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Copernicus Sentinel imagery for more risk-resilient historic cities in coastal zones: contribution to the monitoring of Albenga archaeological site and delta of river Centa

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Abstract

Earth observation (EO) technologies and products are traditionally providing an extremely important contribution to a more efficient management of built areas and people during emergencies. Their employment could be extremely useful in monitoring and risk assessment of protected monument and sites situated in potentially vulnerable areas such as costal zones. Change detection has a crucial role in such activities, especially in case of hazardous events—on one side, this method can provide inputs in the phases of risk assessment and rapid mapping for immediate response; on the other side, over prolonged periods of time after the event, change detection can be used for purposes of option analysis of technical solutions and for overall recovery planning of the site. Workflow proposed is based on the use of Copernicus Sentinel-2 data to provide the comparison of changes occurring during extreme flooding events of river Centa, Liguria. Firstly, an investigation of NDVI and NDWI of the extreme flooding event occurring in November 2019 was conducted. The event was then put in correlation with another previously studied flooding hazard occurring in 2016 in the same area that has caused severe damages to the archaeological remains of the medieval church of San Clemente, situated within the Centa riverbed. In conclusion, the results from both years have been compared with ground truth data of topographic database in order to observe the extension of the flooded area and to provide contribution to the monitoring activities. The aim of the research was to offer some novel insight for a more informed decision-making during the risk assessment, risk management and resilience phases regarding the vulnerable built heritage sites found in coastal areas.

Keywords Copernicus programme · Sentinel-2 · NDWI · Impact of extreme flooding · Risk assessment · Historic cities · Albenga

Introduction

Studies in cultural heritage preservation and preventive maintenance evaluate that the archaeological site of Albenga hosted within the boundaries of the Centa riverbed is still missing an accurate analysis linked with its surroundings and within a context of precarious environmental balance (Van Meerbeek et al. 2017). The site, located in Liguria region (Italy), is extremely significant for the scientific community as it is a unique stratification of historic layers (Fig. 1). The church of San Clemente is located on the right bank of the river and is mostly out of the water; however, in case of extreme flooding events, it becomes partially or even totally submerged. In fact, there is a direct physical bond between the site and Centa river—while hosting the site within its riverbed, Centa seems to be the major threat to its integrity and stability. Sensitivity to change of this peculiar context of San Clemente, which is very likely influenced by issues linked to climate change, has been extensively described in (Previtali et al. 2018).

Extreme flooding events exert significant pressure to the structures of the built remains and to the surrounding landscapes. Nevertheless, it seems that protection of the site would clash with that of public safety—on one side, the riverbed cannot be reduced as this would reduce its width in proximity of the river mouth; hence, the site cannot be potentially reburied for future conservation; on the other side, it seems also impossible to propose embankments as protection of vertical structures as it is necessary to guarantee the outflow of the water in case of a flooding event (Previtali 2019). In September 2019, local press referred to a project proposal

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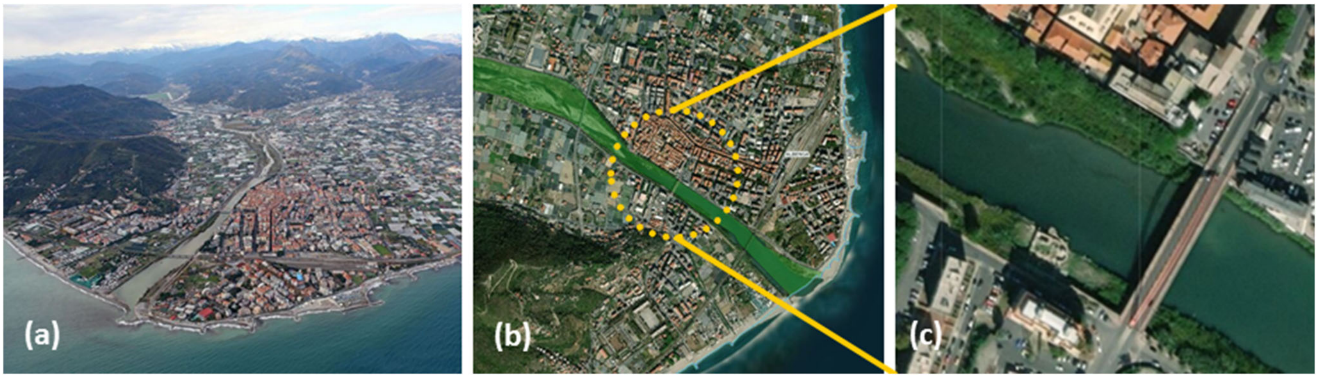


Fig. 1 Albenga case study: bird view of the coast (**a**); protected sites area as defined by regional authorities within the cultural landscape system of Albenga (**b**); close-up to the area of St. Clemente church archaeological site (**c**), found within the riverbed of the Centa river, ortofoto © Geoportale Regione Liguria

for protection of the San Clement site that foresees a collection of upstream riverbed material and its relocation in the stretch in front of the archaeological area; a sort of fence should be created using micro-piles and thus reducing the erosive effect of the river current on the foundations of the ancient complex, without interfering with the regular water flow. At the moment, the site and its surrounding area are deprived of any kind of protection devices.

Earth observation (EO) imagery and products, which are traditionally used in monitoring and mapping of natural hazards, have become particularly useful in long-term monitoring and simulation for its compatibility with Geospatial Information System (GIS) applications. In Agapiou et al. (2020, authors evaluate that EO datasets and products can play important roles in all steps of disaster risk management (DRM) cycle as defined by the World Heritage Resource Manual for World Heritage Sites (WHS) (UNESCO (Paris) 2010). Authors make a specific reference to Sentinel missions, to the Copernicus Contributing Missions and the Copernicus Emergency Management Service that could in the future support the specific requirements for preservation of archaeological sites and monuments. Quite a few research studies rely on EO and other geospatial data integration for mapping and monitoring of heritage endangered due to flooding and/or coastal erosion, especially in Mediterranean region. Cultural heritage sites in coastal areas have been widely documented and preserved; however, to date, there have been limited monitoring actions and targeted recording on the recent increasing impact of both natural and man-made disasters (Masini and Lasaponara 2017). Specific examples on the use of Sentinel-2 data, often integrated with SAR techniques, can be found in the study of flooding events affecting Bosra WHS and Sergiopolis site in Syria (Tapete and Cigna 2020) or in a study on monitoring soil erosion of Paphos WHS situated at south-west coastal area of Cyprus (Cuca and Agapiou 2017). When considering the estimation of how extreme flooding events effect nearshore areas, literature suggests remote sensing as essential data source for evaluation of effects on nearshore bathymetry due to storm-induced changes (Trembanis et al. 2019), while in Alicandro et al. (2019), authors evaluate a series of algorithms for shoreline detection (and its possible variations) on high-resolution imagery.

When it comes to coastal areas, integrated coastal zone management (ICZM) and marine spatial planning (MSP) are commonly applied tools for their management in Europe. Even though ICZM has addressed the importance of cultural ecosystems, cultural resources have been mostly overlooked in holistic coastal management plans (Khakzad et al. 2015). In terms of geospatial information update, public regional and local authorities (often cities and municipalities) are obliged by INSPIRE Directive (2006) to duly provide information on the Annex III theme “Protected areas”, including sites and monuments. Nevertheless, this practice often requires a tailor-made approach considering also the requirements of built heritage in danger or of heritage situated in areas considered vulnerable to natural threats.

