Spatiotemporal Pattern Detection of Ground Deformations Induced by Extreme Rainfall using InSAR EGMS: The case of Cortina d'Ampezzo after Vaia Storm

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Abstract

During October 2018 Vaia Storm occurred in the north of Italy, resulting in a huge amount of rainfall that was recorded. The focus here is given to Cortina d'Ampezzo area in the Veneto Region, due to the high importance of the area from touristic and sport perspectives and the presence of landslides. This study is devoted to investigating the impact of the severe sudden rainfall caused by this extreme atmospheric disturbance on the trends of ground deformations over this area, adopting a risk assessment perspective. The ground deformation Time Series (TS) have been derived from the European Ground Motion Service (EGMS) Ortho products derived from Sentinel-1 InSAR data. Then, according to the daily precipitation records and considering the time of this event as a turning temporal point, the TSs of all data points have been divided into pre-event and post-event phases. After obtaining the displacement rates in each phase, the quantified magnitude of changes in the pre-post rates has been calculated through a proposed simple formulation. The spatial distribution of the deformation parameters (i.e., pre-event displacement velocity and change in the pre-post displacement velocities) is found to be a practical tool for gaining comprehensive knowledge regarding the ground deformation and the effect of the extreme weather conditions on the displacement trends over the area. Furthermore, the positioning of the occurrence of deformation parameters has been compared to the landslide inventory of the area. The results showed that the extreme rainfall caused severe acceleration of displacements, more significant in horizontal East-West direction rather than vertical Up-Down direction. Some slight deceleration has been also detected. No initiation (or reactivation) of the stable zones was witnessed, and the portions with high magnitude of pre-event velocities are the ones whose displacement rates have been remarkably modified due to the severe event.

1. INTRODUCTION

Vaia storm occurred at the end of October 2018 in the north of Italy, severely impacting Friuli Venezia Giulia, Trentino - Alto Adige/South Tyrol and Veneto regions. This meteorological disturbance, also known as "Tempesta Vaia", caused 15 million trees torn down, excessive damage to hectares of forests, and 1.8 billion Euros damage to the region, with the wind speed up to 200 km/h, as reported by local authorities of Veneto region. During the storm, i.e., 27th-29th October 2018, up to 870 mm of rainfall lead to lots of areas being flooded.

The extreme event has severely affected several portions of the abovementioned regions, such as Val di Fiemme, Comelico, Cadore, Carnia, and Feltrino. Cortina d'Ampezzo is an important mountain resort in the area which was not an exception. This mountain resort has been world-renowned to be used for winter sports purposes. Following the Winter Olympics of 1956 (Galvani, 1993), the resort will be one of the hosts for the Olympic and Paralympic Winter Games in 2026, also known as "Milano-Cortina 2026." The area is home to several touristic and sportive attractions, ski slopes and famous mountains in the Dolomites mountain range.. Accordingly, from a risk management point of view, the area is characterized by high socio-economic values and the roads to this area show a higher level of systemic vulnerability. On the other hand, the area, being settled in the Dolomitic Alps, suffers from geological hazards such as landslides. There are different types of landslides, from debris flows to deep-seated gravitational landslides over this area which have been studied, analysed and monitored through a few research works, see, e.g., Panizza et al. (1996), Soldati (1999), and Scotton et al. (2011).

Besides the tangible impact of such a violent event, the extreme values of precipitation may initiate some disastrous and/or destructive phenomena, which are not clearly visible: the extreme rainfalls may cause catastrophic or slow-moving activation, reactivation, and acceleration of existing landslide movements (Notti et al., 2021; Guzzetti et al., 2022; Zhou et al., 2022). This initiation and acceleration of landslides may eminently endanger a great number of people's lives, as well as jeopardise the man-made structures, infrastructures and natural assets, which are critical from several points of view, such as social and economic aspects. Therefore, there is always the call for assessment and analysis of the impact of extreme events for risk management and mitigation purposes.

