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Deliverable D.E2.3: Susceptibility map of the Canary Islands test site.

A deliverable of

TaskE: Geohazard impact assessment

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Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
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EXECUTIVE SUMMARY

SAFETY is a two years research project funded under the ECHO (European Commission's Humanitarian aid and Civil Protection department call "Prevention and preparedness projects in Civil Protection and marine pollution", and it started 1 January 2016. The mission of the project is to improve the efforts in detecting and mapping geohazards (i.e. landslides and subsidence), by assessing their activity and evaluating their impact on built-up areas and infrastructures' networks. SAFETY will enhance ground deformation risk prevention and mitigation efforts in highly vulnerable geographic and geologic regions. The outcomes of the project will provide Civil Protection Authorities (CPA) with the capability of periodically evaluating and assessing the potential impact of geohazards on the selected sites.

D.E2"Susceptibility and hazard maps" is the deliverable of Task E "Geohazard impact assessment". This deliverable is focus on generating susceptibility map of the Canary Islands test site.

Safety

REFERENCE DOCUMENTS

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1 INTRODUCTION

Rockfalls are a common type of fast mass movement and represent a major hazard in mountain areas. When a rockfall event occurs, the main problem use to be located at the foot of the slope, where numerous blocks can impact on dwellings and infrastructures causing personal and/or property injuries (Figure 1). To carry out mapping and simulation studies is essential in this kind of geohazard and specifically to identify prone areas and their rockfall hazard level. Thus, the hazard assessment mainly involves three stages: detection and identification of the source areas, calculation of boulder reach distance and determine its energy intensity.

Figure 1: Example of property injuries produces by rockfall in GC-200 road.

Rockfalls are generally initiated by a small slid, or toppling, and continue by travels down-slope by bouncing, flying and rolling. In this process, the amount of energy lost at each impact point or during the rolling depends on a large variety of factors, being very significant those related to the type of the material cropping out along the slope and the presence of vegetation (Jones et al., 2000). The impact and friction between blocks to blocks and blocks to ground produce a dissipation of the energy and, as a result, boulders stops near the edge of the slope, where the slope is less steep, although in many cases reaching beyond this limit (Evans and Hungr, 1993).

A rockfall event is controlled by numerous factors difficult to determine precisely: the location of the source area, the shape and the geometry of the boulder, the mechanical properties of the rock, the slope angle and the topography profile, etc. On the other hand, rock terrain becomes unstable by conditioning factors, mainly related to its geology (lithology, stratigraphy, tectonics, etc.) as well as its geomorphological and hydrological pattern (Selby, 1993; Dorren, 2003). Most of the rockfalls are triggered by: (a) rainfall (Mateos et al. 2007, Wieczorek and Jäger, 1996); (b) freeze-thaw cycles (Mateos et al. 2012) or earthquake, of magnitude greater than M_w4.5 (Keefer, 1984). On several cases, recognize the link between the event and its origin is a complicated work, even when the rockfalls are monitored (Crosta et al., 2015).

At first glance, a rockfall represents an example of a relatively simple mechanical system and an effortless process to model. Reality is different, because its behavior cannot be forecasted and calculated exactly in space and time, and often there are difficulties to model it with accuracy (Guzzetti et al, 2010).

2 DESCRIPTION OF THE TEST SITE

2.1 The study area: GC-200

The Canary Islands is a populated outermost Spanish region and one of the most popular touristic destinations in Europe (Figure 2). More than 2 million people live and work in the 7,447 km^2 of the archipelago, resulting in an average population density three times greater than the rest of Spain. The archipelago is one of the major volcanic oceanic island groups of the world and have a long magmatic history, which began at the bottom of the ocean more than 40 million years ago (Araña and Ortiz, 1991). This volcanic archipelago is constructed on the passive continental margin of the African Plate on Jurassic oceanic lithosphere and comprises seven main volcanic islands that form a chain extending for some 500 km across the East Atlantic Ocean (e.g. Carracedo et al., 2002).

Figure 2: Image showing the Canary Islands archipelago in the Atlantic.

Most of the historical eruptions in the Canary Islands have been short lived (from few weeks to few months) basaltic, strombolian to violent strombolian eruptions, which have generated scoria cones of different sizes and lava flows of different extend (Romero, 1991). Table 1 summarizes the historical eruptive activity in the Canarias Archipelago and Figure 3 shows the extent of the eruptive products.

Year	Name	Island	Start/End	days	Damages
2011/12	E. de El Hierro	El Hierro	10 Oct 2011 / 5 May 2012	147	Damages in the submarine environment
1971	V. Teneguía	La Palma	26 Oct / 18 Nov	24	1 casualty (due to gas inhalation)
1949	E. San Juan	La Palma	24 Jun / 30 Jul	47	Destruction of houses due to earthquakes, destruction of farmlands
1909	V. Chinyero	Tenerife	18 Nov / 27 Nov	10	No damage
1824	V. Tinguatón	Lanzarote	10 Oct / 24 Oct	86	Destruction of farmlands and water deposits
	V. Chinero		29 Sep / 5 Oct		
	V. Tao		31 Jul / 31 Jul		
1798	V. Chahorra	Tenerife	9 Jun / 14-15 Sep	99	No damage
1730/36	E. Timanfaya	Lanzarote	1 Sep 1730 / 16 Apr 1736	2055	Destruction of houses and water supply systems, destruction of farmlands and pastures, losses of livestock due to gas inhalation, population emigration
1712	E. Charco	La Palma	9 Oct / 3 Dec	56	Destruction of houses, destruction of farmlands
1706	E. Garachico or V. Arenas Negras	Tenerife	5 May / 13 Jun	40	Destruction of Garachicoharbour, destruction of houses, destruction of farmlands, forest fires
1704/05	V. Arafo	Tenerife	2 Feb / 27 Mar	54	16 casualties due to earthquakes, collapse of more than 70 houses due to earthquakes
	V. Fasnia	Tenerife	5 Jan / 16 Jan	12	
	V. Sietefuentes	Tenerife	31 Dec / 4 or 5 Jan	5	
1677/78	V. de San Antonio	La Palma	17 Nov / 21 Jan	66	4 casualties, destruction of houses and water deposits, losses of goat livestock, destruction of pastures
1646	V. Martín or V.de Tigalate	La Palma	2 Oct / 21 Dec	82	Destruction of houses and water deposits, forest fires and losses of livestock
1585	Tehuya	La Palma	19 May / 10 Ago	84	Destruction of farmlands and forest fires
1492	E. de Colón	?	?	?	?
1430/ 1440	E. Tacandeor Montaña Quemada	La Palma	?	?	?

Table 1: Historical eruptions in the Canary Islands, E. means 'eruption' and V. 'volcano'.http://www.ign.es/ign/resources/actividades/volcanologia/TablaAmpliada.pdf.

