MULTI-HAZARD RISK ASSESSMENT USING GIS IN URBAN AREAS: A CASE STUDY FOR THE CITY OF TURRIALBA, COSTA RICA

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ABSTRACT

In the framework of the UNESCO sponsored project on "Capacity Building for Natural Disaster Reduction" a case study was carried out on multi-hazard risk assessment of the city of Turrialba, located in the central part of Costa Rica. The city with a population of 33,000 people is located in an area, which is regularly affected by flooding, landslides and earthquakes. In order to assist the local emergency commission and the municipality, a pilot study was carried out in the development of a GIS –based system for risk assessment and management.

The work was made using an orthophoto as basis, on which all buildings, land parcels and roads, within the city and its direct surroundings were digitized, resulting in a digital parcel map, for which a number of hazard and vulnerability attributes were collected in the field. Based on historical information a GIS database was generated, which was used to generate flood depth maps for different return periods. For determining the seismic hazard a modified version of the Radius approach was used and the landslide hazard was determined based on the historical landslide inventory and a number of factor maps, using a statistical approach.

The cadastral database of the city was used, in combination with the various hazard maps for different return periods to generate vulnerability maps for the city. In order to determine cost of the elements at risk, differentiation was made between the costs of the constructions and the costs of the contents of the buildings. The cost maps were combined with the vulnerability maps and the hazard maps per hazard type for the different return periods, in order to obtain graphs of probability versus potential damage.

The resulting database can be a tool for local authorities to determine the effect of certain mitigation measures, for which a cost-benefit analysis can be carried out. The database also serves as an important tool in the disaster preparedness phase of disaster management at the municipal level.

Introduction

The increased vulnerability of many urban areas, especially in developing countries is a major reason of concern (Munich Re., 2000). Therefore emphasis should be given to the reduction of vulnerability in urban areas, which requires an analysis of potential losses in order to make recommendations for prevention, preparedness and response (Ingleton, 1999). The survey of the expected damages for a potential disaster essentially consists of risk evaluation. Risk is defined as the expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to particular hazard for a given area and reference period. Based on mathematical calculations risk is the product of hazard, vulnerability and cost of the elements at risk (WMO, 1999).

Most of the data required for disaster management has a spatial component, and also changes over time. Therefore the use of Remote Sensing and Geographic Information Systems has become essential in urban disaster management.

In the framework of the UNESCO sponsored project on "Capacity Building for Natural Disaster Reduction" a "Regional Action Programme for Central America" was established. Within this project a number of case studies throughout Central America are carried out. The first of these is the multi-hazard risk assessment of the city of Turrialba, located in the central part of Costa Rica. The city with a population of 33,000 people is located in an area, which is regularly affected by flooding, landslides and earthquakes. The city is also near the Turrialba volcano, which had its last eruption about 100 years ago.

In Costa Rica, disaster management is the responsibility of the National Commission for Risk Prevention and Emergency Response (CNE). The commission also has regional and local bodies, which act under its coordination and support. The Local Emergency Committee is responsible for disaster management at a municipal level. In order to assist the local emergency commission and the municipality, a pilot study was carried out in the development of a GIS –based system for risk assessment and management.

The objectives of this study were to support the local authorities with basic information required for disaster management at the municipal level, through the development of a GIS database, containing the following types of information:

a. Hazard maps indicating the probability of occurrence of potentially damaging phenomena within a given time period. This was done by generating hazard maps for earthquakes, flooding and landslides for different return periods.

b. A database of elements at risk, concentrating on the buildings and the infrastructure in the city.

c. Analysis of vulnerability of the elements at risk, taking into account the intensities of events as indicated in the hazard maps, combined with information from damage curves;

d. Cost estimation of the elements at risk, concentrating on the buildings and their contents;

e. Multi-hazard risk assessment.

An overview of the methodology for seismic risk assessment is presented in figure 1, and for flood risk assessment in figure 2.