One of the practical tools for such assessments is an analysis of deformation time series (TSs) captured over time from an area. On the contrary of the conventional approaches for measuring land surface displacement with low spatial and temporal resolutions and requirements for installation of ground stations, Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) is an efficient, practical, and modern technology for obtaining ground deformation time series from all over the world. Availability of SAR images from 1992 and the corresponding advantages of using this tool rather than conventional approaches (Scaioni et al., 2018) made the technology gaining significant attention for retrospective studies, as well as assessment and monitoring purposes in different fields of applications such as tectonic, volcanic and seismic research, subsidence analysis (Eskandari, 2022; Raspini et al., 2022), structural monitoring (Eskandari and Scaioni, 2023a), as well as landslides (Solari et al., 2020; Casagli et al., 2023). Detection of the impact of extreme rainfall on the ground deformation trends using InSAR TSs is another interesting field of research (Wasowski and Pisano, 2020; Shi et al., 2022). As an active microwave remote sensing imagery, the SAR satellites orbit around the globe in ascending and descending tracks. This allows to retrieve millimetric-accuracy deformation TSs with almost global coverage at different spatial resolutions (from tens of meters up to a few tens of centimetre, depending on the functional band of the sensor) and temporal resolutions (some days). Geo-services such as the European Ground Motion Service (EGMS) can also freely provide this type of data, which diminishes the load of management, processing, and computational costs.

This work presents the results of the investigation carried out on the effect of the extreme rainfall of Vaia Storm on the spatiotemporal deformation pattern over the Cortina d’Ampezzo area and the nearby surroundings. Besides proposing a general framework for performing such analysis based on EGMS data (or generally, InSAR-derived products) for the detection of accelerations and decelerations due to severe climatic events, the applicability of the EGMS dataset has undergone a detailed inquiry throughout this research.

2. STUDY AREA

The Area-of-Interest (AoI) for this work is Cortina d’Ampezzo town and the nearby surrounding (northern part of Veneto Region, Italy), located in Eastern Dolomites, as shown in Figure 1. Being settled in the Dolomitic Alps, the weather conditions follow the alpine climate conditions, with precipitation occurring mostly as snowfall. The valley bottom is covered by recent alluvial deposits as well as sediments accumulated during the post-glacial period, and the geological structure of the area formed complex geomorphology at the slopes at higher altitudes (Armento et al., 2008).

As mentioned before, from a risk management perspective, the roads ending in the town are characterized by a high degree of systemic vulnerability (due to the geographic positioning and the high socio-economic level of the town) and may be directly or indirectly exposed to this geological hazard, i.e., ground deformation. Therefore, a part of these roads close to the town has been included in the AoI.

3. MATERIAL AND METHODS

The exploited material extracted for the study area and the methodological approach of analysing the data for comprehending the spatiotemporal evolution of ground deformations over this district are thoroughly described in the following subsections.

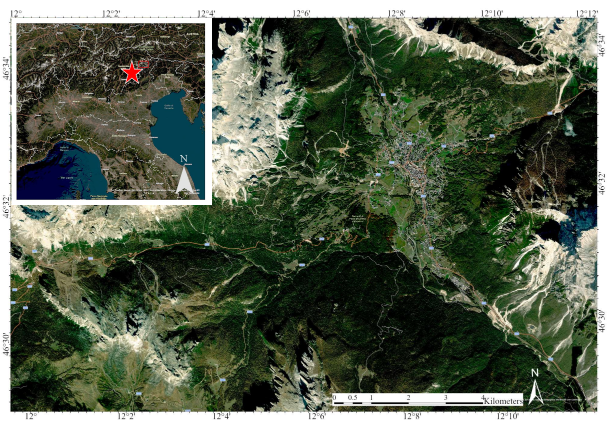

Figure 1. The Area-of-Interest (AoI) around Cortina d’Ampezzo mountain resort, Northern-Eastern Italy.

3.1 Ground deformation data

The ground deformation Time Series (TS) used in this research is extracted from the European Ground Motion Service (EGMS) (Copernicus, 2024), provided by Copernicus Land Monitoring Service (CLMS). The service offers millimetric-accuracy ground displacement TS at different levels of products (Crosetto et al., 2020; Costantini et al., 2022). Taking advantage of the European Space Agency (ESA) Sentinel-1 Synthetic Aperture Radar (SAR) Interferometry (InSAR), the EGMS geoportal is freely available to access the deformation data for almost all over Europe with the temporal coverage from Jan 2015 - Dec 2021 (first release) and from Jan 2018 - Dec 2022 (second update) which will be constantly updated for new periods.

Level 1 and Level 2 products present deformation information along the Line-of-Sight (LoS) on a sparse grid of data points (corresponding to the Sentinel-1 resolution), separately for both ascending and descending satellite orbit tracks. On the other hand, Level 3 (L3), namely Ortho products, propose deformation TS, separately along vertical Up-Down (U-D) and horizontal East-West (E-W) on a uniform grid of 100 m spatial resolution with a nominal temporal resolution of 6 days.

