Catastrophic flooding caused by a mudflow in the urban area of Copiapó (Atacama Desert, northern Chile)

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Abstract: During the extraordinary hydro-meteorological event that occurred in March 2015 between Tuesday 24 and Thursday 26 more than 50 mm of rain fall in the Atacama Desert (Chile) between 22º and 32º S and a maximum range of 50 to 90 mm fell between 26º-29º S (Atacama Region). These intense rains caused flashfloods in 17 ravines of this region that affected more 7 municipalities. The most extensive damage occurred in the cities of Chañaral and Copiapó. The city of Copiapó (~160,000 inhabitants) is the administrative capital of this Chilean Region and it is located at the confluence between Quebrada Paipote and Copiapó River. The run-off generated in the 3 upper subbasins of the Copiapó watershed (18,400 km^2) was stored at the Lautaro dam. However, Quebrada Paipote subbasin (6,600 km^2) that also drains the Andes Cordillera has its junction with the river further downstream. This tributary is dry under normal climatic conditions but during this event a large volume of water mixed with fine sediments arrived to the Copiapó River at its confluence where the city of Copiapó is located. This process involved very rapid surging flow (2.5 - 5.5 m/s) that carried on a huge volume of sand, clay and silt transported by high density and viscosity flows that buried the city under a 31 cm mean thick layer of massive sandy mud. Although in other ravines debris flow occurred, neither Quebrada Paipote nor the Copiapó River transported large boulders. Mudflows are characterized by their transport capacity and the main problem they caused in urban areas is the accumulation of the sediment they transport once the energy decreases. A total area of 12.2 km^2 was flooded what corresponds to the 72% of the urban area of Copiapó. Four sectors of the city had flood heights higher than 2 m with a maximum measurement of 3.8 m close to the confluence of Quebrada Paipote and a mean flood height of 45 cm across the city. The estimated volume of accumulated sediment in the city is 2.2 million m^3 that infilled houses, sewerage, etc. This event highlights the need of developing accurate hazards maps that combined with vulnerability analysis of the population and the infrastructures makes possible to evaluate the risk of flooding in the city as well as the direct and indirect impacts caused by this process.

Keywords: mudflow, rainfall extreme event, urban flood, Copiapó, Atacama Desert

1. Introduction

Floods leading to mudflows and debris-flows are a global hazard particularly in high relief areas of the world. In arid Central Andes, characterized by a young relief, abrupt topography and high slopes, intense rainfall is the main trigger of these processes in lower altitude regions (Moreiras and Sepúlveda, 2013). Rainfall in the Atacama Region (26º-29º S; Figure 1) varies with topography due to orographic effects (Valdés-Pineda et al., 2014) and even though the whole Atacama Desert experiences a hyper-arid climate at elevations between sea level and 3500 m (Houston and Hartley, 2003) a few perennial rivers exist such as Copiapó River (CR). Mean annual precipitation declines from over 300 mm/year at 5000 m.a.sl. to less than 20 mm/year at 2300 m.a.s.l. and to less than 1 mm/year at sea level (Houston, 2006). El Niño Southern Oscillation (ENSO) has been directly linked to above-average river flows and other major landslide hazards although extreme precipitation processes leading to debris and mud flows are still poorly understood (Sepúlveda et al., 2015).

