates (mm/yr)	(5) References	(6) Base map	(7) References
Northern Adriatic 1 (from Trieste to Caorle)	−0.40	Ferranti et al. (2006); Antonioli et al. (2007); Antonioli et al. (2009)	−0.12	Lambeck et al. (2011)	2003	Regions of Friuli Venezia Giulia and Veneto, INGV
Northern Adriatic 2 (from Caorle to Chioggia)	−0.60		−0.13		2003	Regions of Friuli Venezia Giulia and Veneto, INGV
Northern Adriatic 3 (from Chioggia to Cesenatico)	−0.95		−0.21		2008	Italian Ministry of the Environment, Emilia Romagna Region
Northern Adriatic 4 (the Comacchio lagoon area)	−0.78		−0.21		2008	Italian Ministry of the Environment, Emilia Romagna Region
Gulf of Taranto	+0.14	Amorosi et al. (2014); Negri et al. (2014); Lisco et al. (2016); Mastronuzzi and Sansò (2003)	−0.45		2008	Italian Ministry of the Environment
Gulf of Cagliari	0.0	Ferranti et al. (2006); Orrù, et al. (2004, 2011, 2014); De Falco et al. (2015)	−0.58		2007	Autonomous Region of Sardinia, Italian Ministry of the Environment
Gulf of Oristano	0.0		−0.62		2008	Autonomous Region of Sardinia, SRTM

Table 2. Vertical land motion rates obtained from the historical and recent GPS stations.

	Vertical land motion rates (mm/yr)
North Adriatic	
Po Delta	−5
Veneto-Romagna Plain	−5
Gulf of Trieste	~0
Venice Lagoon	from −2.2 to −9.2
Gulf of Taranto	~0
Gulf of Oristano	Unknown
Gulf of Cagliari	−0.5

Table 3. Sea level rates for the ISPRA Tidal network and historical stations with the relative time span.

Sea level trends			
ISPRA Tidal Network (www.mareografo.it)	Historical station from the Permanent Service for Mean Sea Level (www.psmsl.org)	Time span	Rate (mm/yr)
Adriatic Coast			
	Trieste	1875–2011	+1.32 ± 0.1
Venezia		2000–2013	+10.7 ± 0.3
	Venezia – Punta della Salute	1909–2000	+2.44 ± 0.1
Ravenna		2000–2013	+8.3 ± 0.3
Ancona		2000–2013	+3.9 ± 0.2
Gulf of Taranto			
Taranto		2000–2013	+9.4 ± 0.1
Sardinia			
Cagliari		2000–2013	+6.8 ± 0.1
Carloforte		2000–2013	+5.6 ± 0.1

3. Conclusions

The four maps show land flooding scenarios that will most likely cause the loss of densely populated territories playing a significant economic role. The IPCC (RCP 8.5) and Rahmstorf projections were applied. Our results confirm and quantify the dramatic effects connected to the sea level rise due to climate change similarly to most coasts of the world (Carter & Woodroffe, 1994; Douglas et al., 2001; Woodworth, 2003). The innovative approach here adopted consists in the integration of long-term and short-term coastal behavior. Using only geological constraints to individuate relative VLMs, the flooding scenarios could be under-estimated; in fact, modern instrumental data indicate rates of relative sea level rise larger than those based on geological evidence.

In the northern Adriatic region, land subsidence (tectonic, isostatic either natural or anthropogenic) together with global and regional sea level rise will soon have severe effects along the low elevated coastal areas, both on the environment, due to land flooding and retreating beaches, and on the anthropic activities, such as harbors and tourist installations, cultural heritage sites, etc.

Table 4. The map limits for each area are reported as projections (WGS84_UTM 32/33N) together with both the main map and inset map scale.

