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Codifying a database framework of climate change geomorphological markers: a study case from southern Italy

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Abstract. Climate change is globally recognised as a key driver of geomorphological transformation increasingly impacting natural systems, particularly through the intensification of erosion processes and modifications to landforms in vulnerable landscapes. This study focuses on landforms, processes, measurement approaches, quantitative methods, and a suitable sampling area from southern Italy, specifically in the middle valleys of Bradano and Basento rivers in Basilicata. The study is undertaken as part of one of the most significant research projects of the Italian National Recovery and Resilience Plan (NRRP), called "Technologies for Climate Change Adaptation and Quality of Life Improvement (Tech4You)". This project aims to study – among many topics also related to cultural heritage protection and climate change adaptation – the specific framework of natural risks, with particular emphasis on the impact of global climate change in Mediterranean semi-arid areas and soil erosion rates in socio-economically "inner" areas. In this work, we focused on the multiproxy approach needed to discriminate the components of erosion processes at different temporal and spatial scales. Such a goal was approached through the construction of a complex relational database associated with thematic maps produced in a GIS environment. The framework enables the identification of priority areas affected by accelerated erosion and provides a methodological base for replicable climate-change monitoring, including in other Mediterranean semi-arid contexts. Further, it aims to offer a strategic tool for early-warning systems and long-term adaptation planning.

Key words:
soil erosion,
climate change,
multiproxy database,
semi-arid areas,
southern Italy

Introduction

In recent years, an increase in extreme events related to climate change has been observed whose effects are directly proportional to the vulnerability of the territory. Many scientific data show the global impact of climate change: more-frequent heat waves, forest fires, floods and drought. Global warming reached an estimated 1.28°C in June 2024. According to the Director of Copernicus Climate Change Service, June marks the 13th consecutive month of record-breaking global temperatures, and the 12th in a row above 1.5°C with respect to pre-industrial temperatures (the Copernicus Climate Change Service website can be found at https://climate.copernicus.eu/).

Climate change, variations in land use, and anthropogenic pressure have caused land degradation and desertification phenomena that are also significant in the Mediterranean countries of Europe.

The effects of climate change require multi-stakeholder involvement (research, businesses, society and government) in a joint action towards resilient communities. For this reason, regional research and business sectors have recently been showing interest in the topics of climate change adaptation and ecological transition.

Over the last 200 years, the onset of climate changes recorded in the Mediterranean areas has coincided with the decline and end of the Little Ice Age and the subsequent warming period. Several studies at macro and mesoscale (Brunetti et al. 2001, 2002, 2004a, 2004b; Alpert et al. 2002; Peñarrocha et al. 2002; Piccarreta et al. 2013) have documented a tendency toward an increase in temperature and extreme events in these areas. As indicated in the literature, climate constitutes one of the main driving factors (besides the anthropogenic factors of land cover change, channelling, sediment extraction) in the evolution of river dynamics (Scorpio et al. 2015; de Musso et al. 2020; Mandarino 2022; Zingaro et al. 2022; Cusano et al. 2023; Pavlek 2023). Fluvial dynamics are highly dependent on the interaction between water flow and sediment (as well as topography, slopes and vegetation) and are influenced by anthropogenic and natural factors. Very fast climate and environmental changes are influencing river systems, inducing long- and short-term assessable morphological variations.

In Europe, prolonged dry periods followed by heavy erosive rains falling on steep slopes comprising fragile soils are affecting Mediterranean countries, which exhibit the worst conditions of soil erosion, i.e. natural phenomenon consisting mainly of water erosion and anthropic activities. Soil loss rates are higher than soil formation rates in the Mediterranean basin. In such areas, soils are easily eroded due to various characteristics: marked relief, 45% of the area having a slope greater than 8%; a high frequency of heavy rains in autumn and winter; poor, shallow and skeletal soils; and sparse natural vegetation linked to severe summer droughts (Gioia et al. 2021). In some of these areas, erosion has reached a stage of irreversibility, with the phenomenon having practically ceased in some places because there is no more soil left (Capolongo et al. 2007; Samela et al. 2022). Soil erosion represents a serious threat in the Mediterranean environment, where many areas are widely affected by accelerated erosion, largely promoted by the peculiar geological and climatic setting, as well as by land use (Aucelli et al. 2012). It is a dynamic and complex process with high spatial–temporal variability at the basin scale, and the comprehensive management of soil loss in small watersheds is a valuable strategy of soil conservation (Wang et al. 2024). In semi-arid environments, high-magnitude, low frequency events are assumed to be dominant with respect to both river channel processes and soil erosion. Consequently, it is during such events that the linkages between hillslopes and channels become very important. The importance of extreme events in controlling erosion and sediment transport in semi-arid areas has long been appreciated, but their effects on specific landforms are not widely recognised (Coppus and Imeson 2002). The increasing number of extreme events of high intensity represents the trigger and driving factor of fluvial erosion and mass-wasting processes, in terms of efficiency and rates, and contributes to the alteration of slope stability in the Mediterranean badland areas (Piccarreta et al. 2005; Coratza and Parenti 2021; Stark et al. 2022). Global change has made it of particular interest to monitor the environmental changes occurring in such areas, and to analyse the evolution of rill-and-gully erosion processes, which constitute the most intense form of soil erosion.

Land degradation and badland development constitute a common problem in the foredeep area of the southern Italian Apennines (Gioia et al. 2021). For instance, Basilicata (a 10,000 km^2 region of southern Italy) shows a significant vulnerability to land degradation similar to that of the hardest-hit Mediterranean countries. In certain areas, climate is becoming the determining factor amplifying the vulnerability to land degradation, further exacerbated by the increasingly occurrence of extreme events and, in recent years, by human activities that have deeply modified landscape patterns through improper land management (Scorpio et al. 2015; de Musso et al. 2020). The nature of cropping terrains coupled with the climate dynamics have brought several “inner” areas (i.e., territories, often rural or mountainous, characterised by distance from essential services) to desertification (Piccarreta et al. 2006; Capolongo et al. 2008; Piccarreta et al. 2013). Data from the literature (Samela et al. 2022) has shown that medium-high levels of soil loss are typical in the Matera hills in the south-eastern part of Basilicata, where accelerated erosion landforms are widespread.

The research and innovation programme of Tech-4You (Technologies for Climate Change Adaptation and Quality of Life Improvement), through a systemic approach structured in six “Spokes” that operate in an integrated manner, contributes to the achievement of several objectives in the context of territorial, national and EU policies of reference. The “Adapting to climate change” mission of Horizon Europe focuses on the ecosystem and is consistent with the priorities of the national research and the areas of the National Recovery and Resilience Plan (NRRP). The Tech4You action programme is part of a framework of policies regarding two regions of Southern Italy, namely, Calabria and Basilicata, which are the most exposed to hydrogeological risk, coastal erosion and, in some areas, desertification processes: every partner of the ecosystem participates in various programming and implementation phases. Tech4You will address climate change from five perspectives: natural risk, energy, food, culture, and healthy communities.