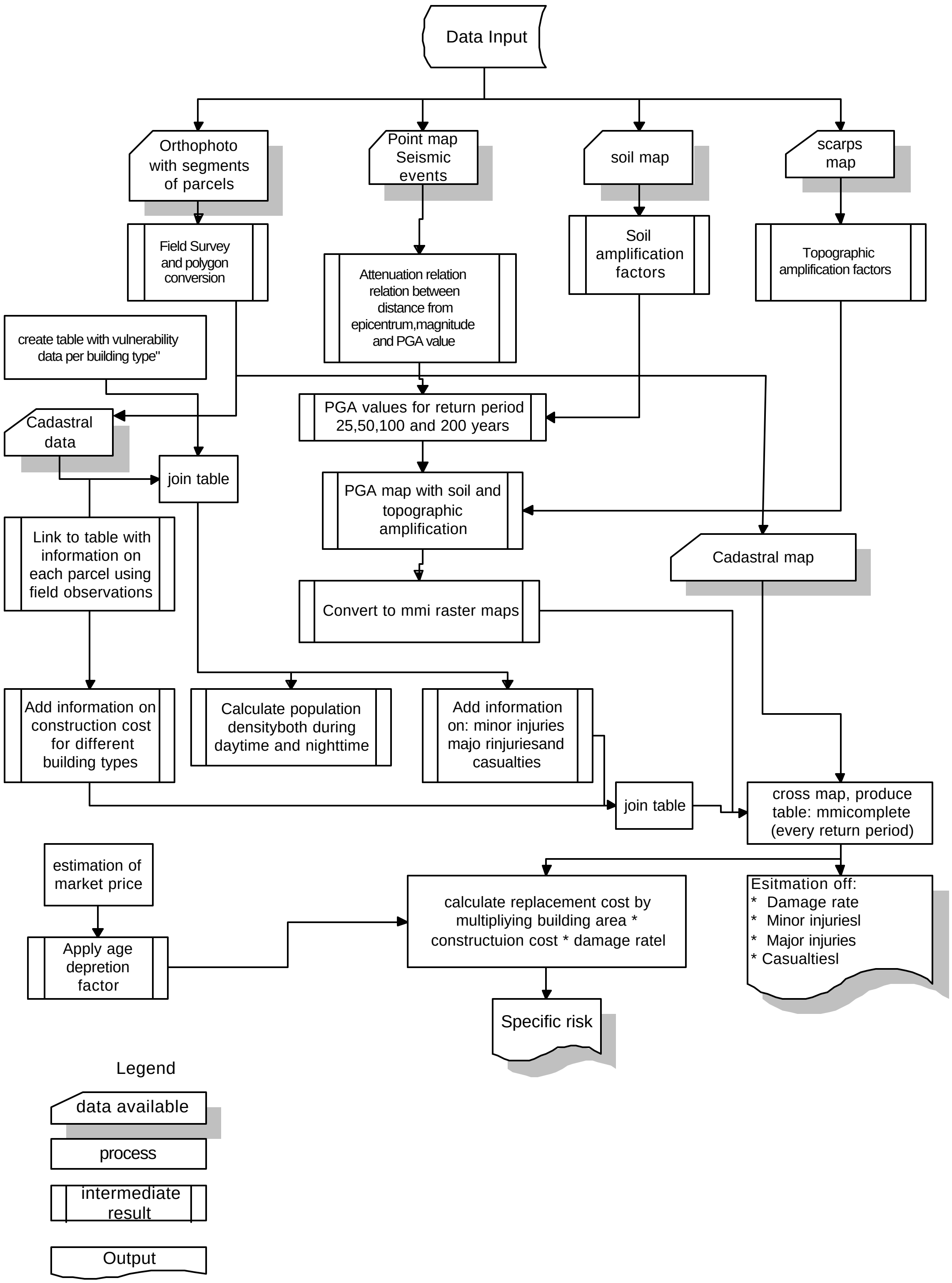


Figure 1: Schematic overview of the seismic risk assessment procedure using GIS.

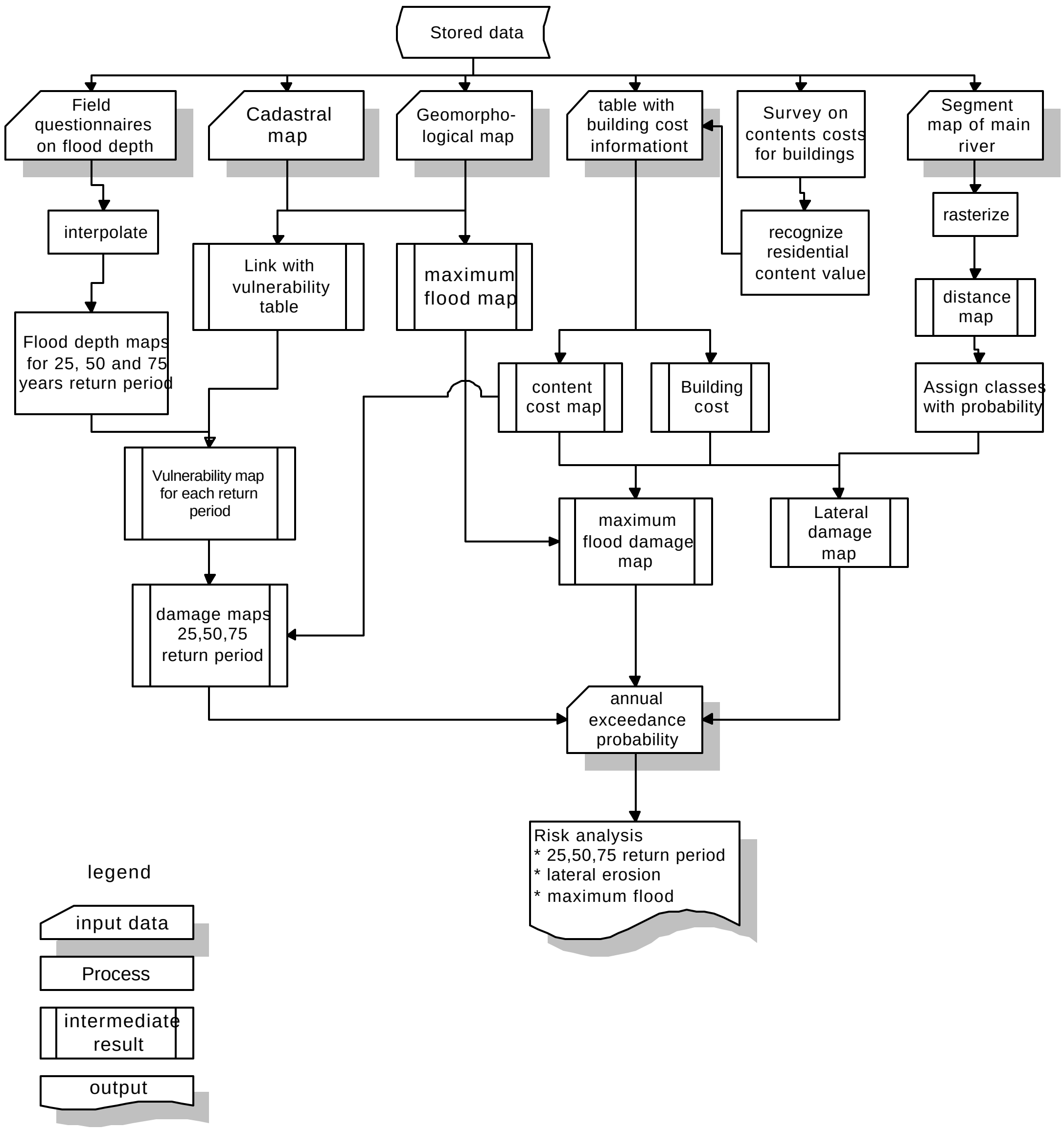


Figure 2: Schematic overview of the flood risk assessment procedure using GIS.

