Geografia Fisica e Dinamica Quaternaria
GFDQ 48 (2025), 59-71

DOI 10.4454/fgrt74jk

Giulia IACOBUCCI[1], Valeria RUSCITTO[1*], Michele DELCHIARO[1], Francesco TROIANI[1], Marta DELLA SETA[1], Daniela PIACENTINI[1]

The contribution of Geomorphology on climate services: recent developments on the assessment of climate-impact indicators in the frame of the PNRR RETURN project

Abstract: Iacobucci G., Ruscitto V., Delchiaro M., Troiani F., Della Seta M., Piacentini D., *The contribution of Geomorphology on climate services: recent developments on the assessment of climate-impact indicators in the frame of the PNRR RETURN project.* (IT ISSN 0391-9838, 2025). As part of Italy's National Recovery and Resilience Plan (PNRR), the Extended Partnership RETURN (multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate) aims at strengthening advancing research chains on climate-related environmental risks, to enforce the key competences, the technological and knowledge transfer, and to strengthen Italian governance in managing them. According to the National System for Environment Protection SNPA (2021), a *climate impact indicator* describes the consequences of climate variability on ecological, social, and economic functions, as well as on human and animal health. In this perspective, the present research intends to discern the climate-impact indicators for different natural sectors (mountainous and hilly, alluvial plain, and coastal environments). The Geomorphology Group of Sapienza University of Rome contributed to the project focusing on three specific indicators: i) landslide frequency and distribution (mountainous and hilly environments); ii) river channel bankfull variations (alluvial plain environment); iii) shoreline position and morphology (coastal environment). In mountainous and hilly sectors, landslides serve as key geomorphic indicators of climate change. Changes in rainfall regime as well as the snow cover variability can influence landslide occurrence. Rainfall acts both as a preparatory factor, gradually saturating soil layers, and as a triggering factor, rapidly initiating failures during high-intensity events. Meanwhile, variability in snow accumulation and melting influences pore water pressures in soil and contributes to slope failure during critical periods of thaw. In the alluvial plain sector, the confinement index – defined as the ratio between the active channel (bankfull) and the floodplain width - can be considered as one of the most representative climate-impact indicators capable of recording the climate change impact, specifically through changes in rainfall regime and related discharge variations. Finally, in the coastal sector, shoreline position and its morphological variations are recognized as a key indicator for coastal zones, since its configuration is constantly evolving due to both natural factors (e.g., waves, sea level fluctuations, tides, wind, and currents) and anthropogenic forcing.

Key words: Climate services, RETURN project, Geomorphic impact indicators, Climate change.

Riassunto: Iacobucci G., Ruscitto V., Delchiaro M., Troiani F., Della Seta M., Piacentini D., *Il contributo della Geomorfologia ai servizi climatici: sviluppi recenti nella valutazione degli indicatori di impatto climatico nell'ambito del progetto PNRR RETURN.* (IT ISSN 0391-9838, 2025). Nell'ambito del Piano Nazionale di Ripresa e Resilienza (PNRR), la Partnership Estesa RETURN (*multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate*) si propone di rafforzare e sviluppare le catene di ricerca sui rischi ambientali legati al clima, con l'obiettivo di consolidare le competenze chiave, favorire il trasferimento tecnologico e di conoscenze, e potenziare la governance italiana nella loro gestione. Secondo il Sistema Nazionale per la Protezione dell'Ambiente (SNPA, 2021), un *indicatore di impatto climatico* descrive le conseguenze della variabilità climatica sulle funzioni ecologiche, sociali ed economiche, nonché sulla salute umana e animale. In questa prospettiva, la presente ricerca intende individuare gli indicatori di impatto climatico per differenti settori naturali (montuosi e collinari, pianura alluvionale e ambienti costieri). Il Gruppo di Geomorfologia della Sapienza Università di Roma ha contribuito al progetto concentrandosi su tre indicatori specifici: i) frequenza e distribuzione delle frane (ambienti montuosi e collinari); ii) variazioni della sezione idraulica del canale attivo fluviale o bankfull (pianura alluvionale); iii) posizione e morfologia della linea di riva (ambienti costieri). Negli ambiti montuosi e collinari, le frane rappresentano indicatori geomorfologici chiave del cambiamento climatico. Le modifiche nei regimi di precipitazione, così come la variabilità del manto nevoso, possono influenzarne l'occorrenza. Le precipitazioni agiscono sia come fattore preparatorio, saturando progressivamente il suolo, sia come fattore innescante, attivando rapidamente i movimenti di massa durante eventi di alta intensità. Parallelamente, la variabilità nell'accumulo e nello scioglimento della neve influenza le pressioni interstiziali nel terreno, contribuendo all'innesco di instabilità durante i periodi critici di disgelo. Nel settore di pianura alluvionale, l'indice di confinamento – definito come il rapporto tra l'alveo attivo (*bankfull*) e l'ampiezza della pianura alluvionale – può essere considerato uno degli indicatori di impatto climatico più rappresentativi, capace di registrare gli effetti dei cambiamenti climatici in particolare attraverso le variazioni dei regimi pluviometrici e delle relative portate fluviali. Infine, nel settore costiero, la posizione della linea di riva e le sue variazioni morfologiche sono riconosciute come un indicatore chiave per le zone costiere, poiché la sua configurazione è in costante evoluzione sotto l'effetto sia di fattori naturali (onde, fluttuazioni del livello del mare, maree, vento e correnti), sia di forzanti antropiche.

Termini chiave: Servizi climatici, Progetto RETURN, Indicatori geomorfici di impatto, Cambiamento climatico.

[1] *Department of Earth Sciences, Sapienza University of Rome, Rome (Italy).*

**Corresponding author: Valeria Ruscitto (valeria.ruscitto@uniroma1.it)*

Paper published on the 25th anniversary of AIGeo, the Italian Association of Physical Geography and Geomorphology. GFDQ vol. 48, Guest Editors: Pappalardo M., Rotigliano E., Ferrando A.

INTRODUCTION

As part of the National Recovery and Resilience Plan (PNRR) *Italia Domani*, the Extended Partnership PE3 - RETURN is committed to strengthening national research capacity on environmental, natural, and anthropogenic risks, while enhancing participation in European and global strategic value chains. The RETURN initiative contributes to consolidating key competencies, promoting technological and knowledge transfer, and engaging public administrations, stakeholders, and the private sector.

The primary scientific objectives of RETURN are to:

i) advance knowledge of environmental, natural, and anthropogenic risks, particularly in relation to climate change;
ii) improve prevention, adaptation, and mitigation strategies;
iii) develop new methodologies and technologies for risk monitoring;
iv) promote more effective use of data, products, and services;
v) strengthen the link between research and actionable outputs.

The PE3 RETURN is structured into four Vertical Spokes (VS), each dedicated to specific risk categories: i) VS1: Water-related risks; ii) VS2: Ground instabilities; iii) VS3: Earthquakes and volcanoes; iv) VS4: Environmental degradation. It also includes three Transversal Spokes (TS), addressing the impact of risks on populations, buildings, and critical infrastructure, and supporting mitigation through citizen engagement before, during, and after disasters: i) TS1: Urban and metropolitan settlements; ii) TS2: Multi-risk resilience of critical infrastructures; iii) TS3: Community resilience to risks. A Diagonal Spoke (DS) focuses on climate change as the overarching driver of many hazards – such as floods and landslides – providing cross-sectoral coordination.

To identify specific climate- and weather-related hazards, the DS has defined climate-impact indicators tailored to natural systems, as referenced in the SNPA Report (2021). *Climatic-impact* is defined (IPCC, 2023) as the effect on natural and human systems caused by extreme meteorological and climatic events or ongoing climate change within a given timeframe. A *climate indicator* serves to describe climate patterns and their evolution over time, supporting the understanding of the causes behind the climatic impact. In turn, *climate-impact indicators* describe how the effects of climate variability induced changes in ecological, social, and economic functions, as well as in human and animal health. In the frame of the RETURN project, the joint initiative *Adopt an Indicator* has been crucial in identifying the most significant *climate-impact indicators* for predicting extreme geomorphic events across various natural environments, under a changing climate. The purpose of this work is to highlight the contribution of geomorphology and current methodological approaches in assessing geomorphic indicators of climate change across mountainous and hilly (separated by the 600 m a.s.l. marker), alluvial plain, and coastal environments (fig. 1).

