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Geographical Distribution of Disasters Caused by Natural Hazards in Data-scarce Areas

Methodological exploration on the Samala River catchment, Guatemala

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Abstract

Soto Gómez, A. J. 2015. Geographical Distribution of Disasters Caused by Natural Hazards in Data-scarce Areas. Methodological exploration on the Samala River catchment, Guatemala. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1275. 77 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9310-3.

An increasing trend in both the number of disasters and affected people has been observed, especially during the second half of the 20th century. The physical, economic and social impact that natural hazards have had on a global scale has prompted an increasing interest of governments, international institutions and the academia. This has immensely contributed to improve the knowledge on the subject and has helped multiply the number of initiatives to reduce the negative consequences of natural hazards on people. The scale on which studies supporting disaster risk reduction (DRR) actions are performed is a critical parameter. Given that disasters are recognized to be place-dependent, studying the geographical distribution of disasters on a local scale is essential to make DRR practical and feasible for local authorities, organizations and civilians. However, studying disasters on the local scale is still a challenge due to the constraints posed by scarce data availability. Social vulnerability in many disaster-prone areas is however a pressing issue that needs to be swiftly addressed despite of the many limitations of data for such studies.

This thesis explored methodological alternatives to study the geographical distribution of natural disasters and their potential causes in disaster-prone and data-scarce areas. The Samala River catchment in Guatemala was selected as a case study, which is representative of areas with high social vulnerability and data scarcity. Exploratory methods to derive critical disaster information in such areas were constructed using the geographical and social data available for the study area. The hindrances posed by the available data were evaluated and the use of non-traditional datasets such as nightlights imagery to complement the available data were explored as a way of overcoming the observed limitations.

The exploratory methods developed in this thesis aim at (a) deriving information on natural disasters under data-scarce circumstances, (b) exploring the correlation between the spatial distribution of natural disasters and the physical context in order to look for causalities, (c) using open data to study the social context as a potential cause of disasters in data-scarce areas, and (d) mapping vulnerabilities to support actions for disaster risk reduction. Although the available data for the case study was limited in quantity and quality and many sources of uncertainty exist in the proposed methods, this thesis argues that the potential contribution to the development of DRR on a local scale is more important than the identified drawbacks. The use of non-traditional data such as remotely sensed imagery made it possible to derive information on the occurrences of disasters and, in particular, causal relationships between location of disasters and their physical and social context.

Keywords: natural disasters, Guatemala, data-scarce areas, natural disaster science methods, natural disaster maps

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Resumen en español

Soto Gómez, A. J. 2015. Distribución Geográfica de Desastres causados por Amenazas Naturales en Áreas con Escasez de Datos. Exploración metodológica en la Cuenca del Río Samalá, Guatemala. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1275. 76 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9310-3.

El número de desastres y personas afectadas por esos desastres en el mundo han mostrado una tendencia creciente, especialmente en la segunda mitad del siglo veinte. El impacto físico, económico y social que las amenazas naturales han causado a nivel global ha causado que gobiernos, instituciones internacionales y la academia se interesen cada vez más en los desastres causados por esas amenazas. Este interés ha contribuido a mejorar el conocimiento existente sobre desastres así como a multiplicar las iniciativas orientadas a reducir sus efectos negativos en las personas. La escala en la cual las iniciativas para la reducción del riesgo de desastres (RRD) se llevan a cabo es un parámetro crítico para su materialización. Hoy en día se reconoce la estrecha relación que existe entre los desastres y los lugares donde éstos se registran. Por esta razón, estudiar la distribución de los desastres en una escala local es esencial para que la RRD sea práctica y factible para autoridades y organizaciones locales, y también para la sociedad civil. Sin embargo, estudiar desastres naturales en una escala local es aún un problema por resolver debido a las restricciones impuestas por la escasa disponibilidad de datos de alta resolución. A pesar de las dificultades y limitaciones identificadas, la vulnerabilidad social en las regiones propensas a desastres es un problema importante que necesita ser atendido con prontitud.

La presente tesis exploró alternativas metodológicas para estudiar la distribución geográfica de los desastres naturales y sus causas potenciales, particularmente en áreas propensas a desastres y en condiciones de información limitada. La cuenca del Río Samalá fue seleccionada como caso de estudio debido a que es un área representativa de zonas propensas a sufrir desastres con el agravante de una alta vulnerabilidad social y escasez de datos. El trabajo de investigación propone métodos exploratorios para extraer información crítica sobre desastres utilizando la información geográfica y social que esté disponible y evaluando los obstáculos impuestos por la reducida disponibilidad de datos. La información existente fue complementada con el uso de fuentes de información no tradicionales, e.g. imágenes satelitales de luces nocturnas, como una manera de superar las limitaciones identificadas.

Los métodos desarrollados en este trabajo de tesis tuvieron como objetivos (a) obtener información sobre desastres naturales en condiciones de escasez de datos, (b) explorar la correlación entre la distribución espacial de los desastres naturales y su contexto físico para identificar relaciones de causalidad, (c) utilizar información de libre acceso para estudiar el contexto social como causa potencial de desastres naturales en áreas con escasez de datos, y (d) mapear vulnerabilidades para sustentar acciones para la RRD. Este trabajo de tesis sostiene que, en la zona de estudio, la contribución potencial de los métodos propuestos para el desarrollo de la RRD en la escala local es más importante que las incertidumbres que estos implican y las limitaciones creadas por la reducida calidad y cantidad de información. El uso de fuentes de información no tradicionales tales como imágenes satelitales hizo posible incrementar la información sobre las incidencias de desastres y, en particular, buscar relaciones de dependencia entre los lugares particulares en los que los desastres fueron registrados y su contexto físico y social.

Palabras clave: desastres naturales, Guatemala, áreas con escasez de datos, ciencia de desastres naturales, métodos para estudios desastres naturales, mapas de desastres naturales

To the ones in my heart

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Soto, A. (2015). Deriving information on disasters caused by natural hazards from limited data: a Guatemalan case study. *Natural Hazards*, 75:71–94. © Springer Science+Business Media Dordrecht 2014. Reprint made with permission.

II 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. © 2015 Swedish Society for Anthropology and Geography. Reprint made with permission.

III Soto Gómez, A.J., Di Baldassarre, G., Rodhe, A. and Pohjola, V. (2015). Remotely sensed nightlights to map societal exposure to hydrometeorological hazards. *Remote Sensing. Under review.*

IV Soto Gómez, A.J., Di Baldassarre, G., Pohjola, V. (2015) A simple method to map spatial vulnerability and support crisis management. *Manuscript.*

In paper II, I performed the GIS analysis for the geomorphological classification and the analyses on disasters, precipitation, and slope. In paper III, I contributed to the discussions from which the paper originated and I carried out the analysis. In paper IV, I contributed to the discussions that originated the paper and designed the method, and I performed the analysis. In all the papers, I had the overall responsibility for writing the papers. All co-authors have contributed with ideas and by giving advice and feedback on the analyses and on the papers. Reprints were made with permission from the respective publishers.

Contents

Abbreviations

CONRED	*Coordinadora Nacional para la Reducción de Desastres* (Guatemalan Coordination Agency for Disaster Reduction)
CRED	Centre for Research on the Epidemiology of Disasters
D	Critical Distance
d*	Population Density
DEM	Digital Elevation Model
DesInventar	*Sistema de Inventario de Efectos de Desastres* (Disaster Information Management System)
DHA	UN Department of Humanitarian Affairs
DRR	Disaster Risk Reduction
EM-DAT	The International Disaster Database
GDP	Gross Domestic Product
GIS	Geographical Information System
IDNDR	International Decade for Natural Disaster Reduction
INE	*Instituto Nacional de Estadística* (Guatemalan National Statistics Institute)
INSIVUMEH	*Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología* (Guatemalan National Institute for Seismology, Volcanology, Meteorology and Hydrology)
I_{wet}	Wetness Index
La Red	*Red de Estudios Sociales en Prevención de Desastres en América Latina* (The Network of Social Studies on Disaster Prevention in Latin America)

NOAA	US National Ocean and Atmospheric Administration
P	Precipitation
RSVI	Relative Spatial Vulnerability Index
SEGEPLAN	*Secretaría de Planificación y Programación de la Presidencia* (Guatemalan Secretariat for Planning and Programming of the Presidency)
SISMICEDE	*Sistema de Manejo de Información en Caso de Emergencia o Desastre* (Information Management System in Case of Disaster Emergency)
UN	United Nations
UNDRO	UN Disaster Relief Organization
UNISDR	UN International Strategy for Disaster Reduction

1. Introduction

People around the world have been negatively affected by natural hazards over time. An increasing trend in both number of disasters and affected people has been observed, especially in the second half of the 20th century (Adikari and Yoshitani 2009; Guha-Sapir et al 2011). However, even if the negative effects of disasters on people and material resources have increased in the world over time, the number of people killed by each event has decreased (*Figure 1* and *Figure 2*).

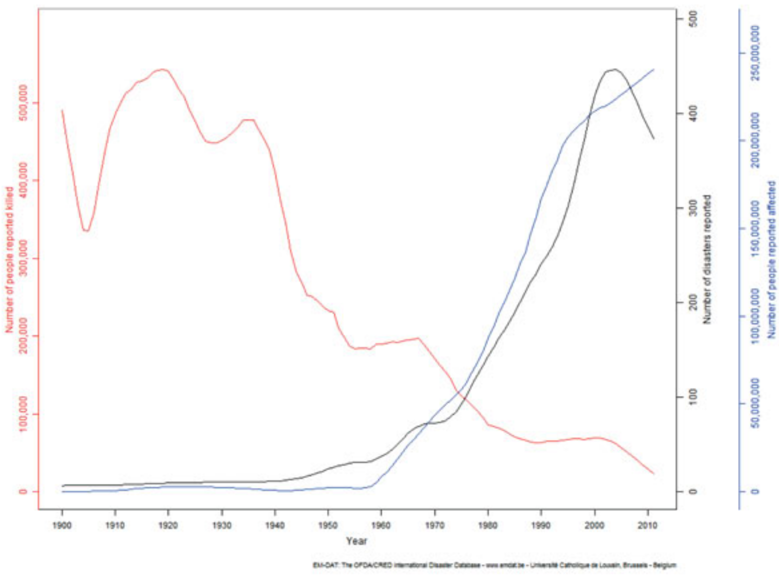

Figure 1. Natural disasters occurrences in the world from 1900 to 2011 and their impacts on people. Graph source: EM-DAT: The OFDA/CRED International Disaster Database –www.emdat.be– Université Catholique de Louvain, Brussels, Belgium.

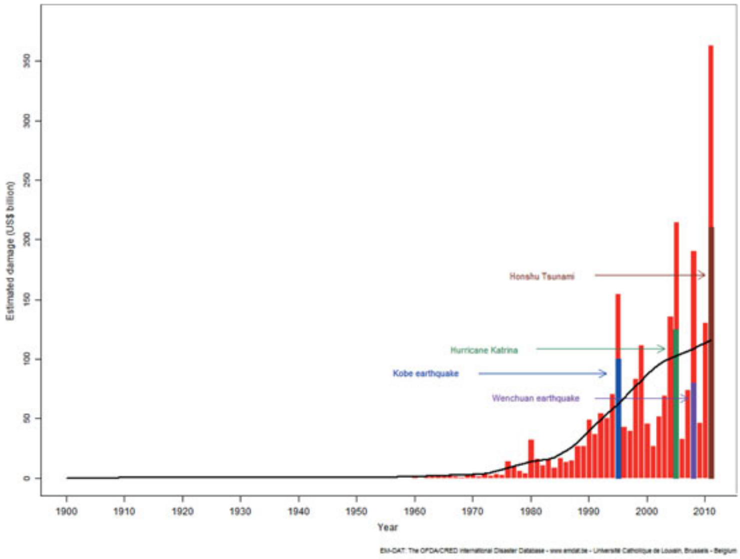

Figure 2. Estimated damage of Natural disasters in the world from 1900 to 2011. Graph source: EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be– Université Catholique de Louvain, Brussels, Belgium.

The disasters of hydrometeorological origin are the most recurrent type of disasters and the ones that have the strongest impact on people in the world. Among them the effects of floods and windstorms are the ones that have increased the most (Guha-Sapir et al 2011). Some areas of the world are more prone to be affected by disasters than others because of their geographical location or their particular living conditions (Dilley et al 2005; Kreft and Eckstein 2013).

The significant impact of disasters on people and their development (lives, health, and economy) both individually and collectively, has promoted research aimed at improving the way we cope with the effects of disasters. The Rio Declaration on Environment and Development (UN 1992) recognized the importance of accounting for disasters when planning for sustainable development. The relationship between disasters and development is recognized to be two-way: in order to fulfill its objectives, any action aiming to contribute to sustainable development should take into account disaster risk management and vice versa. Mainstreaming disaster management into sustainable development is still an ongoing work (Amaratunga and Haigh 2010). The interrelation between disasters and development can be both positive and negative. On the negative side, disasters could slow down development. Also, development actions always have consequences that could increase the likelihood of disasters (O'Brien et al 2006). On the positive side, disasters could create opportunities for development initiatives while development could decrease the likelihood of disasters (UNDP/DHA 1994).

The recognition of links between disasters and human development opens an opportunity to improve the quality of people's living conditions while enhancing their disaster-coping capacity (Anderson 1985). Giving people a more active role, for example, would make the application of the principles of sustainable development into disaster risk reduction DRR more meaningful (Berke 1995). Neglecting the links between disasters and development could, on the other hand, be risky. Development projects could have a short lifetime if natural hazards are not considered during their planning stage and valuable resources could be lost. Development projects could produce new vulnerabilities over time as occurred in El Salvador, when agricultural lands were turned into homes for ex-combatants who were later severely affected during Hurricane Mitch (Lavell 2004). Often, people with lowest development levels are also the most affected by disasters because they are also the most economically, socially and environmentally vulnerable (Anderson 1985; UNDP/DHA 1994; Berke 1995). The interdependency of disaster risk and development should be of national and global concern. If a part of the population of a country is vulnerable, everyone's efforts and resources are put at risk and the national goals are set back.

The physical, economic and social impacts that natural hazards have had on a global scale and in the long term are significant. The increasing trends in the occurrence of disasters and their negative effects have prompted governments, international institutions, and the academia to show an increasing interest in natural hazards and their related disasters since the 1940s (Guha-Sapir et al 2011). The growing interest has improved the knowledge and multiplied both the governmental and non-governmental initiatives aiming at reducing the negative consequences of hazardous events. Today, the reduction of the disastrous consequences of natural hazards is a global concern and it is acknowledged to be an urgent necessity. The need for such actions is paramount in the most disaster-prone areas. In this context, research may contribute to improving sustainability by increasing the understanding of the processes related to and triggering natural disasters. This knowledge is vital to reduce the risk of disasters onset and their negative consequences. Nowadays it is recognized that disasters are place-dependent (UNISDR 2009), therefore the geographical distribution of past disasters is capable of providing vital information on the occurrence of future disasters as well as on their processes and causes in the natural and social contexts. Studying the geographical distribution of disasters is thus essential. For this reason the scale on which studies are performed becomes a critical parameter. National level studies are good to provide general directions to governments, but practical plans and actions require knowledge on the local scale. For instance, decisions on land use affecting people's activities and infrastructure are dependent on knowledge at this resolution. Spatial and urban planners should, for instance, be actively engaged in reducing disaster risk through their actions. The production of the required knowledge to improve DRR actions demands further research, which is strongly dependent on data availability. Informative data is nowadays not an abundant resource, and such lack of information is even more acute in many areas of the world that face multiple hazards. These areas are incongruously the ones that need data the most. Devising research methods that are applicable in data-scarce areas is thus needed to fill the knowledge gap that hinders DRR actions in highly vulnerable, data-lacking areas.

