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

REMOTE SENSING-SUPPORTED MONITORING OF NATURAL AND ANTHROPOGENIC HAZARDS TO CULTURAL HERITAGE IN VENTOTENE AND S. STEFANO ISLANDS, ITALY

Daniele CERRA(*), Peter GEGE(*), Stefan PLATTNER(*), Federico FELIZIANI(**), Guglielmo GRECHI(**), Gian Marco MARMONI(**), Francesca BOZZANO(**) & Salvatore MARTINO(**)

(*)Earth Observation Center (EOC) - German Aerospace Center (DLR) - Wessling, Germany
(**)Sapienza University of Rome - Earth Science Department and CERI Research Centre for Geological Risks - Rome, Italy
Corresponding author: daniele.cerra@dlr.de

EXTENDED ABSTRACT

Le isole di Ventotene e Santo Stefano, situate nel mar Tirreno, ospitano importanti siti archeologici come la cosiddetta Villa di Giulia, una residenza imperiale di epoca romana, e Panopticon, carcere Borbonico di Santo Stefano. Questi siti sono esposti a pericoli di origine sia naturale che antropica quali, in particolare, gli incendi boschivi e l'erosione costiera che causa instabilità delle scarpate litoranee. Un monitoraggio efficace e una corretta valutazione dei rischi sono fondamentali per definire piani di conservazione e misure di protezione a lungo termine. Questo articolo propone l'uso di tecniche di telerilevamento basate su immagini satellitari ottiche per stimare i danni causati da incendi e derivare parametri delle acque nelle isole tra il 2017 e il 2024. In questo intervallo temporale sono stati identificati otto incendi, alcuni dei quali in prossimità o all'interno dell'area protetta per la presenza di siti di rielvanza storico-culturale, e i danni sono stati valutati mediante indici spettrali multitemporali.

In aree particolarmente predisposte, gli incendi possono favorire l'innesco di frane, alterando la funzione delle radici e influendo sulle condizioni di stabilità delle coperture detritiche dei versanti. I risultati evidenziano che i siti di rilevanza storico-culturale sono esposti a questi rischi in assenza di interventi tempestivi e strategie di conservazione mirate. Inoltre, l'analisi di immagini multispettrali permette la ricostruzione della batimetria in acque poco profonde e la stima di parametri delle acque. Attraverso l'uso di modelli di inversione e la validazione con dati batimetrici ad alta risoluzione acquisiti tramite ecosonde multibeam, sono state ottenute mappe di profondità e riflettanza del fondale, anche grazie a spettri misurati su campioni di sabbia raccolti a Ventotene. Da queste analisi possono essere dedotti parametri e condizioni di controlli sui processi geomorfologici che contribuiscono all'erosione delle scogliere, minacciando direttamente la stabilità strutturale di siti come Villa Giulia, e supportare simulazioni di modelli idrodinamici. Questa ricerca suggerisce che l'integrazione di tecniche di telerilevamento consente di valutare e mitigare minacce climatiche e antropogeniche su larga scala, supportando la conservazione dei siti nell'ambito di iniziative come il progetto TRIQUETRA, con metodologie trasferibili ad altri siti di interesse storico-culturale nel bacino Mediterraneo, esposti a simili pericoli.

IJEGE, Special Issue 1 (2025): 65-81, DOI: 10.4408/IJEGE.2025-01.S-05
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Cultural heritage sites are increasingly at risk due to climate change and environmental hazards, which can include floods, erosion, and ground instabilities. Climate forcing may also favour the impact of more severe anthropogenic hazards, as in the case of wildfires. In this framework, remote sensing may provide hazard quantifications and risk assessment, supporting the definition of conservation planning and protective measures. This study explores the analysis of optical satellite images to monitor and assess natural and anthropogenic threats to Ventotene and Santo Stefano islands, Italy. Specifically, we quantify damage by wildfires nearby cultural heritage sites from 2017 to 2024, while multispectral images allow a first assessment of bathymetry around the islands and deriving water constituents parameters. This enables a more comprehensive hazard analysis with a lookout on the process understanding and definition of the risks these sites face.

Keywords: *cultural heritage, Sentinel-2, remote sensing, wildfires, bathymetry*

INTRODUCTION

Cultural Heritage (CH) sites are increasingly vulnerable to the impacts of climate change, which manifests through fluctuating temperatures, altered precipitation patterns, shifting atmospheric moisture levels, and the rising of sea levels (Sesana *et alii*, 2021). These factors, coupled with extreme weather events, accelerate the deterioration of cultural heritage sites, posing a significant threat to their preservation (Kapsomenakis *et alii*, 2022, Tringa *et alii*., 2023). UNESCO has recognized climate change as a critical issue affecting cultural heritage, leading to a surge in research efforts aimed at developing mitigation strategies (UNESCO, 2008). However, while numerous studies have been conducted (Howard, 2013; Fatoric *et alii*, 2017; Bertolin, 2019; Harkin *et alii*., 2020; Orr *et alii*, 2021), there remains a lack of a structured and comprehensive approach to assessing and mitigating these risks at a broader scale.

To address this gap, the TRIQUETRA project proposes a framework designed to evaluate and counteract climate-related threats to cultural heritage (Ioannidis *et alii*, 2024). The initiative seeks to create a centralized knowledge base that consolidates research findings on climate risks and protective measures while simultaneously developing a systematic methodology for identifying and analyzing emerging hazards. By integrating advanced technologies, such as real-time risk assessment tools and monitoring systems, the project aims to enhance the precision and effectiveness of conservation efforts.

The TRIQUETRA methodology is based on a structured, three-phase process designed to comprehensively address risks associated with climate change and environmental stressors (Ioannidis *et alii*, 2024). The first phase focuses on identifying potential hazards that could affect cultural heritage sites. This includes an extensive assessment of climate-driven threats, such as extreme heat, storms, and rising sea levels, as well as hydrological challenges like flooding, erosion, and water contamination, alongside chemical and biological deterioration caused by pollutants, acid rain, and microbial growth.

Additionally, geological risks, including seismic activity, landslides and ground subsidence, are carefully analysed. Once risks have been identified, the second phase involves quantifying their impact using cutting-edge modeling tools. The project employs high-resolution climate models, remote sensing technologies, and spectroscopy to provide an accurate assessment of the severity of threats. These analytical tools enable researchers to establish risk levels for different sites, ensuring that mitigation strategies are both targeted and effective.

The final phase is dedicated to the implementation of mitigation strategies tailored to the specific conditions and vulnerabilities of each cultural heritage site. A key component of this phase is the development of the Decision Support System (DSS), which facilitates informed decision-making by providing a structured evaluation of risk severity. This system allows for the prioritization of threats and the optimization of protective measures, ensuring that resources are allocated efficiently. The DSS incorporates historical climate data, remote sensing imagery, and field observations to refine its predictive capabilities and enhance conservation planning. For a detailed workflow of the TRIQUETRA project, the interested reader is remanded to (Ioannidis *et alii*, 2024).

This paper focuses on the landslide, wildfire risk, and water analysis at the pilot site of Ventotene and Santo Stefano Islands, which are threatening, directly or indirectly, cultural sites. Because of their geographic and geomorphological features, the two islands have historically represented a place of exile; first in Roman and then in Bourbonic and Fascist times. From the late 1st century BCE onwards, several women of the imperial family were exiled in the regal imperial palace renamed “Villa Giulia”, located in the northernmost promontory of Ventotene island known as “Punta Eolo”. Later, from the 18th century onwards, the Bourbon prison (named “Carcere Borbonico”) of Santo Stefano was an important prison facility that housed hundreds of inmates until 1965, including several political dissenters exiled to the island by the fascist regime (Fig. 1).

Nowadays, both the Villa Giulia in Ventotene and the Carcere Borbonico in Santo Stefano represent important cultural heritage sites on a national level, managed and protected by the Italian Ministry of Culture and by the Special Government Commissioner for the recovery and enhancement of the former Bourbon prison on the island of S. Stefano-Ventotene - David Sassoli. The preservation of these sites is however threatened by several hazards, of which wildfires and landslides are the most

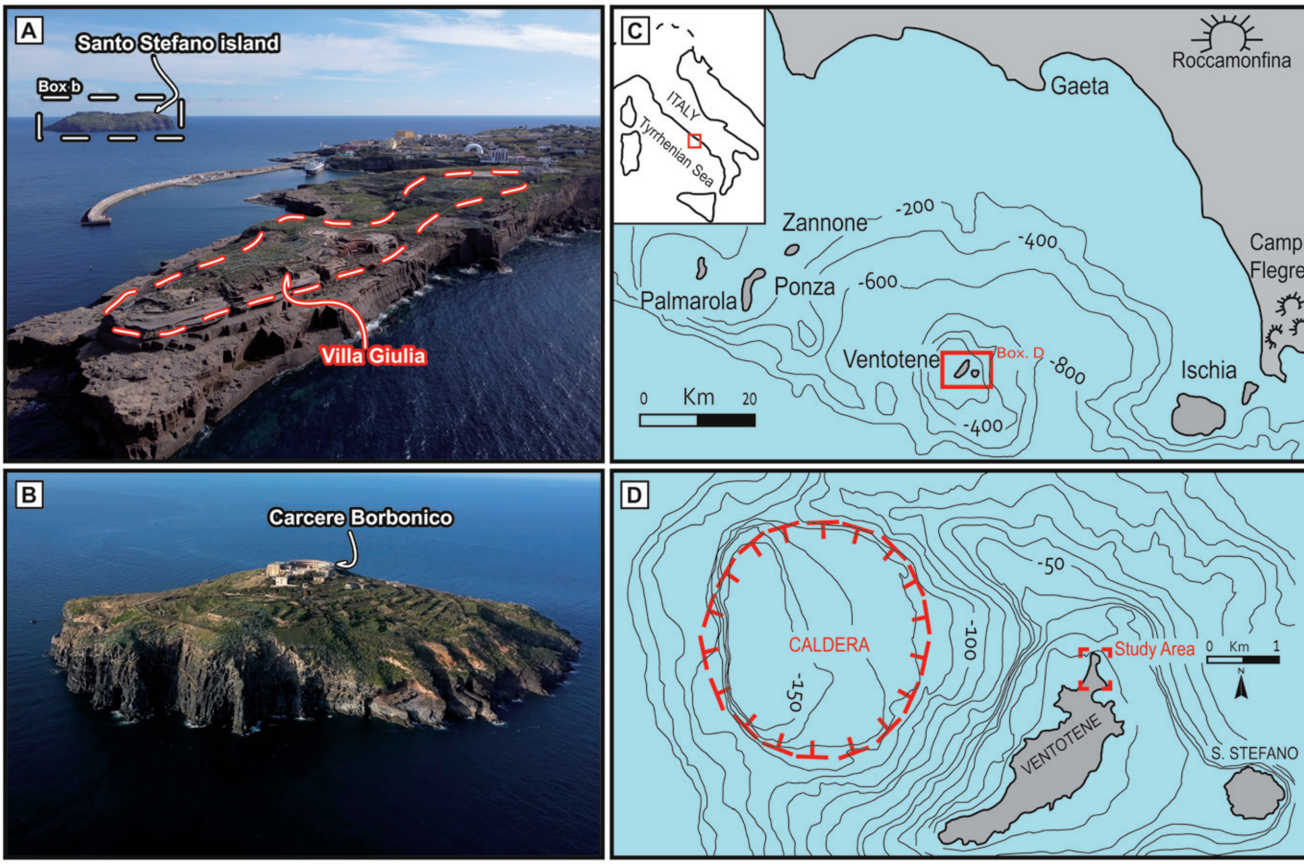

Fig. 1 - A) Aerial view of the Ventotene and Santo Stefano islands from the Punta Eolo promontory with a detail on Villa Giulia archaeological site; B) The Carcere Borbonico on island of Santo Stefano; C) Geographic location of the Pontine archipelago and D) of the Ventotene and Santo Stefano islands (mod. after Feliziani *et alii, 2024)*