MOUNTAIN AND HILL ENVIRONMENTS

Mountain and hilly landscapes are among the most dynamic geomorphic systems on Earth and are particularly sensitive to changes in climatic conditions. The assessment of climate change impacts on these environments represents a significant scientific and societal challenge (e.g., Alvioli *et al.*, 2018; IPCC, 2023). In these sectors, geomorphology provides critical insight into the detection and interpretation of climate-sensitive landscape changes. Of particular importance are landslides, which serve as key geomorphic indicators of climate change. The latest landslide classifications went deep into the mass wasting processes and the proper-

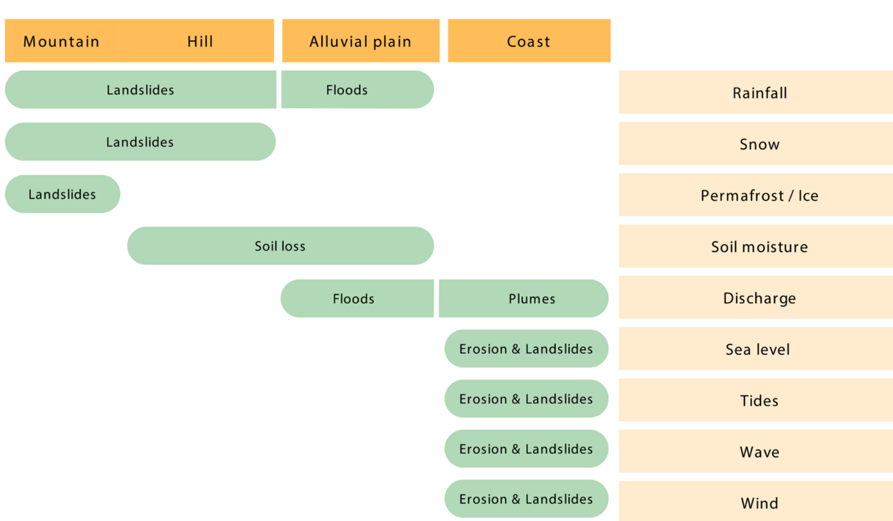

Figure 1 - Schematic representation of the impacts (green) associated to each variable (light orange) and natural geomorphic environments (orange).

ties of involved geomaterials, thus contributing significantly to the detection of predisposing, preparatory and triggering factors for landslides (Hungr *et al.*, 2013). These processes vary in style, ranging from flows and slides to topples and falls, and often occur in combination, evolving over time and space. Beyond shaping the physical landscape, landslides pose severe threats to infrastructure and human life (Petley, 2012). Slope stability is influenced by a suite of environmental and anthropogenic factors, including precipitation intensity and frequency, snowmelt, temperature fluctuations, seismic activity, and land use changes. Among these, climate and its variability are pivotal, particularly in regulating precipitation and temperature regimes (e.g., Crozier, 2010; see fig. 2). Two key climate-related variables affecting slope stability are snow cover and rainfall patterns. Variability in snow accumulation and melting influences pore water pressures in soils and contributes to slope failure during critical periods of thaw. Rainfall, on the other hand, acts both as a preparatory factor, gradually saturating soil layers, and a triggering factor, rapidly initiating failures during high-intensity events (Popescu, 2002). Interactions with other drivers such as wildfires, vegetation loss, or earthquakes further complicate the picture and must be integrated into comprehensive climate-landslide assessments.

Nevertheless, our understanding of how climate variability and change influence landslide activity remains limited and uncertain (Dijkstra and Dixon, 2010). While advances in climate modeling allow for increasingly reliable projections of temperature and precipitation patterns (Giorgi and Lionello, 2008; Ciccarelli *et al.*, 2008; IPCC, 2023), the translation of these outputs into predictions of slope behavior, landslide frequency, and hazard dynamics is far from straightforward (Gariano and Guzzetti, 2016; Gariano *et al.*, 2017).

Methodological approaches

To investigate the effects of climate change on landslide activity in mountain and hilly environments, researchers have adopted modelling, empirical, or combined approaches. These approaches differ in spatial and temporal scales, data requirements, and their capacity to incorporate future climate scenarios.

The modelling approach focuses on simulating variations in slope stability driven by forecasted climatic changes, especially rainfall and pore water pressure, derived from downscaled outputs of global climate models (Fowler *et al.*, 2007). These synthetic climate series are then used as inputs for physically-based, statistical, or regional slope stability models. Gariano and Guzzetti (2016, and reference therein) reveal that a common limitation is that the calibration period, based on observed data, is often much shorter than the projection period, potentially undermining the reliability of future forecasts (e.g., Coe, 2012; Gassner *et al.*, 2015).

In contrast, the empirical approach is rooted in the analysis of historical or paleo-environmental records of landslide occurrences, aiming to identify correlations with climatic variables such as temperature and precipitation. This approach can be subdivided into two main types:

- The historical empirical approach compares landslide inventories with climatic records spanning decades to centuries. These studies often focus on detecting recent trends and anomalies in landslide occurrence relative to climate fluctuations.
- The paleo-environmental empirical approach reconstructs landslide histories over millennial timescales, using stratigraphic, geomorphic, or sedimentological evidence to identify periods of heightened or reduced landslide activity. These studies, covering the Last Glacial Maximum to the Holocene (from ~40,000 BP to the 20th century), provide long-term baselines for understanding the impact of past climatic transitions.

The spatial extent of the studies also varies significantly. Most model-based approaches are conducted at the local scale, often focusing on individual slopes or single landslide sites (e.g., Buma and Dehn, 1998; Dehn and Buma, 1999; Comegna *et al.*, 2013). Only some studies have expanded to assess populations of landslides in homogeneous geomorphological areas (Jakob and Lambert, 2009; Chang and Chiang, 2011; Ciabatta *et al.*, 2016). On the other hand, empirical approaches typically operate at regional scales (e.g., Fischer *et al.*, 2013; Polemio and Petrucci, 2010; Wood *et al.*, 2016; Brunetti *et al.*, 2025). More recently, integrated approaches have emerged that incorporate future climate projections into regional-scale assessments of landslide susceptibility and hazard, including applications in early warning systems (e.g., Piciullo *et al.*, 2018; Guzzetti *et al.*, 2020).

Overall, the current body of research underscores the need for improved integration of geomorphological data, climate projections, and multi-scale modeling to enhance our understanding of landslide responses to climate change in mountain and hilly systems. This integration is essential for developing effective mitigation and adaptation strategies tailored to these sensitive and high-risk environments.

ALLUVIAL PLAIN ENVIRONMENT

The alluvial plain sector is extremely receptive to changes in environmental variables, in particular changes in rainfall regime and consequential discharge variations and sediment transport. Notably, there is a clear connection between changes in climate conditions and flood occurrence (Blöschl *et al.*, 2019). Publications investigating comparatively the river trends in the last decades reported the occurrence of a series of major floods in Europe (Ulbrich

