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GEAM GEOINGEGNERIA E ATTIVITÀ ESTRATTIVA

DX.DOI.ORG//10.19199/2024.172-173.1121-9041.044

Application of a cluster analysis-based methodology on InSAR data to detect ground deformations in the Po plain (Northern Italy)

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The Po Plain basin in the Emilia Romagna Region (Italy) has been historically affected by strong land movements ascribed to both anthropogenic and natural sources, as well as their superposition. The paper aims to the identification, geolocation and quantification of the main land movement phenomena of the Region via the time-series decomposition and the clustering analysis on the vertical component of satellite DInSAR time-series. The results were interpreted on the basis of ancillary information, such as: land use maps, water production (in terms of wells positions and produced volumes) and position of underground gas storage sites. In particular, the analysis of the purely seasonal components allowed a straightforward correlation between the identified land movement phenomena and the gas storage operations or aquifer recharge/ground water productions seasonality.
***Keywords**: InSAR, cluster analysis, seasonal ground movements, subsidence, water production, underground gas storage.*

1. Introduction

The Po Plain is an extensively anthropized sedimentary basin in northern Italy, which has been the focus of numerous studies concerning the natural and human-induced land movements (e.g., Caputo *et al.*, 1970; Arca and Beretta, 1985; Darini *et al.*, 2008; Modoni *et al.*, 2013; Garcia *et al.*, 2024). Natural causes, including sediment compaction, consolidation, and tectonic activities, have been contributing up to a few millimeters per year (Carminati and Di Donato, 1999, Carminati and Martinelli, 2002; Bitelli *et al.*, 2020. among others). Human activities, such as groundwater extraction for agricultural, civil and industrial purposes, hydrocarbon production and the storage of gas in geological underground formations (UGS), can result in significantly higher land movement ranges (Teatini *et al.*, 2006, Eid *et al.*, 2022).

In particular, the southeastern Po Plain has experienced significant land movements at various spatial and temporal scales due to natural causes, human activities, or both (e.g., Zerbini *et al.*, 2007; Stramondo *et al.*, 2007; Baldi *et al.*, 2009; Farolfi *et al.*, 2019; Nespoli *et al.*, 2021, Galloway *et al.*, 2016; Eid *et al.*, 2022): impacts range from regional flooding to infrastructure damage.

Researchers have analyzed ground movements using various geodetic techniques, revealing spatial and temporal variability across the region. Recently, advancements in monitoring have been achieved particularly through techniques like ground-based Global Navigation Satellite Systems (GNSS) and remotely sensed such as the Synthetic Aperture Radar (SAR). The differential SAR interferometry (DInSAR) can detect and quantify slow terrain movements (in the order of mm/year) by analyzing the phase variances of SAR acquisition in time; and compared to GPS/GNSS it covers wider investigation areas with higher measurement density, ensuring systematic acquisitions in time (e.g., Berardino *et al.*, 2002; Manzo *et al.*, 2006, Lanari *et al.*, 2007).

The need for efficient processing strategies to deal with massive datasets (with large spatial and temporal coverage) sees in machine learning and artificial intelligence applications for automating the detection of movement patterns caused by both natural processes and human activities (e.g., Confuorto *et al.*, 2021; Nespoli *et al.*, 2021; Festa *et al.*, 2022). In particular, Garcia Navarro *et al.* (2024) proposed and tested a methodology to identify and quantify ground movements linked to gas storage operations in underground formations, offering insights into related deformation trends and seasonal anomalies. The methodology is substantially based on the analysis of the vertical component of DInSAR data via the time series decomposition and clustering algorithms. The scope of the present research is to adopt the methodology for the investigation of a complex scenario such as the southeastern Po Plain area to identify and quantify the main land movement phenomena. The area was subdivided in different case studies characterized by important seasonal or trend behavior, or even both. Ancillary information, such as the land use map, water well

If there are references to colour figures in the text, the articles are available in open-access mode on the site www.geam-journal.org positions and UGS site locations, was then used to cast some lights on the possible sources of the detected land movements.

2. Methodology

The DInSAR dataset at disposition corresponding to the vertical component of the ground deformations has a monthly periodicity covering a timespan from August 2016 to October 2021, and comes from the P-SBAS processing of Sentinel 1 images as reported on Table 1.

The analysis started by subsampling and combining the available DInSAR time series that partially correspond to the Ravenna province in northeast Italy, previously studied in terms of the velocities of the deformations (Emilia-Romagna Region Subsidence report from 2023). On this step all the time series were adjusted to be coherent in time: sliced using a common initial and final date, and all deformative values referred to the new initial date, ensuring consistency and comparability.

The entire regional area was analyzed using the methodology described by Garcia *et al.* (2024) and adopted for further researches (Eid *et al.*, 2024 and Garcia *et al.*, 2024). The workflow adopted is as follow: each measurement point (MP) from satellite surveys (i.e., physical reflector targets commonly found in poorly vegetated and urbanized areas) is associated with its displacement in time; the decomposition of the time series of ground deformation of each MP produces three components: seasonality, trend and random or residual (Cleveland *et al.*, 1990); the unsupervised clustering method subsequently allows to group the measured points according to their seasonal or their trend components. The adopted partitive clustering technique is K-means: an unnested method with non-overlapping classes which finds a user-defined number of clusters, represented by their centroids (e.g., the mean value of a group of points) (Hartigan and Wong, 1979). The cluster analyses outcomes are finally visualized on a georeferenced environment.

As a first approach, the DInSAR data available for the entire regional area (Fig 1) was investigated via clustering analysis on both seasonal and trend components, with the main goal of highlighting zones prone to display phenomena more aligned to one of these behaviors, of both. On the base of the outcomes and the ancillary information of representative anthropogenic activities, different sub domains of analysis were defined and further investigated to better depict the land movement phenomena at local scale. For the sake of brevity and representatively only three local cases where defined and described in the paper: one case showing a distinctive behavior when the seasonal component was clustered, and two portraying effects on the ground deformation (GD) related to the seasonal and trend components.

3. Case study descriptions

3.1. Geological framework

The Po Plain corresponds to the foredeep-foreland domain of the Northern Apennines. This region is a complex Oligocene-to-Neogene evolution resulted in a buried, arcuate fold-and-thrust belt. Compressional tectonics drove the northward migration of folds and blind thrusts, progressively incorporating the Po Plain clastic infill and underlying substratum. The current subsurface architecture of the Po Plain has been analyzed through seismic reflection data gathered since 1945, mainly for hydrocarbon exploration (Pieri and Groppi, 1981).

The Po Plain region host a multi-aquifer freshwater system in the upper 500 m of the Quaternary sedimentary sequence and several gas reservoirs, nowadays converted into and operated as underground gas storages, in the lower part. The aquifers in the

Tab. 1 – Features of DInSAR dataset (*Manunta *et al.*, 2019).