important. In such context, the use of remote sensing techniques represents an important tool for framing the above-mentioned hazard or getting valuable information or ancillary data for approaching hazard analysis. Concerning wildfires, it is generally important to be able to map areas that have been burnt in the past. Wildfire catalogues are indeed essential tools for rapid mapping, and monitoring the damage inflicted on the territory on vegetation and human goods. Relevant information for such purposes can be obtained by analysis of multispectral and thermal satellite images (Chuvieco, 2020; Allison, 2016; Leblon, 2012). The derived maps can be used to monitor both loss and recovery of vegetation cover, and are therefore crucial to perform analyses of forward scenarios. It is also known that wildfires can represent a preparatory factor (sensu Gunzburger *et alii*, 2005) for landslide triggering, including both shallow mechanisms (Di Napoli *et alii*, 2020) and rockfalls (Sarro *et alii*, 2021), by removing the resistant action of the grass or bushes' roots, as well as jeopardizing the mechanical parameters (strength and stiffness; Heap *et alii*, 2018; Kushnir *et alii*, 2021). Such impact favours the rock mass weathering operating a thermal stress in the rock near the surface. Wildfires are also able to alter the local conditions of hillslopes in the long-term, making them more susceptible to external triggers, like earthquakes or heavy rainfalls (Gill & Malamud, 2014; Abdollahi *et alii*, 2023; Chicco *et alii*, 2023; Abdollahi *et alii*, 2024; Vahedifard *et alii*, 2024).

Remote multispectral and hyperspectral sensing could also support the flip side of the coin, making successful applications in water environments: regarding landslide hazard, some studies are trying to understand whether the sea-wave action can play a controlling predisposing or preparatory role in coastal retreat processes (Thompson *et alii*, 2019; Varley, 2019). In this context, the reconstruction of shallow water bathymetry becomes prominent to better focus on the impact of sea waves. Such topics have been examined in this context using hydrodynamic modelling simulations (Feliziani *et alii*, 2024; 2025; Khosravifardshirazi *et alii*, 2025). Remote sensing techniques (*e.g.*, Gege, 2014) can be used to reconstruct the bathymetry of a site, representing an important tool for hydrodynamics models, which together with stress-strain slope stability analysis, can represent a value chain for landslide hazards mitigation strategies. In this sense, the use of open Sentinel-2 imagery which are available worldwide, lay the fundamentals for numerical modelling applications. Furthermore, water constituents can be derived to characterize water quality and estimate the amount of optically active natural water components, such as phytoplankton, sediments, and coloured dissolved organic matter.

This study features the results of a remote sensing-supported analysis of hazard and analytical approach carried out to mitigate risks associated with natural (*i.e.* rock cliff instabilities) and anthropogenic hazards (*i.e*. wildfires) for the Ventotene and Santo Stefano islands. Specifically, several wildfires occurred in the last seven years on both islands nearby relevant CH sites have been detected, and water parameters derived from recent satellite acquisitions have been analysed.

GEOMORPHOLOGICAL SETTING OF VENTOTENE AND SANTO STEFANO ISLANDS

Approximately 50 kilometres off the Gaeta Gulf, the Pontile Archipelago is a group of islands that includes the islands of Ventotene, Santo Stefano, Ponza, Palmarola, and Zannone. (Fig. 1). Ventotene and Santo Stefano islands represent the summit of a large stratovolcano which had to reach a maximum height of 800 m (Metrich *et alii*, 1988; Perrotta *et alii*, 1996). The islands are composed of basaltic to trachytic lavas (0.80-0.48 Myrs; Metrich *et alii*, 1988) unconformably covered by pyroclastic products erupted in the time span 0.3-0.2 Myrs (Metrich *et alii*, 1988). While the entire base of the small Santo Stefano consists of lava products (Bellucci *et alii*, 1999), Ventotene island's cliffs are characterized by the outcropping of both lava products (in the South-Western part) and tuffs.

The geological setting of Ventotene and Santo Stefano islands makes them highly predisposed to rapid geomorphological evolution, especially controlled by coastal erosion processes and, therefore, by landslide phenomena. Coastal erosion varies in intensity depending on the litho-technical characteristics of the area: where softer pyroclastic materials predominate, erosion rates are significantly higher, whereas lava outcrops are linked to slower coastal retreat. Inland landslides, often triggered by rainfall, occur at the interface between the volcanic bedrock and loose recent deposits (*i.e*., eluvium-colluvium). The predisposing controls of landslides (*sensu* Gunzburger *et alii*, 2005) are mostly due to the lithology of which the cliffs are composed, as well as their geomechanical setting. Among the preparatory processes for these phenomena, the most significant consists in the constant impact of waves breaking on the cliffs, which, over the long term, can generate slope overhang, and notches capable of driving the coastal cliff towards a progressive rock failure.

The landslide effects constitute a relevant cause of risk for the exposed elements of the island, including its population, tourism, historical-cultural and archaeological heritage sites and the associated tourism activities. In recent times, landslides have threatened the preservation of the Roman ancient port and Villa Giulia. In this framework, several landslides have affected the western flank of the Punta Eolo promontory, even compromising the island's monumental cemetery preservation. Other landslides have impacted the accessibility of beaches such as Cala Rossano and Parata Grande, as well as private buildings, as observed in the Cala Nave area (Ruberti *et alii*, 2020).

RISK IDENTIFICATION: THE GEOHAZARD SEVERITY CHART

Within the TRIQUETRA project, the geological conditions characterizing each pilot site have been investigated in order to identify the most relevant geological hazard related to the exposed cultural heritage. This was accomplished for the Ventotene and Santo Stefano case study by drafting a so-called "Geohazard Severy Chart" (GSC) (Fig. 2). A GSC is a matrix-based analytical tool designed to assess and categorize the severity of geological hazards affecting a given site. It integrates two key components: Type of Process (ToP), which represents the specific geological hazard (*e.g*., landslides, seismic activity, flooding), and Time of Recurrence (ToR), which defines the expected return period of the hazard. By combining these parameters, the GSC assigns an Intensity Level (IL) to each potential geohazard scenario, classifying it into predefined severity categories (*e.g.*, low, medium, high, very high) using a colour-coded system. The GSC provides a structured framework for evaluating geological risks, facilitating hazard prioritization, and informing mitigation strategies for cultural heritage sites, infrastructure, and other exposed elements (see Ioannidis *et alii* (2024) for further details).

The geological hazards characterizing Ventotene and Santo Stefano islands are strongly related to the insular setting of the area. The islands are constantly struck by sea waves and wind gusts, which govern coastal retreat processes and act as preparatory factors for landslides triggering. On the other hand, sea waves and wind gusts transfer moisture and saline solutions in the surrounding area contributing to the deterioration of the archaeological remnants of Villa Giulia and the Carcere Borbonico. Similar effects are produced by heat waves and thermal cycles in general, which can cause archaeological remains to deteriorate over time.

Despite the small size of the two islands, Ventotene and Santo Stefano are also threatened by wildfires. In fact, a number of wildfires in recent years have destroyed small portions of the islands near the archaeological sites of Villa Giulia and Carcere Borbonico, as well as other archaeological sites (*e.g*., Cisterna Villa Stefania), which, despite not being part of the TRIQUETRA project, are significant assets for the islands' archaeological heritage (Fig. 3).

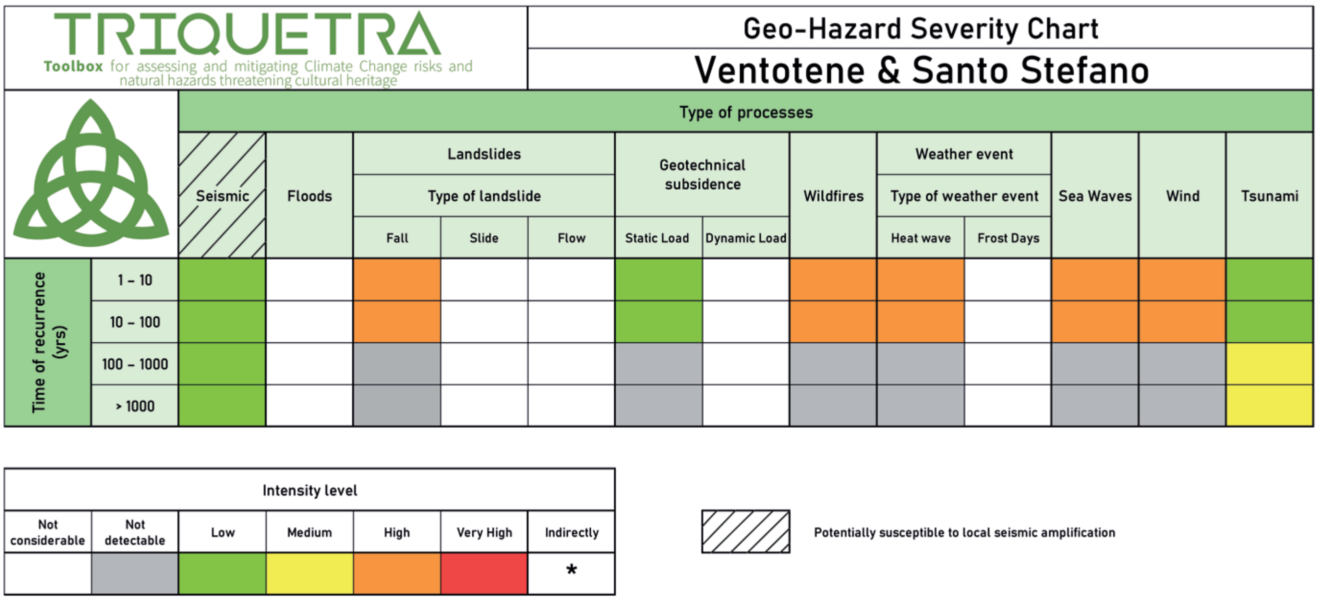

Fig. 2 - *Geohazard Severity Chart (GSC) drafted for the TRIQUETRA case study of Ventotene and Santo Stefano*

