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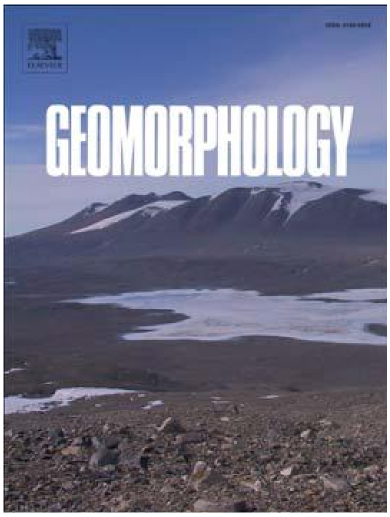

Simone Tarquini, Luca Nannipieri

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The 10 m-resolution TINITALY DEM as a trans-disciplinary basis for the analysis of the Italian territory: current trends and new perspectives

Simone Tarquini and Luca Nannipieri

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via U. Della Faggiola, 32, 56126, Pisa, Italy. E-mail: simone.tarquini@ingv.it

ABSTRACT

The increasing availability of high resolution digital elevation models (DEMs) is changing our viewpoint towards Earth surface landforms. Nevertheless, large-coverage, intermediate-resolution DEMs are still largely used, and can be the ideal choice in several applications based on the processing of spatially-integrated information. In 2012 the Istituto Nazionale di Geofisica e Vulcanologia opened a website for the free download of the "TINTALY" Digital Elevation Model (DEM), which covers the whole Italian territory. Since then, about 700 users from 28 different countries have been accredited for data download, and a report of 4 years of data dissemination and use is presented. The analysis of the intended use reveals that the 10 m-resolution, seamless TINITALY DEM is of use for an extremely assorted research community. Accredited users are working in virtually any branch of the Earth Sciences (e.g. Volcanology, Seismology, and Geomorphology), in spatially integrated humanities (e.g. History and Archaeology), and in other thematic areas such as in applied Physics and Zoology. Many users are also working in local administrations (e.g. Regions and Municipalities) for civil protection or land use planning purposes. In summary, the documented activity shows that the dissemination of seamless, large coverage elevation datasets can fertilize the technological progress of the whole society providing a significant benefit to stakeholders.

Keywords: Digital Elevation Model; GIS; Italy; TINITALY DEM.

1. Introduction

The geographic information technology is effective when data under scrutiny are spatially integrated and/or multi-layered. A similar data structure is often found in entirely different scientific disciplines irrespective of scale (e.g. Tarquini and Favalli, 2010a; Sui and Goodchild, 2011; Pei et al., 2014). When the data considered are distributed over the Earth surface, the relief of the area involved can have a critical weight, and the choice of a suitable elevation dataset, typically a digital elevation model (DEM) becomes important (e.g. Wise, 2007). Current progresses in remote sensing technologies provide a spectrum of solutions for the acquisition of very high resolution (VHR) DEMs (e.g. James and Robson, 2012; Whelley et al., 2014; Sofia et al., 2016). However, it is shown here that a high resolution DEM is not always necessary, and intermediate resolution DEMs are suited to successfully tackle several specific problems.

The present contribution summarizes about 4 years of free dissemination and use of a 10-m resolution DEM, indicating current trends and highlighting how intermediate resolution DEMs can contribute in the understanding of a variety of processes occurring over the Earth surfaces.

In early 2012, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) opened a website designed for the free distribution of the seamless “TINITALY” DEM, which covers the whole Italian territory (http://tinitaly.pi.ingv.it/; Tarquini et al., 2007, 2012a). The creation of the TINITALY dataset involved a team of researchers and technologists for several years (Tarquini et al., 2007). The idea of Tarquini et al. (2012a) was that the obtained DEM could have been of use for a large, international scientific community and for anyone interested in the Italian territory in digital format for any research, administrative and outreach purposes. The correctness of the original idea is briefly illustrated and discussed in the present paper.

The TINITALY DEM is currently the DEM having the highest resolution and the lowest error (on average) covering the whole Italian territory (e.g. Pulighe and Fava, 2013; Alvioli et al., 2014), and it represents, at a country or (trans-)regional scale, a substantial step forward with respect to global DEMs such as the ASTER DEM and the SRTM DEM (e.g. Tarquini et al., 2007, 2012; Fornaciai et al., 2012).

Throughout the Italian territory, several relatively small areas have been recently covered by airborne LIDAR surveys, providing locally VHR DEMs (e.g. Mazzarini et al., 2007; Cavalli et al., 2008; Tarolli, 2014). However (as of 2016), VHR DEMs are still scattered, and represent only a fraction of the whole country. Therefore, the TINITALY DEM is currently an ideal bridge between the coarse-resolution global DEMs (ASTER and SRTM) and the emerging very high resolution DEMs.

