Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

ENHANCED MAPPING AND MODELING OF MULTIPLE DEBRIS FLOW BY LIDAR-BASED FIXED WING UAV SURVEYING

Teresa GRACCHI(*,**), Teresa NOLESINI(***), Guglielmo ROSSI(***), Carlo TACCONI STEFANELLI(*), Luca TANTERI(***), Tommaso CARLÀ(*), Giovanni GIGLI(*), Federico DI TRAGLIA(****) & Nicola CASAGLI(*,**)

(*)University of Florence - Department of Earth Sciences - Florence, Italy
(**)National Institute of Oceanography and Applied Geophysics - Trieste, Italy
(***)University of Florence - Civil Protection Centre - Florence, Italy
(****)Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano - Naples,
Corresponding author: teresa.gracchi@unifi.it

EXTENDED ABSTRACT

Le colate detritiche rappresentano uno dei principali fattori di pericolosità geo-idrologica in aree caratterizzate da versanti ripidi, depositi incoerenti e rapida evoluzione morfologica. Nel contesto vulcanico dell'Isola di Stromboli, tali fenomeni sono ulteriormente amplificati dall'interazione tra depositi piroclastici recenti, incendi che riducono la copertura vegetale e precipitazioni intense concentrate in brevi intervalli temporali. La gestione della pericolosità in questi contesti richiede non solo il monitoraggio delle aree a rischio, ma anche strumenti quantitativi capaci di stimare i volumi mobilizzabili e prevedere gli scenari di propagazione verso gli insediamenti abitati.

Questo studio propone un approccio integrato basato su rilievi da UAV (*Unmanned Aerial Vehicle*) ad ala fissa equipaggiati con sensori ottici e LiDAR (*Light Detection and Ranging*), combinati con analisi multitemporali dei modelli digitali del terreno e con simulazioni numeriche della propagazione delle colate detritiche. L'uso di UAV ad ala fissa consente di superare i limiti operativi dei rilievi terrestri e dei droni multirotore, garantendo una copertura sinottica di bacini multipli, continuità spaziale e risoluzione centimetrica anche in aree densamente vegetate o difficilmente accessibili.

Le campagne di rilievo sull'Isola di Stromboli, condotte tra luglio e novembre 2024, hanno permesso di ottenere modelli digitali di superficie (DSM) ad alta risoluzione, che sono stati confrontati con modelli preesistenti per identificare zone caratterizzate da erosione e/o deposizione. L'integrazione con l'analisi idrografica in ambiente GIS ha consentito la delimitazione dei bacini idrografici e l'individuazione delle aree sorgenti, mentre la differenza tra modelli temporali ha permesso la stima quantitativa dei volumi mobilizzati. I risultati mostrano come i processi erosivi siano prevalentemente concentrati nelle porzioni sommitale dei versanti, con incisioni locali fino a diversi metri e canali principali che trasferiscono efficacemente i sedimenti verso valle, spesso in direzione degli insediamenti abitati.

La modellazione numerica della propagazione, basata su un modello digitale del terreno (DTM) derivato dai rilievi UAV, ha tradotto le informazioni morfologiche e volumetriche in scenari di impatto potenziale, stimando spessori e velocità dei flussi lungo i canali principali. Anche volumi relativamente contenuti, se convogliati in canali stretti o ostruiti, possono generare condizioni di elevata pericolosità. L'integrazione tra mappatura ad alta risoluzione e simulazione numerica consente così di identificare bacini critici, pianificare interventi di mitigazione strutturale e non strutturale, e supportare le attività di protezione civile.

In conclusione, l'approccio proposto costituisce uno strumento efficace per la geologia applicata, permettendo di passare dall'osservazione dettagliata del territorio alla modellazione predittiva dei processi detritici, con un impatto diretto sulla gestione del rischio in contesti vulcanici caratterizzati da rapida evoluzione morfologica e accessibilità limitata. I risultati ottenuti evidenziano il potenziale dei rilievi LiDAR da drone combinati con analisi multitemporali e modellazione numerica come supporto operativo per la pianificazione di interventi e la riduzione del rischio residuo.

IJEGE, Special Issue 1, (2026): 123-131, DOI: 10.4408/IJEGE.2026-01.S-12
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Debris flows are a major geo-hydrological hazard in areas with steep slopes and unconsolidated deposits. Accurate characterization of source areas and flow paths is essential for hazard assessment and for planning mitigation measures. In contexts where initiation zones are distributed across multiple slopes or small catchments, traditional terrestrial surveys or multirotor UAV techniques are limited in spatial coverage and continuity.

To overcome these limitations, this study proposes a methodological approach based on fixed-wing UAVs equipped with LiDAR and high-resolution cameras, aimed at the synoptic mapping of multiple debris flow channels and the quantitative assessment of morphological changes. Survey campaigns enabled the generation of high-resolution Digital Terrain Models (DTMs) and the derivation of elevation difference models using GIS-based techniques, allowing the estimation of eroded and deposited volumes, the delineation of source areas, and the identification of main flow paths through flow accumulation and watershed analysis algorithms.

Analysis of multitemporal surveys, conducted a few months apart, revealed that the most significant erosional processes are concentrated in the upper portions of slopes, with average erosion depths of several tens of centimeters and localized incisions exceeding 5–10 meters. Delineating of flow lines and drainage basins also allowed mobilized volumes to be correlated with specific channels, identifying basins with the highest reactivation potential.

The use of fixed-wing UAVs proved particularly effective for covering large areas within short operational times, ensuring centimeter-scale spatial resolution even at poorly accessible sites. Integration with LiDAR technology allowed for the accurate reconstruction of ground morphology in densely vegetated areas, providing a solid basis for subsequent numerical simulations of debris flow propagation. These simulations enabled the estimation of potential inundation scenarios and supported the design of structural mitigation measures.