Area	North (m)	South (m)	West (m)	East (m)	Main map scale	Inset maps scale
Northern Adriatic	57,579,821	5,463,846	1,287,228	1,519,909	1:300,000	1:150,000
Oristano	4,874,152	4,817,775	894,173	993,297	1:60,000	1:33,000
Cagliari	4,780,625.5	4,740,135.5	995,546	1,027,377	1:60,000	1:30,000
Taranto	4,947,271	4,926,155.5	1,901,828	1,935,899	1:30,000	1:10,000

The Taranto coastal areas correspond to those few still retaining a minimum of naturalness. The stress induced, at present, by the scarcity of fluvial input and relative sea level rise suggests that they are significantly exposed to the risk of flooding.

In the Oristano coastal plain, the large area of Sassu, located in the central sector of the gulf, is already below the present sea level and is kept dry by drainage pumps. It is reasonable to predict that, without specific drainage system enhancements, this area could be partially flooded. Other main sectors currently located below the roughly 1.4 m elevation are the Tirso river plane and the Cabras-Mistras lagoons, northwards. Without the construction of natural banks, there is a high risk that these areas will be partially flooded.

A relative tectonic stability of the Cagliari coastal plains, locally corresponding to moderate subsidence situations, is more evident in its western part where the most important flooding trends have been recorded. The element of fragility of the two lagoon-barrier systems that characterize the coastal plain of Cagliari is represented by flat littoral ridges; without anthropic protection works or beach re-nourishment interventions, sea level rise and the possible increase in wash-over processes would cause the dismantling of the geomorphological features of the lagoons, leading to an open bay.

Finally, such detailed maps represent a starting point for both the reliable estimation of climate change impacts, vulnerabilities, and environmental risks along the Italian coastal areas, as well as the physical basis upon which to forecast possible adaptation strategies.

Software

The assessment of the sea level rise according to the IPCC AR5, RCP 8.5 (2013) and Rahmstorf (2007) scenarios, together with the data processing are explained in detail in Antonioli et al. (2017). The analysis resulted in the shoreline trends expected by 2100 (in response to relative sea level rise) for each area. They were then used to produce the maps shown in this study, using the ESRI ArcGIS 10.1 software (http://www.arcgis.com). Distinct coastal-flooding scenarios were obtained converting the lines of marine ingression predicted for 2100 and the present-day coastline into polygons. In order to speed up the layers refresh, the IPCC AR5-8.5 maximum polygons were clipped onto the size of the smallest IPCC AR5-8.5 minimum layer, and the Rahmstorf one, onto the size of the IPCC AR5-8.5 maximum polygon; as a result, the three scenarios do not overlap. For each map, one or more inset maps were drawn to highlight the scenario extent. The cartographic base of the main maps is a low-resolution DTM layer beneath some features of the Open Street Map (OSM) geographic dataset, downloaded and managed using ArcGis Editor for Open Street Maps. The OSM database is available under the Open Database License. The inset maps contain ortho-photo images as cartographic bases, available from the ArcGis 10.1 online database. The maps are drawn at different scales (Table 4).

Acknowledgements

LIDAR data were provided by Ministero dell'Ambiente e della Tutela del Territorio e del Mare-Geoportale Nazionale with license Creative Commons 3.0 Italy (CC BY-SA-3.0IT). Bathymetric data were provided by GEBCO, ISPRA, IAMCCNR and EMODNET project. We thank Luisa Perini, Paolo Severi, and Paolo Luciani (Geological, Seismic and Soil Survey of Regione Emilia Romagna) who provided the DTM of the Emilia-Romagna Region.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

These maps are the result of a research study funded by the Italian National Research Council (Consiglio Nazionale delle Ricerche, CNR) within the framework of the RITMARE Project and the Italian Ministry of Education, University and Research (Ministero dell'Istruzione, dell'Università e della Ricerca) within the National Research Program 2011–2013 PRIN (*Response of morpho-climatic system dynamics to global changes and related geomorphologic hazards*) under the umbrella of the IGCP Project n. 639 from UNESCO and IUGS.

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