It should be noted that regardless of L1 products providing ground motions relative to local reference points, L2 products are calibrated with Global Navigation Satellite System (GNSS) measurements and preset deformation values independent of local references. Furthermore, the measurements contained in each Measure Point (MP) within L3 products are obtained by a mathematical procedure of combining all the measurements of all the MPs of L2 products falling into a 100 m x 100 m square around the corresponding L3 MP (in order to obtain E-W and U-D deformations from the calibrated measurements from ascending and descending tracks). Therefore, all the measurements within L2 and L3 products have a unique reference point which is the earth’s centre of mass. The EGMS ground deformations have been widely validated (Calero et al., 2023) and successfully used for several applications (e.g., Crosetto and Solari, 2023; Eskandari and Scaioni, 2023b). Interested readers may refer to the EGMS documentation (Ferretti et al., 2021) for more information on the processing and technical aspects.

Due to the scope of this study and the great advantage of EGMS L3 containing extracted vertical and horizontal ground motion TS, here, the first release of this dataset has been selected as deformation data. The distribution of available MPs of the EGMS L3 dataset over the area, coloured with the mean velocity of the corresponding whole period, is shown in Figure 2(a).

3.2 Environmental and landslide data

The precipitation data have been accessed from VCWDtool (Eskandari and Scaioni, 2023c), a practical tool for downloading, visualizing, managing and analysing historical meteorological data for a chosen geographic location and desired time and date. According to the period of first release of L3 products (covering Jan 2016 to Dec 2021), the daily rainfall data from 1-Jan-2015 to 31-Dec-2022 and the annual format (cumulative rainfall in each calendar year) have been used in this study. The time histories of both daily and annual rainfalls are simultaneously shown in Figure 2b and 2c.

Landslide inventories are useful and informative geospatial data for gaining a general perspective on the spatial extent and the types of landslides over an area. The Italian national landslides inventory obtained through the IFFI (*Inventario dei Fenomeni Franosi in Italia*) project is an interesting dataset of detected landslides with several types of movements and activities. This huge inventory, divided based on the adminastrative regions of Italy, has been prepared and updated over the recent decades through different techniques, such as field surveys, data archives, photo interpretation, historical documents, etc. (Trigila et al., 2007). The landslide inventory of the Veneto Region for this work is extracted from the IdroGEO portal of the Italian Institute for Environmental Protection and Research (ISPRA) (www.idrogeo.isprambiente.it). The spatial distribution of the polygons of different types of landslides from this inventory is illustrated in Figure 2a.

3.3 Data interpretation method

As discussed previously, the Vaia Storm affected the AoI at the end of October 2018. Consequently, huge amounts of rain fell over the 3-day period of the rainstorm: 67 mm, 146 mm, and 200 mm over 27 to 29 October 2018, respectively, according to the collected weather data.

As shown in Figure 2, these daily rainfalls can be considered abnormal measures, showing a big jump with respect to other daily rainfall measures. Considering this rainstorm as an extreme event and to see the corresponding effect on the ground motion patterns in both spatial and temporal domains, the deformation TSs (on both directions of E-W and U-D) of all the EGMS L3 Measure Points (MPs) have been divided into two temporal phases: Pre-Event (from 05-Jan-2016 to 27-Oct-2018) and Post-Event (from 02-Nov-2018 to 16-Dec-2021).

Then, a linear model has been fitted to each phase separately to derive the trend, i.e., the mean velocity of the specific phase. As shown in Figure 2b, the trend of the pre-event phase has been modified after the event and the movement toward East direction (considering the positive value of the slope of the fitted linear model, illustrated with the green line) has occurred with higher velocity. The same happens for the trend of the subsiding phenomenon (considering the negative value of the slope of the fitted linear model), shown in Figure 2c: the ground surface lowering is happening with a higher velocity after the event, concerning velocity corresponding to the pre-event phase. Although in both figures the green and blue lines represent the fitted linear model on the Pre-Event and Post-Event phases, respectively, both have been extended into the opposite phase to make the comparison clearer in this stage.

