1 INTRODUCTION

1.1 BACKGROUND AND PROBLEM DESCRIPTION

Between January 2008 and September 2010 – the approximate time frame for this thesis work – floods affected 133,730,961 people and caused a monetary damage of 39,372,391 US$ worldwide (CRED 2010). Most of the damage occurred because people settled in flood prone areas and interrupted the natural catchment and flowpath of the waterways in the course of urban expansion.

1.1.1 Urbanization trends: Chile in a worldwide context

Urbanization and especially mega-urbanization is one of the most prominent phenomena and at the same time one of the great challenges of the 21st century (Hansjürgens et al. 2008, Hazel & Miller 2006, Kraas et al. 2005). The percentage of urban population worldwide grew from 29.0 % of the total population in 1950 to 48.7 % in 2005. Estimations predict nearly 60 % of the total population to live in urban areas within the next two decades (UN Habitat 2008). The current average urban growth rate in developing countries is 5 million people per month (UN Habitat 2008).

The geographic focus of this research is on Latin America and Chile because Latin America is with 77 % (UN Habitat 2008) the most urbanized developing region in the world. In some Latin American countries, the urban population has reached 90 % and beyond (ECLAC/CEPAL 2000). In Chile, 87 % of the population lived in urban areas in 2008 (INE 2008).

Urban growth, and particularly the development of megacities, is a phenomenon of growing importance for social and environmental scientists (UN Habitat 2008, Hansjürgens et al. 2007, UNDP 2004). Megacities can be defined according to their size (minimum population 5 million and upwards depending on the definition) or according to their function as an economic, political, and cultural center of the country that has global importance (Hansjürgens et al. 2008, Wenzel et al. 2007, Bronger 1996). Megacities concentrate demographic and economic growth, resources, and labor and do therewith provide “a space of opportunity”. At the same time, they are “a space of risk”, as the development of mega-agglomerations with high densities of buildings, urban infrastructure, industry, and people poses a number of risks for the inhabitants and for protected goods (Büscher 2008, Romero et al. 2008, UN Habitat 2008, Hansjürgens & Heinrichs 2007, Wenzel et al. 2007, Heinrichs & Kabisch 2006, Romero & Vásquez 2005).

The study area for this research is Santiago de Chile, the capital city of Chile and a megacity because of its high dynamics and functional value. It is the political and economic center of the country with approximately 6.7 million inhabitants (INE 2008) and it is undergoing a rapid process of urbanization with changes in land use and urban morphology in a planned but also in an informal way (Romero et al. 2008). With respect to the speed of growth and development in combination with the insufficiently regulated urban planning, Santiago de Chile can be regarded as a representative example for urbanization and mega-urbanization in a Latin American country (Hansjürgens et al. 2007). Its urban area grew from 31,419 ha in 1970 to 64,140 ha in the year 2002 (Figure A–35). The area open for urbanization after the Metropolitan Regulatory Plan (*Plan Regulador Metropolitano de Santiago*, PRMS) has been as large as 110,319 ha since 2007. Thus, a continuation of the spatial expansion of the city can be expected during the next years. More detailed information about the past urbanization process of Santiago is given in Chapter 4.1.3.

1.1.2 The influence of urban expansion on flood risk

Spatially seen, urban growth is frequently associated with an expansion of impervious surfaces, the loss of natural areas, and therefore a severe impact on the ecosystem. Agricultural land is converted into residential areas; bushland makes way for transport infrastructure and recreation areas. Land-use/land-cover (LULC) changes frequently lead to an increase of the occurrence of hazardous events, such as floods, landslides, and heat stress (Romero et al. 2008, Ducci & González 2006, Solway 2004, Pelling 2003, Bronstert et al. 2002). Accompanying the issue of urban expansion is the lack of ecological and environmental awareness in the urban planning process and the deficit of adequate planning instruments and competencies.

The time lines of physical growth and the necessary adaption of urban governance structures do in many cases diverge, resulting in malfunctioning steering and control mechanisms with respect to urban planning. Hansjürgens et al. (2008) discuss that large urban agglomerations face higher risks to experience damage from hazardous events as they are constructed in a complex and dense way.

The factors relevant for the generation of flood risk have not been quantified yet, thus are not sufficiently known. Rather, adaptation measures were taken without considering the root causes of hazard generation on the one hand and the susceptibility to experience damage on the other hand.