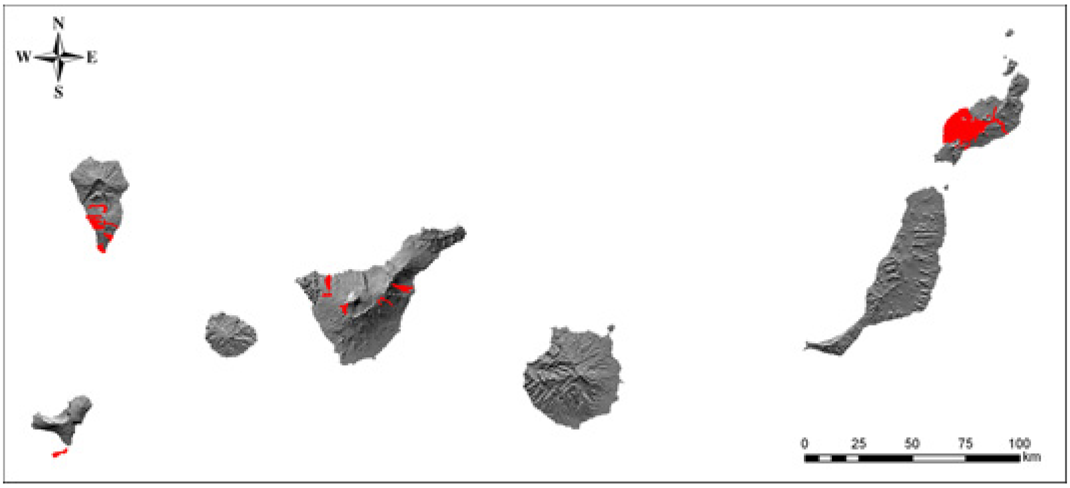

Figure 3: Area affected by the well documented eruptions since 1585 in the Canary Islands (source: IGN, www.ign.es).

In addition to the volcanic hazard SAFETY project will also address landslide susceptibility in the Canary Islands. In particular, rockfalls are the most frequent and damaging landslide type in the archipelago, in the past decade the Emergency Services from Gran Canaria and Tenerife Island accumulate more than 7000 rockfall events producing damages to communication networks.

A pilot study will be made in the northwestern part of Gran Canaria Island, along the GC-200 road. The choice of this pilot area is due to Gran Canaria island emergency services priorities. Subsequently, depending on the performance of the susceptibility model and the confidence on the results on this first pilot site, another test site will be probably included in the Tenerife island (Anaga road in Tenerife island). This test site will be described in future updates of the SAFETY deliverables. The first study area is located in the western extreme of Gran Canaria, and specifically between the localities of Agaete (5767 inhabitants) and Aldea (8633 inhabitants). The GC-200 road constitutes the main transportation corridor between both localities. With a length of 34 km, the road path is very tortuous following the contour of the coast, a very step coastline (Figure 4 and Figure 5) with the highest cliffs in Europe (Risco Faneque, 1027 m a.s.l.). From the point of view of mobility, the GC-200 is a strategic road as it is the transportation via of the tomato production cultivated in numerous plastic greenhouses in Aldea. Additionally, the road is very attractive for tourism due to the spectacular landscape views. The road has heavy traffic estimated on average at 1500 vehicles per day, with a greater influx of vehicles during the months from October to May.

Figure 4: The road cut the alkaline basaltic formation (hard rocks) from the shield stage deposited during Middle Miocene.

Figure 5: The GC- 200 road between the localities of Agaete and Aldea. It is considered one of the most hazardous roads in Europe. Numerous rockfalls cut the road off every year.

2.2 Physiographic and geological setting

The Canary archipelago is located in a transitional zone between temperate and tropical conditions. The conical morphology of Gran Canaria retains the humidity of the predominant north/northeast trade winds of the subtropical Azores anticyclone on the north side of the island. As a result, the northern flanks are humid and vegetation is vigorous, while the south is very dry and the conditions are very arid and desert-like. Rainfall increases with altitude, ranging between less than 200 mm/yr at the coast and over a wide area in southern Gran Canaria, and more than 1400 mm/yr in the higher peaks of the central part of the island. The climate in the test-site area is very dry, with annual average precipitation of 190 mm and annual average temperature of 20.6ºC. The maximum precipitation takes place during the autumn and winter months, being December the rainiest month. Heavy storms are frequent, accompanied by intense rainfall and strong winds, with episodes of up to 250 mm in 24 h.

From the geological point of view, the Canary Islands are developed over Jurassic oceanic lithosphere, as a result of the eastward movement of the African plate over a mantle hotspot (Holik et al., 1991). The origins of the scenery of Gran Canaria began about 15 million years ago with the first submarine building stages of the Gran Canaria Volcano. The first sub-aerial activity took place about 14 Million years ago. This shield-building phase (growth phase) continued until about 9 Million years ago when there was a massive collapse that formed the 20 km in diameter Tejeda Caldera.

After the collapse, the Caldera gradually filled up with lava and other volcanic material over the next few million years. This period was followed by 3 million years of volcanic inactivity and erosion. The next major stage, between 4.5 and 3.5 Million years ago, was characterized by explosive eruptions. Gran Canaria is now in an erosional stage. The last eruption took place about 2000 years ago.

Figure 6 shows a simplified geological map of the island with the main volcanic features. The main stages of evolution of Gran Canaria are the shield stage, including a basaltic shield volcano; the vertical caldera collapse, giving place to the Tejeda-Fataga complex, with a salic post-caldera resurgence; and a rejuvenated stage, including the Roque Nublo stratovolcano and the post-Roque Nublo volcanism (late eruptive phase) which created a composite monogenetic volcanic field. Additionally, massive flank failures are mapped (see gravitational failures) giving place to chaotic deposits which cover large areas.

The geology of the test-site area is within the domain of the basaltic shield stage, Middle Miocene in age (Figure 6). Along the road, an alternance of alkaline basaltic deposits (hard rocks) and piroclastic flows can be observed. Both materials can be the source areas for rockfalls blocks. In some parts, gravitational deposits also outcrop and some boulders frequently invade the road.

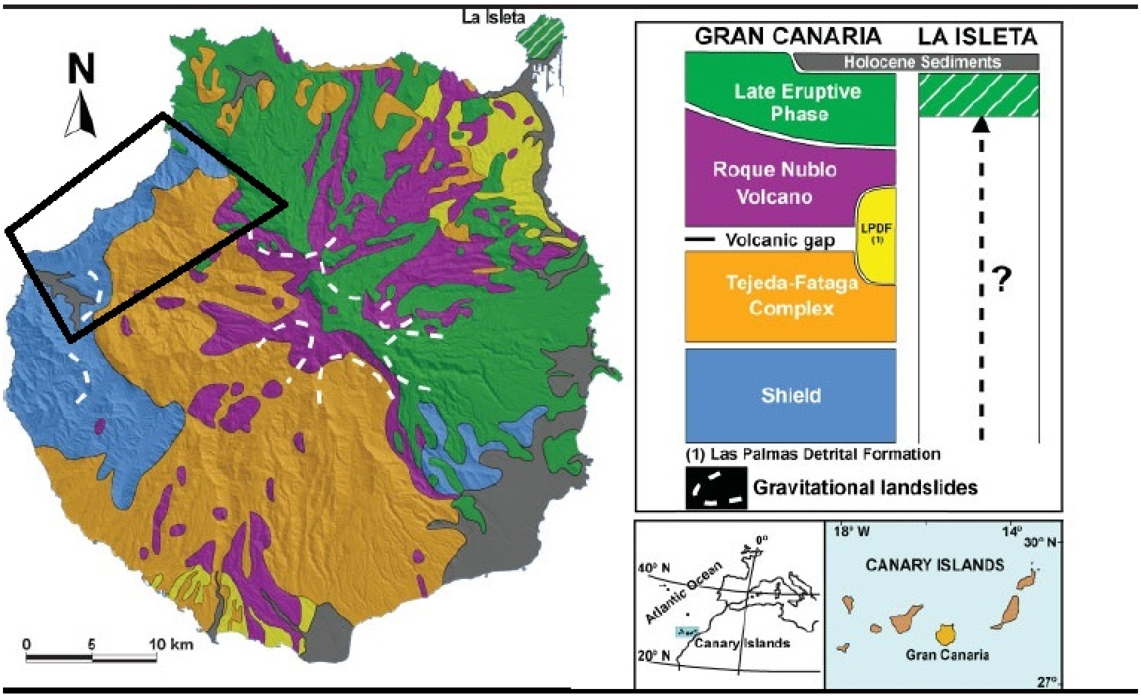

Figure 6: Simplified geological map of Gran Canaria, with the main volcanic phases and deposits (Rodríguez-González et al., 2009). Massive flank failures are indicated.

