Assessment of flooding risk in Lima, Peru, through change detection based on ERS-1/2 and Sentinel-1 time series

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Abstract: Catastrophic floods that happened in Lima in 1997–1998 and 2017–2018 caused hundreds of fatalities and significant economic loss. To test the hypothesis that information mined from satellite synthetic aperture radar (SAR) images can provide valuable inputs into the common workflow of flooding hazard assessment, the complete archives collected over the Rímac River basin by the European Space Agency’s ERS-1/2 missions and the European Commission’s Copernicus Sentinel-1 constellation were screened. SAR backscatter color composites and ratio maps were created to identify change patterns occurred prior, during and after the catastrophic flooding events mentioned above. A total of 409 areas (58.50 km²) revealing change were mapped, including 197 changes (32.10 km²) due to flooding-related backscatter variations and 212 (26.40 km²) due to other processes (e.g., new urban developments, construction of river embankments, other engineering works, vegetation changes). The areas inundated during the flooding events in 1997–1998 and 2017–2018 mostly concentrate along the riverbanks and plain, where low-lying topography and gentle slopes (≤5°), together with the presence of alluvial deposits, also indicate greater susceptibility to flooding. Through geospatial integration with ancillary data (topography, geology, permanent and seasonal water bodies, urban footprint, new urban development, roads and infrastructure, and population at the district level), a risk classification map of Lima was produced. The map highlights the sectors of potential concern along the Rímac River, should flooding events of equal severity as those captured by SAR images occur in the future. Key findings are presented in this short paper, while the full study is published in the journal Applied Sciences.

Keywords: flooding; synthetic aperture radar; change detection; radar backscatter; urban remote sensing; GIS-based analysis; risk classification

1. Introduction

In recent years, Lima, the Peruvian capital, has experienced severe and catastrophic floods [1]. These events became more frequent, especially in the coastal area of the Peruvian mainland, as a consequence of El Niño. A chronological long-term ground-based data analysis has allowed the identification of major flooding events occurred in the last century along the Peruvian coast, specifically in the areas near Lima. In particular, two main flooding events that occurred in 1997–1998 and 2017–2018 were selected as the focus of this study because, according to the Emergency Events Database [2], they caused significant damage to urban infrastructure.

The aim of this research was to assess whether a flood risk map of the city could be generated based on the evidence of flooded areas during these events, as recorded in satellite Synthetic
Aperture Radar (SAR) images. The basic processing workflow in order to achieve this goal consisted in pre and post-processing of SAR data, generation of RGB composites that showed “where” the change patterns occurred, and the ratio maps providing the information on the magnitude of such changes. These products jointly with three key spatial hazard datasets (terrain slope, alluvial deposits and land cover) and ancillary data related to topography, geology, urban footprint, roads and population, allowed us to undertake an integrated evaluation of the hazards and a risk analysis.

Key findings from this integrated analysis are presented in this paper. For the detailed analysis and discussion of the results, the reader can refer to the full article published in the journal Applied Sciences [3].

2. Experiments

Figure 1 shows the timeline of the El Niño events that were taken into account vs. the whole SAR archive images acquired by European Space Agency (ESA)’s European Remote-Sensing (ERS-1/2) [4] and Copernicus Sentinel-1 Interferometric Wide-Swath (IW) mode data [5] that were processed and analyzed. Given that no images collected by ESA’s ENVironmental SATellite (ENVISAT) satellite were available to cover any of the other El Niño-related events, these data were not used in the end.

Pre-, cross- and post-event SAR pairs were considered to investigate the 1997–1998 and 2017–2018 flooding events affecting Lima (Table 1).

![Figure 1. Flood events and El Niño phenomenon vs. availability of C-band synthetic aperture radar (SAR) satellite data from ESA’s European Remote-Sensing (ERS-1/2), ENVironmental SATellite (ENVISAT), and Copernicus Sentinel-1 missions. The most intense events are indicated in blue. Full paper source: [3].]

Table 1. SAR image working pairs made of ERS-1/2 and Sentinel-1 scenes over Lima, Peru.

| SAR Image Working Pairs | Pre-Event | Cross-Event | Post-Event | Total |
|------------------------|-----------|-------------|------------|-------|
| 1997–1998              | 1         | 4           | 4          | 9     |
| 2017–2018              | 10        | 10          | 10         | 30    |

The SAR processing workflow ran in the Sentinel Application Platform (SNAP) v.6.0 software, using the Sentinel-1 toolbox (SITBX), and included: (i) radiometric calibration and precise co-registration of the SAR scenes; (ii) terrain correction and geocoding to map coordinates; and (iii) generation of SAR amplitude color composites and ratio maps.

Hazard and risk analysis was conducted by combining SAR amplitude change patterns and geospatial data related to topography, geology, alluvial deposits, urban footprint, new urban development, roads and infrastructure, population at district level.