The issues resulting from urban expansion with regard to flood risk are twofold and represent a lack of sustainable urban planning: The first impact affects the urban water cycle (Figure 1) and the flood hazard (read the box "The water cycle" in Appendix 1), the second affects the increasing exposure of people, properties, infrastructure, ecologic, and economic values (in the following only referred to as values) in flood-prone areas.

The changes in LULC lead to a reduction of infiltration and interception capacities and a higher amount of surface runoff. The likelihood of a flood event (i.e. the flood hazard) is consequently increasing in those watersheds that are prone to or subject to anthropogenic disturbances. In the course of urbanization, the construction of mitigation measures for extreme flood events and the setup of flood risk management programs provide the notion of security.

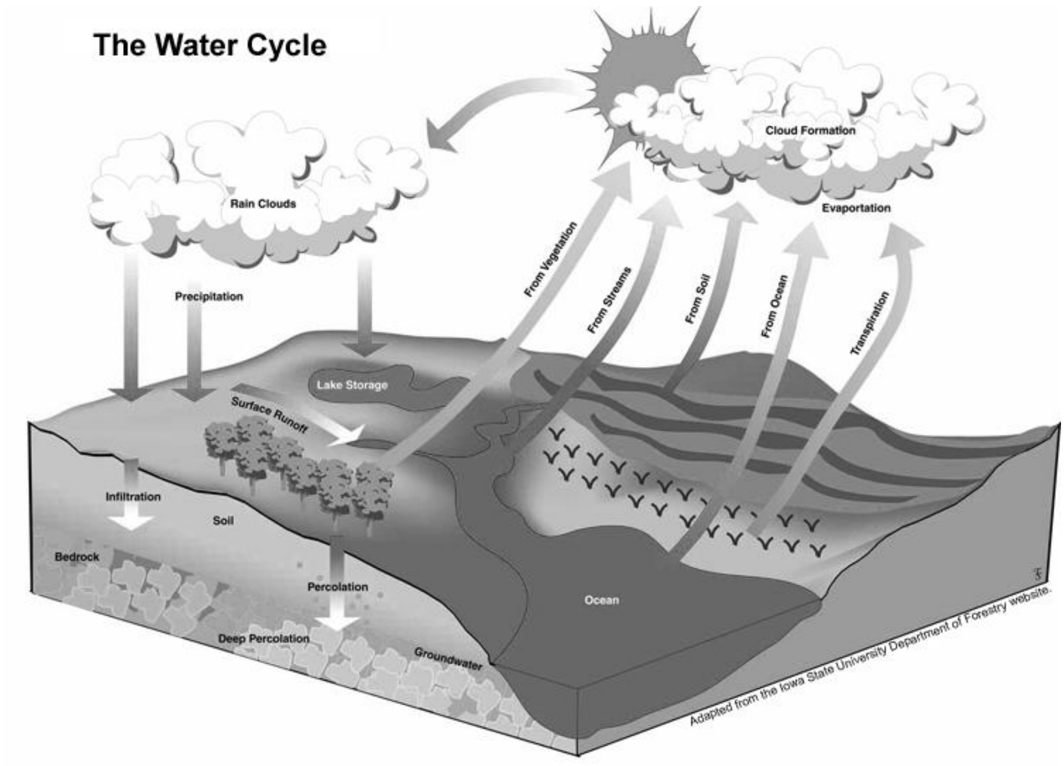
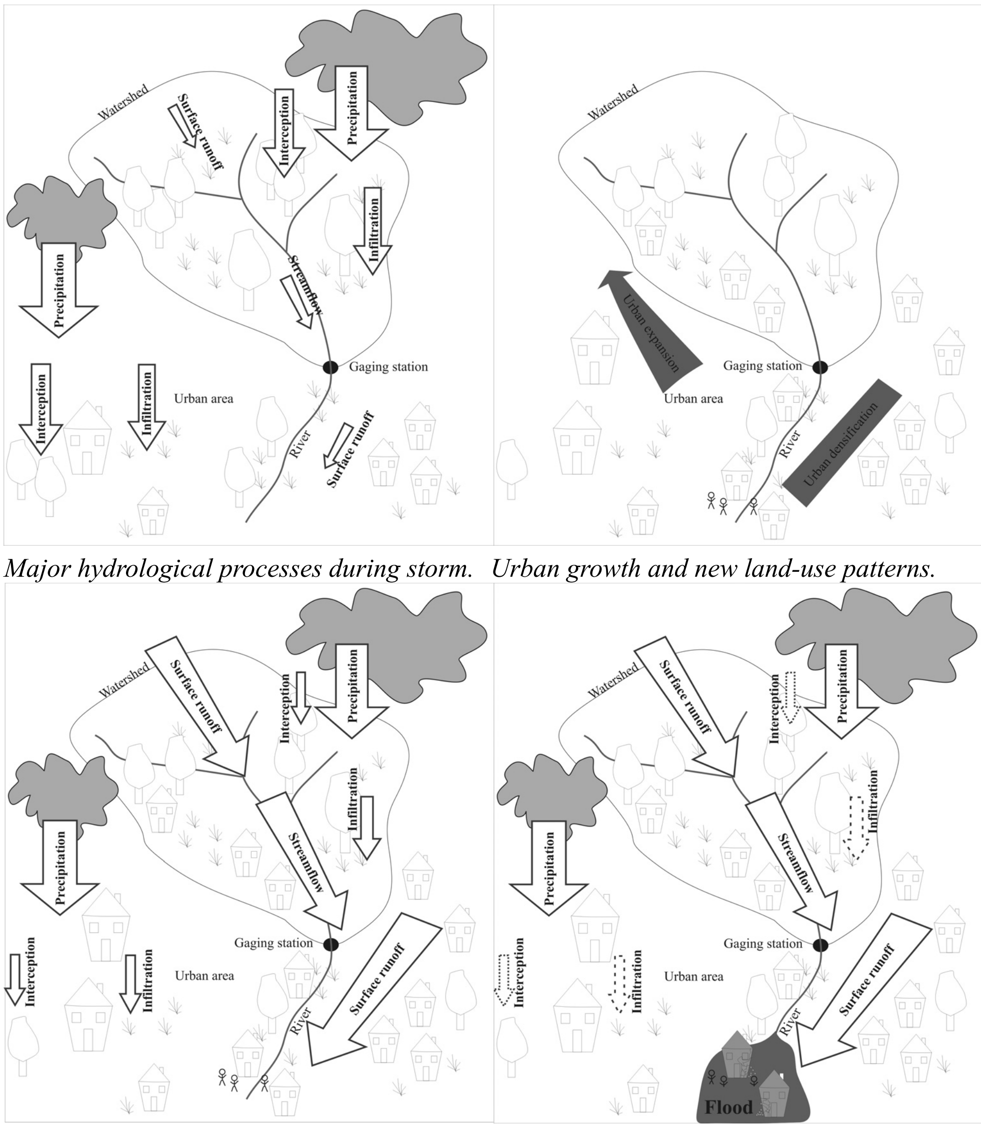