The results show that the integrated UAV–LiDAR and numerical modeling approach constitutes an effective tool for the geomorphological characterization of multiple basins affected by debris flows, providing quantitat

Keywords: *UAV LiDAR surveys, debris flow, digital terrain models, multi-temporal analysis, numerical modeling*

INTRODUCTION

Debris flows represent one of the main geo-hydrological hazards in contexts characterized by steep slopes, unconsolidated deposits, and rapid morphological evolution (Cussot & Meunier, 1996; Hungr *et alii*, 2008). In insular volcanic environments, such as Stromboli Island, these phenomena are amplified by the interaction of recent pyroclastic deposits, wildfires that reduce vegetation cover, and intense rainfall concentrated over short periods. Stromboli, part of the Aeolian archipelago, is an active volcano known for almost continuous strombolian eruptions and deeply incised slopes, features that increase its susceptibility to debris flows and shallow landslides (Casalbore *et alii*, 2010).

In recent years, numerous events have directly affected the settlements of Stromboli and Ginostra, highlighting the need for up-to-date morphological information to inform practical hazard mitigation strategies. This underscores the importance of an integrated approach for hazard management and the planning of both structural and non-structural mitigation measures, linking high-resolution surveys to decision-making in local civil protection.

Traditional surveying techniques and multirotor UAVs are often limited in areal coverage and spatial continuity, especially when debris-flow source catchments are distributed across extensive and difficult-to-access slopes (Gracchi *et alii*, 2022). Fixed-wing UAVs, on the other hand, allow the coverage of large areas in short operational times while providing high-resolution and continuous data across catchments, essential for basin-scale analyses and numerical modeling of debris-flow propagation (Rau *et alii*, 2012; Anders *et alii*, 2013).

This study proposes an integrated approach based on fixed-wing UAV surveys equipped with optical and LiDAR (Light Detection and Ranging) sensors, aimed at high-resolution reconstruction of slope morphology, quantification of erosional and depositional processes, and implementation of numerical simulations of debris-flow propagation, to support hazard assessment and the planning of targeted mitigation interventions.

STUDY AREA

Stromboli Island, part of the Aeolian archipelago in the northern Tyrrhenian Sea, is one of the most well-known active volcanoes worldwide, characterized by almost continuous strombolian eruptions (Di Traglia *et alii*, 2025; Di Traglia *et alii*, 2023). The island covers an area of about 12 km² and rises up to 924 m a.s.l. The landscape is dominated by steep and highly inclined slopes, deeply incised by numerous channels that convey water and debris toward the settlement of Stromboli and Ginostra, on the southwestern flank (Casalbore *et alii*, 2025). The surface deposits consist mainly of unconsolidated, recent volcaniclastic materials, easily mobilized during intense rainfall events, overlying lava flows and more consolidated pyroclastic products (Di Traglia *et alii*, 2023-b; Rosi *et alii*, 2000).

The terrain is subject to rapid morphological changes due to the interaction between volcanic processes, surface erosion, and human activities. Wildfires that occurred in May 2022 particularly affected the southwestern and northern slopes of Stromboli, reducing vegetation cover and increasing slope vulnerability to surface runoff and debris flows (Nannipieri *et alii*, 2023). Paroxysmal volcanic events in July 2024 further

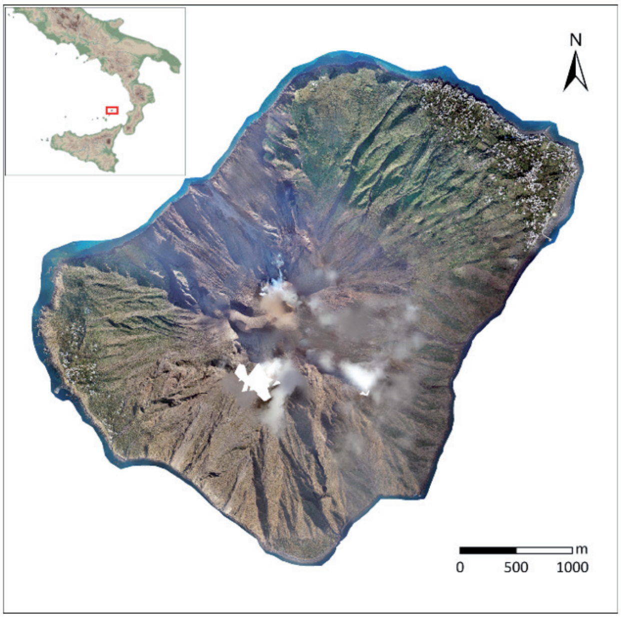

Fig. 1 - Orthomosaic of Stromboli Island derived from a fixed-wing UAV photogrammetric survey. The absence of data in the southern sector of the island, between approximately 700 and 820 m a.s.l., is related to dense cloud cover during the aerophotogrammetric acquisition

contributed to the availability of loose material through the deposition of ash and pyroclastic blocks on the slopes (Civico *et alii*, 2024; Di Traglia *et alii*, 2025).

Between July and November 2024, several intense rainfall events triggered diffuse and channelized erosion, with debris flows affecting primarily the catchments upstream of the settlements, highlighting the need to have an updated representation of slope morphology (Areu-Rangel *et alii*, 2020). The most vulnerable areas correspond to slopes steeper than 30–35°, characterized by unconsolidated loose material and concentrated drainage channels that convey debris toward infrastructures and inhabited areas.

These conditions make Stromboli an ideal setting for applied geology studies aimed at assessing and managing debris-flow hazards, enabling the integration of high-resolution surveys, geomorphological analyses, and numerical modeling to support local civil protection and territorial planning.

MATERIALS AND METHODS

UAV surveys and digital models

A survey campaign covering the entire Stromboli Island was conducted on 27–28 November 2024 using a fixed-wing vertical take-off and landing (VTOL) UAV (Trinity PRO, Quantum Systems). A total of 11 flights were carried out, including four photogrammetric flights at an altitude of approximately 400 m a.g.l. using a Sony RX1 RII digital camera (42 Mpix), and seven LiDAR flights (Qube 240 sensor) at an altitude of approximately 100 m a.g.l., targeting densely vegetated areas and the urban sectors of Stromboli and Ginostra.