Aim of the thesis

As discussed in the previous section, there is a demand for knowledge on natural disasters on a local scale to support plans and actions for DRR. It has also been discussed that many disaster-prone areas are also data-scarce. Considering these premises, this thesis aims at proposing methods that can be applied on a local scale and under data-scarce conditions. The specific objectives within this aim are:

I Characterize a case of data scarcity to develop methods for disaster research on the local scale with Samala River catchment in Guatemala as case study

II Develop exploratory methods to:

- derive information on disasters caused by natural hazards under data-scarce circumstances
- study the physical context as a potential cause of disasters using their spatial distribution
- use open data to study the social context as a potential cause of disasters in data-scarce areas
- map vulnerabilities to support actions for DRR

2. Basic Definitions

The basic concepts used in disaster research may be defined differently depending on the disciplinary approach or purpose of the study. Therefore the definitions of the disaster science concepts that are frequently used in this thesis are given below in order to provide the setting for the research work carried out.

Hazard is a potentially damaging phenomenon or condition that may cause the loss of human life or health, property damage, social and economic disruption or environmental degradation (UNISDR 2009). Hazards may be the result of geological, meteorological, hydrological, biological and technological sources and can be single, sequential or combined. They are quantified by the probability of occurrence in a particular location with a defined intensity and frequency (UNISDR 2009). A hazard is not a disaster; it is rather an indicator of the probability of the occurrence of an agent that could turn into a disaster if it happens to meet with a social system that is susceptible of being negatively affected.

Vulnerability is the condition of a community or social system that makes it susceptible to the negative effects of a hazard. The vulnerability of a social group is determined by the quality of its economic, social, physical and environmental structures (UNISDR 2009). Since vulnerability can arise from all kind of particularities of a social group, it may be different for different social groups, locations, and times.

Reducing vulnerability may improve the general capacity of a social group to resist the effects of hazards. Vulnerability is however a composite of several aspects that are interrelated. For research purposes, the vulnerabilities of a social system can be classified in material (resources), organizational, and socio-psychological (attitudes and ideology) (Anderson 1985). Strengthening people's resources, organizational capabilities and attitudes in daily life as well as during times of crisis, may improve their capacity to cope with hazards.

Resilience is the capacity of a social system to resist the exposition to a hazard, to absorb and adapt to its effects, and recover from it by keeping the vital structures and functions ongoing or restoring them by its own means

(UNISDR 2009). Resilience depends on the resources of the social system (physical, organizational, educational, etc.).

Understanding the vulnerability and resilience of a social group to a hazard and how they are dynamically related is important because it contributes to a better understanding of how that specific social group could cope better with the effects of such hazard (Cutter 2005). Assessing vulnerability and resilience is a challenge because these concepts are created from all the characteristics of a community. A full assessment of all such characteristics is thus very unlikely. A common alternative is to identify key characteristics of a social group as indicators that provide sound and methodologically useful estimations of vulnerability and resilience. However, since there are no two identical social systems, a predetermined hazard may represent an episode of differing severity for different communities. Consequently, to establish a standard process to assess the vulnerability and resilience of a community to a hazard is a difficult task. The assessment of the vulnerability and resilience terms is an important problem that needs to be tackled despite the obvious difficulties and methodological challenges involved. For this reason it is an important research niche within disaster science (Cutter et al 2003).

A **natural disaster** is, for the purpose of this study, understood as the intersection of a hazardous natural event and a vulnerable community that produces negative consequences such as damage to life, health, or property in a way that the social functions that the community carries out in normal conditions are interrupted.

Many definitions of disaster have been constructed along with the development of disaster science and across different disciplines. The concerns of each time period shape how disasters are understood and perceived (Alexander 2005). Different definitions of disasters are the result of different historical and disciplinary contexts (Britton 1986; Perry 2007). The approaches of social and earth sciences have often also been divergent as earth scientists have mainly focused on the cause of the disasters – or physical agent – while social scientists have put the accent on the social disruption (Perry 2007). The approach taken in the earth sciences considers natural hazards as part of the natural processes that can be analyzed in space and time. Under this light, people can move away from the thought of natural hazards being unknown phenomena to be feared towards a more knowledgeable position of better understanding the processes of which the hazards are a part. The social sciences' approach attempts to study societies and their functioning in order to understand what makes them weak and vulnerable, ultimately contributing to finding ways to make them stronger when facing natural hazards. At present time there is an ongoing shift towards a new conceptualization of disasters that includes the causal agents as well as the social structures and conditions that make people more or less able to resist a disruption (Perry 2007). This shift is bringing disaster researchers from different disciplines together into a common study arena. The convergence of the points of view of the different disciplines enriches the research of disasters and favors a more comprehensive approach. Establishing a unique definition of disaster may be unlikely, but a more comprehensive and multidisciplinary approach is possible and needed (Perry and Quarantelli 2005).

Disasters have been classified over time attending different characteristics and needs, and as more disciplines are becoming involved in disaster research, more specific classifications are being constructed (Perry 1989). Such classifications focus on the properties of disasters, the type of causal event, the impacts, the social responses, etc. In general, classifications of disasters distinguish between those caused by natural hazards and the ones caused by technological hazards (Silver 2006; UNISDR 2009). Disasters caused by natural hazards are classified as being related to geological, meteorological, hydrological, or biological causes (Guha-Sapir et al 2009). This work is limited to the kind of disasters caused by natural hazards. Disasters caused by natural hazards are commonly called “natural disasters”. This term has been the topic of many conceptual discussions due to the risk of giving disasters the character of being “natural” as in being supposed to happen and unavoidable, and therefore out of any human responsibility or management capacity (Cannon 1994; Steinberg 2000; Blaikie et al 2014). However, in the recent scientific literature, the term natural disaster clearly corresponds to those disasters caused by a natural hazard. The later meaning is the one used along this work.

Conceptually, ***disaster risk*** is expressed by the notation

$$Risk = Hazards \times vulnerability$$

Disaster risk is therefore a function of the hazards faced by a social group and the vulnerabilities of such group (UN/ISDR 2004). Technically, disaster risk is defined by the potential harmful consequences for life, health, property, livelihoods, or the environment resulting from interactions between hazards and vulnerable conditions in a particular case (in terms of, for instance, number of lost lives, persons injured, or damage to property) (UNISDR 2009). The consequences or losses are often difficult to quantify. However disaster risk has been assessed and mapped in broad terms by using the knowledge of the main hazards as well as the patterns of population and socio-economic development (UNISDR 2009).

3. Historical Background

Disaster science has developed over time within different disciplines that have defined it in various ways. The definition of the subject of research is useful and needed in order to understand what is to be studied (Perry 2007).

Disasters as objects of scientific enquiry are relatively new and started formally with the sociological studies on damage caused by World War II (Silver 2006). Historic studies show that at the beginning actions were reactive and mostly limited to disaster relief and humanitarian help (Britton 2002). The paradigm changed over time towards the idea that there was more to do about disasters than just repairing their damage and that the losses could be reduced by measures planned forehand (Afedzie and McEntire 2010; Amaratunga and Haigh 2010). In this context the concepts of comprehensive emergency management and integrated emergency management systems came up and the focus shifted from emergency response to management, the former being included in the latter (Britton 2002). This paradigm change started at a supranational level (e.g. the United Nations and its initiatives) and was thereafter adopted by national governments globally.

Disaster management is today focused on the comprehensive idea of facing natural hazards through preventive actions like preparedness, mitigation and vulnerability reduction and, after a disaster, through recovery (Amaratunga and Haigh 2010). This approach is referred to as Disaster Risk Reduction (DRR) and aims at reducing the potential impact of natural hazards that cannot be eradicated. In this framework hazards are considered to be natural processes that are not, or not entirely, subject of human modification. DRR is "the concept and practice of reducing disaster risks through systematic efforts to analyze and reduce the causal factors of disasters" (UNISDR 2009). The idea of vulnerability as a determining factor for disasters is an important advancement for DRR because it allows human beings to recognize their involvement in the occurrence of disasters and to assume their responsibility, hopefully moving away from the idea that disasters are a matter of fate (Steinberg 2000).

The United Nations has greatly contributed to putting together the advances on disaster reduction at the global level. The Department of Humanitarian Affairs (DHA), which was established in 1991, was the responsible body for humanitarian assistance within the UN, and incorporated the former UN Disaster Relief Organization (UNDRO) and the Secretariat for the International Decade for Natural Disaster Reduction (IDNDR) into one single organization (UNDP/DHA 1994). In 2000 the UN International Strategy for Disaster Reduction (UNISDR) was created to continue with the objectives of the IDNDR as a strategic framework, aiming at coordinating the efforts to reduce disaster losses and building resilient nations and communities as an essential condition for sustainable development. UNISDR functions as the center for the implementation of the Hyogo Framework for Action (UNISDR 2005) and its successor, the Sendai Framework (UNISDR 2015). These frameworks are plans of action adopted by governments to prevent the loss of lives and livelihoods from disasters. These global initiatives have encouraged similar actions to be taken at national levels in many countries around the world. Right now the biggest challenge is to integrate the global plans into local practices and processes to make DRR really effective (Britton 2002). This would enable working with the underlying causes of disasters and not only with their symptoms and would therefore improve the use of the available resources.

4. Disaster research today

The current approach to disaster management

The current approach to disaster management, DRR, aims to reduce the conditions that trigger disaster risks by influencing their causal factors in a systematic way and, in turn, reducing the potential negative outcomes. The process of DRR is systematized in four stages related to the triggering event (Gándara Gaborit 1990; Mileti 1999; Garatwa and Bollin 2002), which permits to establish clear objectives for the actions within each stage. The first stage, prevention and mitigation, begins before the occurrence of the event and aims to avoid or alleviate the potential adverse effects of natural hazards in the medium and long term. This phase includes legal, administrative, and infrastructure related measures. The second stage, preparedness, includes the actions needed to prepare institutions and population at risk in order to prevent or minimize death, injuries and other losses that can be caused by a forthcoming natural hazardous event and potential disaster. The third stage, response, refers to the actions taken immediately after the occurrence of a disaster and includes sheltering and the provision of health and food supplies. The fourth stage corresponds to recovery and includes all the actions taken post-disaster, i.e. after the emergency period is over, aiming at restoring the living conditions of people affected by the disaster in short, medium, and long terms and to reconstruct their livelihoods. The four stages can be seen as a cycle that continues without break: once a disaster is over and the recovery phase has taken place, new preparedness actions are started in order to construct an improved and more resilient system (RICS/ICE/RIBA/RTPI 2009).

The core objective of DRR is to reduce risks and losses (O'Brien et al 2006). The complexity of the circumstances linked to the risk of disasters makes it important to understand the individual components of the processes as well as their composite and its dynamics (Mileti 1999; Yodmani 2001; Britton 2002; Cutter 2005). A multidisciplinary approach is thus needed to complete such challenging task. The combined knowledge and expertise from natural and social sciences, paired with applied techniques (e.g. building techniques), is required to analyze and influence the processes that could lead to disasters and to prevent and reduce their potential negative consequences. Moreover, DRR requires an active participation of all the different people and actors involved in the process, including those that might be potentially affected, and its related strategies and plans should be created with the local population in mind (Trim 2004). All the parts involved in DRR should also understand the circumstances of the people experiencing the disasters including their realities, strengths, lacks, and needs (Trim 2004).

Disaster science advances

The evolution of the approach taken towards disasters leading to the current comprehensive DRR paradigm as well as the global need of reducing their negative effects has brought important advances to disaster science. Nowadays research is carried out both on the social and physical processes behind disasters (Delica-Willison and Willison; Heijmans; Britton 1986; Dynes et al 1987; Dales and Reed 1989; Aleotti and Chowdhury 1999; Alwang et al 2001; Begueria and Vicente-Serrano 2006; Biswajeet and Mardiana 2009; Wisner et al 2012), risk analyses are a common practice (Guarín et al 2004; Tesliuc and Lindert 2004; UN/ISDR 2004; Sperling and Szekely 2005; Fernandez and Sanahuj 2012), and risk maps are frequently used to inform actions within DRR planning (Zerger 2002; Viera Cepero 2003; Tsai et al 2008).

The involvement of different disciplines in disaster science enriches the methods and tools that can be used for DRR and also sparks the debate on the nature of the most important driving force (natural or social) behind the risk of disasters (Cannon 1993; Mileti 1999). Assessing the importance of each side of the physical-social duality is no easy task as each side is a composite of different and interrelated factors that are dependent on the specific place in focus (UNISDR 2009). The social side of the dichotomy, for instance, is the result of the interaction between people and their conditions and is studied through vulnerability assessments. Such assessments can later point to actions aimed at improving disaster-coping capabilities and avoiding preventable risks.

In order for vulnerability assessments to be useful on a local scale, studies on the geographical distribution of vulnerability are required. Several methods exist to perform this task such as the Total Place Vulnerability Index. This index determines the vulnerability of counties from the combination of a total probability of occurrences of hazards score and a total social vulnerability score, providing a weight of 50% to each factor. The probability of occurrence considers the historical hazard data without consideration of extent or magnitude while the social vulnerability considers age, gender, population, race, income, and number of mobile homes per country (Sutanta et al

2008). Another example is the Integrated Risk Assessment of Multihazards, which maps the risk through integrated hazard maps and vulnerability maps. Vulnerability maps are created from the hazard exposure, which is the representation of the financial capacity to cope with disasters in terms of GDP per capita and population density (Sutanta et al 2008). Although being useful to provide a general idea on how the vulnerability is distributed over a territory, the applicability of such methods to reduce people's vulnerability in practical situations is limited. In particular, the tendency of using GDP or other economic indicators to estimate vulnerability makes the vulnerability results a matter of monetary impact which, although important, is not representative of the impacts as a whole. There are many aspects of vulnerability that cannot be directly related to the GDP of a country, such as gender, age, and ethnicity composition of the population.