Figure 1: Schematic diagram of the water cycle (Laude Horton Watkins Highschool 2010).

This false sense of security, the lack of alternatives or the pure lack of knowledge lets people perpetually get settled in flood-prone areas along river beds and floodplains (GFZ 2006). Thus, besides the increasing flood hazard, urban expansion leads to a higher exposure of people and values to these potentially damaging events – and thus to an increase of risk. The schematics in Figure 2 demonstrate these relationships and consequences.

Official disaster statistics show a fluctuating but increasing amount of reported flood events and an increasing number of people affected. The largest share in terms of the total number of disasters and affected people do in fact have hydrometeorological disasters (floods, wet mass movements, and storms (Vos et al. 2009), p. 5). Millions of people, especially in Asia, are affected each year. However, the number of fatalities has been relatively constant during the last years and shows a decreasing trend in the Americas (Vos et al. 2009), which expresses better disaster preparation and disaster risk management.



Major hydrological processes during storm. *Urban growth and new land-use patterns.*

Less infiltration capacities lead to higher surface runoff. *Higher surface runoff and more people and buildings exposed result in high flood risk.*

Figure 2: The impact of land-use/land-cover changes on flood risk in the scope of urban expansion. Schematic representation of the main influencing factors and consequences.

1.1.3 Floods in Santiago de Chile

Floods are a regularly occurring phenomenon in Santiago de Chile (Table A–34 in the appendix). It is now examined what type of floods occur, how they can be characterized, and what research was carried out with respect to flood generation and flood risk.

1.1.3.1 Triggers for floods

Three main triggers lead to floods in the Metropolitan Region:

- Water emerging to the surface arising from a high-lying groundwater table,
- overflow of rivers and channels due to high water levels in the water course (river floods),
- accumulation of storm water on the roads and in local depressions, e.g. under bridges (urban floods).