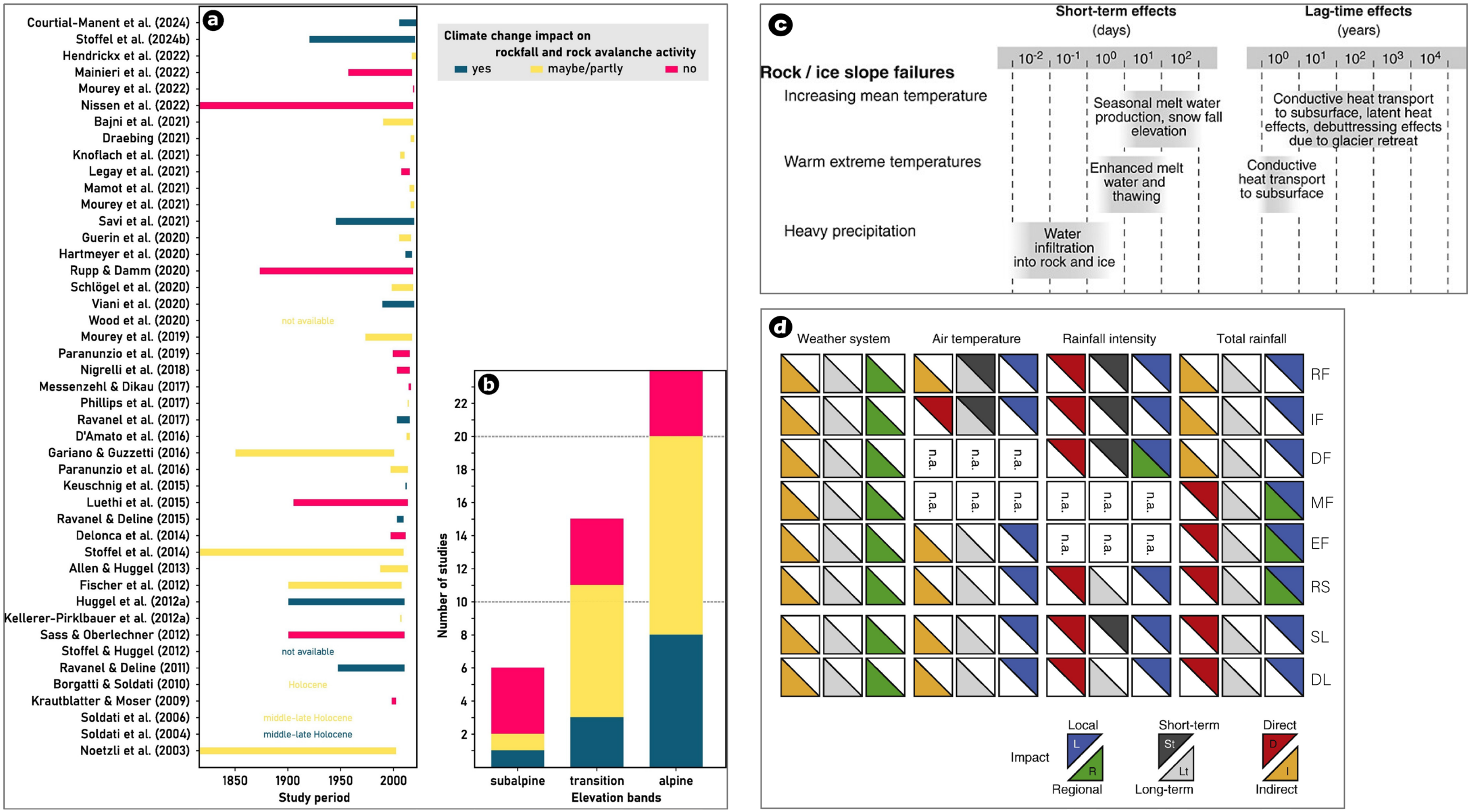

Figure 2 - From Jacquemart *et al.* (2024) *a*nd references therein, studies on observed climate change impacts on rockfall activity and rock avalanches. (a) Publications considered in the review with corresponding study period. (b) Bar plot showing the number of publications and whether they detected an impact of climate change, by elevation; (c) From Huggel *et al.* (2012) temporal relationships between processes that affect slope stability and climate drivers; (d) From Gariano and Guzzetti (2016) the geographical, temporal, direct and indirect expected impact is shown, respective to four climate variables and eight landslide types (RF, rock fall/avalanche; IF, ice fall/avalanche; DF, debris flow; EF, earthflow; MF, mudflow; RS, rock slide; SL, shallow landslides; DS, deep-seated landslides, columns).

et al., 2003; Hannaford and Marsh, 2008, Pinskwar *et al.*, 2012, Kundzewicz *et al.*, 2013) and Italy (Montanari, 2012). Extreme precipitation events will become more intense and frequent by the end of the century (IPCC, 2023), indicating an increased likelihood of major flood events in the future. The physical causes of flood regime changes in the river system can be grouped into different categories of drivers, among which are river training, hydraulic structures and sediment trapping (Surian and Rinaldi, 2003; Luppichini *et al.*, 2024). Those drivers affect river morphology and associated water level, discharge and river channel vegetation, influencing the flood wave propagation (Hall *et al.*, 2014).

Analyzing river morphology is therefore fundamental for flood prediction. Moreover, geomorphic features identification is essential for understanding the relationship between such natural processes and the associated risks to human safety. By the use of Digital Terrain Models (DTMs) geomorphic features can be identified and river morphology analyzed. Among floodplain features, the *confinement index*, as the ratio between the active channel width (also called bankfull width) and the floodplain width, can be considered the most representative climate-impact indicator. The semi-automatic extraction of this parameter can be a considerable ally in the definition of the impact of climate change on the alluvial plain sector.

Methodological approaches

The term 'bankfull' refers to the water level (also called stage) that approximates the elevation above the thalweg and the associated width at which the water surface is at a condition of incipient flooding (Williams, 1978). Correspondingly, bankfull discharge is regarded as the channel-forming or effective discharge (e.g., Phillips *et al.*, 2022), with a recurrence interval of about 1.5 years (Wolman and Leopold, 1957; Wolman and Miller, 1960). Bankfull channel stage and discharge serve as consistent morphological indices, which can be related to the formation, maintenance, and dimensions of the channel under the modern climatic regime (Rosgen, 1997). Different methodologies are employed for extracting the bankfull stage that can be classified into the following groups (Keast and Ellison, 2022): i) qualitative field observations ii) hydrological modelling, and iii) geometric terrain classification.

- The first group involves on-field identification of bankfull indicators, represented by a collection of distinct and consistent geomorphic features that align to the water surface elevation at the time of field study (Schumm, 1960; McCandless, 2003; Lee and Choi, 2018). While this approach offers detail and precision, especially if paired with the use of geodetic instruments, it is expensive and time-consuming, making it unsuitable for broad-scale applications across extensive river networks.
- The hydrological modelling approach comprehends various techniques including stage-discharge curves, that describe river discharge as a function of water-surface elevation, and numerical simulations (e.g., HEC-RAS; Eidmann and Gallen, 2023; Soil and Water Assessment Tool SWAT, Douglas-Mankin *et al.*, 2010), that enable the reconstruction of bankfull channel stage and discharge, starting from a LiDAR (Light Detection and Ranging) DTM of the stream area. In the HEC-RAS method (Brunner, 1995) the one-dimensional (1D) Steady Flow hydraulic model allows users to intervene in the initial stages, specifically in the delineation of the stream and banks, to ultimately obtain the bankfull discharge and stage. Implementing this methodology requires advanced expertise in specialized software, as well as access to data describing key riverbed characteristics (e.g., roughness and grain size), which are often difficult to measure accurately.
- Geometric terrain classification techniques use measurable morphological parameters to derive a variety of fluvial indicators. In the case of the bankfull stage, this approach identifies morphological inflection points along the river's cross-sectional profile to delineate the bankfull geometry, enabling reproducible and objective assessments.

Among these different approaches, Delchiaro *et al.* (2025) implement the geometric terrain classification method within the *BankfullMapper* tool, developed in MATLAB. This tool is designed to remotely extract from high-resolution DTMs the bankfull geometry along river channels and adjacent floodplains, with a particular focus on semi-confined channels, where it supports the estimation of bankfull discharge and the analysis of morphological dynamics. This underscores its potential for monitoring spatial and temporal changes in bankfull conditions. By tracing cross-sections transversal to the river centerline, the tool computes the hydraulic depth of the river at 10 cm increments from the thalweg, delineating profiles relative to each section (fig. 3). Breakpoints in channel morphology (that can be associated with potential bankfull stages) are indicated by the peaks in the profiles. By selecting the peaks (see fig. 4), the bankfull elevation correspondent to each section is extracted, together with the area and perimeter of the channel. This semi-automated methodology effectively extracts riverbank geometry (see fig. 5) and can also estimate the associated bankfull discharge with high accuracy, with the application of Manning's equation (Manning, 1904) from the extracted geometry. The results are scalable, adaptable insights into river morphology, also requiring, however, careful consideration in areas affected by human activities or complex terrain. Future improvements – such as enhanced field validation and parameter tuning – will further refine the precision of the tool and broaden its applicability.

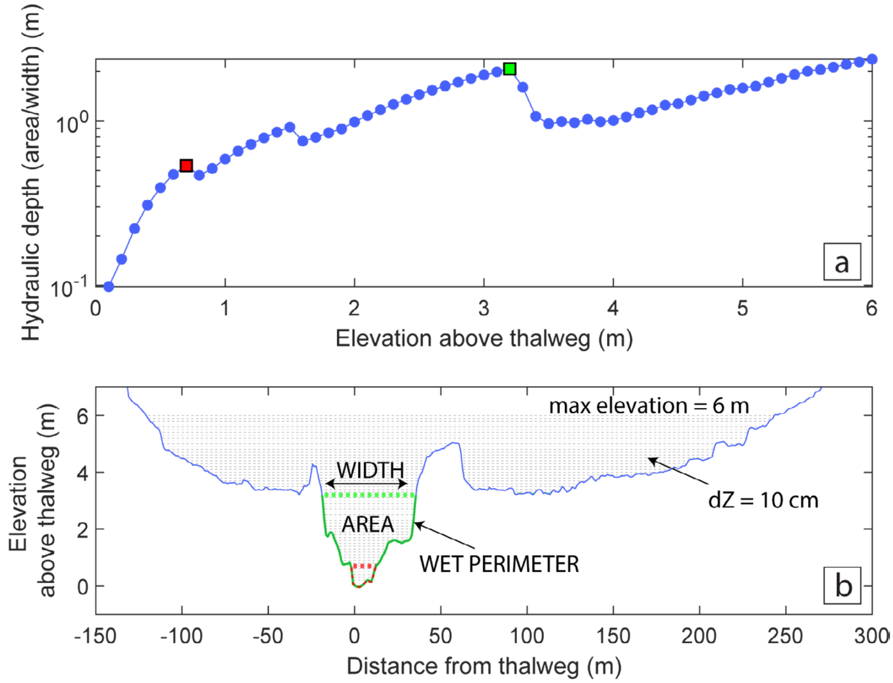

Figure 3 - Example of the hydraulic depth function application on a transverse river profile. Every 10 cm (dZ) from the thalweg elevation the hydraulic depth is computed as the area-width ratio. The peaks are highlighted in green and red.

