DInSAR data for landslides mapping in UNESCO World Heritage sites: Cuenca (Ecuador) case study

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Abstract

The ground displacement monitoring plays a key role in urban development planning. Among ground instabilities, the landslides are a significant natural hazard that can cause costly damage when occurring in or impacting constructed areas. According to the natural hazards risk management plan, it is very useful to use new technologies to improve the survey. Differential Synthetic Aperture Radar Interferometry (DInSAR) is a worthwhile device widely implemented for the detection and the monitoring of ground deformation phenomena. In this work, a DInSAR technique has used to study terrain deformation at large scale in the city of Cuenca (Ecuador). The latter has a high vulnerability to natural phenomena such as landslides and earthquakes. The topography and the geology of the country can promote the slope instability, in addition, in this area, the earthquakes also can be causing the landslides. Indeed, the Cuenca area is well known for one of the most important landslide events occurred. This phenomenon called "la Josephina"; was the most destructive landslide ever took place on 29 March 1993. Recently, a high urban development is involving in the study area, increasing the slope instability vulnerability. Thus, the aim of this study is to apply SAR technology for a preliminary investigation of the landslides that occurred in the area. The DInSAR dataset that cover a period from 2016 to 2019, it has been obtained by means of Sentinel-1 data. Using the SUBSOFT software, developed by the Remote Sensing Laboratory (RSLab) group from the Universidad Politècnica de Catalunya (UPC), the Coherent Pixels Technique (CPT) algorithm has applied to satellite images. The results have been allowed to detect terrain deformations in the urban and peri-urban area. These preliminary results confirm that the DInSAR technique improves the landslides monitoring and could be very useful for the natural hazard risk management.

1. INTRODUCTION

Nature and man are in constant interaction, all activities that take place in the territory are conditioned by natural phenomena, and at some point, these processes cause mismatches between nature and humans, which depending on the degree can become catastrophes (Ayala y Olcina, 2002). Within these imbalances, are mass movements, that are within the category of natural hazards, this type of phenomena develops in the earth's crust and can cause major disasters with incalculable losses. A correct definition of these phenomena would be that they are mass transport systems of soil, rock or debris, downhill attracted by gravity when the stresses that support the masses of soil or rock exceed the resistance of the materials (Iriondo. M, 2007). This article presents a first identification of areas affected by mass movements by means of Differential SAR Interferometry (DInSAR) technique in the Cuenca-Ecuador canton. This area is located in the Andes mountain region characterized by a varied morphology, and steep slopes. Geology is manly characterized by clays and sedimentary materials typical of a basin of accumulation, all this, added to the changing climatic patterns which goes from strong droughts, to extensive rains, conditions that only favor the occurrence of earthworks land change dynamics that can create great complications, going from, the destruction of civil works to problems associated with the population (Fig. 1), deriving in a strong influence regarding the activities of the settlements near them, as well as strategic projects located in the mention territory. Studies undertaken on these natural events have been carried out within the scope of risk management and planning, such as the project called PRECUPA (*Prevención-Ecuador-Cuenca-Paute*) in 1995, where the mapping of landslides was carried out within and around the city of Cuenca that include six topographic charts at 1:25000 scale; As of this date, no new in-depth study on this topic has been generated. So an update of areas subject to mass displacement should be treated as a priority, due to the changing nature of these phenomena, therefore the importance of studying them in the most objective way possible, expanding the knowledge regarding their location, extension and hazard, embodying them in documents to have a clear and updated source of information a priority dataset for land planning and management.

Figure 1. Examples of building damage in Cuenca induced by landslides.

Therefore, in order to update the inventory map of landslide phenomena, Differential SAR Interferometry technique (DInSAR) was used (Bonì et al., 2016; Di Martire et al., 2016; Di Martire et al., 2017; Costantini et al., 2017) by means of the SENTINEL-1 image processing derived from Europe Space Agency of the Copernicus Programme.

2. GEOLOGICAL SETTING

The study area is bounded to the east on edge of the Eastern Cordillera (Litherland et al., 1994) and to the west by uplifted Tertiary volcanic arc (Fig. 2). The Cuenca basin is filled with Mesozoic marine and subaerial deposits set above a Paleozoic metamorphic basement. This depression is subsequent compressional deformations controlled by major NE-trending faults (Bristow, 1980; Noblet et al., 1988; Hungerbuhler et al., 2002). The basin fill occurred in two distinct periods. The first period is characterized by almost continuous sedimentation in a deltaic to marine/brackish environment, with a dominant source by flow directions, fades relations and metamorphic clasts derived from the Eastern Cordillera. The second period is characterized by coarse-grained fluvial and alluvial sediments derived from the West, which were deposited unconformably on the older deformed deltaic deposits.