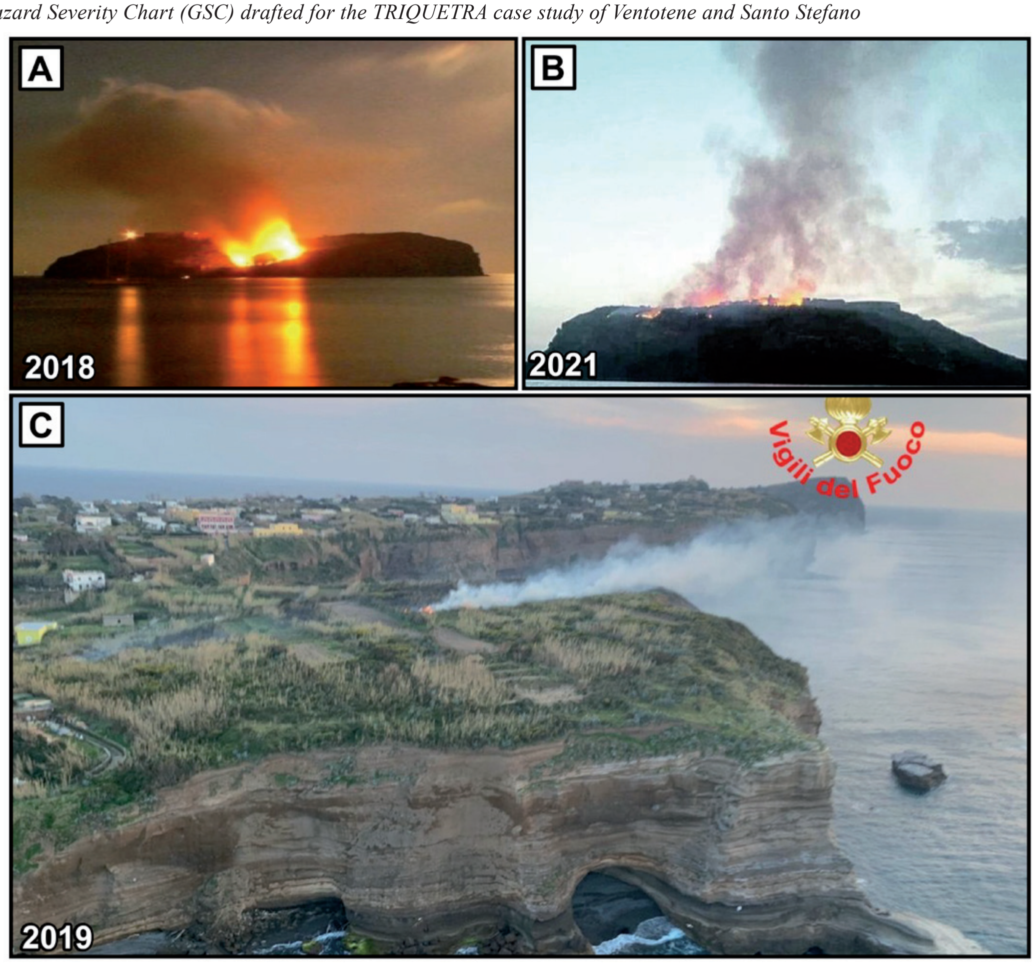

Fig. 3 - *Top: Wildfires occurred on Santo Stefano during S. Candida festivities, from (A) 2018 (Temporeale, 2018) and (B) 2023 (Latinaquotidiano, 2023). Bottom: wildfire on Ventone islands (C) from 21.3.2019 (Latina Today, 2019)*

CASES OF STUDY

Wildfire hazard

The use of satellite-based fire detection offers a powerful method for monitoring and mitigating such fire risks. This section explores the application of satellite-based fire detection technology in monitoring wildfire risks on S. Stefano and Ventotene Islands. We used optical satellite images acquired by the spaceborne Sentinel-2 sensor, which is a multispectral mission launched in the framework of the European Space Agency (ESA) Copernicus program. In this work, we employed the four Sentinel-2 bands at a 10 m spatial resolution, namely in the visible and near-infrared (NIR) range. We relied on band 12 in the shortwave infrared (SWIR) at a 20 m spatial resolution to detect burned areas. The products used were at processing level 2A, which provides data that are radiometrically corrected, georeferenced, orthorectified, atmospherically corrected, and converted to the bottom-of-atmosphere reflectance. The data selection and processing were carried out on Google Earth Engine (Amani *et alii*, 2020), which is at the same time a multi-petabyte repository of georeferenced and harmonized Earth observation raster, vector, and tabular datasets, which include the whole Sentinel-2 archive.

To quantify the damage caused by fire events to the vegetation, different Sentinel-2 scenes aggregates are analysed. To estimate vegetation loss and total burned area, we derived the normalized burn ratio (NBR), defined for a multispectral image x, as:

$$NBR(x) = (NIR - SWIR) / (NIR + SWIR) \qquad (1)$$

where NIR and SWIR indicate reflectance in the near-infrared and shortwave infrared, represented for Sentinel-2 by bands 8 and 12, respectively.

The NBR is a commonly used index to detect burned area and burn severity (Key & Benson, 2006) and is particularly sensitive to the changes in the amount of live green vegetation, moisture content, and some soil conditions, which may occur after a fire (Lentile *et alii*, 2006). Relying on the availability of multitemporal images, we used the differenced NBR (*dNBR*) since it performs well in capturing the spatial severity within fire perimeters (Picotte & Robertson, 2010). The *dNBR* related to pre- and post-event images, respectively acquired at times t0 and t1, is the delta of the two measurements (multiplied by 1000 for convention):

$$dNBR(x_{t0}, x_{t1}) = 1000\,(NBR(x_{t0}) - NBR(x_{t1})) \qquad (2)$$

A positive *dNBR* indicates damage, with severity proportional to the value. The affected area are derived by applying the damage classes defined in Key & Benson (2006), illustrated in Fig. 4, with one difference: in order to detect damaged areas with increased confidence, the interval of values related to low-severity damage is split in two equal ranges, and damage is considered only for values larger than 190.

The remainder of this subsection documents anthropogenic wildfires that occurred in the islands of S. Stefano and Ventotene from 2017 to 2024.

Severity Level	dNBR Range
Low Severity	+100 to +269
Moderate-low Severity	+270 to +439
Moderate-high Severity	+440 to +659
High Severity	+660 to +1300

Fig. 4 - Legend for severity of fire damage maps derived in this section, adapted from (Keeley, 2009)

Island of S. Stefano

S. Stefano Island, a small, uninhabited island located near Ventotene in the Tyrrhenian Sea, Italy, is vulnerable to wildfire hazards during the annual traditional S. Candida festivities held every September. As part of this celebration, lit lanterns (named "palloni") are released into the sky on the 20th of September from nearby Ventotene, with some occasionally landing on S. Stefano Island, posing a significant fire risk. The island's natural vegetation and its status as a protected area make it particularly susceptible to damage from fires caused by these airborne lanterns.

Sentinel-2 scenes acquired in a relatively short time span were aggregated to generate pre- and post-event images. An image composite of the island before the events was derived by considering up to four acquisitions with cloud cover below 10% acquired from the beginning of September until the day before the main celebration of S. Candida, for the years 2017-2024 and considering the median reflectance for each image element. This allows the removal of abnormal values due to specific atmospheric conditions inducing errors in the reflectance estimation process, undetected clouds, and cloud shadows in the scene.

The postfire reflectance image was chosen as the first cloud-free acquisition after that day, with dates ranging up to 10 days after the event. Pre-event image composites, post-event images, and detected damage computed according to equation (2) are reported in Fig. 5. In addition to consequences of San Candida fires, documented in (Temporeale, 2018) and (Latinaquotidiano, 2023) an additional case is reported for particularly severe damage caused by a cigarette fire on the 28th of June 2022 (il Messaggero, 2022).