Due to the critical importance of data in disaster research, one of the most important achievements of disaster science is the creation of disaster databases. There are nowadays global, regional, and national (for many countries) databases that collect information on disasters. Several databases have been created for insurance purposes, e.g. Munich RE and Swiss RE databases, which, despite their high quality, are not often used for research purposes because they are not publicly available. Some other databases are created to support research on disasters, e.g. EM-DAT, DesInventar, or Glide. Each has a different resolution, data sources, and also different criteria to define what a disaster is and therefore which events are to be recorded. Some criteria are quantitative, such as establishing numerical thresholds for affected people, casualties, or economic losses. These criteria have been criticized on the grounds that numerical thresholds are not equally useful or valid for different social systems (Dynes 1998), e.g. the same number of fatalities or affected persons may have a different meaning for different social systems. Other definitions and criteria are established in qualitative terms and seem to be potentially more applicable to identify what is a disaster for different social systems. However, even if it has some advantages, qualitative data remains difficult to evaluate for quality and consistency. For example, the question of what is considered by "widespread losses" is rather open (UN/ISDR 2004) The answer would not be the same, for instance, in a rural village in Latin America as in a big city in the United States, so the answer is not easy to define. The differences in data collection systems might create limitations for particular research goals and/or uncertainties when using the information. Even so, the collection of disaster data is crucial to study disasters and, ultimately, to reduce disaster risk. Data collection systems should be maintained and enhanced when possible to enable better informed DRR actions.

Research on the local scale: the challenge

The concern for the impacts of disasters in both people's lives and economy over time has mainstreamed DRR into the global agenda. Nations and communities have engaged in the global initiative for disaster risk reduction to reduce the losses caused by disasters (UNISDR 2005; UNISDR 2015). The increasing interest in DRR has in parallel promoted the development of disaster research.

As discussed before, research has helped to understand the processes linked to disasters and to prioritize countries and regions where investments on DRR are most needed. Global trends, for instance, provide important knowledge on the number of disasters and provide feedback for the design and implementation of global frameworks. However, these global frameworks are only general outlines of the global necessities and need to be taken down and adapted to the local level in order to define practical actions that may, in turn, contribute to the achievement of the global goals. Indeed, the ultimate purpose of disaster research is to support DRR actions and plans that need to be undoubtedly carried out on the local scale. By targeting the appropriate scale through properly dimensioned policies, regulations, or appropriate systems and technologies, DRR can have a positive impact on people's lives. This implies that authorities, professionals, technicians and civilians need to plan and deal with DRR on the right scale according to their needs. Ultimately, this means that a high spatial and temporal resolution is generally needed for specific disaster research.

Much research has been carried out in, for instance, outlining areas exposed to natural hazards, identifying potentially vulnerable populations, identifying social dynamics that can lead to increased vulnerability, and other applications that are useful to increase resilience. The scale of the input data, however, conditions the resolution of the results. When research is carried out on a coarse scale (e.g. national, regional), the singularities of specific places where disasters tend to occur may be overlooked. If the detailed characteristics and processes behind disasters are not understood, the measures and action plans to reduce the risk of disasters may not be useful or less effective than planned. Research at a high temporal and spatial resolution is therefore not only required but essential, especially in physically and socially complex areas. Such studies strongly rely on the availability of good quality data. However, in many regions of the world quality data are either not available or very limited. This is the case of many disaster-prone areas and it is especially problematic on local scales. In the current data state-of-art many local-scale studies tend to be much less accurate than what is needed because the available data are coarser than what is needed for the required scale (Downton and Pielke 2005).

One of the most important challenges for advancing disaster risk reduction is thus to improve the quality and volume of research on local scales.

Studying the conditions of the specific locations where disasters actually occur should provide a deeper understanding of the processes behind those disasters. There are many disaster-prone areas of the world that need such knowledge to promote and support meaningful DRR actions on a local scale. The need is even bigger in data-scarce areas, where methodologies that can successfully be applied in other places are not feasible. The challenge is then broadened: to carry out research on a local scale and under data-scarce conditions.

Facing the challenge: the bottom-up approach

The place-dependency of disasters and the subsequent uniqueness of each case pose only one part of the challenge that needs to be overcome. The difficulties arising from working on a local scale and in data scarcity conditions constitute the other side of the same challenge. Facing this challenge demands methods that can produce knowledge on disasters on a local scale and that are capable of including the uniqueness of the place using the resources (i.e. data) that are available, even if limited. Such demand requires an approach that is different from the traditional top-down one (Blöschl et al 2013).

The top-down approach relies on a probabilistic modelling of the processes causing hazards and their potential adverse consequences. Plans and decisions are then produced to reduce the estimated risk. This approach requires a reliable model of the hazardous processes, which in turn depends on the availability of sufficient good quality data. Its application is therefore difficult (if not impossible) in data scarce circumstances. The uncertainty associated to traditional top-down methods becomes even larger when multiple hazards are present, not to mention unpredictable cascading effects, e.g. black swan events (Taleb 2007).

The bottom-up approach (Blöschl et al 2013), on the other hand, is focused on the local context of a society facing multiple natural hazards. It begins from the analysis of the particular conditions of people that have to deal with the natural hazards, i.e. societal vulnerabilities. The application of this approach requires the development of vulnerability maps portraying features, characteristics, and processes within the social systems that create potential weaknesses of people, especially when they are put under stress as during the occurrence of an extreme natural event. Such weaknesses can undermine the capabilities of people to cope with the effects of natural hazards.

The bottom-up approach analyzes the particular conditions as they are and is consequently dependent on the particular context of the research object. Because of this dependency, the research procedures within the bottom-up approach tend to require a methodological exploration when designing the research.

The bottom-up, vulnerability-based approach is valuable as a complementary counterpart to the top-down, hazard-based approach. The former deals better with scarce data on the physical processes and potential occurrence of essential unpredictable events, and provides a depiction of the conditions that can potentially make social groups subject to harm. The latter can support the estimation or prediction of (some) natural hazards in a determined time and place.

An important advantage of the bottom-up approach, when compared to the top-down one, is given by the fact that, by focusing on the people, it identifies conditions that are part of the social system and that make it weak when put under stress, regardless the specific source of the stress (which can be unknown). The top-down approach needs to focus on particular natural hazards, which have different ways to affect people and thus demand a specific way to be dealt with.

5. Study area

The Samala River catchment (N 14° 10' - 15° 3', W 91° 17' - 91° 53') is located in Southern Guatemala and is part of the Pacific Ocean basin. It is elongated and has an area of 1500 km^2 with elevations ranging from 0 to approximately 3770 m a.s.l. (*Figure 3*C).

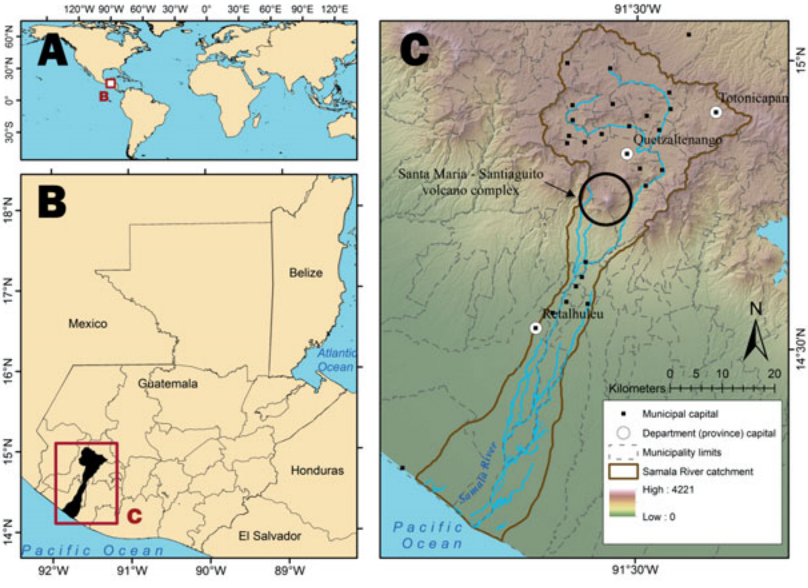

Figure 3. The Samala River Catchment. A and B show the location of the Samala River catchment in the world and in Guatemala respectively. The catchment (c) shows a mountainous relief that includes the Santa Maria – Santiaguito volcano complex (black circle). GIS data source: USGS and SEGEPLAN.

Guatemala is part of the Central American isthmus, which is a narrow land bridge of recent geological formation between South and North America created by the convergence of the Cocos plate with the North American and Caribbean plates. Tectonic and volcanic processes working together produced the specific geological configuration and dynamics of the isthmus (Mann 2007) (*Figure 4*). A volcanic cordillera runs across the isthmus parallel to the Pacific Rim and includes numerous active, dormant and extinct volcanoes.

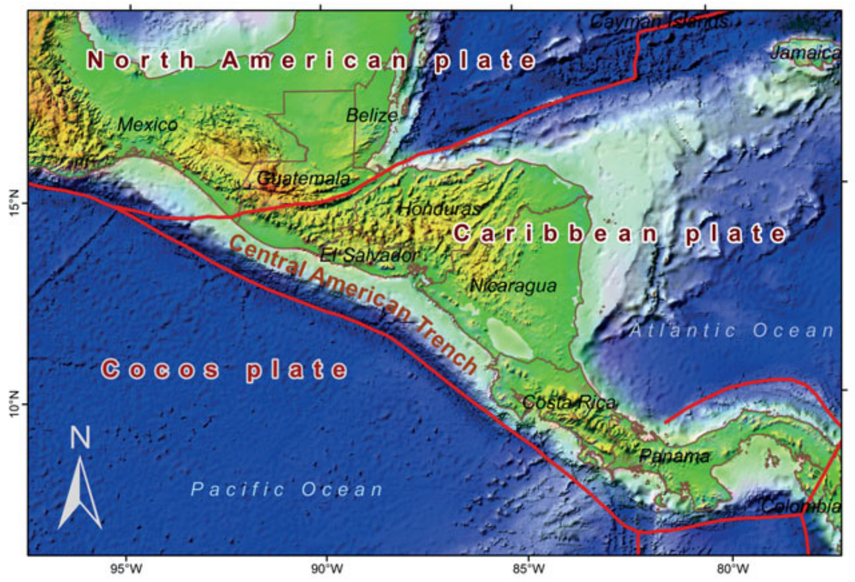

Figure 4. Central America tectonic setting. The Cocos plate subducts in a northwest direction. The volcanic cordillera that runs across the Central American isthmus includes numerous volcanoes (active, dormant, and extinct). Data sources: ESRI/NOAA/NGDC (ESRI 2012) and USGS (2014).

The northern section of the Samala River catchment comprises part of the volcanic cordillera, including the active Santiaguito volcano[1], whereas its southern part is composed of alluvial coastal lands. Steep volcanic flanks separate the two main geographical domains (*Figure 3*C).

The climate of the study area is generally determined by its tropical location within the hurricane alley. Temperatures are quite stable along the year because of the closeness to the equator and they are influenced by the airflows from the Atlantic and Pacific oceans. Local climates are, however, diverse due to the large elevation range. The lowlands and coastal plains are hot humid areas, while the mountain slopes closest to the oceans are very humid and hot, and the highlands are humid and with variable temperature depending on the elevation (Herrera 2003). The annual mean temperature in the study area ranges from 15 to 28°C and the mean annual precipitation from 1000 to 4000 mm (INSIVUMEH 2003). The geographic distribution of

[1] The Santa Maria volcano exploded in 1902 and a big crater was created. From this crater a new dacitic cone started to form in 1922 and has been under constant evolution since then, constantly producing new material (Kuenzi et al 1979). The new cone system was named Santiaguito and it is one of the most actives volcanoes in the country. The Santa Maria – Santiaguito volcano system was declared as one of the 16 world's decade volcanoes during the International Decade for Natural Disaster Reduction in 1990 because of its history of destructive eruptions and proximity to populated areas (USGS 2002).

precipitation is highly variable due to the orography and the oceanic influence, with the precipitation maxima occurring in the volcanic slopes (IARNA/URL/IIA 2004). Rainfall occurs intensely from May to October (rainy season) and precipitation peaks tend to occur when tropical storms pass the Central American region during the hurricane season (IARNA/URL/IIA 2004).

The topographical drivers, the abundance of loose materials produced by volcanic activity, and the intense rain periods create favorable conditions for the development of a meandering river system originating in the highlands. The Samala River then cuts the volcanic range through a steep sharp canyon transporting volcanic material that is deposited in a large alluvial fan with gradually decreasing grain sizes downstream. The river continues as a braided system on the coastal plains and finally drains into the Pacific Ocean. The sediment transportation capacity of the Samala River is enhanced during the rainy season (*Figure 5*).

Vegetation is diverse and abundant throughout the catchment except for the volcanic flanks, which are barren due to the constant deposition of new volcanic material. The mineral-rich sediments that are transported by the Samala River create favorable conditions for agriculture along the coastal flood plain. Guatemala has historically been an agricultural country and people have settled and grown crops in this area since pre-Columbian times, especially in the coastal plains and in the flat areas of the highlands.

The geological origin, geomorphology, and climatic features of the Samala River basin make it susceptible to the occurrence of many natural hazards, including volcanic eruptions, ash falls, landslides, flooding, lahars (debris flows of loose volcanic material), and flash floods (Alcántara-Ayala 2002; Harmeling and Eckstein 2012). This is especially the case towards the coastal plain where the amount of material that is intermittently transported may eventually force the river channel to shift laterally. Channel shifting in the braided sections of the river changes people's living conditions and impacts infrastructure during flooding events.

Population projections for the year 2015 estimate that over a million people live in the municipalities that lie totally or partially within the catchment. Agriculture and livestock are the most extensive economic activities in the area while trade is the main economic activity (MAGA 2002). The study area encloses the second center of economy, trade, education, health and other services in the country (Quetzaltenango) and the most important roads in the country for international and domestic transportation traverse the catchment east-westwards (Central American Roads CA1 and CA2). The catchment area belongs administratively to 29 municipalities (only partially to 16 of them). The hydrological unit was used as boundary for this case study because the focus of the research work was on natural hazards, which are ruled by processes enclosed in natural units.

The Samala River catchment provides a case study representative of an area where people are exposed to multiple natural hazards and conditions that make them potentially vulnerable to disasters. The frequent reports of disasters in the area confirm that comprehensive research on natural disasters is needed to support DRR actions. Several studies have focused on some of the physical processes responsible for disaster risks in Guatemala (Kuenzi et al 1979; Vallance et al 1995; Viera Cepero 2003; Guarín et al 2004; Chigna and León 2010; Chigna and Mota 2011) while others focused on the disasters that result from those processes (Gándara Gaborit 1991). Further studies are however needed to improve the understanding of disaster risk in the area and, more importantly, to promote progress regarding DRR that can have an impact in terms of quality of life for the local communities.