In order to propose a quantitative measure of this graphical representation of changes in the velocity (and/or trend) of ground deformation TSs from the Pre- to Post-Event phase, the following simple formulation has been adopted for each MP over the area after fitting the linear models:

$$\Delta V_{sgn} = \left(V_{post} - V_{pre}\right) \times sgn(V_{pre}) \quad (1)$$

where V_{pre} and V_{post} are the velocities (slope of the fitted linear model) concerning Pre- and Post-Event phases, respectively, and ΔV_{sgn} shows the difference of Pre-Post velocities multiplied by the sign of V_{pre}. Regarding the properties of ΔV_{sgn}, it should be mentioned that in the case of $\Delta V_{sgn} > 0$ represents the “*acceleration*” while $\Delta V_{sgn} < 0$ reveals “*deceleration*” in the velocity. Here, acceleration means the intensified magnitude of ground deformation velocity maintained within the same velocity sign from the Pre- to Post-Event phase, while deceleration represents the decay of magnitude of ground deformation velocity or change in the sign of the Pre-and Post-Event velocities.

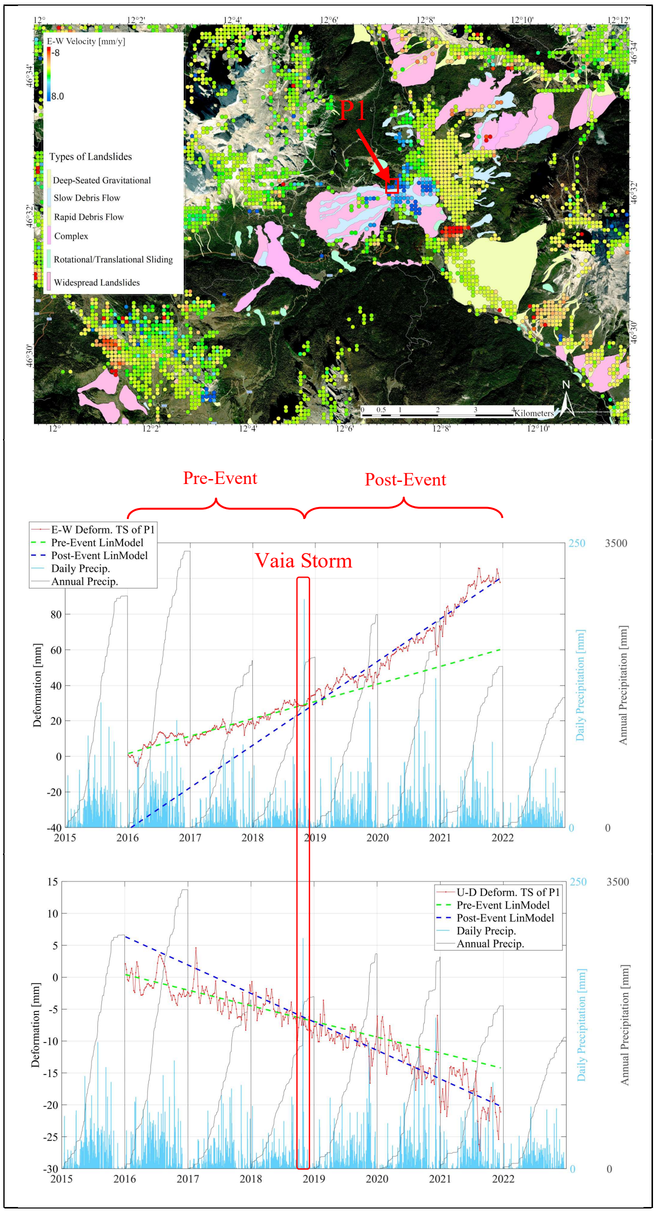

Figure 2. Exploited data and adopted methodology in this work: (a) Spatial distribution of EGMS (European Ground Motion Service) L3 datapoints (coloured with East-West mean velocity of the whole period 2016-2021) and Landslide polygons; (b) and (c) Daily and Annual precipitation measurements, and deformation time series along East-West and Up-Down directions, respectively, and the fitted linear models on Pre- and Post-Event phases.

3.4 Technical Considerations and Final Investigation

EGMS L3 MPs, as previously stated, are derived from a spatial down-sampling procedure of actual data points (from InSAR processing of Sentinel-1 SAR images) with the GNSS-Calibrated measurements (see Subsect. 3.1). It is obvious that the ground motion information contained in each L3 MP is representative of a relatively large area (100 m x 100 m). Regardless of this and the fact that some single MPs may reveal meaningful occurrences of ground deformation, it is noteworthy that a group of MPs, gathered in a local zone, with similar significant deformation behaviour or with a distinctive deformation pattern is more reliable and informative for making decisions regarding a local geological process, specifically in the case of the massive volume of land gradually and/or slowly deforming. Hereafter, this aspect is recalled as *Spatial Integrity*. According to the definition of Risk, as a critical index which is a function of hazard, vulnerability and exposure (Schneiderbauer et al., 2004), the local zones with a high degree of spatial integrity are detected as high-risk zones according to the following conditions:

i) the zone represent significant values of displacement rates V_{pre} (considered as pre-existing hazardous area) and/or considerable acceleration $\Delta V_{sgn} > 0$ (considered as accelerated hazardous area);
ii) the capability of the zone to be modified under the influence of the extreme rainfalls; and
iii) the hazardous zone directly or indirectly exposes the anthropogenic or natural elements with different types of vulnerability.

