SPATIAL DISTRIBUTION OF DISASTERS CAUSED BY NATURAL HAZARDS IN THE SAMALA RIVER CATCHMENT, GUATEMALA

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Soto, A.J., Rodhe, A., Pohjola, V. and Boelhouwers, J., 2015. Spatial distribution of disasters caused by natural hazards in the Samala River catchment, Guatemala. *Geografiska Annaler: Series A, Physical Geography*, 97, 181–196. DOI:10.1111/geoa.12097

ABSTRACT. Understanding the conditions of the locations where disasters are reported and applying that knowledge to disaster risk reduction actions is essential and especially needed on the local scale. This study assessed how important the physical configuration is as cause of disasters by studying the links between the locations where disasters have been reported and the physical attributes of those locations. The Samala River catchment in Guatemala was used as a case study because it is a relatively small but complex area exposed to multiple natural hazards. Disasters of hydrometeorological origin were addressed for the study because they are the most frequent type of disasters reported in the area. The method proposed in this work classified the study area into geomorphological units that were used to analyze where disasters were reported, the physical conditions of the particular locations of disaster reports, and to what degree disasters are spatially linked to slope and temporally to precipitation. We found that analyzing the study area based on the geomorphological configuration was useful and allowed analyses on comparatively homogeneous zones and to hypothesize on the particular geomorphological processes related to the occurrences of disasters. For steep geomorphological units we found a clear spatial relationship between the number of disasters reported and the slope of the locations, with higher frequency of disasters in the less sloping areas of the unit. The need to consider social factors for understanding this relationship was emphasized. As expected there was a very strong temporal relationship between disaster occurrence and wetness, as estimated from the antecedent rainfall, with high risk for disaster at high wetness. The applied methodological approach provides a tool for disaster research on physically complex areas, which is common to active tectonic and volcanic regions.

Key words: spatial distribution, natural disasters, physical causes of natural disasters, Guatemala

Introduction

Natural disasters, i.e. disasters caused by natural hazards, are place dependent and research on such disasters is thus closely linked to the geographical location. Understanding the physical and social conditions on the local level where natural disasters occur is important to plan for disaster reduction.

Research on disaster and disaster risk has developed greatly over time. Today, the combination of natural and social settings is recognized as important to fully understand and predict potential disasters. There has been a debate in the disaster community whether natural or social causes are the most important driver for natural disasters (Cannon 1993; Mileti 1999). To determine how much disasters depend on each part of that physical–social combination is a difficult matter because disasters are site specific (UNISDR 2009). Risk analysis is a quite common practice nowadays (Guarín *et al.* 2004; Tesliuc and Lindert 2004; UNISDR 2004; Sperling and Szekely 2005; Fernandez and Sanahuj 2012) and risk maps are often used to support actions for *disaster risk reduction* (*DRR*) (Zerger 2002; Viera Cepero 2003). Studies like these examples have been used to outline geographical areas exposed to natural hazards, to identify populations potentially threatened by natural hazards, and to prioritize areas where investments or DDR actions are needed.

Studies to support DRR are often focused nationally or regionally and may overlook singularities of the specific places that could lead to disasters. Studies on a local scale are therefore imperative, particularly in physically and socially complex areas. Guatemala is an interesting country

DOI:10.1111/geoa.12097

for studying DRR because it suffers from frequent disasters caused by hydrological, meteorological, and geological processes. Several studies have focused on the physical processes that create such risks (Kuenzi *et al*. 1979; Vallance *et al*. 1995; Viera Cepero 2003; Guarín *et al*. 2004; Chigna and León 2010; Chigna and Mota 2011) as well as the disasters that result from those processes (Gándara Gaborit 1990; Soto 2015).

Valuable efforts have been made in Guatemala to increase the understanding of disaster risk (CONRED 2009, 2011; CONRED, http://www.conred.gob.gt, 20 Jan., 2010) and to be part of the global development of disaster risk reduction efforts, as those promoted by the United Nations for example. As a part of the Guatemalan efforts, disaster risk maps are being produced, nets of knowledge exchange are being settled between national agencies (CONRED 2011; SEGEPLAN 2012), and campaigns focused on information and preparedness are sent to the population using media and social networks. The challenge pending is to make this initiative an integrated part in the planning in Guatemala, from the national to the local scale, with an emphasis on the local scale.

The purpose of this work is to assess how significant the physical configuration is as a potential cause of natural disasters, particularly those of hydro-meteorological origin, by investigating the links between the places where disasters have been reported and the physical attributes of those places.

The Samala River catchment in Guatemala was selected as a case study. It is a relatively small, but highly complex area, both physically and socially, in a geographical location exposed to multiple natural hazards making it highly sensitive to disasters (Alcántara-Ayala 2002; Harmeling and Eckstein 2012), especially disasters with hydro-meteorological causes (Soto 2015). In this catchment a population of almost 1 million is frequently exposed to disruptions affecting its life quality and development potential. By this, we find the Samala River catchment to be an interesting case to test what relations physical and social parameters play on influencing natural disasters. Our study is focused on disasters of hydro-meteorological origin because they are the most frequent types of disasters reported in the area and the ones that affect most people (Soto 2015). This work is a step on the path to do a full comparative study on physical and social causes of natural disasters, and here we will focus on the physical factors, i.e. natural hazards.

There are several definitions of natural disaster in the literature (Perry 1989, 2007; Alexander 1993; Dynes 1998; Quarantelli 1998; Jigyasu 2005; Perry and Quarantelli 2005). A natural hazard, which is a potentially dangerous natural phenomenon, may cause a disaster if it affects a social system (UNISDR 2009). The United Nations Office for Disaster Risk Reduction defines a disaster as a hazard intersecting with a vulnerable social system producing negative outcomes such as damage to life or property in a way that the social functions are modified from their normal conditions (UNISDR 2009). Although there is a strong social aspect on the definition of disasters, the present study is limited to the physical factors behind disasters. Social factors will be analyzed in a forthcoming paper.

The word ‘natural’ is used here to design disasters which are caused by natural hazards, but the term does not exclude anthropogenic causes intervening on the natural hazards leading to the natural disaster. The natural processes creating the hazard might have been triggered by human activities. A certain weather condition could, for instance, be harmless before man’s intervention but cause landslides or flooding after forest clear cutting. Disasters are by definition related to human activities. If people were not living in the area affected by a natural hazard, there would have been no disaster.

Specific aims of this study are to perform a geomorphological classification of the study area as a basis for analysis of where disasters occur, to assign geomorphological conditions to the particular locations where disasters have been reported, and to analyze to what degree disasters are spatially linked to slope and temporally linked to precipitation.

Study area

The Samala River catchment (N 14° 10′–15° 3′, W 91° 17′–91° 53′) is located in Guatemala and drains to the Pacific Ocean (Fig. 1). The area is 1500 km^2 and the catchment has an elongated shape with elevations from 0 to 3773 m a.s.l. Guatemala is located at the convergence of the Cocos plate with the North American and Caribbean plates and this geologic situation and history has given the basic background to the geological and geomorphological processes that are active in the area today.