2. Dataset description and dissemination service

The downloadable dataset is a 10 m-resolution DEM in grid format encoded as “ESRI ASCII Raster” obtained by interpolating the original TINITALY DEM in the Triangular Irregular Network (TIN) format (Tarquini et al., 2007). The TIN version benefited from the systematic application of the DEST algorithm (Favalli and Pareschi, 2004), which enhances the TIN mesh with respect to the standard Delaunay triangulation. In agreement with current international standards, the projection is UTM, the World Geodetic System 1984 (WGS 84). To provide the dataset as a single seamless DEM, the sole zone 32 was selected, although about half of Italy belong to zone 33. The database is arranged in 193 tiles (50 × 50 km) and cumulatively occupies about 12 GB of disk memory.

By filling in the online request form, each potential user indicates his affiliation (e.g. a university or a local administration), the area of interest (e.g. specific tiles, regions or the whole country), and an intended use of data. The latter information allows us to attribute each request to a given subject-category (e.g. Volcanology, Seismology, and Agronomy). New applications are processed by the staff at INGV-Pisa on a daily basis as a rule, and users are accredited by e-mail communication. Typically, the requested data are ready to be downloaded through a customized ftp link within 24–36 h from the receipt of the request. Terms and conditions of use are stated in the website and reminded in the email of acceptance. Users are asked not to provide our DEM to third parties, thus our data distribution service should maintain the control over the TINITALY DEM dissemination and use.

As for the metadata, users can refer to Tarquini et al. (2007) who describe the details of the construction of the TINITALY DEM, including source data and the procedures used to create the seamless DEM structure. The DEM is stored in a web server in Pisa (local INGV section), while a link redirects to the Centro Nazionale Terremoti (INGV-Rome), where a web navigation engine allows for the visualization of DEM-derived images in color-shaded or anaglyph mode.

3. Results

As of February 2016, about 700 users from 28 different countries around the world (e.g., Japan, Australia, Brazil, Canada, Israel and Russia) have been accredited for DEM data download (Figs. 1 and 2). Top countries are Italy (~500 users), USA (44), UK (37), the Netherlands (14), Germany and Austria (12 each). Top cities in Italy are Rome (71), Milan (26) and Bari (20); top cities abroad (outside Italy) are London (UK, 10), Zurich (Switzerland, 6), Delft and Leiden (the Netherlands , 5 each).

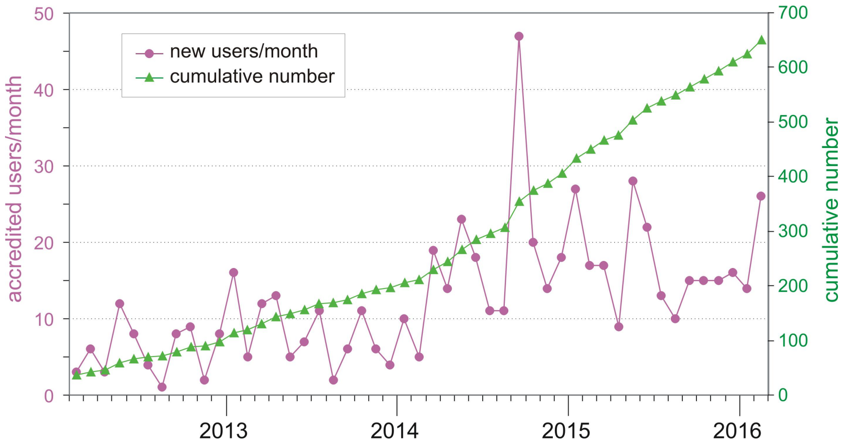

Fig. 1. Number of accredited users per month (and cumulative number) from February 2012 onward. Note that an individual user in our statistics is often represented by a research team made of several individuals, hence the number of actual users is higher.

The analysis of the database of intended uses shows that users are working not only in all the classic subfields of the geological sciences, but also in other domains such as many subfields of biosciences and humanities (e.g. Ornithology, History, and Archaeology), Architecture and Civil Engineering (Fig. 3).

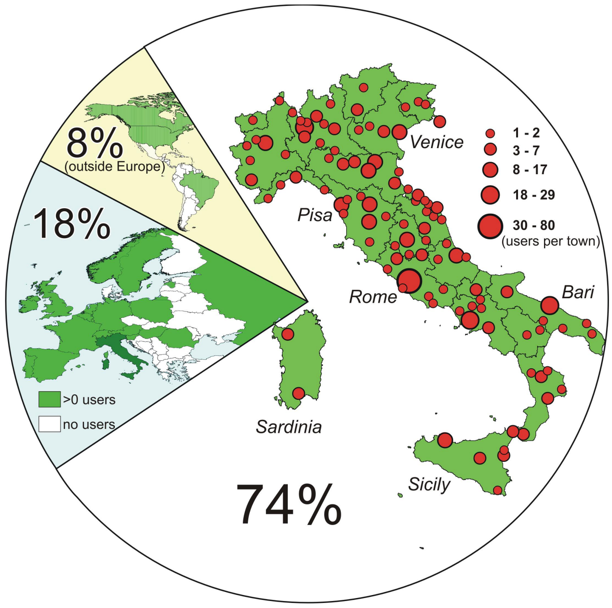

Fig. 2. Geographic distribution of accredited users: Italy 74% (individual research centers highlighted, sorted per number of users), Europe 18% (outside Italy) and the rest of the world 8% (outside Europe, only Americas are shown in the map).