This work focuses on the specific framework related to natural risk and to the contribution of geomorphological studies to the estimation of the impact of global change in Mediterranean semi-arid areas, and specifically, the assessment of erosion rates in “inner areas” of Basilicata (southern Italy). The analysis of some categories of markers (such as geomorphological and sedimentary ones) in key areas where climate changes may cause environmental hazard seems a best practice for territorial safeguarding. In this paper, a database framework of climate change geomorphological markers is preliminarily proposed. It is designed to provide a multi-scale approach based on the analysis and monitoring of different types of parameters, in order to offer to geoscientists a multi-proxy procedural protocol for estimating the impact of global change in semi-arid areas, and the possibility to evaluate actions and strategies for geomorphological risk mitigation. In addition, we present a collection of diversified test sites from Basilicata region where climate change is rapidly inducing a landscape evolution. Those sites represent significant examples of south-European semi-arid areas where the above-delineated approach can be used for climate change monitoring.

Study area and climate framework

The key sites identified for this work are small catchment areas mainly located in the Bradano and Basento river basins (3,018.78 km^2 and 1,530 km^2, respectively), in the foredeep portion of the southern Italian Apennine (Fig. 1). The NW–SE-trending Bradano foredeep basin is a narrow Pliocene-Pleistocene sedimentary basin located between the Apennine chain and the Murgia carbonate platform of the Apulian foreland, in southern Italy (Ricchetti 1981; Pieri et al. 1996; Boenzi et al. 2008). The foredeep basin is filled by several-km-thick Pliocene-Pleistocene deposits (Balduzzi et al. 1982; Tropeano et al. 2002). The upper Pliocene to lower Pleistocene outcropping succession (Ricchetti 1967) is made of several-hundred-metre-thick clayey marine deposits (*Argille subappennine* Fm) passing toward the top to regressive sands (Sabbie di Monte Marano) and conglomerate (Conglomerati di Irsina).

From a geomorphological viewpoint, the key-sites (Table 1 reports on the ones falling in the

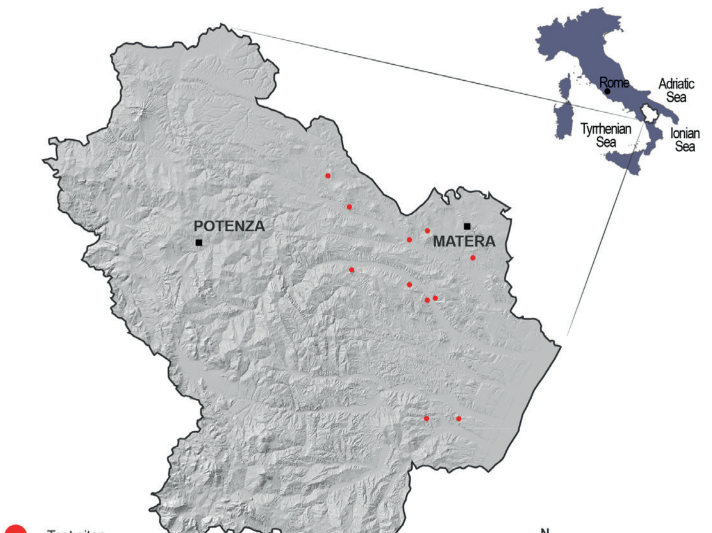

Fig. 1. Location map of the test sites

Bradano River valley) share similar morphological features and may be considered valuable examples of how climate change is affecting Mediterranean semi-arid areas to induce rapid landscape evolution. Here, most of the slopes are rapidly evolving due to accelerated erosion processes, so that rill-and-gully erosion contributes to the overall denudation at the catchment scale, as a result of extreme episodic events. These events occur at the hillslope scale and are triggered by intense rainfall events, the peculiar geological setting, and land-management factors.

From a climate viewpoint, the Mediterranean is characterised by a close interaction between atmospheric and marine processes and highly differentiated regional topographies. This results in specific subtropical climatic conditions with strong seasonal variability, relatively warm temperatures and highly fluctuating precipitation. Variations in climatic parameters have a direct impact on efficiency and denudation rates. The study area is characterised by different local climates and ecosystems: the temperate climates (Csa and Csb), the steppic climate (Bsk), and the Mediterranean mountain climates (Dsb and Dsb). This last climate type characterises some isolated areas of the mountain chain and is a particularly suitable representative of the biogeographical complexity of Mediterranean Italy (Samela et al. 2022). Climate features are mainly influenced by the complex orography, which is characterised by very steep gradients, altitudes reaching over 2200 m a.s.l., and its geographical position (i.e., straddling three seas: the Adriatic to the north-east, the Tyrrhenian to the south-west, and the Ionian to the south-east. The Apennine chain intercepts most of the Atlantic perturbations in the Mediterranean basin and influences the distribution and type of precipitation, favouring the concentration of rainfall in the south-western area of the region. Snowfall, on the contrary, is mainly concentrated in the north-eastern part of the region and is not uncommon even at relatively low altitudes. In general, the seasonal distribution of rainfall is typically Mediterranean. The rainiest months are November and December, and the least rainy are July and August. The rainfall pattern is highly variable, both over the annual cycle and year-on-year, and often a considerable proportion of the rainfall is concentrated in a few days of very intense precipitation. Specifically, data of the last approximately twenty years from the Matera weather station (located at 475 m a.s.l.) show that the rainiest months are November and December, and the least rainy are July and August. Analysis of rainfall (mm/y) from 2001 to 2023 shows a maximum total value of 762.2 mm in 2009 and three minimum total values of 371.9 mm in 2001, 375 mm in 2011, and 396.6 mm in 2021 (Fig. 2).

November exhibits the maximum average rainfall value (65.39 mm) in the same time interval, as Figure 3 shows. Further, the analysis conducted on this temporal range confirms that rainfall is concentrated in autumn (155.17 mm, Fig. 4).

Seasonal rainfall average comparison of the 2001–2012 and 2013–2023 periods highlights that, in the last ten years, the mean amount of rainfall has almost doubled in summer and decreased in winter. Spring and autumn remain mostly unchanged and, in the last time span, are the rainiest seasons. The average annual temperature is 15.2°C. July and August are the hottest months and have very similar monthly averages, whereas the coldest month is January. According to Thornthwaite's climate classification, the climate is subarid, with an aridity index of 33 and an annual potential evaporation (ETP) of 816 mm (http://www.basilicatanet.it/suoli/clima.htm).

Methodology and criteria for database framework construction

The database framework of climate change geomorphological markers proposed herein (Table 2) shows some of the geomorphic parameters and indices, as well as techniques that might be used to obtain them in a certain time span and at an adequate spatial scale. The table provides an overview that shows a possible way for the detection of the listed parameters and other climate change indicators through methods and modalities either known from the literature or proposed herein. To this scope, nine taxonomic categories were codified (Table 2). The selection of macro-categories was the result of an in-depth analysis of scientific literature, combined with our field experience in semi-arid areas of southern Italy. Indicators that show a direct and measurable response to climate change were prioritised. Therefore, those excessively influenced by non-climatic local factors or difficult to standardise were excluded. In this way, each included category appears robust and measurable with repeatable methodologies.

