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Natural hazards vs human impact: an integrated methodological approach in geomorphological risk assessment on the Tursi historical site, Southern Italy

Abstract The Tursi–Rabatana historical site is very representative of the cultural heritage of Basilicata, Southern Italy. Morphological evolution of the landscape is characterized by very intense erosive phenomena such as landslides, deep gullies, rills, and piping, which affect the perimeter of urban settlements and threaten the conservation of these sites. Rainfalls and the lithology of the substratum are the main factors to which the landscape evolution is linked, triggering landslide and linear erosion phenomena. Climate analysis carried out during the last century showed an increasing trend in the rainfall intensity over extremely short periods. This condition also induced an increase in the vulnerability level of the slopes. Integrated analysis between territorial data (geology, geomorphology, climate) and historical documents showed that, at least from the last century, the geomorphological hazard has been accentuated by the intense human activity of cave excavation along several fronts under the present urban area. The geophysical investigation also permitted the mapping of shallow caves and tunnels in the subsurface reconstructing the multilevel complex hypogeal system. This work also produced evidence that the human interventions occurring during the historical period have been a determining factor in increasing the hazard level and accelerating the preexisting morphological processes.

Keywords Natural hazard · Human impact · Landslide · Pipe erosion · Geophysics · Southern Italy · Basilicata

Introduction

Tursi and its medieval citadel called “Rabatana” is one of the sites most representative of the cultural heritage of Basilicata. Geographically, the site selected for this study is located in the southwestern sector of the Basilicata region (40°15′ and 40°18′ N and 16°14′ and 16° 17′ E) at an average altitude of 310 m above sea level along the hydrographic watershed between the Agri and Sinni main rivers (Fig. 1).

Since 1973, this site has been subjected to the evacuation of its inhabitants in a new urban site due to catastrophic landslides caused by intense rainfalls that occurred on January 1972. Starting from 1974, the Rabatana has been almost completely deserted. Recently, a renewed interest for this site has been developed to recover the historical center, removing the current constraint of total evacuation. However at present, the site is still characterized by a particular morphological history and environmental factors that generate widespread risk conditions for the inhabitants and built-up areas.

This work, carried out with an integrated methodological approach, represents an effort to assess the relative geomorphological hazard and risk levels of the Tursi site, through a better knowledge, not only of the geomorphological processes acting on the site, but also of all the possible factors that can create the geohazard conditions such as climate, sun exposure, water drainage systems, human activities, etc. In particular, the evaluation of natural and human factors has been carried out in developing the following phases:

- Search and critical analysis of the historical documentation (reoccurrence of the events, typology, damages, etc.)
- Knowledge of the geologic-environmental context
- Analysis of the climatic character of the territory (rainfall, temperatures, wind, exposure of the slopes)
- Study of the morphological characteristics and natural processes acting on either urban areas or in the neighboring areas
- Field surveying and mapping of the hypogeal system, using also an integrative geophysical analysis, compared with the evaluation of the human impact on the geomorphic evolution of the site

Geological setting

The study area is located along the outer outcropping front of the southern Apennines thrust belt, exactly on the outer margin of the Plio-Pleistocene Sant’Arcangelo basin (Fig. 2), which is interpreted by several authors as the largest and most recent onshore piggyback basin (Caldara et al. 1988; Casero et al. 1988; Hippolyte 1992; Hippolyte et al. 1994). This basin was filled by huge volumes of synsedimentary (Hippolyte et al. 1994; Pieri et al. 1994; Zavala and Mutti 1996) siliciclastic deposits ranging from alluvial conglomerates in the west to marine shelf mudstones in the east (Fig. 2).

Recently, Zavala (2000) recognized five unconformity-bounded geological units in the Sant’Arcangelo basin succession, the age of which was between late Pliocene and mid-Pleistocene.

The main unit (Group) outcropping on the studied site is the Tursi Group (early–middle Pleistocene, Sabbie di Tursi Fm.), characterized by a total thickness of 500 m and composed of two subunits corresponding to an alluvial fan and fan delta system, outcropping in angular unconformity above previous stratigraphic units (Fig. 3). The alluvial facies of the conglomerates outcrop extensively with flood-dominated shelf sandstone lobes. In particular, the Rabatana area is based on Sabbie di Tursi Fm. (lower Pleistocene) characterized by a maximum thickness of 130 m of clay sands and sandstones with thin interbedded conglomerate levels (Fig. 3). The depositional environment of this formation was a delta system supplied by Apennine watercourses (Soldani and Loiacono 2000; Soldani et al. 2003). The substratum of the Plio-Pleistocene Sant’Arcangelo deposits is represented by tectonostratigraphic units derived from the deformation of distinct pre-Miocene paleogeographic domains (Fig. 2), which have been amassing since the Oligo-Miocene age and are still moving (Ogniben 1969; D’Argenio et al. 1973; Knott 1987).