A map showing the flood hazard zones of Santiago de Chile was created by Fernández & Montt (2004). In this study, river floods and urban floods are of interest. During orographic storms with high precipitation values especially in the Andean foothills the Metropolitan Region experiences floods. The increasing amount of sealed surface is adding to the quantity and velocity of surface runoff into the lower-lying parts of the city, but also in the urbanized hills, what leads to even larger areas of potential flood risk (Hansjürgens et al. 2007, Reyes 2003).

The flood hazard has been increasing additionally through inappropriate urban planning in the past and partly still today. A complete canalization system only exists in the historic city center as the construction of storm water infrastructure has for a long period been regarded as irrelevant. Today, storm water sewers have to be built in all new construction sites. To construct an appropriate storm water sewer system for the RM, 1,500 million US$ would have to be invested. Estimations claim that Santiago is losing 43 million US$ annually under the assumption that 50,000 people are affected by floods every year (Reyes 2003). The Hydraulic Works Directorate (DOH) identified 117 points in 33 municipalities where floods occurred (Fernández & Montt 2004).

1.1.3.2 Characteristics of floods

The floods in Santiago are typically slow (i.e. no flash floods), carrying large amounts of sediment and branches from deforested slopes that remain on the streets after the water disappears (Figure 3, Reyes 2003, Silva 2008). In contrast to other countries, such as the Philippines, where urban floods have a severe impact on the economic growth of the area, floods in Santiago de Chile do not have such a very severe negative economic impact. The floods do rather occur regularly (almost annually) and people have in most cases adapted to a certain hazard level or adopt as soon as they have suffered damage once (Reiter 2009). Nevertheless, floods – even with a lower intensity – cause monetary costs as well as alternative costs, e.g. if people are hindered going to work. The flood height seldom exceeds 20 cm, but regularly interrupts the urban functioning and harms vulnerable households in one way or the other. Most frequently, front yards, outer walls, floors, and furniture are affected, moisture remains in the walls (physical damage) or people are trapped in gated communities and cannot go to work (immaterial and economic damage) (Reiter 2009). Also, floods in other regions of the world are the disasters that affect the highest numbers of fatalities per event. That is not the case in the study area. Even though there are single events that affect a very high number of people, the average flood does fortunately not cause that many victims. A field survey conducted by Reiter (2009) showed that 69 % of interviewed people in the study area declared that they suffered immaterial damage after a flood with limited mobility being the most important concern. Sufficient food, energy, and water supply, health and mental problems resulting from moisture in walls and floor, as well as fear are other issues (compare Section 9.4.1.2).

With all the negative impacts, the importance of flood hazard diminishes during the dry times of the year where problems like crime and job security or earthquakes prevail (Reiter 2009).

Helpers evacuating water from the streets.

Wall of sandbags protecting property from damage.

Sediment load remaining on the streets after water disappears.

Small branches accumulating along the sandbags.

Figure 3:Situation one day after a flood event in the municipality of La Reina, June 2008.

1.1.3.3 Flood risk related research done in Santiago de Chile

Hazard maps for floods resulting from natural stream and canal overflow, high ground water tables, and accumulation of storm water on streets are published in a study carried out by Ayala et al. in 1987. Maximum runoff values were determined based upon a hydrological analysis. Return periods of 2, 5, 20, 25, 50, and 100 years were considered. The study also comprises a hydraulic study for all streams and creeks. Associated to the results is a proposal for appropriate land-use planning and official hazard zoning. Respective maps were incorporated in the fundamental planning instrument, the Metropolitan Regulatory Plan (PRMS) of Santiago de Chile. The study was carried out by order of the Ministry of Housing and Urbanism (MINVU) and is referenced as such in all flood hazard-related maps of this study.

The hazard maps developed by Ayala et al. (1987) were updated in 1996 (Ayala & Cabrera 1996). Nevertheless, the new information has not yet been incorporated in the PRMS as it has not yet been renewed with respect to hazard zoning (Paredes 2009).

Flood hazard analyses were furthermore conducted in the scope of previous research projects, such as OTAS (*Bases para un Ordenamiento Territorial Ambientalmente Sustentable en la Región Metropolitana de Santiago*, Basis for an Environmentally Sustainable Territorial Planning in the Metropolitan Region of Santiago de Chile, map at the scale of 1:100,000, (Ferrando 1998, Ferrando & Cueto 1998)), and by SERNAGEOMIN (*Servicio Nacional de Geología y Minería*, National Service for Geology and Mining (Antinao et al. 2003)). These studies are based on findings from older studies and did not deliver updated hazard maps.