The geological history is in short explained by the tectonic processes building the Central American isthmus and the volcanic cordillera that divides

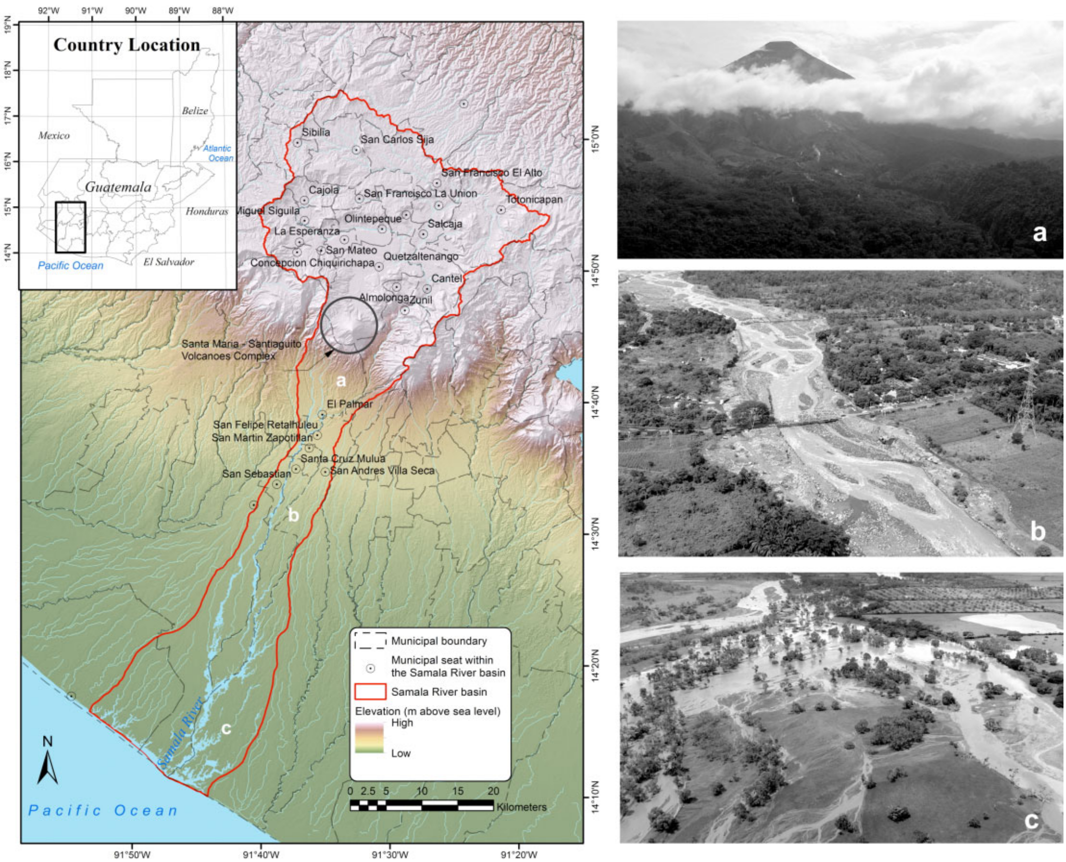

Fig. 1. Samala River catchment. The map shows the shape of the catchment, the relief, the drainage net, and the location of the volcano complex. White letters identify the locations of the photographs on the right. The top-left insert shows the location of the catchment in the country. (a) The volcano complex and the meandering section of the river, (b) the beginning and the (c) end of the depositional plain. Photographs source: CONRED (2010). Map base shapefiles source: Segeplan (2012).

the highlands at the north of the catchment from the alluvial fan and coastal plain at the south. The main volcanic landform in the area is the Santa María volcano, which had a large eruption in October 1902. During this eruption the Santiaguito volcano formed as a feeder cone to Santa Maria. Santiaguito is an extrusive dacite dome complex. It is very active, usually with minor explosions that produce constant influx of volcanic material into the Samala River catchment (Kuenzi *et al*. 1979).

The climate of the study area is in general determined by the tropical location. The local climate is highly varied but due to the large elevation span, the climate spans from dry subtropical to wet montane conditions with annual mean temperatures ranging from 28 to 15°C and mean annual precipitations ranging from 1500 to 4000 mm (INSIVUMEH 2003). Rain usually falls intensely from May to October with rainfall peaks occurring when tropical storms pass the Central American region during the hurricane season (IARNA/URL/IIA 2004). The topographical drivers, the abundance of loose material through the volcanic complex and the intense rain periods create conditions needed to develop a river system that starts in the highlands through a meandering phase. When the Samala River cuts the volcanic range through a steep sharp canyon, volcanic material is mobilized, and the river finally spreads out on a large alluvial fan downstream as a braided system on the coastal plain.

The transport of mineral-rich sediments by the Samala River creates favorable conditions for agriculture along the flood plain. Vegetation is diverse and only the volcanic flanks stay barren due to the constant deposition of new volcanic material. The unvegetated slopes combined with the seasonal precipitation create the potential for lahars (debris flows of volcanic loose material) that feed volcanic debris into the river. These lahars transport large volumes of loose material intermittently, and through the large input of sediments into the flood plain the river channel is forced to shift laterally. The shift of channels in the braiding process dramatically changes the conditions for habitation and infrastructure during flood conditions. The Samala River catchment is by this process dynamic by nature and potentially hazardous for human settlements.

Material and methods

Available data

Global disaster databases such as EMDAT (CRED 2009) could not be used, since they do not have the spatial resolution needed for this study. There are, however, two important databases for disasters in Guatemala: the Guatemalan *Coordination Office for Disaster Reduction* (*CONRED*) and the one of *Disaster Inventory System* (*DesInventar*). CONRED, established in 2008, collects the information through the members of the national system for disasters reduction that report the occurrences from the places where they take place. The local delegates of the institution then verify that the occurrence and the reported damage are valid in order to put them in the system for emergency and recovery attention. Most of the reports in the system have detailed location information and this makes CONRED the only dataset available that includes geographical coordinates or identifiable location references and it is therefore valuable despite its short time span. DesInventar comprises data since 1988. It collects the information mainly using local media reports on disasters that are later verified by comparing the information with official reports of disasters (such as CONRED) if available. The two databases have similar structure to collect the data but DesInventar comprises less detailed information of the disasters, for instance concerning location; its advantage is that it comprises the longest records available of disasters reported in Guatemala on a municipal scale. The purposes of the two databases are different. CONRED information is operative and used mainly for emergency attention and monitoring while DesInventar focuses on the aftermath of disasters. We used CONRED data from 2008 through 2011 (CONRED 2012) for spatial and temporal analyses of disaster occurrence. DesInventar data were used only for a final comparative analysis of the type of disasters reported in the study area.