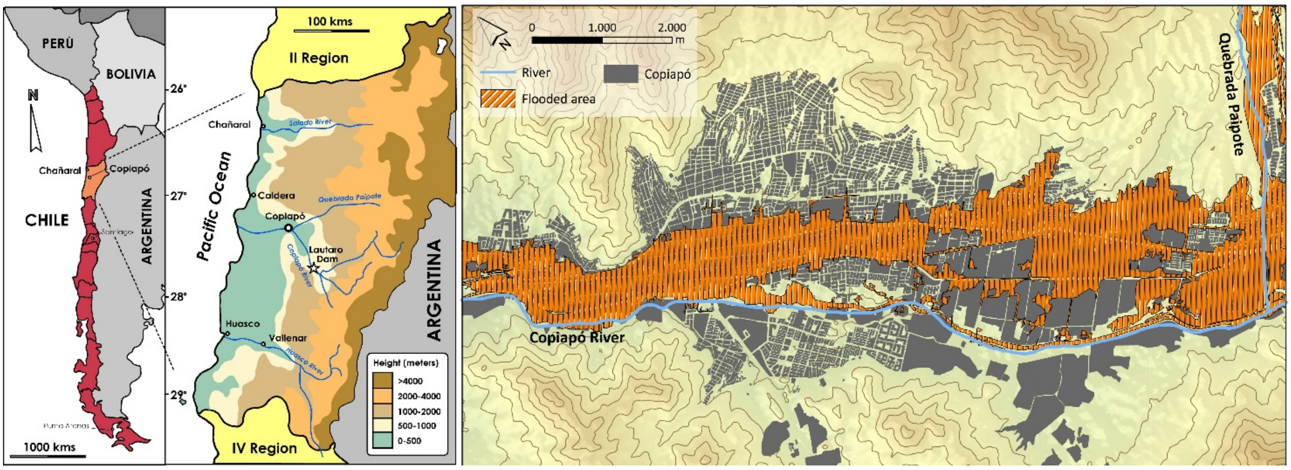

Figure 1 – Location of the city of Copiapó in the Copiapó River (CR) watershed, Atacama Region; and mapped flooded area inside the urban area

During the extraordinary hydro-meteorological event that occurred in March 2015, between Tuesday 24 and Thursday 26, a cold upper-level low located at 30ºS, 75ºW while another low pressure zone at a lower height brought warm and humid air form the tropical Pacific to northern Chile (Jordan et al., 2015). Reported rainfall varied from 10 mm at the coast to >85 mm in the eastern mountains and a maximum range of 50 to 90 mm fell in the Atacama Region. These intense rains caused flashfloods in 17 ravines, locally known as "quebradas", of the Atacama Region that affected 7 municipalities. The most extensive damage occurred in the cities of Chañaral and Copiapó (Figure 2).

The city of Copiapó (~160,000 inhabitants) is the administrative capital of this Chilean Region and it is located at the confluence between Quebrada Paipote (QP) and Copiapó River (CR), in its alluvial plain. In this sector, the main geoforms that appear isolated and elevated in the landscape are the alluvial fans and fluvial terraces that record the origin of the present fluvial drainage and the uplifting of surrounding relief during the Upper Neogene. In areas attached to the present river channel, the fluvial staircase terraces constituted the most recent geomorphologic units. Their deposits are formed mainly by mudstones and aeolian sandstones, with less abundant fluvial conglomerates, that record long periods of alluvial inactivity accompanied by the development of dunes, several times broken by flooding and mass wasting processes. Due to its geomorphological location the study area is affected by mudflow events and the city has been flooded several times during the 19th and 20th century being those of 1888, 1917, 1987 and 1997, among the worse (Partarrieu and Parra, 2009). Rainfall episodes are very scarce and no return periods have been estimated as the few rain gauges in the Region have short time series records (no longer than 30 years). However, based on the historical record, a rain episode triggering a mudflow event occurs approximately every 20-30 years.

The CR presents a regime fed by both snow and precipitation and its mean discharge during the 1974 – 2005 time series was 2.4 m^3/s. The last 10 years the river has carried no water as it passes through Copiapó due to its consumption for essentially agricultural uses upstream. Its watershed (18,400 km^2) can be subdivided into 3 zones: (1) the upper course watershed (7,412 km^2) formed by 3 different subbasins (Jorquera, Manflas and Pulido) that join at the Lautaro dam (40 Hm^3); (2) the middle course watershed formed by 2 subbasins that join at Copiapó, middle CR subbasin (2,943 km^2) and QP subbasin (6,689 km^2); and (3) the lower course watershed where no other main affluent appear (1,356 km^2) (Figure 1). Most of the run-off generated in March 2015 in the upper course watershed was stored at the Lautaro dam. However, QP subbasin, that is dry under normal climatic conditions, drains also the Andes Range and during this event a large volume of water mixed with fine sediments arrived to its mouth, at Copiapó. During the March 25 event, a maximum peak discharge for the CR has been inferred before its confluence with QP in ~110 m^3/s and after in ~600 m^3/s (Naranjo and Olea, 2015).

The aim of this research is to reconstruct the catastrophic mudflows that occurred in March 2015 in Copiapó and to understand its causes in order to integrate this information in the future development of flood hazard maps for the urban area of this city.