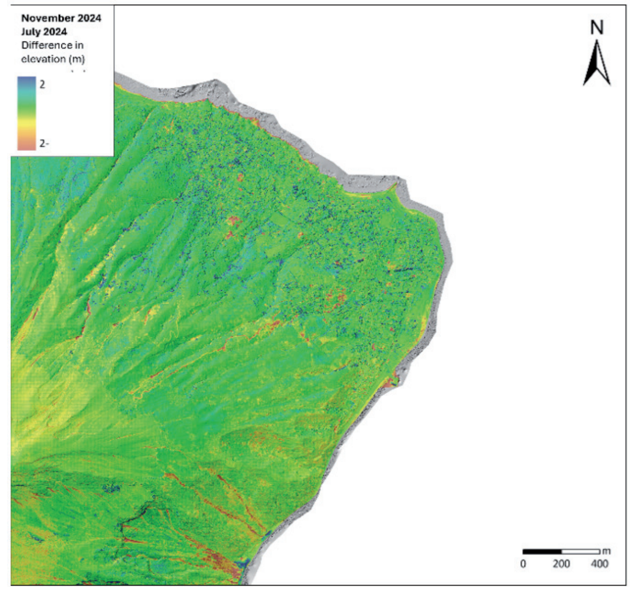

Fig. 2 - Elevation difference between November 2024 and July 2024 DSMs. Detail of the eastern area including the Stromboli inhabited area, displayed on the November 2024 DSM. Minimum and maximum values reported in the legend were selected to enhance the visualization of the observed morphological changes and do not represent the absolute maximum values of accumulation or erosion

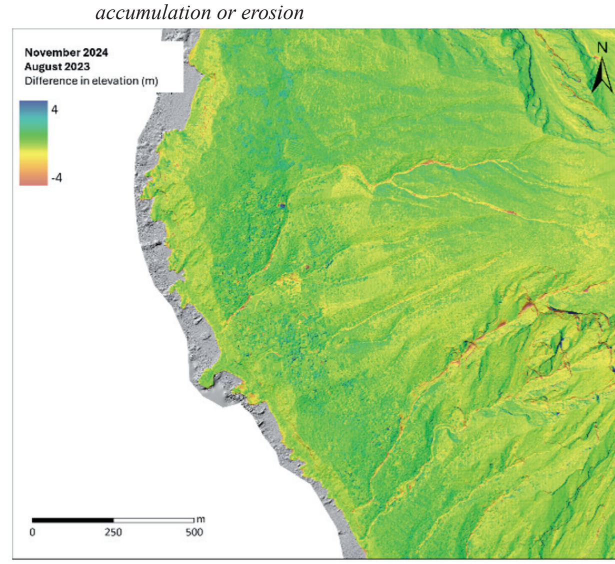

Fig. 3 - Elevation difference between the DSMs generated from UAV-based topographic surveys conducted in November 2024 and August 2023 in the Ginostra area

Photogrammetric images were processed using Structure-from-Motion techniques to generate point clouds, Digital Surface Models (DSMs), and high-resolution orthomosaics (Figure 1). LiDAR data were used to increase the density and reliability of morphological reconstruction, particularly in vegetated areas. Photogrammetric and LiDAR point clouds were integrated to generate DSMs with a spatial resolution of approximately 6 cm.

Multi-temporal analysis of morphological changes

For the area upstream of the Stromboli settlement, the November 2024 DSM was compared with a DSM obtained from a UAV survey conducted in July 2024 (Figure 2). For the Ginostra area, the comparison was performed with a DSM derived from a survey acquired in the previous year (Figure 3).

Elevation differences between the models were used to identify erosion and accumulation areas and to estimate mobilized sediment volumes.

Vertical accuracy was assessed by comparing ground control point (GCP) elevations with the corresponding elevations extracted from the DSM. The resulting vertical differences provided an estimate of model uncertainty, which was approximately ±10 cm for the July–November 2024 comparison and ±14 cm for the multi-temporal comparison in the Ginostra area. Based on these values, a Level of Detection (LoD) of approximately ±0.17 m was derived through error propagation and considered in the interpretation of the DEM of Difference results to distinguish significant elevation changes from noise (Wheaton *et alii*, 2010).

Hydrological analysis and catchment delineation

Based on the November 2024 model, the surface drainage network was derived through GIS analysis (flow direction and flow accumulation) and classified according to Strahler order (Strahler, 1957). Catchments of the main channels were delineated to identify debris-flow source areas and correlate eroded volumes, with debris-flow paths traced using the high-resolution orthomosaic (Figure 4, Figure 5, Figure 6).

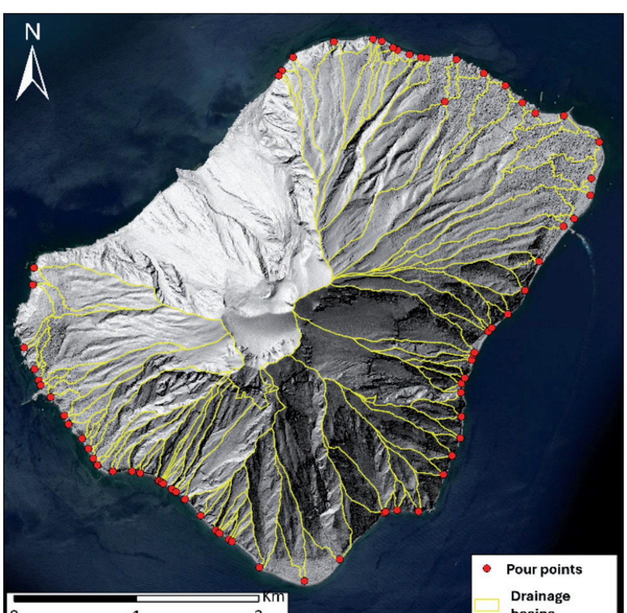

Fig. 4 - Map of the main catchments of the island, calculated based on the pour points shown in red. Pour points, i.e., the hydrological outlet points of each catchment, were manually defined according to the drainage network