The Study Area

The city of Turrialba is located in the province of Cartago, to the east of San José, the capital of Costa Rica, in Central America (refer to figure 3). Turrialba City is a rather small city, with an extension of about 3.7 km^2 and about 33,000 inhabitants. Recently the city has shown a significant growth and due to this reason it is desirable to plan seriously for further expansion towards safe areas.

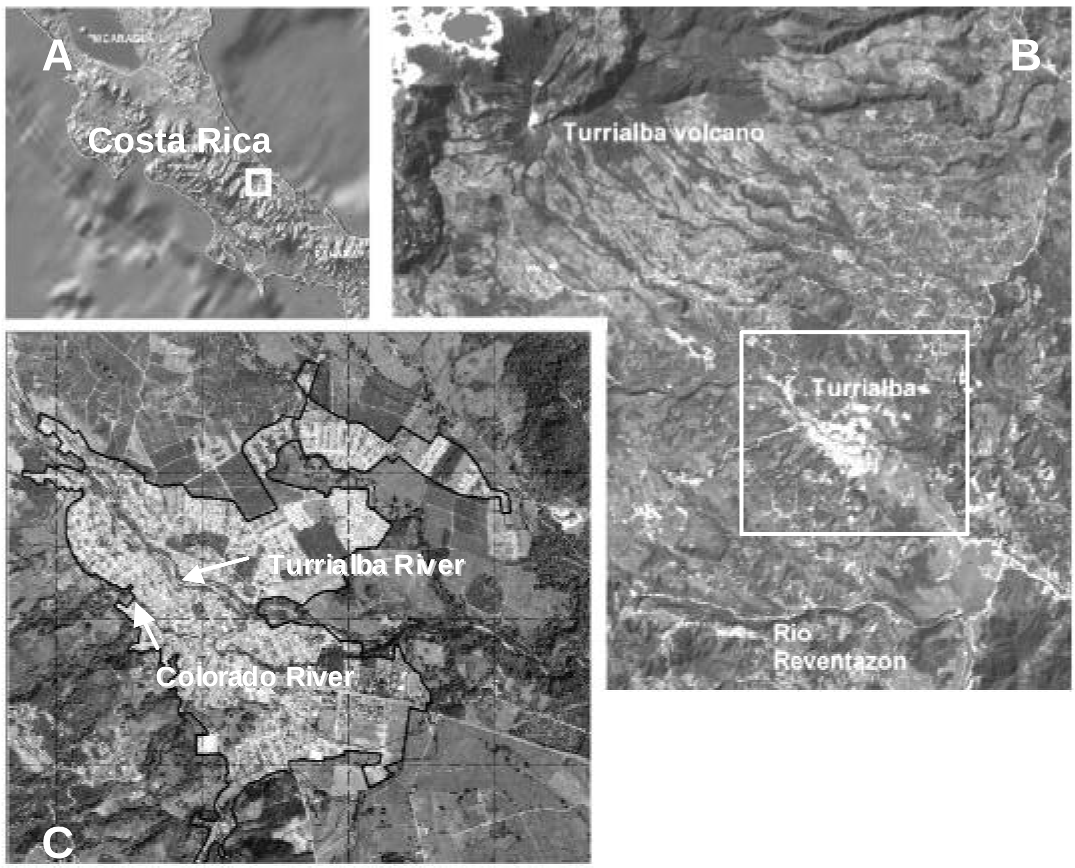


Figure 3: A: Location of the study area; B: Landsat TM image of the Turrialba region; C: Orthophoto of the city of Turrialba.

Geologically the area is underlain mostly by Quarternary (fluvio)volcanic deposits. Pyroclastic deposits and andesitic lavas are located around the Turrialba valley. The city itself is located on debris avalanche deposits, which are related to a large mass movement event that took place 15.000 years ago. The debris avalanche deposits have been buried in the lower part by lahar sediments and recent alluvial deposits. Colluvial deposits are found mainly at the foot of the hills.

The Turrialba area is affected by several types of hazards, such as volcanic activity, flooding, landslides and earthquakes. The city has been affected mostly by flood events, which are both related to the lateral erosion of the main river (Turrialba) which passes through the city in a channel with a depth of about 5 meters, and which has been straightened and partly protected by dikes. Most of the flooding, however is related to local streams (such as the Colorado river) which pass through the city in highly entrenched, and partly covered under designed channels. Consequently flooding takes places often due to the narrow cross sections under bridges and tunnel sections. The last heavy earthquakes in the surroundings of Turrialba occurred in LÍmon in 1991 and in Pejibaye in 1993, which resulted in an average MMI seismic intensity of VII affecting approximately 300 buildings.

Data Collection

The work was based on a series of color aerial photographs with a scale of 1:40,000, which were scanned at high resolution and combined with a Digital Elevation Model and a series of ground-control points for the generation of an orthophoto-map. On the orthophoto all buildings within the city and its direct surroundings were digitized, as well as the land parcels, the roads and other infrastructures. This resulted in a digital parcel map, consisting of 7800 polygons. Each polygon was described in the field by a team of surveyors, making use of checklists for the collection of data on hazard and vulnerability.