2. Methodology

A field survey was carried out during the weeks after the mudflow, once it was possible to walk along the streets of the city, focused on two objectives: (1) the temporal reconstruction of the mudflow; and (2) water and sediment height measurements (Figure 3). A total of 291 measurement point were survey and were gathered into a Geographic Information System (GIS) that allow us identifying the water movement along the city streets, to calculate the affected area, mean water and sediment height as well as the volume of sediment accumulated in the city. Finally, using video recorded during the flood peak is has been possible to estimate the maximum water velocity in different points of the city.

Figure 2 – The streets of Copiapó flooded during Maarch 2015

Figure 3 – Example of a water and mud height measurement point

3. Results and discussion

According to the gathered information from witnesses, the rain that fell on Tuesday 24 did not cause any damage in the city. The generated runoff on the CR was enough to increase its discharge and surface water started flowing along the river channel after many years, it arrived to the city by that evening. Little runoff was generated on the ravines surrounding the urban area after this first day of rainfall. The following day, Wednesday 25, a higher amount of rain fell and as the arid soils had reached their field capacity with the previous day rainfall, net precipitation increased. This increase in the CR runoff caused bankfull floods along the main channel at some points upstream Copiapó. However, surface water did not only arrive to Copiapó along CR but runoff also started to happen in QP. This usually dry ravine was at that moment highly anthropized and it was used as an illegal dumping site. The washed away materials obstructed the culvert that allows QP join CR in the early morning of Wednesday 25. As water was not able to reach the river channel it found two new paths along the two main streets that go parallel to the river across the city.

This process involved very rapid surging flow (2.5 - 5.5 m/s) that carried on a huge volume of sand and mud transported by high density and viscosity mudflows. A total area of 12.2 km^2 was flooded what corresponds to the 72% of the urban area of Copiapó (Figure 4a). Four sectors of the city had flood heights higher than 2 m, with a maximum measurement of 3.8 m close to the confluence of QP, and a mean flood height of 45 cm across the city. The easternmost area presents those high heights as a consequence of the channel obstruction by anthropic materials that acted as a dam. The two areas inside the city with flood heights higher than 1 m are located along the main street water make its new channel. Finally, the westernmost affected area is where the main "channel street" and the CR meets. This area coincides with the historic centre of the city and it was where the CR had its worst flood as along the rest of the city it kept inside its channel (Figure 4a).

The mudflow buried the city under a 31 cm mean thick layer of massive sandy mud. Although in other ravines debrisflow in the Andes Range occurred, neither QP nor the CR transported large boulders. Maximum mud heights are found in the same areas of maximum water height as the sediment was transported mix with the water in a single phase (Figure 4b). The estimated volume of accumulated deposit in the city is 2.2 million m^3 that infilled houses, sewerage, etc.

The consequences of this catastrophic event in the region of Atacama caused the death of 31 people, 16 people are still missing and more than 35,000 people affected. In addition, about 2,000 houses were completely destroyed and more than 15,000 had damages. In Copiapó, more than 160,000 m of the sewerage system were collapsed and over 50% of the houses were under sanitary sewer overflow conditions (Atacama Regional Government). Water was still running through the streets more than 2 weeks later and the city was almost paralyzed for a month what had an economic impact of more than 44 million €.

In the last two decades, only during June 1997 the city of Copiapó has undergone flooding although under very different meteorological conditions. This event resulted in a flooding of the urban area caused by mud and debrisflows from the ravines surrounding the city. In that occasion, the eastern sector was not affected while the northern area, not affected during this studied event, was severely damaged. On the other hand, the westernmost sector was importantly impacted in both events as, again, water flowing along the streets met CR in this area (Garrido, 1998).