2.3 Frequency of rockfalls

The first pilot-site is located in the GC-200 road. A total of 7811 historical rockfall events have been documented in the road during the last 6 years. The data of rockfalls events was assembled from observations and historical accounts by the Canarian CPAs. All the reports concentrate on events that affected GC-200 road and historical reports for each rockfall event were classified by size. Rockfall events are very frequent in this road, which can be divided into two main sections:

- From Agaete to El Risco, 13.380 km. Numerous rockfalls have been recorded in this section, and specifically between the PKs 10-11. Most of the rockfalls are small in volume (below 0.5 m^3) and very frequent (one event per week). During rainy and windy periods, rockfalls with a larger volume (over 50 m^3) usually occur, with an average of two significant events per year that cause the blockage of the road. Erosion control measures to maximize the slope stabilization have been carried out along the stretch, and wire netting over the road-cuttings helps to prevent rockfalls from bouncing outward.
- From El Risco to Aldea, 20.2 km. It is the most hazardous section where the largest rockfalls occur. Dynamic retaining walls and numerous steal wire-nettings have been installed in this section. Currently, and alternative route (with numerous tunnels) is going to be opened in the following months.

One of the goals of the present work is to carry out an updated rockfall inventory in the GC-200 road and to define accurately the location of each impact on the road by means of the orthophotos available in the region. In the present work, in a first stage, we have used the information and observations carried out by the Canarian CPAs. The information for each event includes the following data: (1) kilometer point (PK), (2) Number of events, (3) Date, (4) boulder size: big, medium, small and gravel. We have elaborated a data base including all these data.

For the inventory, we firstly selected the rockfall events occurred from January 2010 to March 2016 in the first 15 kilometers of the GC-200 road (the section from Agaete to El Risco) where a detailed inventory is available. Finally, rockfall inventory maps have been developed for different time-periods. Some examples in the section from Agaete to El Risco can be seen Figure 7 and Figure 8.

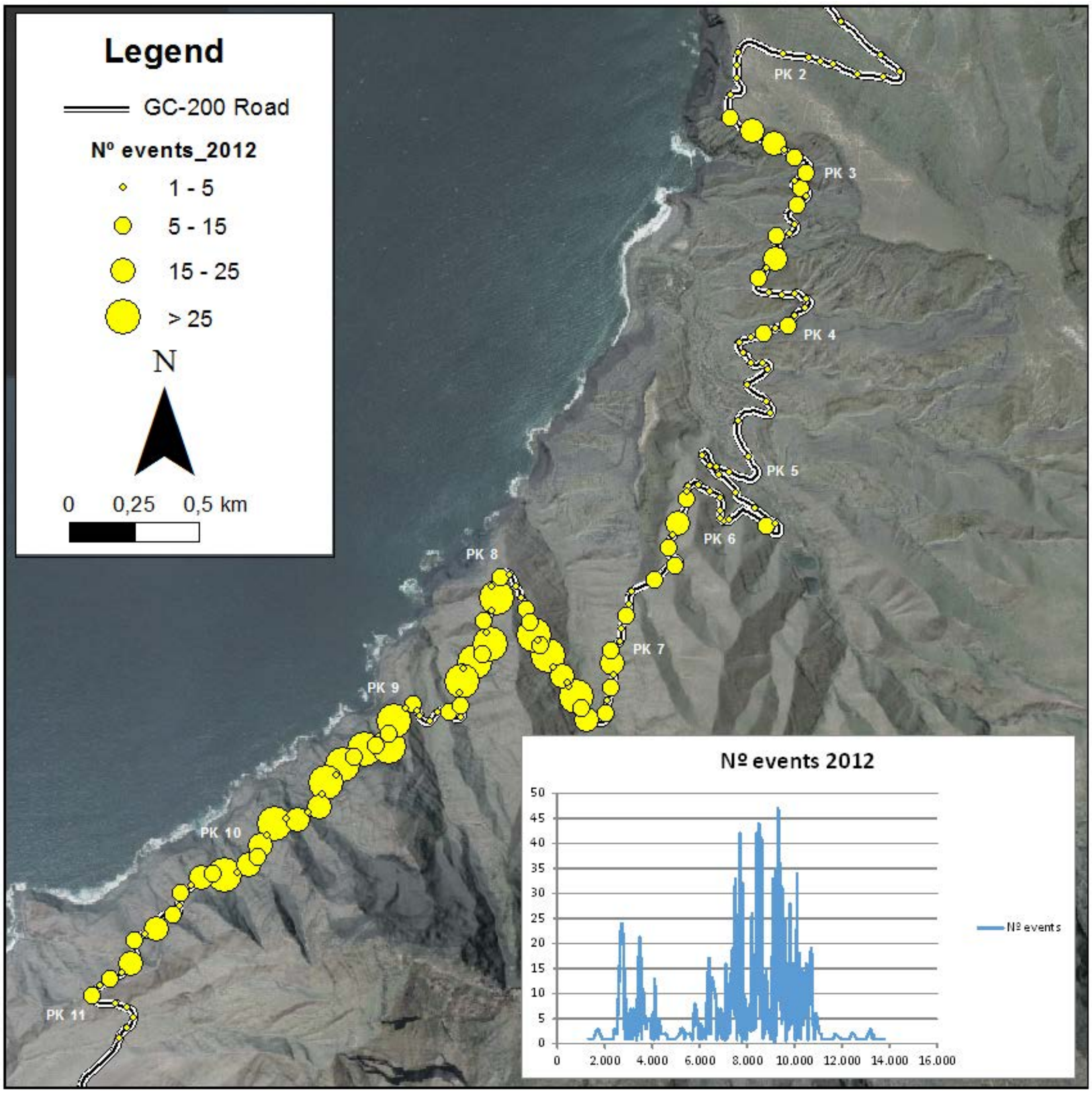

Figure 7: Number and location of impacts of the boulders. 2012.