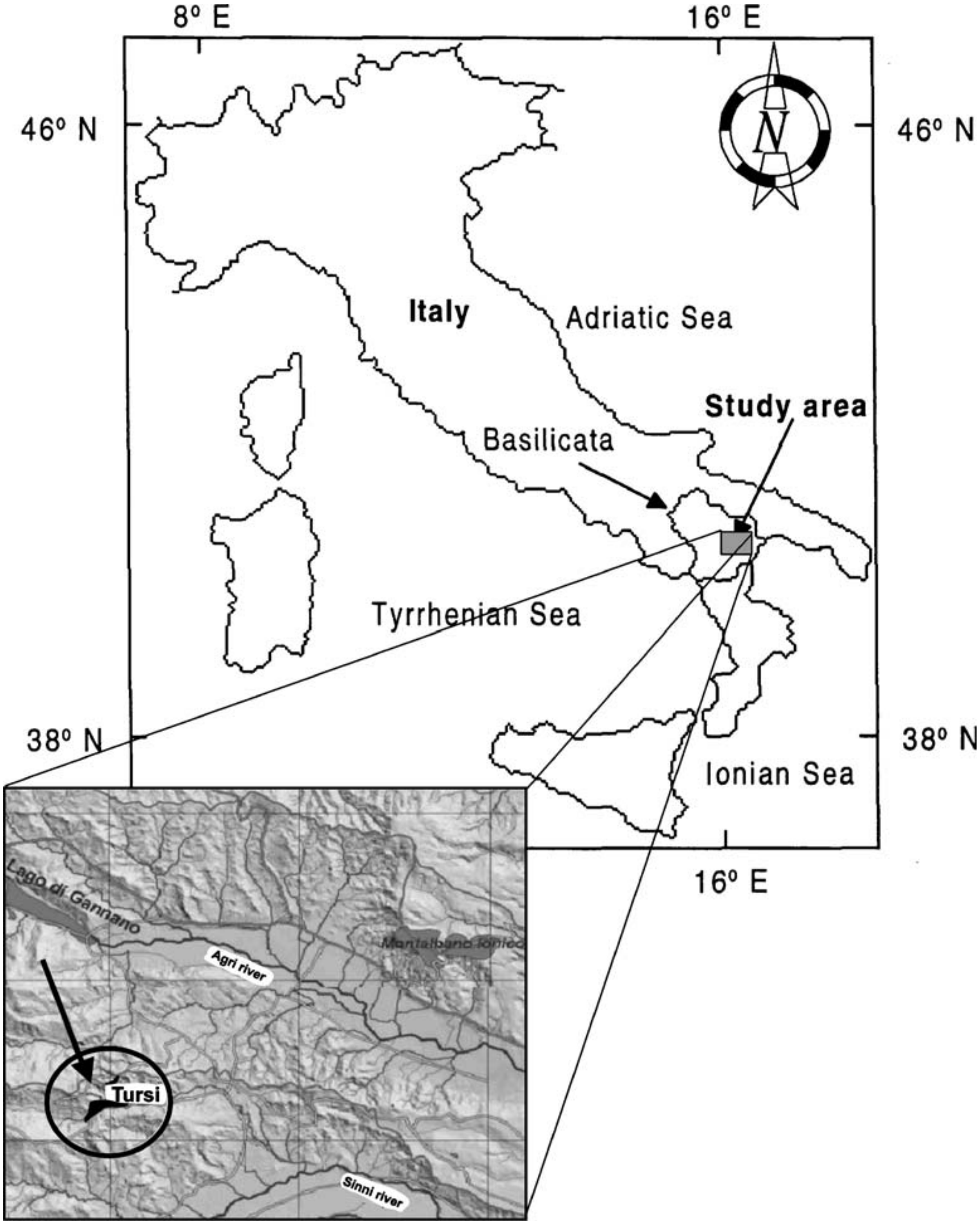


Fig. 1 Geographical location of the study area

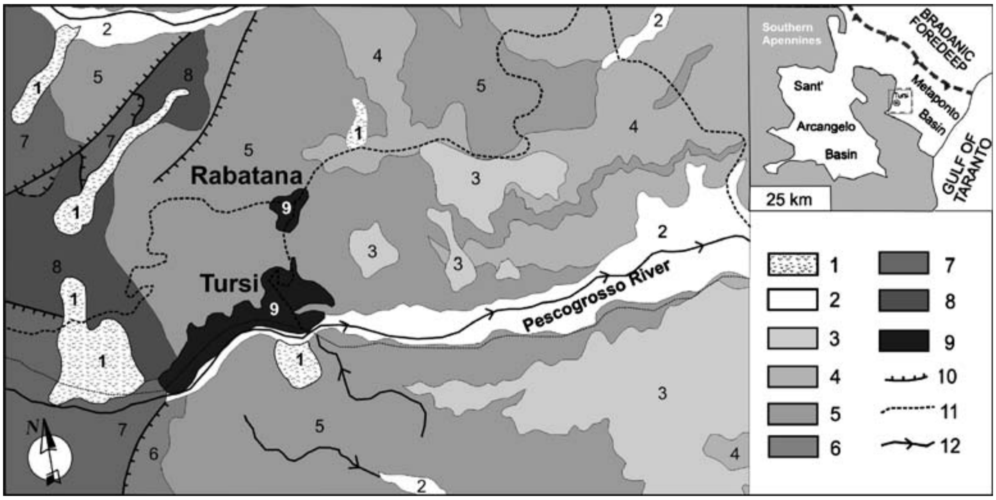


Fig. 2 Geological map of the Tursi–Rabatana site (modified after Lazzari and Lentini 1980). *1* Landslides, *2* alluvial deposits, *3* gray-blue clays formation, *4* fluvial terraces, *5* Tursi Group (lower Pleistocene), *6* Pliocene deposits, *7* Argille Varicolori Fm. (Cretaceous–Oligocene), *8* Flysch of Serra Palazzo (Miocene), *9* built-up areas, *10* main faults, *11* main roads, *12* water course (perennial streams)

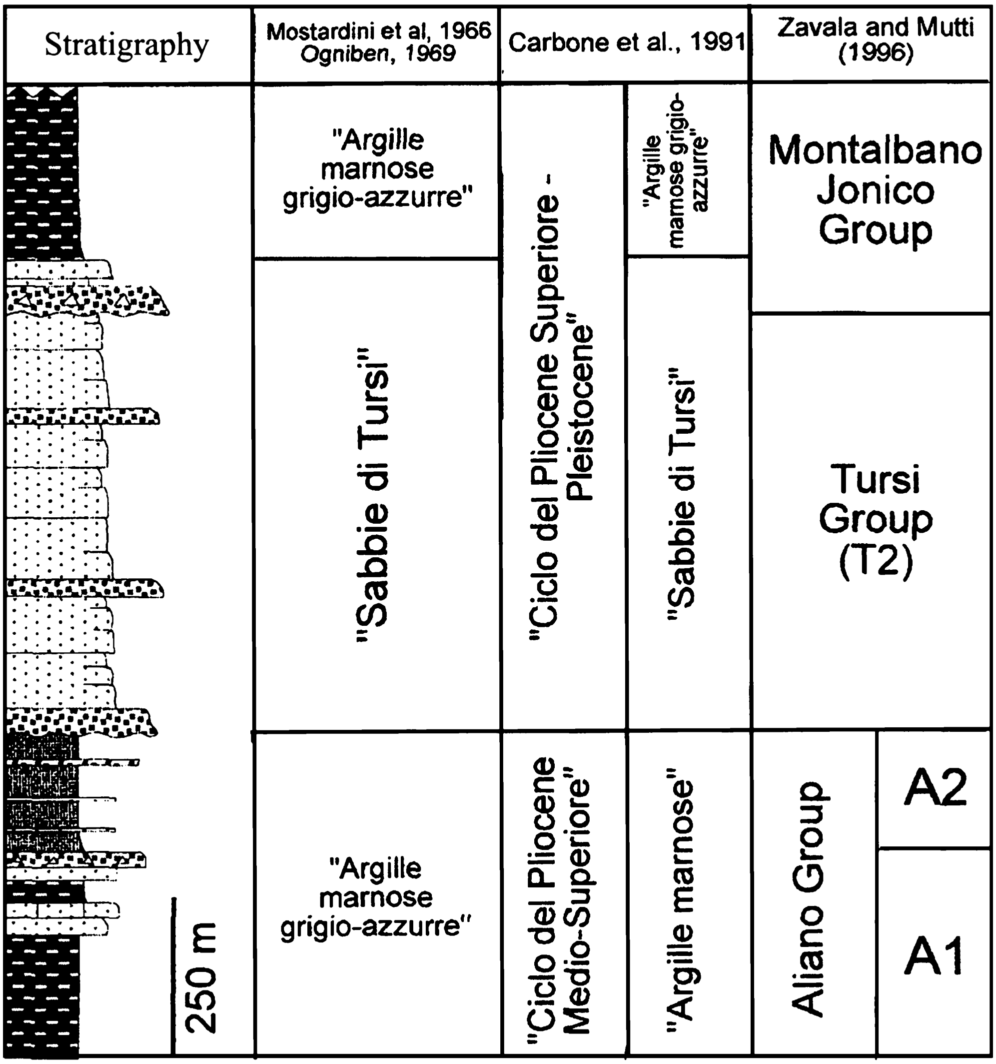


Fig. 3 Comparison between different stratigraphic schemes of the Plio-Pleistocene deposits in Sant' Arcangelo Basin exposed in the Tursi area (modified after Zavala 2000)

Two main sectors (Fig. 2) can be distinguished by important tectonic, stratigraphic, lithological, and geomorphological differences: (1) the western sector, where the oldest Apennine formational units (Cretaceous to mid-lower Miocene) outcrop (Argille Varicolori Fm. and Serra Palazzo Fm.); and (2) the eastern sector, which is characterized by younger successions of Plio-Pleistocene referred to foredeep piggyback deposits (Sabbie di Tursi Fm. and Argille grigio-azzurre Fm.). These two units are between them in tectonic contact (Argille Varicolori overlapped on Sabbie di Tursi).

The Argille grigio-azzurre (gray-blue clays) Formation consists of marly clays, silts, and rare beds of sands, covering a considerable part of the study area. The gray-blue marly clays are folded and heavily jointed. The joint system in the clays has developed mainly as a result of the tectonic activities during the synsedimentary deformation (Caldara et al. 1988; Hippolyte et al. 1994) of the Sant'Arcangelo basin.

Landscape evolution

The lithology of the substratum (well-cemented sands, silt-clayey sands, and subordinately sandy conglomerates) and rainfalls are the main factors to which the landscape evolution is linked. These represent the main determining elements for landslide triggering and linear erosion phenomena. Morphological history of the landscape is characterized by a different evolution of the Rabatana's slopes with respect to other nearby slopes.

The Rabatana's slopes are very steep and characterized by very intense erosional phenomena (rockfall and mudflows, deep gullies and rills, badlands, pipes), which affect the whole perimeter of urban settlements, threatening the conservation of the site (Fig. 4). From the point of view of the process of physical degradation, the sandy facies (as opposed to the silty–clayey facies) show a smaller resistance either to the impact of raindrops or to the washing away or to the physical disaggregation linked to the temperature ranges and, finally, to the different phases of water absorption and desiccation due to evaporation. The last phenomenon causes the development of desiccation cracks to which the piping erosion and detachment blocks along the slopes are closely linked.