4. RESULTS AND DISCUSSION

As shown in Figure 2b and 2c for only one Measure Point (MP) of EGMS L3 data points, as the first outcome of this research, it was obvious that the normal trend of deformations over the AoI has undergone a significant modification due to the extreme rainfall related to Vaia storm. Although some MPs shown in Figure 2a represent considerable rates of displacement in the area under investigation, these values are obtained considering the mean velocity of land displacements: based on the TS of the whole available period from Jan 2016 to Dec 2021 (Pre- and Post-Event periods together). Hence, it is of great importance to understand the ground motion condition by revealing the deformation parameters, i.e., velocity (Pre-Event) and change of velocity (due to the extreme event, detected using Eq. 1) on the spatial domain, which is the basis of the final analyses and results discussed throughout this section.

4.1 Spatial representation of results

Figure 3a and 3b) illustrate the spatial pattern of ground deformation velocity concerning the Pre-Event phase in the direction of E-W and U-D, respectively. Although the values of deformation rates have been limited to 8 mm/y, absolute rates of approximately 25 mm/y and 17 mm/y have been observed in the direction of E-W and U-D, respectively. As a preliminary observation, it can be witnessed that the area is subjected to a relatively high degree of ground deformations in both horizontal and vertical ground deformations. The high velocities of land surface displacement toward the east (positive values) and west (negative values) are mostly an acceptable coincidence with the slope orientation, which strongly relates these significant deformations to slow-moving landslides. Regarding the vertical displacements, there is no area with high spatial integrity showing a significant uplift phenomenon. On the contrary, several groups of MPs with reasonable spatial integrity show remarkable subsiding processes, mostly in the areas with considerable horizontal deformations. This may connect the majority of the areas with ground lowering before the extreme event to the landslide phenomena mentioned above.