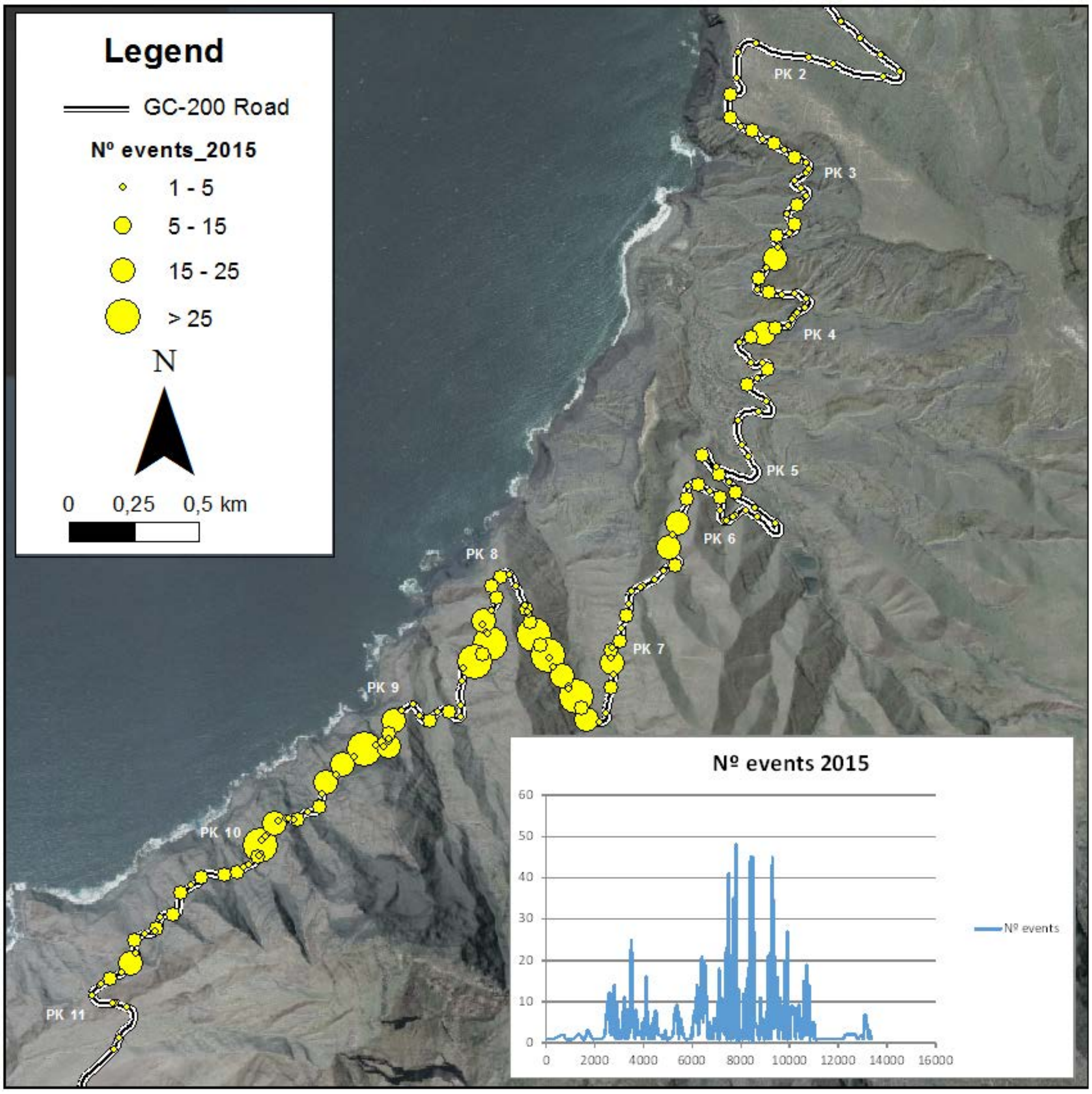

Figure 8: Number and location of impacts of the boulders. 2015.

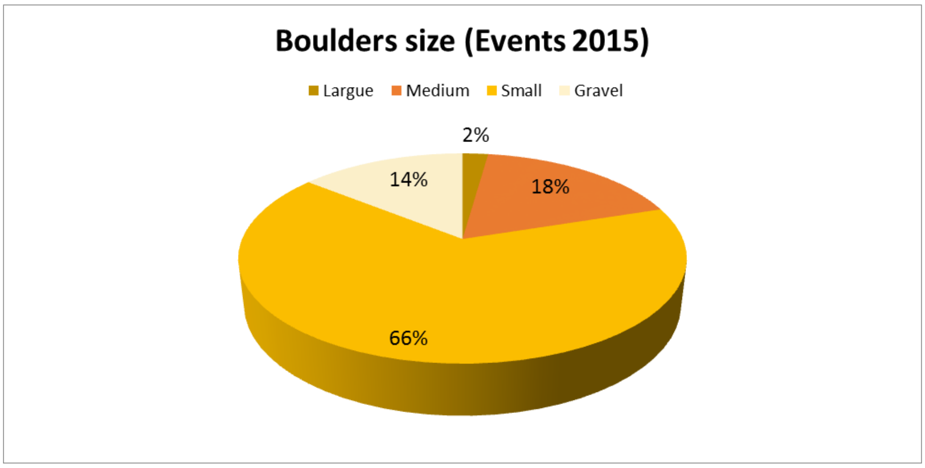

Figure 9: Boulder size. Events 2015.

3 STONE ROCKFALL SIMULATIONS FOR THE SUSCEPTIBILITY ASSESSMENT ALONG THE GC-200 ROAD (GRAN CANARIA)

3.1 Modelling software: STONE

To assess rockfall susceptibility along GC-200, we applied the STONE software. It is a physically based software capable of modelling rockfall processes in three dimensions (3D), and of providing relevant information to rockfall events. STONE is described in detail in Guzzetti et al. (2002a). The software uses a lumped mass approach to simulate the falling of a boulder along topography described by a Digital Elevation Model (DEM). The falling boulder is considered dimensionless (i.e., a point) and a kinematic simulation of the rockfall process is performed.

STONE requires the following input data: (1) the known location of the source areas of the rockfalls, (2) the number of boulders falling from each detachment area, (3) the starting velocity and the horizontal starting angle for each rockfall, (4) a velocity threshold below which the boulder stops, (5) a digital elevation model to describe the topography, and (6) the coefficients of dynamic rolling friction, and of normal and tangential energy restitution to simulate the loss of energy when rolling and at impact points.

STONE differs from other rockfall simulation computer programs in two ways: (a) topography is provided by a DEM, and not as pre-defined slope profiles, and (b) values for the coefficients are provided in a spatially distributed (i.e. geographical) form. As a result, the outputs produced by STONE are also spatially distributed.

The software computes 3-D rockfall trajectories and produces raster maps of the same size and resolution of the input grids showing the kinematics (velocity and height) and frequency of rockfalls. In particular, STONE produces for each DEM cell: (1) the cumulative count of rockfall trajectories that passed through the cell, (2) the maximum computed velocity, and (3) the largest flying height (distance above the ground) computed along all of the rockfall trajectories. In this way, STONE can model three of the four states that a rockfall can show, namely: the free fall of a boulder along parabolic trajectories, the impact of the boulder with the ground and the subsequent rebound, and the rolling of a boulder along the slope. Sliding is not modelled because it is considered as negligible part of the rockfall movement process.

The map results is a proxy for the probability of occurrence of rockfalls and shows the maximum computed rockfall velocity and the maximum computed flying height, both outputs provide information on the (maximum) expected intensity of a rockfall. For the rockfall simulation carried out along GC-200, only the rockfall-counts map was used.

3.2 Inputs data

3.2.1 Digital elevation model (DEM)

The input digital elevation model (DEM) was generated by the National Geographic Institute (www.ign.es) at a 5m x 5m resolution under the Spanish National Plan of Aerial Orthography and LiDAR (http://www.ign.es/ign/main/index.do) (Figure 10). Derived datasets: aspect and slope maps are also available.