Table 1. Some of the test-sites showing rapid landscape evolution in Mediterranean semi-arid areas

River basin	N.	Test site	XY Coordinate	Area (km²)	Altitude (m a.s.l.)	Slope (°)	DTM (cell size, year)	Wildfire	Temperature station	Rainfall station
Bradano	1	***Fosso di Salati*** **catchment**	LAT=4496690; LONG=637009	1.98	MIN=108.44; MAX=287.83; MEAN=168.57	MEAN=14.9	1; 2013	2011, 2016	Matera (LAT: 4502237.9; LONG:634831.5; ALT: 475)	Matera (LAT: 4502237.9; LONG:634831.5; ALT: 475)
	2	***Picciano*** **catchments**	LAT=4505240; LONG=622669	0.22	MIN=187.83; MAX=265.72; MEAN=226.73	MEAN=6.8	1; 2013	--	--	S. Giuliano (LAT: 4499670.92; LONG: 621174.5; ALT: 107)
	3		LAT=4502090; LONG=620310	0.88	MIN=108.55; MAX=377.42; MEAN=211.47	MEAN=13.2	1; 2013	--		
	4		LAT=4501430; LONG=619747	0.18	MIN=109.38; MAX=193.55; MEAN=150.26	MEAN=8.7	1; 2013	--		
	5		LAT=4502640; LONG=620040	1.02	MIN=109.76; MAX=395.64; MEAN=257.67	MEAN=10.7	1; 2013	--		
	6		LAT=4502040; LONG=619206	0.98	MIN=112.30; MAX=258.45; MEAN=159.22	MEAN=7.4	1; 2013	--		
	7	***Taccone - Serra Montavuto Piccolo*** **catchment**	LAT=4517060; LONG=600310	0.43	MIN=276.54; MAX=501.12; MEAN=374.73	MEAN=14.3	5; 2013	--	Irsina (LAT: 4511632.5; LONG: 604597.3; ALT: 550)	Irsina (LAT: 4511632.5; LONG: 604597.3; ALT: 550)
	8	***Fosso dei Greci*** **slopes**	LAT=4509520; LONG=605477	0.09	MIN=301.35; MAX=425.07; MEAN=362.07	MEAN=26	5; 2013	--	Irsina (LAT: 4511632.5; LONG: 604597.3; ALT: 550)	Irsina (LAT: 4511632.5; LONG: 604597.3; ALT: 550)
Basento	9	***Le Vigne*** **catchment**	LAT=4486930; LONG=627170	0.9	MIN=130.84; MAX=434.36; MEAN=260.19	MEAN=33.4	0.4; 0.05; 2013 and 2025	2012	Ferrandina SP (LAT: 4482713.2; LONG: 623061.2; ALT: 486)	Ferrandina SP (LAT: 4482713.2; LONG: 623061.2; ALT: 486)
	10	***Madonna di Pompei Church*** **excavation**	LAT=4493790; LONG=604982	0.06	MIN=282.4; MAX=338.84; MEAN=299.28	MEAN=23.6	0.4; 0.02 2013 and 2025	--	Grassano SP (LAT: 4498793.1; LONG: 607400.5; ALT: 542)	Grassano SP (LAT: 4498793.1; LONG: 607400.5; ALT: 542)
	11	***Grassano-Garaguso railway station*** **artificial slope**	LAT=4493970; LONG=605712	0.01	MIN=251.3; MAX=281.98; MEAN=263.83	MEAN=27.2	0.02; 0.02; 2013 and 2025	--	Grassano SP (LAT: 4498793.1; LONG: 607400.5; ALT: 542)	Grassano SP (LAT: 4498793.1; LONG: 607400.5; ALT: 542)
Agri and Sinni	12	***Tursi catchments***	LAT=4456590; LONG=624943	0.04	MIN=182.17; MAX=339.83; MEAN=254.54	MEAN=38.8	5; 2013	2023	--	Tursi (LAT: 4456992.8; LONG: 625440.1; ALT: 348)
	13		LAT=4456620; LONG=625329	0.27	MIN=161.41; MAX=320.94; MEAN=228.39	MEAN=33.7	5; 2013	--	--	Tursi (LAT: 4456992.8; LONG: 625440.1; ALT: 348)
	14	***S. Maria d'Anglona - Calanchi di Marone*** **slopes**	LAT=4456350; LONG=632891	0.46	MIN=50.7; MAX=260.4; MEAN=130.8	MEAN=23.04	1; 2013	--	--	Tursi (LAT: 4456992.8; LONG: 625440.1; ALT: 348)

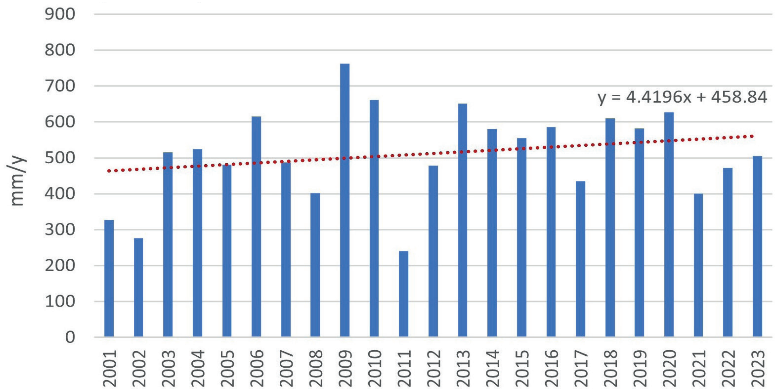

Fig. 2. Rainfall (mm/y) data from 2001 to 2023 related to Matera weather station

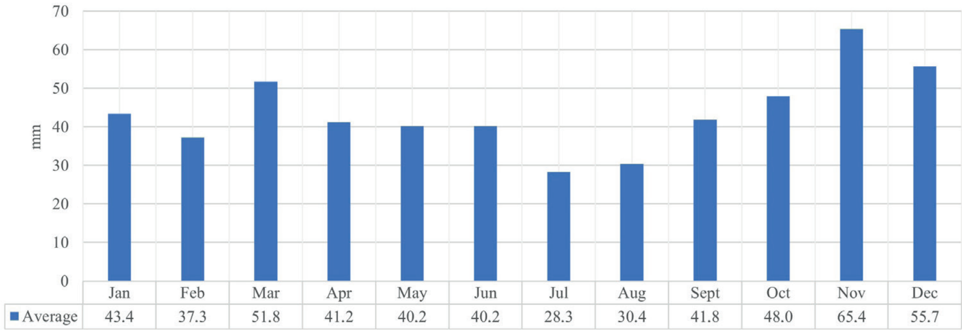

Fig. 3. Monthly rainfall data (mean values) from 2001 to 2023 related to Matera weather station

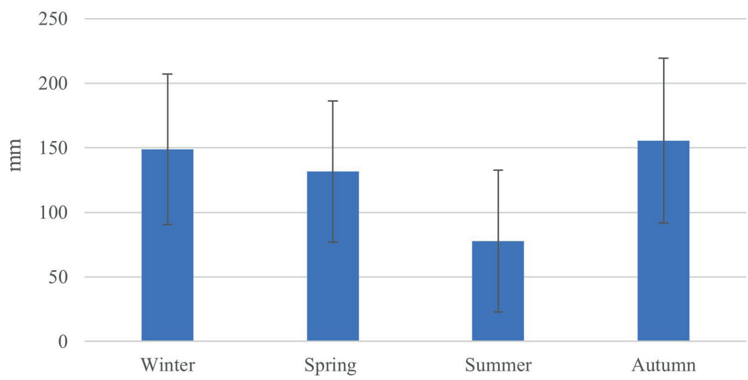

Fig. 4. Seasonal rainfall data (mean values) from 2001 to 2023 related to Matera weather station