Case	Covered area [km^2]	Number of Measuring Points (MPs)	Grid spatial resolution [m x m]	Satellite	Processing algorithm	Time-frame
Regional – Ravenna	5468	629.803	40 x 30	Sentinel 1	Parallel SBAS Interferometry Chain(*)	01-08-2016 01-10-2023
Case 1 – UGS	67	5.873	40 x 30	Sentinel 1	Parallel SBAS Interferometry Chain(*)	01-08-2016 01-10-2023
Case 2 – Highway	478	60.836	40 x 30	Sentinel 1	Parallel SBAS Interferometry Chain(*)	01-08-2016 01-10-2023
Case 3 – Urban area	50	15.538	40 x 30	Sentinel 1	Parallel SBAS Interferometry Chain(*)	01-08-2016 01-10-2023

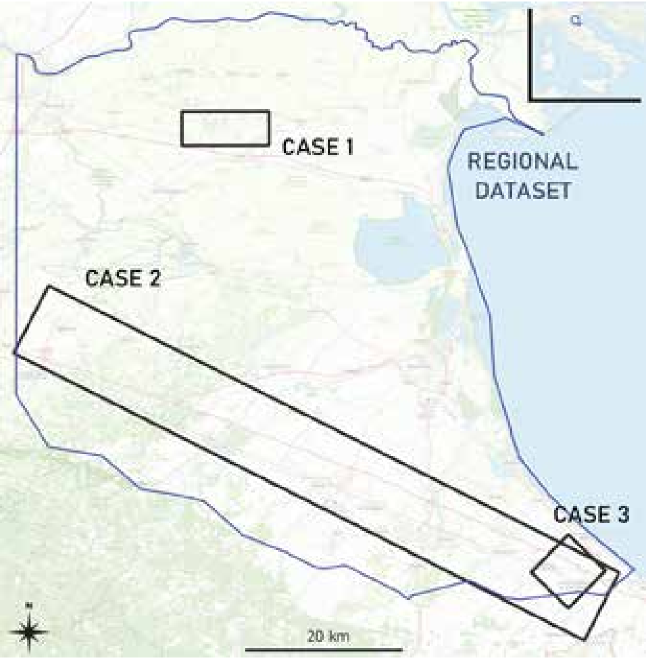

Fig. 1 – DInSAR regional dataset and case studies.

Tab. 2 – Land use percentual distribution across the studied area.

Cathegory	Percentage (%)
Agricultural and vegetated areas	80,50
Urban areas	8,27
Water bodies	6,89
Industrial areas	1,55
Road and railways networks	1,77
Others	1,02

Emilia-Romagna alluvial plain are composed of gravel deposits in the southern region, near the Apennine border, and sandy deposits in the northern part of the plain. Gravel formations are characteristic of the alluvial fans of Apennine rivers, while sandy deposits are typical of both Apennine rivers and the Po River. The alluvial fans of Apennine rivers represent the primary and most utilized aquifers in the Emilia-Romagna region (Regione Emilia-Romagna, 2004; Bonzi *et al.*, 2012). The underground gas storage sites are mainly hosted into clastic gas-bearing formations described by anticline structures against thrust faults linked to the front thrusts and located in depths ranging between 1000-1500 m below the sea level. Throughout the region, the reservoirs are sealed by the Pliocene-early Pleistocene transgressive marine shale known as the Santerno Formation, which serves as the caprock (Marzano *et al.*, 2020; Benetatos *et al.*, 2023).

3.2. Study cases

The investigated area expands over about 5 10^3 square kilometers and it is located in the Ravenna Province of the Emilia-Romagna Region. As the land use map updated to 2020 shows (Fig. 2 and Table 2), it is predominantly occupied by agricultural areas; it is also characterized by the presence of small concentrated urbanized zones, important water bodies to the east and north, and communication networks (such as highways and railways). Furthermore, underground formations

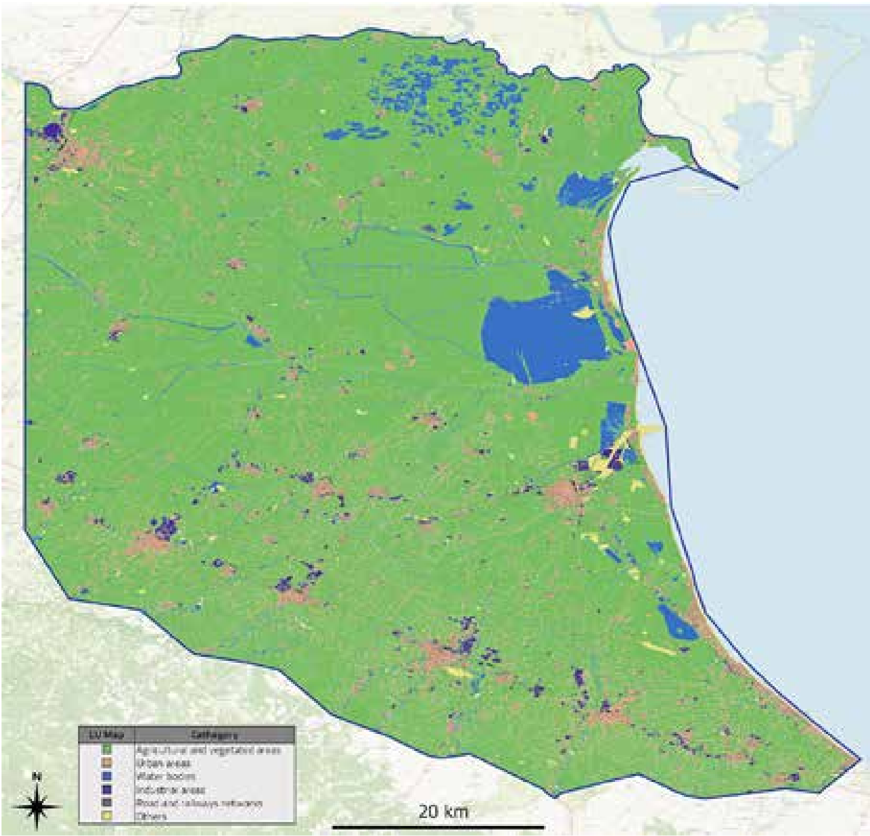

Fig. 2 – Land use map of the study area, 2020 update (*Regione Emilia-Romagna*).