For each parcel the following attributes were described:

Use: landuse of the parcel, with main division in residential, institutional, commercial, industrial, recreational, agricultural and others

Material: material and structural type of the building

Age: age of the building, obtained through interviews

Value_building: estimation of value of building

Value_contents: estimation of value of contents of building

Number of floors: direct observation

Hazard: the hazard as observed or inferred by the experts in the field

Damage: reported damage due to natural or human-induced hazardous events

An overview of the categories used is presented in table 1, and an example of part of the map is shown in figure 4.

The initial parcel database was provided by the Tropical Agricultural Research and Higher Education Center (CATIE) in Turrialba (Wesselmans, 1998). An initial effort to survey the elements at risk by Central American specialists (Cardona et al. 2000) funded through UNESCO-IDNDR yielded a large amount of information about Turrialba City and its hazards. Later, the data collection was expanded by Cheyo (2002), Urban La Madrid (2002) and Badilla Coto (2002).

Table 1: Categories used in the elements at risk database

Attribute	Category	Record name	
Landuse	Residential	Res. high class	Res. middle class
		Res. middle-low class	Res. low class
	Institutional	Primary school	Kindergarden
		High School	Technical school
		University	Fire brigade
		Police station	Red Cross
		Ministry of Public Works	Telecommunications
		Electricity company	Municipal office
		Government office	Bank/financial
		Doctor's practise	Hospital
		Rehabilitation centre	Elderly's rest house
		Community centre	Church
		Cemetery	Water tank
		Water treatment plant	
	Commercial	Hotel	Restaurant/bar
		Shop	Supermarket
		Market	Other commercial
		Workshop/garage	Warehouse
		Gas station	Parking
		Bus station	
	Industrial	Quarry	Hidrocarbon plant
		Dangerous industry	Oil pumping factory
		Coffee processing plant	Electricity plant
		Other industry	
	Recreational	Sport field	Park
		Playground	Gymnasium
		Stadium	Swimming pool
	Agricultural	Banana plantation	Coffee field
		Sugar cane	Other agriculture
		Forest	Grass land
		Green house/garden	Farm
		Dairy farm	Farm for crops
	Other	Area under construction	Empty space
		Abandoned house	Shrubs
		River	
Age		Before 1960	1960–1970
		1970–1980	1980-1990
		1990-2000	After 2000
		Not applicable	
Floors		1 floor	2 floors
		3 floors	4 floors or more
		1 in front/2 behind	1 in front/3 behind
		Not applicable	
Material		Reinforced concrete blocks	Concrete and wood
		Reinforced concrete on poles	Asbestos
		Prefabricated concrete	Wood
		Wood on poles	Metal
		Mix of different materials	Not applicable

Apart from the parcel map the following information was collected and generated:

Digital contourlines, digitized from 1:50.000 scale topographic maps, were used to generate a Digital Elevation Model (DEM), and a slope steepness map, as well as a map showing major scarps and breaks of slopes;

A digital Landsat ETM image (bands 1-6 and panchromatic) from January 2001, was used in combination with the DEM to generate a pseudo anaglyph image. The stereo image was used for mapping geomorphological features, such as faults, volcanic deposits and landslides. Also scanned aerial photographs were used for the geomorphological interpretation. A software programme (ILWIS, 2002) allowing digital stereo image interpretation was utilized for a more detailed landslide inventory.

Geological information was also collected and digitized. This consisted of a lithological map (at scale 1:50.000), a fault map, an earthquake catalog and a soiltype map.

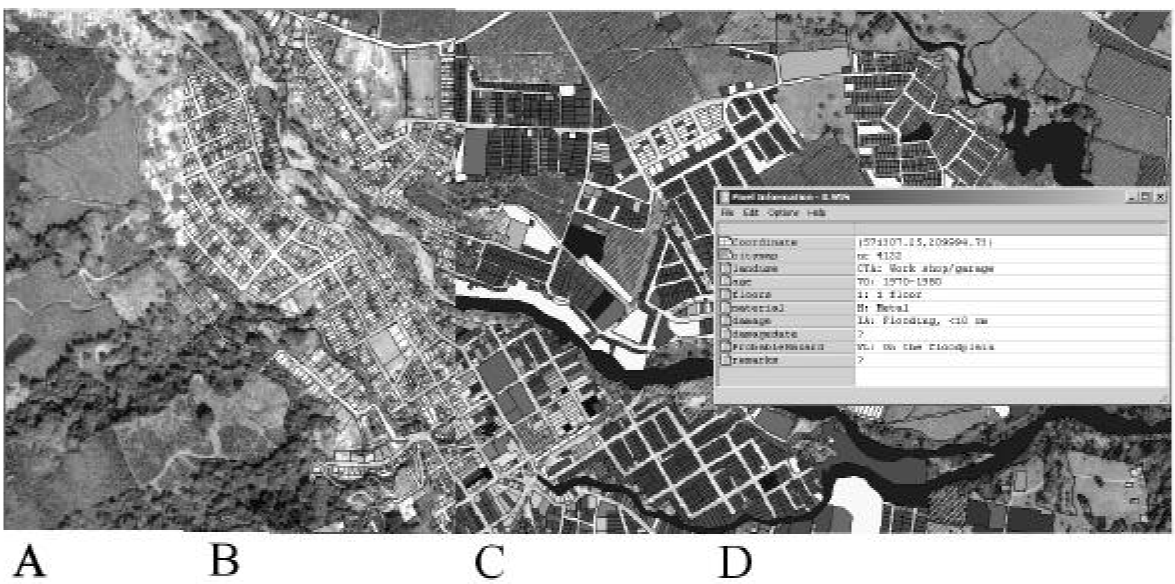


Figure 4: Different views of the large-scale database for the city of Turrialba. A: orthophoto, B: vector overlay of parcels, C: polygons displaying landuse type, D: reading information from the attribute database.