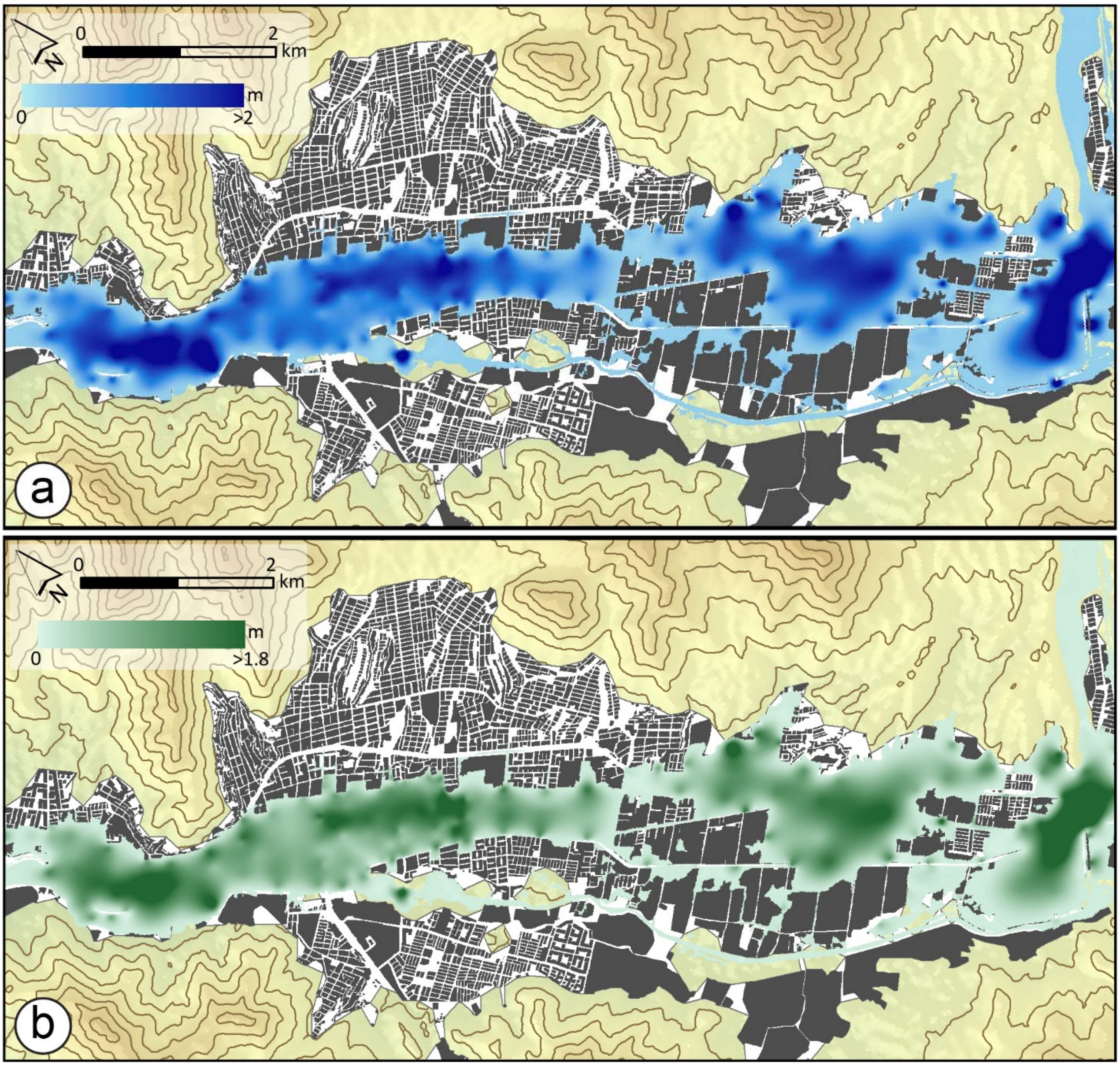

Figure 4 – a) Maximum water height map during the March 25 event in the city of Copiapó; b) Maximum mud height during the March 25 event in the city of Copiapó

With a return period of approximately 20-30 years catastrophic flooding in this area of the Atacama Desert are a major hazard to the city of Copiapó. In order to decrease the risk two main variables are possible to considered, hazard and vulnerability. The development of an accurate flood hazard map will help identifying those areas with the highest probability of flooding and, if possible propose hydraulic solutions, and those where shelters can be stablished. On the other hand, vulnerability can be reduced not only by improving the engineering methods but also by means of education. As suggested by Bodoque et al. (2016), social risk perception and awareness should be included in emergency management plans, especially in urban areas prone to flash-floods where response times are limited.

4. Conclusions

Urban areas located in alluvial plains under hyper arid climatic conditions are exposed to destructive flood and mass flow processes intensified by a false security perception of the population due to their high return period and the uncontrolled city growth and expansion. The March 25 event highlights the need of developing accurate hazards maps that combined with vulnerability analysis of the population and the infrastructures makes possible to evaluate the risk of flooding in the city as well as the direct and indirect impacts caused by highly destructive flash floods in hyper arid areas.

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