COASTAL ENVIRONMENT

Nowadays, approximately 40% of the world's population resides in coastal regions (United Nation 2007; Pang *et al.*, 2023), where population density and economic pressures have significantly increased in recent decades. These areas are among the most sensitive and dynamic environments on Earth, and are particularly vulnerable to coastal erosion and shoreline retreat. Such vulnerabilities are worsened by the combined effects of global climate change and increasing human pressures, which are deeply altering natural coastal processes (Aucelli *et al.*, 2018; Alves *et al.* 2020; Pang *et al.*, 2023). Climate change is intensifying the frequency and severity of extreme weather events, modifying sea\oceanic and atmospheric circulation patterns, accelerating sea-level rise, increasing acidification, and altering sediment transport dynamics (Pang *et al.*, 2023). As a result, coastal morphodynamics are constantly shaped by complex interactions among atmospheric, marine, terrestrial, and anthropogenic drivers (Chowdhury *et al.*, 2023), and coastal morphological responses to these can be summarized into erosion, stabilization, and accretion (Zhang and Arlinghaus, 2022). Moreover, the recent warnings issued by the IPCC on the impacts of sea-level rise (Oppenheimer *et al.*, 2019) must be incorporated into assessments of coastal vulnerability and flood hazard. These evaluations are crucial especially in the light of the increasing rate of the shoreline retreat, which poses an important threat to both natural systems and human settlements in low-lying coastal zones (Antonioli *et al.*, 2017).

Indeed, among coastal features, the shoreline can be considered as a key climate-impact indicator, receiving attention due to its sensitivity to both natural processes and human influences (French and Burningham, 2009; Jackson *et al.*, 2013; Mastronuzzi *et al.*, 2017). Given that coastal zones are among the most intensively developed and inhabited areas globally, the accelerating occurrence of coastal hazards - such as shoreline erosion, coastal flooding, and storm surges - poses a growing threat, particularly in regions where residential areas, critical infrastructure, and economic activities are exposed to risk. Understanding shoreline dynamics is therefore essential for deciphering the complex interactions between natural processes and anthropogenic influences. Shoreline position and change are influenced by multiple factors, including sediment supply, wave energy, storm activity, and land-use practices. Continuous monitoring is crucial for detecting spatial and temporal changes, and for mitigating the geomorphological and ecological impacts of coastal hazards (Ojala *et al.*, 2013; Le Cozannet *et al.*, 2014; Castelle *et al.*, 2021; Palanisamy *et al.*, 2024).

Methodological approaches

Several studies have presented how coastal changes vary globally, essentially through different tools and methodologies (e.g., cartography, aerial photos, differential GPS, drones, satellite imagery, in-situ data collection) (Vos *et al.*, 2023; Luppichini and Bini, 2025).

Remote sensing is a powerful and cost-effective approach for observing and analyzing Earth's surface (Iacobucci *et al.*, 2020). It is widely acknowledged as an effective tool for shoreline extraction and monitoring (Gomezo-Pazo *et al.*, 2019; Quang *et al.*, 2021, Torre *et al.*, 2025).

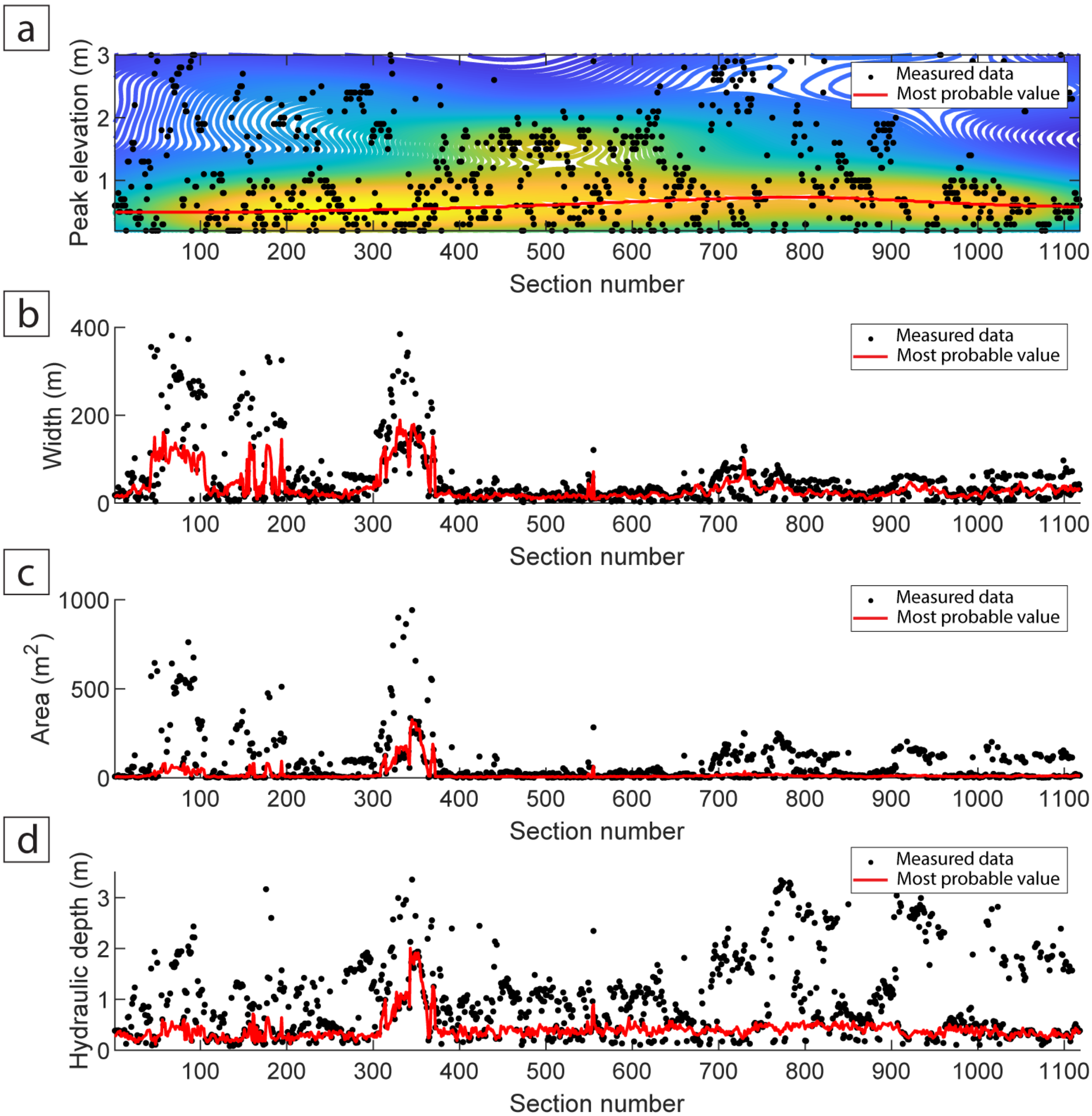

Figure 4 - Outputs of the peaks extracted from the hydraulic depth profiles traced on the Tesino River (Marche, Italy) test site. In (a) section number vs. peak elevation above thalweg, with contour lines showing the density probability from which the most probable peak elevation (red line) is extracted; in (b) section number vs. peak flow width; in (c) section number vs. peak flow area; in (d) section number vs. peak hydraulic depth. The red lines correspond to the y-axis variable computed considering for elevation parameter the most probable peak elevation.

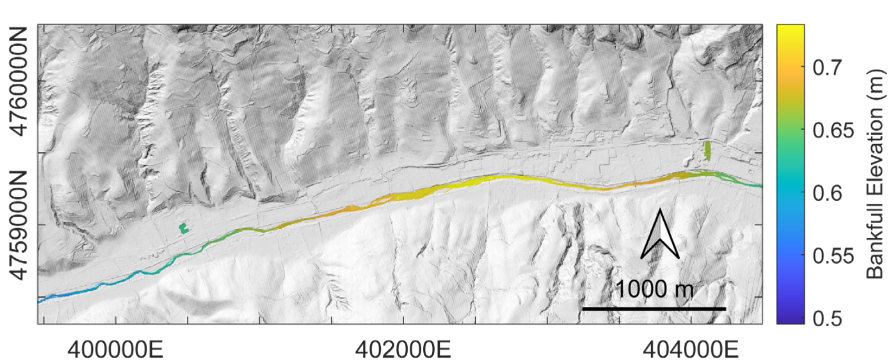

Figure 5 - Map view of the bankfull elevation extracted from the high resolution DTM of the Tesino River test site. Coordinate system: WGS84 UTM33N (EPSG: 32633).