The events examined on San Clemente regard (i) November 2016, when the site of Albenga has undergone serious damages due to an important flooding event caused by the winter precipitations, and (ii) November 2019, when another extreme flood of analogue intensity took place. The paper examines the extension of the flood impact in 2019, and it provides the comparison with the effects of the previous destructive event. The author opts for multispectral optical imagery as the most suitable choice because they provide (i) possibility to perform both spatial and radiometric analysis and (ii) further possibilities to compare and discuss the results obtained from UAV-born RGB orthophoto imagery. In fact, a more comprehensive workflow assessing damages due to extreme flooding events would include satellite, UAV, and close-range images used in a multi-scale approach for change detection.

Data and methodology adopted

As the site of interest is situated within the actual riverbed of Centa river, the aim of the work here proposed was to investigate the main regions of the riverbed impacted by the extreme flooding events. For this purpose, work has been conducted in three phases: (i) the official reports of Liguria region on main hydro-meteorology events have been studied in order to select flooding events of highest intensity affecting the area of interest; (ii) NDVI and NDWI indexes have been calculated before and after an event, together with their mathematical differences, in order to identify the changes in water content caused by the flooding and possibly affecting the area of the archaeological site; (iii) NDWI mathematical differences of the two significant flooding events of the similar intensity occurring, respectively, in 2016 and 2019 have been compared. The last procedure was proposed in order to detect possible major "hot-spots" worth of investigating further with targeted multi-scale recording campaigns including UAV flights. The results were further integrated with ground truth data information provided by the geographical database of Liguria region.

The overall methodology layout is illustrated in Fig. 2:

Consultation of the information regarding significant hydro-meteorology events—ARPAL reports

The news of hazardous flooding affecting the area of archaeological sites was registered by the media in the latest months of 2019. In order to have a full insight in the intensity of the event, the publicly available official records of significant events have been examined for years 2016, 2017, 2018 and 2019 (Agenzia per la protezione dell'ambiente ligure – ARPAL (Agency for environmental protection in Liguria) n.d.). The data was collected for station "Albenga-Molino Branca – MOBRA" situated within the Centa riverbed (geographical alert zone A, with coordinates 436,861, 4,877,792 WGS84 UTM 32 N). The data collected for autumn months of the aforementioned years was then structured in Table 1.

The comparison of data provided a confirmation regarding similar intensity between the flooding event occurring on 24–25 November in 2016 and the one occurring in 22-23 November in 2019. The two events have produced an increase in water level registered as 5.36 m and 5.1 m, respectively, in 2016 and 2019. The results are graphically illustrated in Fig. 3.

More specifically, in 2016, the official report highlighted that the state of the sea has been moderate for most of the period but on the 24th of November it rose to rough, while media news and websites have reported about a sea storm that on the morning of November 24th that has flooded the coastal road between the town of Albenga and the smaller municipality Ceriale located in the north. The hydrometric levels of the monitored water bodies, which were already significantly high due to the rainfall occurring in the previous days, showed clear increases especially in response to the second precipitations surge. The report further specifies that river Centa had exceeded the extraordinary flood threshold.

In the event of 22-24 November 2019, the report cites "the widespread and persistent rainfall caused significant increases in the hydrometric levels of the recording stations", stating

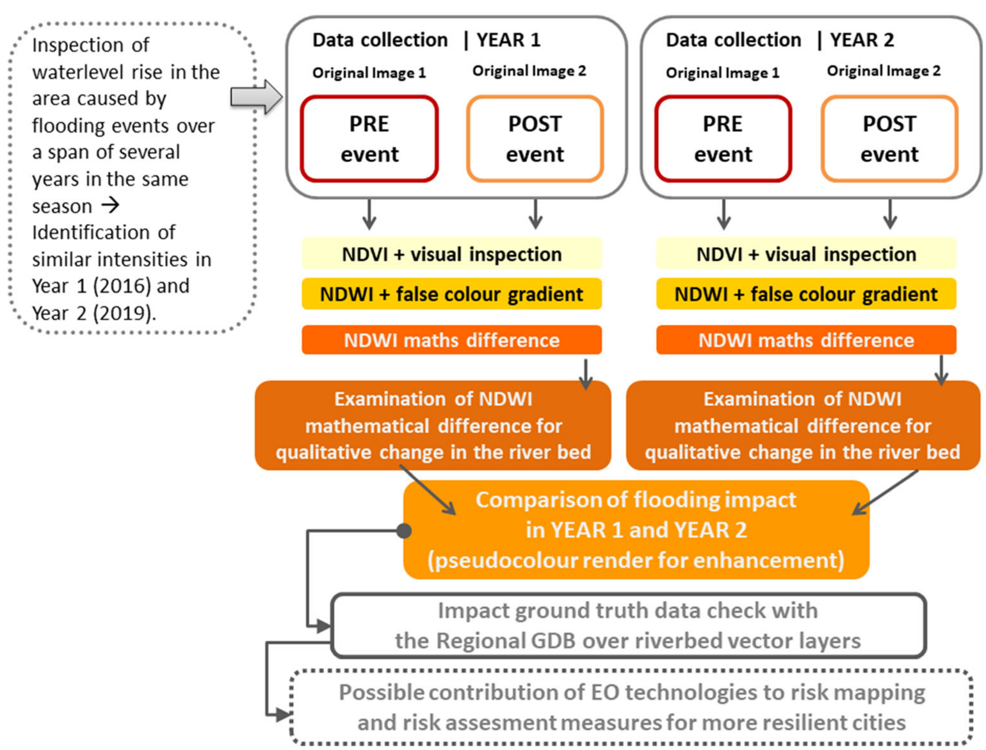


Fig. 2 The overview of the workflow proposed

Table 1 Increase of water level in meters as registered for the station MOBRA (Albenga—Molino Branca) over the autumn months in years 2016, 2017, 2018 and 2019. Source: ARPAL, Liguria region

2016		2017		2018		2019	
Date of the event	Increase of water level MOBRA (m)	Date of the event	Increase of water level MOBRA (m)	Date of the event	Increase of water level MOBRA (m)	Date of the event	Increase of water l evel MOBRA (m)
15/09	0.09	09–10/09	0.00	11/10	2.6	19–22/10	0.88
13–14/10	0.21	04–06/11	0.15	27–30/10	1.77	02–03/11	0.5
05–06/11	1.05	10–12/12	1.22	23–24/11	0.52	07–08/11	0.23
20–25/11	*5.36*	26–27/12	0.49			14–15/11	0.83
						22–24/11	*5.1*
						27/11	1.58
						20–21/12	3.81

that many watercourses have exceeded the first threshold while many others including river Centa have exceeded even the second extraordinary flood threshold. Two other successive events significant to the area have been registered on November 27th and December 20–21st of the same year. Hence, it was decided to further investigate the effects of extreme flooding events occurring at the end of 2019 (for the period Nov and Dec) with the use of freely available earth observation imagery, in particular Sentinel-2 data.