Table 2. Proposed scheme for a database of geomorphological climate-change indicators

N.	Macro-category	Key geomorphological indicator of climate change in Mediterranean semi-arid areas	Description	Spatial scale of the investigation	Temporal scale of the process	Type of detection/data source (e.g., field research, equipment measures, remote sensing, historical research)	Basic references
1	**Fluvial morpho-logical changes**	Channel bed modifications (sinuosity/ confinement/ connectivity index; channel width/ length; channel bed elevation; channel pattern)	To analyse physical and morphological changes in river courses in response to climatic and anthropogenic factors	Watershed to regional	From decades to centuries (short-term processes)	Map and aerial photo comparison and historical research, remote sensing, desktop study	Rinaldi et al. 2011; Scorpio et al. 2015; Molliex et al. 2016; de Musso et al. 2020; Mandarino 2022; Papangelakis et al. 2023; Zingaro et al. 2022; Magliulo et al. 2023; Pavlek 2023
2	**Acceler-ated erosion**	Accelerated erosion landforms/soil erosion processes (rilling, gullying)	To monitor the formation of erosion features like rills and gullies, indicative of accelerated soil loss	Local	From years to decades (very short-term processes)	*In-situ* measurements, desktop study, aerial photo, remote sensing, mapping and morphometric analysis, modelling techniques	Piccarreta et al. 2005, 2012; Ciccacci et al. 2008; Nadal-Romero 2011; Aucelli et al. 2012 ; Faulkner 2013; Vergari et al. 2013; Dewitte et al. 2015; Moreno-de las Heras & Gallart 2018; Vergari et al. 2019; Bufalini et al. 2022
3	**Erosion rates**	a. Sediment yield at badland outlet	To measure sediment quantity and eroded volumes, helping to understand the intensity of erosion processes in various contexts	Local to watershed	From years to decades (very short-term processes)	*In-situ* measurements (e.g., sediment traps), desktop study, aerial photo, remote sensing, mapping, modelling techniques	Schiattarella et al. 2004; Beguería Portugués 2005; Clarke & Rendell 2006; Ciccacci et al. 2008; Nadal-Romero 2011; Aucelli et al. 2012; Piccarreta et al. 2012; Muller & Pitlick 2013; Frankl et al. 2015; Cappadonia et al. 2016; Guerra & Lazzari 2020; Millares et al. 2020; Stark et al. 2020; Coratza & Parenti 2021; Palmeri et al. 2024; Wang et al. 2024
		a.1 - Vegetated slope					
		a.2 - Bare slope					
		a.3 - Slope angle less than the angle of repose					
		a.4 - Slope angle greater than the angle of repose					
		b. Sediment yield at gully outlet			From years to decades (very short-term processes)	*In-situ* measurements (e.g., sediment traps), desktop study, aerial photo, remote sensing, mapping, modelling techniques	
		b.1 - Vegetated slope					
		b.2 - Bare slope					
		b.3 - Slope angle less than the angle of repose					
		b.4 - Slope angle greater than the angle of repose					
		c. Sediment yield at the base of the slopes prone to sheet washing and rilling (ephemeral streams outlet)			From years to decades (very short-term processes)	*In-situ* measurements (e.g., sediment traps), desktop study, aerial photo, remote sensing, mapping, modelling techniques	
		c.1 - Vegetated slope					
		c.2 - Bare slope					
		c.3 - Slope angle less than the angle of repose					
		c.4 - Slope angle greater than the angle of repose					
		d. Eroded volumes with respect to different base levels (in main river basins)			10^4-10^5 years (mid- to long-term processes)	Mapping and desktop study	

Continuation of Table 2

		e. Mean annual suspended sediment yield (in main river basins)			10^3-10^4 years (mid-term processes)	Mapping and desktop study	
4	**Sediment-ation rates**	a. River channel sedimentation (coarse-grained channel deposits and fine-grained overbank sediments)	To assess sediment accumulation in different geomorphological settings and their correlation with anthropogenic and climatic activities	Local to watershed	10^3-10^4 years (mid-term processes)	Field survey and measurements, remote sensing	Coppus & Imeson 2002; Beguería Portugués 2005; Nadal-Romero et al. 2008, 2011; Nadal-Romero 2011; Piccarreta et al. 2012; Mueller & Pitlick 2013; Savi et al. 2020
		b. Downslope sedimentation in fan environments (alluvial fans)			10^3-10^5 years (short- to long-term processes)	Field survey and measurements, remote sensing	
		c. Sedimentation rate related to archaeological sites			10^2-10^3 years (short-term processes)	Field survey and measurements, remote sensing	
5	**Sediment connectivity**	Sediment connectivity evolution	To analyse sediment transport and deposition patterns across fluvial landscapes	Watershed to regional	10^2-10^3 years (short-term processes)	Field and desktop studies	Fryirs & Brierley 2001; Hooke 2003; Borselli et al. 2008; Cavalli et al. 2013; Najafi et al. 2021; Liu et al. 2022
6	**Climatic indicators**	Rainfall/temperature multi-temporal values; dry/wet period distribution; flood event frequency	To provide information on climate change and its interaction with geomorphic processes	Regional to global	From years to decades	Archive data and desktop study	http://www.scia.isprambiente.it/wwwrootscia/scia.html; http://valori-climatici-normali.isprambiente.it/; https://www.i4ccs.com/; https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity; https://www.drought.gov/data-maps-tools/global-gridded-standardized-precipitation-index-spi-cmorph-daily; https://climate.copernicus.eu/; https://www.ipcc.ch/; https://lcsc.csic.es/
7	**Drainage density**	Drainage density (Dd) variations	To assess changes in drainage networks and hydrological structures indicative of climatic and geomorphic alterations	Watershed to regional	From decades to centuries (short-term processes)	Mapping and desktop study	Collins & Bras 2010; Clubb et al. 2016; Gao et al. 2022
8	**Vegetation indicators**	Normalised Difference Vegetation Index (NDVI) and Normalised Difference Moisture Index (NDMI)	To analyse changes in vegetation cover and soil moisture, useful for monitoring desertification	Local to regional	From years to decades	Satellite data archives, remote sensing, desktop study	Oueslati et al. 2013; Bufalini et al. 2022 ; Wu et al. 2023; Shah et al. 2024
9	**Slope instability**	Mobilised material volumes; movement speed; landslide index; frequency of landslide occurrence	To monitor gravitational processes and slope destabilisation in contexts vulnerable to climatic or anthropogenic factors	Local to regional	From years to decades	Satellite data archives, regional datasets, field and desktop study	Santangelo et al. 2013

The measurements can be made directly or indirectly, where "direct" indicates field observation and in-situ measurements through appropriate equipment, and "indirect" indicates the interpretation of information obtained through map and aerial photo comparison and interpretation, historical research and archive data collection, and remote sensing techniques. Moreover, such a multi-scale approach entails the need to establish appropriate spatial and temporal scales. The multiscale approach allows the combination of local data (relating to slopes and to specific areas of erosion or sedimentation such as rills, gullies, dejection cones), regional data (analyses involving multiple catchment areas or covering large semi-arid areas), and sometimes global data (trends affecting large areas, such as temperature/rainfall variations and global extreme events). Meanwhile, multitemporal integration allows the identification of long-term trends and more recent variations, providing a holistic view of geomorphological dynamics.