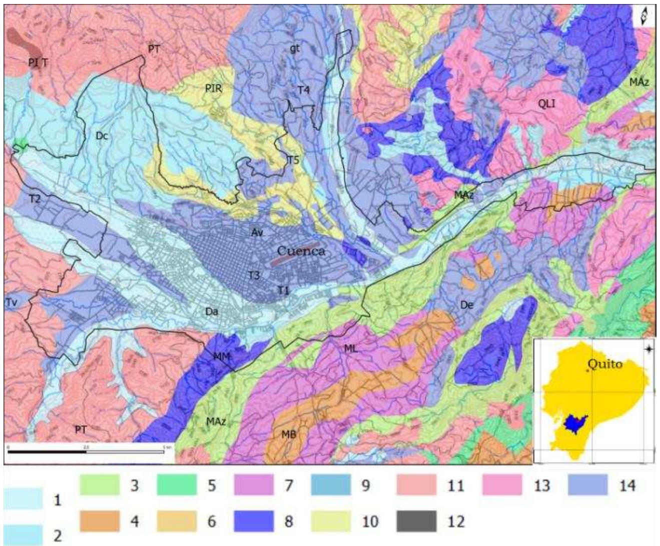

Figure 2. Geological sketch map. 1, 2, 14: Alluvial, colluvial, fluvial deposits; 3: Azogues Fm.; 4: Biblian Fm.; 5: Celica Fm.; 6: Guapan Fm.; 7: Loyola Fm.; 8: Mangan Fm.; 9: Paute; 10: Santa Rosa Fm.; 11: Tarqui Fm.; 12: Turi Fm.; 13: LLacao Fm.

In the Cuenca area, Faucher et al. (1971) and Bristow (1973) identify three distinct lithologic units:

1. Cherts and greywackes, commonly silicified, yield scarce, poorly preserved fossils referred to the Maastrichtian. They consider this unit the lower part of the ‘‘Yunguilla Formation’’;
2. Poorly consolidated shales with limestone lenses and arkosic sandstones beds, dated with microfossils as Maastrichtian. These rocks are interpreted as the upper part of the ‘‘Yunguilla Formation’’ (Faucher et al., 1971). Ammonites collected from these units are assigned to the lower Maastrichtian (Bristow, in Bristow and Hoffstetter, 1977);
3. According to Bristow (in Bristow and Hoffstetter, 1977), marine shales and limestone lenses of the Cumbe area, referred to the ‘‘Yunguilla Formation,’’ grade upward into continental, volcanogenic redbeds.

From the ‘‘Yunguilla Formation,’’ Bristow (in Bristow and Hoffstetter, 1977) reports one Inoceramus sp. and an unidentified ammonite, and Pratt et al. (1997) collected ammonites Hoploscaphitessp. and Baculites sp. of Maastrichtian age. From the overlying fine-grained redbeds, Bristow (in Bristow and Hoffstetter, 1977) collected Paleocene molluscs and Pratt et al. (1997) the bivalve and Pterotrigonia sp., known from the Maastrichtian of Peru. In the Cuenca area, the Yunguilla Formation is overlain by middle Eocene volcanics (Chinchín Formation, approximately 43 Ma) and unconformable continental volcanogenic redbeds of mid to late-Eocene age (Quingeo Formation, 42–34 Ma) (Steinmann, 1997; Hungerbhler et al., 2002). Pratt et al. (1997) correlate the continental volcanogenic redbeds of the Cumbe area with the Quingeo Formation, defined and dated farther northeast by Steinmann (1997). According to Noblet (in Noblet, Duglas and Vera, 1986) The continental sedimentary units of the third period are located along the NNE-SSW direction, between the western and Oriental mountain ranges, also located south of Ecuador.

The Turi Fm. corresponds to the third period and characterized by the presence of conglomerates between 0.9m and 2.5m of width, alternated with sandstones and limonite. The Biblian Fm. corresponds to the early Miocene (Bristow 1973) and can reach 1200 meters of depth. This formation contains the first continental conglomerates deposits. The Loyola Fm. is also present in the canton Cuenca area. The formation corresponds to the medium Miocene, in general its composed of grey color friars' shales and weathered cream slime shales, frequently above the Yunguilla Fm. or the Biblian Fm. In the period of the Azogues Fm. materials are organized in a fluvio-lacustrine ambient. In a more proximal, ambient the Mangan Fm. with a lithology composed by brown sandstones, green and red shales usually laminated associated with the coal deposits. In the quaternary period the Llacao Fm., originated by volcanic activity that consists in a matrix of agglomerates of white glass in terraces with presence of white tuffs (Ministerio de Energia y Minas, 2000).