Regarding regrowth, it was analysed how long vegetation on the island needed to recover after the fire, as described in (Guarino, 2024). Vegetation was considered to be recovered if the dNBR index between the composite before the event and a

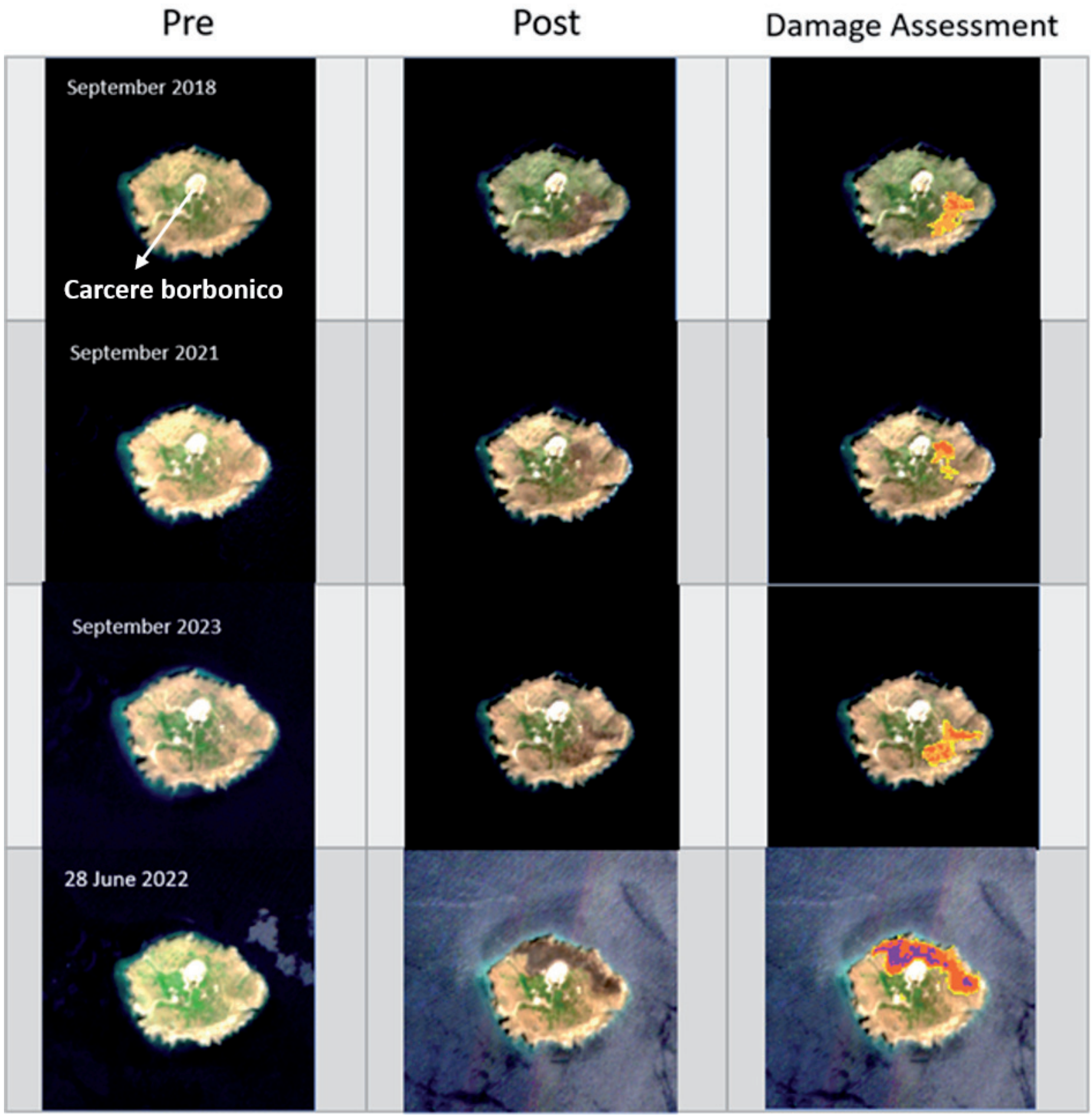

Fig. 5 - S. Stefano Island with analysis of damage caused by fire events due to S. Candida festivities in September 2018, 2021, and 2023. The last row documents the damage caused by a cigarette fire in June 2022. Mapping from yellow to purple denotes moderate to severe damage (see Fig. 4). Images are arranged columnwise as pre-event image aggregate, post-event acquisition, and post-event acquisition with overlaid estimated damage. Results were validated by reports in local newspapers about the fire events on the relevant dates. Some photos from articles therein are reported in Fig. 3

later image would not detect any damage. In all cases, images from mid-November showed the surface affected by wildfire covered again by vegetation, although nothing can be concluded on the species of vegetation dominating the regrowth. It is interesting that also the most serious event, happened in June 2022, needed until mid-November of the same year to recover, possibly because of the most serious damage combined with the summer period where precipitation is scarce. In one case (2021) no suitable cloud-free images were available for the month of November, so the above could only be verified for December.

Island of Ventotene

Three anthropogenic wildfire events were analysed and assessed for the island of Ventotene. Out of these three, one was relatively close and one was inside the perimeter of the archaeological site of Villa Giulia, in the north of the island. Fires propagating to the archaeological site could damage the archaeological material, in particular the surviving fragments of frescoes discovered in the villa. Another fire took place instead in the proximity of the Roman cistern of Villa Stefania.

The first fire detected, both in temporal order and distance

Fig. 6 - Sentinel-2 pre-event image composite (September/October 2017) and post-event image (17.11.2017) acquired over the area of Calabattaglia, with evident burned areas (true color combinations)

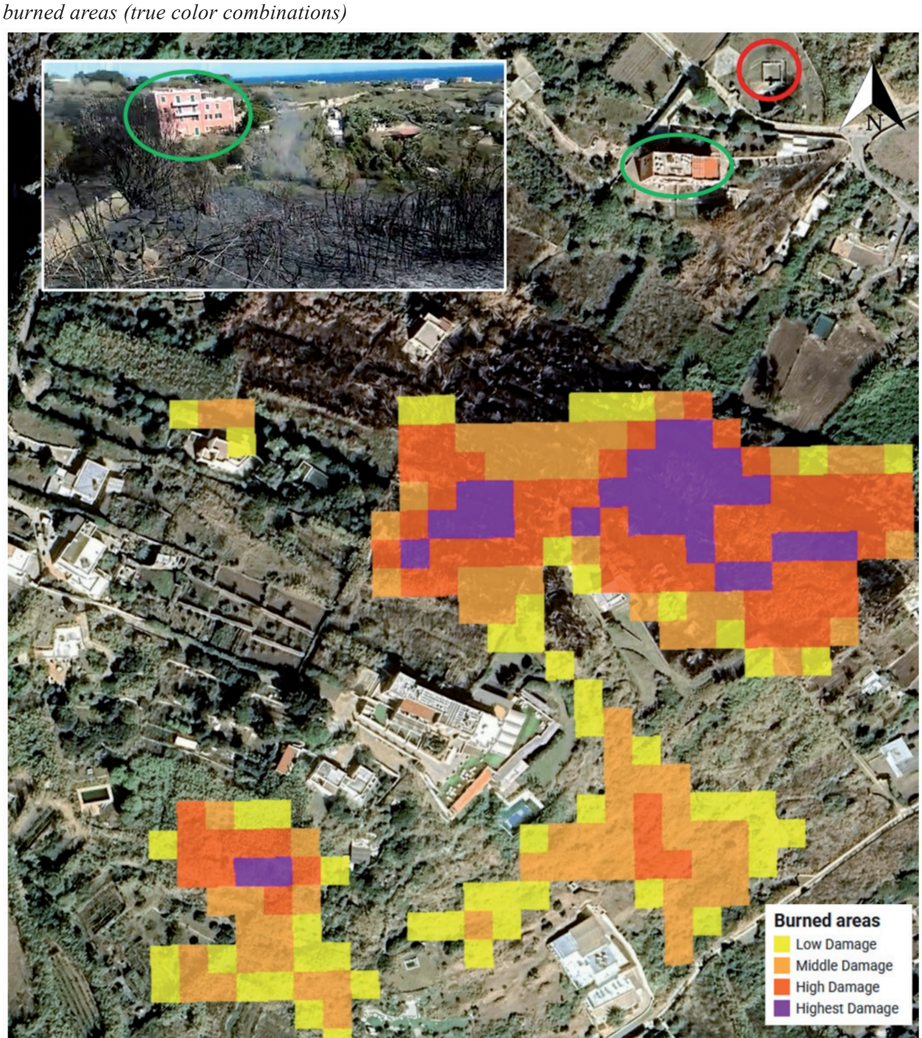

Fig. 7 - Detected fire damage (ref. legend in Fig. 4), derived from images in Fig. 6, overlaid on a high resolution base map (© 2025 Airbus, Maxar Technologies) to provide context. Circled in red in the upper right is the Roman cistern of Villa Stefania. In the insert and circled in green an identified guesthouse in the area, immediately after the event (Marangon, 2018)

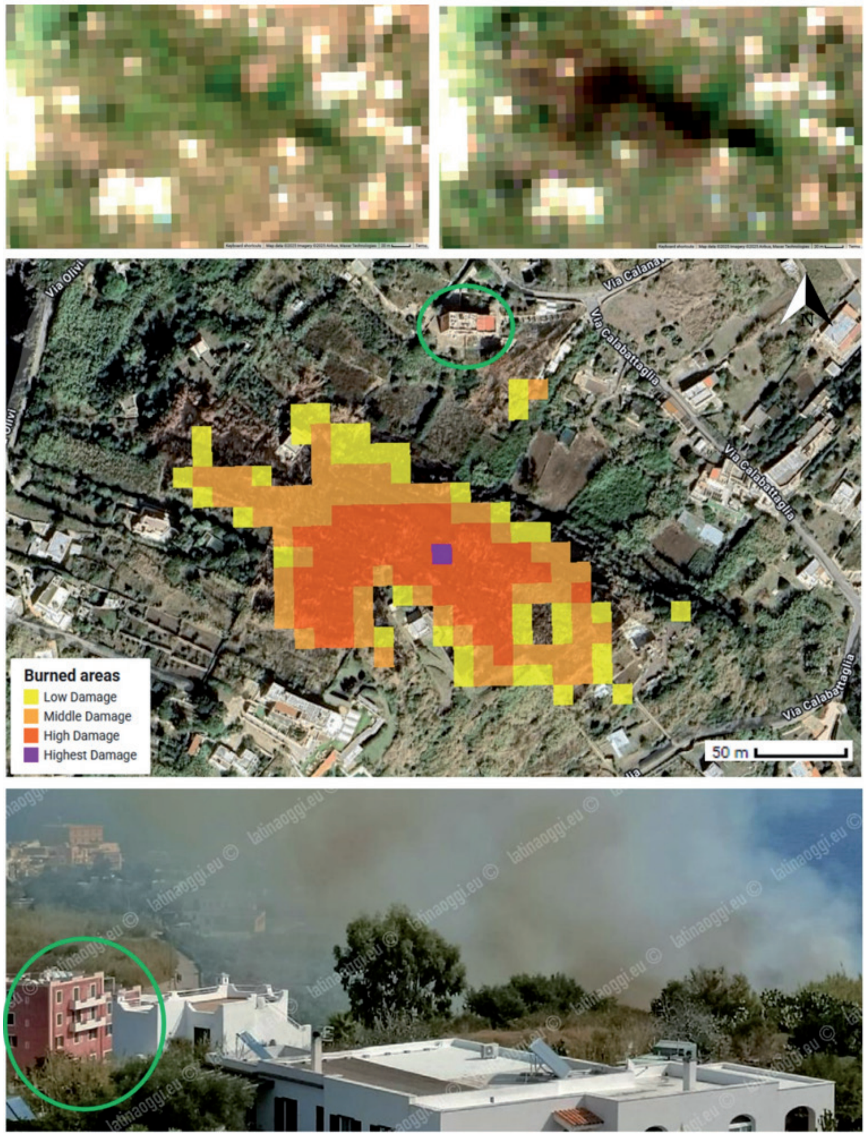

Fig. 8 - Top: Sentinel-2 pre-event image composite (September 1 to October 7 2023) and post-event image composite (October 9 to November 25 2023) acquired over the area of Calabattaglia, with evident burned areas (true color combinations). Middle: detected fire damage, overlaid on a high resolution base map (© 2025 Airbus, Maxar Technologies) to provide context. Circled in green is the same guesthouse identified in Fig. 7. Bottom: photo acquired during the event (Latina Oggi, 2023), with the same guesthouse circled in green

from the archaeological site of Villa Giulia, happened in the area of Calabattaglia, in the southwest of the Island, on the 24th of October 2017. Fig. 6 reports a Sentinel-2 median true color combination for pre-event acquisitions, acquired in the time frame 5.9 - 8.10 2017, and a post-event image acquired on 17.11.2017, where burned areas are evident in bands in the visible range of the spectrum.