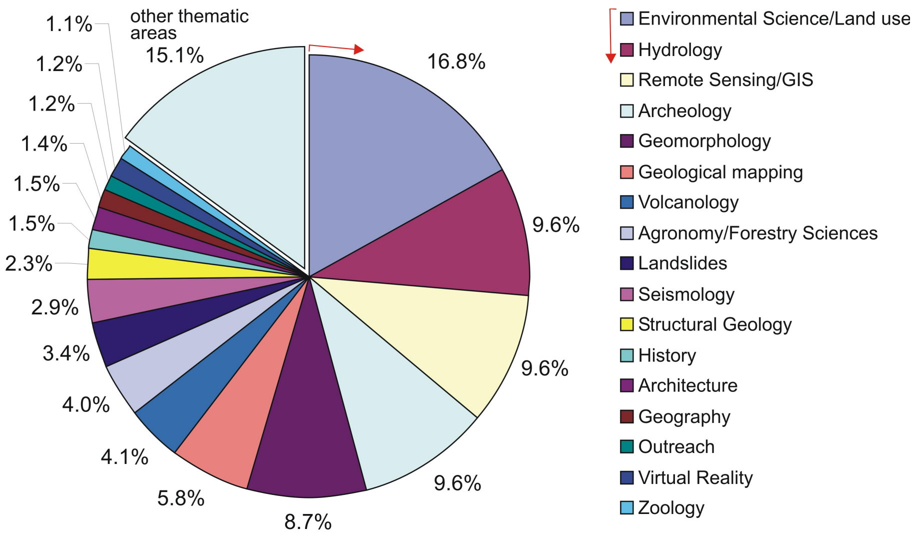

Fig. 3. Data requests per thematic areas, sorted by the percentage of accredited users.

So far, the TINITALY DEM has been downloaded by accredited users affiliated to ~50 different universities in Italy and ~80 universities outside Italy, in addition to tens of research Institutes both in and outside Italy such as CNR (seven departments: IBIMET, IGAG, IGG, IREA, IRPI, IRSA, and ITABC), ISPRA, ISTAT, OGS and INFN in Italy; CNRS, CEREGE and BRGM in France; CREALP in Switzerland; GFZ in Germany and USGS in the US.

The ways in which our DEM has been used are extremely varied (Figs. 3 and 4). The common ground among all these applications is that they are spatially integrated, and hence data are handled in a GIS environment at least in part. To mention some scientific applications, we begin with chronologically early ones in Volcanology (Neri et al., 2008; Tarquini and Favalli, 2010b, 2011; Tarquini et al., 2012b), then Geomorphology (Intrieri et al., 2013; Fubelli et al., 2014; Marchesini et al., 2015), tectonics (Mazzoli et al., 2014), Seismology (Vessia et al., 2013), Geodynamics (Roberts et al., 2013), Gravimetry (Lo Re et al., 2016), Hydrology (Domeneghetti et al., 2015; Carisi et al., 2015), Sedimentology (Fontana et al., 2014), Glaciology (Pellitero et al., 2016), disaster simulations (Ward and Day, 2011), climate change (Salerno et al., 2014), Zoology (Imperio et al., 2015) and Archaeology (Huyzendveld et al., 2012; Pelgrom et al., 2014; Patacchini and Nicatore, 2016; Casarotto et al., 2016), with other applications covering also Ecology (Pornaro et al., 2016; Jona Lasinio et al., 2017), Ornithology (Brambilla et al., 2016), Forestry (Van doninck et al., 2013), and environmental and city planning (Ellul et al., 2013, Paladini Mendoza et al., 2016). The TINITALY DEM demonstrated to be particularly useful for the routinely processing of satellite images such as orthorectification and georeferencing, and has been often used in conjunction with remote sensing analyses (e.g. Intrieri et al., 2013; Bisson et al., 2014).