3. DInSAR DATA

In this work, a DInSAR technique has used to assessment of terrain deformation in the area of Cuenca. The Sentinel-1 images, as Single Look Complex (SLC) data derived from Europe Space Agency of the Copernicus Programme have been obtained in two orbit modes. The dataset refers to 114 images acquired in ascending and 99 in descending geometry, respectively covering the period from October 2016 - May 2019. The Coherent Pixels technique (CPT – Mora et al., 2003; Iglesias et al., 2015) algorithm has applied to satellite images using the SUBSOFT software, developed by the Remote Sensing Laboratory (RSLab) group from the Universidad Politècnica de Catalunya (UPC). The database reports the qualitative information on the data, the value of LoS displacements and the mean displacement rate relative to the entire data processing interval. In an area of 375 km^2 has been detected in each orbit mode, 574 thousand (ascending) and 303 thousand (descending) PS-points. In order to simplify the detection of land surface deformation affected areas, the results have been interpolated by means of Qgis Plugin, called “Heatmap” (docs.qgis.org). The latter uses Kernel Density Estimation to create a density map (heatmap) of an input point. The density is calculated based on the number of points in a location, with larger numbers of clustered points resulting in larger values. Heatmaps allow quick identification of "hotspots" of points. To increase the influence of PS data, the average velocity like weight field has been used.

4. RESULT

From interferometric processing has been obtained two PS-deformations maps (Figg. 3a and b), each for both acquisition geometries. The results have been allowed to determine the surface ground displacements in terms of mean displacement rate map and time series of deformation, along the Line of Sight (LoS) of the satellite. The PSs obtained describe the mean velocity, in cm\year, recorded during the period covered by the acquisitions. The visualization factor is made by using a color scale from red to blue, respectively the negative values conventionally indicate a movement of the target away from the satellite, while the positive values indicate movement towards the sensor, the green color identifies the stable area. In order to identify concentrations of PSs characterized by higher mean displacement rate, the maps have been interpolated by means of Kernel density (Figg. 3c and d).

Figure 3 shows the LoS mean displacement rate and the kernel density maps within the area of
Cuenca basin, covering the chief town and its fifteen municipalities. The kernel result displays
the density of PS velocity field reflecting the ascending (Fig. 3a) and descending (Fig. 3b) maps. Specifically, the areas with red color have negative value while the blue areas are positive corresponding respectively to the values of LOS-velocity. The deeper colors display the more intense zones of higher velocity PS. The shape of the hotspots can indicate a potential ground surface displacement. Thus, according with a preliminary analysis about three hundred Displacement Susceptible Areas (DSA) have been detected. It is possible to observe that the areas characterized by highest displacement rates are located in the municipalities of Cuenca, Sinincay, Nulti, Pacha, Baños and Ricaurte. The latter, in fact, are those that are historically affected by instability.