Along the other slopes, under the same conditions of lithology, sun exposure and slope gradient, these morphological effects and processes are far more mitigated. One of the most interesting aspects surveyed in the study area is the piping erosion (Bryan and Jones 1997), which is an important factor in gully initiation and their rapid extension (Bocco 1991). Moreover, Farifteh and Soeters (1999) describe the piping tunneling erosion as a widely spread process occurring in the Plio-Pleistocene marine clays of the

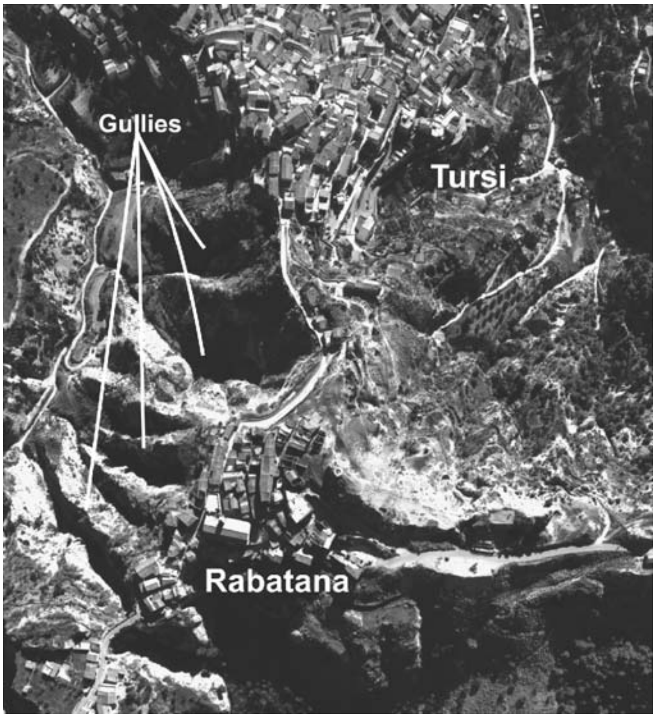


Fig. 4 Aerial view (scale 1:2,000) of the study area with evidence of deep gullies and steep slopes that surround the urban areas of Tursi town and its oldest nucleus, called "Rabatana"

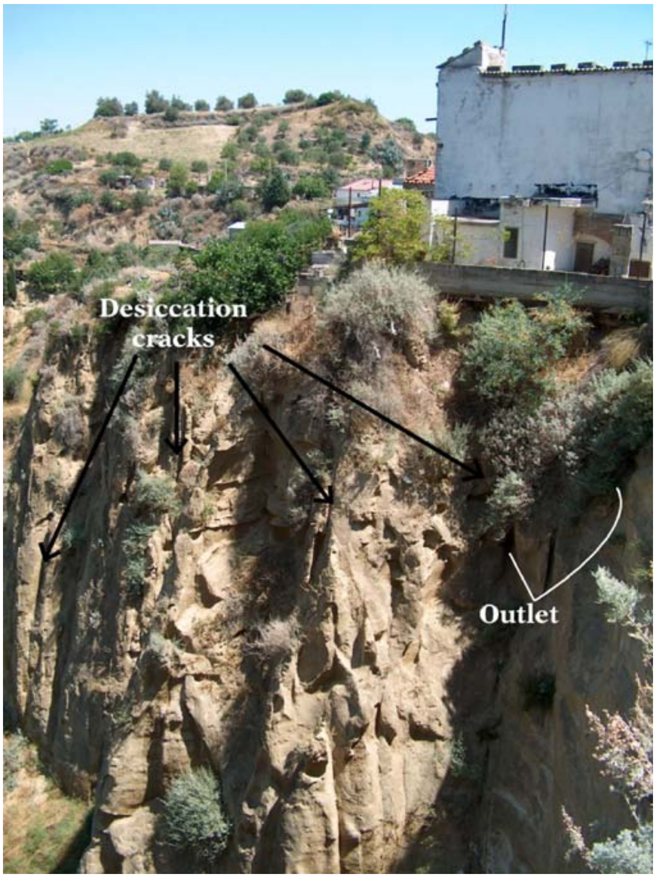


Fig. 5 Desiccation cracks and furrows into the sandstones along which runoff and water infiltration occur, favoring the development of micropipes under the buildings located at the cliffs edge. In particular, the furrows develop when the runoff water sheets are broken from an obstacle, such as a root, defining one or more lines where the erosive action is concentrated. The desiccation cracks develop during the concentrated rainfall periods or downpours, when the water imbibition of soils induces at the same time a reduction of cohesion and an increase in specific gravity

Basilicata and that the pipes are concentrated near and along the surface drainage network, particularly along gullies and major rills on the face slope.

In general, in the study area, two main types of pipes associated with desiccation cracks have been distinguished: micro pipes and small pipes. The micro pipes have a short tunnel length and a diameter (width) varying from just a few centimeters to tens of centimeters, and have originated from subsurface runoff along discontinuities (fractures or more clayey levels) in sandstones (Fig. 5). Another less widespread type of piping is linked to lithological contact between sand and silt–clay levels, where moderate to large pipes can develop.

The small pipes have started from rills and concentrated flows, and dispersion in small channels, associated with shallow tectonic cracks, desiccation cracks or decay of roots and with other biotic activities.

These types of piping are linked to the process of particle entrainment under high hydraulic gradients, developing subsurface passages due to variable lithological permeability. The micro pipes can dilate spreading in sandy bodies along the interbedded clayey levels. Moreover, the underlying impermeable clayey substratum facilitates the water movement along the plan of contact between the two layers.

In some cases large voids do not develop, but seepage erosion and running sand cause morphologically similar surface collapse phenomena (sinkholes). Outlets spreading (Fig. 6) can cause landslide phenomena (rockfall and toppling) along the steep sandy–clayey slopes. These events represent the first step of the geomorphological evolution of the slopes on which the urban settlement is located. After that the displaced material reaches a viscous liquid state of consistency, thus producing earth flows, channeled into the narrow canyons cut in the Tursi group deposits, moving downward with displacement velocities, which in many cases may be classified as "rapid" (WP/WLI 1993).

During the last century, the urban area of Rabatana has been affected by this type of phenomena due to water main breaks or sewer collapses when old pipes give way. In fact, during rainstorms, a considerable amount of water, coming from the slope faces and from old ruined houses without roofs, is spread over these areas, promoting infiltration. The short distance between the foot slopes and the top of the steep slopes provides easy outlets for the subsurface drainage. Geomorphological conditions, such as these described above, increase the pipe development on site and, consequently, also the hazard of geomorphological collapses.

Climatic conditions

The piping erosion discussed above is also a function of the climatic conditions. In fact, it is relatively common in semiarid environments, where climate presents strong seasonal contrasts and, especially, high rainfall variability, such as Mediterranean climates (Jones 1981; Stocking 1981; Parker and Higgins 1990; Gutierrez et al. 1997).

According to UNESCO/FAO (1963), the study area belongs to the mid-Mediterranean type of climate, characterized by hot dry summers and mild, wet winters with bimodal rainfall distribution.