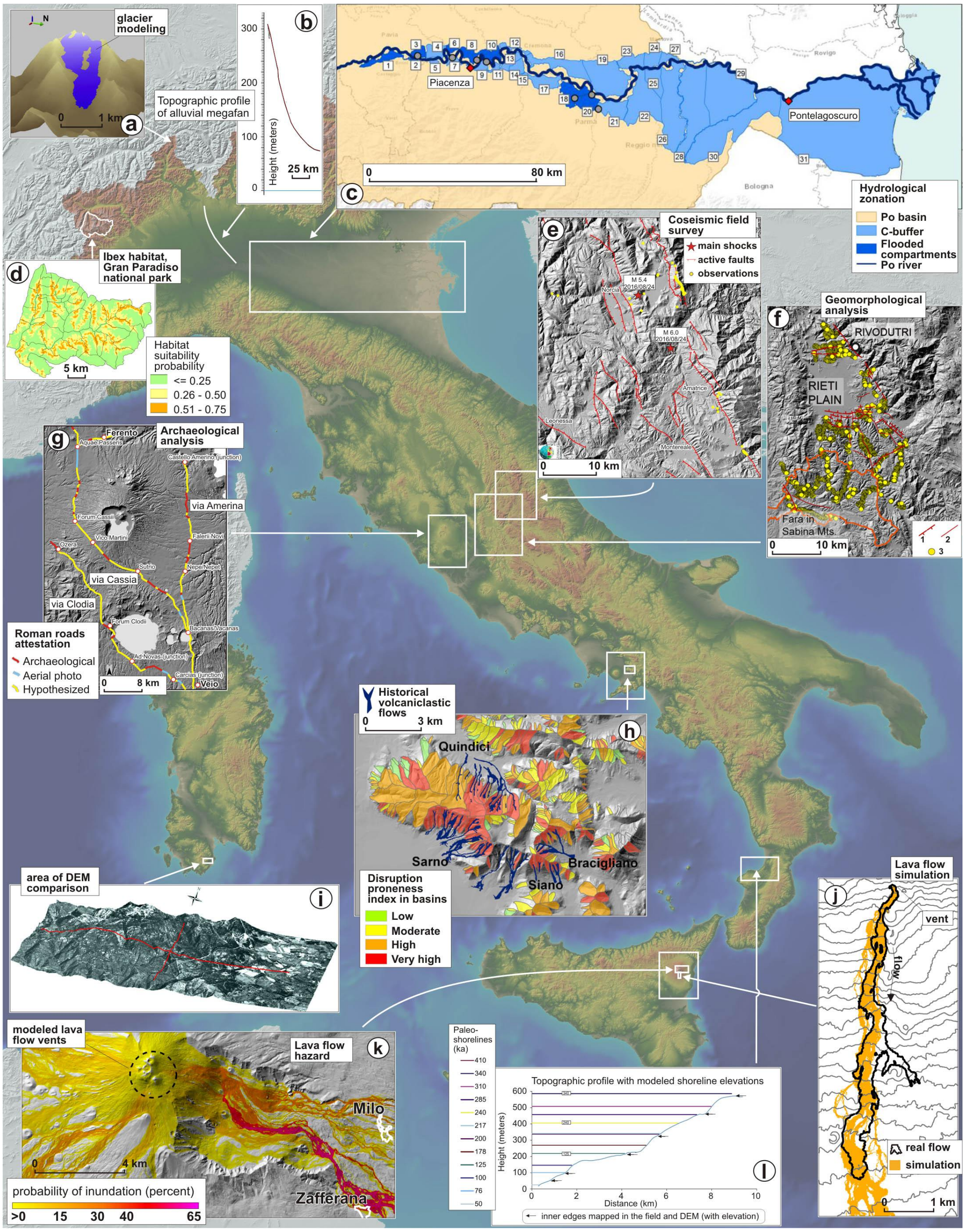

Fig. 4. Examples of use of the TINITALY DEM. From left to right and top to bottom: (a) glacier modeling (modified after Pellitero et al., 2016); (b) topographic profile of the surface of alluvial megafans formed during the last glacial maximum in the southern Alpine foreland (the Olona river case, plot modified after Fontana et al., 2014); (c) preliminary flood risk assessment over large areas (case study of the Po river after Domeneghetti et al., 2015, see reference for more details); (d) analysis of the ibex habitat in the Gran Paradiso national park (image modified after Imperio et al., 2016; (e) collection and interpretation of coseismic effects during the seismic crisis started on August 24th 2016 with an M = 6.0 quake in central Italy (EMERGEO working group, 2016); (f) geomorphological analysis for paleo-shoreline and paleo-river

reconstruction (1: normal fault, 2: undefined fault, 3: basal surface points; modified after Fubelli et al., 2014); (g) archaeological analysis of ancient roads with the DEM used for predictive purposes (image modified after Patacchini and Nicatore, 2016); (h) quantification of the proneness to the onset of volcaniclastic flows in steep basins (Vesuvian area, image after Bisson et al., 2014); (i) quality assessment of DEMs derived from archive aerial photos (after Pulighe and Fava, 2013); (j) simulation of historical lava flows using the specific pre-emplacement topography (after Tarquini and Favalli, 2015); (k) quantification of the susceptibility to lava flow inundation upon vent opening in the summit area of Mt Etna (modified after Tarquini and Favalli, 2010b); and (l) geodynamic modeling of uplift rate compared to paleo-shorelines derived using also the TINITALY DEM (modified after Roberts et al., 2014, profile 26). Background image is obtained from the TINITALY DEM (re-sampled to 100 m) joined with the SRTM (Europe and Africa) and GEBCO datasets (bathymetry). The same image is available at http://tinitaly.pi.ingv.it/.

Although the requests from the mixed scientific community constitutes the large majority, the single subject area with the highest percent in Fig. 3 (Environmental Science/land use with 16.8%) is essentially constituted by users dealing with the territory as a mere "habitat for people" without any specific scientific purpose. Those users include people affiliated to local administrations (e.g. regions, provinces, and municipalities) and many private professionals. Other users outside the scientific community are affiliated to civil protection institutions (e.g. army, fire departments, and mountain and cave rescue), weather forecast facilities, leisure associations such as mountain guides and cycling associations, and cultural and natural heritage Institutions such as museums and national parks (Imperio et al., 2016). Finally, people interested in landscape for whatever reason or in applications for mobility including apps for smart phones or accessibility for disabled people (Demontis et al., 2013) benefited from the use of the TINITALY DEM.