The dNBR computed as in equation (2) yields the results reported in Fig. 7, which allows better identifying the most severely affected areas. The reported maps match very well the reports on the two main areas where the fire developed, with highest damage reported in purple, with the fire starting in the southwest on the image and spreading to the north, according to locals who witnessed the event (Martino, 2025). The Roman cistern of Villa Stefania, an important CH landmark located nearby to the North-East of the affected area, is circled in red in the same figure. An article reported on a national newspaper (Marangon, 2017) shows the fire in a video, for which a frame is reported as an insert in Fig. 7 where a guesthouse in the area (at coordinates 40.792 N, 13.422 E) has been identified by the authors of this paper. The article therein estimates the affected vegetation as about 3 hectares, which agrees with the

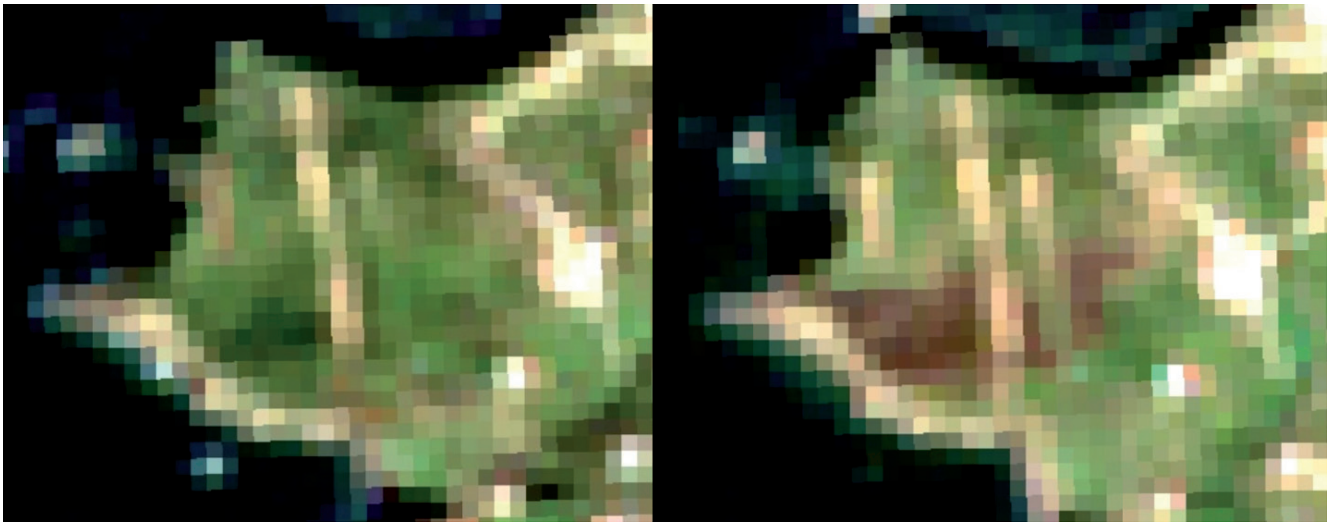

Fig. 9 - Sentinel-2 pre-event image and post-event image composites (17.11.2017) acquired before and after the 21.3.2019 over the area of Parata grande, with evident burned areas (true color combinations)

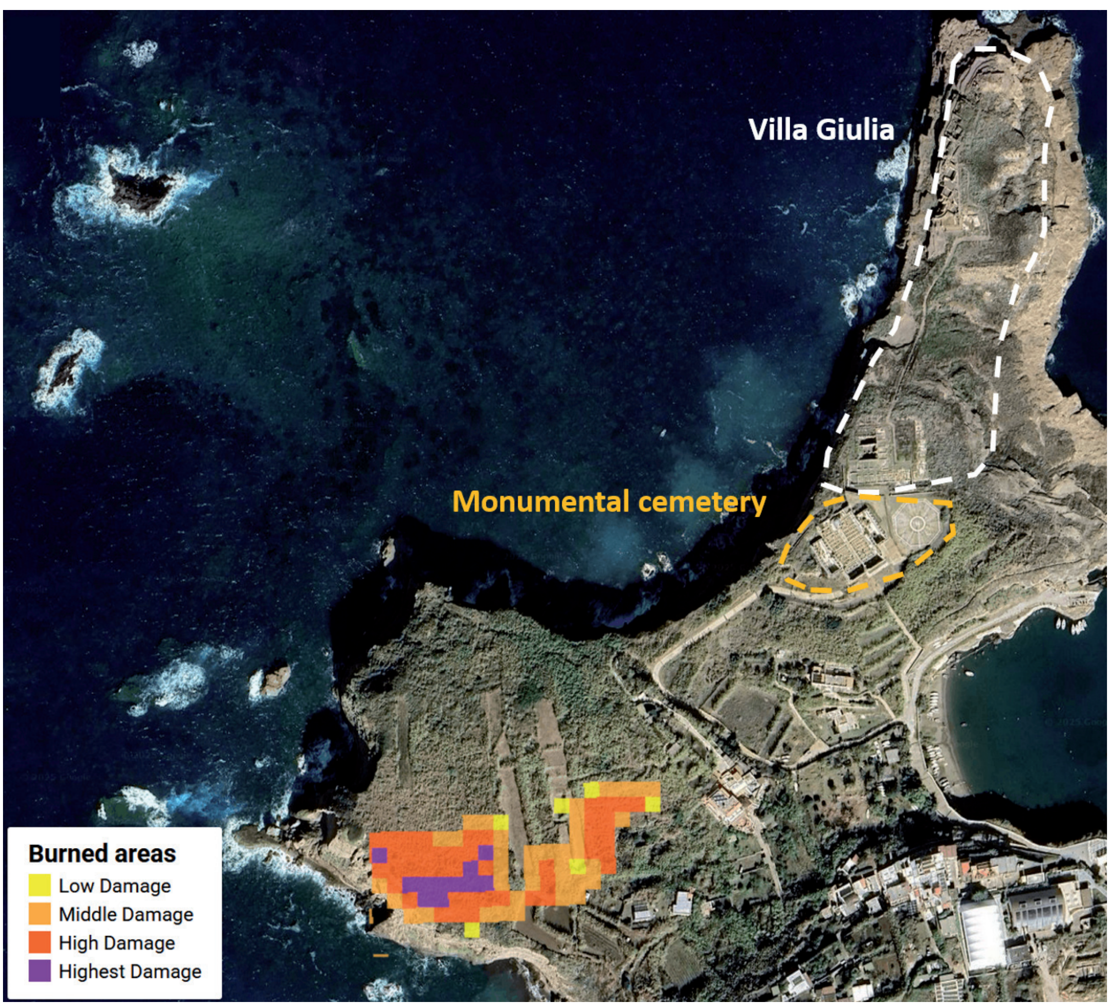

Fig. 10 - Detected fire damage derived from images in Fig. 9, overlaid on a high resolution base map (© 2025 Airbus, Maxar Technologies)

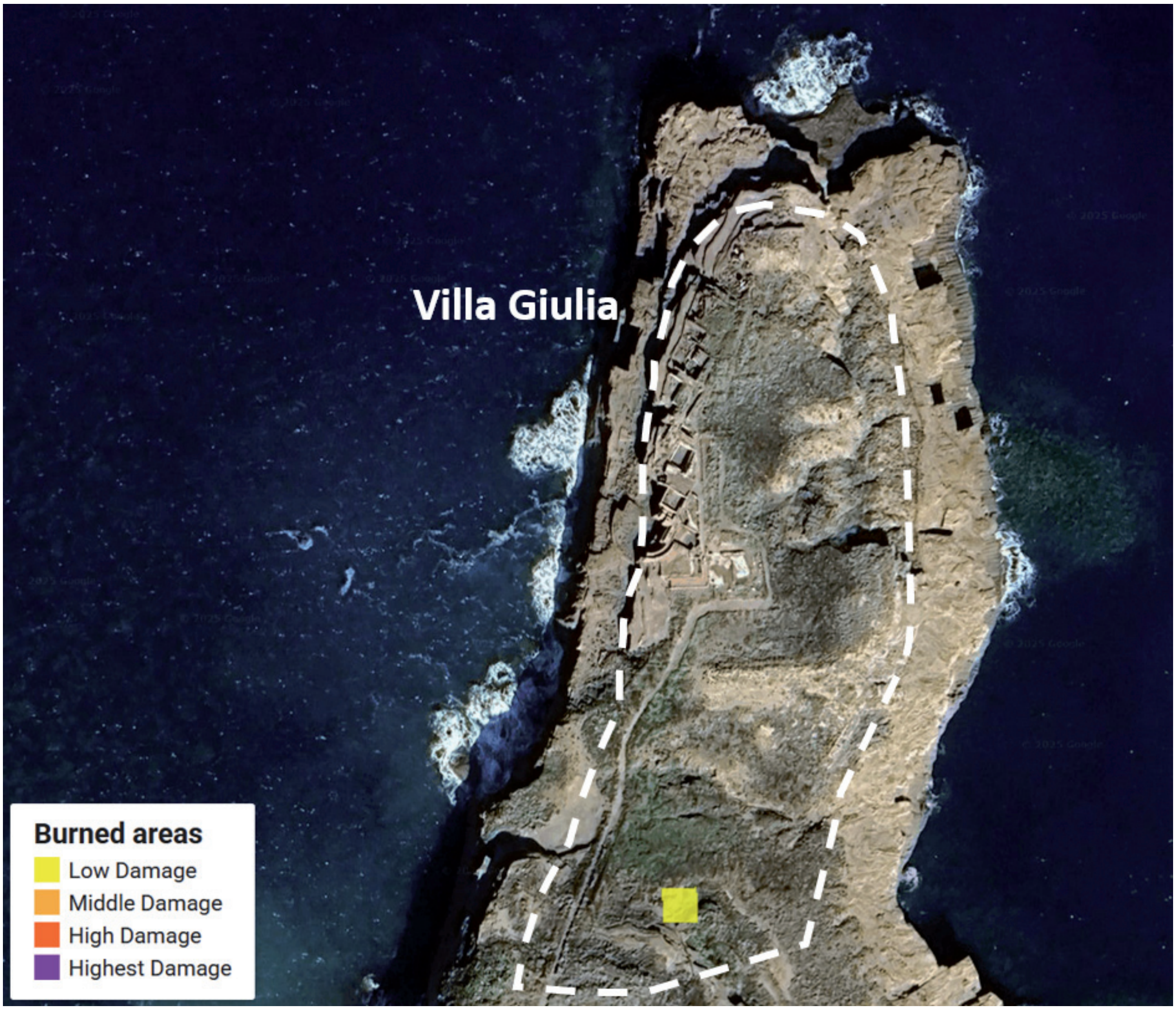

Fig. 11 - Detected fire damage nearby Villa Giulia (September 2024), overlaid on a high resolution base map (© 2025 Airbus, Maxar Technologies)

extent of the damaged area in Fig. 7, corresponding to 2.3 hectares.