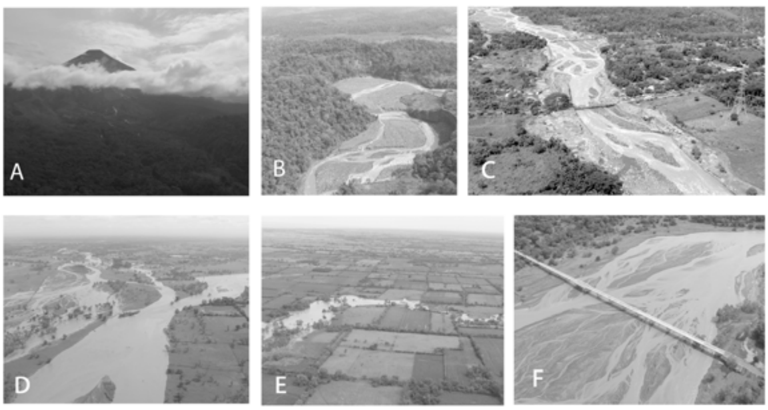

Figure 5. Characteristic landscape of the Samala River catchment: (A) The Santa María – Santiaguito volcano complex and the highlands; (B – F) Profile of lower section of the Samala River: interface between the transfer and deposition zones, intersection of the river with the CA2 road, lateral channel shifting, agricultural floodplain, and river mouth respectively. The size of the deposited sediments gradually decreases downstream. Source: CONRED (2010)

6. Data

Geographic data

A digital elevation model (DEM) with a cell size of 15 x 15 m and a set of digital geological and geographical maps of the study area were provided by the *Guatemalan National System of Territorial Information* (SEGEPLAN 2012), including data on geography (e.g. geological origin, general land use, rivers), key buildings and infrastructure (roads, bridges, schools, hospitals), and administrative boundaries (*Figure 6*). Roads and basic infrastructure data are available for many countries (e.g. SEGEPLAN for the case study) and open source data can supply any lacking information (e.g. OpenStreetMap).

Precipitation data

Data on rainfall in Guatemala was provided by the *Guatemalan Institute of Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH)*. Three meteorological stations were identified in the study area: one in the highlands (Labor Ovalle), one in the lowlands (Retalhuleu), and one in the steep slopes between the two (Santiaguito). The latter station is actually a volcano observatory that has recorded precipitation data only as secondary data. Retalhuleu data has the longest daily precipitation record in the catchment and is the one with comparatively best quality (*Figure 7*). The temporal variations of the three datasets were similar but the absolute amount of precipitation of each station was different. After some consideration Retalhuleu station was chosen as representative for the temporal variation of precipitation of the area, assuming that the increments and decrements would be similar in the whole area, but that the actual amounts would be different from place to place. The missing rainfall data were not filled because the studies that were carried out were looking for relationships between the occurrences of disasters and the actual amount of rainfall in the day of the occurrences.

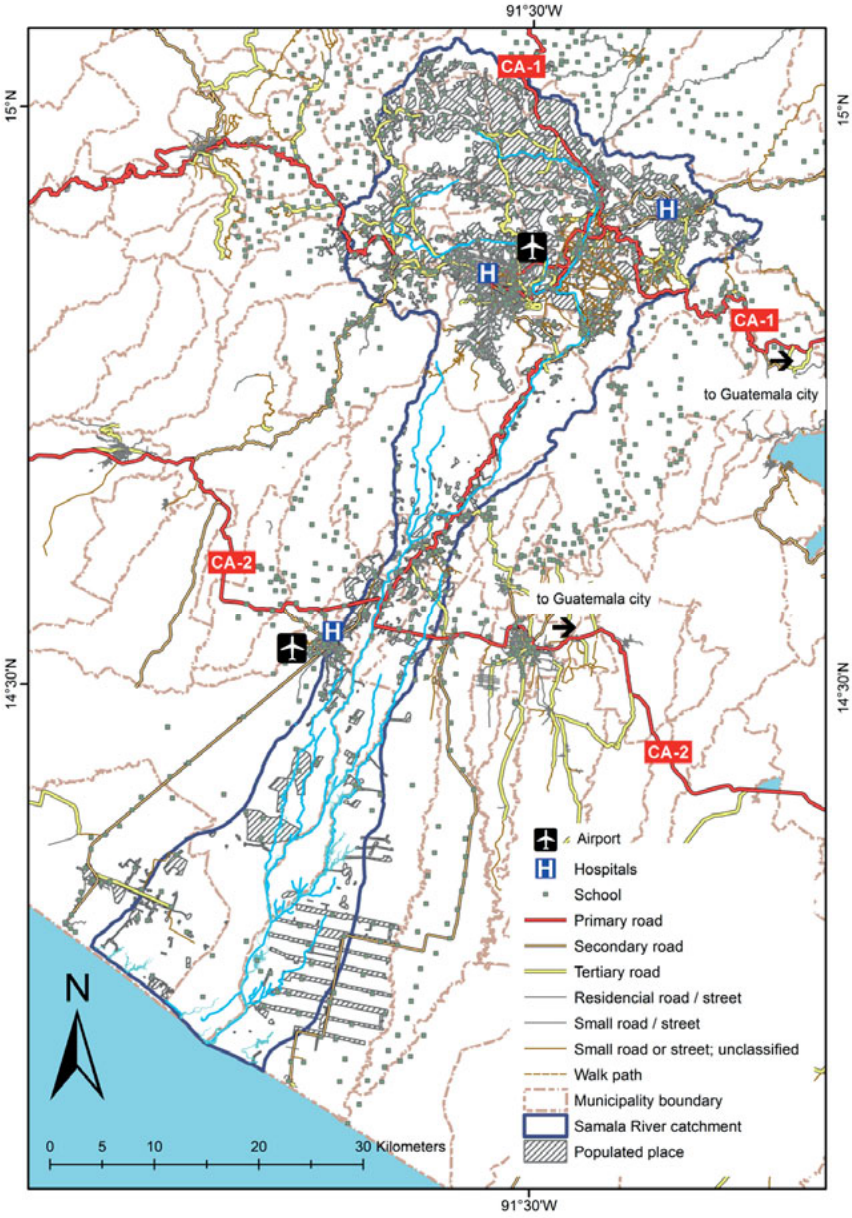

Figure 6. Infrastructure in the Samala River catchment. Data source: SEGEPLAN (2012).

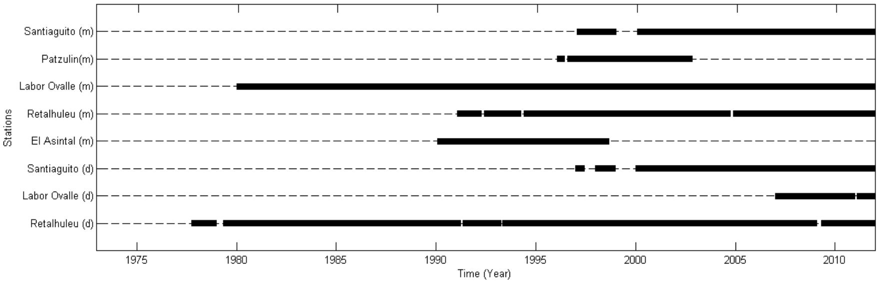

Figure 7. Precipitation data available for the Samala River catchment. The bars show the daily (d) or monthly (m) available data in the different stations as well as the data gaps in each. Patzulin and El Asintal stations existed in the past but are no longer functioning. Source: INSIVUMEH.

Disaster data

EM-DAT

Created by the Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT is one of the best-known international sources of disaster data and it is available online. According to the website, their goal is to provide foundations for vulnerability assessment and rational decision making in case of disasters (Guha-Sapir et al 2009). EM-DAT data are collected globally at country level and comprise information starting from 1900. The database aims to collect information on the underlying natural hazards, and disaster duration, location, description, and associated losses and damage in general terms. Events are only considered as disasters and included in the database if they fulfill one of the following criteria: at least 10 or more people reported killed, 100 or more people affected, a declaration of a state of emergency, or a call for international assistance. For Guatemala, EM-DAT has 25 reports of floods, storms, volcanic eruptions, earthquakes, and landslides from 1900 to 2011 that could be located or related to the municipalities lying in the study area. The selection criteria favor the inclusion of large national level disasters and, in some cases, regional ones as well. Potential limitations are the exclusion of local scale disasters and the over-generalization of the provided information. Even so, the systematic basis of EM-DAT made the database useful to guide data management tasks during the research work. Its limitations, however, prevented the database from being used for specific studies because the scope of the data reaches only the national level.

Disaster Inventory System (DesInventar)

DesInventar is created by the Network of Social Studies in the Prevention of Disasters in Latin America (La Red), which aims to construct national databases of losses caused by natural disasters in such a way that local-scale disasters are visible (DesInventar 2011). The system was later implemented in the Caribbean, Asia, and Africa, and it is currently sponsored by the United Nations (UN) to create a larger network of disaster databases using a homogeneous methodology. DesInventar seeks to enable spatial and temporal analyses of the effects of disasters for risk-management purposes by recording these effects at a fine resolution (OSSO/La Red 2009). The main sources of information for DesInventar are national institutional reports and local media reports (newspapers). The data are later verified by comparison with official reports of disasters (such as those of the *Guatemalan Coordination Office for Disasters Reduction -CONRED-*) if available. The database aims to collect information on the type of hazard causing each disaster (using a classification system based on the actual data systems that feed the database), duration, magnitude, location, description, source, losses, and damage (human and material). Part of the data included in DesInventar is robust (quantitative) and another part is fuzzy (description of unmeasured effects) (Serje). Data for Guatemala includes 356 reports of incidents caused by natural hazards from 1988 to 2011 in the municipalities completely or partially lying within the catchment. Those reports are related to volcanic activity, torrential floods, storms, sedimentation, rainfall, landslides, inundations, hail, gales, frosts, electrical storms and earthquakes (wording from the source).

The Guatemalan Information Management System in case of Emergency or Disaster (SISMICEDE)

SISMICEDE was established in 2008 by CONRED. It includes all disaster occurrences and related information (e.g. damage, if any) in Guatemala that is reported by people *in situ* to the members of the national system for disaster reduction. The main purpose of SISMICEDE is to provide information to decision makers during emergencies (CONRED 2010) and therefore all the information needs to be verified by local delegates of the institution before being included in the system. This system is nowadays used to build the national database of disaster occurrences and can be assumed to be reliable. The information comprised should include the hazard's class, origin, duration, location, and probable cause, together with a description of the incident, and human and material damage. Most reports in the system have detailed location information, which makes SISMICEDE the only dataset for Guatemala that includes geographical coordinates or identifiable location references (e.g. town/village name) for individual reports. SISMICEDE data are therefore valuable information because of its high spatial resolution. It does however come at the cost of a limited time span. SISMICEDE data are not open to the public but it is available upon request to CONRED. The dataset includes 653 records of disasters in the municipalities related to the study area from 2008 to 2011, out of which 632 were kept and used after data quality control (Paper I).

The analysis of the three identified disaster datasets for Guatemala showed how different the picture of disaster occurrences can be depending on the consulted source. The national database records the events that required being managed or at least known by the authorities to be solved. This suggests that the closer the database administrator is to the source, the more complete the provided picture of the actual disaster situation will be. Potential uncertainties in the sources are, however, always present and care should be always be taken in order to detect them and, if possible, handle them.

Remotely sensed imagery

Nighttime imagery from the US National Ocean Agency (NOAA) is a series of global cloud-free composites of the images, each collected by one of six satellites (called F10 to F18) during nighttime at yearly intervals (from 1992 to 2013, although the images of 2012 and 2013 were not used in this work). The series are freely available through the NOAA website (NOAA 2014). Each image is a raster grid with a cell size of 30 arcseconds (approximately 0.90 x 0.90 km in the Equator). Each cell in the images has an integer unitless value between zero and 63 that corresponds to the average brightness of the cell during the corresponding year. The NOAA recommends an intercalibration of the composite images if they are to be used for temporal comparisons. The intercalibration method proposed by Elvidge (2009) was applied using a rectangular section of the yearly images that enclosed Guatemala and averaging the intercalibrated images corresponding to the same year (Ceola et al 2014). A section corresponding to the Samala River catchment was then extracted from each image for the studies in Paper III and IV.

Population data

Data from the Guatemalan national census of 1981, 1994, and 2002 (INE 1981; INE 1994; INE 2002) and the official population projections (INE 2004) were used to analyze population over time. The spatial unit of the census data is the municipality.

7. Methods

This section describes the methods that were developed in the 4 papers. In Paper I disaster data were studied to identify the difficulties and problems that such data can present in the selected case study. Two different datasets, one with high spatial resolution but very short time span and one with longer time span but lower spatial resolution, were selected and used to characterize the natural disasters in the area. In Paper II geomorphological data of the area were used to look for patterns on the spatial distribution of disasters that a general analysis on the data was not able to show. Finally satellite data were used to explore the causality of natural disasters in the study area by studying the spatial distribution of exposure to natural hazards (Paper III) and social vulnerability (Paper IV).

The different methods are based on experimental procedures and are here described conceptually to allow them to be replicable regardless of the location of the study area. The results from the application of each method in the study area are explained in Section 8. The methodological conclusions drawn from the methods used, which aim to complete the descriptions of the methods for further developments and applications are described in Section 9.

Puzzling out data issues (Paper I)

The aim of this study was to investigate the temporal trends of the occurrences of disasters when data on disasters are limited. The work was carried out by compiling two different databases, one with high-spatial resolution but short time span and the other one with longer time span but coarser spatial resolution.

The first step of the method was a general search for open databases. Organizations concerned with disasters, emergency response organizations, and national authorities in charge of disaster risk issues were the potential sources of data. Online availability enabled worldwide searches. Suitable data should be selected: data must be available for the selected country, the information must provide information on the location of disasters (the more specific the spatial unit the better), and data must cover a considerable time span. For the case study, data covering a minimum time span of 10 years was aimed for. Unsuitable data should, in principle, be rejected. However, in data scarce conditions particular considerations may be taken into account to be able to derive some useful information. The template used by the databases to collect information was identified to visualize how the information is codified and what information is expected to be included, which indicated the level of detail that each database is capable to provide.

A quality control was performed for the acquired data. The general attributes of the different data bases were compared in a table. The volume of data included, time span, and spatial resolution determined the informative capacity of the datasets. The data quality control determined whether a single database had the potential to provide enough information for spatial and temporal analyses or if data compilation would instead be needed. The completeness of the data according to the respective data entry layout and the accuracy of the geographic information according to national geographic information were then evaluated. Only complete and accurate information was considered valid. If possible, incomplete information was verified without alteration by using complementary data (e.g. geographical data of census tracts, town names, school locations, etc.). Wrong, deficient, or inaccurate data were disregarded.

Data compilation was carried out using the verified data with the assumption that a specific disaster state of affairs should be comparable when depicted by different databases of similar temporal and spatial resolution. Therefore, the information of two or more databases can be compiled to complement the provided information. The information set that the data compilation process aims to gather includes a description of the events (identification of the type of event, magnitude, duration, location), information of the origin and cause of the event (e.g. presumed or recognized causal natural hazards, origin, other observations), information on the effects of the event in terms of people (fatalities, wounded, evacuees, relocated, sheltered, etc.), houses (damaged, destroyed), other infrastructure (roads, bridges, water and sewage systems, power infrastructure, schools, etc.), and economy (money, crops, livestock, forest, etc.). Data compilation required a reclassification of the data according to a common set of classes that included all the identifiers in the input databases. The reclassified data of each dataset was aggregated by (a) class, (b) type of underlying natural hazard, (c) month of occurrence, and (d) location at the finest common scale. The aggregated results were compared (in percentages, in order to reduce potential noise) to determine if the depiction of the disaster situations was similar for the different databases.