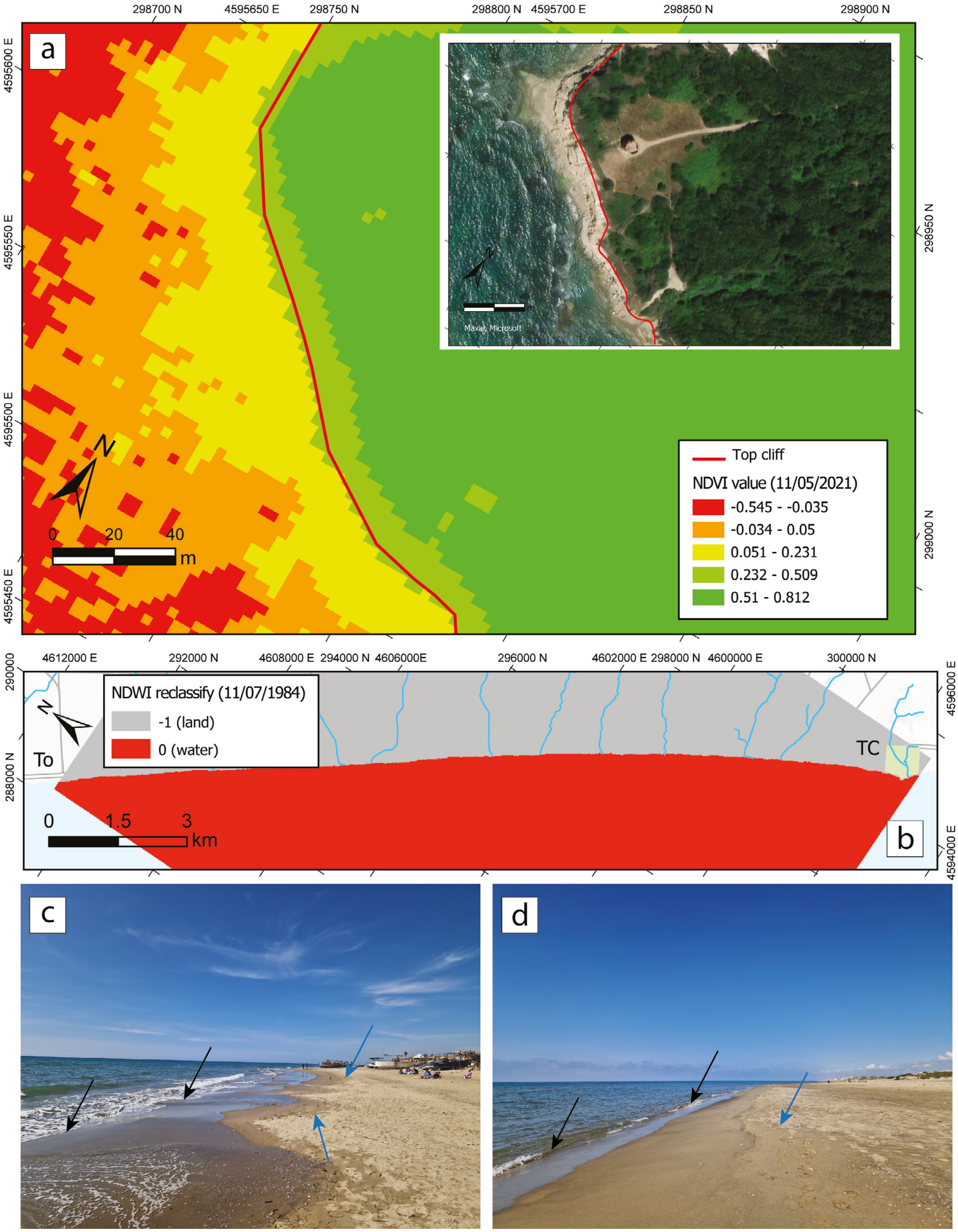

Figure 6 - Examples of multispectral indices, such as NDVI (a) and NDWI (b), applied to two case studies conducted within the RETURN Project. In (a) we adopt the NDVI for detecting the limit of the top cliff in Tor Caldara Natural Reserve (Latium Region), using the optical imagery of PlanetScope, with WGS84 UTM 33N coordinate system (Torre *et al.*, 2025). In (b) we show the reclassification of NDWI for automatically extracting the instantaneous waterlines from Torvaianica (To) and the Natural Reserve of Tor Caldara (TC), using Landsat 5 imagery, with WGS84 UTM 33N coordinate system (Iacobucci *et al.*, 2025). In (c) and (d), the black arrows point at the instantaneous waterline, while the blue arrows indicate the mean high water level along the coastal sector in Torvaianica area (southern Latium). The photos are acquired in April 2025 by Authors.

Optical and multispectral imagery are suitable for index- and threshold-based techniques for mapping the shoreline position and change over time (Dike *et al.*, 2023). However, their effectiveness is often compromised by environmental factors such as cloud cover, haze, snow, ice, and sun glint. To address these limitations, various index- and threshold-based methods have been developed, including NDVI (Normalized Difference of Water Index), NDWI (Normalized Difference of Water Index), MNDWI (Modified Normalized Difference of Water Index), TCW (Tasselled Cap Wetness), and AWEI (Automated Water Extraction Index), each aiming to distinguish land from water in different conditions (fig. 6). For example, missions such as Landsat and Sentinel 2 are extensively used due to their free accessibility and ability to identify water surfaces through suitable spectral bands and moderate spatial resolution (Sunder *et al.*, 2017; Quang *et al.*, 2021; McAllister *et al.*, 2022; Iacobucci *et al.*, 2025).

Similarly, synthetic-aperture radar (SAR) imagery has been widely applied to shoreline detection and image analysis, due to its weather-independent, day-and-night imaging capability (Zhu *et al.*, 2021; Shamsaie and Ghaderi, 2025). Methods like edge detection, thresholding-based, region-based segmentation, and object-based image analysis show varying levels of accuracy, with some achieving positional accuracies of few tens of meters (Ciecholewski, 2024). Validation was often performed using in situ data or digital elevation models, revealing that while many techniques are simple and robust, challenges remain, especially with single-polarization SAR images producing discontinuous shorelines (Dike *et al.*, 2023 and reference therein).

In-situ data enables the direct measurement of a wide range of environmental parameters, offering accurate and real-time insights into ecosystem conditions. This type of data is essential for detecting temporal changes and trends, and it supports physics-based, real-time ecosystem modelling (Lee *et al.*, 2022). Additionally, in-situ measurements serve a critical role in validating remote sensing data by providing ground-truth information to assess its accuracy. Furthermore, in-situ data enhances machine learning applications by supplying training datasets, enabling accuracy validation, and addressing challenges related to data heterogeneity (Elmes *et al.*, 2020).

Finally, empirical and numerical modeling approaches are often supported by physical experiments and validated using in-situ or remotely sensed observations. The accuracy of these simulations is strongly influenced by the underlying model framework, the inclusion of key hydrodynamic processes – such as wind shear, wave forces, wave transformation (e.g., breaking, shoaling, diffraction, transmission), and tidal dynamics – as well as the spatial and temporal resolution of the application. Recent advances in computational technologies have facilitated the development and application of a wide range of numerical methods, including the finite element method, finite difference method, boundary element method, and Eulerian–Lagrangian method (Chowdhury *et al.*, 2023 and reference therein). Nevertheless, model performance remains highly sensitive to the specification of open boundary conditions, parameterization choices, and the numerical schemes adopted (Martin *et al.*, 2018).

DISCUSSION

This research presents the state of art on the climate-impact indicators adopted in the framework of the PNRR RETURN project, among those treated in the SNPA 2021 framework, that also include non-natural contexts. The selection of climate-impact indicators within the RETURN project goes beyond the availability or pre-existing adoption as in the SNPA 2021 framework, and it is based on their representability of the cause-effect relationships between climate drivers and measurable geomorphological responses in different physical environments (mountains and hills, fluvial and coastal). It is worth noting that across all natural geomorphic sectors presented here, the integration of multi-source data is essential for enhancing the reliability and applicability of the climate-impact indicators. However, these indicators serve as critical tools for filling the gap between scientific research and actionable climate services, especially in the context of Italy's PNRR. Moreover, the integrated use of multiple indicators provides greater clarity and robustness in the assessment of the geomorphological responses to climate change, especially when considering different temporal and spatial scales.

This study highlights the crucial role of geomorphology in advancing climate services through the identification and characterization of climate-impact indicators across different geomorphic systems (i.e., mountainous and hilly sectors, alluvial plains, and coastal areas). The findings demonstrate how the geomorphic indicators are effective in detecting the physical consequences of climate variability, as well as essential in risk management and adaptation strategies.

In mountainous and hilly sectors, landslides result as key indicators due to their sensitivity to changes in rainfall regime and snow cover (Gariano and Guzzetti, 2016). Despite both modeling and empirical approaches offering insights into climate-induced slope instability, accurate forecasting of landslide occurrence is still challenging. Therefore, the integration of high-resolution climate data, geomorphological mapping, and temporal landslide inventories is essential for improving early warning systems and hazard assessments.

In alluvial plain environments, the confinement index is one of the most suitable indicators for describing the hydrological and sedimentological response of the river channel to climate changes (Ruiz-Villanueva *et al.*, 2023; Scorpio *et al.*, 2024). The development and application of semi-automated tools such as *BankfullMapper* (Delchiaro *et al.*, 2025) enable the extraction of morphological parameters from high-resolution DTMs, providing scalable and reproducible assessments of river behavior. However, further efforts are required to validate these methods across diverse geomorphic and anthropogenic settings and to enhance their application in flood prediction models.