Regarding the conceptual context of our study, we went over the definitions of disasters and the features potentially related to them in order to create the framework of our work. We took into account that differences on definitions and concepts exist at all scales when dealing with disasters (Guha-Sapir and Below 2002). We considered how local people described the events reported to grasp the content of the input data and define the terminology used in this study.

Meteorological information on rainfall from the Guatemalan *Institute of Seismology, Volcanology, Meteorology, and Hydrology* (*INSIVUMEH*) was used to analyze the precipitation in the study area. Three meteorological stations were identified in the area, one in the highlands (Labor Ovalle), one in the lowlands (Retalhuleu), and one in the steep slopes between them (Santiaguito). Only Retalhuleu has daily records of precipitation that cover the time span of the disaster databases. Considering the data availability and noting that the temporal variations were roughly similar for the three stations, although the absolute amount of precipitation differed strongly, we decided to use one station (Retalhuleu) as representative for the temporal variation of precipitation in the area. For the spatial analyses of this work we used geological and geographical maps, a 15 × 15 m DEM, and orthophotos of the study area from the Guatemalan geographical information system (SEGEPLAN 2012) to analyze the geological, geographical, and geomorphological characteristics of the area.

Geomorphological analysis

Profile graphs of DEMs and orthophoto imagery were used to visualize the general configuration of the landscape in the Samala River catchment and to identify the most outstanding physical features in it. The relief of the study area is complex and the area was subdivided into smaller areas with more homogeneous physical features and expected geomorphological processes. The principles of geomorphological classification of the Dutch International Institute for Aerial Survey and Earth Sciences ITC (Verstappen and van Zuidam 1975) were used to define these distinctive landscape units. The particularities of the physical configuration of the land were analyzed using ArcGIS in order to draw the boundaries between distinctive geomorphological units. The 15×15 m DEM was used in Esri ArcGIS to perform analysis of the relief and physical configuration of the area to define boundaries of the geomorphological units. Slope values were calculated using the cell elevations of the DEM. The slope values were aggregated creating areas of similar characteristics using the cluster by maximum likelihood ArcGIS tool. The resulting classes were revised and reclassified to define the areas that were mainly flat and those that were mainly steep. A second stage of this analysis used physiography and geology maps from the Guatemalan Geographical Atlas (MAGA, 2002) overlapped to identify important differences in the geological origin of soils.

The land cover of the volcanic slopes was analyzed using orthophotographs of the area. The presence of recently produced volcanic material was used to identify the boundary of the active volcanic area. The flanks of the volcanoes are steep and undulated, therefore runoff paths are determined by the relief of those flanks. ArcGIS hydrological tools were used to define water divides on the slopes of the volcanoes in order to draw the boundaries for water on the volcanic flanks. Once the different geomorphological units were defined, the most significant physical features of each were identified to characterize them and theorize on the potential types of disasters that could result there.

Links between reported disasters and local physical factors

The reported disasters were assigned values of the slope at the location using the geographical locations reported in CONRED database, and the number of disasters in different slope classes was counted. In a corresponding way each reported disaster was connected temporally to precipitation. This was made using a wetness index, I_{wet}, taking the rainfall of the day and also the rainfall of the preceding 9 days into consideration according to Eqn (1), where P is precipitation and the indices 1–10 denote day 0 to 9 before the rainfall.

$$I_{wet} = P_1 + 0.95P_2 + 0.85P_3 + 0.75P_4 + 0.65P_5 + 0.55P_6 + 0.45P_7 + 0.35P_8 + 0.25P_9 + 0.15P_{10} \quad (1)$$

The number of disasters occurring in different wetness classes was counted. This analysis, for slope and wetness, was made for the whole catchment and for each identified geomorphological unit within the catchment.

In order to analyze the link between reported disasters and physical factors, histograms showing the relative frequency distribution of disaster occurrence in different slope classes were compared with graphs showing the relative frequency distribution of slope within the units. For the temporal analysis of the link between wetness and disasters, histograms were prepared showing the relative frequency of disaster occurrence per wetness class and compared with graphs showing the relative frequency of wetness index over the disaster time series.

Histograms were also prepared by plotting the ratio between the relative frequency of reported disasters in each class and the relative frequency of slope, and histograms showing the number of disasters per day within the different wetness classes. These histograms show the relative probability distribution for disasters with respect to slope and the probability distribution for disasters with respect to wetness.

Finally the number of disasters reported by type of disaster in CONRED and DesInventar databases was graphed in percentages for each geomorphological unit to investigate how the type of hydrometeorological disasters varied among the geomorphological zones and also to determine how similar the depictions of the disasters were in the two datasets. Since DesInventar data have a municipal resolution, the number of disasters per zone was obtained by calculating the number of disasters of the municipalities completely or with significant percentage of its territory belonging to the zone in question. For this work and those municipalities partly outside the catchment 20% of the municipal territory within a geomorphological unit was considered significant.

Results

The complexity of the relief of the study area and the main features in it are seen in the longitudinal relief profile analysis (Fig. 2). Three main sections of the catchment were identified: the highlands, the lowlands, and the volcanic cordillera. The highlands consist of a valley behind the volcanic cordillera, surrounded by escarpments and an undulating plateau in the northernmost area. The lowlands consist of a transport zone (of mainly loose volcanic material) and a deposition zone, where an alluvial fan has been formed. The main feature in the volcanic cordillera is the Santa Maria volcano and the active Santiaguito dome complex.

A further subdivision of the catchment was performed in ArcGIS using relief as the main quality