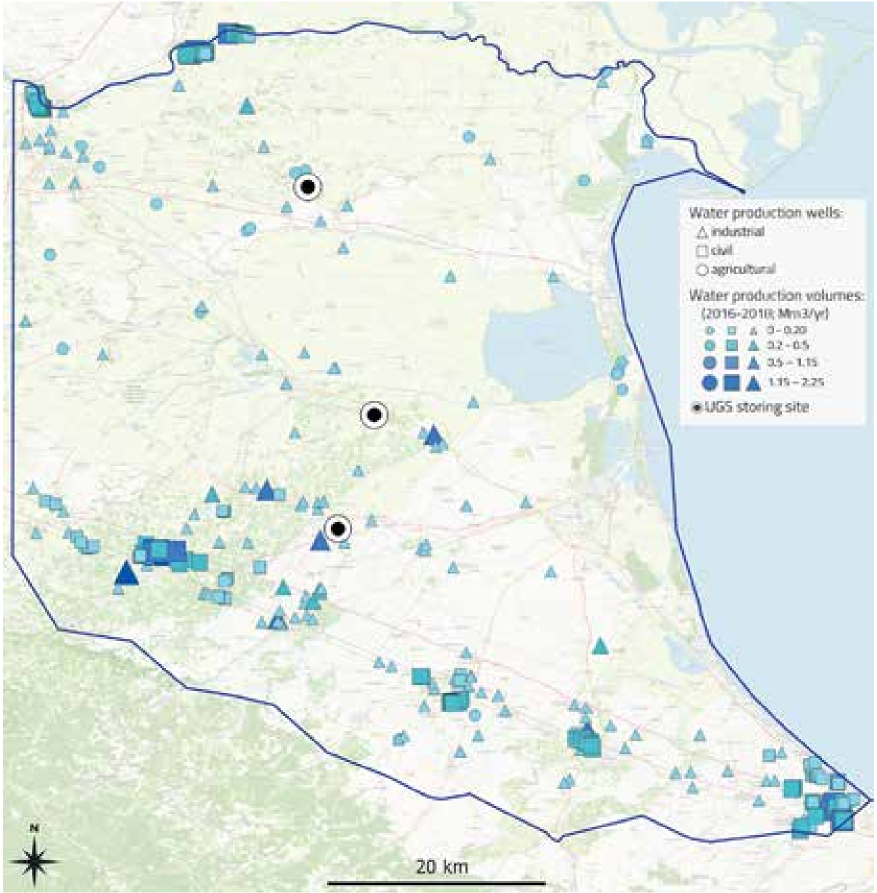

Fig. 3 – Production water wells and UGS locations over the study area.

host some underground gas storage systems (Fig. 3). Due to strong agricultural activities, the area is also interested by the presence of numerous water production wells. Fig. 3 shows the position of the official water production wells categorizing according to both their purpose, i.e. industrial, civil or agricultural, and the production volumes. The reference period is [2016-2018] (Eid *et al.*, 2024). There are strong evidences of a certain number of unofficial water production wells spread out all the regions.

4. Results and discussion

4.1. Regional Case

The cluster analyses of the regional case were conducted testing different numbers of clusters, founding 6 the one that better highlighted areas of potential interest, both at trend and at seasonal level. Fig. 4 shows the spatial distribution of clustering analysis outcomes on seasonal components, whereas Fig. 5 shows the results related to trend components. Concerning seasonality, cluster 1 shows the highest average amplitude of its centroids but it collects around 0.1% of the MP without any spatial correlation: as a consequence, it is assumed to be not representative of any relevant phenomena. Instead, cluster 2 and cluster 3 -surrounding cluster 2, exhibit higher spatial continuity and density and show an appreciable amplitude. As a further point of attention, the analysis at regional scale is not able to distinguish the effects of any storage activities because of their amplitudes are in the order of the mean seasonal movements widespread all over the area of investigation. Generally speaking, the average seasonal amplitude affecting the overall area is negligible. Concerning trend component analysis, cluster 1, 2 and 3 identify spatially cohesive areas with important subsidence effects and they are close to each other. In particular, cluster 1 shows the lowest number of points (around 0.3% of the total MP) with the highest average total displacement of its centroids for the investigated time frame; whereas cluster 3 collects a significant number of points (around 8% of the total MP) affected by lower subsidence. Generally speaking, the subsidence component is the leading factor of the overall area: clusters from 1 to 4 collect around 34% of the MP and show an average centroid total displacement in the order of 1 cm and higher for the investigation time frame. Furthermore, the most relevant seasonal and trend phenomena take place in the southern area which host the majority of water production wells.

The sub domains of analyses are shown in Fig. 4 and Fig. 5: the criteria of selection were defined according to the outcomes of the analyses at regional scale, together with ancillary information (such as the public information about the location of UGS sites) and the features of the DInSAR data, privileging high spatial continuity and density areas. In particular, the UGS site is studied on case 1 according to its seasonal component due to the characteristic periodical behavior of storage operations, as it will be explained in the following. Cases 2 and 3 pinpoint well localized and defined effects of ground movements both in terms of trend and seasonal components and they were further explored. While Case 2 comprises around 90 km^2 of NW-SE direction highways at the south, Case 3 analyzes an urban area highly interested by water production in the vicinity to a coastal zone.

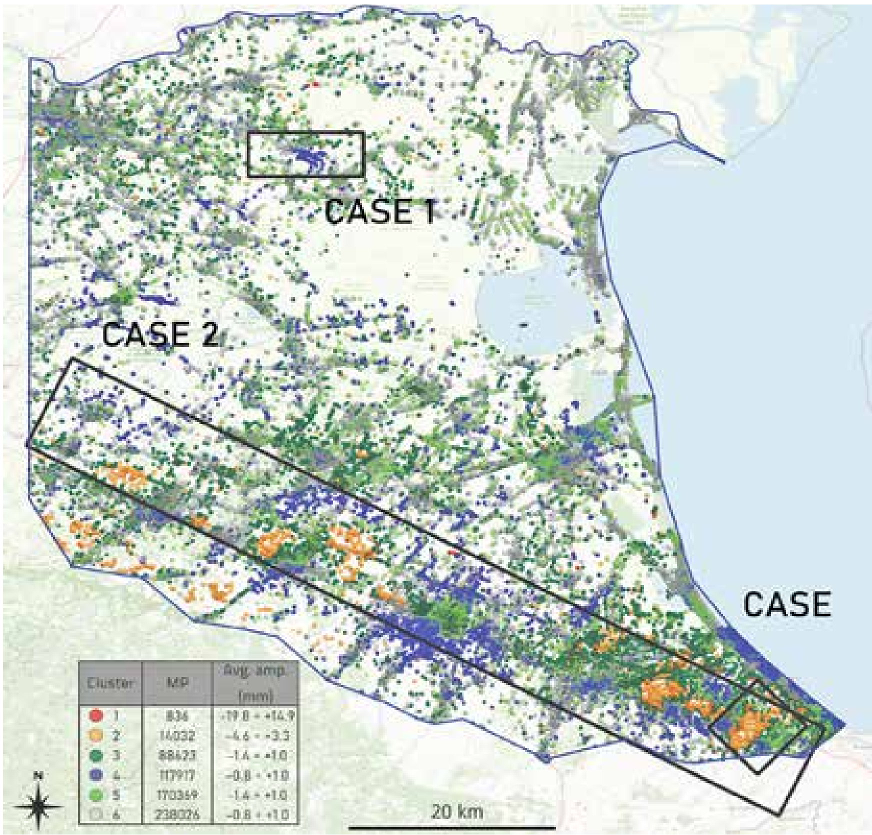

Fig. 4 – Spatial distribution of the results of the clustering analysis on seasonal components for the regional case.