4. Discussion

A DEM is a digital encoding of a natural landscape. Thus, to analyze and decrypt the acquired data about the TINITALY DEM requests, we have to begin by outlining the main characteristics of the real landscape. The majority of the Italian territory is geologically rather young, and current landforms can be viewed as the result of complex geodynamic processes which are still at work (e.g. Montone et al., 1999). Northern Italy includes a significant portion of one of the highest mountain chains of Europe (the Alps), formed by the collision between the African and the European plates (e.g. Serpelloni et al., 2007). The Italian peninsula, instead, is mainly constituted by the younger Apennine chain (Doglioni, 1991; Lucente and Margheriti, 2008; Roberts et al., 2013). Southern Italy also hosts a bunch of active volcanoes including Mt. Etna and Vesuvius. A consequence of such active geodynamics is the strong seismicity of a large portion of Italy (Stucchi et al., 2011), joined with a remarkable proneness to landsliding (Guzzetti et al., 2012) and to other hazardous gravitative movements (e.g. Pareschi et al., 2000; Bisson et al., 2014).

The above cannot explain the appeal of the TINITALY DEM in humanities, and it is necessary to introduce also a human factor. Prehistoric humans settled in the peninsula about half a million years ago, and archaeological vestiges are found in Italy all through the Paleolithic, Mesolithic and Neolithic. Then, during early historical times, the Italian territory witnessed the flourishing of wealthy civilizations (e.g. Etruscans and Romans in the Center, Greek colonies in the South and Sicily). Later, strategic territories dotted with charming cities promoted a rather tumultuous history, in which other European countries such as France, Spain and Austria often played a role. The complex history joined with contrasting landforms, which also granted a significant biodiversity, supported the diversification of the many regional cultures that still characterize the modern country.

Thus, it seems that an unusual natural, cultural and historical richness can explain why the Italian territory attracts the interest of researchers outside the country over a large variety of different domains (Figs. 2 and 3). The interest for the TINITALY DEM has been the meeting point of such varied community. The success of our digital model distribution can also be viewed as a consequence of the current evolution of our society, with spatially integrated information technologies on our portable technology devices, taking control over many facets of the everyday life. Elevation data are becoming indispensable not only for scientific purposes such as the simulation of lava flows and flooding, but also for leisure and tourism such as the planning of a simple bike ride or a mountain hike.

4.1. Who looks where for what?

We queried the database of DEM requests to map the times each of the 193 square tiles constituting the TINITALY DEM dataset has been requested by selected users for given purposes. The resultant maps of the Italian territory (Fig. 5) illustrate the local level of interest of the TINITALY DEM for selected thematic areas and/or selected type of user.