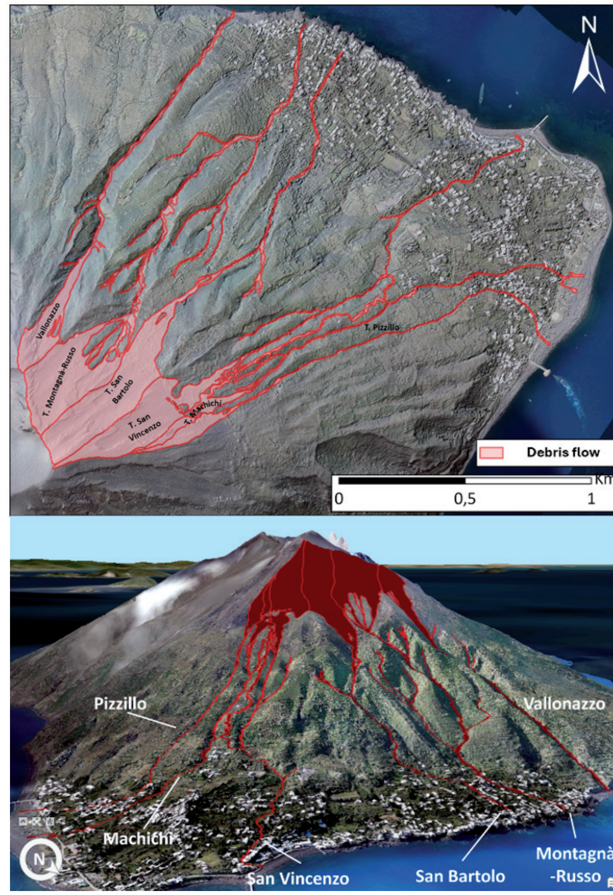

Fig. 5 - Debris-flow mapping on the flank containing the Stromboli inhabited area. Top: map view; bottom: 3D perspective

RESULTS

Erosional And Depositional Processes

Upstream of the Stromboli settlement, the main erosion areas are concentrated in the upper portions of the slopes, generally between approximately 850 and 300 m a.s.l. Zones of diffuse erosion with average thicknesses of about 0.3 m were identified, together with newly formed channels showing incisions up to 0.7 m, converging at intermediate elevations (around 450 m a.s.l.) into larger channels (Figure 7, Figure 8). The observed channel network includes both natural ephemeral gullies and more persistent incision channels, highlighting different geomorphological processes driving debris mobilization. In these main channels, localized incisions reach depths of up to 11 m, with lateral widening of up to approximately 19 m (Figure 9).

Accumulation areas are mainly located in the middle to lower portions of the channels, with maximum thicknesses of up to about 3.5 m, in some cases traceable down to the coastline.

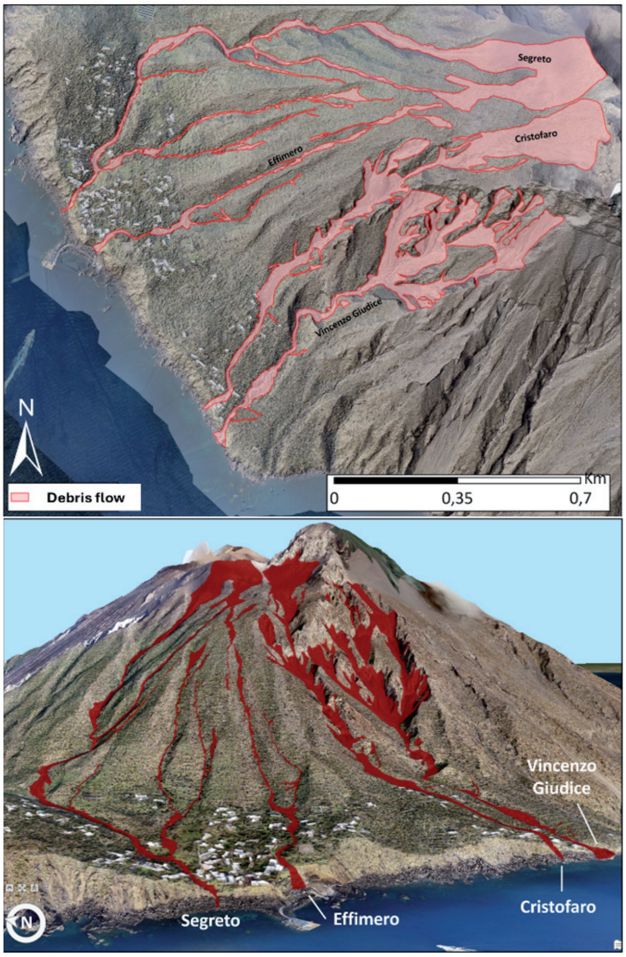

Fig. 6 - Debris-flow mapping on the flank containing the Ginostra inhabited area. Top: map view; bottom: 3D perspective

These morphological patterns suggest a clear connection between slope gradient, channel convergence, and sediment delivery to areas of human exposure. However, part of the deposited material was removed prior to the November 2024 survey, making accumulation data less representative than erosion data.

In the Ginostra sector, DSM comparison highlights diffuse erosion in the upper slopes, with average thicknesses comparable to those observed at Stromboli, and more concentrated processes within the four main channels, where incisions reach depths of up to 7.4 m (Figure 10). The differentiation between diffuse sheet erosion and concentrated channelized erosion provides critical information for prioritizing interventions in the most vulnerable catchments.

Eroded volumes and critical catchments

Eroded volumes were calculated through DSM differencing within debris-flow affected areas, allowing catchments to be classified in terms of criticality by considering both mobilized volumes and interaction with exposed elements (Figure 11, Table 1, Table 2).

In the Stromboli sector, the most critical catchments are Montagnà–Russo and San Bartolo, with eroded volumes of approximately 26,300 m³ and 22,100 m³, respectively, followed by San Vincenzo, Machichi, Pizzillo, and Vallonazzo. The latter, despite significant volumes, currently does not interfere with exposed elements.