Analysis of historical information

Historical information on the occurrence of previous disastrous events has been given emphasis in this study. This was done through interviewing elderly people, newspaper searches, and through the damage reports available in the INS (National Insurance Institute). Also information was collected from the national and local emergency committees. Based on this information a database was generated, which is linked to the parcel database in GIS, and which allows for the generation of thematic maps on each of the above-mentioned parameters.

Hydrologic studies have been carried out in the area with the use of HEC-1, (Rojas, 2000; Solis et al. 1993; Solis et al. 1994; Badilla Coto, 2002) and peak discharges for different return periods calculated for the main rivers in the study region. Unfortunately, no discharge data is available for the area in order to calibrate the results. The studies have also indicated a number of possible bottlenecks along the local streams (Gamboa and Colorado) and the main river (Turrialba). In this way it was established that the main Turrialba river has enough capacity for a 100-year return period discharge while the Gamboa stream and the Colorado river may overflow once every one or ten years respectively.

Historical flood data available dates back to 1737, (GarcÍa, 1990; Zuñiga and Arce, 1990; Aparicio, 1999, Cardona et al. 2000; Badilla Coto, 2002). The most important flood events reported in the city are from the following dates: September 1737, October 1891, December 1908, November 1923, November 1928, November 1933, November, 1936, December 1949, February 1966, December 1970, September 1983, December 1987, May 1990, August 1991, February 1996, and May 2002. The flood events of 1996 and 2002 were studied in detail. The event from 1996 was related to the flooding of the Colorado river, which overflowed in a number of critical points, covering most of the city center. The flood event from 2002 was related to the main Turrialba river, causing severe lateral erosion which destroyed most of the protective dikes along the city leaving the city center exposed to severe flood hazard from the main river. Also a series of houses and bridges were destroyed.

Since no discharge data was available the historical data has been used in combination with precipitation records in order to find out possible return periods. In this way it was established that the 1996 represents an event with a return period of 50 years. For this flood event a map was prepared based on the point information of flood depths reported during the field questionnaire survey (refer to figure 5).

Hazard Assessment

In the study three types of hazards were analyzed: seismic, flooding and landslide hazard. An overview of the procedure for seismic hazard and risk assessment is presented in figure 1, and for flooding in figure 2.

A database of earthquakes records in digital format is available as part of the main seismic information. Historic and recent regional earthquake information has been processed (Climent et al 1994, Schmidt et al 1997, Laporte et al. 1994). The historic seismicity of Turrialba indicates that 9 seismic events within the range of 5.0-7.5 and depths of around 15 km have occurred within a 50 km distance to the area. It is assumed that Pacuare and Atirro are the faults responsible for seismic events close to the area. The most recent events experienced in the neighborhood of Turrialba are Pejibaye-1993 (M=5.3), Límon-1991 (M=7.6).

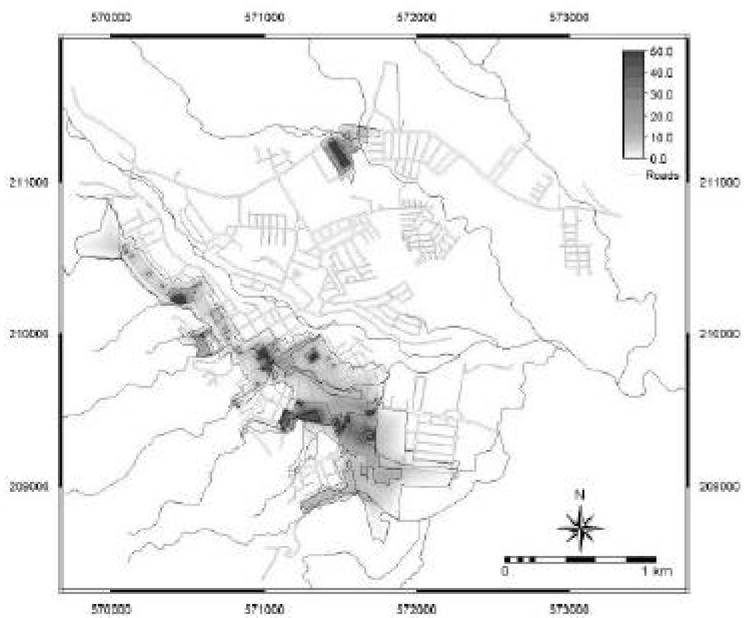


Figure 5: Flood depth map based on the historical data from 1996, representing an event with a return period of 50 years.

Probabilistic methods were used in order to obtain the respective values of PGA (peak ground acceleration) of rocks for different return periods, based on the work by Laporte et al. (1994) and Climent (1997).

Table 2. Return periods and peak ground acceleration values in rock conditions (from Laporte et al., 1994)

Return period	Peak ground acceleration (in g.)
100	0.205
200	0.240
500	0.360
1000	0.450

Soil amplification was estimated by means of a soil type map with a table with amplification values for each soil type for the return periods 25, 50, 100, and 200 years. Topographic amplification has been based on the location and distance from the scarps in the study area. Certain weights have been given to different distances from the scarps.

These weights were multiplied with PGA maps with soil amplification for all the return periods resulting in new PGA maps with amplification for soils and topography. To convert the PGA values to the Modified Mercalli Intensity, the relation from Trifunac and Brady (1975), was applied. The analysis resulted in four MMI maps for return periods 25, 50,100 and 200 years.