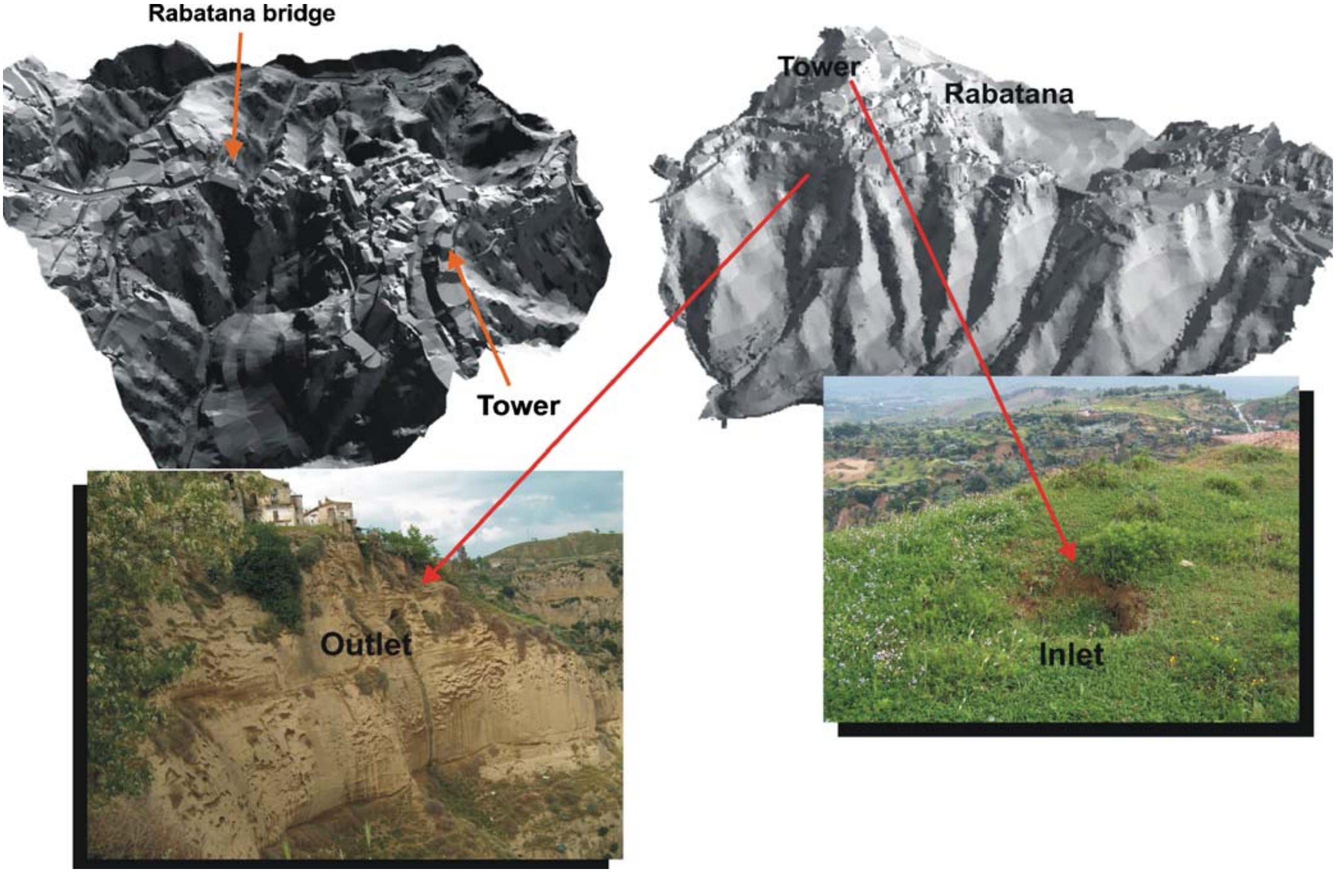


Fig. 6 The 3-D view of the Rabatana shows deep gullies distributed around all the urban perimeter and two examples of outlet and collapsed area (inlet opening) caused by piping erosion: the first is located along the south eastern steep slope of Rabatana, the second outcrops on the top surface where the medieval castle tower was built

Rainfall data, recorded at the meteorological station of Tursi (National Hydrographic Service), homogenized and calculated on a period of 79 years (1923–2001), show a maximum yearly rainfall of 1,323 mm (1946) and a minimum of 271 mm (1977), with a yearly average rainfall of 753 mm (Fig. 7a,b). The maximum amount of rainfall (Fig. 7b) occurs in the period from November to January (97–102 mm) and minimum rainfall in the period from June to August (25–34 mm).

Comparing the trend lines of the yearly rainfall intensity (Fig. 7d; ratio between yearly total precipitations, Pt, and the number of total yearly rainy days, Gp) and of the number of total yearly rainy days (Fig. 7c), we can see a marked increase in the rainfall intensity and a progressive decrease in rainy days (Gp). In agreement with Piccareta et al. (2004), this aspect underlines a progressive increase in the linear erosive processes because of the greater impact of the meteoric events on the soil.

Precise data on temperature in the study area is lacking, but data has been considered from the nearest station of Nova Siri. The Bagnouls and Gaussen diagram from 1959 to 2000 showed that dry periods occur between the end of April and August (Fig. 8). The climate of the area is mainly characterized by periods of desiccation (April–August) and periods of intense rainfall (October–March). In agreement with Crouch (1976), hot, dry summers combined with the exposure of slopes to excessive solar radiation, followed by highly variable rainfall (as in the case in the study area) can represent the critical factors in causing the predisposition of the area to subsurface erosion. This condition is possibly accentuated by the infiltration linked to the water loss of the old man-made urban drainage networks.

Dry periods favor the desiccation cracking of the sandy and silt-clayey grounds (Piccareta et al. 2005), which during the rainy periods are affected by a deep infiltration. If on one hand the water seepage favors hypogeal erosion for underground filtering (piping), on the other hand, it widens laterally the fractures with the consequent lateral migrating of the erosive phenomena.

Historical sources

Field data analysis has also been integrated using a historical approach to reconstruct the main natural calamitous events, which have affected the study sector in the recent past. Historical research, in fact, is a very effective instrument for the assessment of the hazard in probabilistic terms (Bertolini et al. 2005).

During the first step, either natural endogenous events, such as earthquakes, or exogenous events, such as flooding and landslides, were considered. These events, referring to the last two centuries and individualized after 2 years of archive searching, have been tabulated in a chronological sequence (Table 1) describing the damages caused to vulnerable elements (human life, buildings, churches, roads). Landslides and floods, often combined and acting together, are more frequent events that occurred during the analyzed period. Thirty percent of the total cases considered (60) recorded several cave collapses.

To evaluate a possible relationship between the occurrence of natural hazardous events and climatic conditions a link with rainfalls,

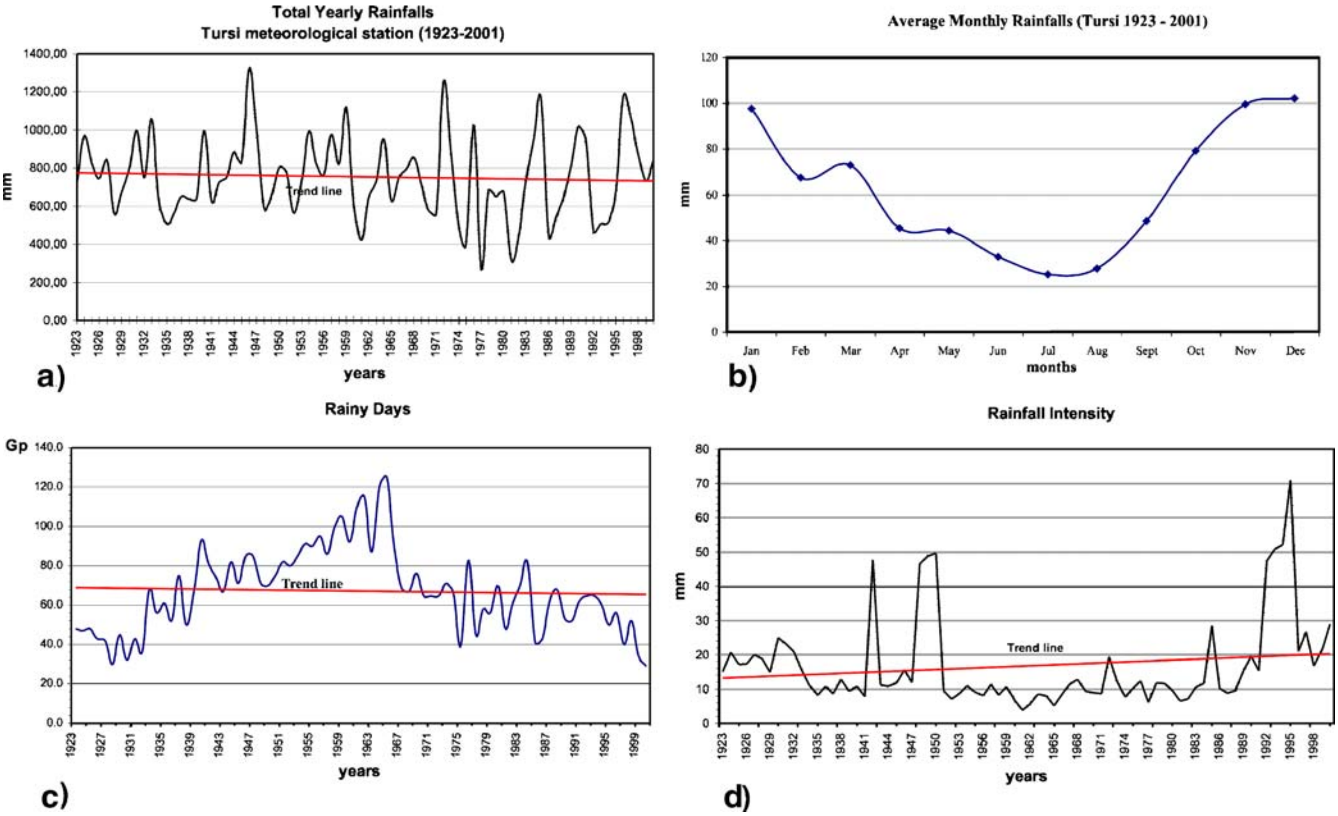


Fig. 7 Synthesis of the climate analysis carried out on meteorological station of Tursi (National Hydrographic Service) from 1923 to 2001. The graphs show respectively the data and trends of total yearly rainfalls (**a**), average monthly rainfalls (**b**), rainy days (**c**), and rainfall intensity (**d**)

the drought index standardized precipitation index (or SPI; McKee et al. 1993; Hayes 2002) was used. This index is based on the probability of precipitation for any timescale and is applied to a long-term series (at least 30 years) of rainfall data. It was designed to quantify the precipitation deficit for multiple timescales, which would have reflected the impact of drought on the availability of the different water resources. It is calculated as the ratio between the rainfall deviation with respect to its median value (for a desired period) and standard deviation. The study case was carried out for 24 months, classifying the considered periods depending on when each event diverges from the median precipitation (McKee et al. 1995).