To develop solutions for the still prominent issue of floods in Santiago, a master plan for storm water evacuation and drainage (*Plan Maestro de Evacuación y Drenaje de Aguas Lluvias del Gran Santiago*, Master Plan for the Evacuation and Drainage of Storm Water for Gran Santiago (CADE IDEPE 2001)) was developed by order of the Public Works Ministry (MOP), DOH in 2001 (CADE IDEPE 2001) (compare Section 4.2).

An updated flood hazard map comprising information on location, causes, and effects of previous flood events was created by the *Departamento de Ingeniería Hidráulica y Ambiental Universidad Católica de Chile* in cooperation with Mapcity and DICTUC (Ingenería DICTUC 2005, Mapcity 2005, Fernández & Montt 2004). Respective information about previous flood events was overlaid for the entire city area (for details refer to Fernández & Montt 2004).

The most important sources of information were the areas listed in the *Plan Maestro de Evacuación y Drenaje de Aguas lluvias del Gran Santiago*, verified and updated using data of the *Servicio de Vivienda y Urbanismo* (SERVIU, Office/Service for Housing and Urbanism), municipalities, the National Emergency Office (ONEMI), the city hall, and press releases (Fernández & Montt 2004). This map, however, has also not been used to update the PRMS.

Detailed flood hazard studies for those parts of the eastern municipalities that are located below 1,000 m at the Andean piedmont were published in 2008 (AC

Ingenieros 2008) although at least the interviewed decision makers in the respective municipalities did not obtain the results of this investigation (Quezada 2009).

Fuentes & Romero (2007) carried out a LULC change detection analysis for three river catchment along the Andean piedmont. The goal was to investigate the influence of LULC changes in the course of urban expansion on the storm water runoff behavior. The study analyses the urban growth towards the Andean mountains by means of remote sensing and GIS analysis in the time frame between 1975 and 2007. The authors applied the Curve Number method to quantitatively estimate the changing runoff coefficients in the area of interest. Even though the chosen approach implies some methodological drawbacks it is found that in the catchment areas of the three water courses the runoff coefficients increased by one tenth every year. This finding can most likely be transferred to the present study area and plays a role in the further course of this research.

In addition, several studies on flood hazard assessment in Santiago de Chile were carried out in the scope of Master and Diploma theses. Perez (2009) investigated the influence of climate change on flood hazard in the catchment of *Quebrada San Ramón* applying the hydraulic models HEC-RAS and MOUSE for hazard analysis. The results from the hazard analysis were combined with data on LULC for a generalized vulnerability analysis to form a flood risk map. The role of regional climate change was investigated in this context. These findings are partly implemented in this research and further discussed in Chapters 6 and 9.

1.1.3.4 Research gaps with respect to flood risk

Despite the large number of flood related studies in Santiago, except of the work of Perez (2009) who investigated the influence of climate change on flood hazard, all flood hazard and risk studies are solely based on the analysis of previous events. Changes in LULC that are currently taking place and that are expected to continue occurring in the future were so far only evaluated by Fuentes & Romero (2007). Even though this study delivers valuable insights into the changes taking place in the urban part of the catchment, this study does primarily focus on current runoff coefficients and does not yet make any predictions about the future. That means that the influence of LULC changes associated with the ongoing urban expansion on flood risk has not been quantified yet. Besides that, more comprehensive flood risk studies are so far only focused on land use as the only determinant of vulnerability. More specific research on coping capacities and exposure issues to further characterize and analyze vulnerability towards floods has not yet been carried out. Recommendations to minimize flood risk are proposed in the before mentioned *Plan Maestro de Evacuación y Drenaje de Aguas Lluvias del Gran Santiago* but focus on mitigation rather than on prevention measures (see Section 2.5). What is lacking so far for the study area is a comprehensive, system-oriented, and integrated approach to analyze and assess flood risk with its causes and interdependencies of determining factors.

1.2 RESEARCH GOALS AND RESEARCH QUESTIONS

As the analysis and assessment of risk and its causes are crucial prerequisites for the development of risk prevention measures, the goals of this research are to investigate the annual problem of floods in Santiago de Chile in a comprehensive way and to develop and apply a methodology to analyze and assess flood risk. The main focus is thereby set on the influence of LULC changes in the scope of urban expansion on flood risk in the study area. It is thus another research goal to get insight into institutions and instruments relevant for urban planning.

