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Detection of Ground Subsidence in the City of Durrës, Albania, by Persistent Scatterer Interferometry of Sentinel-1 Radar Imagery

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ABSTRACT

Persistent Scatterer Interferometry (PSI) analysis of multi-temporal Sentinel-1 synthetic aperture radar (SAR) imagery was carried out to detect ground displacement in the city of Durrës, Albania. The analyzed interferometric stack consisted of fifty-eight Sentinel-1 images in ascending orbit covering the time period January 2017-December 2018. The results show a zone of ground subsidence with values of up to -30 mm/year that occur within and very close to the boundaries of the reclaimed lands of the Durrës marsh. Rapid urbanization, generally in the form of informal settlements, has taken place in this area in the last twenty years. In the Port of Durrës, a recently constructed breakwater shows high rates of ground settlement up to -30 mm/year, as well. The study is the first application of satellite radar imagery for the detection of ground displacement in the city of Durrës, Albania. Further monitoring is needed to better understand the ground subsidence and ground settlement processes that occur in the city of Durrës.

Keywords: Sentinel-1; radar imagery; persistent scatterer interferometry; Albania

1. INTRODUCTION

Ground subsidence is the sinking or settling of the ground surface due to natural or anthropogenic causes. Surface material with no free side is displaced vertically downwards with little or no horizontal movement [1]. The ground subsidence could occur from various reasons including groundwater withdrawal and soil compaction processes. The study, detection, monitoring and mitigation of the subsidence hazard is an important topic of the engineering geology science [2].

Field surveys from engineering geology experts and detailed geodetic measurements constitute standard procedures of ground subsidence investigation and monitoring. However, in order to cover large areas, the use of multi-temporal radar imagery has become an important source of information for the detection and monitoring of the ground subsidence hazard, especially in the urban areas [3-5]. The availability of the Sentinel-1 Synthetic Aperture Radar (SAR) imagery from the European Space Agency (ESA) has opened new opportunities for the use of the satellite imagery to the detection and monitoring of the ground subsidence hazard [6-8].