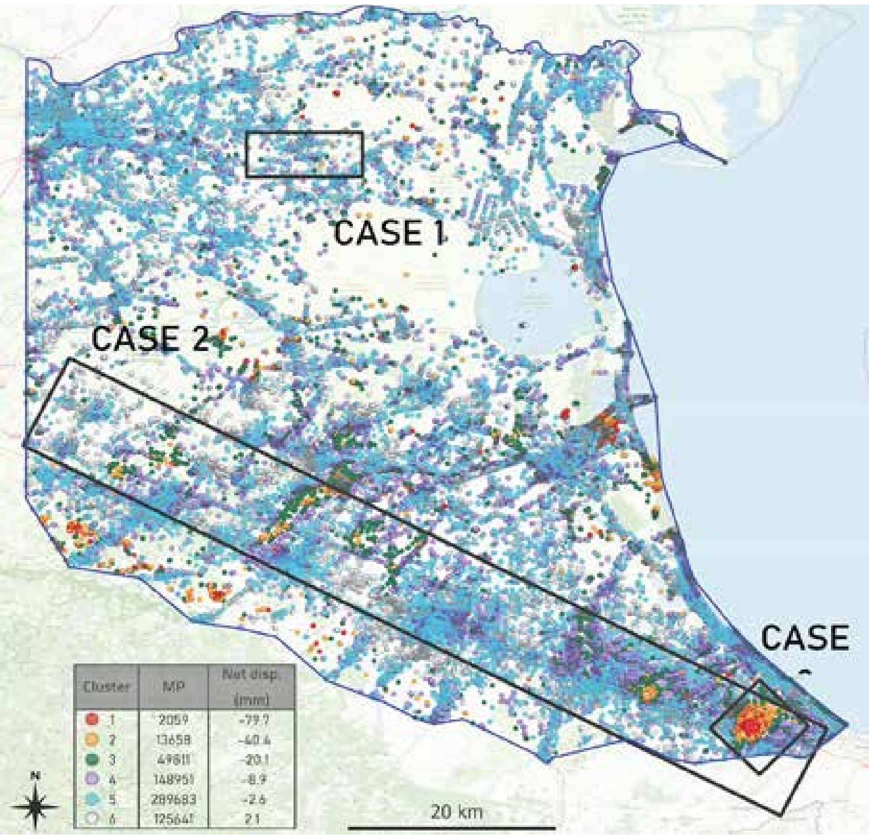

Fig. 5 – Spatial distribution of the results of the clustering analysis on trend components for the regional case.

Case 1

The storage of gas in underground geological formations, such as depleted hydrocarbon reservoirs, aquifers or salt caverns, is a worldwide solution adopted to guarantee a real-time response to the market gas requests, a high degree of elasticity in the management of production and transport structures, and the maintenance of "strategic" reserves. Seasonal and cyclical withdrawal and injection of gas induce an alike seasonal and cyclical oscillation (subsidence/rebound) of the ground surface, the so-called "earth breathing" phenomenon (Benetatos *et al.*, 2020).

The cluster analyses were developed on the seasonal components considering different numbers of clusters. Three clusters allowed the best identification of the phenomenon. Increasing the number of clusters does not impact the identification of the UGS class, which remains stable and consistent in terms of the number of measurement points and the average seasonal amplitude value.

Fig. 6 shows the spatial distribution of the clusters: class 1 depicts the UGS site in agreement with its position. The oscillatory phase aligns with storage operations, showing uplift during the summer injection period and subsidence during the winter withdrawal period, with a maximum amplitude range from nearly –5 to +4 mm, as shown on Fig. 7. The seasonality curves for this cluster reflect strong cohesion, giving good quality to the clustering results. Conversely, classes 2 and 3 represent broader, less intense phenomena with sinusoidal seasonal signals that either lead the UGS effects in time or display opposite-phase behavior.

The cluster analysis outcomes on trend components show no peculiar phenomena potentially ascribed to UGS operations.

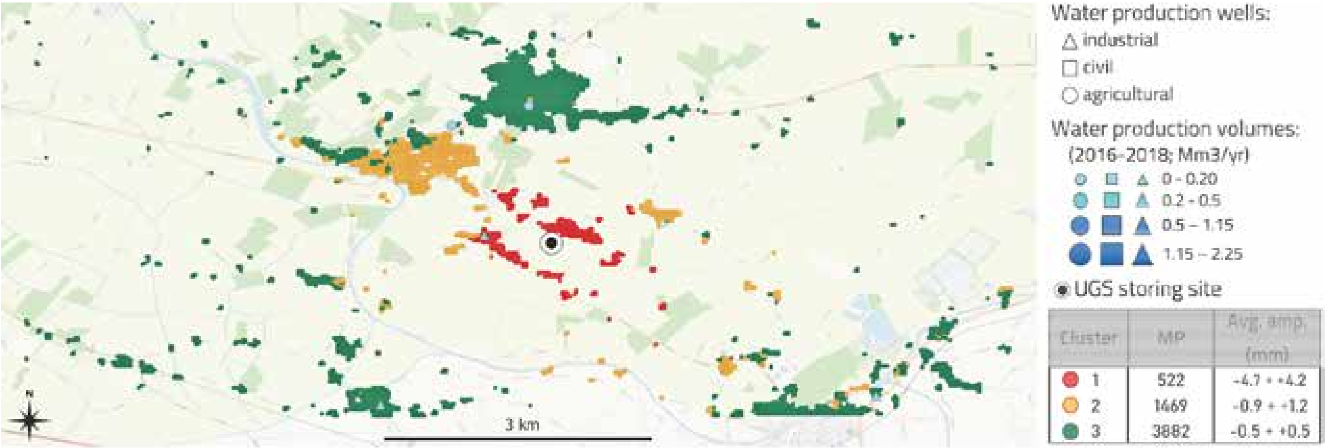

Fig. 6 – Spatial distribution of the outcomes of the clustering analysis on seasonal components for case 1.

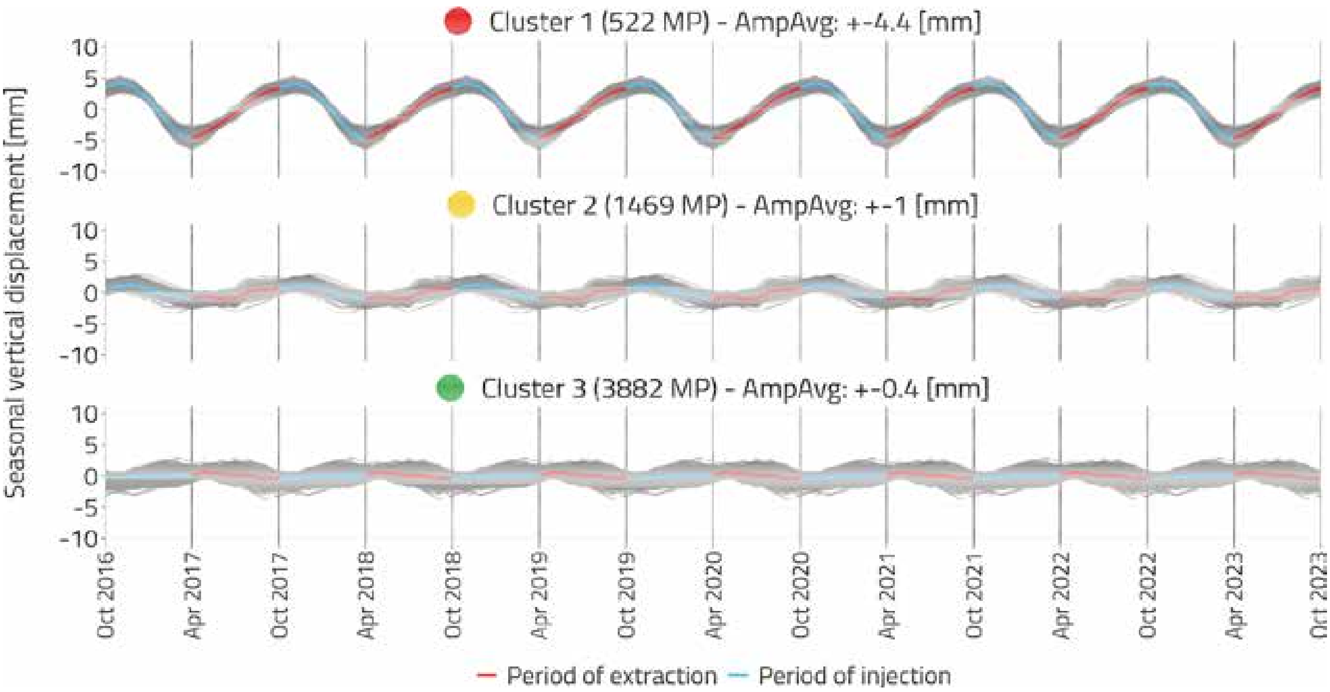

Fig. 7 – Seasonal vertical displacement in time for case 1.