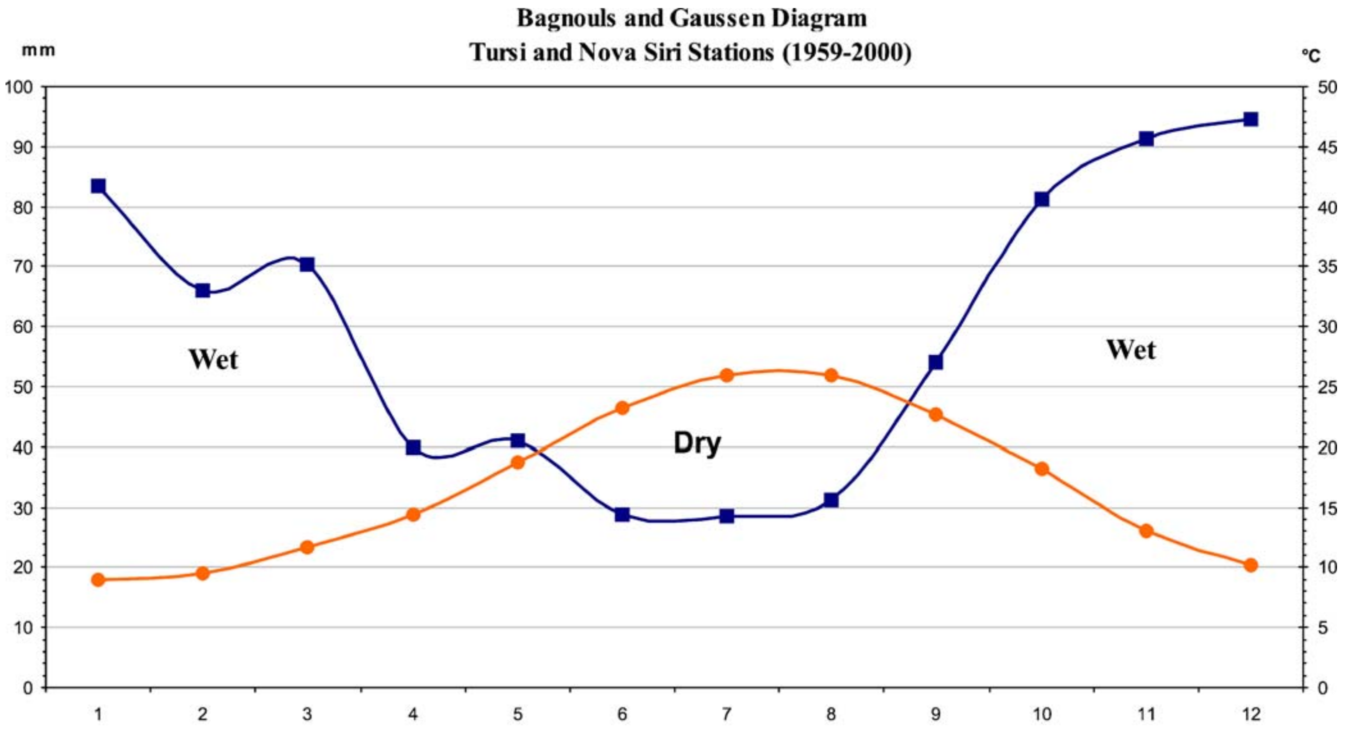
The flooding and landslide events have been plotted on a SPI_{24} diagram to try to relate them to the occurrence of normal, wet, and dry periods (Fig. 9). Generally, wet periods are mostly predisposed to the occurrence of mass movements. The SPI_{24} diagram shows that when the flooding events occurred in dry periods (1933–1934; 1960; 1974; 1980; 1985), this also induced damage to the buildings and victims. This was probably due to the preexisting susceptibility and weakness conditions of the territory.

This last aspect, certainly linked to rainfall intensity and lithology, is also due to human activity of cave excavation, which would have accelerated preexisting geomorphological processes, favoring the subaerial and subsurface erosional phenomena (Lazzari 2004).

Human influence on the natural environment

The birth and urban consolidation of the Tursi settlement and its older nucleus called Rabatana (Islamic toponym) occurred between the ninth and thirteenth centuries as a strategical garrison. It was the capital of the ancient Catepanate of Lucania during the Byzantine domination of southern Italy (Guillou 1965; Von Falkenhausen 1978) and represents an interesting example of the deep bond between natural and man-made environments such as precious cultural heritage, which we must preserve. The history of this settlement has always been deeply connected with the characteristics of the neighboring environment, and it seems possible that the first settlement was built by excavating the slopes of the sandy relief. It was a typical rupestrian settlement, as has been studied in a large area of southern Italy (Fonseca 1978), where meteoric water was stored inside some cisterns excavated on the slopes. During recent centuries, the increase in territory development by humans has produced an increase in cave excavation in the Tursi–Rabatana urban area. In fact, the field survey permitted the examination, for the Rabatana historical site, of about 100 caves for which it is possible to see clear entrances (Fig. 10), while at least 300 other caves are located in the Tursi urban area and surroundings. This survey excludes the caves and cisterns, which were not possible to inspect.

The analysis of the natural environment (reconstruction of climate, landscape and territory resources, such as water and soil) and its transformation into a “man-made environment” (Geraldi 2004) seems to indicate that, starting from the medieval epoch until the present day, relationships between the hypogeal facies and the hydraulic system (water storage) inside the urban landscape represent the central issue in understanding the actual situation. In fact, during the survey of caves located in the Rabatana and Tursi urban areas, wells and water sources were not found, so the water



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Average Rainfalls	83.4	66	70.46	39.41	41.06	28.72	28.55	31.36	53.99	81.21	91.35	94.43
Average Temperatures	8.96	9.5	11.68	14.34	18.74	23.25	26	25.96	22.71	18.21	13.06	10.17

Fig. 8 The Bagnouls and Gaussen diagram shows dry and wet periods obtained comparing rainfall data of the Tursi meteorological station and temperature data of Nova Siri meteorological station. These two stations are comparable as they are at the same altitude above sea level

supply in Rabatana was due exclusively to meteoric waters that flowed in cisterns, which over the centuries have dried up and become lost without trace. To define the complete scene of the hypogeal system and the ancient hydraulic network beneath the urban area, field observations and surveys have been integrated by means of a geophysical approach.

Geophysical approach

To reconstruct the extremely complex near-surface hypogeal environment excavated in the sandy layers, a geophysical investigation in the Rabatana historical site has been also carried out, integrating the new method of Electrical Resistivity Tomography (ERT) with the Ground Penetrating Radar (GPR) profiling. During the field survey, four ERT measurements and eight GPR profiles were carried out along the road network of Rabatana (Fig. 11).

Methods and field data acquisition

The ERT is an active geoelectrical prospection technique used to obtain a high-resolution image of the subsurface. This method has been widely applied in environmental and engineering geophysics to obtain 2-D and 3-D high-resolution images of the resistivity subsurface patterns in areas of complex geology at shallow depths (i.e., Steeples 2001).

In the field, a multielectrode system was used called Iris Syscal Plus with a Wenner–Schlumberger array layout. The maximum exploration depth was 15 m, and the electrode spacing was selected in a range varying from 2 to 3 m. For each geoelectrical profile, more than 320 measurements of apparent resistivity were carried out according to the 2-D pseudo-section scheme. To transform the apparent resistivity pseudo-section into a model representing the distribution of electrical resistivity in the subsurface, the RES2Dinv method was used (Loke and Barker 1996) based on the smoothness constrained least-squares inversion implemented by a quasi-Newton optimization technique.

The GPR method provides high-resolution images of the shallow subsurface and is largely applied in environmental and geotechnical investigations (Sharma 1997). In this study, the GPR profiles were obtained using a SIR 2000-GSSI system equipped with two antennas (400 and 200 MHz) connected by fiber-optic cables to the control unit. Radan NT software was used to process the data (color transforms, table customizing, and distance normalization processing); however, to reduce signal amplitude and background noise and to have a high quality trace, only standard analysis techniques were used.

Results

The geophysical investigation produced a map of the shallow man-made caves and tunnels; some cisterns contributed to a better reconstruction of the multilevel complex hypogeal system underlying the urban area. It has also been possible to give evidence for the water seepage phenomenon and flow direction in the subsurface.