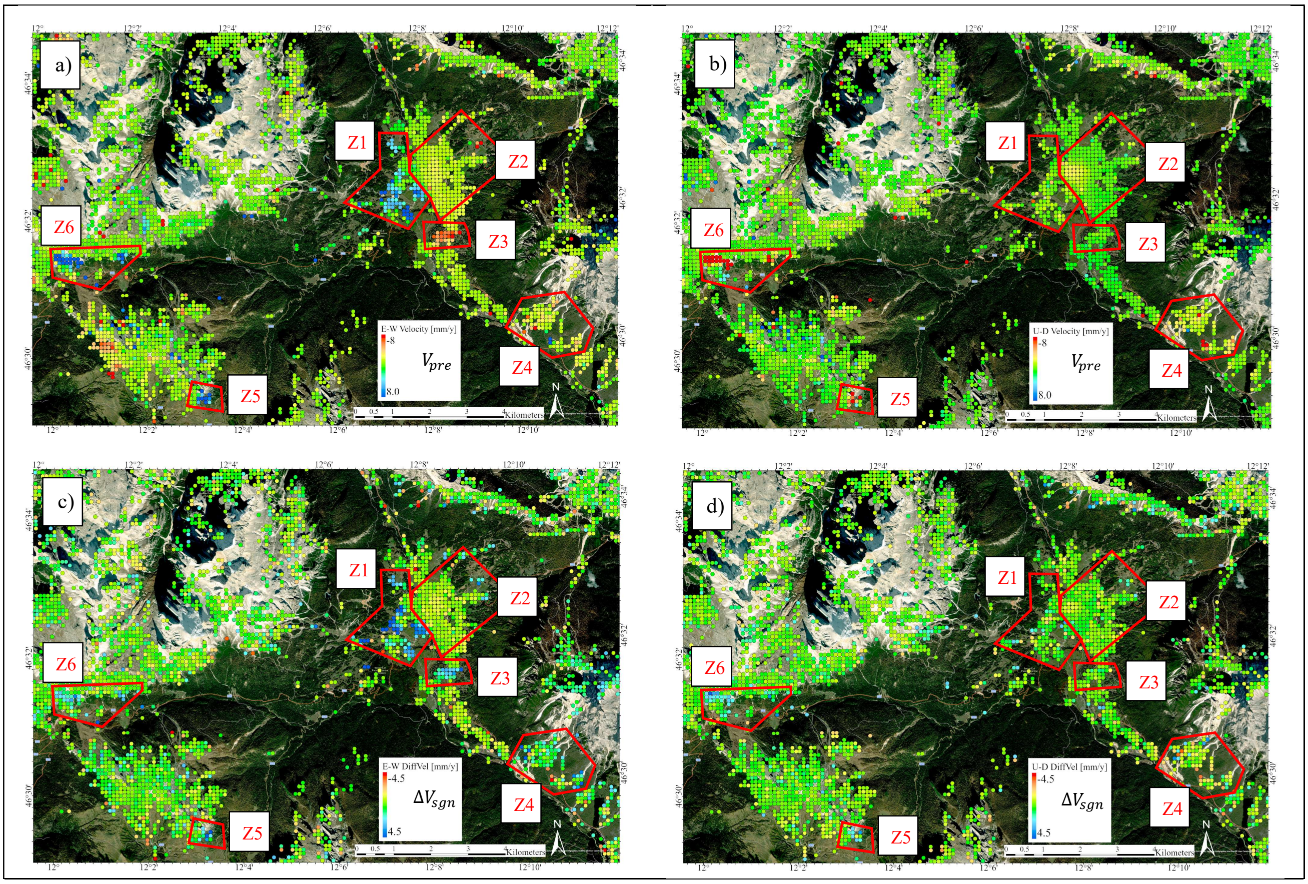

Figure 3. Spatial distribution of velocity V_{pre} and signed difference of Pre-Post velocities ΔV_{sgn} (a) and (c) for East-West, and (b) and (d) for Up-Down directions.

The outcome of Eq. 1 is spatially depicted in Figure 3c and 3d for E-W and U-D directions, respectively. Here the accelerations ($\Delta V_{sgn} > 0$) and decelerations ($\Delta V_{sgn} < 0$) are coloured in blue and red. It is important to note that acceleration means the magnified ground deformation velocity maintained within the same velocity sign from the Pre- to Post-Event phase, while deceleration shows the decay of ground deformation velocity or modification of the sign of the Pre- and Post-Event velocities. Comparing Figure 3c and 3d, the colormap range of 4.5 to -4.5 mm/y of ΔV_{sgn} put in evidence that the intense downpouring of rain caused a higher degree of modification of E-W displacement rates rather than vertical movements. Except few areas with accelerated U-D rates with good spatial integrity, most of the U-D deformations over the AoI are not influenced by the extreme event and some specific areas show very light decelerations.

Following the great influence of the extreme rainfall on the E-W velocities, the values of acceleration up to +10 mm/y and deceleration up to -4 mm/y have been observed over the AoI. As expected, the event has strongly intensified the geological hazard that has been previously jeopardizing the exposures existing in the area. One of the interesting findings could be the fact that the location of the groups of MPs with acceptable spatial integrity showing excessive values of E-W acceleration correspond to the MPs with significant values of Pre-Event E-W velocities (graphical comparison of Figure 3a and 3c). A specific analysis has been carried out to check if the MPs with very small E-W V_{pre} measures (e.g., $|V_{pre}| < 1$ mm/y) have been activated to have higher values of E-W V_{post} (e.g., $|V_{post}| > 4$ mm/y). The result was that only a few points (i.e., 4 sparse points) agreed with this condition. This may cancel out the idea of ground deformation activation over the area and strengthen the claim regarding the strong influence of extreme rainfalls on the E-W accelerations.