3. Results

A total of 197 changes attributed to the “Flooding” group were highlighted, for a total of 32.10 km². These changes are distributed throughout the whole extent of the riverbed of the Rímac River and, as expected, also include the areas that have been affected by the flooding events occurred in the years 1997–1998 and 2017–2018 (Figure 2).
The flooded areas concentrate mainly in the district of Lurigancho-Chosica (orange polygons in Figure 2). This is mainly due to the large residential and commercial sectors that were flooded during the 16/03/2017 flood event. In particular, in the quarter in Carapongo lying on the right bank of the Rímac River, east of Av. Las Torres, the Sentinel-1 ratio map shows an increase of radar backscatter. This outcome can be explained accounting that floodwater was not clear water, but rather contained solid material transported by the strength of the water flow. Field photographs published in the media show that, alongside wide flooded areas, there were several areas with debris accumulation, rubble, uprooted trees, damaged cars and heavy vehicles. This has also likely contributed to increase both the surface roughness and the soil moisture locally and, therefore, increase the radar backscatter.

Among the radar backscatter change patterns associated to riverbed flooded by increased water flow, it is worth mentioning those mapped in the downstream sections of the Rímac River. There, the observed decrease in the radar signal is due to the increase in the water flow and rise in the water level within the river and typically occurs in correspondence with the transition from the dry to the rainy season (e.g., between December and March of each year). While these changes have a relative relevance for the flooding hazard itself (they occur in non-urban areas, with slope ≤ 5°), and are a typical consequence of the rainfall events and water excess, they are important to mark the sections of the river course where waters rise but, depending on the height of the riverbanks, may flow out and inundate the surrounding land, or not.

Figure 3 displays the spatial distribution of the 212 radar backscatter changes (total extent of 26.40 km²) related to the anthropogenic activities that occurred in relation to the periods 1997–1998 and 2017–2018. Of these changes, for the purposes of flooding risk assessment we considered those whose type and spatial position with respect to the known hazard factors (natural, geological and anthropogenic) could suggest a potential impact on increasing the risk locally. For example, changes due to: motorway, new building and road construction.
Figure 3. Distribution of changes in the radar backscatter, likely due to human activities (anthropogenic), observed and mapped within the Rímac River basin. Full paper source: [3].

4. Discussion and conclusions

For the generation of the Rímac River basin flood risk map, three risk levels were defined: high, medium and low risk. The factors determining the level category were, first of all, the terrain slope, the surface occupied with alluvial deposits, and/or the presence of urban or non-urban area. With this approach we found that all the radar backscatter changes with a given significance for flooding risk assessment are located onto alluvial deposits, their most common slope is ≤ 10° [3], and they split among urban and non-urban areas.

The areas identified at a high risk of flooding are those that in the years 1997–1998 and 2017–2018 were directly affected by the flooding event, and where satellite data and/or ground evidence suggest that material loss occurred (e.g., collapse of riverbanks), slope was ≤ 5° or falling between 6° and 10°, and urban fabric is onto alluvial deposits. The medium risk was attributed to non-urban areas that could be affected by flooding events as a result of the combination between slope with values ≤10° and presence of alluvial deposits. In the end, urban areas where neither previous evidence of flooding nor changes in the satellite data were found, and where it is very unlikely that they would be inundated due to their slope characteristics (between 15° and 20°) and/or local geology, were classified at low risk.

Figure 4 displays the resulting map of SAR-based flooding risk assessment. Because this map is the outcome of combining hazard and risk factors, and the changes (both due to flooding or not) found in the SAR data, it provides the zoning of the areas at risk with respect to flooding events of equal or greater magnitude than those occurred in 1997–1998 and 2017–2018, if no hazard and risk mitigation measures are undertaken. By comparison with hazard and susceptibility maps made solely based on geological factors (e.g. published by Villacorta et al. [6]), the present map has the advantage to embed flood event-based information as well as knowledge of the impacts of recent urbanization within the hazard assessment. Therefore, the information mined from SAR time series contribute to improve hazard mapping products.
Figure 4. Map of flooding risk classification at basin scale over Lima, based on the combination of satellite SAR evidence and natural and anthropogenic factors of flooding hazard, vulnerability and exposed elements. Full paper source: [3].

While the hydraulic risk map presented in this paper was developed a posteriori (i.e. after the flood events happened), the SAR-based methodology behind it is indeed suitable to be iteratively applied, should newly acquired SAR images be analyzed and/or other events occur. This means that this approach can be applied in future for regular monitoring of the Rimac River basin, with the aim of updating the knowledge and understanding of flood risk factors and the consequent susceptibility. Such regular mapping of changes (either natural or anthropogenic) is a key element in the framework of disaster risk management, as it contributes to preparedness, resilience building and reduction of impacts of such natural hazard events on socio-economic levels.

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