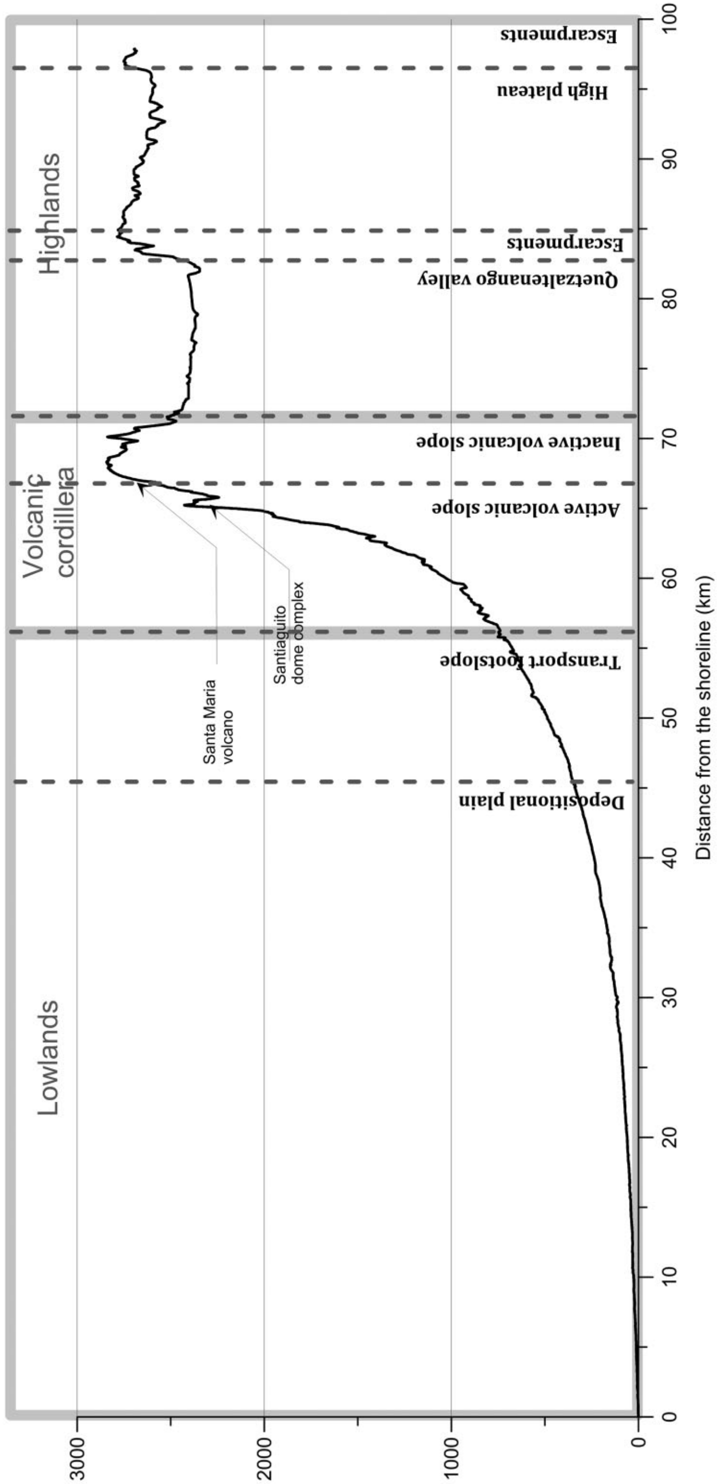

Fig. 2. Samala River catchment longitudinal profile and geomorphological units. Grey lines show the three general parts of the catchment. Dashed lines show the boundaries between the seven geographical units and the names given to the units are written with vertical text. Arrow pointers show the Santa María–Santiaguito complex location in the catchment.

for separation into distinctive zones because the relief determines how gravity works and water behaves in the study area. Physiography and geological data were used to separate areas with igneous origin from areas with metamorphic origin and between zones of transport and deposition of loose material. The subdivision process resulted in seven different geomorphological units (Figs 2 and 3) that are described and characterized in Table 1.

The geomorphological units are very different from each other. The complexity of the relief was evidenced in this characterization; although each unit was created by clustering its characteristics, the slope angles within them are not completely homogeneous. The High plateau, for example, is a high zone with moderate slopes but due to its undulating character it includes slopes up to 16°. The conditions are similar in all geomorphological units. Regarding the particular units, it can be seen that the units in the highlands are older, with moderate annual precipitation and generally without forest cover. The units in the lowlands are more recent, with high annual precipitation, and also without forest. The volcanic slopes, as well as the toeslope transport zone, are also recent, with more forest cover (except those areas where new material is deposited) and very high annual precipitation. The soil origin, topography, and land cover (Table 1) influence rates of infiltration and disposition to overland flow in the study area. These factors combined with precipitation determine the potential of high discharge and debris transportation in the Samala River and its confluents. Consequently, the above factors show the potential exposure of people to hydro-meteorological natural hazards, especially flood and debris flow. The lack of forest cover in the High plateau, in the Escarpments, and in the Quetzaltenango valley for instance, makes these units prone to rapid runoff. The slope and soil origin on the Active volcanic slopes, in combination with high precipitation, make these areas prone to erosion. These are the areas where the volcanic material produced by Santiaguito volcano is deposited, which is loose and easily transported downwards by water. The Inactive volcanic slopes are equally steep, but have older and more stable soils that have been covered with low density woods and crop fields making erosion less likely to occur. The lowlands, although without forest cover, are less likely to suffer from erosion because the low slope makes them a place for deposition of the transported material.

Table 1. Geomorphological units within the Samala River catchment and their characterization. The division of the geomorphologic al units is shown in Fig. 3.

Geomorphological unit	Geology		Geomorphology of the slopes		Climate		Vegetation cover of the land	Potential main disaster type
	Age	Soil origin	Predominant slope angle (°)	Elevation (m a.s.l.)	Mean annual temperature (°C)	Annual Precipitation (mm)		
High plateau	Quaternary	Pyroclastic rocks (ignimbrite) and fillings of pumice	4–16	2000–3000	12	1000	No forest cover	Debris flow
Escarpments	Tertiary (superior – pliocene)	Andesitic and basaltic rocks	10–27	2700–4000	12	1000	Woodland–cropland association	Debris flow
Quetzaltenango Valley	Tertiary superior to inferior Quaternary	Pyroclastic rocks (ignimbrite) and fillings of pumice	0–10	1800–2400	12–15	1500	No forest cover	Flood
Active volcanic slopes	Quaternary	Tephra and lava flows. Andesite and basalt	15–45	925–4000	15–20	3000	Woodland	Debris flow, ash flow
Inactive volcanic slopes	Tertiary (mio-pliocene)	Andesite, basalt and rhyolites	over 35	925–4000	15–20	3000	Woodland, and woodland-cropland association	Debris flow
Transport toeslope	Quaternary	Sedimentary rocks	0–10	500–925	20–25	3500	No forest cover	Flood
Depositional plain	Quaternary	Sedimentary rocks	0–4	0–500	25–27	1500	No forest cover	Flood