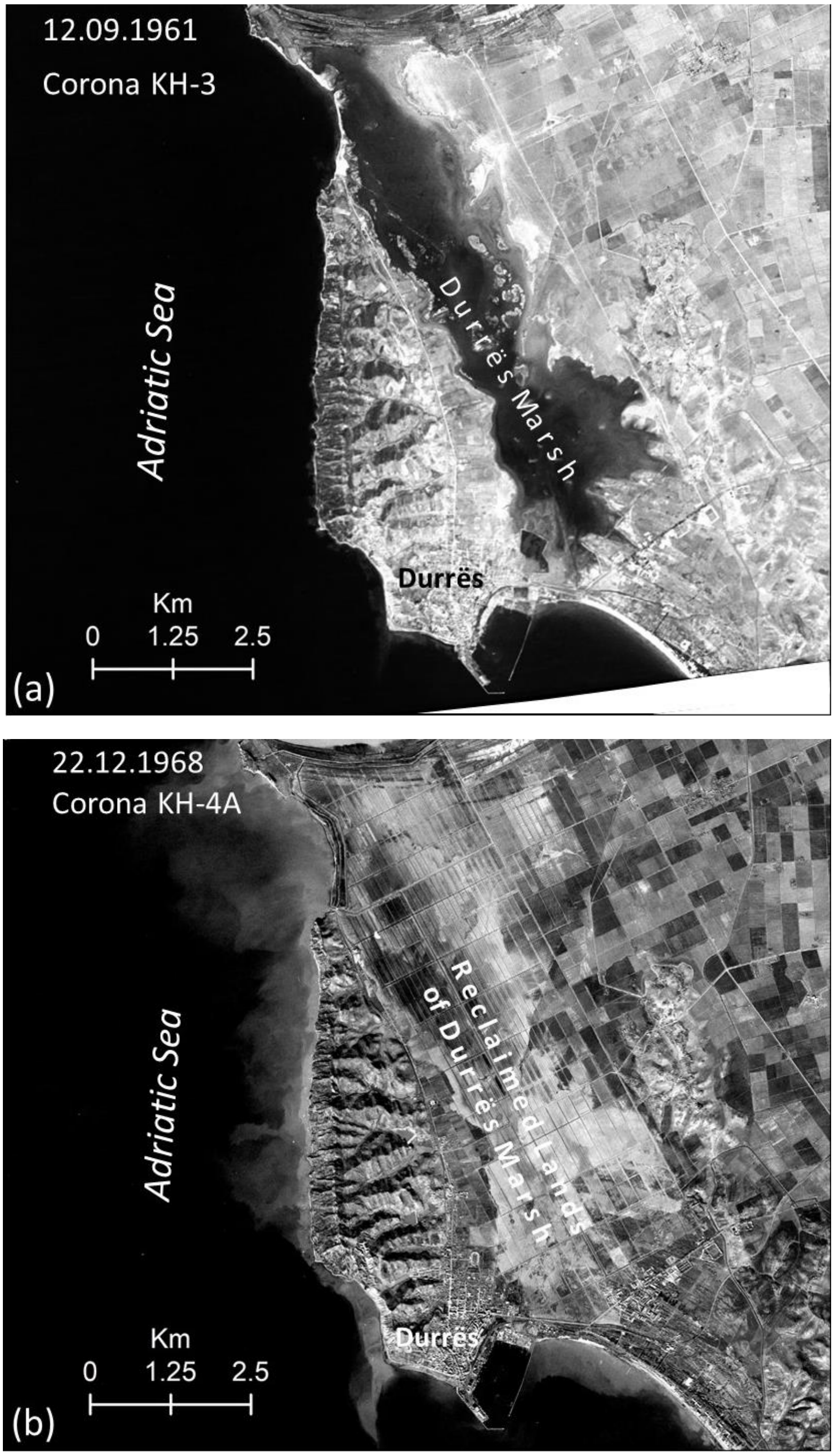

Figure 1. (a) Declassified Corona KH-3 satellite image of September 12, 1961 of the Durrës region. Note the extensive Durrës Marsh that was completely reclaimed by works carried out during 1962-1967. (b) Declassified Corona KH-4A satellite image of December 22, 1968 of the Durrës region. Note the already reclaimed lands of the Durrës Marsh. The Corona KH-4A imagery has a better spatial resolution (~ 2.8 m) than the Corona KH-3 imagery (~ 7.6 m).