Two datasets were found suitable for compilation: the database with finer spatial resolution (SISMICEDE) was used for spatial referencing and the one with longer time span (DesInventar) was used for temporal analyses. The percentage of reports that occurred in the study area among all those registered in the municipalities lying partially within the study area was calculated using SISMICEDE data. These percentages were applied in the DesInventar database to refine the number of disasters to be included in the trend analysis (Paper 1). The refined dataset was then used to perform yearly and seasonally (rainy – dry season) trend analyses of disasters in the study area.

Assessing the importance of place (Paper II)

This study aimed at assessing the importance of the physical configuration of a specific area as a cause of disasters, studying the spatial distribution of disasters in the study area and the physical attributes of the locations where disasters were reported. SISMICEDE data were used for this study because it is the only dataset that includes a particular location for disaster occurrences.

Profile graphs from DEMs and orthophotos were used to visualize the general landscape configuration of the study area and to identify outstanding physical features. The physical complexity of the study area required principles of geomorphological classification (Verstappen and van Zuidam 1975) to be used to define smaller geomorphological units according to the physical features of the landscape where specific geomorphological processes were expected. Geographical Information System (GIS) software was used to analyze the relief and physical configuration, mainly in terms of slope. Slope values were aggregated to create areas of high likelihood of disaster occurrence. Geological and physiographic maps were overlapped to increase the level of geomorphological differentiation in the area. Orthophotos were then overlain to discriminate volcanic processes (indicated by the presence of new material). Water divides were drawn using the DEM and added to the set of overlapped layers of analysis. The overlap of the different layers provided the criteria to define the boundaries of the individual geomorphological units within the study area. Seven units of analysis were finally created.

All the disaster reports were classified in the respective geomorphological unit and paired with the key physical features of their specific location and date (slope, precipitation). An empirical Wetness Index (I_{wet}) was calculated to account for water accumulation in the soil from previous rainfalls.

Equation 1

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

The I_{wet} index is an arbitrary indicator of wetness (with no actual physical meaning) of the moisture in the soil accounting for the rainfall of the day (P_1) and the weighted rainfall of the preceding 9 days ($P_{2 \text{ to } 10}$ in Equation 1 and Paper II, page 185). The resulting I_{wet} was added to the physical features included in the paired analysis of the disasters. The relative frequency of disasters according to the different physical features included in the study was plotted to determine the physical conditions in which most disasters were registered and obtain information on the most likely disaster triggering physical conditions in the study area.

Mapping societal exposure to hydrometeorological hazards (Paper III)

This study aimed at exploring the causality of the trends in disasters caused by hydrometeorological hazards in the study area, considering changes in both natural and social components of risk. The study focused especially in the social component of risk to explore the applicability of remotely sensed data on assessing the exposure to natural hazards on the local scale. The natural component of risk was assessed in terms of the probability of occurrence of hazardous events (extreme rainfall) and the social component of risk was considered in terms of the potential adverse consequences (exposure). Population data from censuses were used in this study. Census years were used to set both the temporal span of the analyses and the limits for the analysis periods, which allowed to use the actual population data for the calculations instead of projections.

The impact of disasters in the study area over time was assessed in terms of number of fatalities per person and year. The number of disasters recorded by DesInventar in the periods of analysis was divided by the average population in the period and the number of years in the intercensus period. The analyses were carried out for the whole study area but also separately for the highlands and the lowlands, the main geographical subdivision of the study area (Paper II).

The trend in hazards was assessed in terms of extreme precipitation maxima: the yearly maxima of daily precipitation, the yearly maxima of accumulated wetness, and the yearly number of days when the accumulated wetness surpassed a threshold value identified in Paper II. The series of precipitation maxima were graphed and linear regressions were calculated together with 5-year running averages to identify any potential trend.

The trend in vulnerability was assessed in terms of exposure, using the nightlights variations as a proxy for spatial population dynamics, i.e. population distribution, growth and densification. The images corresponding to the census years were used for the temporal analysis. A subset of cells corresponding to the path of the Samala River was extracted to be analyzed separately. These are areas with close proximity to the river and the population living there was assumed to be directly exposed to the main types of disasters in the study area: floods and lahars (according to the results of Paper I and II). The frequencies of brightness values were aggregated in empirical ranges of brightness (0, 1-30, 31-55, and 56-63), and the proportion of the area that recorded nightlight over time as well as the characteristic average brightness in the catchment (total brightness divided by the number of cells) were calculated and graphically compared over time to identify any potential trend. Similar analyses were carried out using the subdivision of the study area into the highlands and lowlands.

Mapping vulnerability to support crisis management (Paper IV)

The study aimed at presenting a simple method to map spatial vulnerability (i.e. vulnerability of people in terms of location) to support decision-making during crisis management periods. The proposed method produced spatially distributed maps of *Relative spatial vulnerability index (RSVI)* in terms of critical connectivity and population density as determining factors for the survival of people in the event of a disaster under the conditions of a predetermined crisis management plan. Crisis management plans should include the resources that are expected to provide support for the population in case of a disaster such as shelters, health centers, supply delivery points, etc.

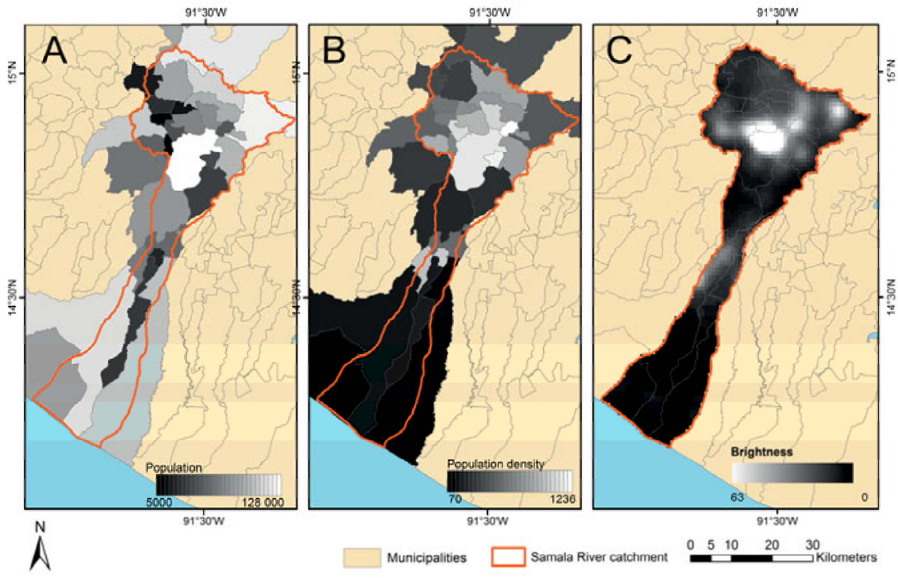

Figure 8. Spatial resolution of censuses and nightlights in the Samala River catchment 2002. The figure shows how different depictions of the distribution of people in the study area are produced depending on the data source: (A) census municipal population, (B) census municipal population density, and (C) nightlights. Data sources: (A) and (B) INE (2002), (C) image and data processing: NOAA's national Geophysical Data Center. DMSP data collected by US Air Force Weather Agency (NOAA 2014).

The grid of cells of the nightlights imagery was used to define geographical study units. The brightness values were used as proxy data for population, which can normally only be quantified on the municipal scale when using census data (*Figure 8*). The assumption that the brighter an area is, the denser is the population in the area was tested by comparing the total brightness of the cells within a municipality with the actual population of the municipality in three selected years. This test was developed when designing the methodology of Paper IV. Put in perspective, the test should have been applied in the setting of Paper III, which is why it is advisable to be included as well. The correlation found is significant at the 95% level (*Figure 9*).

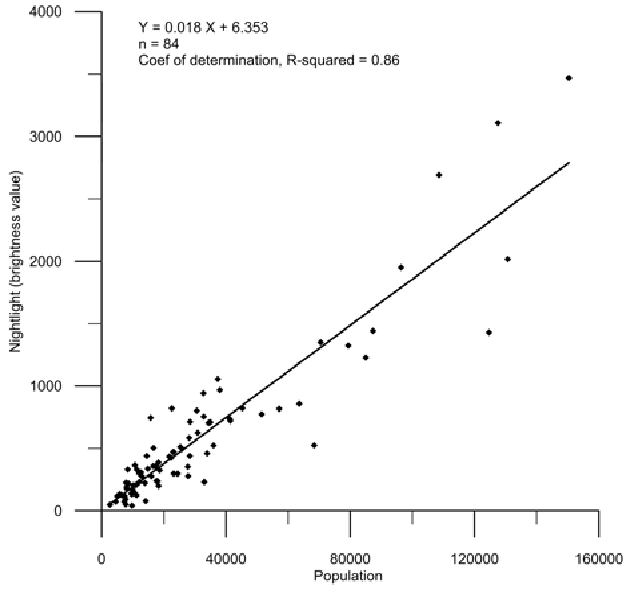

Figure 9. Correlation analysis between total brightness and population by municipality in 1994, 2002 and 2011. data sources: NOAA and the Guatemalan Statistics Institute *Instituto Nacional de Estadística* (INE 1994; INE 2002; INE 2004).

The Relative Spatial Vulnerability of a cell, as defined in this study, is directly proportional to the *critical distance (D)* and *population density (d*)* (Equation 2). In Equation 2, d^* corresponds to the brightness value of the cell as a proxy for population density and D corresponds to the distance from each cell to the closest vital infrastructure element (e.g. hospital, main road, shelter) measured through a transportation network (e.g. roads, train). The terms in the RSVI equation were normalized between 0 and 1 in order to make the results comparable over the different geographic areas under analysis. Additionally, each term was weighted to allow assigning a specific weight to each factor according to the particular conditions of the selected area.

Equation 2

$$RSVI = \propto_{d^*} d^* + \propto_D D$$

ArcGIS was used to compute the distances in Equation 2. In cases where the transportation network did not reach the desired cell, the distance between the cell and the closest point of the transportation network was calculated and considered to be walking distance. The walking distance is a critical connectivity factor because it should be covered right after the hit of a hazard and under the most stressful conditions. This distance it should be added to the main connection distance and then the different distances should be weighted according to the time required to cover each of them. If no crisis management plan is designed, the method can be applied to evaluate the RSVI according to the infrastructure elements identified in the available data. In any case the resulting RSVI may provide valuable information on the weaknesses that people would face due to their location and therefore enable the definition and the prioritization of the actions to be taken.

8. Experimental results

Puzzling out data issues results (Paper I)

The data quality control showed that only the global database (EM-DAT) had a complete set of data according to its layout. Information was missing or given only in qualitative terms in the DesInventar and SISMICEDE databases. The completeness map of the identified databases showed that all the datasets had advantages and disadvantages for local-scale spatial and temporal analyses and that no single database would be sufficient to allow local-scale temporal analyses by itself. Consequently, a database compilation was required. It was determined that the scale of location descriptions in the EM-DAT database was not suitable for local scale studies but it was nevertheless still included in the comparative analysis to corroborate the decision.

DesInventar and SISMICEDE were the databases selected for the study. Both databases showed similarities in the structure of the collected information (Table 1, Paper I) but the actual content varied significantly among them (Table 2, Paper I). The purposes of the two databases showed to be different. While SISMICEDE is meant to be used at an operational level for monitoring and emergency management purposes, DesInventar focuses on the aftermath of disasters. The location is more important when assigning resources for emergency management than when calculating the costs and losses *a posteriori*. The detailed SISMICEDE data were found more useful for research purposes, especially when focusing on a local scale. An analysis of the databases showed that on the one hand, while the spatial resolution of SISMICEDE data was high its temporal span was very short. On the other hand, the spatial resolution of DesInventar was coarser but included a significant longer time span. The usability of the identified databases for local applications was thus limited either because of the short time span or because the coarse resolution.

The comparison between the aggregated data of the different datasets showed that datasets with similar spatial resolution (municipal level) corresponded fairly well but contrasted with the results of the global database (*Figure 10*). The differences might be due to the different focus of the databases: when the focus is on large-scale disasters and at national levels, many occurrences become invisible and the distribution of aggregated data shows different patterns. The analyses showed that, according to all the databases, disasters of hydrometeorological origin are dominant in the case study area and that they show an increasing trend from 1988 to 2011. The refined data of the database used as temporal input and the database used as spatial reference corresponded to each other in terms of showing increases and decreases over time during the coincident 4-year period. Since the coincidence period was only four years, the possibility for generalization of the results is limited. Noting this, it is still considered that the restricted comparison over time of two different databases was useful to build a better understanding of the disasters occurring in the study area.

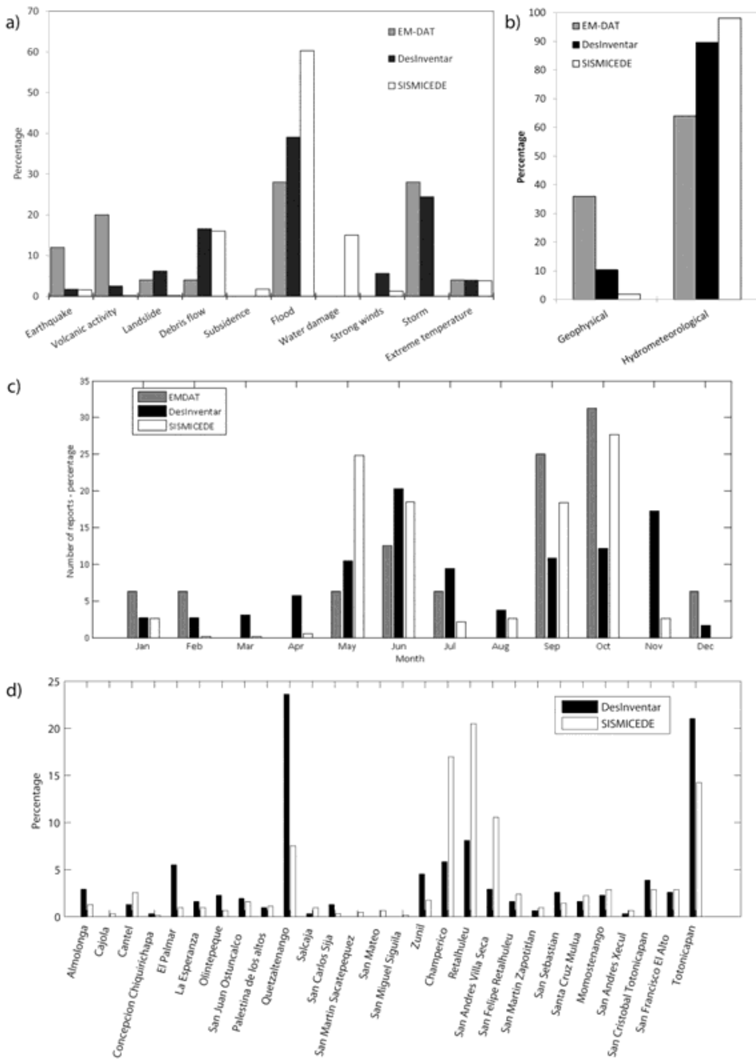

Figure 10. Natural disasters in the Samala River catchment. EM-DAT, DesInventar, and SISMICEDE data agregated by (a) type of disaster, (b) origin of the natural hazard, (c) month of occurrence, and (d) location (municipality) show the different depictions of the disasters in the case study that each database provides (Guha-Sapir et al 2009; DesInventar 2011; CONRED 2012).