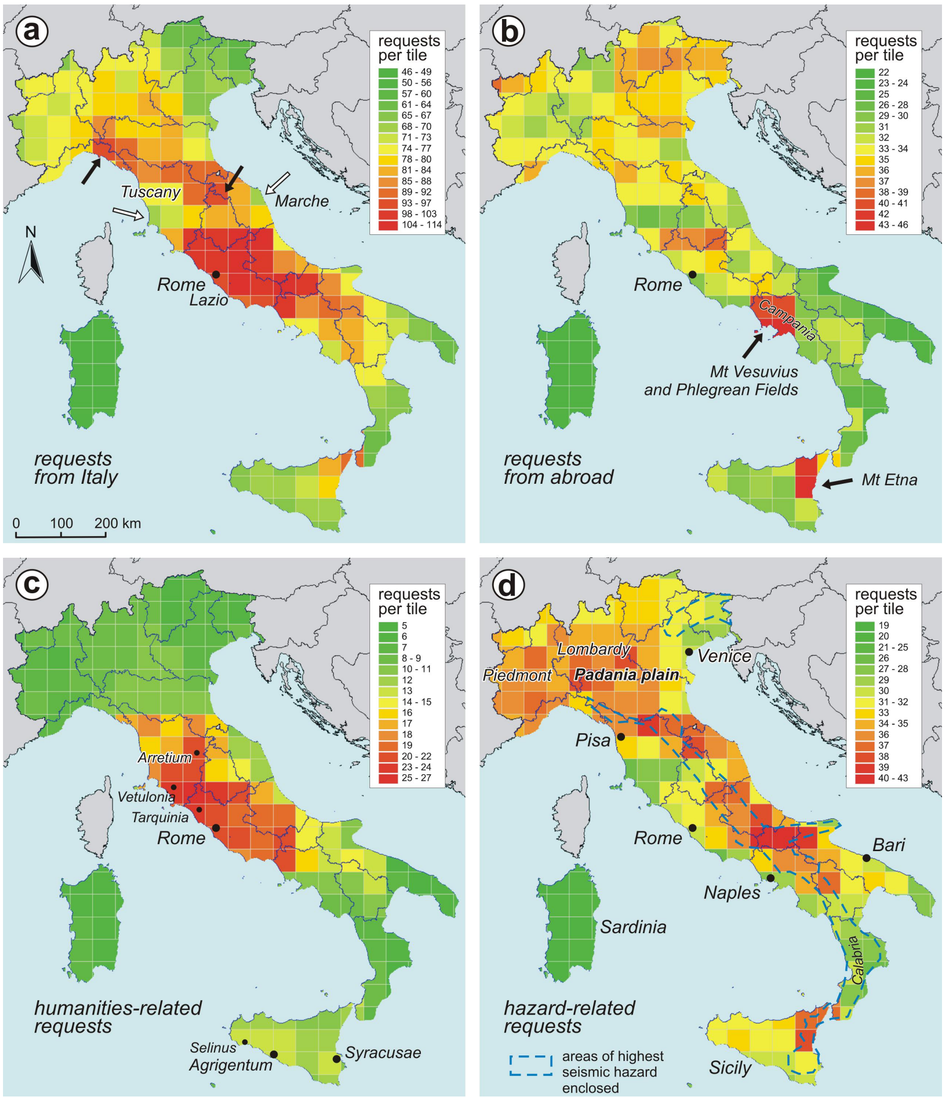

Fig. 5. Density of data request on a tile basis. Boundaries between administrative regions are shown. The TINITALY dataset is arranged in 193 tiles and each map shows the number of requests per tile according to specific filters applied on the database of requests. (a) Requests submitted by users in Italy. (b) Requests submitted by users outside Italy. (c) Requests submitted for research purposes in the macro-area "humanities" gathering thematic areas of Archaeology (A), History (H) and Geography (G) (A – 80% of the macro-area). (d) Requests submitted to carry out natural hazard-related research or applications gathering the four thematic areas of (i) Seismology (e.g. seismics zoning and analysis of site effects), (ii) Hydrology (largely to prevent or mitigate flooding, but not only), (iii) landslides and (iv) Geomorphology (the latter two especially intended to prevent or mitigate hazardous phenomena, e.g. Paranunzio et al., 2015). Dotted lines enclose the areas of highest seismic hazard (redrawn after Stucchi et al., 2011).

Fig. 5a highlights that the requests from Italian users are mainly driven by a local interest, with a significant number asking data according to a regional coverage. The maximum of interest in the Lazio Region is related to the large peak of accredited users in Rome (> 10% of all users, Fig. 2), while the two additional peaks of requests (black arrows in figure) are represented by tiles covering four administrative regions at once (hence summing up the requests for the four regions). The same concept contributes to explaining local minima in tiles that do not touch the regional boundaries (e.g. white arrows in the Marche and Tuscany Regions), while the tiles across the boundary received generally a higher number of requests.

Parts of the requests from users based outside Italy (Fig. 5b) are driven by the administrative boundary issue at a country-scale, because local peaks of requests near the boundaries with neighboring countries are due to the interest of neighbors in extending their DEM datasets towards Italy, beyond their administrative limits. This issue can be easily understood because natural items such as rivers or fires to make a point propagate their impact on the territory regardless of administrative boundaries. The two highest peaks are explained by the presence of three among the most studied volcanoes of the world: Mt Etna (Sicily), Phlegraean Fields and Vesuvius (Campania). The rest of the scattered local maxima and minima have a less apparent explanation, reflecting the large spectrum of essentially unrelated thematic areas of interest (Fig. 3).

Fig. 5c highlights that humanities-driven requests are concentrated in a single, broad peak in the West side of central Italy, with minor peaks in Sicily. This result appears somewhat surprising due to abrupt changes between adjacent areas. We cannot exclude that some cluster of requests issued from specific research centers affects this map (e.g. the University of Siena is accredited for about 12% of the cumulative 82 thematic users considered here). Nevertheless, humanities-related requests were issued from >50 research centers in Italy and those in 10 other countries. Thus, the mapped statistics can be considered somewhat representative. As a preliminary commentary, we note that the main peak area follows ancient *Etruria* (i.e. where the Etruscan civilization flourished – a few Etruscan cities are labeled in the map), plus Rome and nearby areas. Not surprisingly, major archaeological areas such as Greek colonies in Sicily appears as secondary peaks (e.g. the Valley of the Temples near Agrigento).

Fig. 5d shows the distribution of natural hazard-related requests (see also caption). In order to better focus on the other natural hazards, Volcano-related hazards are not considered here; the large weight of Volcanology is already evident in Fig. 5b. Natural hazards are rather widespread in Italy. Thus, minimum values are perhaps more interesting than maximum values, possibly suggesting a local lower sensitivity to the theme, although other DEM sources are available. In the map of Fig. 5d, relative maxima and minima are scattered, demonstrating that the interest of users is mainly local. This localism is perhaps promoted by the many layers of local administrations in Italy, where critical decisions regarding environmental planning and land use are often controlled at a very local level (e.g. Municipalities). The high density of requests along the axis of the peninsula corresponds well to the areas of the highest seismic hazard in Italy (Stucchi et al., 2011), with an apparent exception in Calabria. In the North, instead, the significant density of requests in seismically inactive areas (e.g. Piedmont and Lombardy) corresponds to the high local proneness to flooding and landsliding (Guzzetti et al., 2005).