Flood hazard maps were made related to two different phenomena: lateral erosion hazard and inundation depth. As indicated before flood depth maps were made using historical information from field questionnaires. The resulting point file was converted into a raster map in GIS using contour interpolation and point interpolation. The resulting flood depth maps, for return periods of 25, 50 and 75 years, were classified into a number of classes.

In order to determine the hazard for lateral erosion, distance was calculated from the river channel of the Turrialba and Colorado Rivers. The distance classes were converted to hazard zones, based on historical information, and areas which were likely to be affected by lateral erosion with return periods of 25, 50 and 75 years were indicated (refer to figure 6).

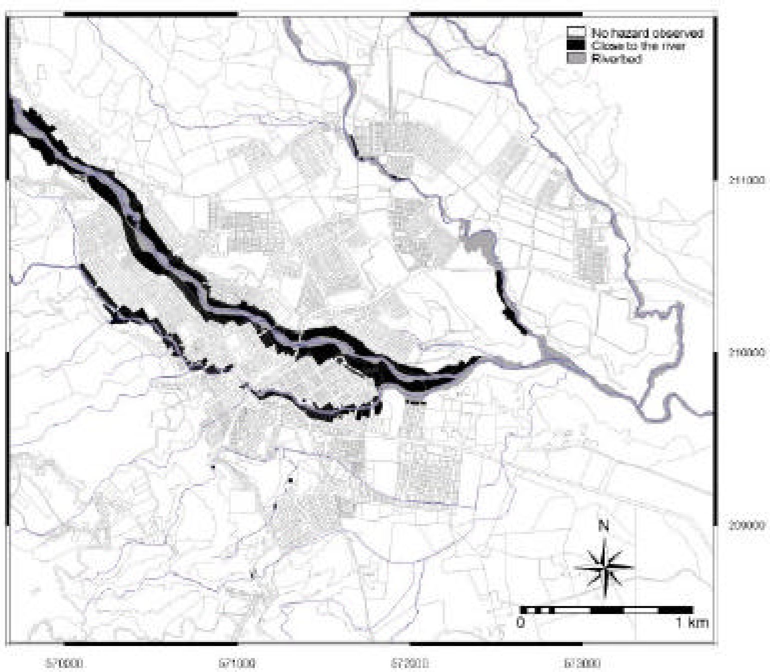


Figure 6: Simplified hazard map for lateral erosion

Also a hazard map was generated for a hypothetical maximum flood event, which might be related to an eruption of the nearby Turrialba volcano, caused by a very large lahar (volcanic debris flow) event that might hypothetically take place. Although information on return periods for such an event were not available (only the knowledge that approximately 15.000 years ago the entire area was devastated by a large debris avalanche) a hypothetical return period of 5000 years was assumed for such an event, which would lead to total destruction of all elements at risk in the area.

Landslide hazard was determined based on the historical landslide inventory and a number of factor maps, using a statistical approach.

Vulnerability Assessment

In this study vulnerability assessment was only carried out for the buildings and the contents of buildings, and basically only looking at direct tangible losses. The basic method used was the application of damage-state curves, also called loss functions or vulnerability curves (Smith, 1994). The cadastral database of the city was used, in combination with the various hazard maps for different return periods to generate vulnerability maps for the city.

Damage due to flooding depends on several factors, such as water-depth, duration of flooding, flow velocity, sediment concentration and pollution. The study only focused on damage related to water-depth, and to velocity in the case of lateral erosion. Generally flooding time is not very important, since most events are related to flashfloods with limited duration. The method used in this study for flood vulnerability assessment can be considered as a GIS-based hybrid between the actual flood damage approach and the existing database approach. This is because the vulnerability assessment is based on a detailed database of elements at risk and on field data collection related to the 1996 flood reported damages. Depending on the building type and the number of floors a degree of loss (ranging from 0 to 1) was assigned to each category of elements at risk, in relation with the different floodwater depth classes used. Separate values were assigned for the expected losses related to the contents of buildings (refer to table 3). In the case of lateral erosion vulnerability was assumed to be 1 (complete destruction) both for the building as well as for the contents.

For the determination of seismic vulnerability, the MMI maps were used in combination with vulnerability functions for different types of constructions adapted from Sauter and Shah (1978), who elaborated functions for Costa Rica as a whole (refer to figure 7). Vulnerability assessment of population for seismic events was made according to the Radius method, based on the building vulnerability and the type of building (residential, school, office etc.) assuming two different scenarios: during daytime and nighttime.

For the landslide vulnerability the size of the potential landslide area determined whether the vulnerability was 0, 0.5 or 1.

All vulnerability data was used in GIS to generate vulnerability maps for each type of hazard and return period.