Satellite imagery dataset—Copernicus programme Sentinel-2 images

A sequence of Sentinel-2 images was used to analyse the land changes occurring after the last major flooding event that has affected the area in the winter of 2019 (Table 2). A multi-temporal time-series of Sentinel-2 data containing 13 bands in the visible, near-infrared and short wave infrared part of the spectrum have been chosen. The data acquired over Albenga coast in distinct moments before and after flooding events, occurring between November 24 and 25, 2016, and November 22 and 24, 2019, have been downloaded from the USGS archive (http://glovis.usgs.gov/). All images used in this analysis are declared to be distributed as Level – 1C.

In particular, Table 2 shows the acquisition dates and spatial and spectral resolution of the chosen images and of the specific band examined. Satellite data were selected keeping 10% as maximum percentage of cloud-coverage and choosing the dates as close as possible to the flooding events.

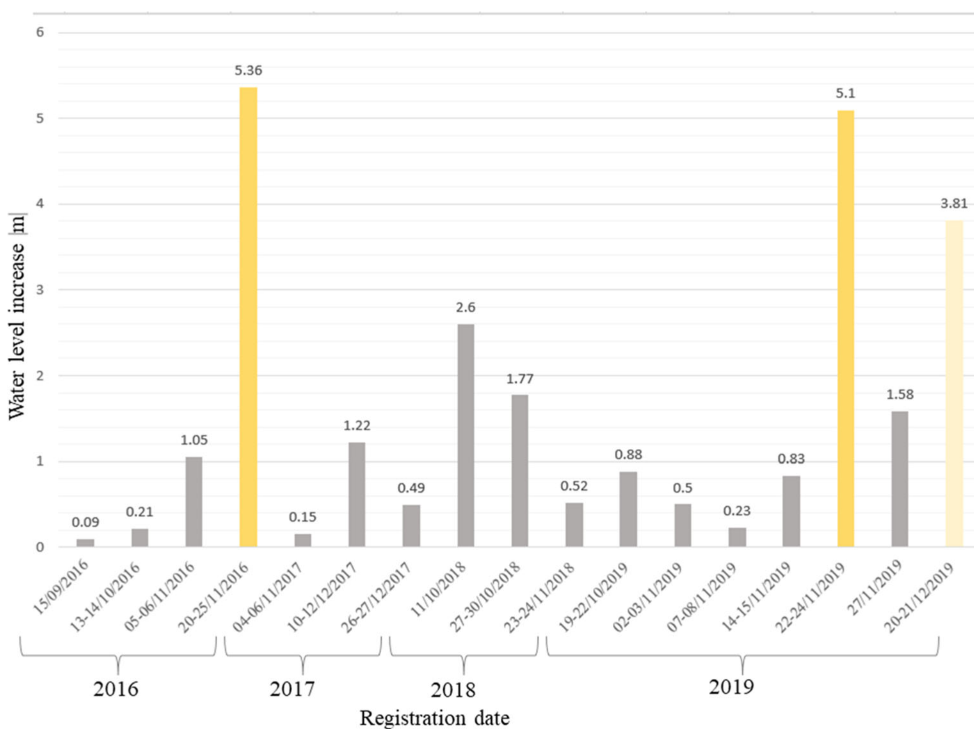


Fig. 3 Graphical comparison of the increase in water level registered at the station MOBRA (Albenga—Molino Branca) over the autumn months in years 2016, 2017, 2018 and 2019

Table 2 Dataset used: Sentinel-2 (S-2) data of Copernicus programme

Sentinel-2 data 2016 (event occurring 24–25 Nov 2016)	Sentinel-2 data 2019 (event occurring 22–24 Nov 2019)	S-2 Spatial resolution in VIS/NIR	S-2 spectral resolution (nm) (only VIS-NIR listed)
Before event			
29 October 2016	13 November 2019	10 m	BLUE: 492.4
After event			GREEN: 559.8
8 December 2016	23 December 2019	10 m	RED: 664.6
			NIR: 832.8

Change detection using NDVI and NDWI indexes

In order to investigate the changes in the Centa riverbed, the 2019 images have been firstly visually investigated in RGB and NIR-RED-GREEN pseudo composite before and after the event. Some effects were already visible from the turbidity of the water and the extension of the landfill material (area within the rectangle in the Fig. 4).

To evaluate the water content changes, further statistical analyses were conducted by applying two significant indexes, namely, Normalized Difference Vegetation Index

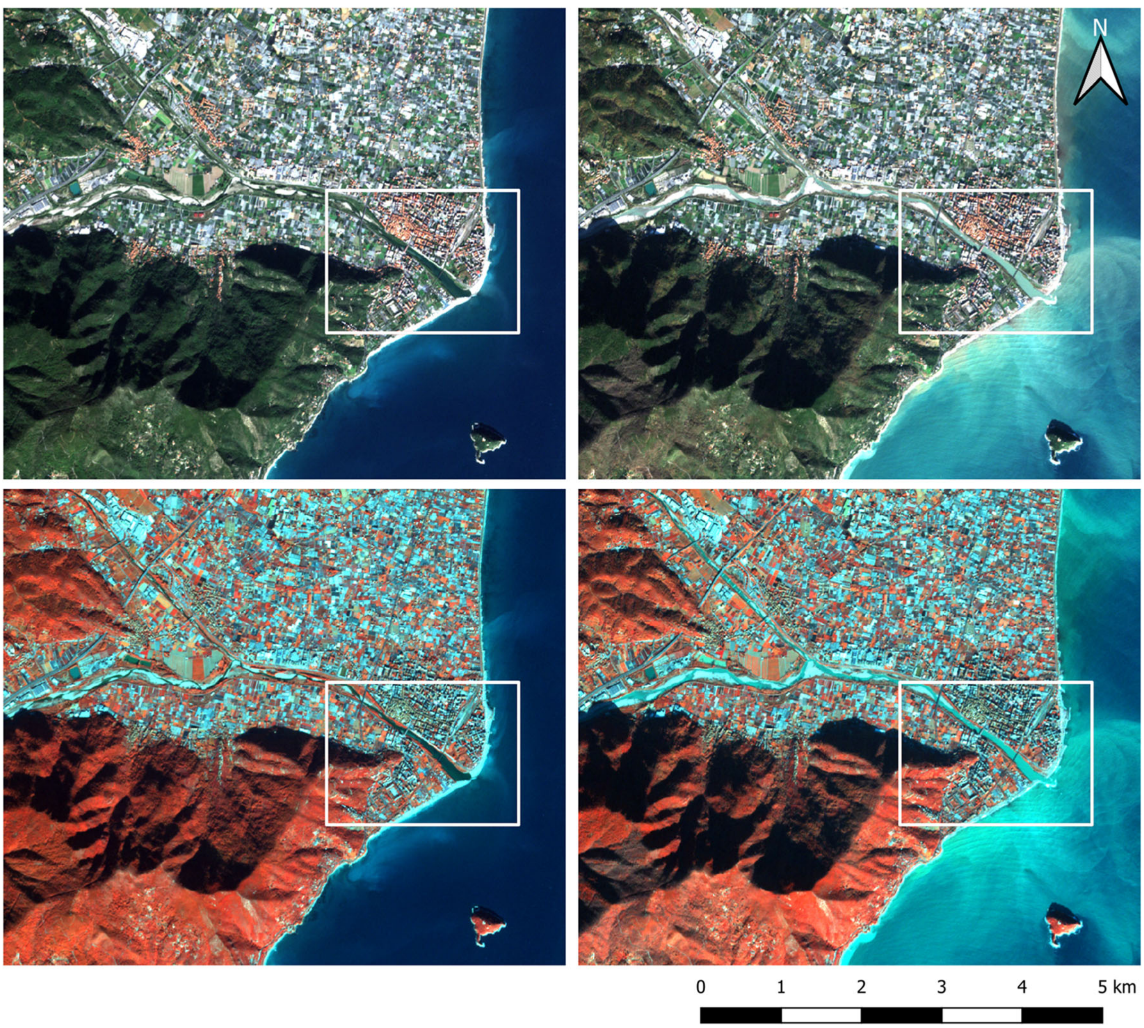


Fig. 4 Sentinel 2A imagery—close-up to the delta of river Centa in the area of Albenga in visible bands-RGB (above) and NIR-RED-GREEN colour composite (below). The images show the scenes before (left) and after (right) of the flooding event occurring between November 22nd and 24th in 2019