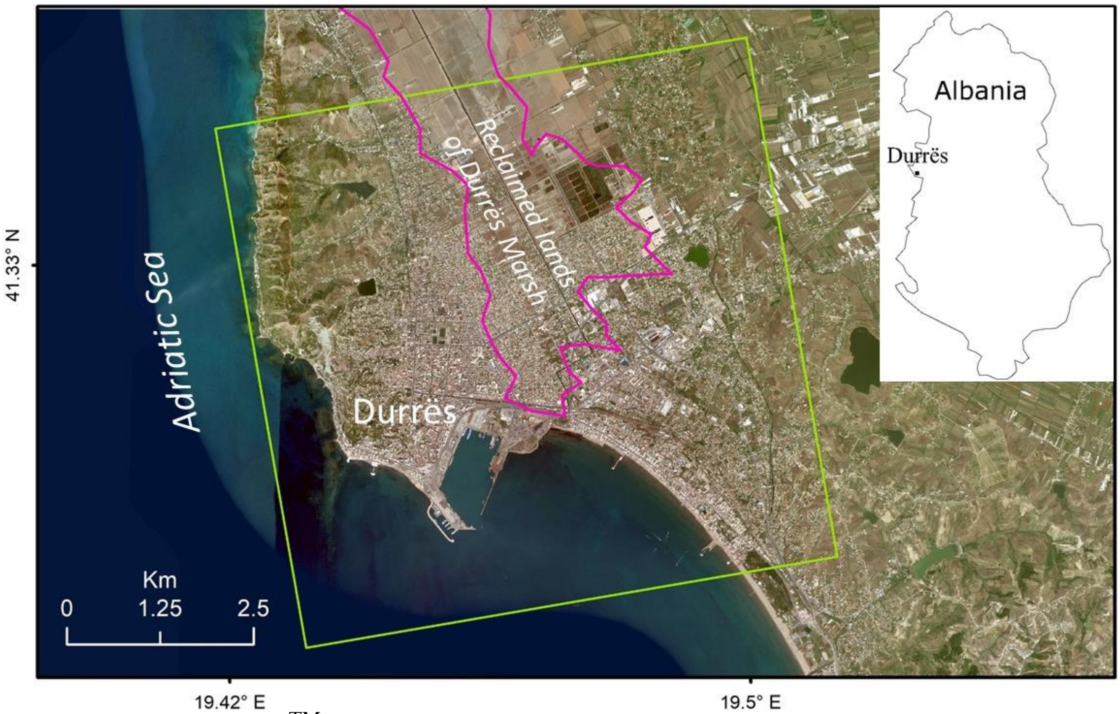

Figure 2. Google Earth^{TM} imagery of September, 2019 of the study area and the spatial extent of the analyzed Sentinel-1 data (green color rectangle). The contour of the former Durrës marsh area (magenta color line) digitized from the Corona satellite image of 1961 shown in Figure 1a is also plotted onto the map. Note the extensive urbanization in the southern part of the reclaimed lands of the marsh. The inset shows the map of Albania with the location of the city of Durrës.

The Sentinel-1A satellite was launched into orbit in April 2014, and the identical Sentinel 1B satellite in April 2016. The Sentinel-1 sensor records C-band (5.3 cm) SAR imagery [9]. The SAR imagery is provided with accurate sensor orbit position useful for interferometric analysis [9, 10]. The revisiting time is 12 days (6 days if both Sentinel 1A and Sentinel 1B are considered). The Sentinel-1 offers an improved SAR data acquisition capability for deformation monitoring, considerably increasing the monitoring potential [11, 12].

The coastal city of Durrës (pronounced *'du:rrəs*) is an important economic, social, cultural, and historical center of Albania. In the last twenty years the city of Durrës has experienced rapid urban expansion. A large part of this urban expansion is in the form of urban sprawl and informal settlements. In addition to the increased density of the built-up area in the city, large areas of agricultural lands have been urbanized. Especially notable, is the case of informal settlement constructions in the area of the reclaimed lands of former Durrës marsh, in the last twenty years. The marsh of Durrës was completely reclaimed by works carried out during 1962-1967 (Figure 1). The reclaimed lands are very susceptible to ground settlement due to soil compaction.

The aim of this paper is to report the use of multi-temporal Sentinel-1 data to investigate the occurrence of ground subsidence hazard in the city of Durrës, central Albania (Figure 2). This research is the first application of satellite radar imagery for the detection of ground displacement in the urban area of Durrës, central Albania. The study investigates the relation of the rapid urbanization with the subsidence hazard, with special focus in the area of the reclaimed lands of former Durrës marsh.

2. MATERIALS AND METHODS

2.1 Sentinel-1 IW SAR imagery

The Interferometric Wide swath mode (IW) is the standard mode of Sentinel-1 data acquisition. The Sentinel-1 IW Single-Look Complex (SLC) SAR images are recorded using the Terrain Observation by Progressive Scans (TOPSAR) acquisition technology [13]. The TOPSAR technology produces SAR image data in sub-swaths. Within the sub-swath, the Sentinel-1 IW images are acquired by recording subsets of echoes of the SAR aperture, which are called bursts [10]. The Sentinel-1 IW images have a ground resolution of 5 m × 20 m. The data have a swath of 250 km, and are distributed by the European Space Agency (ESA) in scenes of approximately 150 km in the azimuth direction.