In addition to the database framework, a database is being constructed that collects representative areas from Basilicata region (Table 1) with main morphological features, where the above-mentioned approach can be used. As an example, landscape evolution occurring in one such area (i.e., Fosso di Salati sub-catchment) has been monitored in a significant timespan (i.e., 2013–23) through field surveys, satellite images (i.e., True-colour images from 2015 to 2023 acquired from Sentinel-2 L1C [Copernicus Browser] with a 7 m/px resolution), and mapping and desktop study. This monitoring also involved analysing the data from these sources using GIS-based techniques for the estimation of erosional processes. The study also employed hourly rainfall and temperature data from the Matera weather station (latitude: 403935; longitude: 163543; altitude: 475 m; time interval: 2013–2023). For a better characterisation of climatic features over approximately the last ten years, we also calculated the number of rainy (annual and seasonal) and dry annual days, average intensity of rain (SDII index), annual and seasonal 90th and 95th percentiles, and 98th percentile related to three-day rainfall values, and rainfall erosivity. The power-law equation developed for the Basilicata region by Piccarreta et al. (2005) and later used by Capolongo et al. (2008) and Gioia et al. (2021) was applied to estimate the average annual R factor from 2013 to 2023. This equation was statistically derived from 20-minute and hourly precipitation records and allows the estimation of rainfall erosivity (EI_{30}) based on daily rainfall amounts (P_{24}), using the formula:

$$EI_{30} = 0.1087 \times (P_{24})\text{^}1.86 \qquad a)$$

where EI_{30} is expressed in MJ mm h^{-1} ha^{-1} yr^{-1}, and P_{24} is the daily rainfall in millimetres. Annual rainfall (*EIannual*) erosivity is then calculated as the sum of daily erosivity (*EIdaily*) values throughout the year:

$$EIannual = \Sigma(EIdaily) \qquad b)$$

Results

The collection and the monitoring of test sites provide an overview of landscape evolution under climate-change effects in the portion of southern Italy most exposed to geomorphological risk and desertification processes. Analysis of some test sites chosen from a significant portion of the region, particularly from the hydrographic basin of Bradano and Basento rivers, show clear features of accelerated erosion processes, such that the development of rills and gullies constitutes the main erosion processes of the study area (Fig. 5). Indeed, the comparison of multi-temporal satellite images highlights a rapid change in soil erosion affecting slopes of one of the representative test sites, namely the Fosso di Salati catchment basin (Fig. 6). Analysis and interpretation of multi-temporal rainfall series for the last ten years show long, dry periods followed by heavy bursts of intense rainfall (Fig. 2) falling on steep slopes with fragile soils. The mean annual average erosivity factor computed for the study area using the hourly rainfall data of the Matera rain gauge is equal to 677.27·MJ·mm·ha^{-1}·h^{-1}·yr^{-1} for the 2013–2023 period, with maximum rainfall erosivity recorded in 2013 and 2020 and a decreasing general trend over the period (Fig. 7). The analysis of rainfall data for the 2013–2023 period in the Matera area reveals considerable interannual variability in both total precipitation and the frequency of intense events. Annual precipitation ranged from the most recent minimum value of 400 mm in 2021 to a maximum of about 651 mm in 2013, showing significant oscillations with a general decreasing trend. The average annual rainfall over the period was approximately 545 mm.

Table 3 shows data collected from 2013 to 2023 highlighting that the number of rainy days per year

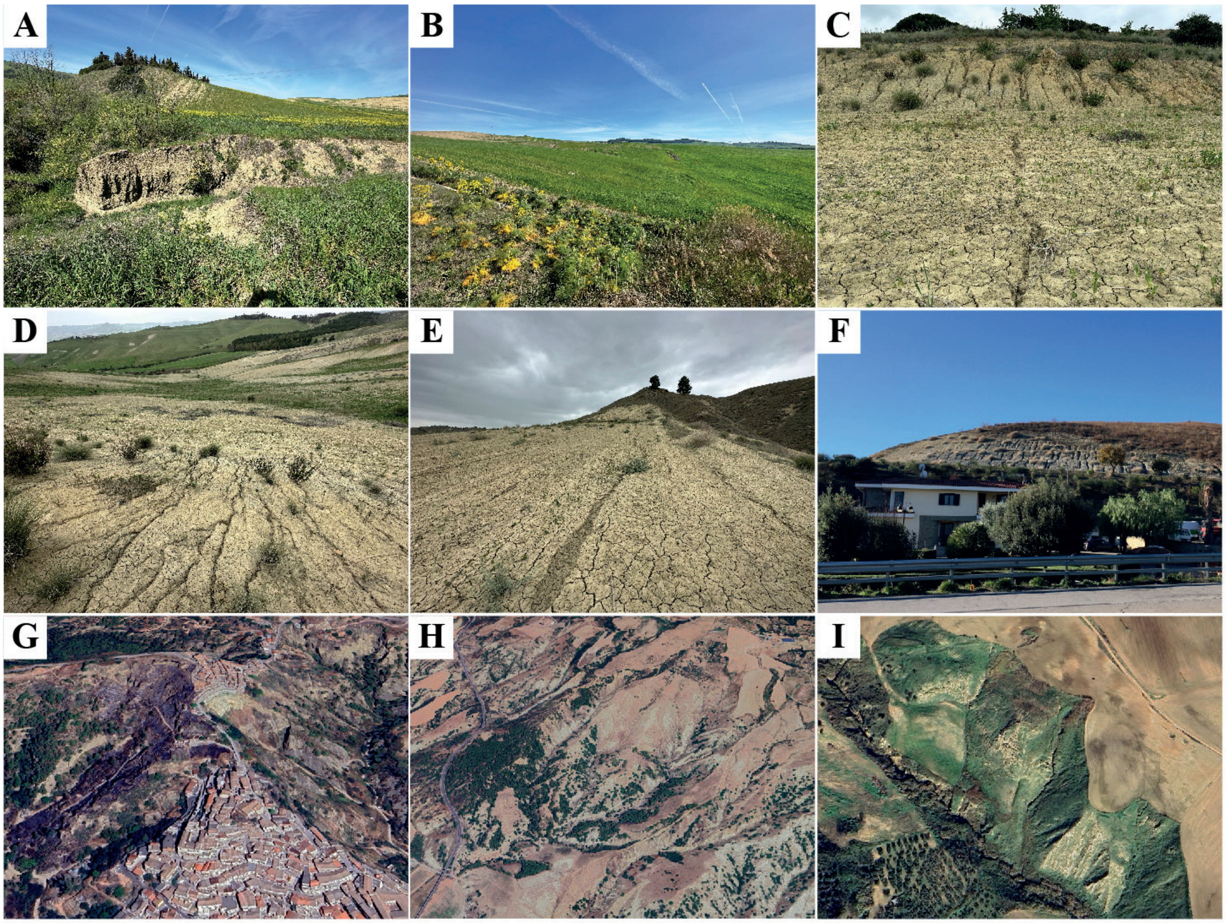

Fig. 5. Pictures and Google Earth images showing: some accelerated erosion landforms from Basilicata. A) and B) Picciano sub-catchments (Bradano River valley); C), D) and E) Fosso di Salati catchment, detail of linear erosion (Bradano River valley); F) accelerated erosion on anthropically modified slope (Basento River valley); G) accelerated erosion landforms from Sinni River valley; H) Le Vigne catchment (Basento River valley); I) accelerated erosion in the Bradano River valley