4.2. Overcoming localisms for a broader perspective

In recent years, regional administrations of Italy have developed rather comprehensive GIS services (e.g., Emilia-Romagna and Tuscany), providing local stakeholder with a substantial amount of cutting-edge data inside each administrative limit (e.g. LIDAR data). Nevertheless, in spite of the local excellence, this policy has the drawback of promoting a local perspective, and when the area of interest lays across regional boundaries, the merging of different data can be tricky. The overcoming of the latter issue was a major task during the creation of the seamless structure of the TINITALY DEM (Tarquini et al., 2007), because different "administrative" batches of data were not cross-checked across the boundaries. The seamless nature of the TINITALY DEM is probably one of the principal reasons why several users chose our elevation dataset as basis for their work. An example is research for handling the ongoing seismic crisis in central Italy since the *M* 6.0 quake on August 24th 2016 that caused hundreds of deaths and severe building damages in four different regions (EMERGEO working group, 2016, Fig. 4e).

4.3. Beyond the quest for higher resolution: new ways to look at elevation data

The recent availability of very high resolution DEMs (VHR DEMs) allows substantial improvements and discloses new perspectives in the analysis of the Earth surface morphology and land-shaping processes (e.g. Tarolli, 2014; Passalacqua et al., 2015). For this reason, a 10 m-resolution DEM can appear outdated. The downloadable TINITALY DEM in grid format has been interpolated from a TIN DEM obtained mainly from elevation contours and elevation points, a conventional way of deriving DEMs from digitized topographic maps. This procedure implies that a significant amount of the details of the actual morphology is smoothed out (e.g. Hengl and Evans, 2009). In contrast, current methods of deriving DEMs (e.g. airborne LIDAR surveys) can keep much more details in a higher resolution grid. In spite of this limitation, a 10 m-resolution DEM such as TINITALY can be a good compromise in several cases, as explained in the following.

As examples, we take two different geomorphic processes: propagation of lava flows and triggering of debris flows. Then we show how we can cope with these processes by using a 10 m-resolution DEM such as TINITALY, and how the availability of new generation VHR DEMs can contribute to improving the analysis.

A 10 m-resolution DEM is well suited for the simulation of lava flows (e.g. Tarquini and Favalli, 2011, 2015), and no improvement is expected by simply increasing the resolution, because the process under consideration is insensitive to topographic details (e.g. Wright et al., 2008). Similarly, the proneness to the generation of debris flows can be linked to the geometry of drainage basins and local topography (Bisson et al., 2014), and these topographic features are correctly derived from a 10 m-resolution DEM, and no significant improvements is expected through the use of a higher resolution DEM (e.g. Tarolli and Tarboton, 2006).

Nevertheless, VHR DEMs demonstrated to be useful in understanding the emplacement of lava flows (Favalli et al., 2010, 2011; Tarquini and de' Michieli Vitturi, 2014) and the sediment transport by debris flows at small scale (Cavalli et al., 2013). Hence, intermediate resolution DEMs such as TINITALY are useful for practical purposes such as large- and intermediate-scale hazard assessment (e.g. Tarquini and Favalli, 2013; Bisson et al., 2014); whereas, VHR DEMs are crucial for some types of cutting-edge research but are not always necessary.

Finally, it is worth noting that several geomorphic parameters are still poorly applied although they can be effective during the standard visual survey of digital landscapes irrespective of the resolution. DEMs in grid format are habitually visualized by mapping basic parameters such as the hillshade or the slope. However, other indexes are able to grab the local geomorphological context, recombining different parameters, and thus conveying a deep understanding of local landforms. Examples are the Red Relief Image Map (Chiba et al., 2008, see Fig. 6), the openness map (Yokoyama et al., 2002) and the sky-view factor (Zaksek et al., 2011). Other geomorphic factors are specific for drainage analysis, such as the wetness index (Tarboton, 1997) and the connectivity index (Borselli et al., 2008), and can be applied to high resolution DEMs (e.g. Conway et al., 2011; Cavalli et al., 2013), as well as on intermediate to low resolution DEMs. Favalli et al. (2012) showed that an additional geomorphic parameter for the characterization of surficial flows (the dispersion index) can be fruitfully applied to the 10 m-resolution TINITALY DEM.