Table 3: Definition of contents of buildings

Landuse type or category	Content definition
Residential: all social classes	Electrical and kitchen appliances, furniture, clothes, books, food, carpets, garden. Social class doesn't influence vulnerab.
Element. educ.: Kindergardens and primary schools	Tables, chairs, desks, books, computers, green areas, playgrounds
High education: high or technical schools, univers.	Same as elementary education but adding chemistry laboratory instruments
Fire brigade and Police	Furniture, computers
Red Cross	Furniture, computers, medical equipment
Gov. offices, Min. Public Works, Elect. Co., Telecommunic., Municipal office	Furniture, computers, documents
Bank/Financial	Furniture, computers, documents (including banknotes). Vulnerab. of documents is low because they are in safety boxes
Doctor's practise	Furniture, basic medical equipment, medicines
Hospital	Furniture, medical equip., medicines, documents, computers. It is assumed a hospital always has at least two floors
Rehabilitation Centre	Tables, chairs, desks, books and medical files, recreational areas, computers, special equipment
Elderly's rest house	Furniture, medicines, food, medical equipment, other electrical appliances
Church and commun. centre	Furniture, decoration
Cemetery	Green areas, gravestones
Water tank	Tanks
Water treatment plant	Pools
Hotel, restaurant, bar	Furniture, electrical and kitchen appliances
Commercial: shops, supermarkets, markets, others	Articles on sale
Work shop/garage	Equipment and tools, cars are not considered
Warehouse	Articles stored
Gas station	Fuel pumps and articles on sale. Water does not affect gas tanks
Industrial	Machinery and materials
Forest, empty areas (abandoned houses, shrubs, areas under construction)	No vulnerability
Sport fields, parks: including playgrounds	Field or lawn
Gymnasium, stadium	Fields and dressing rooms
Swimming pool	Dressing rooms and water filters
Parking, bus station	Toilets and cash decks. Vehicles are not included
Agricultural field: coffee, sugar, banana, others	Plants
Grassland	Grass
Greenhouse, farm for crops	Plants, assuming they are on the floor
Farms, dairy farms	Equipment and animal's food

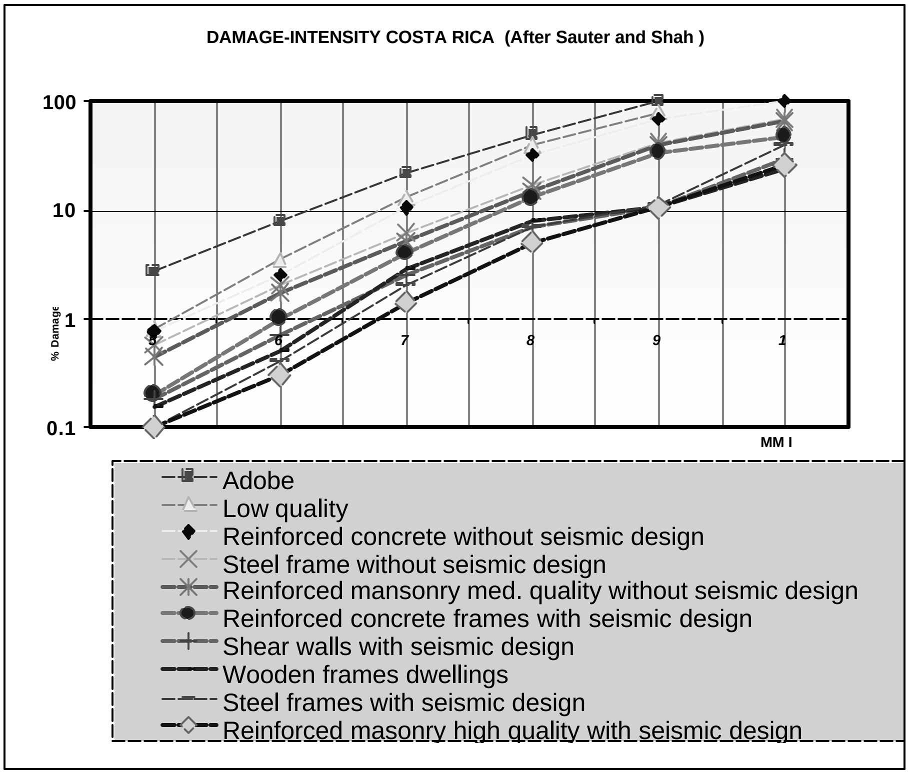


Figure 7: Vulnerability curves in relation with MMI for different types of constructions (After Sauter and Shah, 1978).

Cost Estimation

In order to determine the cost of the elements at risk, differentiation was made between the costs of the constructions and the costs of the contents of the buildings. The costs of the buildings were determined using information from real estate agents and architects in the area. A cost per square meter was entered in the attribute table linked to the cadastral map, and the cost per parcel was obtained by multiplication with the area of the parcel, and the number of floors. A correction factor was applied related to the percentage of the plot, which was actually built-up area, and also a depreciation factor was applied related to the age of the buildings.

An estimation of the cost of the contents of buildings was made based on a number of sample investigations for different building types and socioeconomic classes within the city (refer to table 3).

Based on the cost information three raster maps were generated: one representing the building costs, one representing the construction costs, and one for the total costs.

Risk Assessment

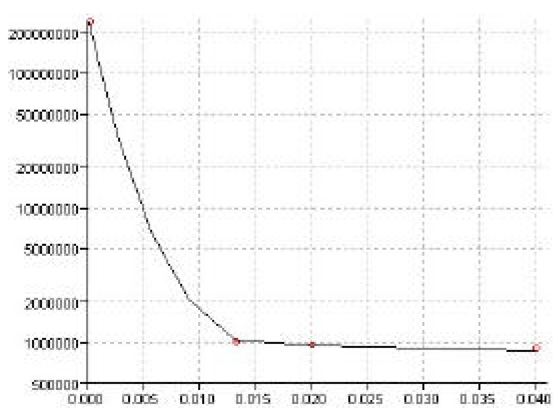
Risk means the expected degree of loss due to potentially damaging phenomena within a given time. In this case there are many different potentially damaging phenomena with different return periods. Therefore risk was determined by first calculating specific risk for each hazard type, through the generation of annual risk curves. Specific risk results from multiplying the annual probability factor, vulnerability and cost or indirectly multiplying annual probability with expected damage. An overview of the three types of input information (return period, costs and vulnerability) is presented in table 4.