(NDVI) and Normalized Difference Water Index (NDWI). It was chosen to firstly observe changes in NDVI as the water has a very low reflectance in wavelengths used by this index, the fact that makes waterbodies easy to detect (Cuca 2017). NDVI has been calculated for the municipality of Albenga with a close-up on the delta of Centa river and its riverbed (Fig. 5).

The segment depicted within the rectangle (repeated in the following images) illustrates the area in proximity of the Emidio Viveri bridge (known as "The Red bridge") located near the archaeological remains of the St. Clemente mediaeval church. Already by the visual inspection, it can be noted how the area covered with water (black pixels) significantly increases in width after the flooding event, probably covering the archaeological remains (black arrow).

Further analysis was conducted applying NDWI as defined by McFeeters in (McFeeters 1996), i.e. using the index to monitor the water content in the water bodies. This Optical Water Index was defined as suitable also for estimating inundation probability using remote satellite optical imagery (Liang and Liu 2020). Within NDWI water features have positive values, usually greater than 0.5, which makes them well enhanced among other features. The index was calculated applying Eq. 1, while results are illustrated in Fig. 6:

$$NDWI = (BGreen - BNIR)\,(BGreen + BNIR) \tag{1}$$

The visual inspection is facilitated by the lighter pixels clearly presenting the water bodies and, again, the significant increase in the width of Centa river in proximity of the archaeological remains (black arrow).

A calculation of a mathematical difference of NDWI considered over the same scene at different moments (before and after flooding events) is capable of providing better insights on the changes occurring (Cuca and Barazzetti 2018). Figure 7 shows the result of such difference for

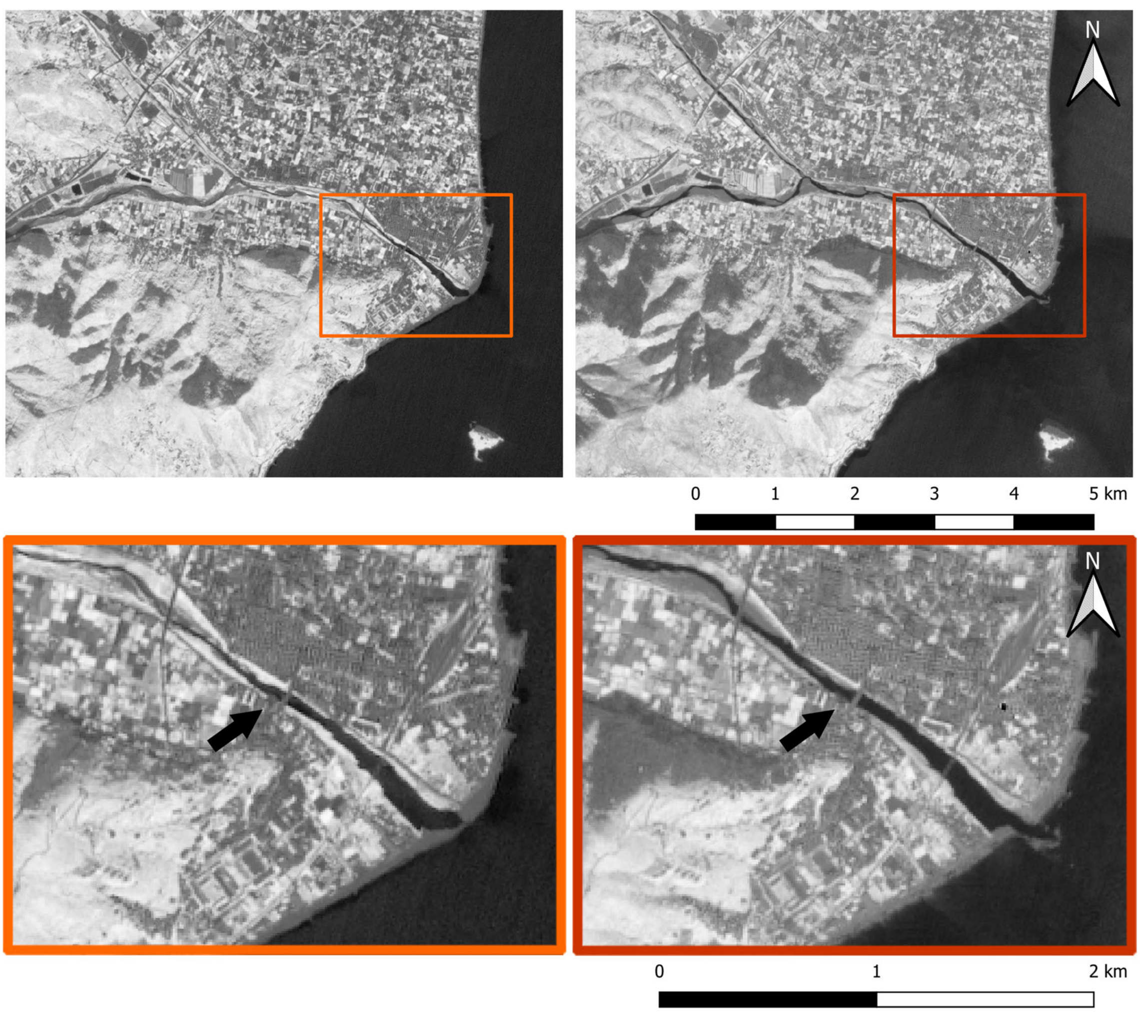


Fig. 5 NDVI calculated over Albenga on November 13th (upper left) and on December 23rd of 2019 (upper right); close-up of the Centa river delta and the inhabited area around the river shores on November 13th (lower left) and December 23rd of 2019 (lower right)