The multi-temporal radar imagery analyzed in this study consisted of 58 Sentinel-1A IW images covering the time period of January 2017 – December 2018, acquired in ascending orbit 175 in VV (vertical transmitting, vertical receiving) and VH (vertical transmitting, horizontal receiving) polarizations. The VV polarization images were processed for the detection of the ground displacement.

2.2 Persistent Scatterer Interferometry technique

The Persistent Scatterer Interferometry (PSI) [3], is based on the Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques. The DInSAR uses the information contained in the radar phase (φ) of at least two complex SAR images acquired in different times over the same area, which are used to form an interferometric pair [5]. The change in the radar phase (φ) at ground target P, between two measurements, unexplained from other factors (sensor position at times t_1 and t_2, noise, atmosphere, topography), is due to ground displacement (φ_{Displ}) (Figure 3). The DInSAR technique (e.g. [14]) has been extensively exploited in the field of seismology, volcanology, glaciology, landslides, ground subsidence and uplift, etc. (e.g. [5]).

In order to achieve millimeter-scale detection of the ground deformation, the PSI technique analyses a time-series of SAR images [3, 4, 15]. PSI requires a large number of SAR images recorded over the same area. A minimum of 15–20 images is needed to perform a C-band PSI analysis. (e.g. [5]). However, the redundancy is considered desirable for the PSI technique, and a larger number of radar images is usually employed (e.g. [16]). In addition, the temporal resolution is important.

2.3 Data analysis

The Sentinel-1A VV SLC images were initially de-bursted, and spatially subsetted to the extent of the study area. One of the images of the interferometric stack (acquired on April 11, 2018) was chosen as the master image. All other images were coregistered to the master image. A time-position plot of the Sentinel-1A images in relation to the master image is shown in Figure 4. Subsequently, the differential interferograms were formed between the master and each of the other images. A Digital Elevation Model (DEM) from the SRTM mission with spatial resolution of approximately 30 m was used to flatten the interferograms.

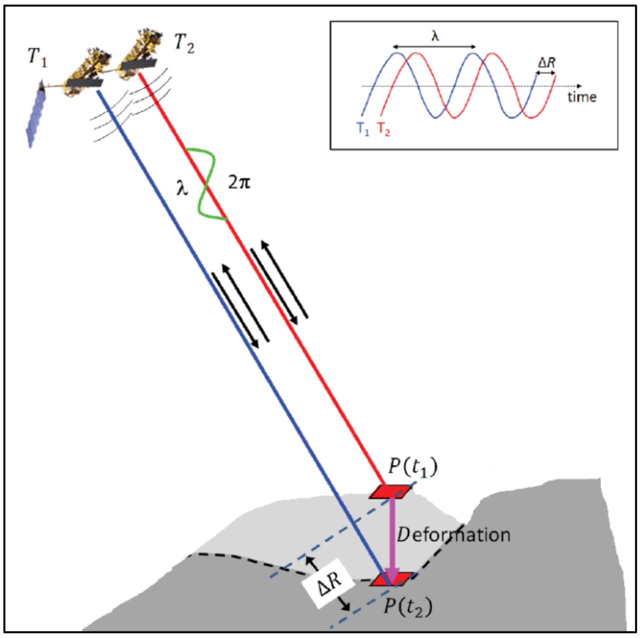

Figure 3. Schematic representation of the DInSAR basic concept. The phase difference of two radar measurements T_1 and T_2 of a ground target P, recorded at time t_1 and t_2, due to a subsidence occurring within this time period at the ground target from position $P(t_1)$ to position $P(t_2)$ (modified from [17]).

The resulting flattened interferograms were used as input to an inversion process to find coherent Persistent Scatterers (PS). Amplitude-based methods [3, 18] analyze the interferograms on a pixel-by-pixel basis to identify reliable PS in urban terrain [19]. At these PS locations is estimated the ground deformation, as displacement of the ground in relation to the sensor, or projected as vertical displacement. The large number of the analyzed radar images reduces the effects of the sensor noise and atmospheric distortion to the phase component. The results were geocoded and presented in a map format.