In particular, the electrical images showed a significant variability in the subsurface resistivity patterns. Also extremely

Table 1 Key examples of the main natural hazardous events that occurred on the Tursi–Rabatana territory during the analyzed period (from 1087 to 2002)

More representative events	Typology	Damages and intervention	Bibliographic and archives sources
16 December 1857	Earthquake	Two churches damaged: S. Michele Arcangelo, almost entirely destroyed with damages to the dome; S. Maria Maggiore collegiate church with a notable lesion on all the aisles and the collapse of a cave developed near the church. Several damages and collapses developed on other historical and religious buildings. Landslides triggered along the roads under the urban area.	High Magnitude Earthquakes Catalogue - I.N.G.V. of Italy ASP Intendenza di Basilicata Busta 1380 Fs. 97, 177. Busta 1360 Fs. 6.
January–February 1907	Floods and landslides	After 7 days of uninterrupted rainfalls, human victims and many damages to the buildings (about 60), streets, bridges, springs and to the old castle have been recorded. Some sinkholes were caused by caves collapsing and landslide events along the main escarpments; overflowing of the Pescogrosso river about 30 m near the built-up area.	ASP Prefettura 1913–1932 Busta 1726 Commissariato Civile, Fs. 1695 Fs. 1692–1694
Winter 1930–1931, February 1931	Landslides and floods	Excavation and demolition of dangerous buildings on Carlo Alberto street. Damages to the S. Maria Maggiore Church, to water pipings, and several caves. Collapses of 15 houses and other 70 houses uninhabitable. Due to these ruinous events the Rabatana citadel has been partially moved in a new site (national law 9/7/1908).	ASMT Genio Civile I versamento Buste 388-828-615-245 Bruno R. 2001
1950–1951, January 1950	Floods	Landslides in Mario Pagano street. Sinking of a cave wide 5 meters full of water near the Rabatana bridge and flooding of houses.	ASMT Genio Civile I versamento Buste 920;1027
February 1951	Landslide	Sinking of a cave on Goldoni and Novelli streets and spreading of abyss and collapse of a building. Several cave instabilities under the houses above all along the higher part of Rabatana.	ASMT Genio Civile I versamento Busta 805, Fs. 8597; IV versamento Busta 100 Fs. 589
September–October 1958	Landslides and floods	Due to intense rainfalls a landslide interrupted the main road to the Rabatana. Some rockfalls of cave vaults occurred near the margin of Pizzo quarter (Dante street).	ASMT Genio Civile 0 versamento Busta 157; 773
January 1972	Landslide	Due to intense rainfalls some landslides were developed along the steep cliffs around the Rabatana quarter causing a few collapses of buildings and 22 uninhabitable houses. One hundred families leave their houses with an evacuation of 40 buildings, 80% of the total existing urban area. The old castle recorded considerable damages. Due to this catastrophic event, the Rabatana quarter has been moved to a different site with an ordinance of the President of Regional Council n° 73 of 29/9/72 and a government law n° 140 del 31/3/1904.	ACT; ASMT Genio Civile VII versamento Busta 590; CNR-GNDCI Progetto AVI
March–April 1973	Flood and landslides	Damages to the castle tower and buildings. Ordinance to demolish the tower and dangerous buildings (Ministry of Lavori Pubblici, Municipal Council of Matera 2/5/73).	ASMT Genio Civile VI versamento Busta 746
23 November 1980	Earthquake	Diffuse fracturation and lesions on the vaults and aisle of S. Maria Maggiore Church with a pronounced deformation of pillars and walls.	ASMT Provveditorato Regionale alle OO.PP. di Matera
January 1985	Flood landslides	Torrential rainfalls after abundant snowfalls in December caused the collapsing of a building (16/1/85) and sinking of a cave, increasing the risk level in Garibaldi, Manzoni, Goldoni-Novelli, Tito Speri, Aspromonte, Duca degli Abruzzi and Solforino streets and Vigliotti quarter. Ordinance of evacuation for 29 buildings and 83 peoples.	ACT, Prot. 2751/156 U.T. del 6/3/85 Fonogramma del 17/1/85 Prot. 708
The end of 1986	Landslides	Instability phenomena caused by erosional processes: sinkings and rock falls on V. Emanuele street due to the high number of multilevel underground caves. Landslide on Roma street.	Catenacci V. 1992
December 1990	Flood and landslides	Torrential rainfalls caused damages to urban area of Tursi recording rock falls of arenaceous block on Duca degli Abruzzi street due to water seepage and erosion. Collapse of a building on Vigliotti quarter.	Catenacci V. 1992 ACT nota del U.T. 30/4/1991

ASP Archivio di Stato di Potenza, *ASMT* Archivio di Stato di Matera, *ACT* Archivio Comunale di Tursi

conductive zones (resistivity values lower than 20 Ω m) and resistivity cores with pseudo-spherical shape (values greater than 1,000 Ω m) were clearly observed. Considering that homogenous sandy layers represent the geological environment of the investigated area, the extreme variability of the resistivity values is probably related to the high level of human activity.

In Fig. 13a, the presence of many resistivity cores located at different depths can be clearly recognized and associated with the presence of cavities and/or cisterns displaced along several fronts under the urban area. The decrease in resistivity values along with the depth seems to be correlated with wet fine sandy layers and are a typical sign of groundwater movements in the subsurface. In fact, parallel ERT profiles carried out along the main road network uncovered the presence of one or more underground flow lines (Fig. 11), which seem to be in agreement with surface runoff lines.

The presence of many cavities in the subsurface has been confirmed by an analysis of the GPR profiles. Figure 11 shows a detailed survey of the tomographic profile obtained with GPR measurements carried out