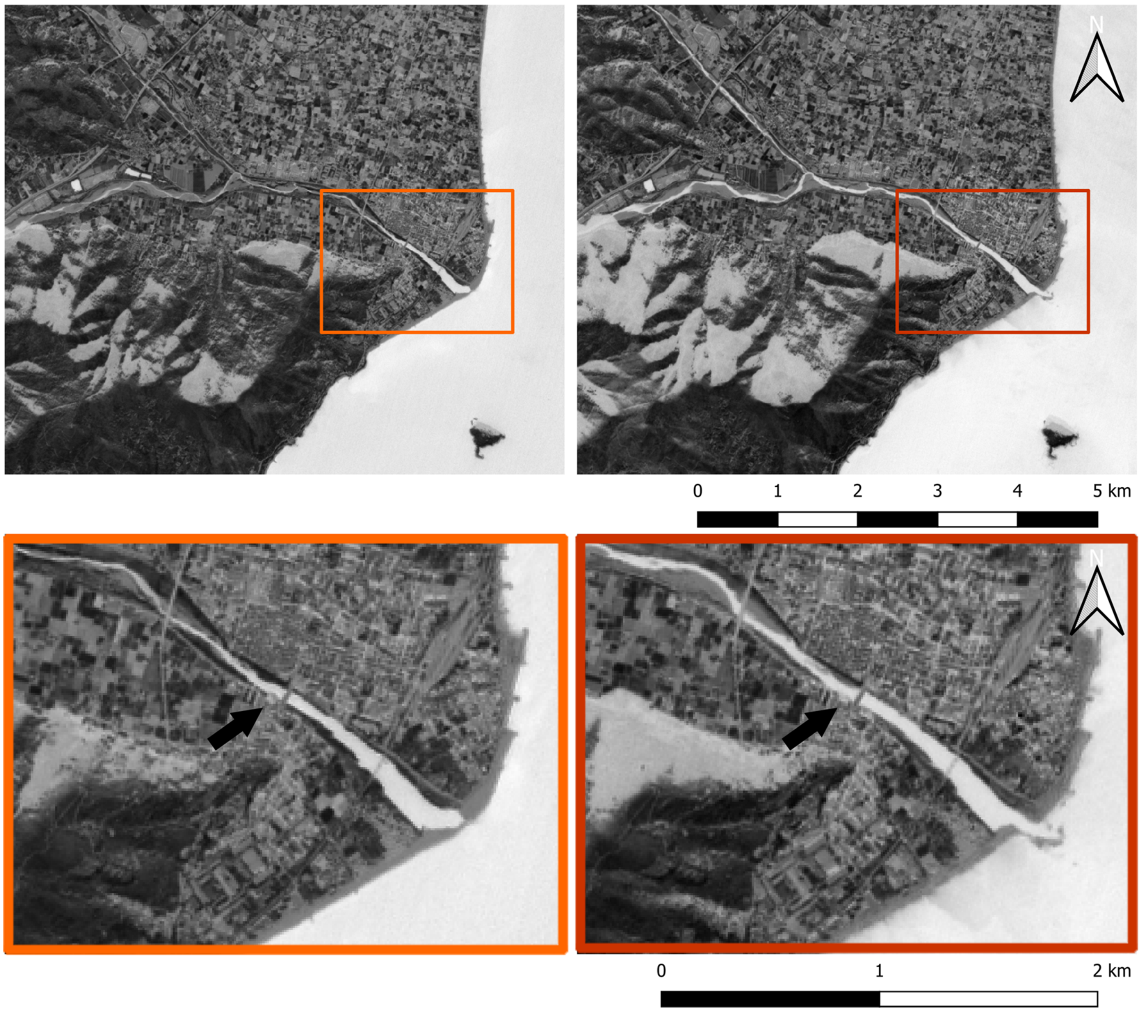


Fig. 6 NDWI in false colour gradient calculated over Albenga on November 13th (upper left) and on December 23rd of 2019 (upper right); close-up of the Centa river delta and the inhabited area around the river shores on November 13th (lower left) and on December 23rd of 2019 (lower right)

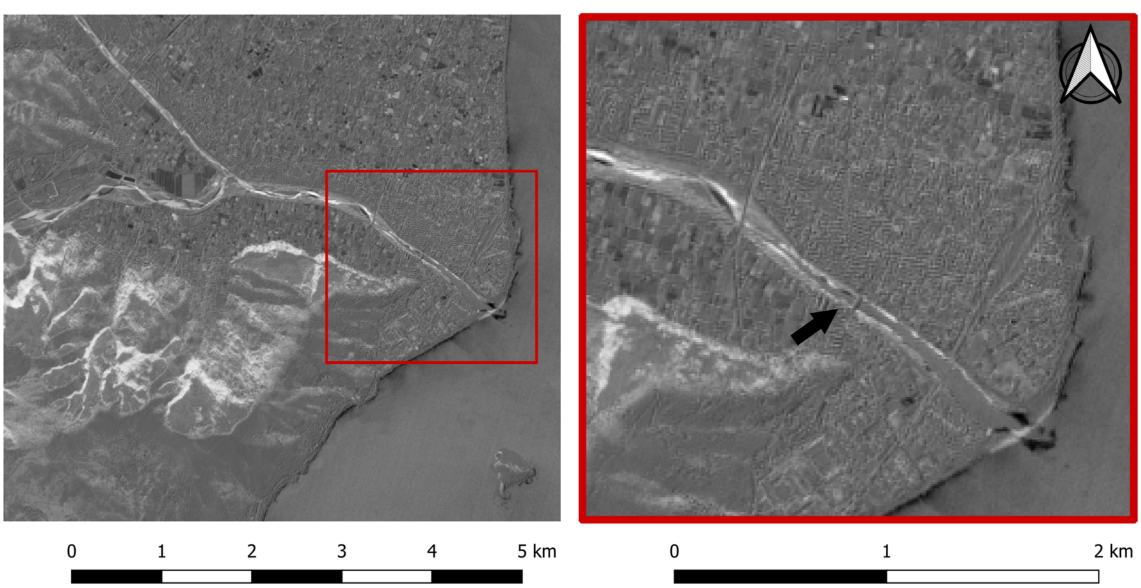


Fig. 7 Mathematical difference of NDWI calculated before and after extreme flooding event in November 2019—an overview of Albenga area (left) and a close-up on Centa riverbed (right). Black arrow on the close-up image indicates the area around the San Clement church situated in the Centa riverbed

Sentinel 2A image on November 13th (acquired any significant water level rises of the season) and for S-2Aimage on December 23rd, 2019 (after the major flooding event occurring on 22–24 November and another two events of water level rise registered, Table 1). Change detection performed on images acquired over a short period of time (in this case several weeks) is more robust against undesirable effects due to possible variations of vegetation layer. Systematic effects in the change detection can be removed through differencing if the same parameters are applied and images are acquired in a relatively short time (Cuca and Barazzetti 2018).

The mathematical difference of NDWI values shows how a quite significant change (light pixels) has been affecting the south-western shore in proximity of the "red bridge" between the two dates in 2019. If considered that NDWI index identifies water content in water bodies, it can be presumed that such change corresponds to increase of water cover in this area hence to a major pressure due to flooding.

Comparison with previous events of analogue intensity

The third step conducted by this research was to confront the results obtained for 2019 with those of storm event of similar intensity in 2016 (Table 1). In that occasion (2016), a significant part of the medieval San Clemente church remains has been compromised on stability and integrity. An extensive advanced geometric documentation of the site done before and after this particular event has enabled experts to document and monitor the losses of valuable material occurred using sophisticated material in user friendly applications (Previtali 2019). Moreover, UAV campaigns have been conducted in 2015 and 2018 by Politecnico di Milano, providing an orthophoto coverage of San Clemente remains. The material has enabled experts and superintendents to have better insights on the damages induced by the sea storm that took place in November 2016 (Fig. 8).

A previous work regarding Sentinel-2 imagery has already been conducted on the 2016 event in (Cuca and Barazzetti 2018). However, the procedure was here repeated with newly selected imagery and in order to provide a more robust analogy to the 2019 investigation. For both images chosen, (Table 2), NDVI and NDWI have been calculated and examined. Mathematical difference of NDWI was calculated subsequently.