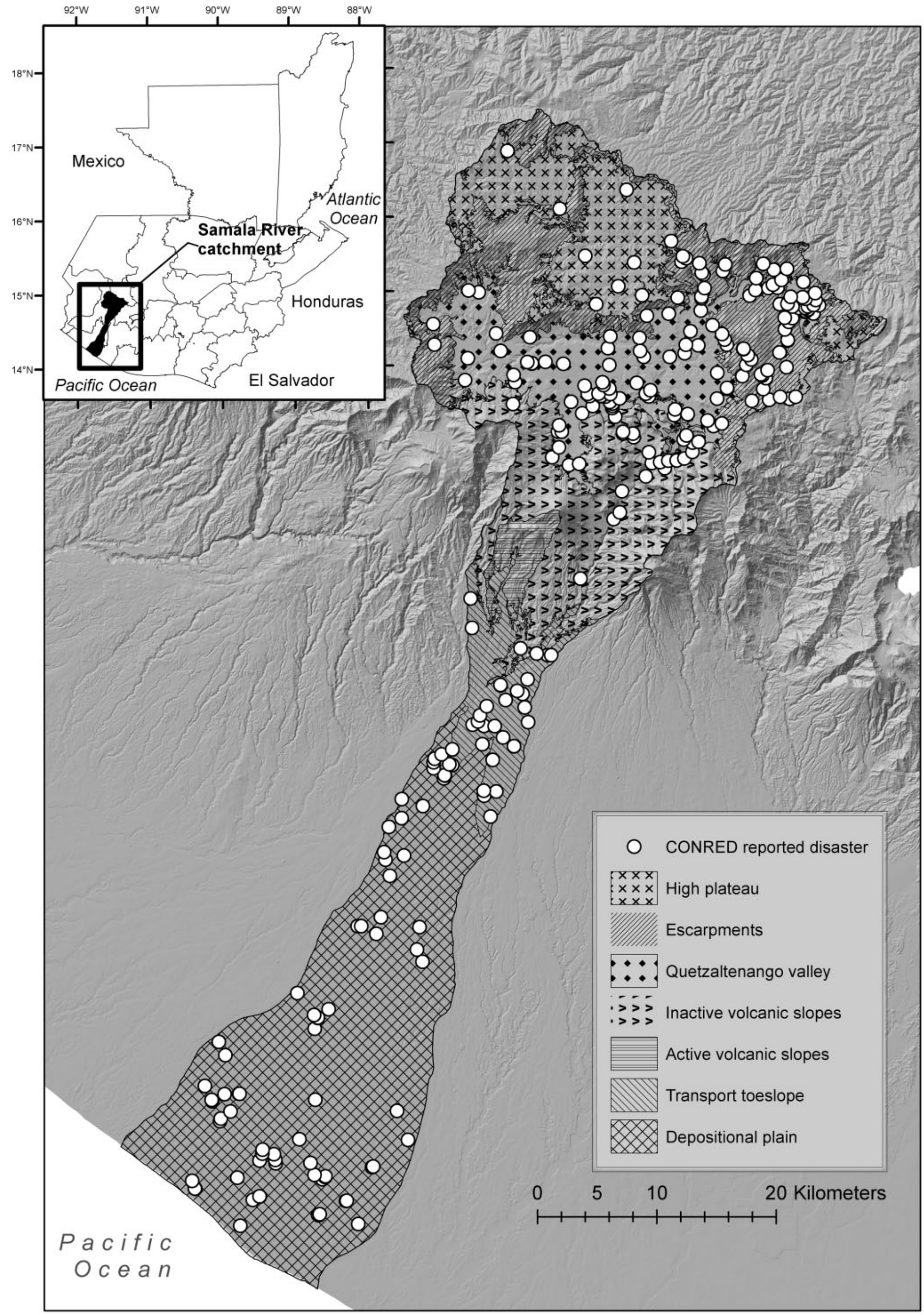

Fig. 3. Geomorphological units in the Samala River catchment. Insert shows the geographical location of the catchment. White circles identify hydrometeorological disasters reported to CONRED from 2008 to 2011 (CONRED 2012). Base shapefiles source: SEGEPLAN (2012).

Four types of disasters were found corresponding to the most significant events in the study area. The terminology to refer to these types of disasters was chosen to be as scientifically correct as possible for the events reported in the datasets, but the terms might not fully correspond to the strict theoretical definitions due to the particularities of the report process. The terminology used to classify the disasters corresponds to the names of the main processes behind the report, e.g. a 'debris flow' record corresponds to a reported event that was mainly caused by a debris flow process. The specific types of disasters used in this work are: (1) debris flow, which comprises reports of mudflows, lahars, sediments on land due to overflowing rivers, and landslides registered as being caused by rains or storms; (2) subsidence, for reports of sinking soil presumably caused by heavy rains; (3) flood, for reports stating floods, overflowing rivers, or flooded streets; and (4) water damage, for reports describing 'structural damage', meaning damages to buildings (walls, houses and schools) and infrastructure (mostly bridges) registered as probably caused by rains or storms.

The geographical distribution of the reported disasters is shown in Fig. 3. There were no disasters reported in the Active volcanic slopes. The majority of the disasters of hydro-meteorological origin in the catchment were reported from flat areas, with slope less than 5% (Fig. 4). For the catchment as a whole, the distribution of disasters with respect to slope is similar to the areal distribution of slope, but slightly more skewed towards low slopes, showing that disasters are more likely to occur in flat areas than in steep areas. This is more clearly seen in the histogram showing the ratio between the relative frequency of reported disasters in each class and the relative frequency of slope, which has a decreasing trend towards high slopes. As for the catchment as a whole, the distributions of disasters and slope are both dominated by low slopes in the Quetzaltenango valley, Transport footslope and Depositional plain and the two distributions are rather similar. The remaining geomorphological units have more complex disaster distributions, and the disaster and slope distributions are quite different from each other. In Escarpments and Inactive volcanic slope the slope distribution peaks around 20–30°. There are quite a few disasters reported at these slopes, but the disaster frequency is high (Escarpments) and highest (Inactive volcanic soils) at low slopes.

The relative frequency distributions of reported disasters of hydro-meteorological origin per wetness class differ strongly from that of the relative frequency distribution of wetness classes (Fig. 5). The disasters are, as expected, more frequent at high wetness indices, i.e. during wet conditions, but there are also disasters reported in the low wetness classes. For the whole catchment the distribution has a clear peak for indices 300–350 mm. As mentioned above, the index is based on precipitation data from one station in the catchment, Retalhuleu, so all geomorphological units are compared with the same wetness distribution, which is strongly skewed towards dry conditions (Fig. 5). About 80% of the days have wetness indices below 100 mm. The combination of the two distributions, shown as number of disasters per day within the wetness class, consequently gives distributions that are much skewed towards high wetness indices. The number of days in the highest wetness classes is very small so even if a moderate number of disasters have been reported, the number of disasters per day within those classes is high for the catchment as a whole and for all geomorphological units except for Transport toeslope and Depositional plain.

So far, only disasters reported in the CONRED dataset have been analyzed in this paper, and the analysis has been restricted to the total number of disasters of hydro-meteorological origin. Figure 6 shows how the different types of disasters of hydro-meteorological origin are distributed within the geomorphological units and in the catchment as a whole. This is done for CONRED and DesInventar in order to compare these two datasets, for the common time span from 2008 to 2011. When comparing the two datasets it should be noted that the type 'Water damage' is only used by DesInventar and 'Storm' only by DesInventar. If the type 'Flood' is combined with these classes, which all are caused by unusually high stream flow, it makes up about three-quarters of the hydrometeorological disasters in the catchment as reported by both datasets. For most units, however, there is a considerable difference in the distribution of disaster type between the two datasets. Debris flow is a frequent type of report in the units where steep slope angles are predominant (Escarpments, Inactive volcanic slopes) whereas floods are the most frequent report in the units where land is predominantly flat (Quetzaltenango valley, Transport toeslope, and Depositional plain), which is a logical outcome.