In the Ginostra sector, estimated volumes are overall higher, reaching approximately 57,600 m³ in the Vincenzo Giudice catchment and more than 53,000 m³ in the Segreto catchment, which directly interacts with the settlement and road network. Differences with respect to the Stromboli sector are mainly attributed to the longer temporal interval covered by DSM comparison and to the greater morphological complexity of the slopes.

NUMERICAL MODELING OF DEBRIS-FLOW PROPAGATION

UAV–LiDAR surveys and multi-temporal morphological analyses provided the knowledge base for setting up numerical simulations of debris-flow propagation, aimed at evaluating potential impact scenarios and supporting hazard mitigation in the settlements of Stromboli and Ginostra.

The simulations were conducted using the RAMMS model: a rheology-based, depth-averaged model for granular and debris flows, which solves shallow-water-type equations adapted for granular flows, allowing the estimation of flow thickness, velocity, and areas potentially affected by debris inundation (Christen *et alii*, 2020; Frank *et alii*, 2017). RAMMS modelling was performed as a back-analysis of observed debris flows. Calibration of the Voellmy rheological parameters showed that the events could be well reproduced using $\mu = 0.2$ and $\xi = 300$, values typical for debris flows of intermediate behavior (*i.e.*, neither solid-dominated nor fluid-dominated). A flow density of 2000 kg/m³ and a stopping criterion of 1 km/h for the velocity of the center of mass were also applied. The model links quantified erosion volumes and channel morphologies to practical hazard scenarios, providing a tool to support decision-making by local civil protection authorities. A high-resolution Digital Terrain Model (DTM) derived from the November 2024 UAV surveys was used as the base surface, obtained by removing vegetation from the DSM while retaining buildings and relevant infrastructure.

Debris source areas were defined based on catchment boundaries and the main erosion zones identified from multi-temporal analyses, while potentially mobilizable volumes were estimated from the eroded volumes calculated for each catchment. By explicitly connecting morphometric features to expected flow behavior, the model provides actionable insights for prioritizing structural mitigation in critical channels.

The modeling allowed simulating debris-flow propagation along the main channels, showing maximum flow thicknesses

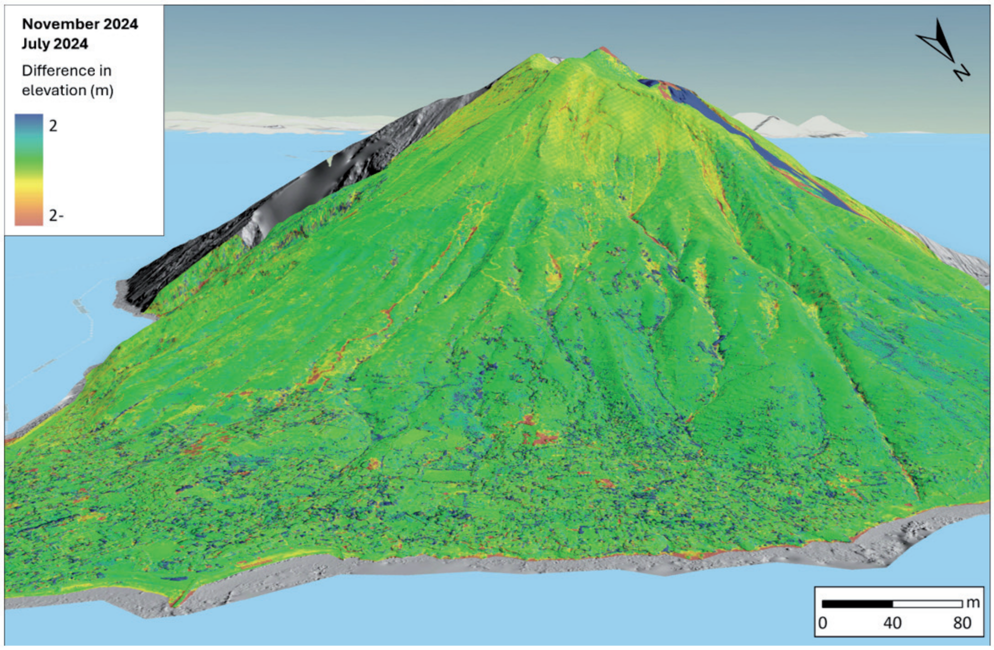

Fig. 7 - 3D view of elevation differences between DSMs from UAV surveys (Nov 2024 vs. Jul 2024), detail of the eastern area including Stromboli village

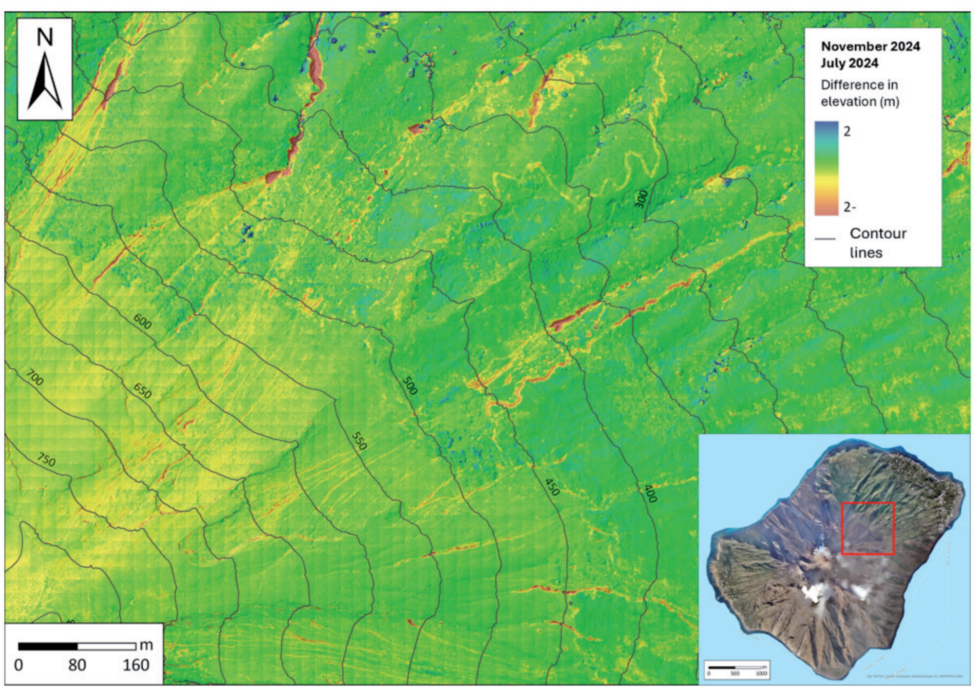

Fig. 8 - Detail of elevation differences between DSMs from UAV surveys (Nov 2024 vs. Jul 2024)