Coastal areas, as highly dynamic and densely populated zones, are increasingly vulnerable to climate-related hazards (Antonioli *et al.*, 2017; He and Silliman, 2019). Therefore, the reconstruction of shoreline position and morphology over decades is a key indicator of both natural and anthropogenic pressures. Remote sensing methodologies, integrated with in-situ data and numerical models, enable effective shoreline monitoring. Nevertheless, environmental constraints (*e.g.*, cloud cover, tidal influences) and technical limitations (*e.g.*, single-polarization SAR discontinuities) still present obstacles to shoreline detection (Tsiakos and Chalkias, 2023; Ciecholewski, 2024). Ongoing development of multisensor approaches and machine learning algorithms certainly improve the spatial and temporal resolution of coastal monitoring.

Despite the advances highlighted in this research, several critical gaps remain for further investigation to improve the operational relevance of the climate-impact indicators. First, the poor availability of standardized protocols for combining and validating heterogeneous datasets, such as remote sensing, field surveys, and modelled outputs, limiting the replicability of the indicators across different geographical contexts (Crespi *et al.*, 2024). Second, the temporal resolution and historical depth of many indicators are still insufficient for deciphering long-term trends and extreme events, limiting especially early warning systems and the climate impact models calibration (Gariano and Guzzetti., 2016). Moreover, while tools like *BankfullMapper* and satellite-derived shorelines mapping platforms are promising, their validation across different morpho-climatic contexts and anthropogenic settings is still incomplete (Surian *et al.*, 2016; Scorpio *et al.*, 2022; Delchiaro *et al.*, 2025).

Therefore, future research should prioritize: i) the harmonization of indicator frameworks at national and European levels to support transregional comparisons (EEA, 2020); ii) the integration of climate scenarios and socio-economic data to move from impact detection to vulnerability and risk assessment (IPCC, 2023).

By addressing these gaps, climate-impact indicators can evolve from diagnostic tools into proactive instruments for climate adaptation, enabling geomorphology to play a central role in shaping resilient landscapes under the pressures of a changing climate.

CONCLUSIONS

In order to strengthen the competence and knowledge on climate-related environmental risks, several climate-impact indicators are adopted by RETURN Project, following the SNPA report (2021) for their distinction and definition. Building on this classification, the present work illustrates how geomorphological analysis provides an essential lens for the identification and understanding of climate-impact indicators in mountainous, hilly, alluvial plain and coastal environments.

Specifically, the main outputs can be summarized as follows:

- Mountain and hill sector: unravelling changes in landslide occurrence due to extreme precipitation events requires a geomorphological perspective for reconstructing and interpreting past and ongoing landslide processes through modelling, empirical, or combined approaches.
- Alluvial plain: bankfull width variations deliver important details on how the confinement index parameter changes with time, particularly in response to extreme events driven by climate change. This parameter can be extracted with a range of methodologies, encompassing qualitative observations, hydrological modeling and geometric terrain classification. Our contribution in geometric terrain classification delivers a novel and rapid methodology to assess the confinement index, contributing to enhance and simplify already available methodologies.
- Coastal areas: shoreline position and morphology is detectable through multiple remote sensing and field-based approaches, whose geomorphological interpretation is essential for deciphering the response of coastal processes to climate change.

Geomorphology provides a valuable framework for detecting, interpreting, and forecasting the impacts of climate change. Future research should focus on standardizing methodologies, improving data accessibility and interoperability, and fostering interdisciplinary collaboration to support evidence-based decision-making in climate adaptation and risk reduction strategies.

ACKNOWLEDGMENTS

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

REFERENCES

Alves B., Angnuureng D.B., Morand P., Almar R., 2020. *A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done.* Journal of Coastal Conservation, 24, 38. https://doi.org/10.1007/s11852-020-00755-7

Alvioli M., Melillo M., Guzzetti F., Rossi M., Palazzi E., von Hardenberg, J., Brunetti M.T., Peruccacci, S., 2018. *Implications of climate change on landslide hazard in Central Italy.* Science of The Total Environment, 630, 1528-1543. https://doi.org/10.1016/j.scitotenv.2018.02.315

Antonioli F., Anzidei M., Amorosi A., Presti V.L., Mastronuzzi G., Deiana G., De Falco G., Fontana A., Fontolan G., Lisco S., Marsico A., Moretti M., Orrù P.E., Sannino G.M., Serpelloni E., 2017. *Sea-level rise and potential drowning of the Italian coastal plains: flooding risk scenarios for 2100.* Quaternary Science Reviews, 158, 29-43. https://doi.org/10.1016/j.quascirev.2016.12.021

Aucelli P.P., Di Paola G., Rizzo A., Rosskopf C.M., 2018. *Present day and future scenarios of coastal erosion and flooding processes along the Italian Adriatic coast: the case of Molise region.* Environmental Earth Sciences, 77 (10), 371. https://doi.org/10.1007/s12665-018-7535-y

Blöschl G., Hall J., Viglione A., Perdigão R.A., Parajka J., Merz B., Lun D., Arheimer B., Aronica G.T., Bilibashi A., Bohàc M., Bonacci O., Borga M., Canjevac I., Castellarin A., Chirico G B., Claps P., Froloca N., Ganora D., Gorbachova L., Gul A., Hannaford J., Harrigan S., Kireeva M., Kiss A., Kjeldsen T.R., Kohnovà S., Koskela J.J., Ledvinka O., Macdonald N., Mavrova-Guirguinova M., Mediero L., Merz R., Molnar P., Montanari A., Murphy C., Osuch M., Ovcharuk V., Radevski I., Salinas J.L., Sauquet E., Sraj M., Szolgay J., Volpi E., Wilson D., Zaimi K., Živković N., 2019 *Changing climate both increases and decreases European river floods.* Nature, 573 (7772), 108-111. https://doi.org/10.1038/s41586-019-1495-6

Brunetti M.T., Gariano S.L., Melillo M., Rossi M., Peruccacci S., 2025. *An enhanced rainfall-induced landslide catalogue in Italy.* Scientific Data, 12 (1), 216. https://doi.org/10.1038/s41597-025-04551-6

Brunner G.W., 1995. *HEC-RAS river analysis system.* Hydraulic Reference Manual. Version 1.0.

Buma J., Dehn M., 1998. *A method for predicting the impact of climate change on slope stability.* Environmental Geology, 35, 190-196. https://doi.org/10.1007/s002540050305

Castelle B., Masselink G., Scott T., Stokes C., Konstantinou A., Marieu V., Bujan S., 2021. *Satellite-derived shoreline detection at a high-energy meso-macrotidal beach.* Geomorphology, 383, 107707. https://doi.org/10.1016/j.geomorph.2021.107707

Chowdhury P., Lakku N.K.G., Lincoln S., Seelam J.K., Behera M.R., 2023. *Climate change and coastal morphodynamics: interactions on regional scales.* Science of the Total Environment, 899, 166432. https://doi.org/10.1016/j.scitotenv.2023.166432

Ciabatta L., Camici S., Brocca L., Ponziani F., Stelluti M., Berni N., Moramarco T.J.J.O.H., 2016. *Assessing the impact of climate-change scenarios on landslide occurrence in Umbria Region, Italy.* Journal of Hydrology, 541, 285-295. https://doi.org/10.1016/j.jhydrol.2016.02.007

Ciccarelli N., Von Hardenberg J., Provenzale A., Ronchi C., Vargiu A., Pelosini R., 2008. *Climate variability in north-western Italy during the second half of the 20th century.* Global and Planetary Change, 63(2-3), 185-195. https://doi.org/10.1016/j.gloplacha.2008.03.006

Ciecholewski M., 2024. *Review of segmentation methods for coastline detection in SAR images.* Archives of Computational Methods in Engineering, 31, 839-869. https://doi.org/10.1007/s11831-023-10000-7

Chiang S.H., Chang K.T., 2011. *The potential impact of climate change on typhoon-triggered landslides in Taiwan, 2010-2099.* Geomorphology, 133 (3-4), 143-151. https://doi.org/10.1016/j.geomorph.2010.12.028

Coe J.A., 2012. *Regional moisture balance control of landslide motion: implications for landslide forecasting in a changing climate.* Geology, 40 (4), 323-326. https://doi.org/10.1130/G32897.1

Comegna L., Picarelli L., Bucchignani E., Mercogliano P., 2013. *Potential effects of incoming climate changes on the behaviour of slow active landslides in clay.* Landslides, 10, 373-391. https://doi.org/10.1007/s10346-012-0339-3

Crespi A., Napoli A., Galassi G., Lazzeri M., Parodi A., Zardi D., Pittore M., 2024. *Leveraging observations and model reanalyses to support regional climate change adaptation activities: An integrated assessment for the Marche Region (Central Italy).* Climate Services, 36, 100512. https://doi.org/10.1016/j.cliser.2024.100512

Crozier M.J., 2010. *Deciphering the effect of climate change on landslide activity: a review.* Geomorphology, 124 (3-4), 260-267. https://doi.org/10.1016/j.geomorph.2010.04.009