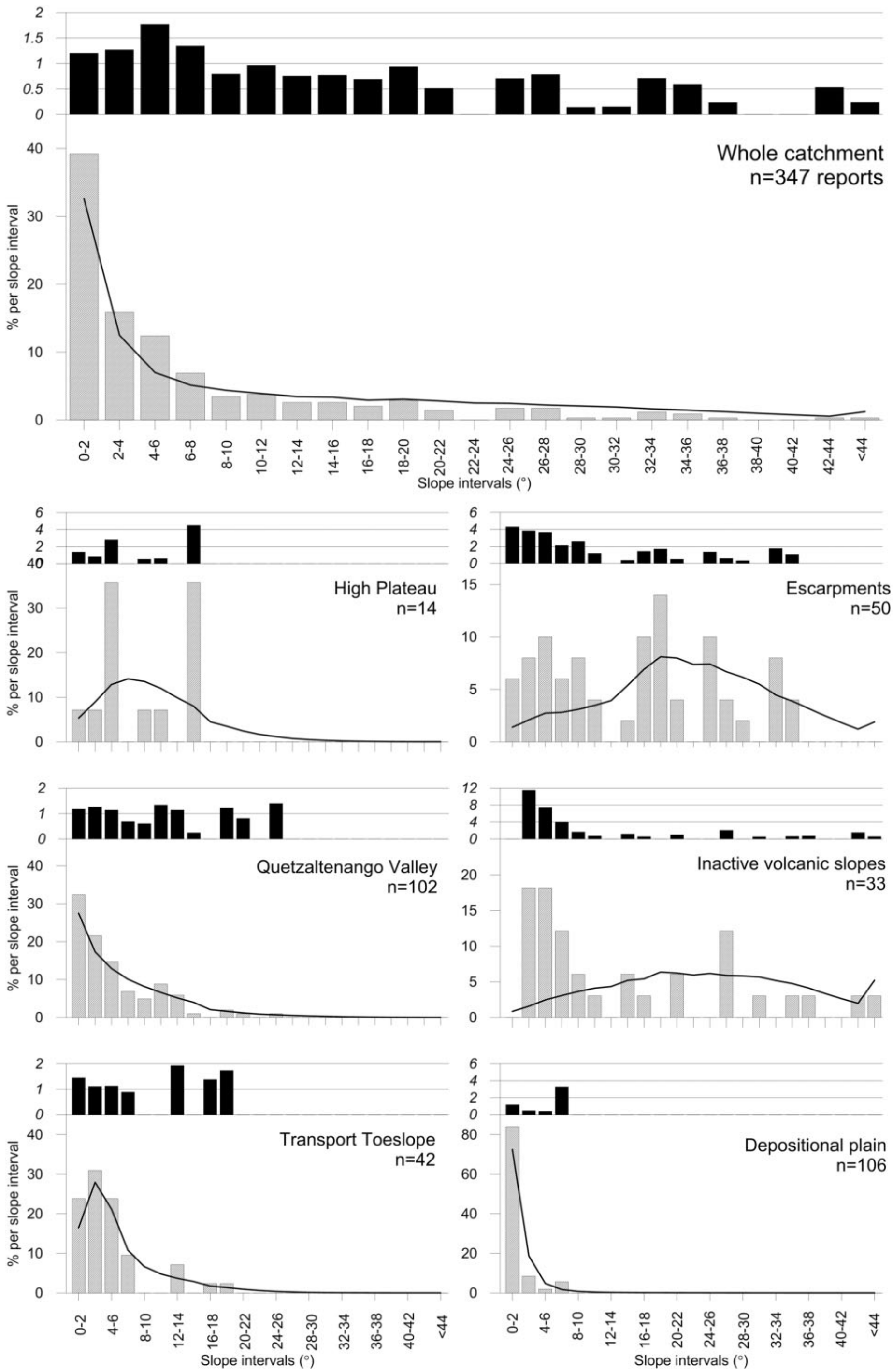

Fig. 4. Relative frequency of reported disasters with respect to slope interval (histograms with grey staples), relative frequency of slope (full line) and ratio between these frequencies (histograms with black staples). Disaster data reported to CONRED 2008–2011 in the Samala River catchment. The graphs show the results for each geomorphological unit where disasters have been reported and for the whole catchment. There were no reports in the Active volcanic slopes.