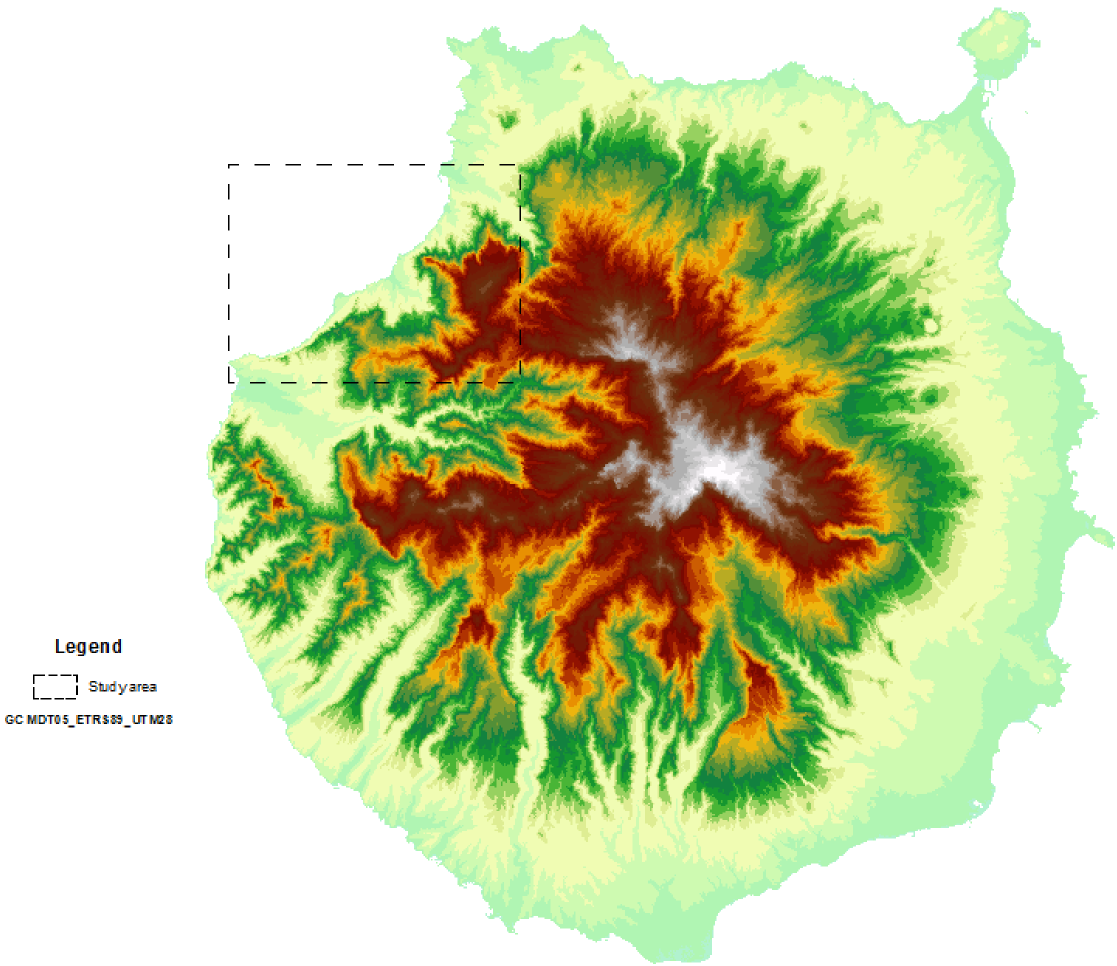

Figure 10: DEM (elevation in meters).

3.2.2 *Source areas*

Delimiting the rockfall source areas could be a difficult task. In the present study, we have considered all slopes above 40º as source areas for the modeling (Figure 11). According to several studies (Houtian, H., 1989; Look, B. G., 2014) 75 % of rockfalls happened on steep slopes with a grade greater than 45°. To carry out a most reliable approach in the future, we are going to meticulously delimit the source areas by means of a field campaign along the region.

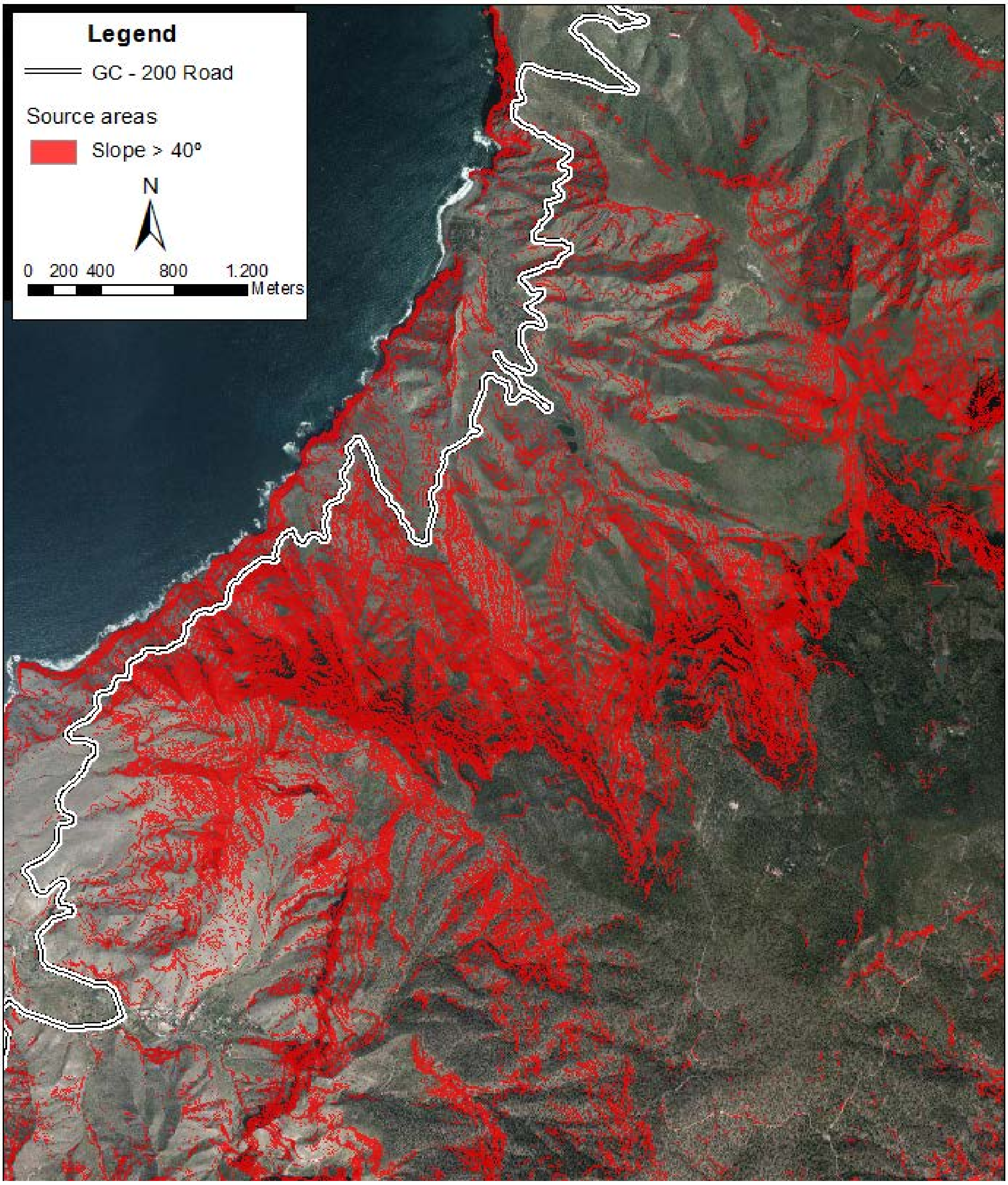

Figure 11: Source areas. Slope > 40.