and velocities in steep upper reaches, with progressive deceleration in distal channel segments and near inhabited areas (Figure 12). For catchments directly affecting settlements, simulations indicate that even relatively small volumes can generate highly hazardous conditions where flow paths are restricted or locally obstructed.

DISCUSSION AND CONCLUSIONS

The results demonstrate that integrating UAV–LiDAR surveys, multi-temporal geomorphological analyses, and numerical modeling enable a quantitative characterization of erosion, sediment mobilization, and debris-flow propagation processes at the catchment scale, even in morphologically

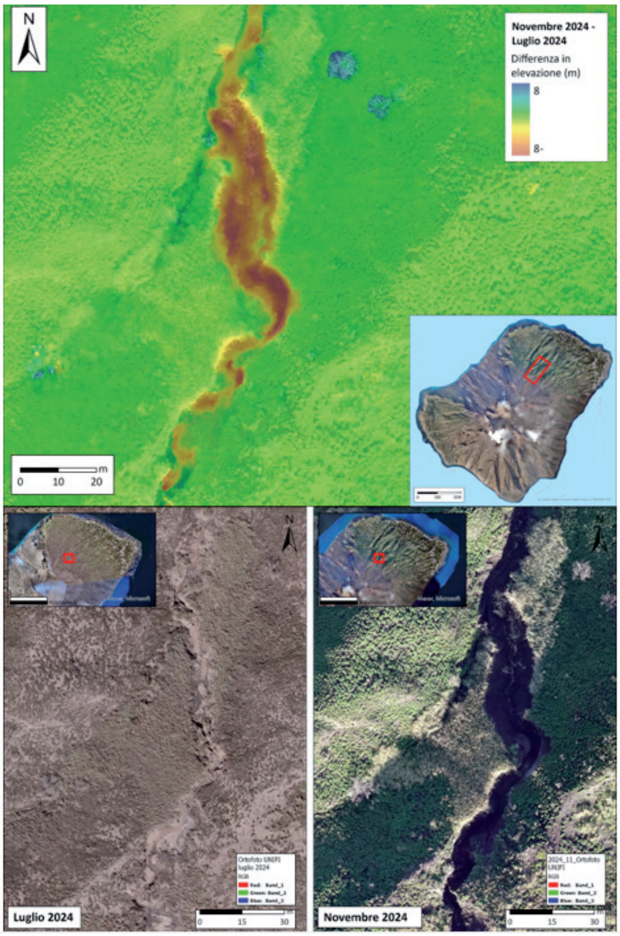

Fig. 9 - Area of maximum erosion. Top: DSM elevation differences (Nov 2024 vs. Jul 2024). Bottom: corresponding orthophotos from July and November 2024

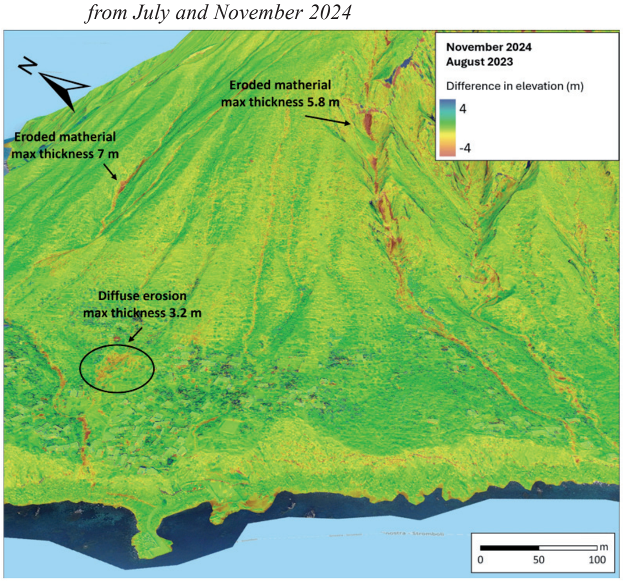

Fig. 10 - 3D view of elevation differences between DSMs from UAV surveys (Nov 2024 vs. Aug 2023), focusing on the Ginostra area