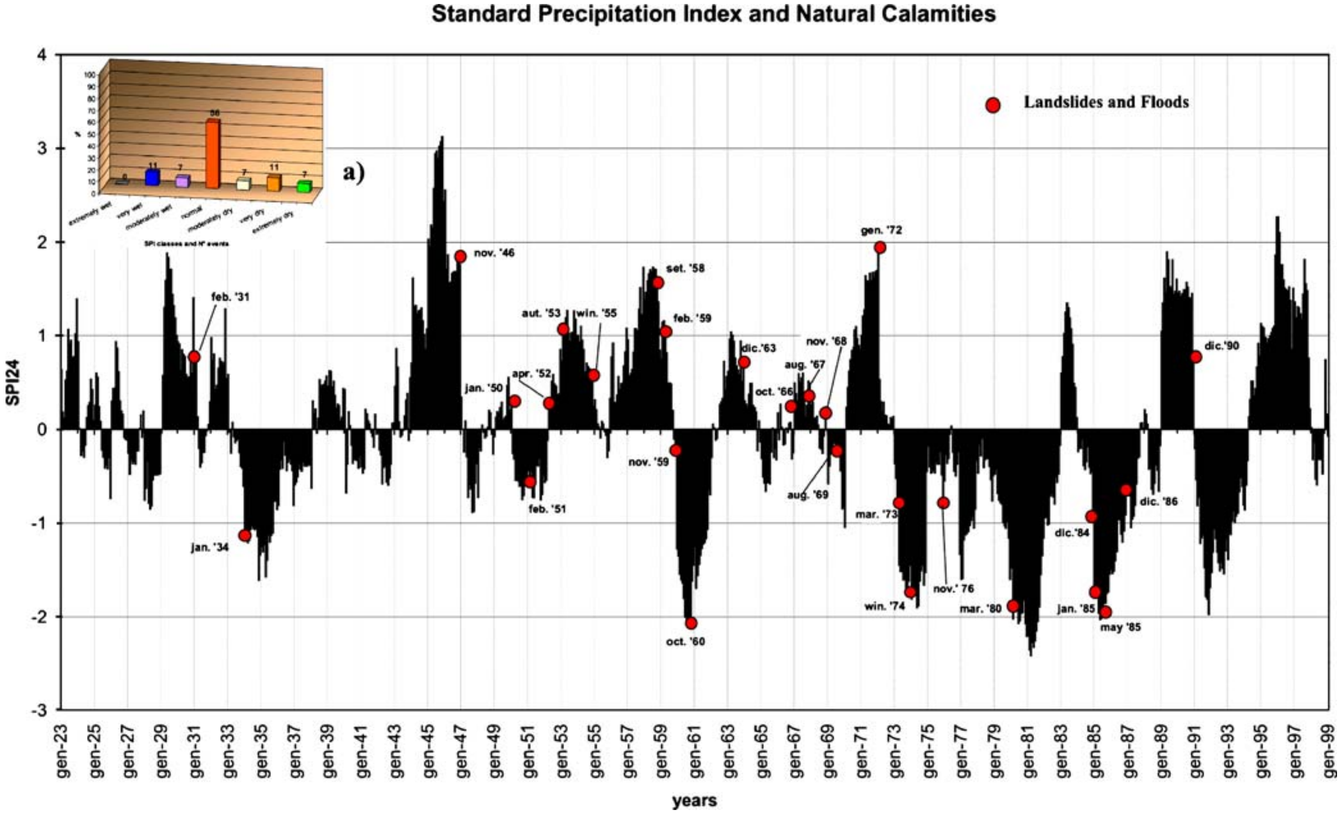
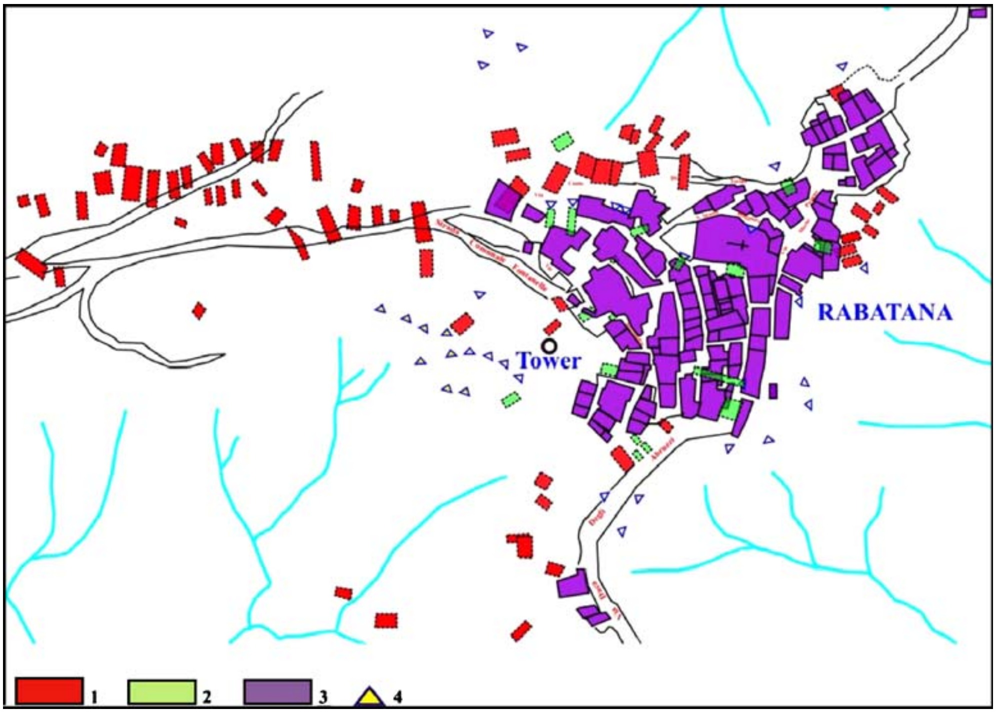


Fig. 9 SPI_{24} diagram on which natural calamities (landslides and flooding) occurred in the study area from 1923 to 2001 have been overlapped. In **a**, the histogram shows the number of calamitous events that occurred for each SPI classes

along the same direction as the ERT-AA′ assuming the sandy formation is a dielectric constant (δ_r) equal to 8. The presence of reflection patterns in correspondence with shallow resistivity cores is rather evident. The attenuation of electromagnetic waves on the right site of the profile (Fig. 11) is due to the high conductivity zone, probably caused by the presence of unconsolidated material.

Surface evidence helps us to interpret some large anomalies as old cisterns. In particular, these cisterns are located along the main

Fig. 10 Caves distribution in Rabatana historical center. *1* Caves registered, *2* new surveyed caves (this study), *3* buildings, *4* hypogeal entries



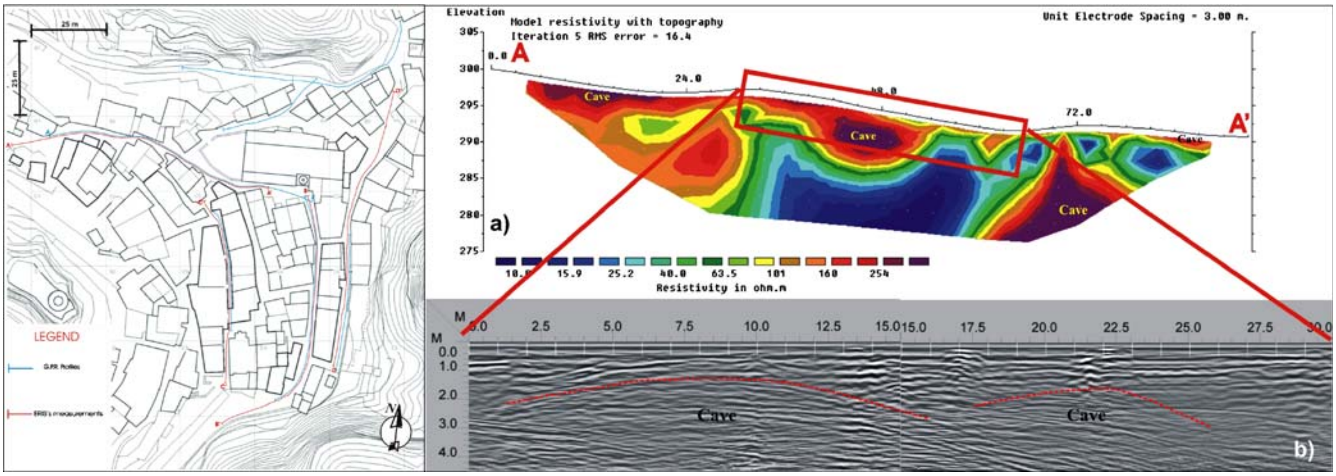


Fig. 11 Photogrammetric map of Rabatana historical center with location of GPR and ERT profiles. The figure shows an example of Electrical Resistivity Image obtained along the profile AA′ compared with a GPR section measured in the central sector of the profile with a 200-MHz antenna

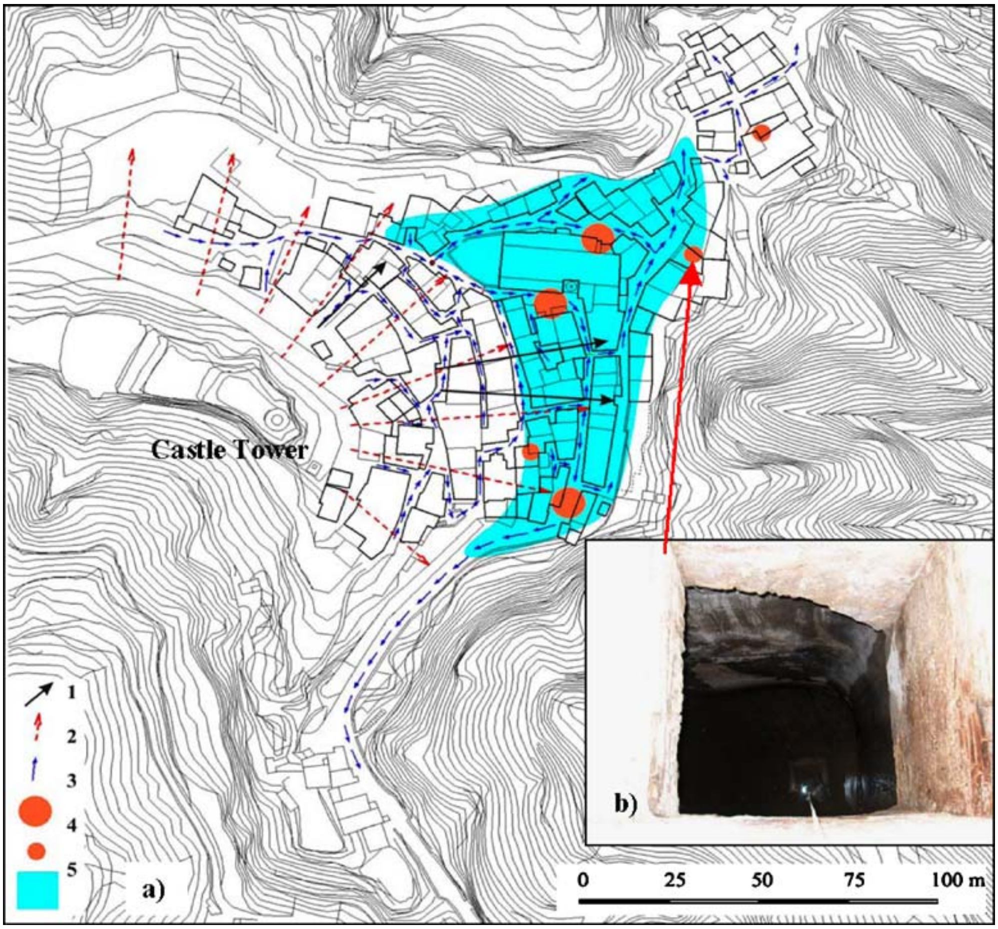
impluvium lines (Fig. 12) and cause an evident water capillary reclimbing along the perimeter walls of buildings located at cliff edges.