Case 2

The area interested by the highway was investigated considering both seasonal and trend components with an optimized number of cluster equal to four. Figure 8 shows the seasonal clustering spatial distribution and figure 9 the corresponding seasonal vertical displacement curves for each cluster. Figure 10 shows the trend clustering spatial distribution and figure 11 the corresponding vertical displacement curves. As a general comments, no homogeneous and strictly referred seasonal or trend phenomena could be associated with the highway structure itself for its entire length: it rather seems to reflect the oscillatory and trend behavior of the crossed areas.

With respect to the seasonal components, the investigated area is affected by very low to negligible phenomena. The only appreciable seasonal events are depicted by cluster 1 which groups very localized areas. Cluster 1 seasonal vertical displacement curves show good agreement with water production /aquifer recharge seasonality, which is: uplift during the autumn/ winter aquifer recharge period, and subsidence during the spring/ summer water production period. Furthermore, the investigated area has been strongly affected by water productions, as shown by well numbers and produced volumes.

Concerning the trend analysis results, around 35% of the MP are affected by an average total subsidence higher than 1 cm in the investigated time frame, whereas the other MP show a quite stable behavior. Cluster 1 depicts a very strong subsidence phenomena in the same area already identified as highly affected by seasonal phenomena in Fig. 8: this area is focus of further

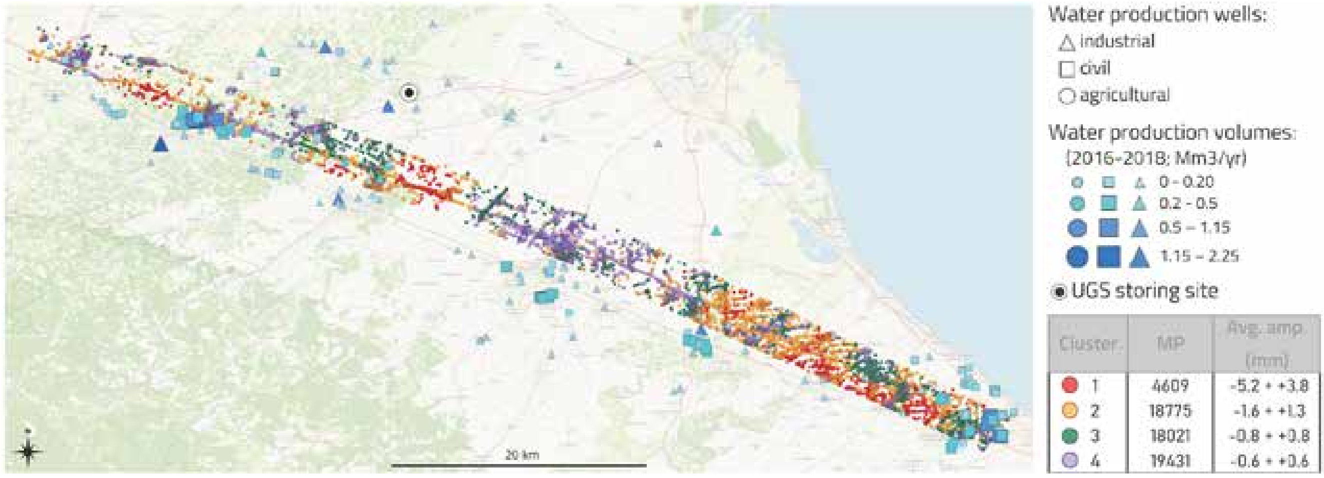

Fig. 8 – Spatial distribution of the outcomes of the clustering analysis on seasonal components for case 2.

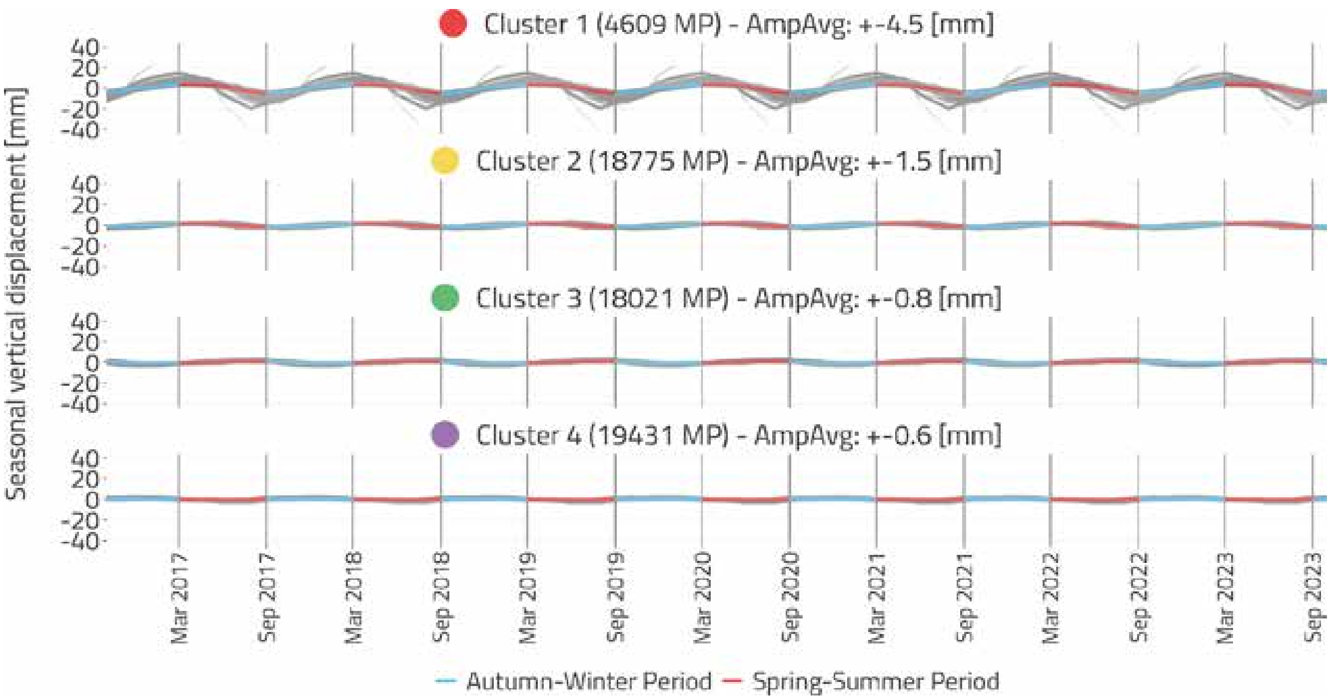

Fig. 9 – Seasonal vertical displacement in time for case 2.