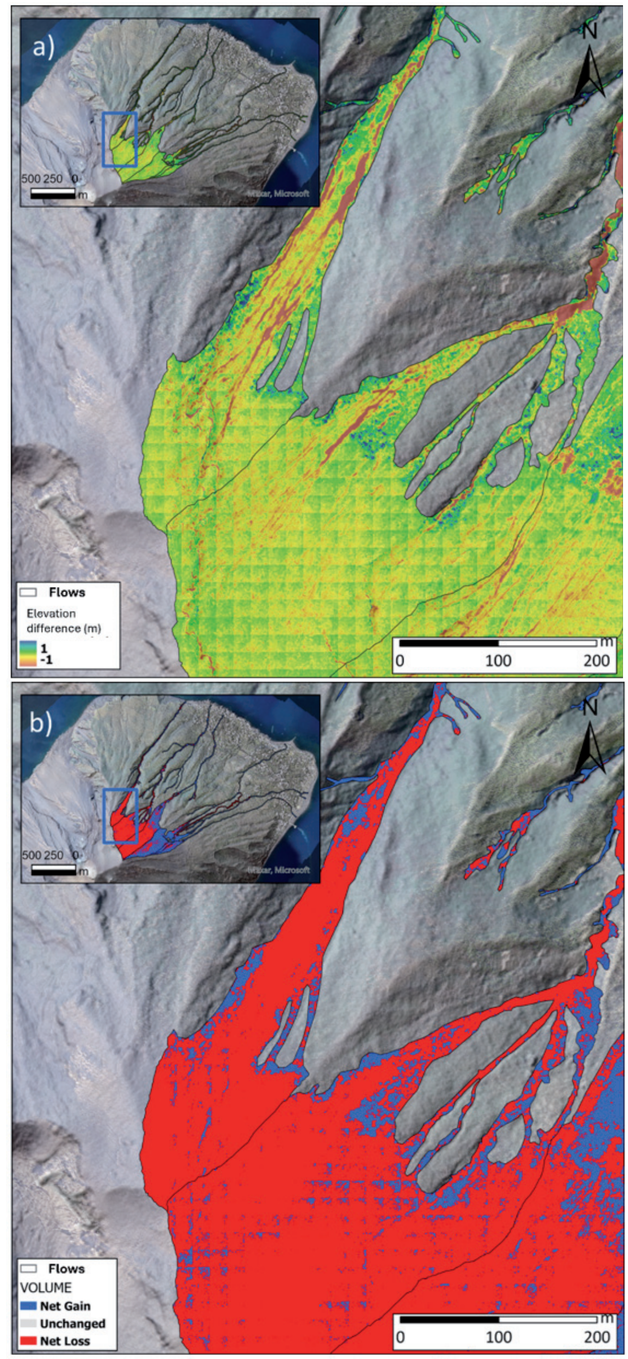

Fig. 11 - Map of elevation differences between the July and November 2024 DEMs (a) and CutFill tool results for volume calculation (b)

complex and poorly accessible settings such as Stromboli Island. The spatial distribution of erosional processes, concentrated in upper slope portions, highlights the role of loose volcaniclastic material, slope gradient, and channel morphology in controlling debris-flow initiation. Minor incisions converge into a few

	Vallonazzo	Montagnà - Russo	San Bartolo	San Vincenzo	Machichi	Pizzillo
Channel length (km)	1,7	2	2	2,2	1,8	1,6
Total catchment area (km²)	0.23	0.44	0.4	0.38	0.2	0.22
Affected area (km²)	0.05	0.11	0.11	0.08	0.03	0.02
Source area extent (km²)	0.03	0.09	0.07	0.06	0.01	0.01
Total eroded volume (m³)	14400	26300	22100	6100	7000	925
Source eroded volume (m³)	11600	17900	18000	550	205	700
Channel erosion volume (m³)	2800	8400	4000	3900	6800	225
Buildings interaction	No	Yes	Yes	Yes	Yes	Yes
Road network interaction	Closed	Yes	Yes	Yes	Yes	Yes

Tab. 1 - Volume calculation results for debris-flow events affecting Stromboli village. Channel names correspond to those shown in Figure 5

	Segreto	"Effimero"	Cristofaro	Vincenzo Giudice
Channel length (km)	2	1	1.5	1.2
Total catchment area (km²)	0.50	0.13	0.23	0.25
Affected area (km²)	0.10	0.02	0.09	0.08
Source area extent (km²)	0.04	<0.01	0.04	0.07
Total eroded volume (m³)	53600	5900	45000	57600
Source eroded volume (m³)	20400	800	18000	38000
Channel erosion volume (m³)	33200	5000	27000	19500
Buildings interaction	Yes	Yes	Yes	3 units
Road network interaction	Yes	Yes	Secondary road	Secondary road

Tab. 2 - Volume calculation results for debris-flow events affecting Ginostra village. Channel names correspond to those shown in Figure 6

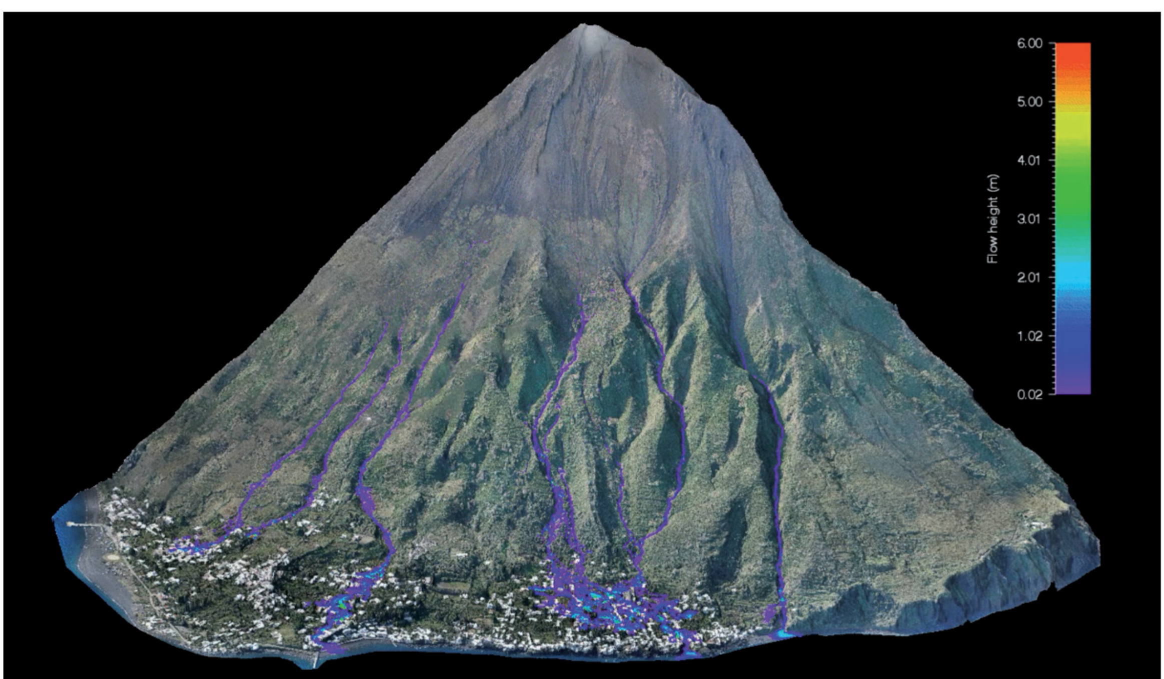

Fig. 12 - Debris-flow propagation simulation showing flow height (maximum flow depth) projected on the DTM using the RAMMS numerical model

main channels, which are typically steep and narrow, indicating efficient sediment transfer toward downstream areas and a higher hazard potential where these channels intersect settlements.