3.2.3 *Lithological units parameters*

The accuracy of rockfall trajectory simulations depends on numerous factors, which include the estimation of the interaction between the ground and the rockfall that affects the behavior of the blocks at the impacts, rebound, rolling and sliding movement. At the impact point, the normal and tangential components of the block velocity are reduced by means of restitution coefficients that take into account the dissipation of energy due to inelastic deformations. Additionally, most of the numerical approaches for rockfall analysis consider coefficients of dynamic rolling friction. For this, coefficients of restitution and dynamic rolling friction are considered critical parameters in rockfall modelling, and their correct identification determines the accuracy of the simulation and its reliability. These parameters are directly related to the outcropping lithology and they will be determined and calibrated in the field.

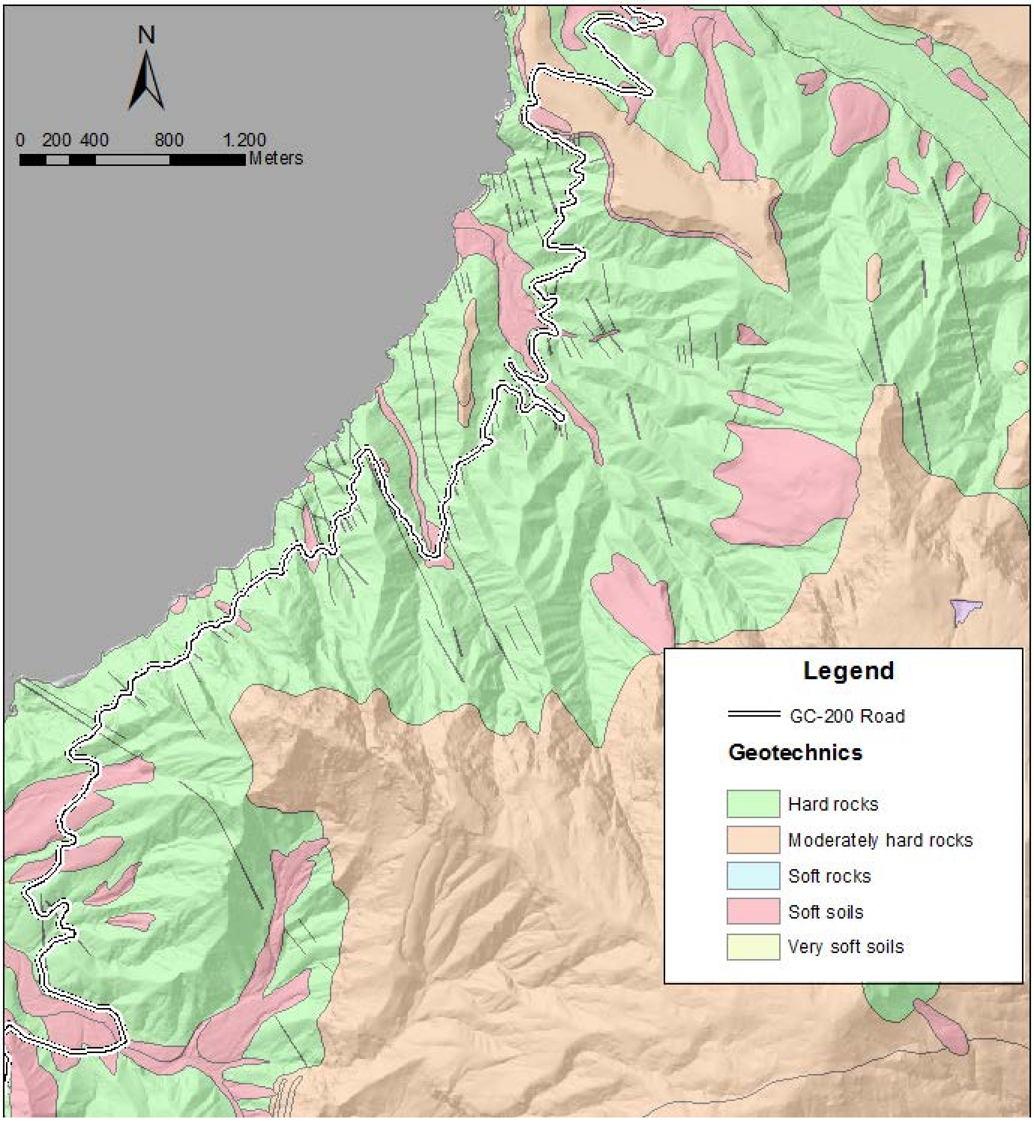

Figure 12: Geotechnical map.

According to the available National Geological Continuous Map of Spain (GEODE) from IGME (www.igme.es), at a 1:50.000 scale, three geotechnical units have been differentiated which include all lithologies outcropping in the area: (1) hard rocks, (2) moderately hard rocks, and (3) soft soils. Therefore, the friction and restitution parameters used for the present simulations were obtained from the literature (Guzzetti et al. 2002; Sarro et al. 2014) and from our own experience in other regions (Mateos et al., 2015). In future SAFETY works, we are going to better calibrate these parameters in the study area.

Geotechnical classification	Rolling friction	Normal restitution	Tangential restitution
Hard rocks	0,40	65	78
Moderately hard rocks	0,50	58	68
Soft soils	0,60	53	56

Table 2: Input parameters for the lithological groups identified in the study area.

3.3 Rockfall simulation

To simulate rockfalls we have employed the STONE software. The input data were previously described. Results can be seen in Figure 13 and Figure 14. Each cell is color-coded corresponding to the number of rockfall trajectories that pass through the cell (CNT).

Comparison of the map of rockfall counts obtained by STONE with the known location of the impact points of historical rockfalls in the road during the last 6 years, confirmed that STONE provided a reasonable preliminary spatial representation for the potential extent of rockfalls along the GC-200 road. Thus, the count map provides the percentage of trajectories that cross each cell of the grid (CNT). In the study area the highest density of trajectories is located in between the PKs 7 and 9 km, where high densities of rockfall events can be identified (Zone A). However, between the PKs 9 and 11 km have also been observed high densities (Zone B). Overall, the numbers of trajectories are in agreement with the information and observations carried out by the Canarian CPAs.