In 2023, a second wildfire took place in Calabattaglia due to uncontrolled agricultural practices. Photographs acquired during the event (Latina Oggi, 2023) allow confirming the affected area to be the same of the 2017 event. The total extent of the damaged areas appears reduced with respect to the previous case, with a total affected area of 1.6 hectares and in general less severe damage. Results are reported in Fig. 8.

On 21.3.2019, a wildfire affected Ventotene, namely the area of Parata Grande, still at a safe distance from but closer to the archaeological site of Villa Giulia, as documented in local newspapers (Latina Today, 2019). Related Sentinel-2 acquisitions and damage estimation are reported in Figs. 9 and 10. The area with high damage (dark orange and purple in Fig. 10) has an extension of 5300 m^2, which would match well the estimate reported in the article of 5000 m^2. The total area including image elements with low damage has an extension of around 9000 m^2 in the image.

Recently, in September 2024, co-authors of this paper have directly witnessed damage caused by wildfire directly within the archaeological site of Villa Giulia. A very small area marked by low damage is identified by the algorithm in the exact spot where the fire developed in Fig. 11. As stated above, only values above 190 are considered as damage in dNBR results, which decreases the probability of this detection being a false alarm. Furthermore, the pre-event image composite is acquired during the dry months of July and August, and the loss of vegetation measured in September is therefore more meaningful.

Two subsets of an image composite acquired before the event (15.07 to 14.08.2024), and an image acquired after the event (21.9.2024) are reported in Fig. 12. In this case, the damage is difficult to visually identify by comparing the two images, and is revealed by computing the dNBR score.

Fig. 12 - Subsets of pre- and post-event Sentinel-2 acquisitions related to the detected damage in Fig. 11, marked by a yellow square in the right image and corresponding to a single image element having an area of 100 m^2. The images are a median composite of 20 Sentinel-2 images acquired in the time frame 15.07.2024 to 14.08.2024, and an image acquired on the and 21.9.2024, respectively

Bathymetric and water parameters

The impacts of climate change, including rising sea levels, coastal erosion, and changes in marine ecosystems, pose risks to the preservation of cultural heritage located in sensitive areas such as Ventotene island. In this section we illustrate the retrieval of relevant water parameters, aiding the monitoring of this phenomenon, from optical satellite images.

A cloud-free Sentinel-2A satellite image acquired on May 11, 2024 over the islands of Ventotene and Santo Stefano is chosen for illustration. Sentinel-2A has 13 bands from 443 to 2200 nm with native resolutions of 10 m, 20 m and 60 m, and data are available as top of atmosphere radiances (Level-1) and bottom of atmosphere reflectances (Level-2). We used the Level-2 data in 10 m resolution, which means that most bands have been sharpened from a coarser resolution. Conversion from Level-1 to Level-2 makes use of the atmospheric correction software Sen2Cor, which has been developed for land applications and is not optimized for water, *i.e*. the uncertainty requirements for water are not met and the specular reflections at the water surface (sun glint, sky glint) are not corrected.

We used the 2D module of the freely available WAter color SImulator (WASI, Gege 2014) for processing the image. The Level-2 image was converted to units of radiance reflectance, R_{rs}. WASI applies a physical model to determine a number of environmental parameters simultaneously from R_{rs} by inverse modelling. The number of these so-called fit parameters is adjustable to the actual data set. Fit parameters can be chosen to correct sun glint and sky glint and minor errors of atmospheric correction, to determine concentrations of water constituents, and to classify the bottom type and determine water depth in shallow waters.

The number of fit parameters must always be kept as low as possible to avoid overfitting that can lead to large errors. In particular in shallow water, the number of unknown parameters is too large to be determined from a R_{rs} spectrum. Therefore, sky glint and the concentrations of phytoplankton, total suspended matter (TSM) and colored dissolved organic matter (CDOM) were determined in a first step from deep water surrounding the two islands and kept constant for the shallow areas, assuming that they are similar there. Phytoplankton was found being dominated by green algae with an average chl-a concentration of 0.19 ± 0.01 µg/l, and TSM concentration was 0.14 ± 0.02 mg/l. CDOM concentration was below detection threshold and was set to zero.

In a second step the green band of Sentinel-2A (band 3 at 560 nm) was used to mask out deep water ($R_{rs} < 0.0035 sr^{-1}$) and land ($R_{rs} > 0.015 sr^{-1}$). Fig. 13 shows the resulting shallow water areas.

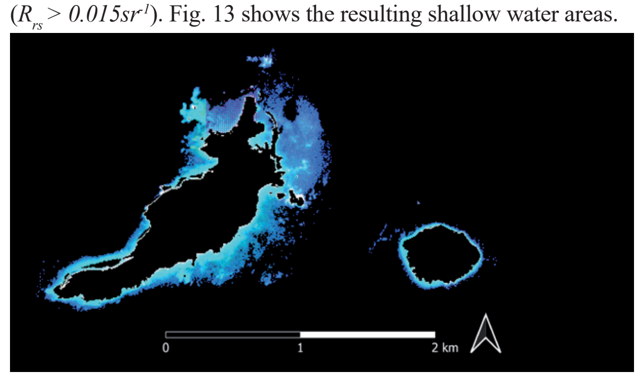

Fig. 13 - Sentinel-2A image from May 11, 2024 of the shallow waters around the islands of Ventotene and Santo Stefano, Italy. Deep water and land are masked out. The pink dots in the NW mark the pixels used for validating the satellite-derived bathymetry

To process a R_{rs} spectrum of shallow water with a physical model, an albedo spectrum of the sea floor is needed. The database of WASI contains a number of typical albedo spectra, *e.g.* from

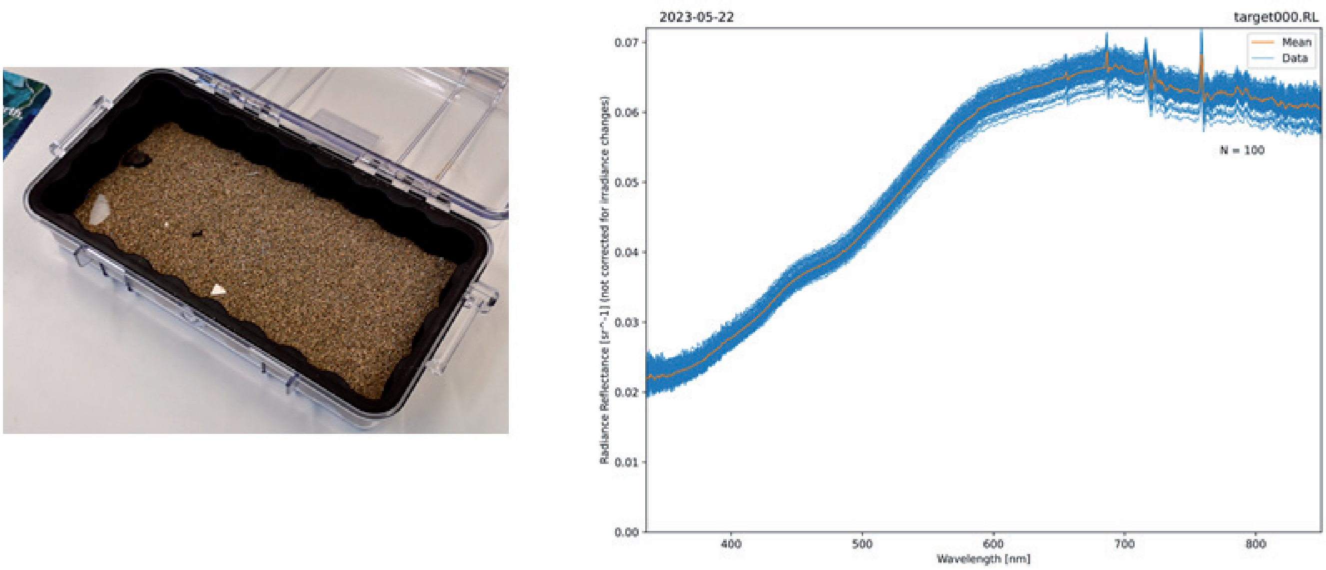

Fig. 14 - Left: collected soil samples; right: spectral measurements of the soil samples