With respect to the goals of this research, a preliminary analysis of the problem of floods in Santiago de Chile, and a revision of the research that has previously been conducted on the subject, the following key research questions were formulated:

- Which conceptual framework can be used to capture, analyze, and assess the flood risk in a growing urban agglomeration? (Chapter 2)
- What are the components influencing the flood risk in the study area on the communal and household level? (Chapter 5)
- How can indicators be used as a tool for flood risk analysis? (Chapters 5 and 9)
- What is the influence of LULC types and their changes on flood risk in the study area? (Chapters 8 and 9)
- How can flood risk be assessed in the study area? (Chapters 9 and 11)
- What measures concerning LULC could be taken to decrease flood risk? (Chapter 10)

1.3 METHODOLOGY AND STRUCTURE OF THE THESIS

Flood risk has its origins on various dimensions that are sometimes hard to capture and to describe precisely and even harder to measure and to evaluate. The deficit of most projects is that they are for the most part focused on just one component of risk and that they lack the multi-disciplinary character that risk studies require. This study connects both physical and social aspects in order to get a comprehensive understanding of the generation of flood risk in Santiago de Chile. The main steps are described in the following subsections.

1.3.1 Development of a conceptual risk framework

Chapter 2 discusses the various definitions of risk, hazard, and vulnerability as well as the approaches for their practical assessment. It was found necessary to adapt the existing conceptual frameworks to match the specific conditions of a complex, megaurban environment and to show at the same time how a conceptual model can be operationalized. The concept proposed here can be formulated as:

*Risk = Hazard * Elements at Risk * Vulnerability.*

The main steps of this investigation are oriented on the 8-step-approach for vulnerability assessment, which is adapted to be a 9-step-approach for risk assessment after Polsky et al. (2003), p. 5):

- Select people and places carefully: choose scale, select stakeholders (Chapter 4)
- Get to know places over time: review literature, contact researchers, spend time in field, explore nearby areas (Chapter 4)
- Hypothesize who is at risk and why: identify people, identify drivers (Chapter 5)
- Develop a causal model of risk: describe factors, describe pathways, examine adaptation, formalize into a model (Chapters 2 and 5)
- Find indicators for the components of risk: exposure indicators, sensitivity indicators, adaptive capacity indicators (Chapter 5)
- Feed indicators: collect data, review different data sources, conduct interviews, bring data in suitable format to match the indicators (Chapters 6 to 9)
- Weight and combine the indicators: combine rigorously, represent results, validate results (Chapter 9)
- Project future risk: choose scenarios, run model (Chapters 8 and 9)
- Communicate risk creatively: be rigorous about uncertainty, trust stakeholders, use multiple media (Chapters 10 and 11)

1.3.2 The choice of an appropriate study area

The flood risk analysis was not carried out for the entire city of Santiago de Chile but for a specific study area in the eastern part of the city: the *Quebrada San Ramón* (Figure 2). The study area was selected for its location along the Andean foothills and its frequent affectedness through floods. The catchment and flowpath of the *Quebrada San Ramón* comprises parts of the municipalities Las Condes, La Reina, and Peñalolén.

For hazard studies, this area is interesting as further urbanization, i.e. land-use changes and sealing of the soils in higher parts of the foothills can be expected for the future. This is a relevant process for flood origination and therefore forms an interesting research aspect. For vulnerability studies, this area is interesting as the inhabitants living in the hazard prone areas cover all existing social classes with all of them being affected by floods.