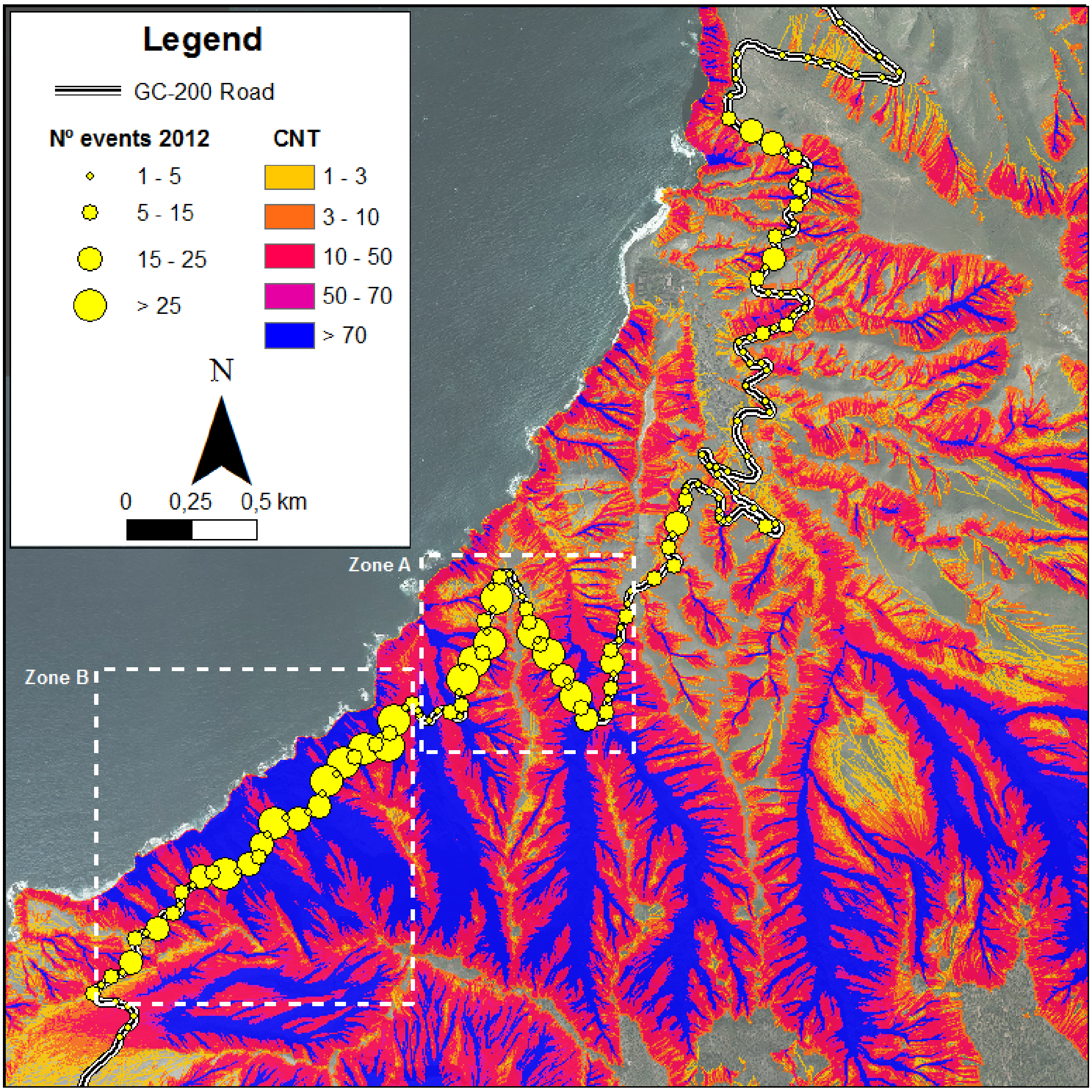

Figure 13: Comparison between the rockfalls identified in 2012 and the simulated rockfall map.

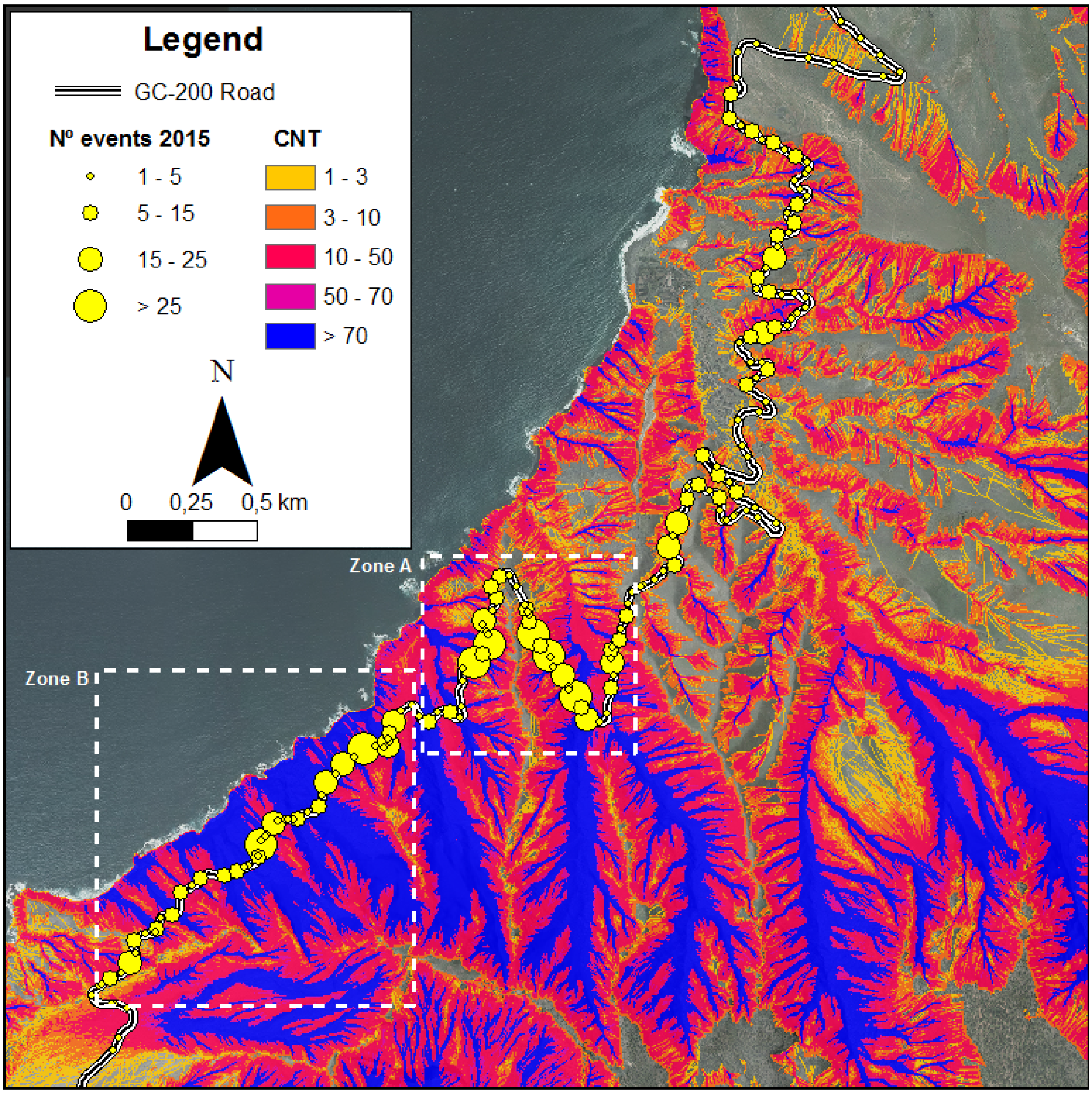

Figure 14: Comparison between the rockfalls identified in 2015 and the simulated rockfall map.

The validation to determine the accuracy of the simulation has been carried out considering the STONE trajectories which run into the rockfall impact areas (PK) along the GC-200 road and analyzing the percentage of cells of the total ones per each rockfall event with STONE rockfall trajectories output.

In order to quantify the matching/mismatching between the rockfalls identified and the modelled rockfall maps, the method applied has carried out the number of trajectories cells run into the rockfall inventory areas. The location of each impact on the road is defined by the rockfall inventory in the GC-200 road. The information for each rockfall includes data such as kilometer point (PK) and number of events. In this sense, several rockfall can be occurred in the same point. A validation was performed by analyzing the distribution of the number of count cells overlapping the kilometer points (PK) defined. The analysis was applied to all rockfall events documented in the road during the last 6 years, calculating the percentage of STONE rockfall trajectories that cross rockfall inventory areas as well as the percentage of the rockfall inventory areas within STONE outputs. For each rockfall, the percentage of cells run out of the total ones is quantified. We can observe that simulations fit quite well the area of the rockfall inventory map and the correlation is very good for the cells where numerous rockfall trajectories are expected. Figure 15 compares the number of identified rockfall areas coinciding with count cells and the number of areas without count cells, occurred each year. We can conclude that we have over 85% in success for all the periods.