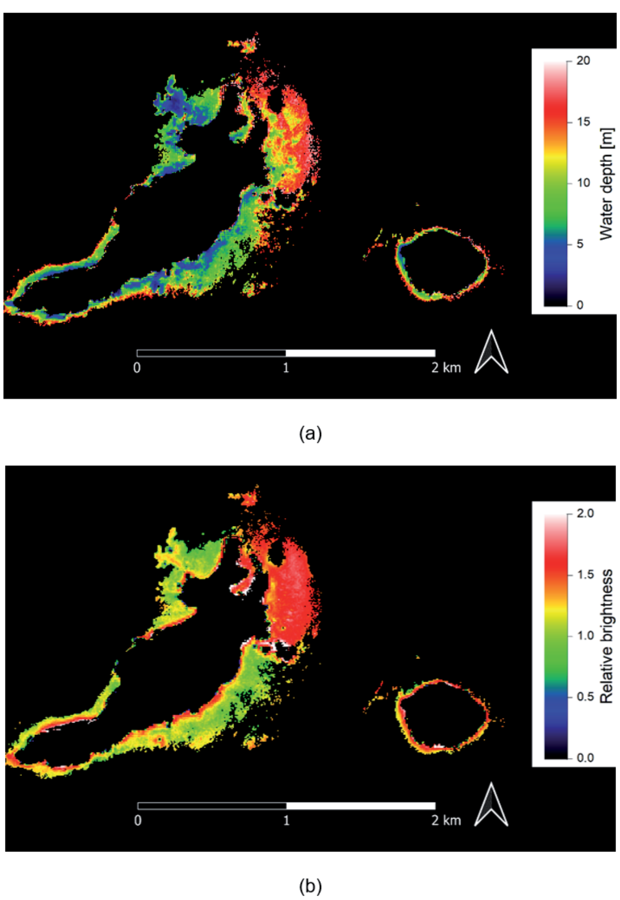

Fig. 15 - Water depth (a) and brightness of the sea floor (b) around the islands of Ventotene and Santo Stefano derived from the image shown in Figure 13

sand, silt, mussels, macrophytes, sea grass; however, as the optical properties of benthic substrates vary from region to region, data processing can be improved by using spectra which represent the substrates from the actual site. For this reason a sample of sand from a beach of Ventotene was collected by the partner Sapienza University of Rome , and its albedo was measured in DLR's labs in both dry and wet conditions. This measurement was used in WASI to represent the spectral shape of sea bottom albedo for the shallow water areas (Fig. 14), based on which the water parameters presented in this section were derived.

The variability of the brightness of the sea floor was taken into account in terms of a wavelength-independent scaling factor for the albedo (f_A). Data processing determined for each pixel in the shallow areas three fit parameters simultaneously: f_A, water depth (z_B) and sun glint (g_{DD}). Fig. 15 shows the results for water depth and brightness of the sea floor.

A very detailed bathymetric survey carried out on the sea floor facing the archaeological site of Villa Giulia was made available by the Municipality of Ventotene. The survey was performed using multibeam technology (MBES - R2 Sonic 2022) and, in the area closest to the cliff, was supplemented with a single-beam echosounder (SBES - Echologger EU400) survey to acquire bathymetric data as close to the shoreline as possible. The derived bathymetric map has a resolution of 10 cm and it was used to validate the satellite-derived water depths. Fig. 16 shows a cutout of this map. The sea floor is covered with rocks and pebbles of different sizes and has a high variability in water depth on small scales.

The comparison of water depth obtained with the two different methods is presented in Fig. 17. The red dots show all matchups,

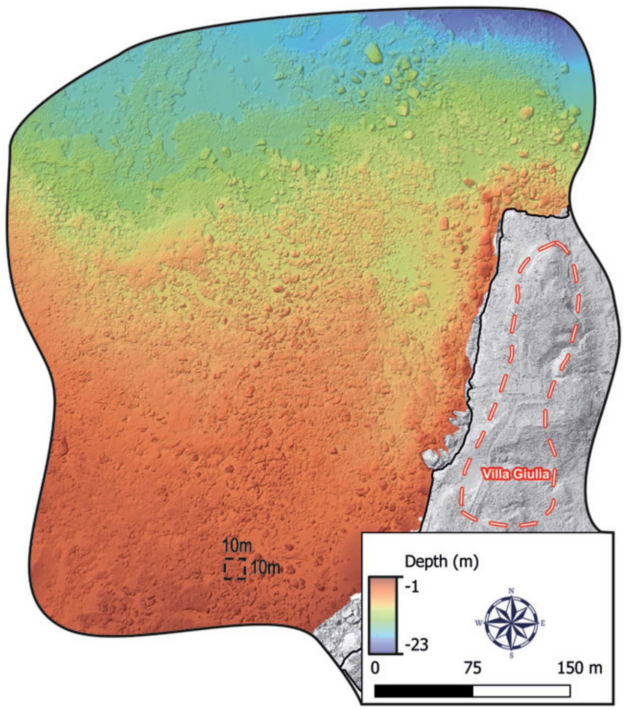

Fig. 16 - Bathymetry of a small area in the North of Ventotene obtained with a multibeam echosounder

while the blue dots show only the results which passed the quality control defined by a spectral mismatch between measured and fitted below a spectral angle (Kruse *et alii*, 1993) of 0.095.

The quality-controlled data are significantly correlated with the echosounding data ($R^2 = 0.67$) and have a root mean square error 1.5 m. Two main factors are responsible for the differences:

- Difference in spatial resolution. While an image pixel of Sentinel-2A covers an area of 10 × 10 m², the spatial resolution of the echosounder is a few centimeters. The depth can be highly variable within 10 × 10 m² as illustrated by Fig. 16.
- Variability of benthic composition. The spectrum of the sand from the beach does not represent well all the different materials on the seafloor, and the more the bottom albedo of a pixel deviates from the used sand spectrum, the larger is error propagation to the other fit parameters, z_B and g_{DD}. An unsuitable albedo spectrum leads to a spectral mismatch between the measured and fitted spectrum R_{rs}, as quantified by the spectral angle. The red dots in Fig. 17 can therefore be attributed to the image pixels where the used bottom albedo spectrum didn't represent well the sea floor. In most cases the inapt albedo spectrum induced a large error of water depth. We attempted to use sea grass as an additional fit parameter to account at least for one other substrate, but it could not be reliably distinguished from sand.

The satellite-derived bathymetry may help in tracking

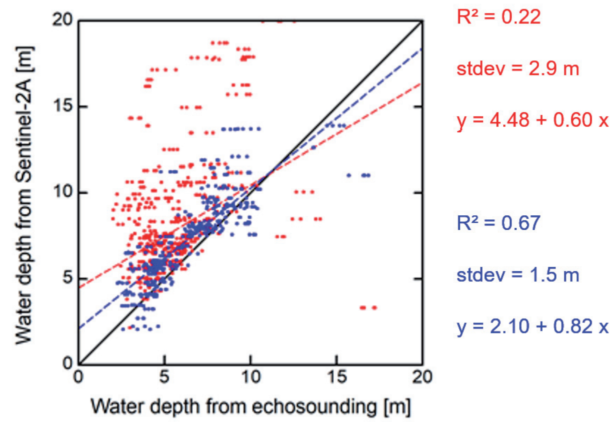

Fig. 17 - Comparison of water depth derived from boat by echosounding and from satellite by inverse modelling of the reflectance spectrum. Red: all matchups; blue: matchups passing quality control

changes in coastal and underwater topography over time, allowing authorities to identify areas most at risk of erosion. The brightness of the sea floor can indicate shifts in sediment deposition, erosion patterns, or pollution.

DISCUSSION

The risk associated with fires near archaeological sites can jeopardize their preservation as well as requiring specific and considered precautions in their usability, for example from a tourist perspective. The possibility of collecting historical data on the distribution of fire events and their propagation (both in terms of areas reached and diffusion times, *i.e.* spatial and temporal features) represents in itself a fundamental tool for designing safety plans sized to the danger.

In addition, having collected scenarios of events, such as those reported here from satellite image analyses, helps to calibrate tools for modeling analysis to obtain propagation scenarios from a forward perspective.

The use of the satellite techniques, presented here and applied to the case study of the islands of Ventotene and Santo Stefano, has also highlighted the possibility of indirectly deriving, with a lower use of instrumental resources, bathymetric data essential for the quantitative study of the propagation along the coast of marine waves. These can have an impact against the sea cliffs, accelerating landslide processes such as those observed at Punta Eolo near the area of the imperial Roman villa known as "Villa di Giulia". Although this study did not specifically focus on the potential applications of bathymetric surveys for coastal slope stability analyses, the procedures and methodologies adopted for bathymetric data acquisition have been thoroughly described. Bathymetric data should be therefore regarded as baseline information that can support future investigations into slope instability phenomena along coastal cliffs. In particular, high-resolution bathymetric datasets can provide critical input for wave propagation modeling and for assessing the spatial distribution of wave energy dissipation along the shoreline. These hydrodynamic factors are known to influence both the mechanical erosion at the toe of the cliffs and the triggering of mass wasting processes, especially in areas characterized by steep submarine slopes or submerged notches. Therefore, the integration of bathymetric information with geomorphological and geotechnical data represents a key step towards a more comprehensive understanding of coastal landslide mechanisms.

The application of the presented remote sensing techniques acquires a specific value in coastal and shallow water areas where, in the absence of more sophisticated and expensive sensors mounted on underwater drones, the use of boats with multibeam sensors can be problematic and, therefore, it is necessary to resort to direct observational detection techniques (perhaps along scanlines), as carried out for the seabed adjacent to Punta Eolo in the TRIQUETRA project.

Overall, therefore, remote sensing analysis may have a significant and direct impact on the design of strategies to mitigate the georisk of the studied archaeological areas, as well as its preservability and, in general, transferability to similar cases.

This makes the techniques discussed here an integral part of a toolbox, such as the one proposed by the TRIQUETRA project, which aims to be demonstrative and at the same time proactive for future applications to cultural heritage in morpho-climatic contexts typical of the Mediterranean basin.

MAIN OUTCOMES

This paper reports how remote sensing technologies may provide critical information for assessing natural and anthropogenic hazards threatening cultural heritage sites on Ventotene and Santo Stefano islands. The use of open satellite data with a revisit time of five days enables monitoring capabilities. A total of eight wildfire events nearby sensitive CH sites on both islands has been detected by analysing Sentinel-2 image time series during the past seven years. A quantitative assessment of the damage, along with the distance from the CH sites, may offer valuable insights to support land management and conservation planning. Additionally, wildfire-induced vegetation loss can increase susceptibility to erosion and landslides, emphasizing the interconnected nature of these hazards. The bathymetric and water constituent analysis further illustrates how remote sensing can contribute to coastal monitoring, providing information to assess the long-term stability of the nearshore CH sites. While this study does not directly implement hazard mitigation measures, the provided maps can support authorities, researchers, and conservators in developing informed strategies to protect the CH sites, especially because events such as wildfires have been found to happen on specific days of the year, during annual traditional festivities.

REFERENCES

Abdollahi M., Vahedifard F. & Leshchinsky B. A. (2024) - *Hydromechanical modeling of evolving post-wildfire regional-scale landslide susceptibility.* Engineering Geology, **335**: 107538.