Assessing the importance of place results (Paper II)

The physical complexity of the study area gave place to three main sections within the study catchment: the highlands, the lowlands, and the volcanic cordillera (slopes). Seven different geomorphological units were defined, mainly distinguishing zones of transport and deposition of loose material from igneous and metamorphic areas that determine the active physical processes in the study area (*Figure 11* and *Figure 12*). The geomorphological units allowed the characterization of the physical features and processes expected in each geomorphological unit and therefore the determination of the most probable disaster type within each unit (Table 1, Paper II). The determined disaster type could later be compared with the disasters recorded in each zone to look for indications of whether the physical context was an important driving factor for the occurrence of disasters.

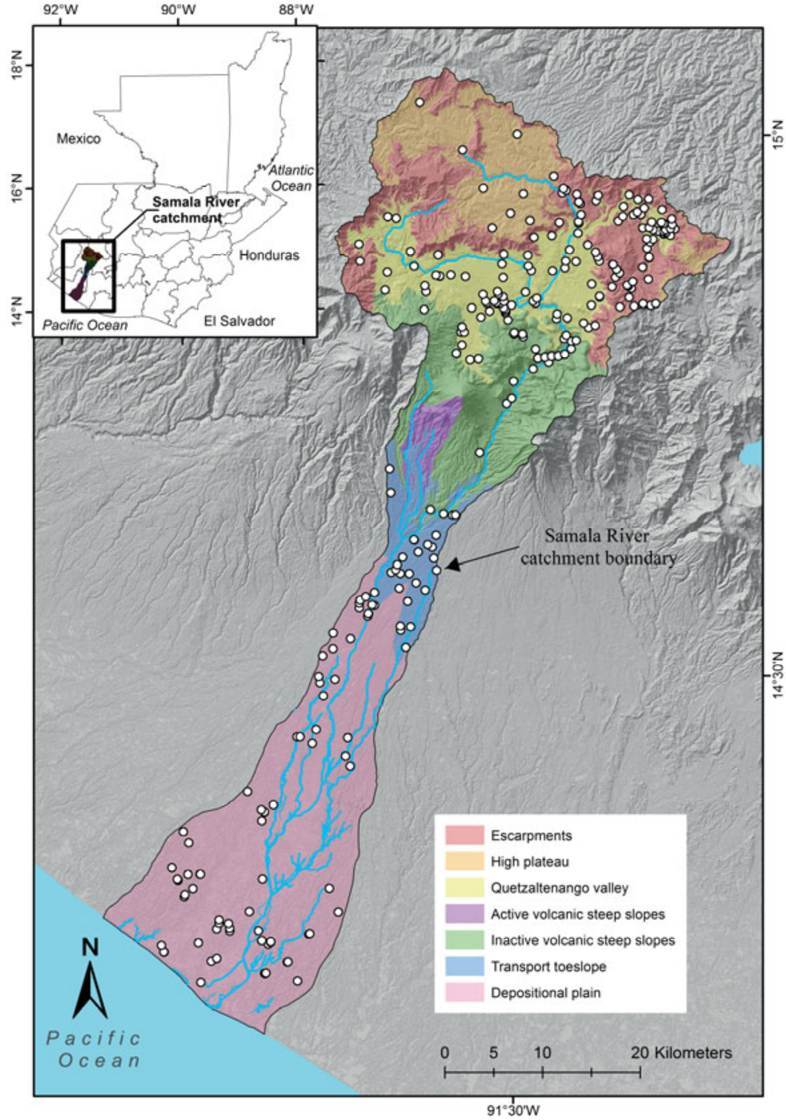

Figure 11. Geomorphological units in the Samala River catchment and location of SISMICEDE reports 2008-2011.

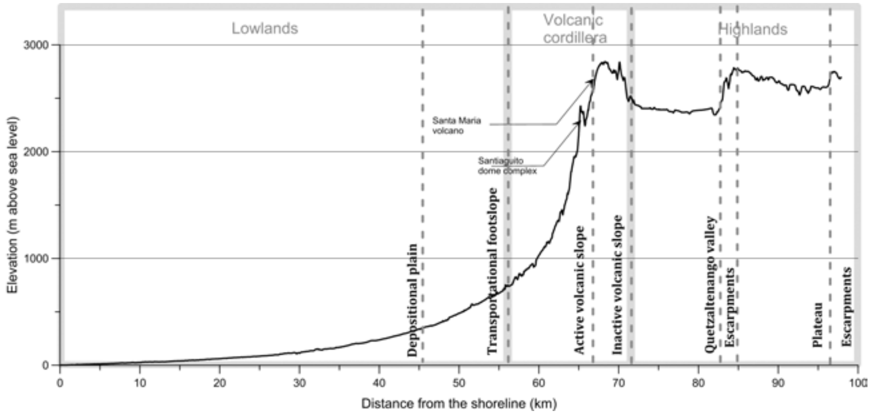

Figure 12. The geomorphology of the Samala River catchment.

A spatial relationship was found between the number of reported disasters and the physical characteristics of the different geomorphological units (slope, precipitation, and soil wetness). The relationship between the number of disasters and slope was moderate with disasters generally taking place most frequently in flat areas of the highlands and in the coastal plain, which are, historically, the most populated places in the catchment. This may indicate a social influence in the frequency of disasters. The same result was shown for the steeper geomorphological zones, where the highest probabilities of occurrence were also found in the flattest areas. A possible explanation to this result is that disasters tend to occur in areas that have been modified for human use, making them artificially flat. It is important to mention that the relationship between slope and occurrence of disasters was not present when analyzing the catchment as a whole. Additionally, it was found that no disasters were reported in the volcanic slopes where new volcanic material is deposited, a result that could be expected since such area is not suitable for human settlement.

The analysis of soil moisture showed a strong relationship between the occurrence of disasters and wetness. A threshold above which the number of registered disasters increased significantly could be identified at around 300 – 350 mm. As previously discussed, this index does not provide a real measurement. The threshold identified in most areas is however indicative of a particular process that is triggered when a certain moisture level is reached in the soil, and which requires further investigation. The most frequent types of reported disasters in the different geomorphological units showed the expected pattern: debris flow is the most frequent type of disaster in the units where steep slope angles are predominant whereas floods are the most frequent report in units with predominantly flat landscapes.

Mapping societal exposure to hydrometeorological hazards results (Paper III)

The analysis indicate that the relative impact of disasters in the study case has steadily increased over time and that this increase is mainly driven by the impact of disasters of hydrometeorological origin, with most occurrences being geographically located in the highlands. These results correspond to the increasing global trend on the impact of disasters of hydrometeorological origin as well as to the increasing impact of disasters in terms of fatalities in Central America, which contrasts with the decreasing trend on the global scale (Guha-Sapir et al 2011). The analysis on yearly maxima of daily precipitation and yearly maxima of wetness index (Paper II) showed no significant trend. An increasing trend significant at the 95% level was identified in the number of days per year when the wetness index was equal to or larger than the threshold value identified in Paper II. The nightlights analysis in the study area showed that vulnerability in terms of exposure to natural hazards has been increasing as well. Dark areas have been steadily decreasing over time and cells with brightness values between 1 and 30 are the ones that have been increasing the most. The ratio of bright cells to the total number of cells as well as the general brightness of the study area has also been steadily increasing. The results showed that the population dynamics in the highlands play a more important role in the overall dynamics of the study area than the population dynamics in the lowlands (*Figure 13*). The population dynamics in the close proximities of the river path are similar to the overall dynamics of the catchment, but the exposure to natural hazards is indeed higher (*Figure 14*c). The final comparative result showed increasing trends for all the factors analyzed in the study area: the disaster risk, the natural hazards, and the vulnerability of people exposed to those hazards (*Figure 14*).

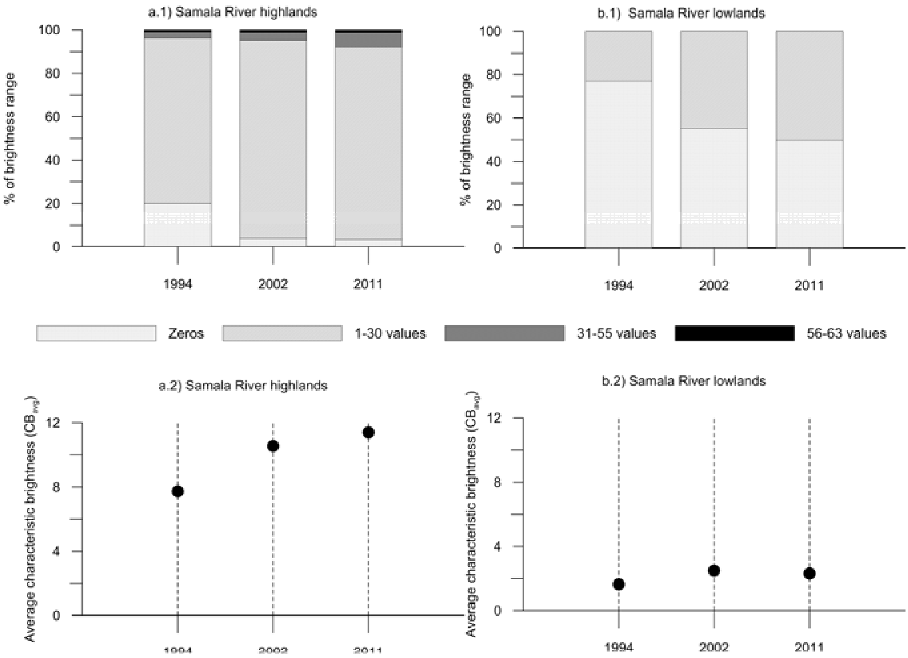

Figure 13. Nightlights evolution in the Samala River catchment for the period 1994-2011. Nightlights in the highlands and Lowlands show a contrasting evolution over time.

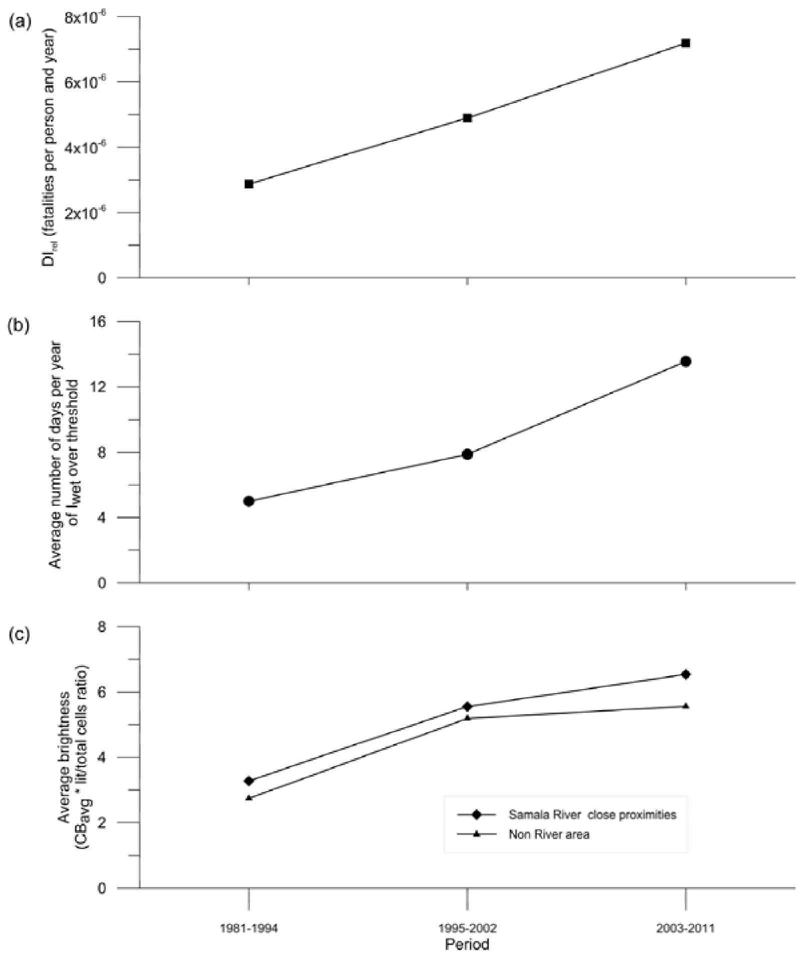

Figure 14. Vulnerability (a), natural hazards (b) and human exposure (c) in the Samala River catchment. The concurrent increases in the three factors indicate that the risk of disasters in the area is related to both causal factors. The exposure to natural hazards is higher in the close proximities of the river (c).

Assessing spatial vulnerability (Paper IV)

This case study used the geographical data provided by SEGEPLAN and the nightlights for the area in 2002 to assess the RSVI (an actual emergency plan could not be obtained from the National agencies). The RSVI was calculated by weighting each factor (D and d*) by 0.5. The results showed that social vulnerability varies spatially depending on the indicator being considered (*Figure 15* and *Figure 16*). This confirms that people can become vulnerable to disasters from a combination of many different factors. It could be seen, however, that the highest values of RSVI in the case study tend to be located in the center of the highlands (Quetzaltenango city) and along the coastal area. The connectivity conditions of each of these areas are contrasting. Even if people in Quetzaltenango city are well connected and have all critical infrastructures within a relative short distance, they are vulnerable because the area is densely populated, which may result in a reduced assistance capacity of the systems. In the coastal areas the main problem for people is the long distances to vital infrastructure, which makes it difficult to reach during crisis periods or even to interrupt the connection, making people become isolated.