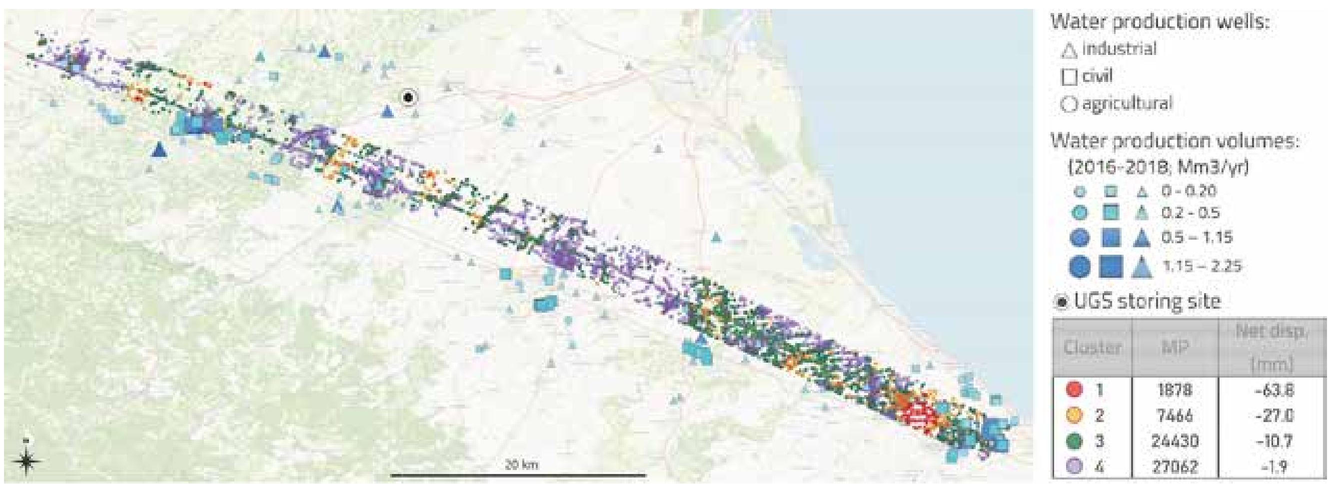

Fig. 10 – Spatial distribution of the outcomes of the clustering analysis on trend components for case 2.

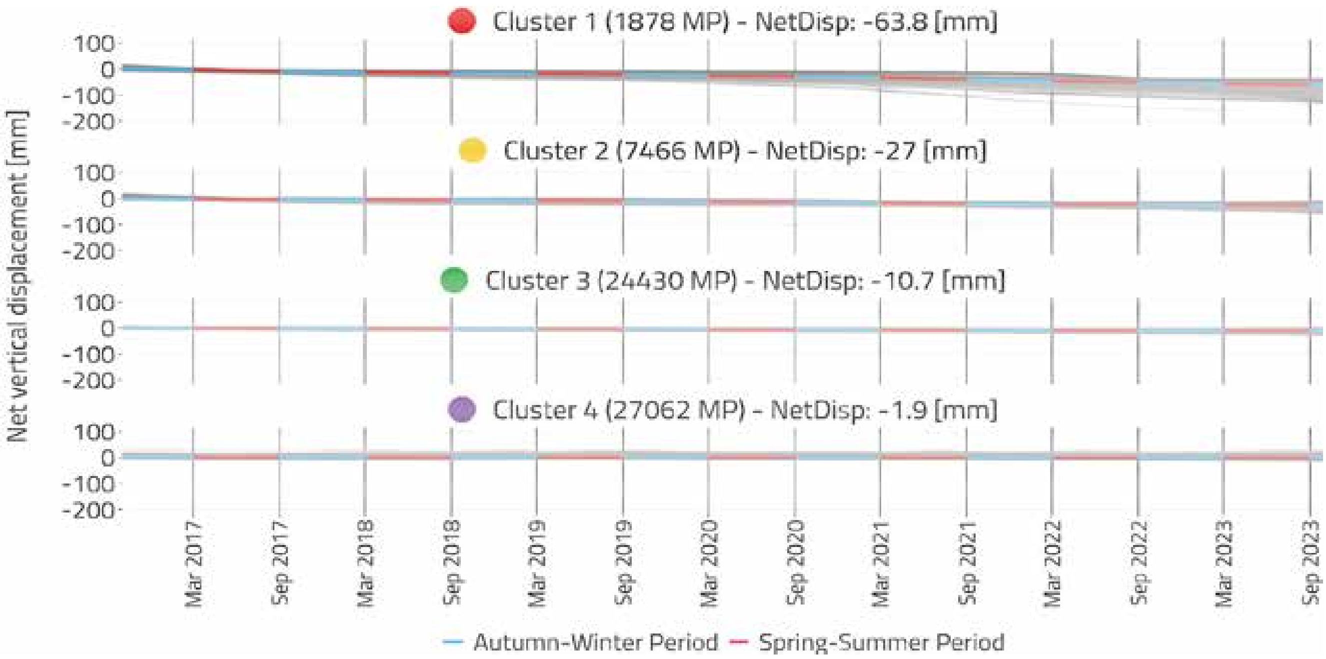

Fig. 11 – Trend vertical displacement in time for case 2.