The results obtained in 2016 and 2019 are shown for confrontation in Fig. 9.

The results of mathematical differences of NDWI were processed on a red-blue scale in order to enhance the presence of areas undergoing significant stress caused by the flooding (Fig. 10). Both events in 2016 and 2019 show the shores of the riverbed that host archaeological site of San Clemente as the area that is undergoing major stress (red pixels): the riverbed areas below and around the "Red bridge" seem to have been heavily impacted in 2016 and again in 2019, although it would seem with a lower intensity.

Unsuitably, some false variations for other elements visible in the images (area with shadows such as the mountain above Albenga) were produced by NDWI and become more visible in the mathematical difference. However, these effects have been filtered out and corrected using additional information from geospatial databases, e.g. adding a river layer and limiting the analysis to a specific buffer area generated around a selected feature (Fig. 11).

In order to make some first comparison with the ground truth data, the results have been confronted with contents of topographic database of Liguria Region. Figure 11 illustrates an extraction of mathematical difference of NDWI values over a Web Map Service (WMS) of a 2016 orthophoto provided by the Geoportal of Liguria region. The elaboration of earth

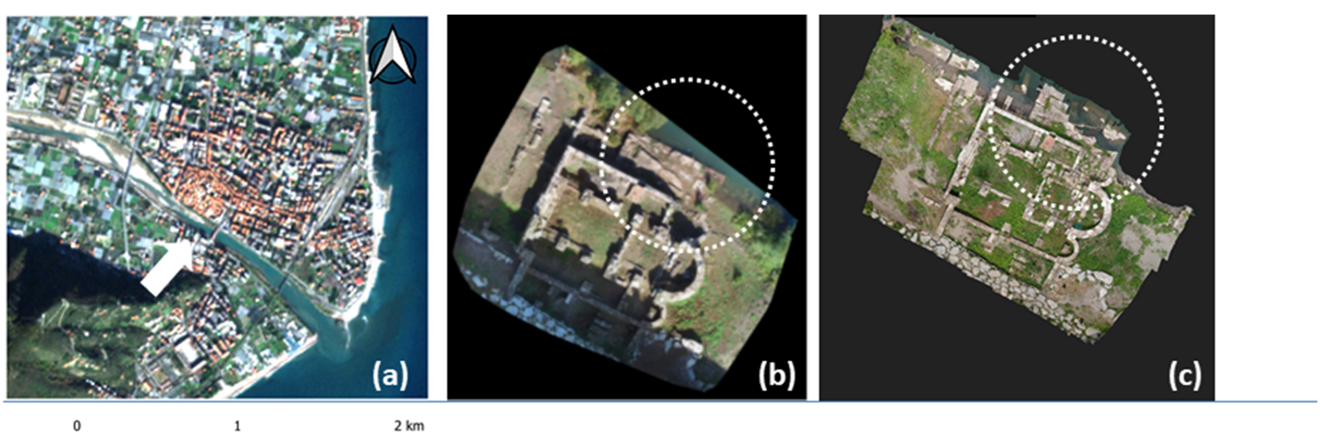


Fig. 8 Close-up on Albenga area in a Sentinel-2A (acquisition date 8 Dec 2016), white arrow indicates the location of the site (**a**); RGB UAV–generated orthophoto acquired on October 15, 2015 (**b**), and RGB UAV–generated orthophoto acquired on May 23, 2018 (**c**), as published in (Cuca and Barazzetti 2018). White circles in (b) and (c) indicate the area damaged by the extreme flooding occurring in November 2016

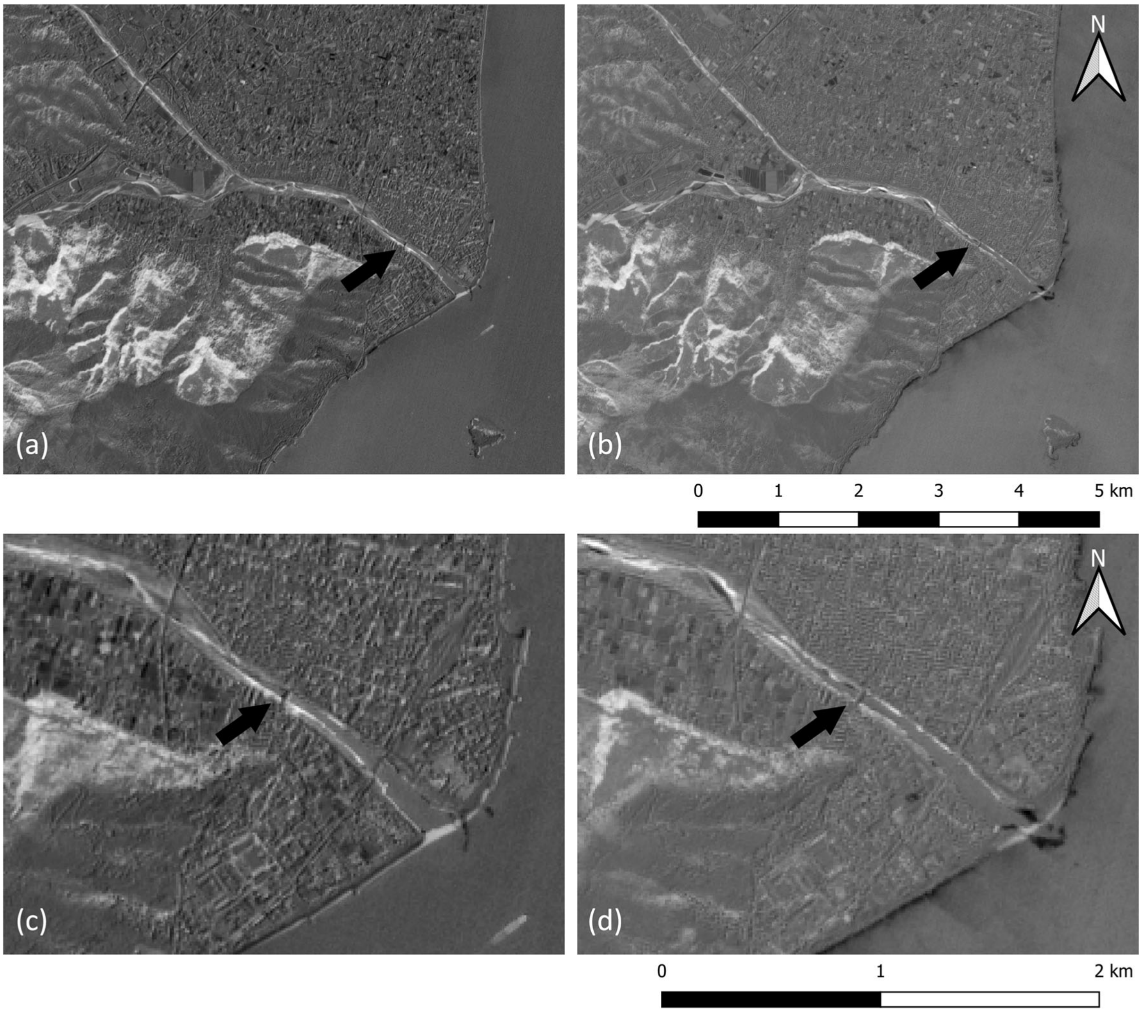
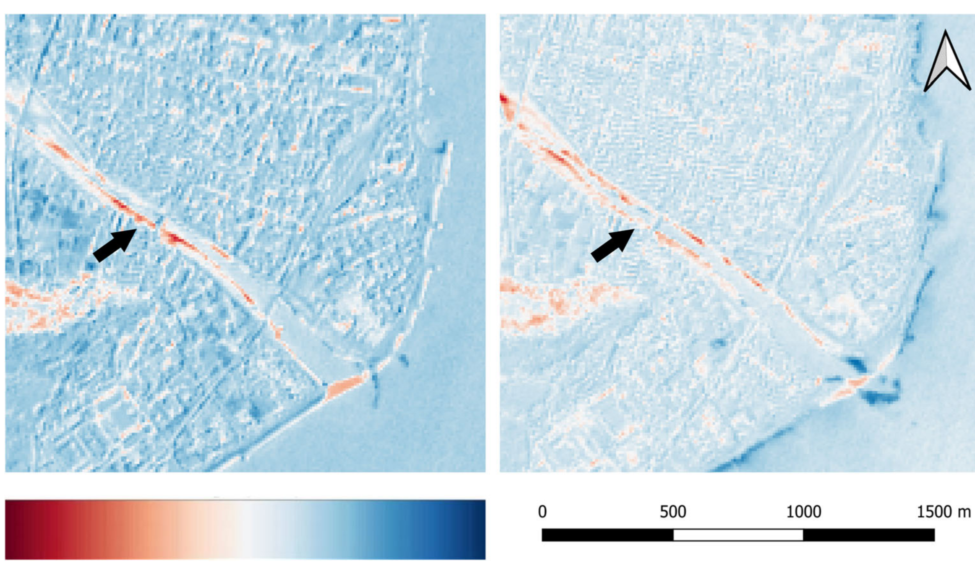