Final remarks

This case study is an example of a multidisciplinary approach to analyze an area with high susceptibility to landslides and where human influence has increased the risk level, favoring the water infiltration and subsurface erosional phenomena to which the landslide events are also linked.

Integrated analysis between geological, geomorphological, climate, and urban history reconstruction data have shown that during the last two centuries the geomorphological hazard has been accentuated by an intense and exacerbated human activity of cave excavation developed along several fronts beneath the urban area. The interaction during recent centuries between human activity (caves excavation, birth, and growth of an urban area and after recent evacuation of the settlement) and the characters of this natural environment were the reasons of a

Fig. 12 Aerophotogrammetric view of the Rabatana with indication of the main cisterns also surveyed with the help of geophysical prospections. The figure **a** shows the good agreement between the runoff flow lines and those underground surveyed with geophysics. *1* Water underground flow lines, *2* surface runoff flow lines, *3* urban runoff along the road gradients, *4* large and little cisterns, *5* main impluvium areas. In **b**, an example of the still active old cistern in Donnaperna's building is showed



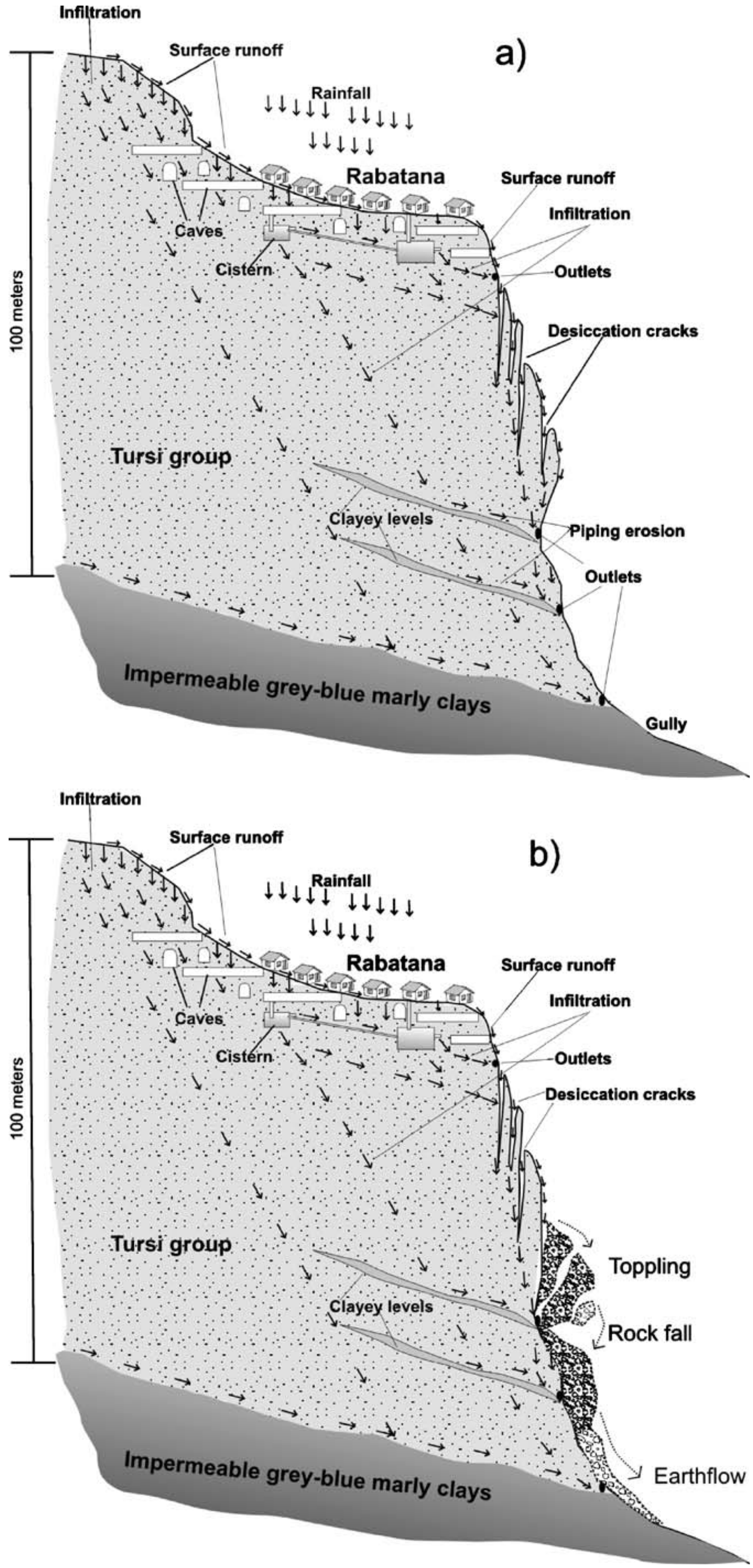


Fig. 13 Representative scheme of the evolution of the morphological processes acting on Rabatana slopes and subsurface. In **a**, the predisposing elements to landslide and collapse phenomena are shown. The following morphological phase is shown in **b**, where the main morphological effect is linked to the slope movements and cave collapses

progressive increase in hazard and vulnerability levels of this site.

In fact, cave excavation accelerated the preexisting morphological processes characterized by widespread surface piping erosion of sandy bodies (Fig. 13a). Moreover, climate analysis carried out for the last century showed an increasing trend in rainfall intensity over short durations, which also induced an increase in hazard conditions of the slopes.

Seepage water would have favored pipe erosion, spreading the outlet along the steep slopes and sinkholes opening up in the urban area. The clayey-sand soils are not cohesive enough to maintain the pipe walls and permit their enlargement; thus, they tend to close and induce collapses upward to the surface (inlets opening).

The foot erosion of slopes developed the landslide events (toppling, rock falls, and earth flows) to which the higher risk level is linked. In fact, the rockfalls that developed along main escarpments, which delimit the urban area, caused the retroverging of the slope margin involving many buildings (Fig. 13b).

The analysis of the climatic and geological characteristics of this portion of territory has, without doubt, been underlined as the rainfall and lithology represent the main predisposing elements in triggering intense linear and areal erosive phenomena. Their direct and uninterrupted action at that time has determined a characteristic badlands landscape developed on sandy and partly clayey substratum.

Besides these last two elements, a hot dry summer combined with exposure of slopes to excessive solar radiation followed by a highly variable rainfall, such as in the case study, can also represent critical factors exposing the area to subsurface erosion. These climatic conditions, in fact, increase the subsurface cracks in the gray-blue marly clays, which often facilitate water flow, thus, leading to the development of the micro pipes and small pipes that cause damage to the buildings and structures.

The dominant type of pipe is linked to the stress desiccation in which surface runoff (including road drainage, subsurface old drainage system with wells and cisterns) drains into a desiccation crack to cause erosion of finer material (Fig. 13a,b).

In conclusion, to assess the relative geohazard and risk for this site, not only the slope processes but also the human factor (linked to cave excavation and widespread water infiltration though the damaged vaults) must be considered.

Natural morphological processes acting on this site were accelerated by a secular multilevel excavation of caves, which has accelerated the infiltration processes and piping erosion. These natural events will happen regardless of human intervention, but the abandonment of the site will accelerate the degradation processes and erosion of the slopes.

The evaluation of the anthropogenic contribution to raise the geomorphological risk level was carried out on the basis of observations of the widespread static conditions and damages of the cave vaults (man-made environment) located under the built-up area caused by water infiltration and piping erosion, favored by the lack of waterproofing of the urban ground and the reactivation of the ancient hydraulic network.

To mitigate the hazard and risk level it is necessary to execute some remedial works, and above all, to reduce the water infiltration rate, thereby waterproofing the urban ground and disabling the ancient hydrological system, as well as effecting a static consolidation of the cave (vaults) network and a decrease in erosion rate along the slopes (for example grassing the slope surface).

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