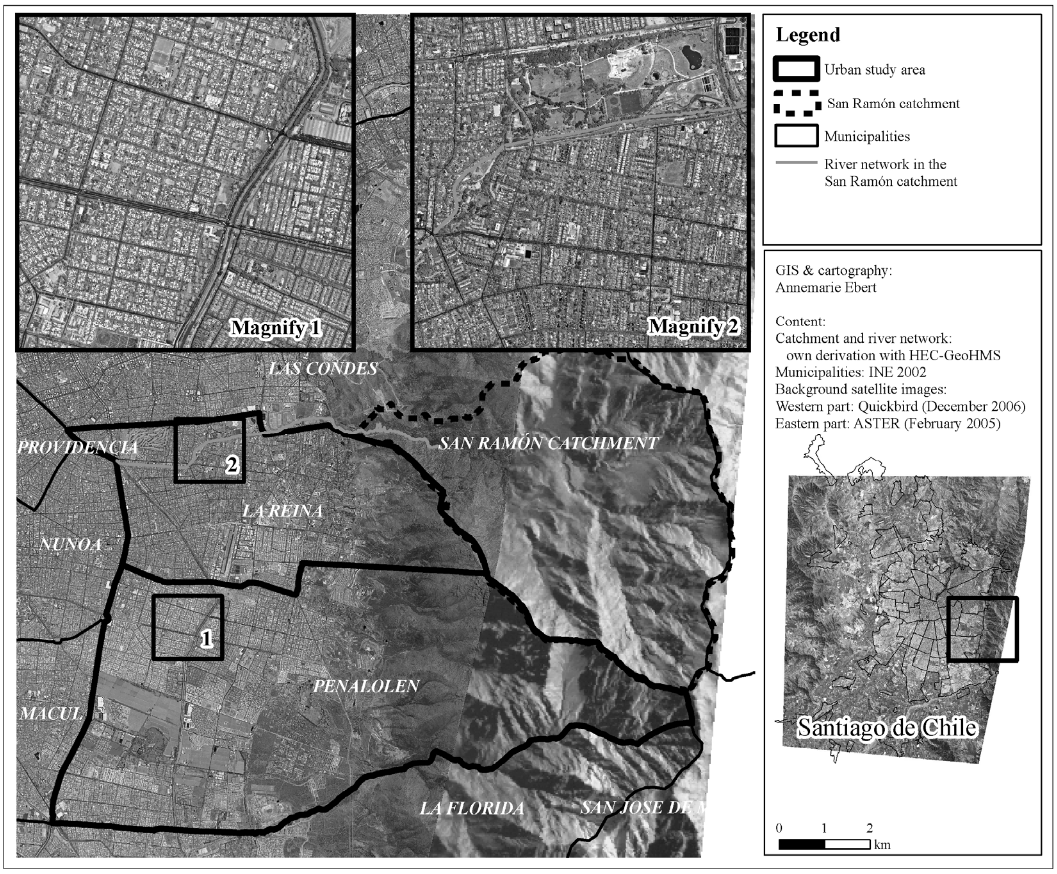


Figure 4: Location of the in-depth study area San Ramón catchment with the adjacent municipalities La Reina and Peñalolén.

1.3.3 The methodologies applied in this research

The methodological outline is shown in Figure 5. It is based on the before mentioned concept of risk. For the practical analysis and assessment of flood risk, a set of multi-scale (individual, household, municipal level) indicators was developed for the study area (Chapter 5). The main intention besides showing the complexity of the processes associated with flood risk is to communicate interdependencies and to show how the flood risk as a whole changes if single indicators, such as land use/land cover, number of elements at risk etc. are altered.

What follows is the geodata processing and analysis. As an introduction to that, Chapter 3 shows how various methods of geoinformatics have successfully been applied in the past to analyze flood hazard, elements at risk or their vulnerability. The main advantages of the use of geodata for flood risk analysis are the large spatial coverage, the homogeneity of the information, the repeatability and transferability of the methods, and the efficiency in terms of time and costs. To account for non-tangible information, the data were complemented by census data, household surveys, and expert interviews.