fluctuated between 48 days (2017) and 86 days (2014), with an average of 68 days/year. The Standardised Daily Intensity Index (SDII), which represents the mean rainfall intensity on wet days, showed values ranging from 6.5 mm/day to 9.6 mm/day, suggesting a moderate to high intensity of precipitation events, even during years with lower overall rainfall totals. Notably, the number of extreme multi-day rainfall events (three-day cumulative precipitation exceeding 30 mm) occurred between four and 13 times per year, with isolated years (e.g., 2019 and 2020) showing over four events, with a maximum of eight events exceeding 50 mm in three consecutive days recorded in 2020. The percentage of annual rainfall during these short-term intense events remains low in most years, with occasional spikes up to 96.7% in 2020, likely reflecting concentrated precipitation episodes in otherwise dry years. Dry days remained consistently high, averaging 294 days per year, highlighting the region's semi-arid character. The number of hot days exceeding 30°C showed a slight increasing trend, peaking at 72 days in 2022, further indicating a shift toward more frequent heat extremes.

The percentile analysis of precipitation data for 2013–2023 (Table 3) provides further insights into the temporal variability of rainfall intensity in the Matera area. The 90^{th} percentile daily rainfall ranged between 2.4 mm (2017) and 6.12 mm (2016), whereas the 95^{th} percentile varied from 7 mm (2017) to 10.3 mm (2015). The 98^{th} percentile related to three-day rainfall values peaked at 50.7 mm in 2020, indicating the occurrence of isolated but very intense daily rainfall events.

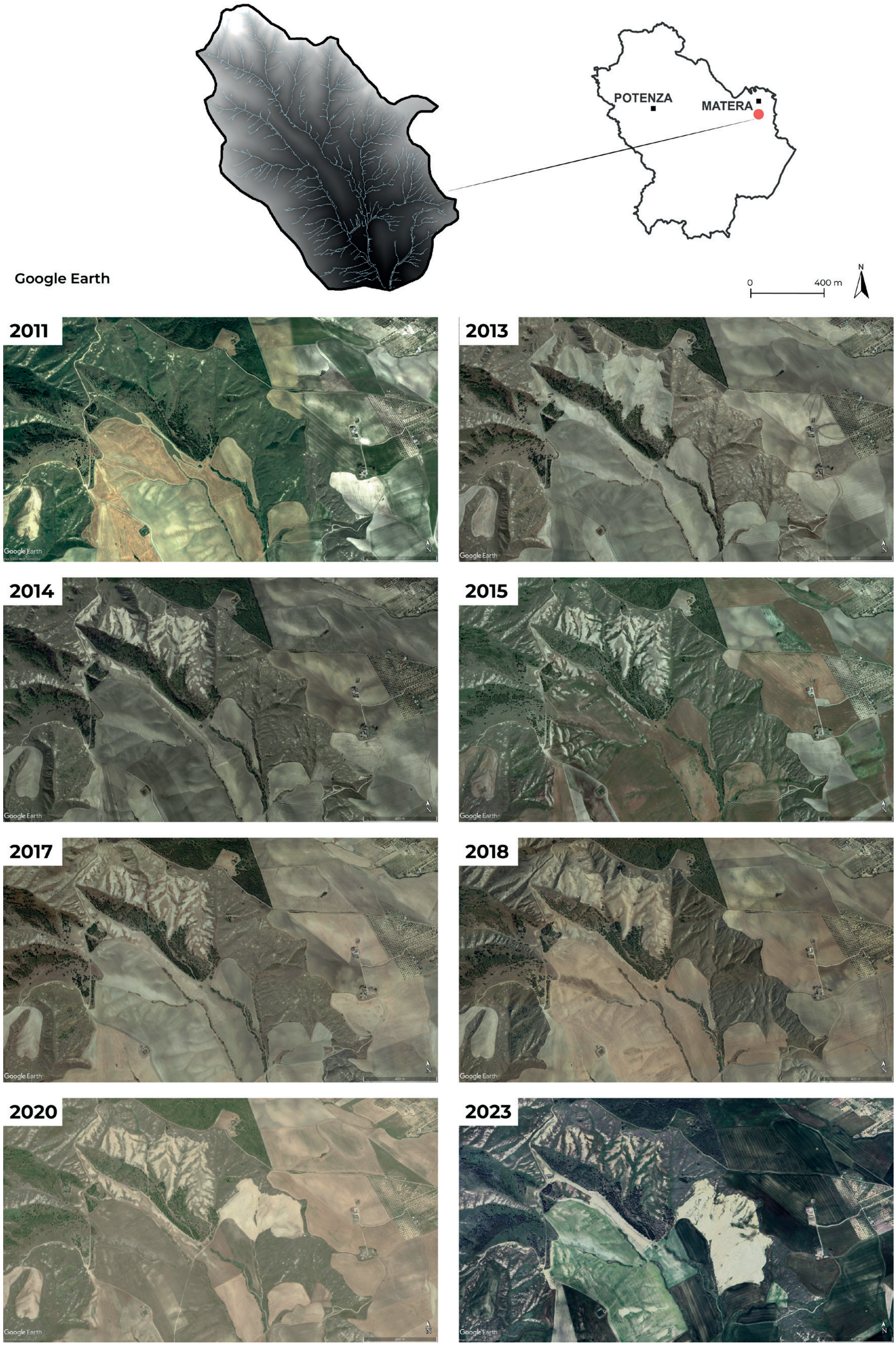

Fig. 6. Multi-temporal satellite images (True-colour from Sentinel-2 L1C) comparison from 2015 to 2023 of Fosso di Salati sub-basin