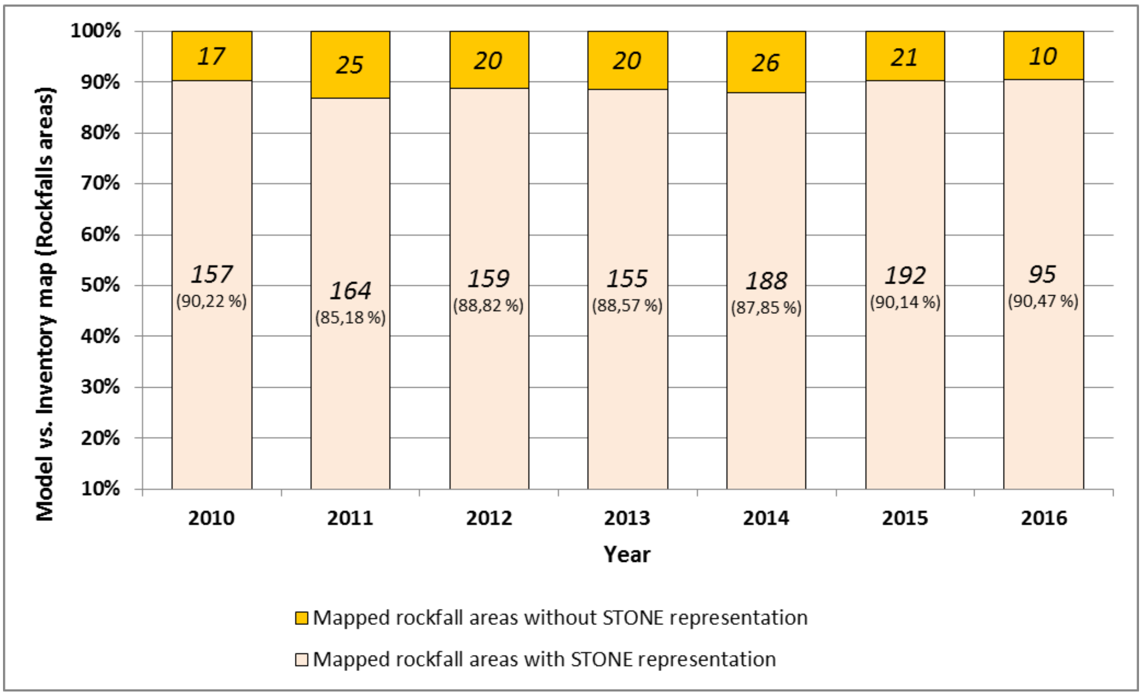

Figure 15: Model vs. Inventory map (Rockfalls areas).

Additionally, a second approach has been performed for this work, comparing the mapped rockfalls and the simulated rockfalls, in other words considering the percentage of cells of the total ones per each rockfall event with trajectories obtained by STONE (Figure 16). The analysis has been applied to the 7811 rockfalls inventoried, calculating the percentage of cells covered by the STONE rockfall trajectories as well as the percentage of the rockfall events identified in GC-200 road within STONE outputs. Thus, histogram shows the mapped rockfall events with and without STONE representation for each year. The percentage of success is greater than in the previous validation-test, for all the time-periods we obtain a success over 91%.

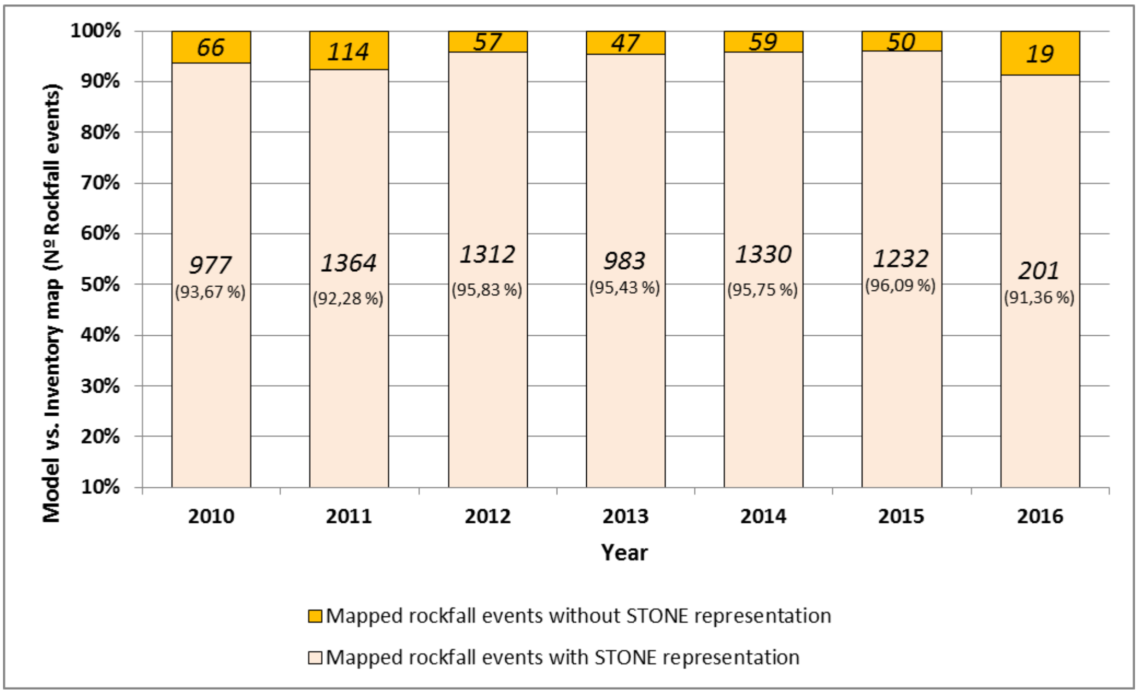

Figure 16: Model vs. Inventory map (Nº rockfalls events)

During 2015, 15 rockfalls with large size has been selected and the validation carried out in the GC-200 road shows that 11 (73.33%) of them are included in the map of rockfall counts obtained by STONE.

4 CONCLUSIONS

In the present work, a rockfall susceptibility analysis has been carried out along the GC-200 road (Gran Canaria) by applying STONE rockfall simulations and developing a detailed rockfall inventory and data base. The preliminary results have provided support for the following conclusions:

1. A detailed representation of the topographic surface (DEM) is required to successfully model rockfalls.
2. Only the cells of the slope with values over 40º have been considered as source areas. We need to carry out a detailed analysis (field supporting) of sources areas in future SAFETY works.
3. The friction and restitution parameters used in the simulations were obtained by recording a combination from the literature and our own experience in other regions. We need to better calibrate them in future SAFETY works.
4. According to the preliminary simulation results, the travel paths and the depositional areas are successfully approached through numerical modelling. The main susceptibility rockfall areas are located between the PKs 7 and 9 km, and specifically between the PK 9 and 11, where high densities of rockfall trajectories have been recorded.

In conclusion, rockfall susceptibility zonation based on the results of the STONE simulation shows a good preliminary correlation between simulated rockfall trajectories and the updated rockfall events inventoried along the GC-200 road. Nevertheless, we need to improve some input data for better results in the study area.

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