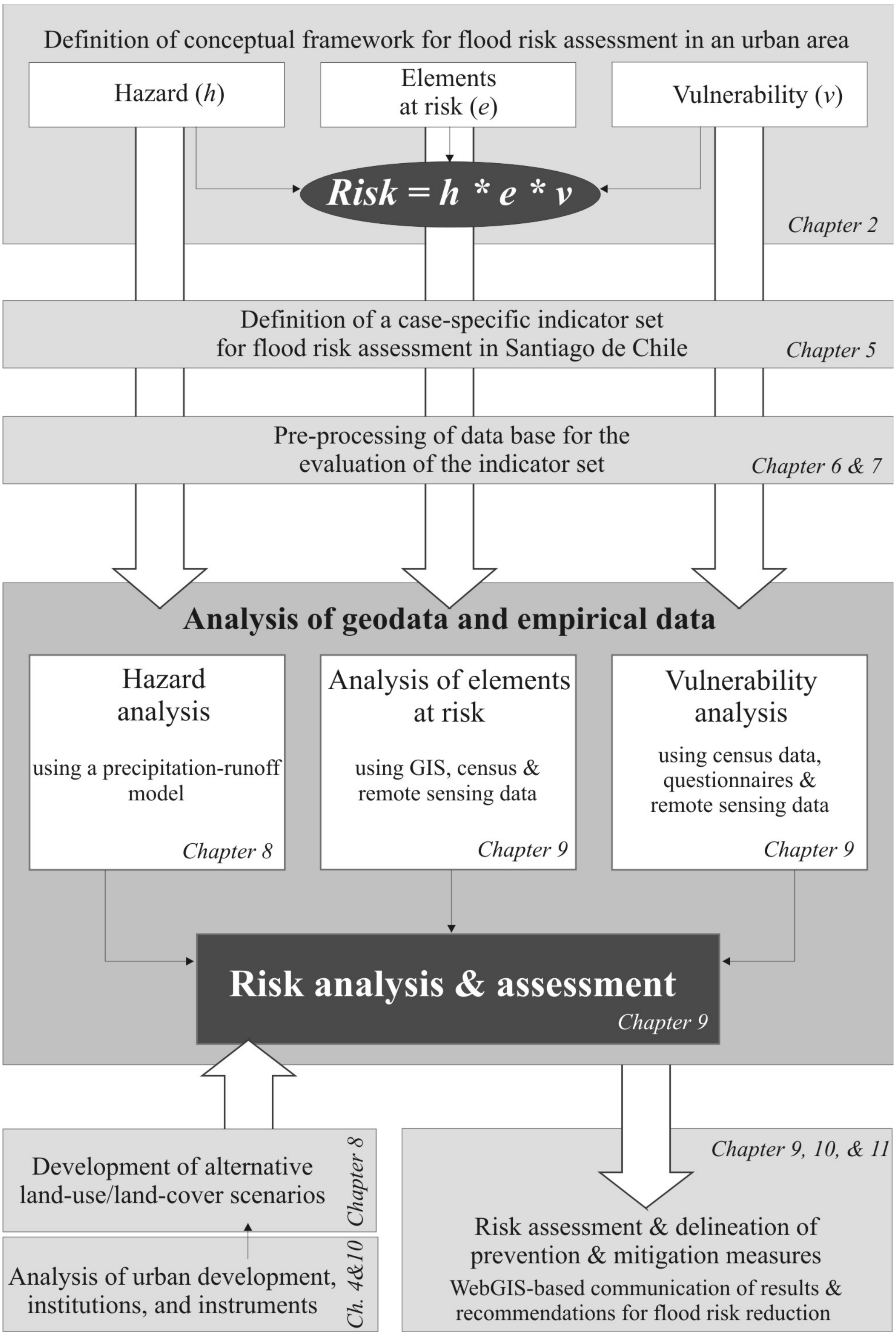


Figure 5: Work flow.

Chapter 6 provides detailed information on the variety of data used for this study and the required pre-processing tasks.

Within the scope of the geodata processing, high resolution multi-temporal ASTER satellite data (15 m geometric resolution) of the watershed are analyzed in combination with geologic and geomorphologic information to delineate updated information that support the analysis of runoff characteristics and their changes over time (Chapters 7 and 8). In addition to that, very high resolution remote sensing data (Quickbird satellite) and data of geographic information systems (GIS) are analyzed to identify elements at risk and their vulnerability in the study area (Chapters 7 and 9). Data from field surveys, expert interviews, and the census are analyzed to obtain in-depth information on vulnerability and elements at risk (Chapters 5 and 9). Chapter 8 relates the current and previous land-use information to the runoff generation and develops possible future land-use scenarios. It investigates the resulting runoff and finally the flood hazard using the hydrological precipitation-runoff model HEC-HMS. The resulting runoff predictions are then combined with existing very recently generated hazard maps for the study area (Perez 2009) to estimate the influence of LULC changes on the future flood hazard. Chapter 9 shows how the indicators are applied for the analysis and assessment of flood risk and how new flood risk maps are generated.

Chapter 10 provides recommendations for risk prevention and mitigation that are elaborated on the basis of adequate land-use management in the interests of sustainable urban development. It is made use of scenario techniques to illustrate the possible impacts of changes of the flood-relevant variables. Chapter 11 discusses the applied methods and the concept and content of this research. Concluding remarks finalize this thesis.

1.3.4 Exchange with stakeholders

A crucial prerequisite for a successful and realistic planning of the research, a good cooperation with the Chilean partners, and a fair evaluation of land-use development trends is indeed the understanding of the administrative and legal frameworks that deal with flood risk management. Several personal interviews with local decision makers and stakeholder workshops were carried out to discuss aspects of this research, to obtain more in-depth knowledge, and to draw the decision maker’s attention to the present research project in order to facilitate the knowledge transfer at the end of this project. One of the very latest developments with respect to GIS, i.e. WebGIS technologies, was applied to allow for an up-to-date communication and presentation of the research results on the Internet (Ebert [Müller] & Müller 2010b). That means that the research results can be accessed via a web browser.