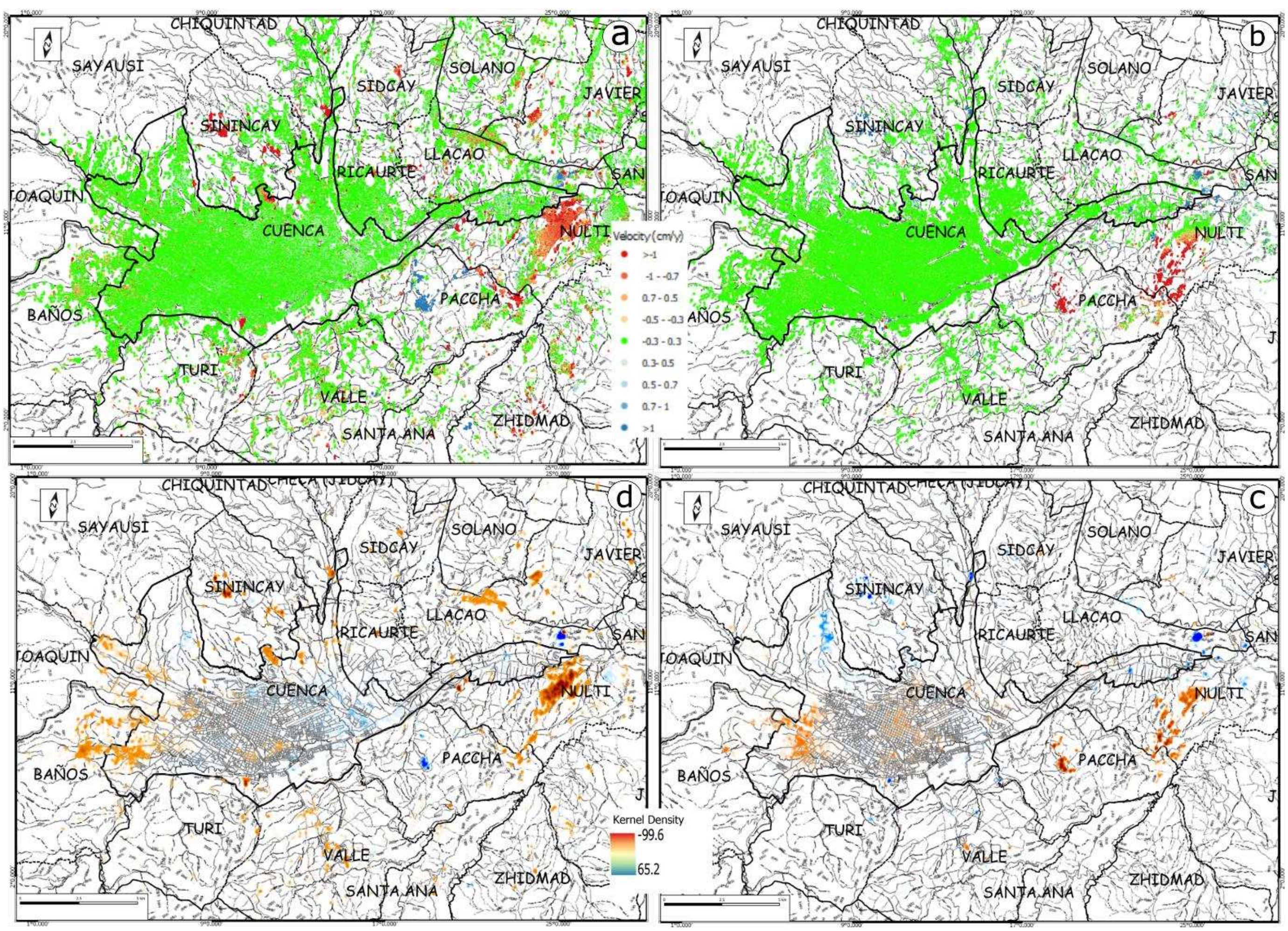

Figure 3. Mean LoS displacement rate map: a) ascending orbit; b) descending orbit; Kernel Density map: c) ascending orbits; d) descending orbits.

5. CONCLUSION

According with Census of Ecuador's National Institute of Statistics and Censuses (INEC) Cuenca is one of the fastest growing cities in Ecuador, after Quito and Guayaquil. The current population of Cuenca in 2020 is 418,000, a 6.7% increase from 2010, the Institute says. The INEC estimates Cuenca's population will grow to 1.3 million by 2050. In addition to population growing, the urbanization from the historical center to rural areas increase too. The latter, if is not managed by urban plan, increase the vulnerability of land stability.

Considering that the Swiss Agency for Development and Cooperation (SDC) and the Ecuadorian Institutions, later the biggest landslide event (the "Josefina") occurred in Azuay province, a natural disasters inventory map has been developed. That prevention project (PRECUPA) have mapped events from 1994 to 1998. Thus, for Cuenca's city, it is necessary a new accuracy landslide maps to decrease the vulnerability of the city. In this study, by means of the SAR processing data a lot of unstable areas have been detected, representing the first step to prevent and mitigate a risk to a natural disaster such as landslides. Based on this information, according with first field survey, in the urban and peri-urban area, several landslides phenomena have been detected (Figure 4).

Figure 4. Landslides in Cuenca territory

Finally, the Remote Sensing techniques have demonstrated to be powerful investigation assuming a paramount task for providing cost-effective solutions in order to mitigate or minimize physical and economic losses. The main objective of this work has been to provide an integrated method which can be used to improve the landslides monitoring and mapping. Future prospective will be use the new DInSAR dataset, integrate the results to the field analysis and finally, will obtain the update of susceptibility landslide map of "Amenaza de PRECUPA" (Figure 5).

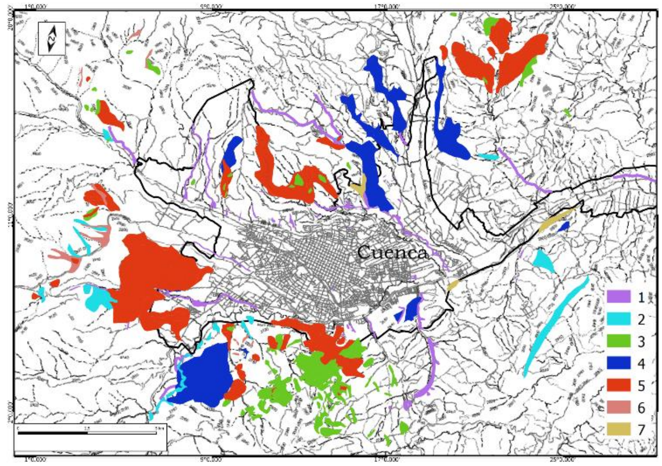

Figure 5. "Amenaza de PRECUPA" map. 1: Flood; 2: Fall; 3: Deep seated landslides; 4: Landslide; 5: Rapid landslide; 6: Erosion; 7: Subsidence.

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