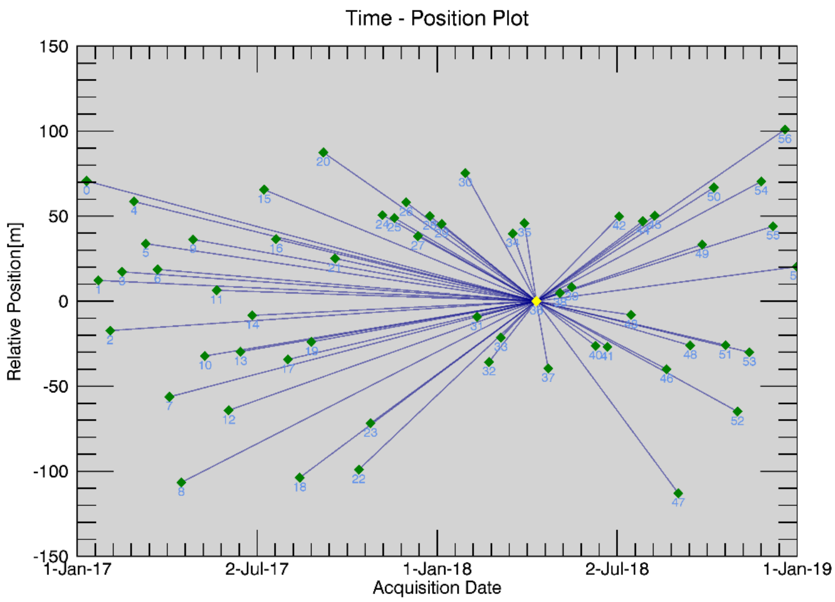

Figure 4. Graph showing the temporal and the relative spatial position of the master image and the other Sentinel-1A 57 images of the ascending orbit stack used to carry out the PSI analysis.

3. RESULTS AND DISCUSSION

The results of the PSI analysis of the Sentinel-1 interferometry stack are shown in Figure 6. The analysis shows zones of ground subsidence mainly corresponding with the area of the reclaimed lands of former Durrës marsh (Figure 5, 6). In this area informal settlements have been built over the last twenty years. The rates of the ground subsidence are considerable reaching up to -30 mm/year.

Although a certain ground settlement is often usual for new buildings, it seems that due to the particular conditions of the reclaimed lands the ground settlement is taking a long time and displays high rates (-20 to -30 mm/year), (Figures 7, 8). The very high spatial resolution Google Earth^{TM} historical imagery is helpful for the analysis of the relation between construction year and the ground settlement. Based on the available satellite high spatial resolution imagery for the area shown in Figure 7 the buildings indicated by the white arrow in the centre of the figure, were built after 2007 but before 2012. Whereas in Figure 8 the construction of the buildings complex showing high rates of ground settlement was completed in 2015.