Fig. 9 Mathematical difference of NDWI calculated before and after extreme flooding event in November 2016 and a close-up on Centa riverbed, respectively (**a**) and (**c**); mathematical difference of NDWI calculated before and after extreme flooding event in November 2019 and a close-up on Centa riverbed, respectively (**b**) and (**d**). Black arrows indicate the area around the San Clement church situated in the Centa riverbed

Fig. 10 Mathematical difference of NDWI calculated before and after extreme flooding event in November 2016 (**a**) and November 2019 (**b**) render over red-blue pseudocolour scale. Black arrows indicate the area around the San Clement church situated in the Centa riverbed



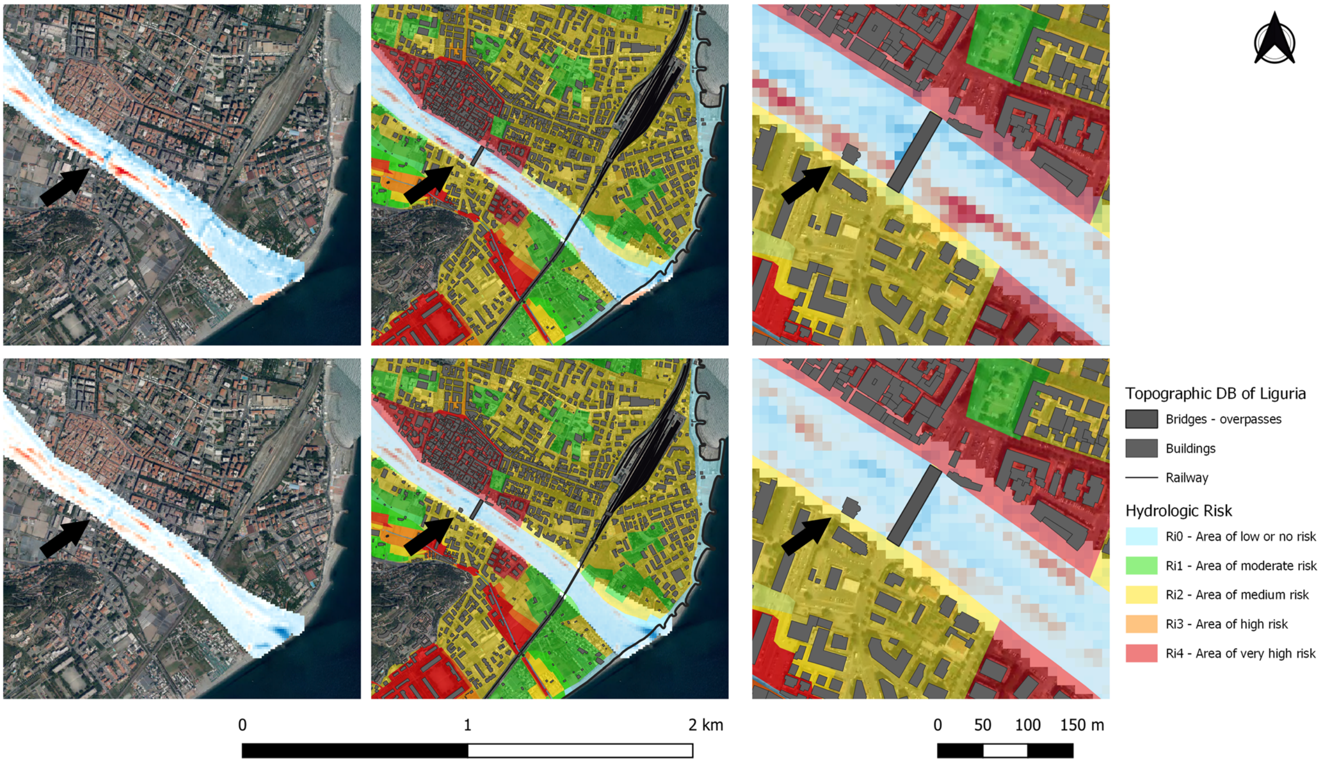


Fig. 11 Control of extreme flooding event impact over ground truth data: mathematical NDWI difference observed within layers of the Geographical Database provided by Liguria region. In particular, over a 2016 orthophoto for 2016 (above left) and 2019 (below left); the extracted portion represented with hydrologic risk zones in 2016 (above middle) and 2019 (below middle), with respective close-ups (right). Black arrows indicate the area around the San Clement church situated in the Centa riverbed

observation imagery indicates the areas in which the increase of water content is encountered in case of a meteorological-hydrological event and in case of significant level rise (red pixels within the riverbed). In particular, the filtered NDWI differences have been confronted with situation of the hydrological risk. The site of San Clemente is integrated within a protected area, but it is also located in the proximity of the area defined of medium risk (yellow colour, class Ri2).

Discussion of work

The paper illustrates a work on change detection in water content in order to investigate the impact of extreme flooding event affecting the archaeological site of Albenga. For the purpose, NDVI and NDWI have been applied on multi-spectral satellite optical images of medium (10 m) resolution. These indexes, especially NDWI, give results that provide a very clear interpretation of changes. A disadvantage of NDWI seems to be the misinterpretation of areas in shadows (Fig. 9). To overcome these issues, a buffered vector layer of "Protected areas" (Geoportale della Regione Liguria n.d.) has been used to mask NDWI results and to perform a ground truth data control check, considering more closely the area of interest (Fig. 10). As a future step, a tresholding procedure per classes could be performed to provide even better results and potentially enabling further quantitative analysis in terms of exact location and area affected by the changes in water content. For this purpose, a targeted UAV campaign should provide training samples that would hence be useful for EO data calibration and classification.