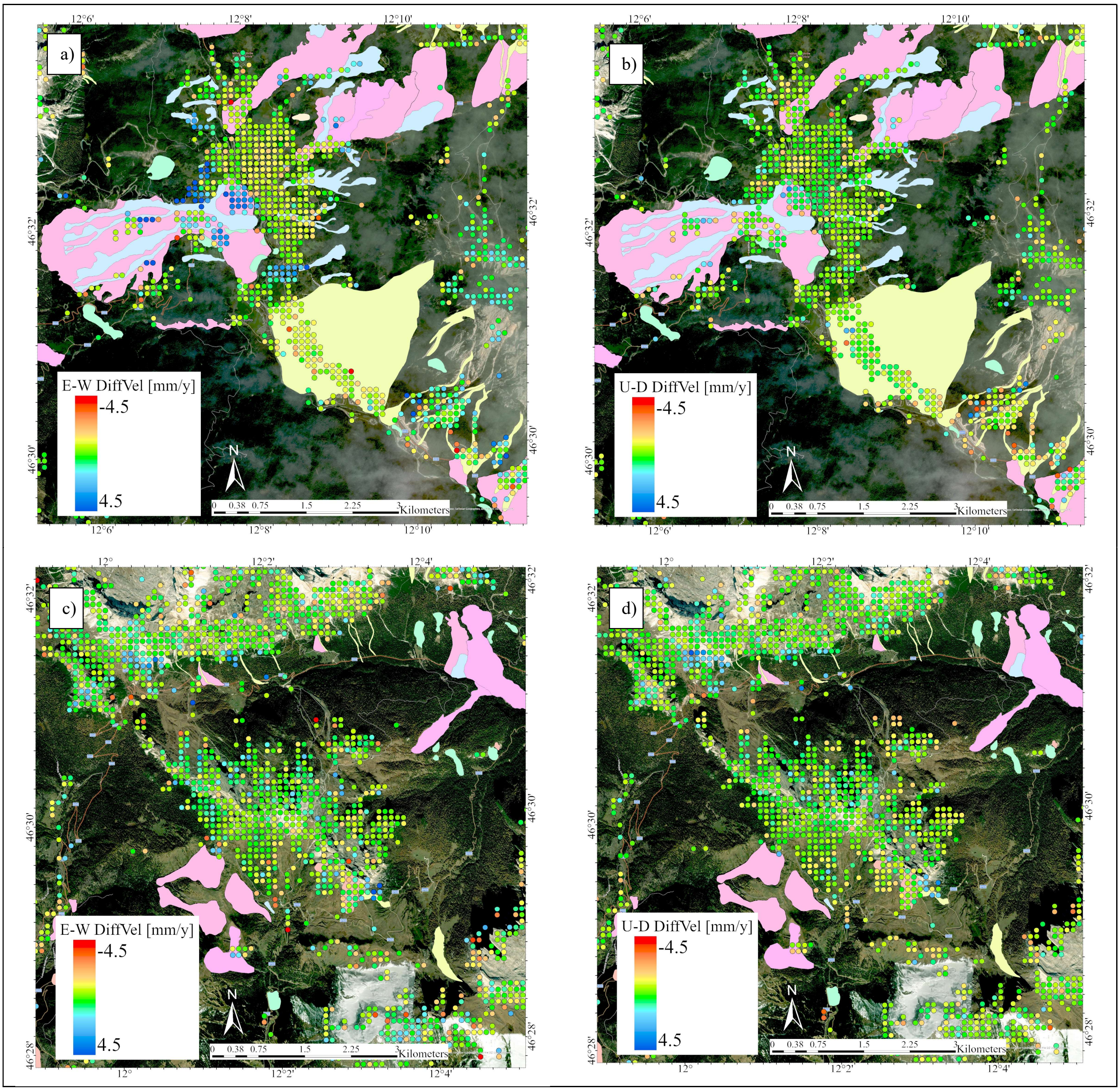

Figure 4. Zoom to the local high-risk zones together with landslide inventory polygons.

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4.2 Local high-risk areas

According to the discussion in the previous section and the final goal of the paper, six zones with considerable ground deformation parameters $V_{pre}$and ΔV_{sgn}have been selected as high-risk areas. Other criteria for the selection of these zones are the capability to be modified by the extreme event (whether acceleration or deceleration) and the presence of critical man-made assets. In each zone, there are some elements exposed to this geological hazard, which may be characterized by high socio-economical values and systemic vulnerability. In this section, these zones have been studied from several aspects.

As can be witnessed in Figure 4a and 4b showing the E-W and U-D ΔV_{sgn} together with the positioning of pre-existing detected landslides from the National inventory (IFFI), Zone 1 (Z1) is showing high values of ΔV_{sgn} representing remarkable accelerations towards East. However, the MPs displaying acceleration in the U-D direction are few. There is mild deceleration of horizontal deformations in West direction at the western part of the Z2 together with slight accelerations in the same direction at the eastern part of this zone. Almost the same spatial pattern can be detected for the vertical deformations. Being Z1 at the proximity of Z2, the interaction of the detected ΔV_{sgn} patterns may represent a specific geological process in this area due to excessive rainfall events and the local stratigraphic structure. These zones, covering the main town of Cortina d’Ampezzo, comprise several touristic attractions and critical infrastructures.