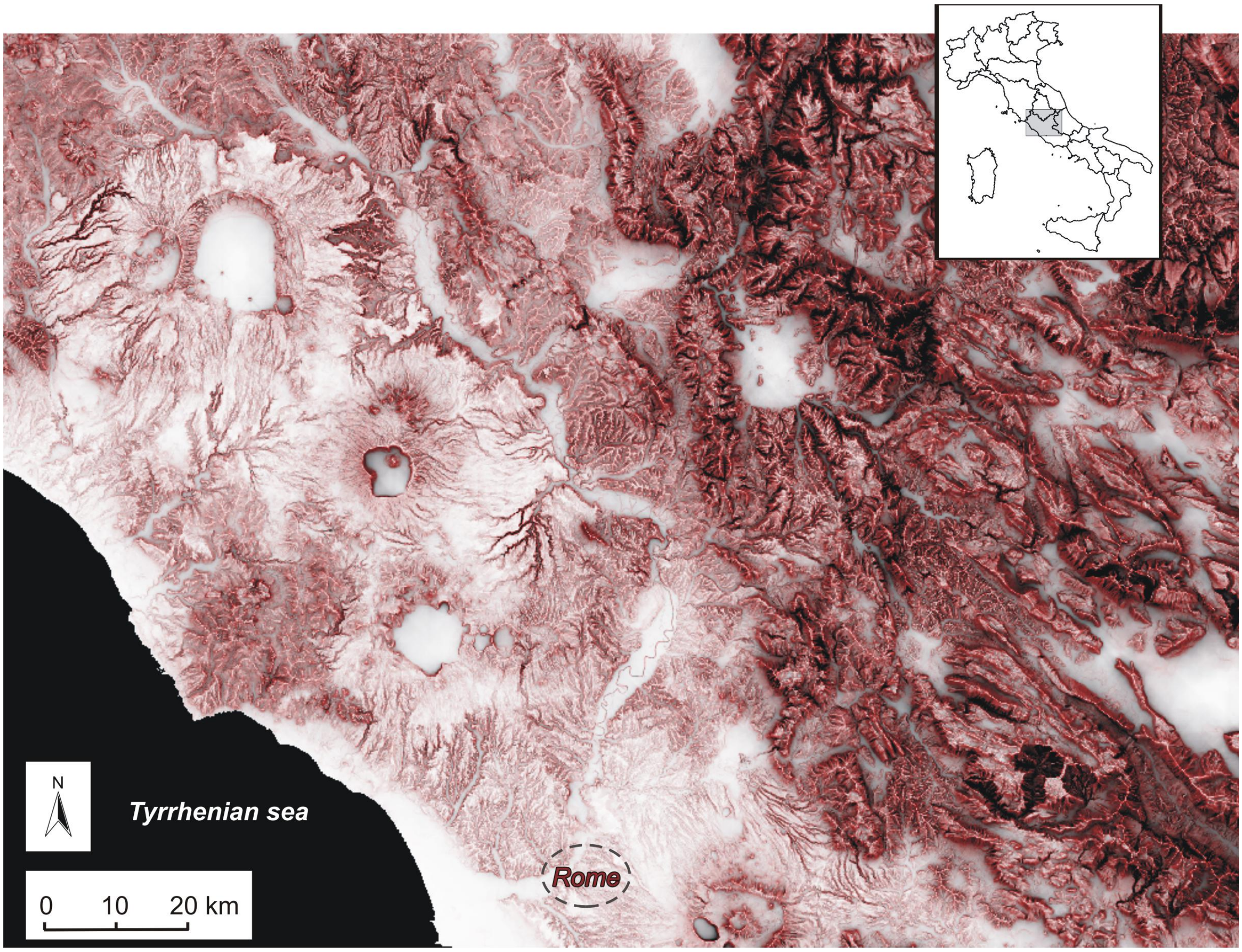

Fig. 6. Red Relief Image Map (Chiba et al., 2008) for an area in central Italy. Although obtained from a coarse-resolution DEM (TINITALY resampled to 60 m), the visualization method is ideal to enhance the difference between the landforms formed by the volcanoes of the Roman Province, whose calderas and characteristic aprons are evident in the western side, and the surrounding areas.

5. Future perspectives and conclusions

The TINITALY DEM was originally presented with a postfix ("TINITALY/01", Tarquini et al., 2007), suggesting that future updates/refinements (ideally "/02", "/03"…) would have been commendable upon availability of updated elevation datasets from new surveys. Several areas may undergo rapid changes that should be accounted for in a continuously updated DEM. Rapid evolution of landforms can result from human activities (e.g. Tarolli et al., 2014; Tarolli and Sofia 2016) or natural processes such as volcanic activity and landsliding (e.g. Neri et al., 2008; Ventura et al., 2011; Guzzetti et al., 2012). The transient lack of dedicated funding had delayed an update of the TINITALY dataset so far. It would be also useful to envisage a EUROPEAN elevation dataset as an internationally shared DEM encompassing the whole European Continent, which would be analog of the National Elevation Dataset (NED) in the US (Gesch et al., 2002). This DEM should be seamless across the administrative boundaries, overcoming the issue of adjacent batches of data coming from different sources (e.g. Tarquini et al., 2007). A further development could bridge the subaerial DEM with the bathymetric data of surrounding seas (e.g. Ryan et al., 2009) to explore the relations between the subaerial and marine environments, as also highlighted by some TINITALY users.

To summarize, the success of the TINITALY DEM demonstrates that a large and varied scientific and social communities can benefit from the free availability of the 10-m resolution, country–wide elevation dataset. Although higher resolution DEMs are locally available, the full potential of the TINITALY DEM appears to be still incompletely exploited, and geomorphometric analyses based on this DEM can be useful to promote a better understanding of the Italian landforms.

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