It is appropriate to mention that the author is aware of literature suggesting synthetic-aperture radar (SAR) as a more suitable technology for rapid mapping in response to emergency conditions (Vassileva et al. 2015, 2017). However, the solution here aims at long-term mapping and a possible contribution of EO technologies to the risk assessments and recovery planning of damaged sites. The optical imagery was hence chosen in order to propose a direct link between data such as Sentinel-2 at 10-m resolution in the bands considered with RGB UAV-born information such as orthophotos that could have a pixel terrain of even few centimetres. The use of satellite imagery is foreseen as more systematic practice in order to identify "hot-spots" on which further terrestrial close-range and UAV-aided survey could be conducted, while specific areas could be identified for systematic UAV monitoring upon regular time periods, even once or twice a year. Such a holistic approach could provide a comprehensive study of the situation for the site managers and public authorities to act upon.

Conclusion remarks

With natural hazards becoming ever more frequent, emergency management of built cultural heritage is in need of a protocol that (i) includes all possible useful contribution of monitoring technologies and (ii) provides a checklist of issues and locations to identify, document, monitor and possibly recover upon specific pre-defined priorities. In addition to first rapid mapping useful for an immediate response, longer term studies can help to investigate possible patterns in the impacts caused by the water elements in support to further activities of risk mapping and recovery of the heritage in question. The results of this paper suggest that (i) EO technology should be used in a more systematic manner to examine the impact of specific events of extreme flooding on the vulnerable features such as built heritage and sites in areas under threat; (ii) additional on-site recording with both terrestrial and close-range UAV technologies could additionally support and verify the suggestions derived from EO optical data. In the specific case of Albenga here examined, features of the San Clemente archaeological site are not visible on the medium-range satellite imagery. However, the study identifies areas where major damage on built heritage could be expected and further investigated. Specific field survey and integration with more systematically generated UAV orthophotos of the entire site location, as well as the verification of the actual changes in the site structure/integrity, could provide a more comprehensive tools for institutions and site managers in charge of documenting, monitoring and protecting the endangered sites such as archaeological complex in Albenga.

Acknowledgements Figures 4, 5, 6, 7, 8, 9, 10 and 11 contain modified Copernicus Sentinel-2 data (2020); original data was provided by USGS Archives.

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Compliance with ethical standards

Consent for publication include appropriate statements.

References

Agapiou A, Lysandrou V, Hadjimitsis DG (2020) Earth observation contribution to cultural heritage disaster risk management: case study of eastern mediterranean open air archaeological monuments and sites. Remote Sens 12(8):1330. https://doi.org/10.3390/RS12081330

Agenzia per la protezione dell'ambiente ligure – ARPAL (Agency for environmental protection in Liguria) (n.d.) website: https://www.arpal.liguria.it/, last accessed July 31st 2020

Alicandro M, Baiocchi V, Brigante R, Radicioni F (2019) Automatic shoreline detection from eight-band VHR satellite imagery. J Mar Sci Eng 7:459

Cuca B (2017) The Contribution of Earth Observation Technologies to Monitoring Strategies of Cultural Landscapes and Sites. Int Arch Photogramm Remote Sens Spat Inf Sci XLII-2/W5:135–140. https://doi.org/10.5194/isprs-archives-XLII-2-W5-135-2017

Cuca B, Agapiou A (2017) Impact of land use change to the soil erosion estimation for cultural landscapes: case study of Paphos District In Cyprus. Int Arch Photogramm Remote Sens Spat Inf Sci XLII-5/W1: 25–29. https://doi.org/10.5194/isprs-archives-XLII-5-W1-25-2017

Cuca B, Barazzetti L (2018) Damages from extreme flooding events to cultural heritage and landscapes: Water component estimation for Centa River (Albenga, Italy). Adv Geosci 45:389–395. https://doi.org/10.5194/adgeo-45-389-2018

Geoportale della Regione Liguria (n.d.) accessible at: https://geoportal.regione.liguria.it/ - Layer of Registered protected areas is provided for in the Water Protection Plan pursuant to Legislative Decree 152/06; these are areas where land management requires particular attention to safeguard the quality of water and aquatic habitats, information last accessed on July 31st, 2020

Khakzad S, Pieters M, Van Balen K (2015) Coastal cultural heritage: a resource to be included in integrated coastal zone management. Ocean Coast Manag 118:128. https://doi.org/10.1016/j.ocecoaman.2015.07.032

Liang J, Liu D (2020) Estimating daily inundation probability using remote sensing, riverine flood, and storm surge models: a case of hurricane Harvey. Remote Sens 12:1495

Masini N, Lasaponara R (2017) Sensing the past from space: approaches to site detection. In: Masini N, Soldovieri F (eds) Sensing the Past. Springer, pp 23–60

McFeeters SK (1996) The use of normalized difference water index (NDWI) in the delineation of open water features. Int J Remote Sens 17:1425–1432

Previtali M (2019) A virtual logbook for the documentation of a continuously changing archaeological site: the San Clemente site in Albenga (Italy). Virtual Archaeology Review, [Sl] 10(21):56–66. https://doi.org/10.4995/var.2019.11916

Previtali M, Stanga C, Molnar T, van Meerbeek L, Barazzetti L (2018) An integrated approach for threat assessment and damage identification on built heritage in climate-sensitive territories: the Albenga case study (San Clemente church). Appl Geomat 10:485–499. https://doi.org/10.1007/s12518-018-0217-3

Tapete D, Cigna F (2020) Poorly known 2018 floods in Bosra UNESCO site and Sergiopolis in Syria unveiled from space using Sentinel-1/2 and COSMO-SkyMed. Sci Rep 10(1):12307. https://doi.org/10.1038/s41598-020-69181-x

Trembanis A, Abla A, Haulsee K, DuVal C (2019) Benthic habitat Morphodynamics-using remote sensing to quantify storm-induced changes in Nearshore bathymetry and surface sediment texture at Assateague National Seashore. J Mar Sci Eng 7:371

UNESCO (Paris) (2010) Managing Disaster Risks for World Heritage; World Heritage Resource Manual. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, p 69

Van Meerbeek L, Barazzetti L, Valente R (2017) From cultural path to cultural route: a value-led risk management method for via Iulia

Augusta in Albenga (Italy). Int Arch Photogramm Remote Sens Spat Inf Sci XLII-2/W5:71–75. https://doi.org/10.5194/isprs-archives-XLII-2-W5-71-2017

Vassileva M, Nascetti A, Giulio TG, Boccardo P (2015) Unsupervised flood extent detection from SAR imagery applying 25 shadow filtering from SAR simulated image. 2015 IEEE international geoscience and remote sensing symposium (IGARSS), Milan, 2015, pp 2707–2710. https://doi.org/10.1109/IGARSS.2015.7326372

Vassileva M, Tonolo FG, Riccardi P, Lecci D, Boccardo P, Chiesa G (2017) Satellite SAR interferometric techniques in support to emergency mapping. European Journal of Remote Sensing 50(1):464–477. https://doi.org/10.1080/22797254.2017.1360155