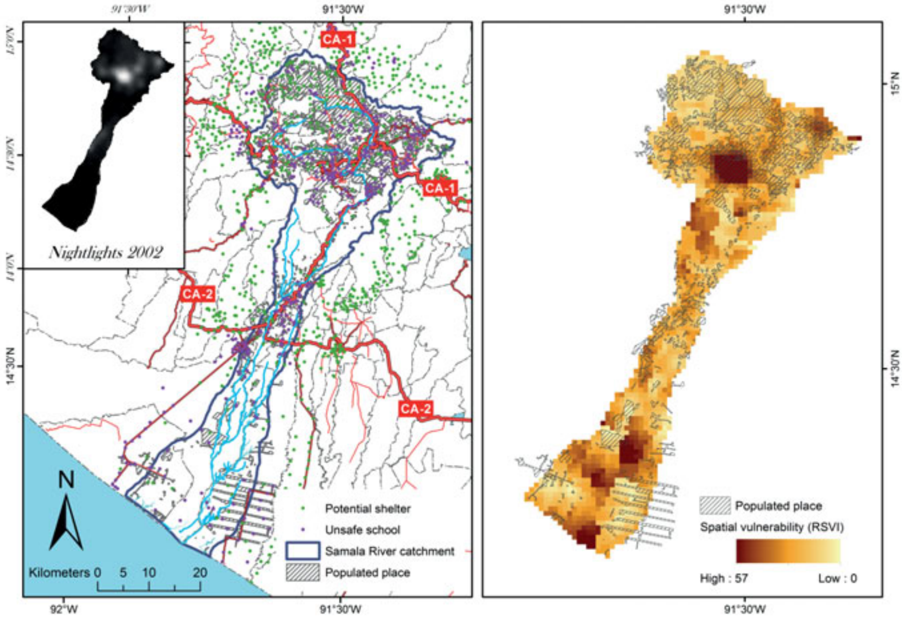

Figure 15. Relative spatial vulnerability in the Samala River catchment due to accessibility to potential shelters. Schools were considered as potential shelters, but all the schools located within a radius of 1 km around reported disasters were considered unsafe. Data sources: GIS from SEGEPLAN (2012), nightlights image and data processing by NOAA's National Geophysical Data Center. DMSP data collected by US Air Force Weather Agency (NOAA 2014).

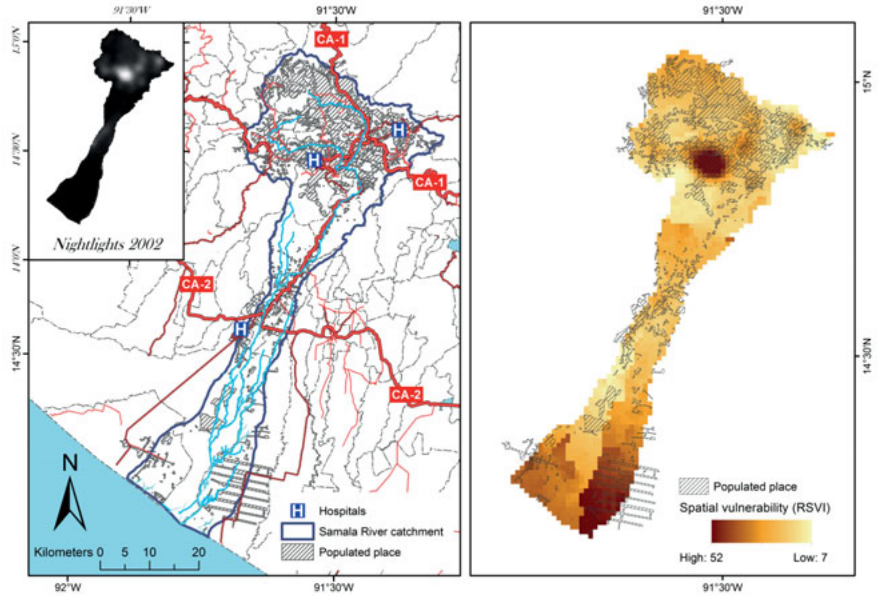

Figure 16. Relative spatial vulnerability in the Samala River catchment due to accessibility to a hospital with permanent attention. Source of the data: GIS from SEGEPLAN (2012), nightlights image and data processing by NOAA's National Geophysical Data Center. DMSP data collected by US Air Force Weather Agency (NOAA 2014).

9. Methodological conclusions and discussion

Paper I: Puzzling out data issues

Information is a fundamental need for disaster research. The search for data showed that, although on the global scale disaster data are abundant, data can be a scarce resource in certain areas. It was found that data collection is commonly carried out by national institutions in charge of DRR issues, by international organizations interested in disasters data collection, or by research institutes. The temporal and spatial ranges and resolution of each dataset were found to be different. The longer disaster records only include the biggest disasters in history because they are more likely to be recorded in the long term. The collection of detailed disaster data has improved in recent years, but the resulting datasets are understandably shorter.

National institutions are closer to the occurrences of disasters and therefore in a better position to gather quality data. However, many reasons can hinder the task (e.g. national focus on emergency response, dependence on political support, budget availability). The general increase in interest in DRR issues promotes consistency and permanency of data collection systems now and in the future. It is however important for national governments to provide sustained support to their local disaster data collection systems, especially in data-scarce areas. Continuous assessments of data quality are needed to establish standards and promote the enhancement of the quality of the data over time.

The availability of more than one database for the same area under data-scarce conditions allows for crossing information and thus enabling verification and complementarity of the data that, in turn, might enhance the available information. The advantages of each dataset can potentially be used to compensate for the weaknesses of other datasets and thus to strengthen the combined data quantity and quality as shown by the proposed method. All data sources are valuable and the coexistence of different databases can help validate the information comprised in them. The case study showed that using complementary data (e.g. infrastructure inventories) may contribute to verify the information of reported disasters.

Disaster data collection is not standardized and the effects of this were evidenced in this study. Different databases have different layouts for data collection and often the information in the reports is not even complete according to the established layout. The comparative evaluation of the data collection layouts and the actual completeness of the available databases provided a map of the advantages and disadvantages of each database. This evaluation was then used to inform which database was most suitable for the analyses, whether individually or through data compilation.

The terminology used to classify disasters also varies between the different databases. Among the different systems, the terminology and disaster classification system created by an international initiative to standardize disaster data registry, which is used for EM-DAT (Guha-Sapir et al 2009; Munich Re 2011) was used in this study as guide to create a common set of disaster classes. These classes were then used to reclassify the data for comparison purposes. Although useful, it was observed that some uncertainties may rise from this decision. The standardized terminology describes the reports in terms of the underlying causes of the events. This classification system is thus useful to understand the overall event but at the cost of being uncertain regarding the consequences produced by the actual disaster. In other cases, the reduced scientific rigor applied to create the classification system might ease the understanding for local communities but reduce the usefulness of the data for scientific analyses (e.g. OSSO/La Red, 2009).

Other issues with the databases were evidenced in the study. On the one hand, some databases create single reports for multi-events while some others disaggregate the events to single disruptions. Grasping these differences requires revising each individual record. On the other hand, the quality of the spatial aspect of disaster data needs to be enhanced considering how important data resolution is for practical applications. The diverse issues found in the case study showed how data quality can be dependent on who collects the data, how the data collection is carried out, and what is the purpose of the information. It also confirmed the different types of errors that data can have (Amin et al 2008).

Developing ways to derive information on disasters when data are much less than ideal is vital because it can provide better fundaments for informed actions and plans at the most practical level and thus positively impact the lives of a big number of people.

Paper II: Assessing the importance of the place

Analyzing such a complex area as the selected study catchment was best approached through subdividing the area. Geomorphological principles provided the necessary resources to classify the area of interest into smaller units within which the characteristics and processes were more homogeneous. Analyzing the study area based on the geomorphological configuration was useful because it enabled performing comparative analyses to investigate which particular physical processes are related to the occurrence of disasters. The analysis of the catchment as a whole showed contrasting results from those based on the geomorphological units thus pointing to the need of more detailed studies (*Figure 17*). Generalizations can conceal important links between the occurrence of disasters and the physical context of the place where they are reported.

The availability of geographical data defines what kind of analysis can be carried out in a specific place. Even if national scale maps can only give a general description of the physical features of the area these might be the only data sources freely available for the analyses. In these circumstances layering different maps together with aerial views of the area and DEMs can provide a more complete view of the physical heterogeneity of the landscape. The layered overview of the landscape provides the necessary information to handle and subdivide the area of interest into homogeneous units for analysis.

Although the proposed approach was used to analyze physical processes, the resulting geomorphological units may also be useful for analyzing social processes and even for multidisciplinary studies since social dynamics can be strongly influenced by the configuration of the landscape.

Paper III: Mapping societal exposure to hydrometeorological hazards

Although simplified, the trend analyses carried out using proxy data to study disaster risk, natural hazards, and vulnerability in terms of exposure over time indicate that the increasing trend in disaster risk is influenced by increases in the exposure to natural hazards as well as by increases in the vulnerability of people in the study area. Most importantly, the results indicate that even when good quality, long datasets are not available, it is still possible to draw conclusions on the etiology of disasters on a local scale by using proxy data. Nightlights imagery showed to be a valuable high-resolution resource for disaster research on spatial terms. The timespan covered by the image series, its spatial resolution, and the public availability makes it a promising tool for in-depth disaster studies.

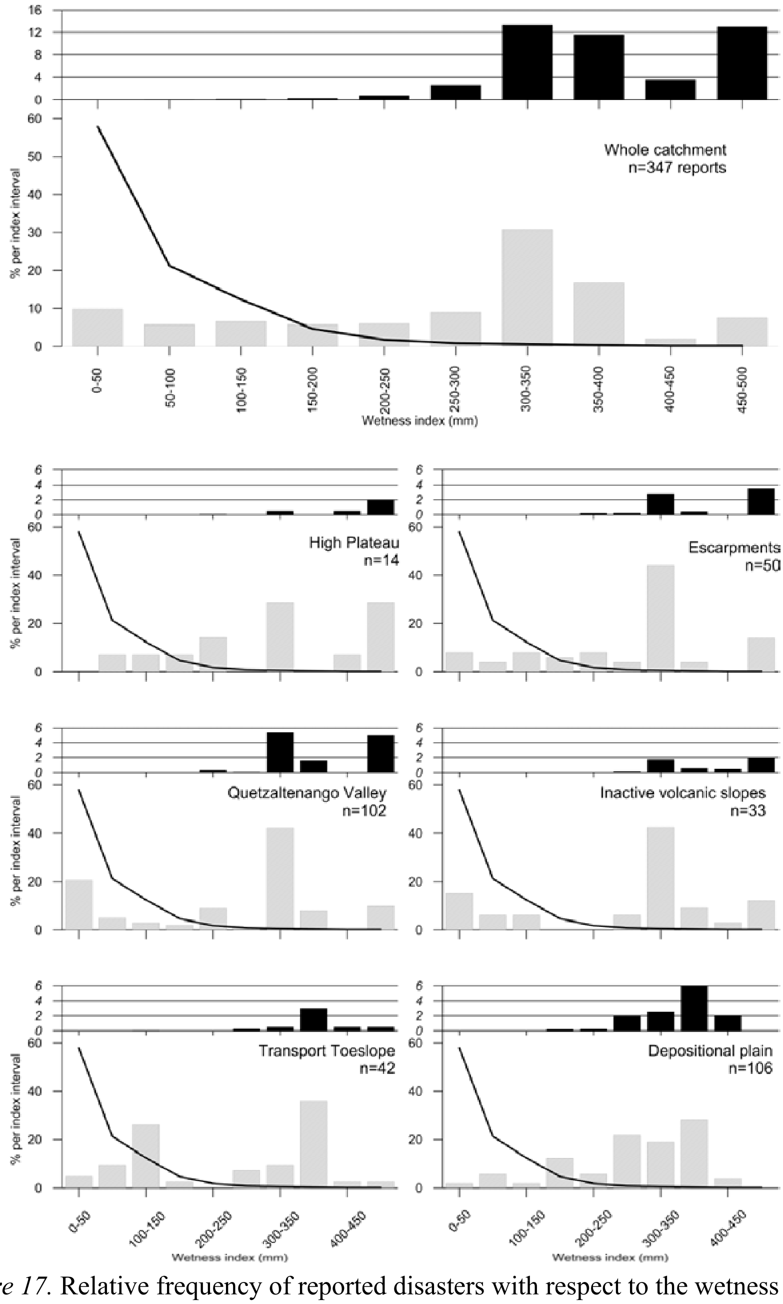

Figure 17. Relative frequency of reported disasters with respect to the wetness index (grey histograms), relative frequency of daily wetness indices (full line) and number of reported events per day in the different wetness classes (black histograms). Data source: CONRED (2012).

Paper IV: Mapping societal exposure to hydrometeorological hazards

As discussed in section 1.2, vulnerability can be assessed using several methods that are described in the literature. Such methods, when focusing on a local scale, use multiple indicators for their assessments that require large amounts of data. The method proposed in this study deals with the problem of mapping vulnerability through a bottom-up approach and uses commonly available data to evaluate the vulnerability of people given their location. During a crisis period, time is a vital variable for people's survival, and connectivity is crucial to define the time in which people can reach for assistance. Thus, a simple method to map the vulnerability of people enables better informed decision making and the prioritization of actions during crisis management situations. Maps are useful tools to communicate issues such as vulnerability. The associated uncertainties of open source data, such as accuracy, completeness, or timeliness were acknowledged but these data were nevertheless considered to be a valuable source of information for the proposed method, which, in turn, provides a valuable tool for decision making within DRR.

Undertaking the tasks of mapping vulnerability and supporting crisis management from a top-down approach was found difficult due to the lack of data to support sound modeling and predictions in a data-scarce area such as the selected case study. The application of a bottom-up approach allowed to map the vulnerability of people in the study area considering their location and resulting connectivity as a key factor for their survival during a crisis phase, i.e. immediately after the occurrence of a disaster. The resultant vulnerability maps are useful tools that can be used for communication, decision making, and planning purposes for DRR, all of them with potential positive impacts on people facing the natural hazards (*Figure 18*).

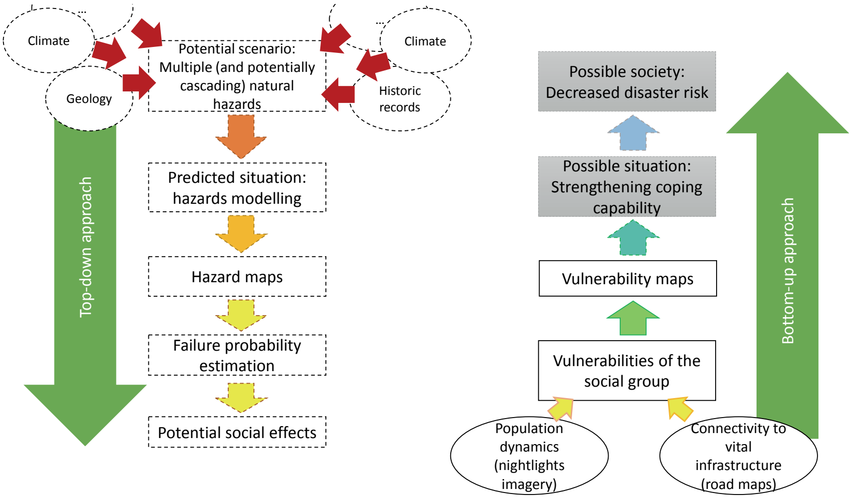

Figure 18. The bottom-up methodology for assessing social vulnerability in the Samala River catchment. The data requirements to enable a top-down approach makes it unfeasible in data-scarce areas of the world (left). The bottom-up approach in the Samala River catchment made it possible to create high-resolution spatial vulnerability maps using freely available data (right).