Table 4: Overview of input data for risk assessment

Hazard type	**Return period**	**Costs**	**Vulnerability**
Flooding depth	25	Contents only	Vulnerability map for this scenario
	50	Contents only	Vulnerability map for this scenario
	75	Contents only	Vulnerability map for this scenario
Lateral erosion	25	Construction and contents	1
	50	Construction and contents	1
	75	Construction and contents	1
Maximum flood (lahar)	5000	Construction and contents	1
Earthquake	25	Construction and contents	Vulnerability map for this scenario
	50	Construction and contents	Vulnerability map for this scenario
	100	Construction and contents	Vulnerability map for this scenario
	200	Construction and contents	Vulnerability map for this scenario
Landslides	50	Construction and contents	0, 0.5 or 1
	100	Construction and contents	0. 0.5 or 1

Specific risk maps were generated for each type of hazard and each return period by multiplication of the potential damage maps and the annual exceedence probability. First damage maps were generated by multiplication between vulnerability maps and cost maps. For flood risk, damage maps were generated for three return periods (25, 50 and 75 years) from the various vulnerability maps multiplied by the cost map of the contents only, because it was assumed that the flooding will normally have little influence on the building itself. This is due to the fact that the floods have generally a small duration, and flood velocities are normally not very high. For the maximum flood damage map the vulnerability was considered to be 1 (total destruction). For the lateral erosion damage map also a vulnerability of 1 was assumed, since both buildings and their contents would be lost due to collapse in the event of undercutting. Specific risk maps for seismic hazard were made for the four return periods mentioned earlier (25, 50, 100 and 200 years), each using its own vulnerability map. Estimation of specific risk for landslides was one of the most difficult tasks, since both the probability, magnitude of the landslide, and therefore the vulnerability are very difficult to predict. Here an expert judgment was made and three vulnerability classes were used: 0, 0.5 and 1.

The resulting specific risk maps gave information on the total amount of damage expected annually due to a certain type of hazard with a certain return period. This damage was aggregated for the entire city and plotted in a graph of probability versus potential damage, though which a curve was fitted (refer to figure 8). The area below the graph represents the total damage for the specific type of hazard. Out of these a total risk curve was derived for the combination of the various hazard types, which represents the annual expected losses to buildings and contents of buildings for the various types of natural hazards in the city of Turrialba. The estimation of annual losses for each hazard type and each return period represents a very important "standardization process" which allows to put hazards into perspective and prioritize accordingly. The data generated can also be used to display a total risk map.



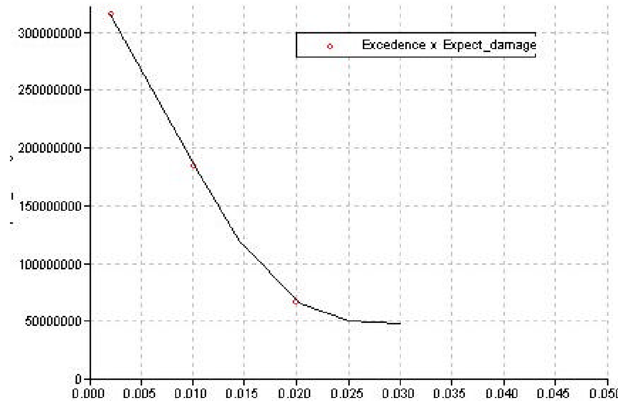


Figure 8: Specific risk curve for flooding (left) and seismic (right). X-axis is annual exceedence probability, Y-axis is estimated damage in Costa Rican currency.

Conclusion

For the vulnerability reduction cities affected by different hazards, this type of results will be very helpful for determining the effect of certain mitigation measures, for which a cost-benefit analysis can be carried out. This type of information products therefore allows to move away from the "response-only" approach to disaster management, which has been endemic throughout the developing world, to one which incorporates prevention and reduction.

Moreover, the database will be of great use for the municipality to find suitable areas for further expansion and also to relocate the people living in hazard-prone areas. Although the system is designed for disaster management, it may also serve as a multi-purpose tool. The municipality is using the orthophoto and the database for updating its land-ownership database in order to improve the tax collection system.

It is important to stress here that the work presented here was aiming primarily on the development of a methodology for GIS-based risk assessment in urban areas, with relatively little basic information available. In such cases the analysis relies heavily on historical information, and expert judgment, also regarding the relationship between magnitude and return period of the different events. Also, due to the limited time for field data collection, a number of assumptions and simplifications had to be made. In the flood hazard assessment, more emphasis should be placed on the other effects of flooding than the water depth only, such as duration of flooding, flow velocity and pollution. Also the evaluation of lateral erosion has to be based not only on the distance of the river channel, but also on the geomorphological situation and the meandering pattern of the river. In the case of seismic hazard assessment, more information should be obtained on the three dimensional configuration of the soil layers, and their geotechnical properties, and earthquake spectra should be used instead of single PGA values. In the vulnerability assessment, more emphasis should be paid to infrastructure, lifelines, critical facilities and population, and also indirect damage should be taken into account. Also more accurate cost information should be obtained, requiring the help of local economic experts and architects. As a whole the data collection could be significantly improved if was carried out over a longer time period by local experts.

Due to these limitations, the resulting risk values are only indicative, and should not be taken as absolute values for individual buildings. But they do serve to indicate the relative importance of each type of hazard, and the degree of impact it is likely to have.

Further investigations using other case study cities in Latin America and in Asia are planned within a research project entitled “Strengthening local authorities in risk management” (SLARIM). This research project, with a duration of three years, has the objective to develop a methodology for GIS-based decision support systems for disaster management in medium-sized cities. The SLARIM project is currently in the process of identifying potential case study cities, and hopes that the AUDMP workshop will provide an opportunity to establish contacts with authorities and organizations from cities in Asia.

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