Dehn M., Buma J., 1999. *Modelling future landslide activity based on general circulation models.* Geomorphology, 30 (1-2), 175-187. https://doi.org/10.1016/S0169-555X(99)00053-7

Delchiaro M., Ruscitto V., Schwanghart W., Brignone E., Piacentini D., Troiani F., 2025. *BankfullMapper: a semi-automated MATLAB tool on high-resolution Digital Terrain Models for spatio-temporal monitoring of bankfull geometry and discharge.* Computers & Geosciences, 106001. https://doi.org/10.1016/j.cageo.2025.106001

Dijkstra T.A., Dixon N., 2010. *Climate change and slope stability in the UK: challenges and approaches.* Geological Society of London, 43 (4): 371-385. https://doi.org/10.1144/1470-9236/09-036

Dike E.C., Oyetunji A.K., Amaechi C.V., 2023. *Shoreline delineation from synthetic aperture radar (SAR) imagery for high and low tidal states in data-deficient Niger Delta region.* Journal of Marine Science and Engineering, 11 (8), 1528. https://doi.org/10.3390/jmse11081528

Douglas-Mankin K.R., Srinivasan R., Arnold J.G., 2010. *Soil and Water Assessment Tool (SWAT) model: current developments and applications.* Transactions of the ASABE, 53 (5), 1423-1431. 10.13031/2013.34915

EEA - European Environmental Agency, 2020. *Monitoring and evaluation of national adaptation policies throughout the policy cycle.* EEA Report 6/2020.

Eidmann J.S., Gallen S., 2023. *New remote method to systematically extract bedrock channel width of small catchments across large spatial scales using high-resolution digital elevation models.* Earth Surface Processes and Landforms, 48 (7), 1470-1483. https://doi.org/10.1002/esp.5560

Elmes A., Alemohammad H., Avery R., Caylor K., Eastman J.R., Fishgold L., Friedl M.A., Jain M., Kohli D., Bayas J.C.L., Lunga D., McCarty J.L., Pontius R.G., Reinmann A.B., Rogan J., Song L., Stoynova H., Ye S., Yi Z., Estes L., 2020. *Accounting for training data error in machine learning applied to earth observations.* Remote Sensing, 12(6), 1034. https://doi.org/10.3390/rs12061034

French J.R., Burningham H., 2009. *Coastal geomorphology: trends and challenges.* Progress in Physical Geography, 33 (1), 117-129. https://doi.org/10.1177/0309133309105036

Fischer L., Huggel C., Kääb A., Haeberli W., 2013. *Slope failures and erosion rates on a glacierized high-mountain face under climatic changes.* Earth surface processes and landforms, 38 (8), 836-846. https://doi.org/10.1002/esp.3355

Fowler H.J., Blenkinsop S., Tebaldi C., 2007. *Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling.* International Journal of Climatology, 27, 1547-1578. https://doi.org/10.1002/joc.1556

Gariano S.L., Guzzetti F., 2016. *Landslides in a changing climate.* Earth-Science Reviews, 162, 227-252. https://doi.org/10.1016/j.earscirev.2016.08.011

Garian S.L., Rianna, G., Petrucci O., Guzzetti F., 2017. *Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale.* Science of the Total Environment, 596, 417-426. https://doi.org/10.1016/j.scitotenv.2017.03.103

Gassner C., Promper C., Beguería S., Glade T., 2015. *Climate change impact for spatial landslide susceptibility.* In: Lollino G., Manconi A., Clague J., Shan W., Chiarle M. (Eds) Engineering Geology for Society and Territory, v. 1, 429-433. Springer, Cham. https://doi.org/10.1007/978-3-319-09300-0_82

Giorgi F., Lionello P., 2008. *Climate change projections for the Mediterranean region.* Global and Planetary Change, 63 (2-3), 90-104. https://doi.org/10.1016/j.gloplacha.2007.09.005

Gómez-Pazo A., Pérez-Alberti A., Otero Pérez X.L., 2019. *Recent evolution (1956-2017) of rodas beach on the Cíes Islands, Galicia, NW Spain*. Journal of Marine Science and Engineering, 7 (5), 125. https://doi.org/10.3390/jmse7050125

Guzzetti F., Gariano S.L., Peruccacci S., Brunetti M.T., Marchesini I., Rossi M., Melillo M., 2020. *Geographical landslide early warning systems.* Earth-Science Reviews, 200, 102973. https://doi.org/10.1016/j.earscirev.2019.102973

Hall J., Arheimer B., Borga M., Brázdil R., Claps P., Kiss A., Blöschl G., 2014. *Understanding flood regime changes in Europe: a state-of-the-art assessment.* Hydrology and Earth System Sciences, 18 (7), 2735-2772. https://doi.org/10.5194/hess-18-2735-2014

Hannaford J., Marsh T.J., 2008. *High-flow and flood trends in a network of undisturbed catchments in the UK.* International Journal of Climatology: A Journal of the Royal Meteorological Society, 28 (10), 1325-1338. https://doi.org/10.1002/joc.1643

He Q., Silliman B.R., 2019. *Climate change, human impacts, and coastal ecosystems in the Anthropocene.* Current Biology, 29 (19), R1021-R1035. https://doi.org/10.1016/j.cub.2019.08.042

Huggel C., Clague J.J., Korup O., 2012. *Is climate change responsible for changing landslide activity in high mountains?.* Earth Surface Processes and Landforms, 37 (1), 77-91. https://doi.org/10.1002/esp.2223

Hungr O., Leroueil S., Picarelli L. 2014. *The Varnes classification of landslide types, an update.* Landslides, 11 (2), 167-194. https://doi.org/10.1007/s10346-013-0436-y

Iacobucci G., Piacentini D., Troiani F., 2025. *Tracking coastal changes in the central-eastern margin of Tyrrhenian Sea through integrated NDWI-derived shorelines from multi-sensor satellite time series.* Remote Sensing Applications: Society and Environment, 101636. https://doi.org/10.1016/j.rsase.2025.101636

Iacobucci G., Troiani F., Milli S., Mazzanti P., Piacentini D., Zocchi M., Nadali D., 2020. *Combining satellite multispectral imagery and topographic data for the detection and mapping of fluvial avulsion processes in lowland areas.* Remote Sensing, 12 (14), 2243. https://doi.org/10.3390/rs12142243

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds)]. IPCC, Geneva, Switzerland, pp. 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Jackson N.L., Nordstrom K.F., Feagin R.A., Smith W.K., 2013. *Coastal geomorphology and restoration.* Geomorphology, 199, 1-7. https://doi.org/10.1016/j.geomorph.2013.06.027

Jacquemart M., Weber S., Chiarle M., Chmiel M., Cicoira A., Corona C., Eckert N., Gaume J., Giacona F., Hirschberg J., Kaitna R., Magnin F., Mayer S., Moos C., Herwijnen A., Stoffel M., 2024. *Detecting the impact of climate change on alpine mass movements in observational records from the European Alps.* Earth-Science Reviews, 104886. https://doi.org/10.1016/j.earscirev.2024.104886

Jakob M., Lambert S., 2009. *Climate change effects on landslides along the southwest coast of British Columbia.* Geomorphology, 107 (3-4), 275-284. https://doi.org/10.1016/j.geomorph.2008.12.009

Keast D., Ellison J.C., 2022. *Evaluation of bankfull stage from plotted channel geometries.* Journal of Hydrology: Regional Studies, 41, 101052. https://doi.org/10.1016/j.ejrh.2022.101052

Kundzewicz Z.W., Pińskwar I., Brakenridge G.R., 2013. *Large floods in Europe, 1985-2009.* Hydrological Sciences Journal, 58 (1), 1-7 https://doi.org/10.1080/02626667.2012.745082

Le Cozannet G., Garcin M., Yates M., Idier D., Meyssignac B., 2014. *Approaches to evaluate the recent impacts of sea-level rise on shoreline changes.* Earth-Science Reviews, 138, 47-60. https://doi.org/10.1016/j.earscirev.2014.08.005

Lee J.H., Nam Y.S., Kim Y., Liu Y., Lee J., Yang H. 2022. *Real-time digital twin for ship operation in waves.* Ocean Engineering, 266, 112867. https://doi.org/10.1016/j.oceaneng.2022.112867

Lee W.H., Choi H.S., 2018. *Characteristics of bankfull discharge and its estimation using hydraulic geometry in the Han River basin.* KSCE Journal of Civil Engineering, 22, 2290-2299. https://doi.org/10.1007/s12205-017-1658-7

Luppichini M., Lazzarotti M., Bini M., 2024. *Climate change as main driver of centennial decline in river sediment transport across the Mediterranean region.* Journal of Hydrology, 636, 131266. https://doi.org/10.1016/j.jhydrol.2024.131266

Luppichini M., Bini M., 2025. *40-Year shoreline evolution in Italy: critical challenges in river delta regions.* Estuarine, Coastal and Shelf Science, 315, 109166. https://doi.org/10.1016/j.ecss.2025.109166

Manning R., 1904. *On the flow of water in open channels and pipes.* Transactions of the Institutions of Civil Engineers of Ireland. Institution of Civil Engineers of Ireland, Dublin.