DSM differencing represents a fundamental step for estimating potentially mobilizable volumes, providing not only quantitative measurements of erosion and deposition but also insights into the geomorphic dynamics shaping the slopes. Its significance is enhanced when integrated with numerical propagation modeling, which translates morphological and volumetric data into potential impact scenarios. This allows identification of areas where even moderate morphological changes could lead to high-hazard conditions due to limited flow paths or channel obstructions. In this sense, numerical modeling represents the link between geomorphological observation and operational support for local civil protection planning and mitigation strategies.

The use of fixed-wing UAVs equipped with LiDAR sensors proves particularly effective for synoptic mapping of multiple catchments, overcoming the operational limitations of ground-based surveys and multirotor UAVs and ensuring the spatial continuity required for catchment-scale analyses. The integrated approach provides an objective basis for prioritizing intervention areas, identifying critical source zones and channels, and supporting proactive decision-making in hazard management. The proposed methodology is therefore well suited to volcanic contexts characterized by limited accessibility and rapid geomorphological evolution.

Funding

This research has benefited from the support from the following project: Accordo tra Università degli Studi di Firenze e Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile 2022-2024 and 2024-2027 (Scientific Responsibility: N. Casagli).

REFERENCES

Anders N., Masselink R., Keesstra S. & Suomalainen J. (2013) - *High-res digital surface modeling using fixed-wing UAV-based photogrammetry.* Proceedings of the Geomorphometry: 2-5.

Areu-Rangel O. S., Bonasia R., Di Traglia F., Del Soldato M. & Casagli N. (2020) - *Flood susceptibility and sediment transport analysis of Stromboli Island after the 3 July 2019 paroxysmal explosion*. Sustainability, **12**(8): 3268.

Casalbore D., Romagnoli C., Chiocci F. & Frezza V. (2010) - *Morpho-sedimentary characteristics of the volcaniclastic apron around Stromboli volcano (Italy).* Marine Geology, **269**(3-4): 132-148.

Casalbore D., Di Traglia F., Favalli M., Fornaciai A., Romagnoli C., Civico R. ... & Stefanelli C. T. (2025) - *Very fast canyon formation and evolution along active volcanic flanks: A case from Stromboli Island.* Geomorphology, **488**: 109961.

Christen M., Kowalski J. & Bartelt P. (2010) - *RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain*. Cold Regions Science and Technology, **63**(1-2): 1-14.

Civico R., Ricci T., Cecili A. & Scarlato P. (2024) - *High-resolution topography reveals morphological changes of Stromboli volcano following the July 2024 eruption*. Scientific Data, **11**(1): 1219.

Coussot P. & Meunier M. (1996) - *Recognition, classification and mechanical description of debris flows.* Earth-Science Reviews, 40(3-4): 209-227.

Di Traglia F., Nolesini T., Gracchi T., Stefanelli C. T., Rossi G., Leva D. ... & Casagli N. (2025) - *Operational radar monitoring of crater rim failure at Stromboli volcano (Italy).* Natural Hazards, **121**(15): 18391-18409.

Di Traglia F., Borselli L., Nolesini T. & Casagli N. (2023-a) - *Crater-rim collapse at Stromboli volcano: understanding the mechanisms leading from the failure of hot rocks to the development of glowing avalanches.* Natural Hazards, **115**(3): 2051-2068.

Di Traglia F., Calvari S., Borselli L., Cassanego L., Giudicepietro F., Macedonio G. ... & Casagli N. (2023-b) - *Assessing flank instability of Stromboli volcano (Italy) by reappraising the 30 December 2002 tsunamigenic landslides.* Landslides, **20**(7): 1363-1380.

Frank F., McArdell B. W., Oggier N., Baer P., Christen M. & Vieli A. (2017) - D*ebris-flow modeling at Meretschibach and Bondasca catchments, Switzerland: sensitivity testing of field-data-based entrainment model.* Natural hazards and earth system sciences, **17**(5): 801-815.

Gracchi T., Tacconi Stefanelli C., Rossi G., Di Traglia F., Nolesini T., Tanteri L. & Casagli N. (2022) - *UAV-based multitemporal remote sensing surveys of volcano unstable flanks: a case study from Stromboli*. Remote Sensing, **14**(10): 2489.

Hungr O., McDougall S., Wise M. & Cullen M. (2008) - *Magnitude–frequency relationships of debris flows and debris avalanches in relation to slope relief.* Geomorphology, **96**(3-4): 355-365.

Nannipieri L., Bevilacqua A., Di Traglia F., Favalli M. & Fornaciai A. (2023) - *The March 2023 UAS-based high-resolution Digital Surface Model and orthomosaic of the NE flank of Stromboli volcano (Sicily, Italy)*. Annals of Geophysics, **66**(5): DM526-DM526.

Rau J. Y., Jhan J. P., Lo C. F. & Lin Y. S. (2012) - *Landslide mapping using imagery acquired by a fixed-wing UAV*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **38**: 195-200.

Rosi M., Bertagnini A. & Landi P. (2000) - *Onset of the persistent activity at Stromboli volcano (Italy)*. Bulletin of volcanology, **62**(4): 294-300.

Strahler A. N. (1957) - *Quantitative analysis of watershed geomorphology*. Eos, Transactions American Geophysical Union, **38**(6): 913-920.

Wheaton J. M., Brasington J., Darby S. E. & Sear D. A. (2010) - *Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets*. Earth surface processes and landforms: the journal of the British Geomorphological Research Group, **35**(2): 136-156.

Received January 2026 - Accepted March 2026