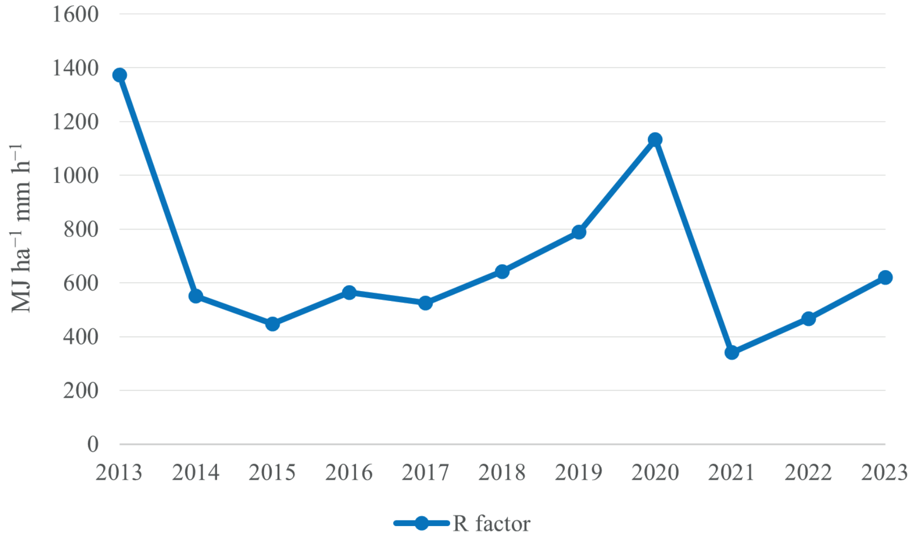

Fig. 7. Rainfall erosivity occurred from 2013 to 2023, computed analysing hourly rainfall data related to Matera weather station

Table 3. Main rainfall and temperature values for the Matera weather station from 2013 to 2023

Year	Total annual PRCP (mm/y)	N. Rainy days	N. Dry days	N. Hot days T.max >30°	SDII – Mean rainfall intensity (mm/day)	90th Percentile	95th Percentile	3-day cumulated PRCP mm)	Events >30 mm in 3 days (events/y)	Events >50 mm in 3 days (events/y)	Annual rainfall in 3 days (%)
2013	651.2	73	286	53	8.9	4.2	9.1	4.2	9	3	67.5
2014	580.4	86	277	39	6.7	4.1	8.7	11.8	11	0	0.0
2015	555.4	68	296	66	8.1	4.4	10.3	26.8	8	0	0.0
2016	585.6	72	288	52	8.1	6.1	10.3	26.2	10	1	9.1
2017	434.6	48	311	71	9.0	2.4	7.0	18.4	13	0	0.0
2018	610.0	79	282	51	7.7	5.2	9.9	1.2	11	1	8.3
2019	581.4	70	290	71	8.3	4.5	9.3	0.2	9	5	53.8
2020	627.2	65	300	53	9.6	4.0	7.5	0.0	10	8	96.7
2021	400.0	61	301	69	6.5	3.1	7.7	0.0	5	0	0.0
2022	472.2	64	299	72	7.3	3.5	9.1	0.0	4	0	0.0
2023	505.0	64	300	66	7.8	3.6	8.8	0.0	7	3	38.1
MEAN	545.7	68	294	60	8.0	4.1	8.9	8.1	9	~2	24.9
MAX	651.2	86	311	72	9.6	6.1	10.3	26.8	13	8	96.7
MIN	400.0	48	277	39	6.5	2.4	7.0	0.0	4	0	0.0

Seasonally, the winter months recorded the highest rainfall totals, with annual values ranging from 88.8 mm (2016) to 246 mm (2013). Autumn also represented a significant contribution to the annual balance, ranging from 127 mm (2017) to 212.8 mm (2020). Conversely, spring showed more variability, with a minimum of 76.6 mm (2022) and a maximum of 222.8 mm (2014). Summer precipitation was consistently lower but not negligible, fluctuating between 41.6 mm (2021) and 193.6 mm (2020). The number of rainy days per season followed a similar pattern, with winter and autumn hosting the majority of events, though summers like 2018 and 2020 recorded an unusually high number of rainy days, that is 18 and 16 days, respectively (Table 4). The seasonal breakdown of rainfall percentiles further highlights significant intra-annual variability in the intensity of precipitation events. The 90th percentile of daily rainfall showed values ranging from 2.6 mm (2015) to 5.6 mm (2017) for winter; from 1.7 mm (2017) to 6.9 mm (2014) for spring; from 0 mm (2017) to 7.2 mm (2016) for summer; and from 3.4 mm (2017) to 6.4 mm (2015) for autumn. Similarly, the 95th percentile exhibited the following seasonal ranges: from 5.8 mm (2014) to ~11 mm (2015) for winter; from about 5 mm (2013) to 11.8 mm (2016) for spring; from 0.6 mm (2017) to 13.1 mm (2016) for summer; and from 6.6 mm (2017) to 12.4 mm (2015) for autumn. These results underline that autumn and winter are the seasons with the highest rainfall intensity, although isolated intense summer events occurred (e.g., 2016), suggesting a shift toward more erratic seasonal rainfall patterns.

Discussion

The role of climate change on accelerated erosion processes is becoming increasingly relevant, and it is widely believed that the most impactful climate factor on erosion processes is rainfall. It is important to consider the ability of rainfall and surface runoff to perform "geomorphic work" in the sense of removing material and modifying the landscape (Piccarreta et al. 2005). Basilicata is one of the areas most exposed to hydrogeological risk and, in some areas, to desertification processes. This makes it a significant example of a Mediterranean semi-arid area where climate change is rapidly inducing a landscape evolution.

As river systems provide valuable evidence of landscape evolution in a particular climatic context, measuring certain geomorphic parameters means monitoring and understanding fluvial evolution over time (i.e., drainage density, channel size, morphological patterns, sedimentation and channel migration rates, and valley floor widening and narrowing processes, cf. Rinaldi et al. 2011; Scorpio et al. 2015; Zingaro et al. 2023, among others). The erosion rates of landforms characterised by complex hydro-geomorphological dynamics, very intense erosional processes and extreme sediment production represent a key element in understanding soil erosion processes and geomorphic changes due to extreme events. The role of vegetation in these areas is another important factor in evaluating the effectiveness of the erosive processes: the removal of vegetation cover due to human activity and the consequent denudation of slopes can strongly influence the morphogenesis of gullies.

Moreover, since foot slopes can represent a temporary space for subaerial sedimentation, the gullying process may favour the deposit supply to the main valley, especially from poorly vegetated slopes. These facts mean that collecting information on the source areas and mobilised volumes is a fundamen-

Table 4. Seasonal rainfall values for the Matera weather station from 2013 to 2023

Year	Annual PRCP Winter (mm/y)	Annual PRCP Spring (mm/y)	Annual PRCP Summer (mm/y)	Annual PRCP Autumn (mm/y)	N. Winter Rainy days	N. Spring Rainy days	N. Summer Rainy days	N. Autumn Rainy days
2013	246.0	100.4	158.0	146.8	21	19	14	19
2014	116.6	222.8	80.4	160.6	20	29	15	22
2015	129.2	155.0	102.8	168.4	17	20	11	20
2016	88.8	172.4	172.4	152.0	13	24	15	20
2017	153.4	90.0	64.2	127.0	18	10	5	15
2018	97.8	136.0	191.4	184.8	18	19	18	24
2019	144.8	181.8	62.4	192.4	21	27	7	15
2020	100.2	120.6	193.6	212.8	13	19	16	17
2021	103.4	90.6	41.6	164.4	20	14	7	20
2022	91.2	76.6	141.2	163.2	20	15	12	17
2023	92.2	213.4	141.0	58.4	15	26	13	10
MEAN	130.1	142.9	121.9	154.2	18	20	12	18
MAX	246.0	222.8	193.6	212.8	21	29	18	24
MIN	88.8	76.6	41.6	58.4	13	10	5	10

tal step towards a better understanding of geomorphic changes caused by extreme events (Coratza and Parenti 2021). In addition, data on multi-temporal rainfall and temperature values, the distribution of dry and wet periods, and flood-event frequency are valuable in the monitoring of how climate change controls landscape evolution. Rainfall erosivity constitutes a relevant factor for understanding the hydrological and geomorphologic processes taking place in a landscape, such as soil erosion, mudflows, flash floods, and so on (Capolongo et al. 2007).