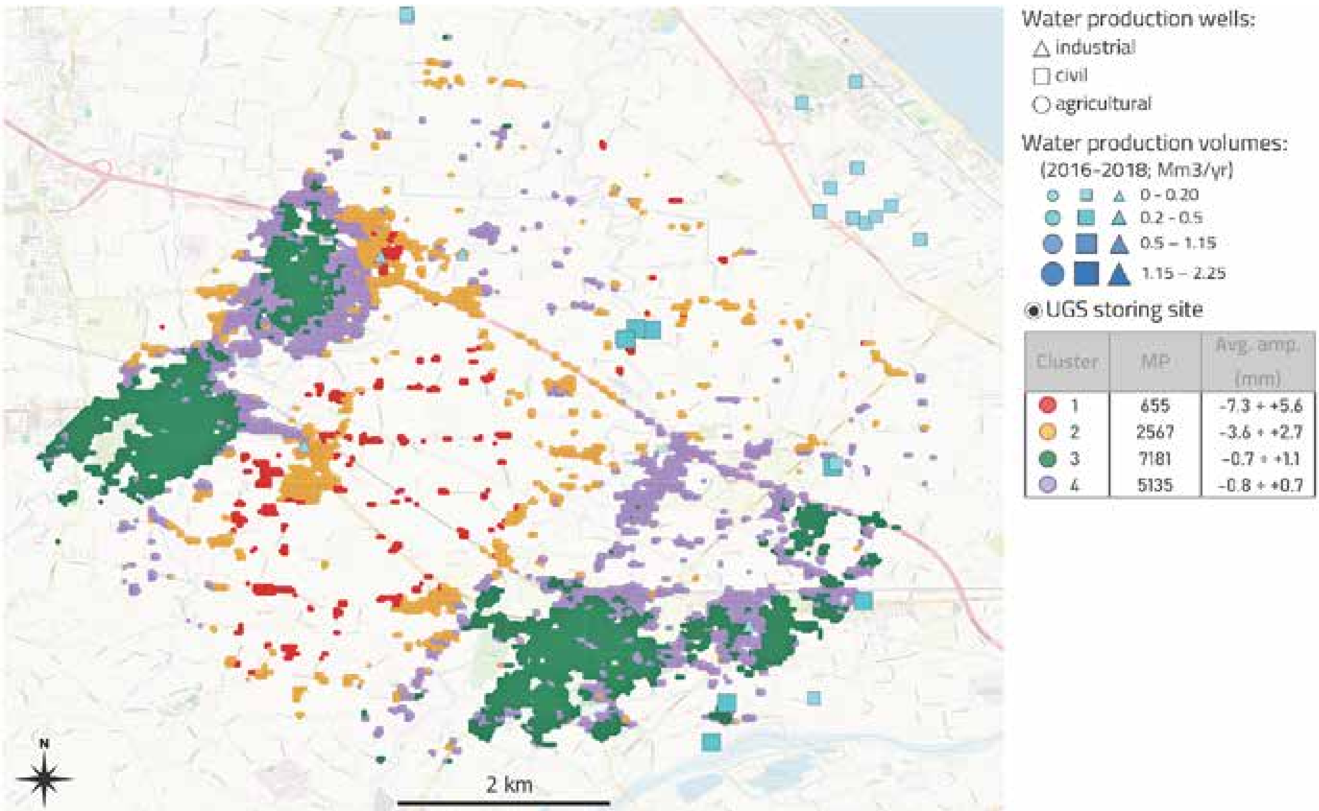

Fig. 12 – Spatial distribution of the outcomes of the clustering analysis on seasonal components for case 3.

analysis (Case 3). The same considerations work for cluster 2 which identify appreciable subsidence phenomena: it groups areas also affected by considerable seasonal phenomena potently ascribed to water production and aquifer recharge.

Case 3

Trend and seasonal analyses of the case 3 identify a very well circumscribed area most affected by both components of the vertical movement.

The outcomes of seasonal analyses are presented in Fig. 12 and Fig. 13, showing the areal distribution of the clusters and the seasonal vertical displacement curves, respectively. Likewise, Fig. 14 and Fig 15 are referred to the results of the

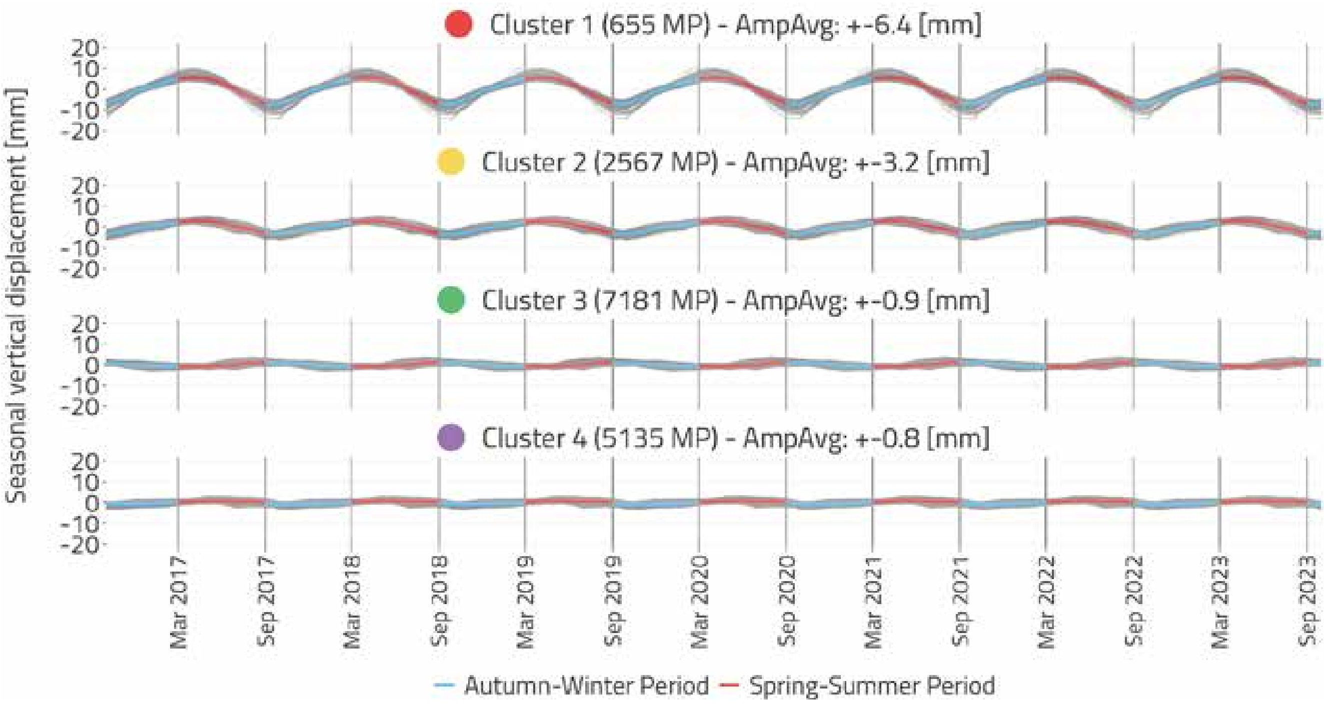

Fig. 13 – Seasonal vertical displacement in time for case 3.