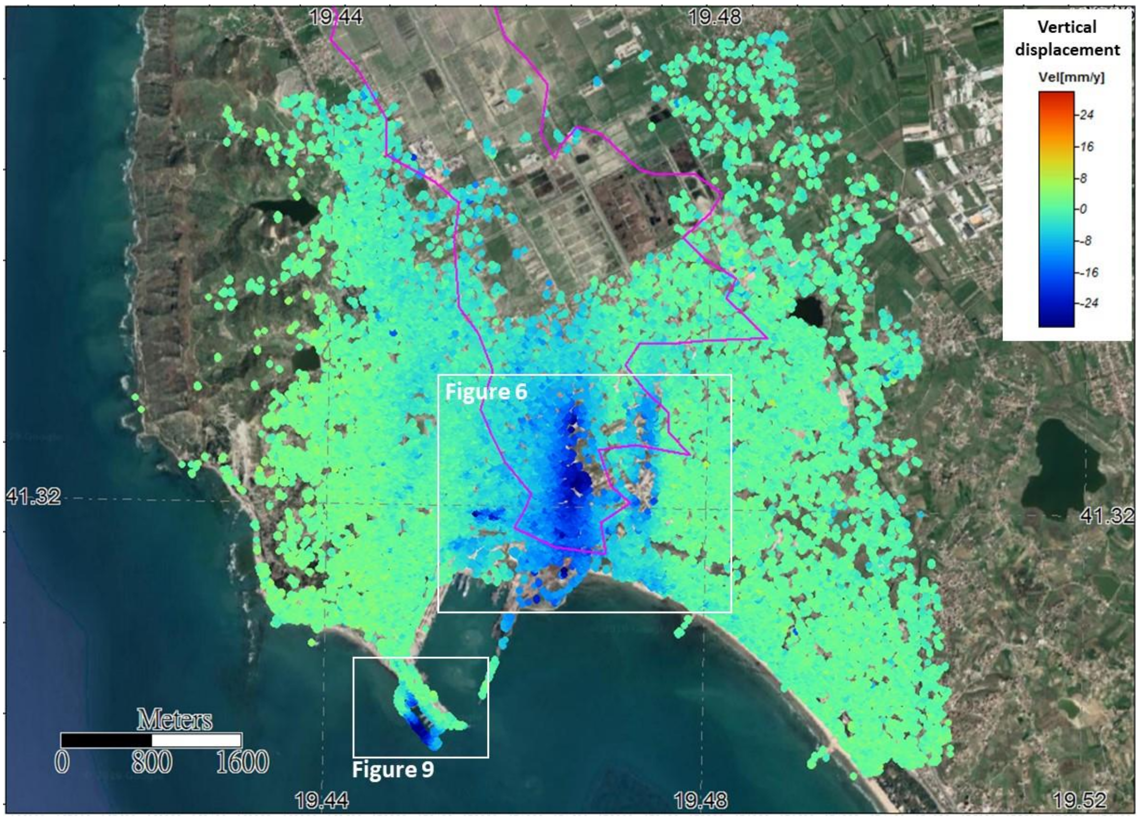

Figure 5. PSI analysis results of the of Sentinel-1 SAR images for the time period January 2017 – December 2018 of the study area, city of Durrës, Albania. The ground displacement rates are shown in mm/year. The results indicate considerable subsidence zones in the southern part of the reclaimed lands of former Durrës marsh. The contour of the former marsh digitized from the Corona satellite image of Figure 1a is plotted onto the map for reference (magenta color line).