Martin J.L., Schottman R.W., McCutcheon S.C., 2018. *Hydrodynamics and Transport for Water Quality Modeling.* CRC Press. https://doi.org/10.1201/9780203751510

McAllister E., Payo A., Novellino A., Dolphin T., Medina-Lopez E., 2022. *Multispectral satellite imagery and machine learning for the extraction of shoreline indicators.* Coastal Engineering, 174, 104102. https://doi.org/10.1016/j.coastaleng.2021.104102

McCandless T.L., 2003. *Maryland stream survey: bankfull discharge and channel characteristics of streams in the Allegheny Plateau and the Valley and Ridge hydrologic regions*. CBFO-S03-01, U.S. Fish and Wildlife Service. Chesapeake Bay Field Office, Annapolis, Maryland.

Montanari A., 2012. *Hydrology of the Po River: looking for changing patterns in river discharge.* Hydrology and Earth System Sciences, 16 (10), 3739-3747. https://doi.org/10.5194/hess-16-3739-2012

Ojala A.E., Palmu J.P., Åberg A., Åberg S., Virkki H., 2013. *Development of an ancient shoreline database to reconstruct the Litorina Sea maximum extension and the highest shoreline of the Baltic Sea basin in Finland.* Bulletin of the Geological Society of Finland, 85 (2).

Oppenheimer M., Glavovic B.C., Hinkel J., van de Wal R., Magnan A.K., Abd-Elgawad A., Cai R., Cifuentes-Jara M., DeConto R.M., Ghosh T., Hay J., Isla F., Marzeion B., Meyssignac B., Sebesvari Z., 2019. *Sea level rise and implications for low-lying islands, coasts and communities.* In: IPCC Special Report on the Ocean and Cryosphere in a

Changing Climate. [Pörtner H.-O., Roberts D.C., Masson-Delmotte V., Zhai P., Tignor M., Poloczanska E., Mintenbeck K., Alegría A., Nicolai M., Okem A., Petzold J., Rama B., Weyer N.M. (Eds)] Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321-445. https://doi.org/10.1017/9781009157964.006

Palanisamy P., Sivakumar V., Velusamy P., Natarajan L. 2024. *Spatio-temporal analysis of shoreline changes and future forecast using remote sensing, GIS and kalman filter model: a case study of Rio de Janeiro, Brazil.* Journal of South American Earth Sciences, 133, 104701. https://doi.org/10.1016/j.jsames.2023.104701

Pang T., Wang X., Nawaz R.A., 2023. *Coastal erosion and climate change: A review on coastal-change process and modeling.* Ambio 52, 2034-2052. https://doi.org/10.1007/s13280-023-01901-9

Petley D., 2012. *Global patterns of loss of life from landslides.* Geology, 40 (10), 927-930. https://doi.org/10.1130/G33217.1

Phillips C.B., Masteller C.C., Slater L.J., Dunne K.B., Francalanci S., Lanzoni S., Merritts D.J., Lajeunesse E., Jerolmack D.J., 2022. *Threshold constraints on the size, shape and stability of alluvial rivers.* Nature Reviews Earth & Environment, 3 (6), 406-419. https://doi.org/10.1038/s43017-022-00282-z

Piciullo L., Calvello M., Cepeda J.M., 2018. *Territorial early warning systems for rainfall-induced landslides.* Earth-Science Reviews, 179, 228-247. https://doi.org/10.1016/j.earscirev.2018.02.013

Pinskwar I., Kundzewicz Z.W., Peduzzi P., Brakenbridge G.R., Stahl K., Hannaford J., 2012. *Changing floods in Europe.* In: Kundzewicz Z.W, Changes in Flood Risk in Europe, 83-96. International Association of Hydrological Sciences Press, Wallingford, UK.

Polemio M., Petrucci O., 2010. *Occurrence of landslide events and the role of climate in the twentieth century in Calabria, southern Italy.* Geological Society of London, 43 (4), 403-415. https://doi.org/10.1144/1470-9236/09-006

Popescu M.E., 2002. *Landslide causal factors and landslide remediatial options.* In: Third International Conference on Landslides, Slope Stability and Safety of Infra-Structures, 61-81. CI-Premier PTE LTD Singapore.

Quang D.N., Ngan V.H., Tam H.S., Viet N.T., Tinh N.. Tanaka H., 2021. *Long-term shoreline evolution using dsas technique: a case study of Quang Nam province, Vietnam.* Journal of Marine Science and Engineering, 9 (10), 1124. https://doi.org/10.3390/jmse9101124

Ruiz-Villanueva V., Piégay H., Scorpio V., Bachmann A., Brousse G., Cavalli M., Comiti F., Crema S., Feràndez E., Furdada G., Hajdukiewics H., Hunzinger L., Lucìa A., Marchi L., Moraru A., Piton G., Rickenmann D., Righini M., Surian N., Yassine R., Wyżga B., 2023. *River widening in mountain and foothill areas during floods: insights from a meta-analysis of 51 European Rivers.* Science of the Total Environment, 903, 166103. https://doi.org/10.1016/j.scitotenv.2023.166103

Rosgen D.L., 1997. *A geomorphological approach to restoration of incised rivers. In:* Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, v. 1, 12-29. Oxford, MS, USA.

Schumm S.A., 1960. *The shape of alluvial channels in relation to sediment type* (No. 352-B).

Scorpio V., Comiti F., Liébault F., Piegay H., Rinaldi M., Surian N., 2024. *Channel changes over the last 200 years: a meta data analysis on European rivers.* Earth Surface Processes and Landforms, 49 (9), 2651-2676. https://doi.org/10.1002/esp.5848

Shamsaie R., Ghaderi D., 2025. *Comparison of efficiency of spectral (NDWI) and SAR (GRD) method in shoreline detection: a novel method of integrating GRD and SLC products of sentinel-1 satellite.* Regional Studies in Marine Science, 84, 104132. https://doi.org/10.1016/j.rsma.2025.104132

Sunder S., Ramsankara R.A.A.J., Ramakrishnan B., 2017. *Inter-comparison of remote sensing sensing-based shoreline mapping techniques at different coastal stretches of India.* Environmental Monitoring and Assessment, 189, 1-13. https://doi.org/10.1007/s10661-017-6273-2

Surian N., Rinaldi M., 2003. *Morphological response to river engineering and management in alluvial channels in Italy.* Geomorphology, 50 (4), 307-326. https://doi.org/10.1016/S0169-555X(02)00219-2

Torre D., Zocchi M., Iacobucci G., Menichetti M., Toselli R., Troiani F., Piacentini D., 2025. *Morphoevolutive drivers on a rapidly-evolving soft rocky cliff and connected shore platform system.* Earth Surface Processes and Landforms, 50 (8), e70117. https://doi.org/10.1002/esp.70117

Tsiakos C.A.D., Chalkias C., 2023. *Use of machine learning and remote sensing techniques for shoreline monitoring: a review of recent literature.* Applied Sciences, 13 (5), 3268. https://doi.org/10.3390/app13053268

Ulbrich U., Brücher T., Fink A.H., Leckebusch G.C., Krüger A., Pinto J.G., 2003. *The central European floods of August 2002: Part 1-Rainfall periods and flood development.* Weather, 58 (10), 371-377. http://dx.doi.org/10.1256/wea.61.03A

Vos K., Splinter K.D., Palomar-Vázquez J., 2023. *Benchmarking satellite-derived shoreline mapping algorithms.* Communications Earth and Environment 4, 345. https://doi.org/10.1038/s43247-023-01001-2

Williams G.P., 1978. *Bank-full discharge of rivers.* Water Resources Research, 14 (6), 1141-1154. https://doi.org/10.1029/WR014i006p01141

Wolman M.G., Leopold L.B., 1957. *River flood plains: some observations on their formation*. US Geological Surveys Prof. Pap. 282-C.

Wolman M.G., Miller J.P., 1960. *Magnitude and frequency of forces in geomorphic processes*. The Journal of Geology, 68 (1), 54-74. https://doi.org/10.1086/626637

Wood J.L., Harrison S., Turkington T.A.R., Reinhardt L., 2016. *Landslides and synoptic weather trends in the European Alps.* Climatic Change, 136, 297-308. https://doi.org/10.1007/s10584-016-1623-3

Zhang W., Arlinghaus P., 2022. *Climate, Coast, and Morphology.* In Oxford Research Encyclopedia of Climate Science. https://doi.org/10.1093/acrefore/9780190228620.013.814

Zhu Q., Li P., Li Z., Pu S., Wu X., Bi N., Wang H., 2021. *Spatiotemporal changes of coastline over the Yellow River Delta in the previous 40 years with optical and SAR remote sensing.* Remote Sensing, 13 (10), 1940. https://doi.org/10.3390/rs13101940

(Ms. received 23 May 2025, accepted 25 August 2025)