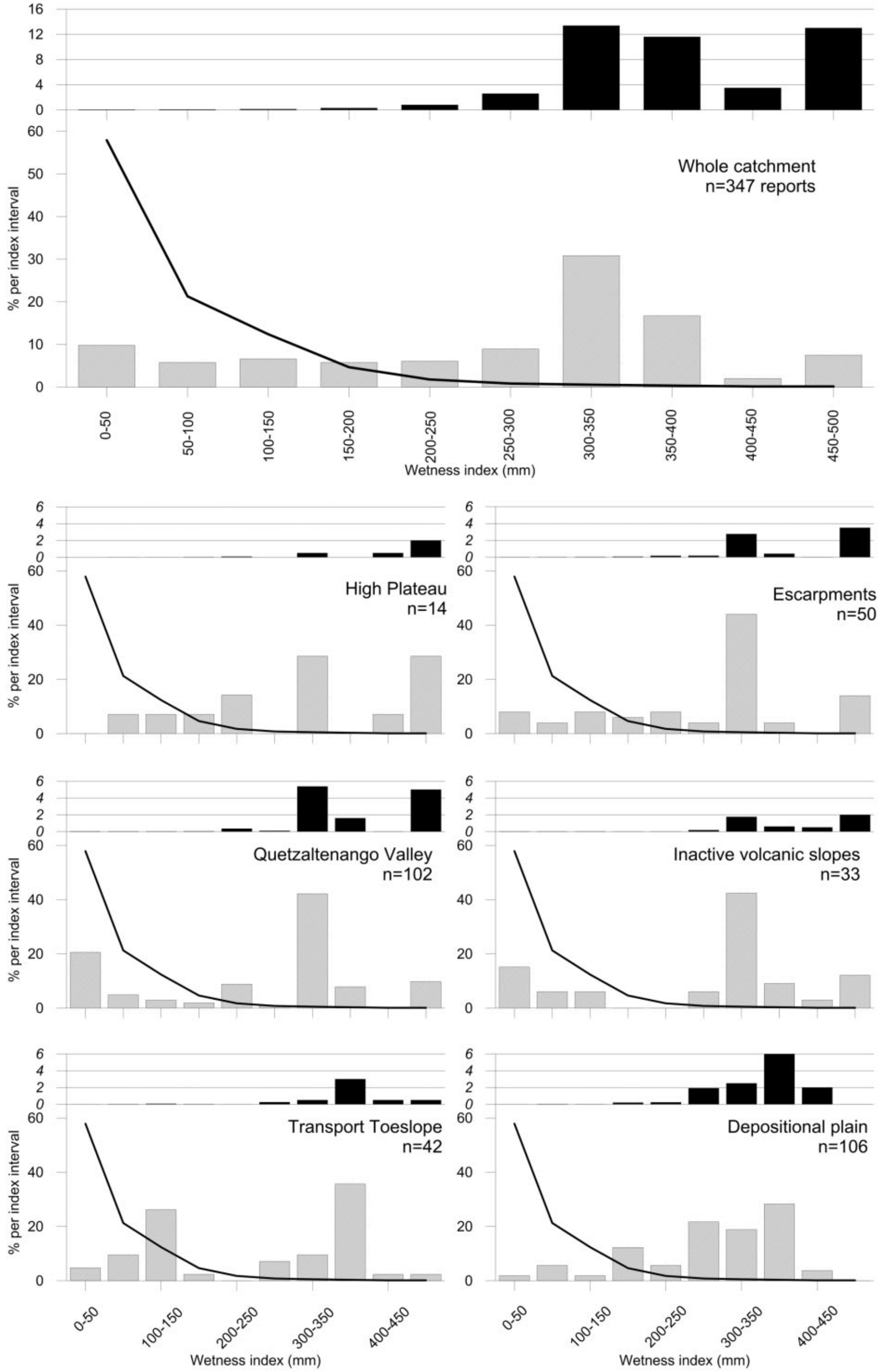

Fig. 5. Relative frequency of reported disasters with respect to wetness index (histograms with grey staples), relative frequency of daily wetness indices (full line) and number of reported events per day in the different wetness classes (histograms with black staples) Disaster data reported to CONRED 2008–2011 in the Samala River catchment. The graphs show the results for each geomorphological unit where disasters have been reported and for the whole catchment. There were no reports in the Active volcanic slopes.

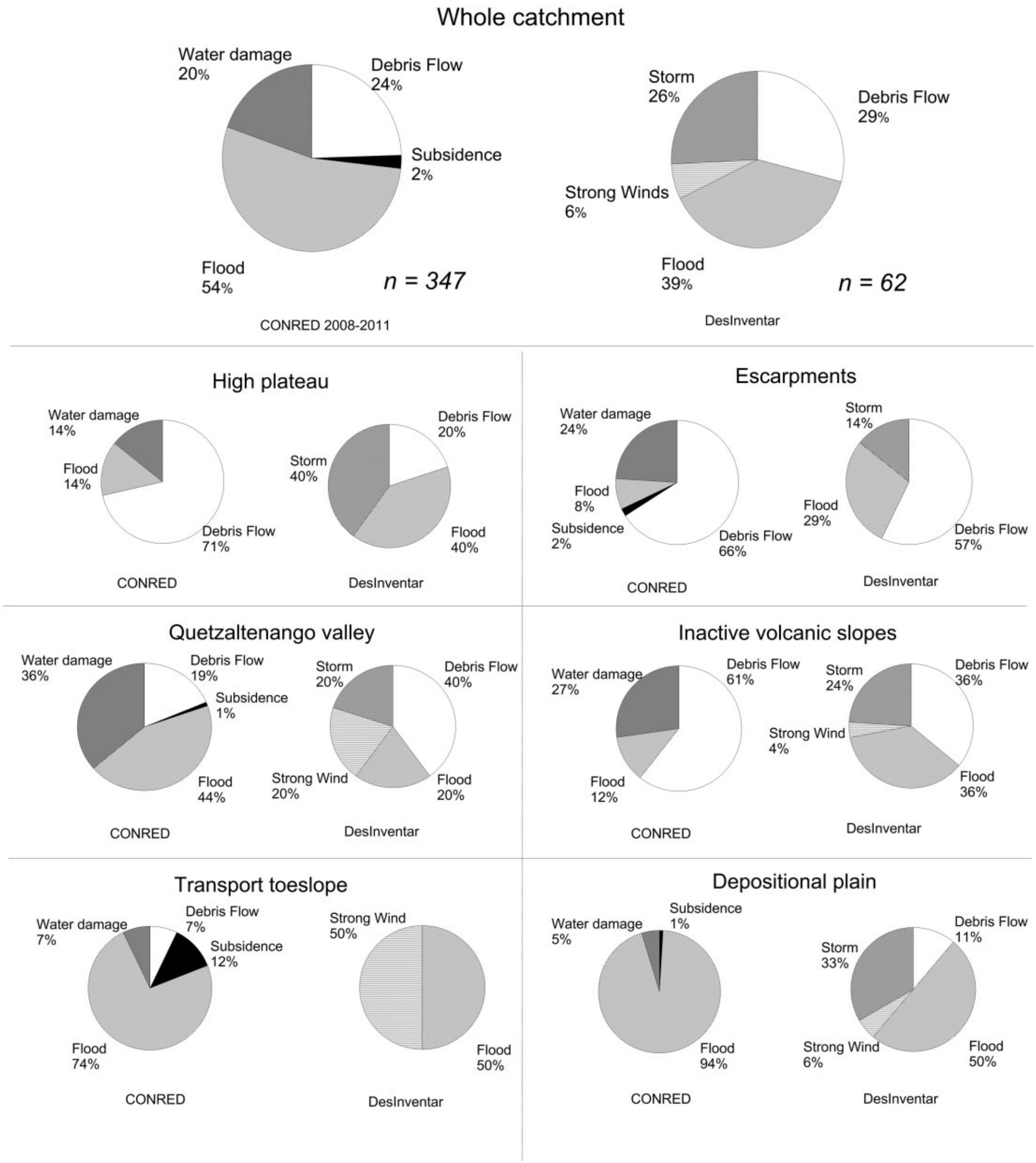

Fig. 6. Percent distribution of disasters per type in CONRED and DesInventar for the 2008–2011 period. The upper set of graphs correspond to the results for the whole catchment and the rest correspond to each geomorphological unit. There were no reports of disasters in the Active volcanic slope.

Discussion

From its general physiography the Samala catchment could naturally be divided into three main sections, the highlands, the lowlands and the volcanic cordillera, with quite different preconditions for disasters of hydro-meteorological origin. This division, and the further subdivision of the catchment into seven geomorphological zones, was useful when analyzing the disaster occurrence in the area and investigating the links between occurrence and physiography.

The physiographical factor for which this link could be investigated was slope. Similar frequency distributions for disaster occurrence and area with respect to slope (Fig. 4) implies that the number of reported disasters per area is constant over the investigated area, regardless of slope, and that slope is not a decisive risk factor. Provided that all disasters are reported and that the number of events is high, the frequency ratios in the top histograms for each unit in Fig. 4 would give a relative measure of the probability for disaster at locations in the different slope intervals. When this ratio is greater than one, the probability for disaster in the slope interval is higher than the mean probability in the investigated unit, and when it is smaller than one the probability is lower. With the limited number of events here, particularly in some of the geomorphological units, the frequency ratios, however, give just a rough indication of how the relative probability of reported disasters is distributed.