The same figures also include Z3, passing from the main southern road to the town with significant deformation velocity after the rainfall event. Although a single polygon of landslide can be seen in the eastern part of the zone, the main portion representing the deformation trend modification has not been previously considered as hazardous area. Z4 located eastbound of Acquabona, contains a well-known debris flow process as well as a dense representation of landslide inventory polygons, including several types of ΔV_{sgn}. However, the majority of the MPs depict remarkable acceleration in displacements toward West and mild deceleration in ground surface lowering.

Going to the western sector of the AoI, there are two high-risk zones, Z5 and Z6, as shown in Figure 4c and 4d, which may strongly affect those roads coming from West and South-West in the direction to the town of Cortina d’Ampezzo. Furthermore, an important cable car station in the area is located at Z6. The extreme event of October 2018 vigorously influenced the trend of deformations in these zones and noteworthy accelerations can be seen in both zones for both E-W and U-D directions.

There are small areas, over Z5 and Z6, previously detected as landslides in the inventory. However, those polygons do not contain the portions with hazardous behaviour of ground deformation. This was seen also for other high-risk zones. Therefore, a modification to the landslide inventory covering this area is strongly suggested. However, since it is not the scope of this study, updating the landslide inventory has not been discussed in this work.

4.3 EGMS applicability

It was seen that a time series of EGMS MPs is significantly helpful in the determination of ground deformation condition over the AoI, as well as the modification of the deformation trends due to the extreme rainfall of October 2018. However, these datasets are characterized by some limitations for such applications which are summarized in the following.

4.3.1 Dimensional Limitation. Although the horizontal E-W and U-D directions of ground displacement can be revealed thanks to the combination of measurements from ascending and descending satellite tracks, the InSAR is insensitive (or with very low sensitivity) to the horizontal North-South direction of deformations. In this concern, if a zone is affected by the extreme event and the deformations towards the North or South directions have been modified, it is not possible to reveal this process.

4.3.2 Spatial Limitation. To obtain reliable measurements from the deforming ground using InSAR technology, the target on the ground should be coherent during the period considered for InSAR processing. Typically, these targets are usually found in urban areas, and the coherence is very poor in vegetated zones and areas with high levels of temporal decorrelations. It was seen that some areas characterized by dense vegetation over the area show a lack of MPs, and no judgement can be made regarding the effect of the extreme rainfall on the deformation trend of these zones.

4.3.3 Temporal Limitation: As can be seen in the daily and annual precipitation values shown in Figure 2, there are some other records (rather than 28 and 29 October 2018) such as daily rainfall of 5-Dec-2020 with 131 mm or annual precipitation of 2016, that may capture the attention. One may wonder that these may impose modifications on the trend of ground deformations. By the way, the temporal limitation of EGMS products and the period considered in each release (2016-2021 first release and 2018-2022 second update) made the assessment of the effect of these other possible accelerators not possible. The analysis of the annual precipitation of 2016 requires a time series before 2016 to check the effect of this high annual rainfall, while the daily rainfall of 5-Dec-2020 calls for further information in the next years.

5. CONCLUSION

In this work, InSAR-derived ground deformation time series extracted from European Ground Motion Service (EGMS) have been successfully used to gain comprehensive knowledge regarding the ground deformation status before and after the extreme rainfall of October 2018 as the result of the Vaia Storm affecting Cortina d’Ampezzo. The event has been considered as an inflexion temporal point, and through a simple formulation, the spatial distribution of deformation parameters has been studied. The following conclusions can be drawn:

- the area has been influenced by significant ground deformations due to the presence of slow-moving landslides before the extreme rainfall event of October 2018;
- the event has remarkably accelerated the pre-existing land displacements in the direction of E-W, with a lower effect (but not negligible) effect on the vertical U-D deformations;
- considering the large ground deformation accelerations as an additive hazard to the valuable exposures over the area, six local zones have been detected as high-risk ares, which may need special attention in future planning and mitigation measures; and
- the EGMS L3 data points are practical and beneficial datasets for understanding the spatiotemporal evolution of ground deformations, with or without the presence of extreme events.

The Vaia Storm has affected a wider area in North-East Italy rather than the small area considered in this study. The future perspective would be the analysis of the effect of this extreme rainfall over a wider area to gain a more extensive knowledge of this effect. Furthermore, the framework showed considerable capability for the purpose of reconsideration regarding the previously provided landslide inventories, which will be considered in future studies.

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