The test sites preliminarily chosen from a significant portion of the region and particularly from the hydrographic basin of the Bradano and Basento rivers show clear features of accelerated erosion processes, such that the development of rills and gullies is the main erosion process of the study area (Fig. 5). The rainfall data from 2013 to 2023 (Table 3) confirm that precipitation in the Matera area is highly variable, both in terms of annual totals and the frequency of intense events. Years like 2013 and 2019 were relatively wet, whereas 2017 and 2021 recorded the lowest totals, consistent with the Mediterranean climatic pattern characterised by alternating wet and dry years. Despite relatively stable annual totals over the decade, the data reveal a trend toward increasing rainfall intensity, as evidenced by the high SDII (Simple Day Intensity Index) values, particularly in 2015, 2016 and 2020. The frequent occurrence of short-term extreme events, including multiple three-day periods exceeding 30 mm, suggests an elevated geomorphological risk, especially in relation to soil erosion and shallow landsliding. The extreme concentration of rainfall in few events, as highlighted by the anomalously high percentage values in 2020 – coincident with a high rainfall erosivity value (Fig. 7) – could lead to runoff amplification, reduced infiltration and surface instability, particularly when preceded by long, dry periods or extreme heatwaves. This pattern is consistent with broader climate change projections for Mediterranean regions that predict an increase in rainfall concentration and extreme weather events. The seasonal disaggregation of rainfall reveals a clear winter–autumn dominance in total precipitation, which is typical of Mediterranean climates. However, the high values of summer rainfall in 2020 and 2018, accompanied by an above-average number of rainy days (Table 4), suggest the increasing occurrence of out-of-season storms or convective events, which may lead to localised but severe geomorphological impacts such as flash floods and gully formation. Years like 2015, 2016 and 2020 stand out as periods of elevated hydrological stress, where both seasonal totals and extreme percentile values converge, increasing the risk of concentrated erosion and geomorphic adjustments. The analysis of seasonal rainfall percentiles confirms that autumn and winter remain the dominant seasons for high-intensity rainfall events in the Matera area. However, the notable peaks recorded in summer 2016, reaching up to 7.2 mm and 13.1 mm, indicate that extreme summer events, although less frequent, can be particularly severe. The presence of zero or near-zero summer percentiles in 2017 further emphasises the high interannual variability typical of Mediterranean semi-arid regions. These fluctuations have critical implications for soil moisture dynamics, as long, dry spells followed by sudden, high-intensity rainfall can enhance surface runoff, gully erosion and flash flood risks. By combining seasonal rainfall totals with percentile-based intensity thresholds, this analysis provides a more comprehensive understanding of the temporal distribution of geomorphological drivers, supporting the development of seasonally adjusted hazard mitigation strategies.

Conclusions and future perspectives and improvements

The database framework of geomorphological indicators of climate change that we proposed herein appears to represent an efficient tool for analysing and monitoring the impact of global change in a very short time span, using appropriate methodologies and referring to data from literature to compare results. The originality of such a database lies primarily in its multiscale and multitemporal approach. While many existing tools focus on single indicators or specific scales, this one integrates data at different levels – from local through regional to global – creating a comprehensive picture of the impact of climate change on geomorphology. Furthermore, we have paid particular attention to practical applicability. The multiscale methodology is deliberately flexible and adaptable to contexts that differ in data availability, making it applicable even in areas with less-developed monitoring infrastructures. The identified “universal” geomorphological indicators can maintain their validity in different geological conditions, allowing interregional comparisons.

In this way, it may represent for geoscientists a procedural protocol for estimating the impact of global change in semi-arid areas, based on a large series of multi-scale proxies; it may also allow public administrations, national technical departments and research institutes to evaluate actions and strategies for risk mitigation. Such an approach may offer public administrations a concrete tool for identifying and prioritising areas at greatest risk, allowing for more efficient allocation of resources. It also enables the evaluation of the effectiveness of adaptation measures already implemented, providing objective feedback based on measurable data. Of course, such a framework is not to be considered an exhaustive collection of geomorphological markers for climate change analyses, but it would represent a first step in improving techniques of landscape evolution monitoring to correctly estimate soil-erosion-influencing factors for more efficient and accurate soil conservation (Wang et al. 2024). Using the methodological approach we propose for areas that share similar characteristics may help to evaluate its transferability, thereby extending its applicability.

The proposed model still presents several limitations. Among the most complex challenges is the integration of multi-scale and multi-temporal data. To address this, it is necessary to develop normalisation systems capable of ensuring the comparability of data that differ in spatial and temporal resolution. Another critical issue is distinguishing the climatic signal from other influencing factors, such as land-use changes or local geological dynamics. In this regard, the adoption of advanced statistical techniques and modelling approaches may help to effectively isolate and analyse the contribution of each variable. Uncertainty management also remains a central challenge: every methodology carries an intrinsic degree of uncertainty, which must be properly quantified and managed – especially when combining heterogeneous datasets – to ensure the reliability of final outcomes.

Looking ahead, the increasing pace of climate change will undoubtedly require continuous methodological adaptations. Enhancing the frequency of data acquisition will become crucial in order to detect extreme and rapidly evolving events, likely pushing toward the implementation of real-time, continuous monitoring systems. Artificial intelligence offers promising potential, particularly in the automatic identification of geomorphological markers from satellite and aerial imagery, which would significantly accelerate the updating of the database. In parallel, the development of an interactive cloud-based platform providing near real-time updates – connected to a distributed network of monitoring stations across the Mediterranean – could represent a strategic evolution of the current system. Such a platform could serve as a shared decision-making tool that would be accessible to a wide range of stakeholders, especially if integrated with other environmental and socio-economic databases to offer a more holistic view of ongoing transformations.

Furthermore, approaches derived from agronomic and forestry sciences – focused on specific markers – should be incorporated to more accurately characterise vulnerable areas. The inclusion of palaeo-climatic data will also become increasingly important to contextualise current dynamics within longer-term environmental trends. Several promising research directions are emerging in this field. One particularly innovative path involves the development of geomorphological biomarkers that integrate biological and physical processes, shedding light on the interactions between vegetation, microorganisms and erosive dynamics.

Disclosure statement

No potential conflict of interest was reported by the authors

Author contributions

Study design: LC, MS; data collection: LC, PG, MS; statistical analysis: LC, GC; interpretation of results: LC, GC, PG, MS; preparation of manuscript: LC, MS; literature review: LC, MS.

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