There was no relationship between slope and disaster occurrence in the less steep geomorphological units (Quetzaltenango valley, Transport toeslope and Depositional plan). This is seen in Fig. 4 by the rough similarity between the relative frequency distributions of disaster occurrence and area with respect to slope, and by the fact that most frequency ratios in these units are only moderately deviating from one. For the steep units the situation is different. High Plateau has too few reports for the analysis, but Escarpments and Inactive volcanic slopes have frequency ratios not too far from one at high slopes, but consistently much higher ratios at the lowest slopes, indicating comparatively high probability of disaster in these areas. These high probabilities in the low slope parts of the steep units are reflected in the histogram for the whole catchment, which shows a weak relationship between reported disasters and slope, with decreasing risk for disaster with increasing slope. Our results seem to contradict the general idea that the steeper areas, together with flood plains, are areas with particularly high risk of disasters (Kreimer *et al.* 2003; World Bank 2011; Blaikie *et al.* 2014). The high probability of disaster in the less sloping areas of the steep geomorphologic units, Escarpments and Inactive volcanic slopes is noteworthy because the most frequently reported type of disaster in these units is debris flow, which is not a common process in flat lands. It is important to consider, however, that the reports of disasters correspond to consequences affecting people, and these consequences may occur at other locations than those where the processes generating the disaster are acting. Debris flow is generated in steep areas, but affecting people in the downstream lowlands.

There are clearly two potential social reasons for the large occurrence of reported disasters in low slope areas. First, people live and use land intensively in these areas, which is a precondition for a natural hazard to create a disaster. Second, reporting of disasters is probably more complete in these more densely populated areas with important infrastructure than in the less densely populated remote areas of high slope. These factors strongly underline the importance of taking social factors into consideration when doing a comprehensive analysis of disaster occurrence. For one of the geomorphological units, the Active volcanic slopes, there were no reports of disasters in any of the datasets. This result was expected, as the conditions of slope instability and constant production of volcanic material impede living and building infrastructure in this area. Without people settled in the area there is no exposure to the hazards and no disasters can be created.

It is likely that the small flat areas in the Escarpments and Inactive volcanic slopes where disasters have been reported do not correspond to the original landscape but to land that has been flattened to provide place for human structures, such as roads and buildings. Therefore, on the one hand the importance of the infrastructure for the people would cause increased interest in reporting events. On the other hand, the relief modifications that must be made to make way for such infrastructures, such as sharp cuts, land fillings, and water collection and channeling can modify the natural hydrological processes. Thereby the risk of disasters may increase due to, e.g., modified moisture infiltration and accumulation or alteration of the repose angles of the slopes. It was noticed that subsidence events were mostly reported in roads. Subsidence reports were included in this study because they are related to saturation of the soil due to rain. We observed that all the reports of this type were linked to infrastructure and thus anthropogenic factors could have a main role in their occurrence.

In contrast to the weak relationship found in the spatial analysis between disaster occurrence and slope, the corresponding temporal analysis showed a very strong relationship between disaster occurrence and wetness. As expected, disasters of hydrometeorological origin were much more frequent at wet conditions than at dry conditions. This is seen by the very different frequency distributions for disaster and wetness index in Fig. 5 and by the strongly skewed distribution towards high wetness classes of the number of disasters per day within the different wetness classes (top histograms in Fig. 5). It is to be noted that the wetness index is based on precipitation data from just one station for which the relative temporal variation in wetness index has been assumed to represent the whole catchment. Due to this rough assumption, a detailed analysis of the frequency distributions of disaster occurrence in the different geomorphological units cannot be made based on Fig. 5. It should also be noted that the used wetness index (Eqn 1) is an arbitrary indication of wetness, based on previous rainfall, and its numerical value has little physical meaning. There seems, however, to be a limit for the wetness index (in this case around 300 mm) above which the disaster risk is high in the catchment (top histogram in Fig. 5).

In the analyses we used two different datasets of natural disasters on a local scale created and available through a Guatemalan national institution (CONRED) and a regional network (DesInventar). The advantage of these datasets is their spatial resolution at least to the municipal level. On the other hand, limitations have been identified for these data (Soto 2015) such as a reduced time span, uncertainty about the accuracy of the comprised information and incompleteness of data. Although much effort is being made to standardize the terminology on natural disasters (Munich Re 2011), the words used to identify different types of disasters and the damages resulting from them could mean different things for different people and in different places, e.g. those in charge of collecting data, civilians, or different stakeholders. The difference in the type of hydro-meteorological disasters in the two datasets (Fig. 6) is partly explained by different classifications and probably also by different words used by those reporting the disasters. It should also be noted that the number of reports from the comparison period is quite different for the two datasets. There are much fewer reports in DesInventar than in CONRED for the investigated period, so a close agreement between the reported types could not be expected, even if all reports were standardized and of high quality.

This study showed how complex a relatively small area, such as the Samala River catchment can be and how a geomorphological approach allows subdividing the area into smaller and more homogeneous zones with distinctive physical structures. We have showed that spatial analysis based on the geomorphological configuration of the landscape provides tools to improve the understanding of the physical settings of disasters. Even if the available data on natural disasters have limitations, high-resolution analyses are essential for the most practical purposes of disaster risk reduction, i.e. making the understanding of disasters useful and applicable to stakeholders on the local scale. Therefore the effort to set methodologies to produce such understanding is worth it. Our approach allowed identifying boundaries that separate seven different geomorphological units within our 1500 km^2 study area and enabled analyzing the disasters reported on each unit to hypothesize on the particular geomorphological processes that could be related to their occurrence. The methodological proposal of this work was therefore based on the complexity of the studied area. This complexity is common to active tectonic and volcanic regions where this approach could be useful not only because the similarities of their landscape complexity but also because of their exposure to natural hazards.

Conclusion

The subdivision of the catchment into geomorphological zones was useful when analyzing the disaster occurrence in the area and investigating the links between disaster occurrence and physiography.

There was no clear relation between slope and occurrence of disasters of hydro-meteorological origin for the catchment as a whole. For the steeper geomorphological units the number of reported disasters per unit area within given slope intervals was high or highest in the flattest areas.

For understanding the spatial distribution of disaster occurrence, social aspects have to be considered. This is true both for evaluating the reporting of disaster data, and thus for the quality and completeness of the dataset to be analyzed, and for the understanding of where disasters occur and the processes behind them.

The temporal distribution of disasters was strongly related to the rainfall of the day and the preceding nine-day period, here quantified as a wetness index. There seemed to be a threshold level for the wetness index above which the risk of disaster was at a high and rather constant level.

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Manuscript received 1 Mar., 2014, revised and accepted 15 Dec., 2014