10. General conclusions

The research work in this thesis developed exploratory methods to study disasters on local scales and under data-scarce conditions to contribute to deriving important information on disasters to support DRR actions and plans. In particular, this work achieved:

I The characterization of the Samala River catchment as a useful case study for developing methods to study disasters on the local scale under data-scarcity conditions using global, regional, and national databases.

II Using the identified available data on disasters and the physical and social context of the study area, the research work proposed four exploratory methods to pursue the specific objectives within the general aim of the thesis. The resultant proposed methods focus on (a) deriving information on natural disasters to evaluate and compile the information comprised in different available databases to compensate for their weaknesses, (b) using geomorphological principles to enable subdivided analyses on the spatial distribution of disasters and the physical characteristics of the places where disasters have taken place to look for causal relationships, (c) using open data such as nightlights imagery to analyze if the social dynamics in the study area and the resultant exposure to natural hazards are an underlying cause for the occurrences of disasters (d) using nightlights imagery in combination with geographical data to estimate and map the vulnerability of people concerning to their location to support actions for disaster risk reduction, specifically during the crisis management phase of the DRR cycle.

The work that was carried out allowed to draw general conclusions that can be useful to apply and further develop the proposed methods especially when dealing with the challenge of studying disasters in data-scarce areas. Data are essential when studying disasters and their causes as well as to support decision making and planning for DRR. The research work that was carried out dealt with the issue of studying disasters when the available data cannot fulfill the information requirements for the most established analysis methods and models (e.g. Section 4.2). Data issues showed to be multiple and of different kind.

The differences in temporal span, spatial resolution, and classification systems among different databases are important issues that need to be taken into account when working with several databases. The results from the different studies showed that using diverse data sources results in a different depiction of the occurrence of disasters. The resulting uncertainties in the obtained results need to be acknowledged and taken into account when drawing conclusions in order to maximize the information content of the data.

When investigating disasters in many places of the world one is likely to come across fragmented data. The case study showed that only a few databases were freely available for Guatemala and that the available data were limited, mainly in terms of spatial resolution and time span. The shortage in data presented an opportunity to explore alternative methodologies suitable to be applied in areas where data are limited resources. Information on the impact of disasters was also found to be incomplete or lacking. Open data are preferable because stakeholders, authorities, professionals, technicians, and the civil society need knowledge to guide their actions in a context where DRR budgets are often limited.

Although the DRR comprehensive approach to disaster management is known and promoted globally, simple emergency management is still the main priority in many areas of the world. Recording and filling detailed information on disasters and their consequences in a systematic way continues to be relegated into the background (Amin et al 2008). It is important to bring up the need for such systematic processes because disaster impact data are crucial for learning from past events and thus enhancing the existing operational systems. It is true that such a task requires additional human and material resources than those that are already in place for emergency management and recovery, but the cost would pay off in the future as this would allow to make a more efficient use of the resources for DRR.

This work indicates that limited data restrict the opportunities for deriving spatial and temporal disaster data needed in DRR. Even if the conclusions that can be drawn from the analyses present limitations and uncertainties they demonstrate that even the scarce data available can provide valuable information that can be used for taking better informed actions oriented towards DRR.

In general, this work deals with the issues of carrying out disaster research in conditions with far from perfect input data. In these circumstances the main challenge is to find ways to extract the most information from the scarce available resources. Even if it is a complicated task it is also an important one as it might help bridging the gap between global disaster risk reduction policies and those that have an impact on the way people live (e.g. planners, designers).

The scarcity of data or the lack of good quality data does not justify the absence of research. Neither society nor the academic community can afford to wait until everything is "built" because natural disasters continue to occur affecting millions of people globally every year. Research on disasters on the local scale is greatly needed, especially in disaster-prone areas. Data needs to be searched, identified, and evaluated in order to update the data state-of-art and to be aware of what is available and, more importantly, what is needed.

The weaknesses identified in the different disaster databases for data-scarce areas may inform and help those involved in the actual data collection systems, which may in turn help to improve the data quality and enable better studies in the future.

It is acknowledged that there are many sources of uncertainty in the methods proposed in this work but, even under these circumstances the potential contribution to the development of methods for studying disasters in areas with data scarcity outnumbers the drawbacks. It is also acknowledged that some resources used in these studies (e.g. GIS software) may not be accessible in all the places; however open source software alternatives broaden the possibilities for applying this and other tools into DRR.

11. Future prospects

The work carried out has been a journey of discovery and experimentation. The ultimate goal of bridging the gap between spatial planning and DRR helped to define the research questions and also uncovered the difficulties that data scarcity poses on such activities. There is still a long way ahead to reach the proposed ultimate goal and therefore many future research prospects remain. A continued work on this is important because spatial planning is a great tool to make DRR tangible (Mileti 1999). The methodological exploration performed in this work has a long path ahead: the proposed methods need to be improved and refined, and the possibility to use new data sources and technologies (e.g. remote sensed imagery) opens potential ways to continue studying the geographical distribution of disasters and to apply the gained knowledge into DRR and spatial planning. Nightlights imagery, for instance, can be further used to explore population dynamics in higher detail, thus complementing the information provided by census data.

Regarding the case study in particular, much work is still needed in the Samala River catchment as it is also the case for the whole country. Many efforts are being made to reduce the risk of disasters in the national framework but the advances are extremely limited in comparison with the needs. Some reasons to this are the large costs that are not covered by the available resources and the lack of technical skills. Disaster research focused specifically at optimizing the systems along the DRR cycle is strongly needed. Additionally, research that promotes bridging the gaps between the institutions in charge of the coordination of DRR actions in the country and the many actors on the local scale (e.g. local authorities, social organizations, civil society, local academia and, for instance, spatial and urban planners and designers) is also needed. The proposed methods can, and should, be improved. Open access resources such as nightlights imagery can be used as proxies for missing data in order to study and enhance the information on the social and physical complexity of the study area. Additionally, the results of these and other studies should be delivered to the different institutions and people involved in DRR in order to be put into actions and plans that provide interesting possibilities for further research.

Disaster risk reduction is a comprehensive concept and requires adequate resources and expertise from different disciplines to be further developed (Mileti 1999; Trim 2004). An improved interaction among the different disciplines involved, with the corresponding wide range of combined knowledge and skills, is needed in order to conceive new and useful tools that have the capacity to improve the capacity of coping with disasters (Simpson et al 2014). Although this work has been carried out in a sort of multi-disciplinary approach with the co-author team providing a multidisciplinary approach, being part of a truly multidisciplinary team working on a common project to deal with the challenges of DRR remains a future prospect.

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Sammanfattning på Svenska (Summary in Swedish)

Naturkatastrofer har påverkat mänskligheten i alla tider. I takt med ökande befolkning och utveckling av infrastruktur har detta fått ett alltmer ökat fokus. De fysiska, ekonomiska och sociala effekter som naturkatastrofer har påverkat det globala samhället med är betydande, och från 1940-talet har naturkatastrofer alltmer engagerat nationell politik, internationella organ och den akademiska världen. Detta växande intresse kring naturkatastrofer har bidragit till att avsevärt förbättra kunskapen i ämnet och har mångdubblat antalet initiativ som syftar till att minska de negativa konsekvenserna av naturkatastrofer. Dessa åtgärder har haft störst effekt i de mest katastrofdrabbade områdena.

Forskningen i ämnet naturkatastrofer bidrar till att öka förståelsen för de processer som är relaterade till naturkatastrofer. Detta kan i sin tur bidra till att minska risken för att en naturkatastrof utvecklas och minska de negativa konsekvenserna av naturkatastrofen om den uppträder.

Naturkatastrofer har ofta en geografisk koppling, vilket gör att kunskap om tidigare naturkatastrofer ger betydelsefull information om risken för framtida katastrofer och därmed en koppling till katastrofernas fysiska och sociala sammanhang. Studiet av den geografiska fördelningen av naturkatastrofer är nödvändigt och därför är den detalj studierna genomförs i en kritisk faktor för förståelsen av de ingående fysiska och samhällsrelaterade processerna. Studier på nationell nivå är bra för att ge allmänna anvisningar till styrande organ när det gäller vilken typ av naturkatastrofer som kan förväntas. I det lokala perspektivet kan dock nationella studier vara alltför grovmaskiga för att hitta de risker som kan påverka organisationer på kommunal nivå och därför krävs information om risker i lokal skala för att tillgodose detta behov. Ett hinder för utvecklingen forskningen kring naturkatastrofer i lokal skala är den begränsade tillgången på data med hög geografisk upplösning. Detta är framförallt ett problem i utvecklingsländer. Därför är det viktigt att ta fram forskningsmetoder kring naturkatastrofer som är användbara i sårbara områden även om tillgången till högupplöst data är knapp.

Det övergripande syftet med avhandlingen var att föreslå metoder för att studera naturkatastrofer på lokal nivå och som är tillämpbara i områden med knapp tillgång på högupplöst data. För att uppnå detta valdes ett område med hög sårbarhet och med fragmenterad information kring naturkatastrofer för att skapa en fallstudie. I studien utvecklades metoder för att: (a) bygga en lokal databas med uppgifter om naturkatastrofer erhållna ur nationella databaser, (b) studera de fysiska processerna som potentiella orsaker till naturkatastroferna med hjälp av processernas rumsliga och tidsmässiga fördelning, (c) använda öppen arkivdata för att studera de sociala sammanhang till vilka naturkatastroferna relaterades, och (d) kartera sårbarheten för naturkatastrofer i området som ett steg mot att föreslå stödåtgärder i syfte att minska riskerna för naturkatastrofer.

Arbetet genomfördes inom den internationella ramen för DRR (Disaster Risk Management). Denna naturkatastrofriskreducering syftar till att minska risken för naturkatastrofer genom att påverka deras orsaksfaktorer på ett systematiskt sätt och i sin tur minska deras potentiellt negativa utfall. I detta arbete definierades en naturkatastrof som en av människan opåverkad farlig händelse som ger ett sårbart samhälle negativa konsekvenser i form av skador på liv, hälsa eller egendom på ett sätt som avbryter de normala sociala funktionerna i samhället under en period. Eftersom orsaksfaktorerna bakom naturkatastrofer har ett ursprung i både sociala och fysiska processer undersöktes båda dessa typer av processer.

Det område som valdes är en region i Guatemala som avgränsas av floden Samalas avrinningsområde. Detta område ligger på det centralamerikanska näset, en bergig och vulkaniskt aktiv region i ett geologiskt sett relativt ungt område. Området ligger klimatologiskt i tropikerna och drabbas återkommande av orkaner. Topografin inom området spänner från havsnivå upp till 3700 m ö.h. och skapar därmed ett flertal olika lokala klimatzoner. Det generella klimatet präglas av två skilda årstider; en regnperiod från maj till oktober och en torrperiod under resten av året.

De metoder som använts är geografiska informationssystem (ArcGIS), folkräkningsdata från lokala guatemalanska källor, nationella uppgifter om naturkatastrofer från öppna internationella databaser och från den guatemalanska institutionen för katastrofriskreducering samt satellitbilder från US Meteorological Agency.

Avhandlingens forskningsarbete är uppdelat i fyra huvuddelar. I den första användes två olika databaser för att undersöka hur väl man kan undersöka förekomst av naturkatastrofer ur nationella arkiv i en regional/lokal skala (Artikel I). Här användes en regional databas med hög rumslig upplösning men med en kort tidsrymd och en nationell databas med lägre rumslig upplösning men med en längre tidsrymd. Resultaten visar att man kan utvinna lokal information i lokal skala om man har tillgång till och kan jämföra olika typer av databaser, även om de har olika täckning i tid och rum.

I den andra delen studerades relationen mellan de fysikaliska processerna och naturkatastroferna genom att identifiera olika landskapsformande geomorfologiska processer och med dem skapa kriterier för att dela in undersökningsområdet i fyra separata fysiska enheter med olika karaktäristik (Artikel II). Denna uppdelning av området möjliggjorde en förbättrad förståelse för naturkatastrofernas spridning och frekvens i området samt vilken typ av bakomliggande fysisk process som hade störst betydelse för bildande av naturkatastrofer i vart av de fyra typområdena.

I den tredje delen undersöktes om den samhälleliga dynamiken i studieområdet hade en relation till förekomsten av naturkatastrofer. Ett index för välstånd/befolkningstäthet konstruerades med hjälp av satellitdata av nattljusintensiteten från området (Artikel III). Lämpligheten att använda fjärranalytisk data för att komplettera de knapphändiga uppgifterna om befolkningstäthet och välstånd från folkräkningsdata undersöktes. Både de fysiska och sociala komponenterna bakom naturkatastrofsrisker beaktades i syfte att skapa en mer fullständig analys av orsaker till naturkatastrofer.

I den fjärde och sista delen, undersöktes svårigheterna att bedöma och kartlägga samhällets utsatthet för naturkatastrofer i området (Artikel IV). Även här användes nattljusintensiteten för att symbolisera befolkningsstrukturer och hur detta index kan kombineras med avståndet till olika typer av infrastrukturella parametrar för att skapa ett relativt sårbarhetsindex över området. Arbetet har ett fokus på krishanteringstadiet efter en naturkatastrof och visar hur sårbarheten varierar inom området och hur denna metod skulle kunna användas i prediktivt syfte för att upprätta krisplaner för området.

Forskning om naturkatastrofer i lokal skala är viktigt för att effektivisera riskreduceringen oavsett hur mycket data det finns i området. Metoder behövs som är tillämpliga i alla situationer, inklusive sådana där informationen är knapp. I många områden som drabbas av naturkatastrofer är informationen tyvärr knapp, vilket visar vikten av att hitta nya väger att öka samhällets möjligheter till riskreducering i sådana områden.

Detta arbete visar på möjligheter att bättre förstå risker i samband med naturkatastrofer i områden med knapphändig information. Hur datainsamling utförs är ett exempel på en viktig fråga. En annan viktig fråga som identifierades är hur naturkatastrofen beskrivs och behovet av att hitta en konformitet i benämningen av olika parametrar för att möjliggöra jämförelser mellan olika databaser. En ytterligare fråga som är viktig är vilken tids- och rumsskala databasen omfattar, vilket kan anses som en nyckelfråga i detta arbete. Bristen på data kring naturkatastrofer i lokal skala skapade dåliga förutsättningar att arbeta med tidigare etablerade metoder, vilket tvingade fram de nya vägar som presenteras i avhandlingen.

Även om den data som fanns tillgänglig för detta arbete var begränsad i både kvantitet kvalitet var data tillräckligt för att användas i kombination med information från distribuerade geografiska system och satellitdata för att utveckla nya experimentella metoder som är tillämpbara för naturkatastrofsforskning i områden med knapphändig rapportering. De nya metoderna kan användas för att bättre förstå förekomsten av naturkatastrofer, deras utveckling över tiden och orsakssambandet mellan det fysiska och sociala sammanhanget vid en viss plats. Även om det finns en betydande grad av osäkerhet i de föreslagna metoderna bedöms de ge ett positivt bidrag till riskreducering av naturkatastrofer i lokal skala.

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