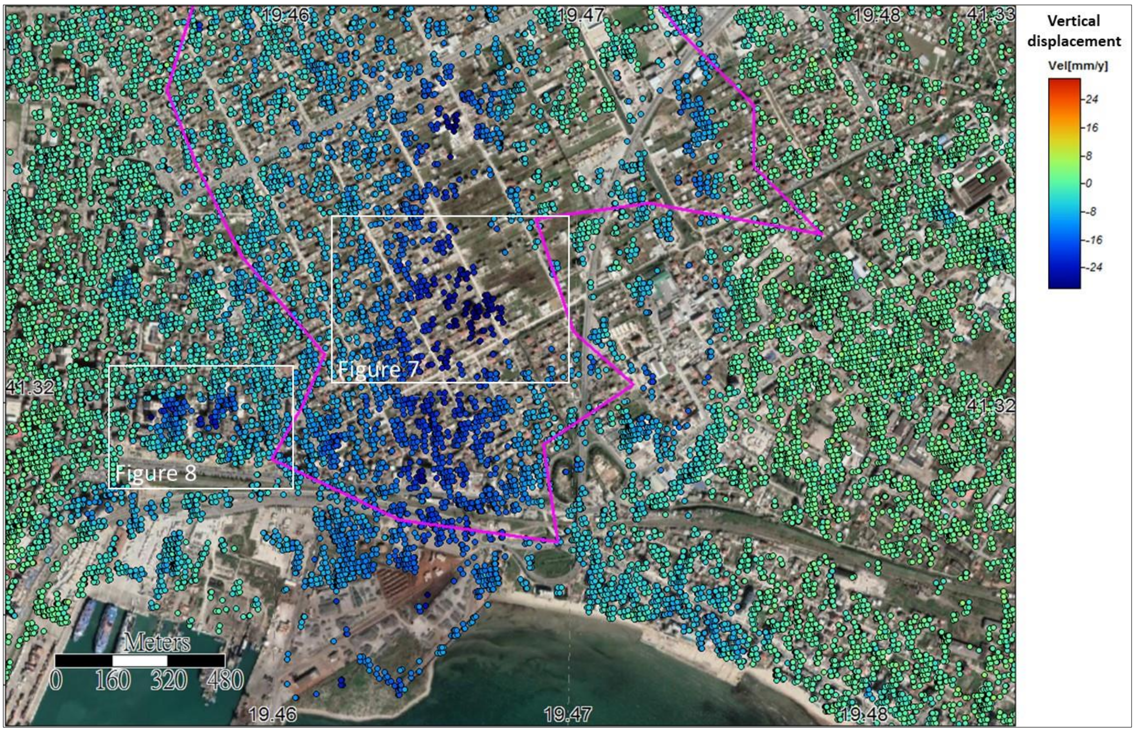

Figure 6. Closer view of the major ground subsidence zones detected by the PSI analysis of the Sentinel-1 SAR images, plotted onto Google Earth^{TM} image. The ground displacement rates are shown in mm/year. The contour of the former marsh digitized from the Corona satellite image of Figure 1a is plotted onto the image for reference (magenta color line).

Figure 7. Detailed view of PSI results in one of the areas with maximal negative vertical displacement rates (up to -30 mm/year).

Figure 8. Detailed view of PSI results in one of the areas with maximal negative vertical displacement rates (up to -30 mm/year).

Figure 9. The PSI results of the Sentinel-1 SAR images at the new fishing port of Durrës constructed in 2013. The displacement rates are shown in mm/year.

It is not excluded, that a part of the ground subsidence is due to the marshy soils compaction or tectonic processes, not related with the ground settlement as a result of the constructions load. Subsidence of reclaimed lands due to soil compaction is a known phenomenon. In addition, the relation of urbanization and subsidence has been considered in several studies (e.g. [20-22]). The ground subsidence could occur due to groundwater withdrawal (e.g. [23]) constructions load on soils, natural soil compaction, and tectonic processes. A detailed discussion on the factors that influence ground subsidence related with urbanization is given in Abidin et al. [20]. Further monitoring is needed to better understand the ground displacement processes that occur in the reclaimed lands of the former Durrës marsh.

Another zone of ground settlement is detected in the Port of Durres. It occurs in a breakwater constructed in 2013. The breakwater shows considerable rates of ground settlement in the order of -20 to -30 mm/year (Figure 9). All the structures displaying negative rates of vertical displacement in Figure 9 were built together with the breakwater during the construction of a new fishing port.

4. CONCLUSION

Large zones of ground subsidence were detected by the PSI analysis in the southern part of the reclaimed lands of the former marsh of Durrës, where rapid urbanization, generally in the form of informal settlements, has taken place in the last twenty years. The ground subsidence rates reach up to -30 mm/year, and are especially excessive in the case of new relatively large buildings constructed in the area. A part of the ground subsidence could also be due to marshy soils compaction processes, not related with the construction load effect. In addition, there are no data available if the urban development has lowered the groundwater table in the area. For these reasons further monitoring is needed using satellite imagery, but especially also engineering geology field investigations and geodetic measurements to better understand the ground subsidence and ground settlement processes that occur in the reclaimed lands of former Durrës marsh.

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