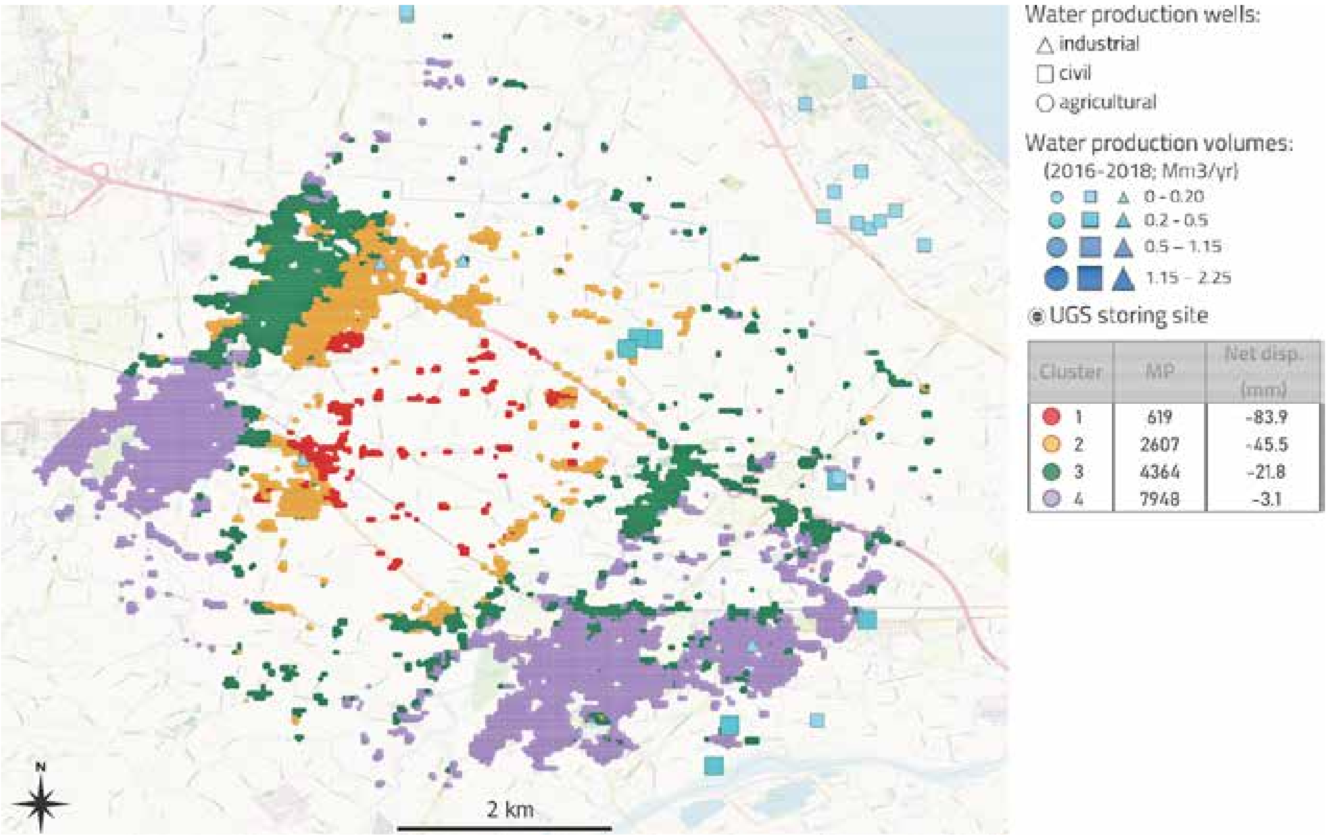

Fig. 14 – Spatial distribution of the outcomes of the clustering analysis on trend components for case 3.

trend components. In both analyses, cluster 1 depicts the maximum ground movements and it is surrounded by cluster 2 which shows an attenuation of the phenomena. In particular, the seasonal results of both cluster 1 and 2 show a strong correlation with aquifer recharge and water production: uplifting behavior during the winter season (in agreement with recharging of the aquifers) and subsidence during the summer (in agreement with water production for crop irrigation). Coherently, the land use

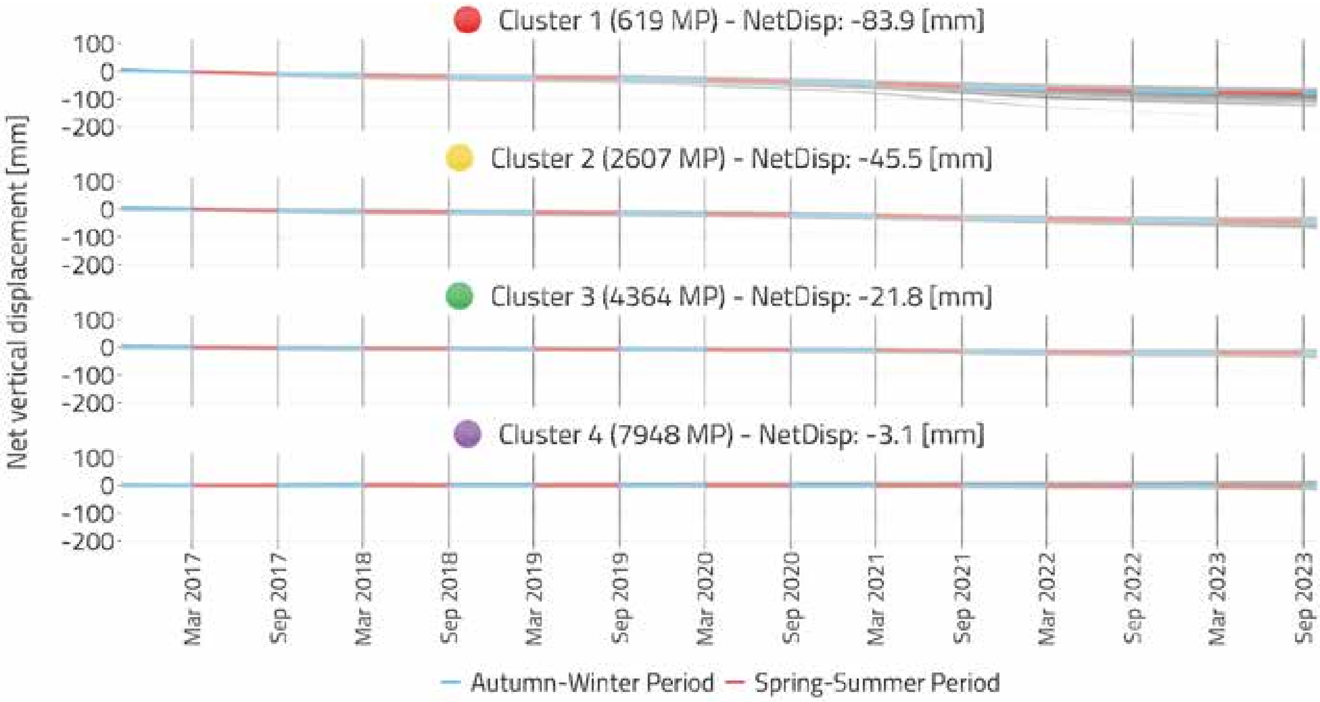

Fig. 15 – Trend vertical displacement in time for case 3.

map zone illustrates strong cultivating habits hosting numerous official and potentially unofficial water production wells.

As a further consideration, case 3 refers to a coastal zone, historically affected by considerable subsidence phenomena.

5. Conclusions

The paper explores the potentialities of time series decomposition and clustering analysis applied on the vertical components of DInSAR time series of ground deformation to identify, geo-locate and quantify the main land movement phenomena affecting the Emilia Romagna Region (North Italy). The area was selected because it has been historically affected by intensive land movement phenomena of both anthropogenic and natural sources as well as their superposition. In particular, the superposition of different effects increases the degree of complexity of the analysis.

Generally speaking, the investigated area turns out to be quite stable concerning the seasonal movements but it shows an average appreciable subsidence. The outcomes of the analyses of the specific areas of interest were interpreted concerning ancillary information, such as the land use map, the location of official production wells and underground gas storages sites, and the location of the main highway. In particular, the area interested by the highway shows no homogeneous and strictly referred seasonal or trend phenomena and it rather seems to reflect the oscillatory and trend behavior of the crossed areas. As a further outcome of the research, the analyses of the seasonal components allowed a clear relation between land movements and both gas storage operations or aquifer recharge/water production. In particular, the effects of the gas storage operations are limited to a very well circumscribed area and they can be appreciated only in terms of seasonal and cyclical ground movement variations; whereas water production induces both cyclical movements and continuous subsidence in a more widespread area.

The next step of the research will be focus on the geological investigation of the shallow aquifers of the Emilia-Romagna Region in other to evaluate their areal continuity, which strongly impacts the propagation of the pressure sink generated by water production and, as a consequence, of the induced subsidence.

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Acknowledgments

PhD Scholarship funded under the project “iENTRANCE@ENL – Infrastructure for Energy Transition and Circular Economy@EuroNanoLab” funded by the European Union – NextGenerationEU under the National Recovery and Resilience Plan (NRRP), Mission 04 Component 2 Investment 3.1 | Project Code: IR0000027 – CUP: B33C22000710006.