Abdollahi M., Vahedifard F. & Tracy F. T. (2023) - *Post-wildfire stability of unsaturated hillslopes against rainfall-triggered landslides.* Earth's Future, **11**(3), e2022EF003213. https://doi.org/10.1029/2022EF003213 Allison R. S., Johnston J. M., Craig G. & Jennings S. (2016) - *Airborne optical and thermal remote sensing for wildfire detection and monitoring.* Sensors, **16**(8): 1310.

Amani M., Ghorbanian A., Ahmadi S. A., Kakooei M., Moghimi A., Mirmazloumi S. M., Moghaddam S. A. H., Mahdavi S., Ghahremanloo M., Parsian S., Wu Q. & Brisco B. (2020) - *Google earth engine cloud computing platform for remote sensing big data applications: A comprehensive review.* IEEE J. Sel. Top. Appl., **13**: 5326-5350. https://doi.org/10.1109/JSTARS.2020.3021052

Bertolin C. (2019) - *Preservation of cultural heritage and resources threatened by climate change.* Geosciences, **9**(6): 250.

Chicco J. M., Mandrone G. & Vacha D. (2023) - *Effects of wildfire on soils: field studies and modelling on induced underground temperature variations.* Frontiers in Earth Science, **11**: 1307569.

Chuvieco E., Aguado I., Salas J., García M., Yebra M. & Oliva P. (2020) - *Satellite remote sensing contributions to wildland fire science and management.* Current Forestry Reports, **6**: 81-96.

Corriere della Sera (2017, October 25) - *Ventotene, fiamme sull'isola: paura per case e alberghi.* https://www.corriere.it/video-articoli/2017/10/25/ventotene-fiamme-sull-isola-paura-case-alberghi/3eba57f4-b9a4-11e7-886b-130d05763311.shtml

Ruberti D., Marino E., Pignalosa A., Romano P. & Vigliotti M. (2020) - *Assessment of Tuff sea cliff stability integrating geological surveys and remote sensing. case history from Ventotene island (Southern Italy).* Remote Sensing, **12**(12): 2006.

Di Napoli M., Marsiglia P., Di Martire D., Ramondini M., Ullo S. L. & Calcaterra D. (2020). *Landslide susceptibility assessment of wildfire burnt areas through earth-observation techniques and a machine learning-based approach.* Remote Sensing, **12**(15): 2505.

Fatorić S. & Seekamp E. (2017) - *Evaluating a decision analytic approach to climate change adaptation of cultural resources along the Atlantic Coast of the United States.* Land Use Policy, **68**: 254-263.

Feliziani F., Marmoni G. M., Gianni V., Ferrandes A. F., Pegurri A., Grechi G. & Martino S. (2024) - *Engineering-geological modelling as a tool for archaeological site preservation strategies.* Italian Journal of Engineering Geology and Environment, (Special Issue **1**): 115-126.

Feliziani F., Marmoni G.M., Grechi G., Montagnese M., Sobhani R., Istrati D. & Martino S. (2025) - *Measuring and modelling the sea-waves impact on a cliff: first results from the Ventotene Field Laboratory (Italy)*. ISRM International Symposium. Eurock 2025 - Expanding the Underground Space. Trondheim, Norway, 16-20 June. https://airdrive.eventsair.com/eventsairwesteuprod/production-atlanticmice-public/af32b084a8494141a68af67206c287db

Gege P. (2014) - *WASI-2D: A software tool for regionally optimized analysis of imaging spectrometer data from deep and shallow waters.* Computers & Geosciences, **62**: 208-215.

Gill J. C. & Malamud B. D. (2014) - *Reviewing and visualizing the interactions of natural hazards.* Reviews of geophysics, **52**(4): 680-722.

Guarino R., Cerra D., Zaia R., Chiarucci A., Lo Cascio P., Rocchini D., Zannini P. & Pasta S. (2024) - *Remote sensing reveals fire-driven enhancement of a C 4 invasive alien grass on a small Mediterranean volcanic island.* Biogeosciences, **21**(11): 2717-2730. https://doi.org/10.5194/bg-21-2717-2024

Gunzburger Y., Merrien-Soukatchoff V. & Guglielmi Y. (2005) - *Influence of daily surface temperature fluctuations on rock slope stability: case study of the Rochers de Valabres slope (France).* International Journal of Rock Mechanics and Mining Sciences, **42**(3): 331-349.

Harkin D. V., Davies M., Hyslop E., Fluck H., Wiggins M., Merritt O. & Westley K. (2020) - *Impacts of climate change on cultural heritage.* MCCIP Sci. Rev, **16**: 24-39.

Heap M., Kushnir A., Griffiths L., Wadsworth F., Marmoni G. M., Fiorucci M., Martino S., Bauda P., Gilgα H. A. & Reuschlé T. (2018) - *Fire resistance of the Mt. Epomeo Green Tuff, a widely-used building stone on Ischia Island (Italy).* Volcanica, **1**(1): 33-48. https://doi.org/10.30909/vol.01.01.3348

Howard A. J. (2013) - *Managing global heritage in the face of future climate change: the importance of understanding geological and geomorphological processes and hazards.* International Journal of Heritage Studies, **19**(7): 632-658.

Il Messaggero. (2022, July 4) - *Incendio sull'isola di Santo Stefano, in fiamme la macchia mediterranea attorno al carcere. Retrieved October 8, 2024*. https://www.ilmessaggero.it/latina/incendio_isola_santo_stefano_fuoco_carcere-6781478.html

Ioannidis C., Verykokou S., Soile S., Istrati D., Spyrakos C., Sarris A., Akritidis D., Feidas H., Georgoulias A. K., Tringa E., Zanis P., Georgiadis C. martino S., Feliziani F., Marmoni G. M., Cerra D., Ottinger M., Bachofer F., Anastasiou A., Charalampopoulou V., Krebs P., Mizaikoff B., Roulet J., Bulliard X., Dudnik G. & Anyfantis G. C. (2024) - *Safeguarding Our Heritage - The TRIQUETRA Project Approach.* Heritage, **7**(2): 758-793. https://doi.org/10.3390/heritage7020037

Kapsomenakis J., Douvis C., Poupkou A., Zerefos S., Solomos S., Stavraka T., Kyriakidis E., Kremlis G. & Zerefos C. (2023) - *Climate change threats to cultural and natural heritage UNESCO sites in the Mediterranean.* Environment, Development and Sustainability, **25**: 14519-14544. https://doi.org/10.1007/s10668-022-02677-w

Keeley J. E. (2009) - *Fire intensity, fire severity and burn severity: A brief review and suggested usage.* International Journal of Wildland Fire, **18**(1): 116-126.

Key C. H. & Benson N. C. (2006) - *Landscape assessment (LA) Sampling and analysis methods.* USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD: 51 pp.

Khosravifardshirazi A., Javadi A. A., Johari A. & Akrami M. (2025) - *A practical method to predict the critical zone of coastal cliffs at high risk of failure considering the effects of fluid–structure interaction.* Journal of Engineering and Applied Science, **72**(1): 60

Kruse F. A., Lefkoff A. B., Boardman J. W., Heidebrecht K. B., Shapiro A. T., Barloon P. J. & Goetz A. F. H. (1993) - *The spectral image processing system (SIPS) - interactive visualization and analysis of imaging spectrometer data.* Remote sensing of environment, **44**(2-3): 145-163.

Kushnir A. R., Heap M. J., Griffiths L., Wadsworth F. B., Langella A., Baud P. ... & Utley J. E. (2021) - *The fire resistance of high-strength concrete containing natural zeolites*. Cement and Concrete Composites, **116**: 103897.

Latina Oggi (2023, October 8) - *Incendio sull'isola di Ventotene, intervento dell'elicottero.* https://www.latinaoggi.eu/gallery/cronaca/214013/incendio-sull-isola-di-ventotene-intervento-dell-elicottero.html

Latina Quotidiano (2018, September 22) - *Incendio a Santo Stefano durante la festa di Santa Candida.* https://www.latinaquotidiano.it/incendio-a-santo-stefano-durante-la-festa-di-santa-candida-a

Latina Today (2019, March 22)- *Incendio a Ventotene, brucia la vegetazione a Parata Grande: canadair in azione*. https://www.latinatoday.it/cronaca/incendio-ventotene-22-marzo-2019.html

Leblon B., Bourgeau-Chavez L. & San-Miguel-Ayanz J. (2012) - *Use of remote sensing in wildfire management*. Sustainable development-authoritative and leading edge content for environmental management: 55-82. Doi: 10.5772/45829

Martino S. (2025) - *Private communication with locals who witnessed the fire event of October 2017.*

Orr S. A., Richards J. & Fatorić S. (2021)- *Climate change and cultural heritage: A systematic literature review (2016–2020)*. The Historic Environment: Policy & Practice, **12**(3-4): 434-477.

Sarro R., Pérez-Rey I., Tomás R., Alejano L. R., Hernández-Gutiérrez L. E. & Mateos R. M. (2021) - *Effects of wildfire on rockfall occurrence: a review through actual cases in Spain*. Applied Sciences, **11**(6): 2545.

Sesana E., Gagnon A. S., Ciantelli C., Cassar J. & Hughes J. J. (2021) - *Climate change impacts on cultural heritage: A literature review.* WIREs Clim Change. 2021;12:e710: 29 pp. https://doi.org/10.1002/wcc.710

Temporeale.info (2018, September 22) - *Ventotene: Incendio sull'isola di Santo Stefano a causa di una mongolfiera di Santa Candida.* https://www.temporeale.

info/84276/argomenti/cronaca/ventotene-incendio-sullisola-di-santo-stefano-a-causa-di-una-mongolfiera-di-santa-candida.html
Thompson C. F., Young A. P. & Dickson M. E. (2019) - *Wave impacts on coastal cliffs: do bigger waves drive greater ground motion?*. Earth Surface Processes and Landforms, **44**(14): 2849-2860.
UNESCO (2008) - *Policy document on the impacts of climate change on world heritage properties.* World Heritage Centre, UNESCO.
Vahedifard F., Abdollahi M., Leshchinsky B. A., Stark T. D., Sadegh M. & AghaKouchak A. (2024) - *Interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards*. Earth and Space Science, **11**(2): e2023EA003498.
Varley S. (2019) - *On the physical interaction between ocean waves and coastal cliffs* (Doctoral dissertation, Durham University).

Received February 2025 - Accepted August 2025