# UNESCO-RAPCA project

# Developing a methodology for multi-hazard vulnerability (risk) assessment, the case study of the city of Turrialba, Costa Rica

This case study has been developed within the framework of the ITC - UNESCO project *Regional Action Program for Central America (RAP-CA),* which is a subprogram of the programme **"***Capacity Building for Natural Disaster Reduction Program" (CBNDR),* funded by the Netherlands government through UNESCO. This program, launched in 1999, focuses on capacity building for natural disaster reduction. For more information visit the following link http://www.unesco.org/science/earthsciences/disaster/disasterRAP-CA.htm

### Summary

The main objective of this exercise is to introduce a methodology for making a multi hazard vulnerability map using as example data from the city of Turrialba, Costa Rica. Different hazard scenarios corresponding to different hazardous phenomena are drawn. For each individual hazard scenario, specific vulnerability maps are prepared using user-defined vulnerability functions. Individual hazard vulnerability maps are combined into a single global vulnerability map (cross operation), keeping in mind differences in hazard scenarios, i.e. return periods. The output map is analyzed and further subdivision is made between those areas exposed to a unique hazard and those areas exposed to two (2) or more hazards for the specified time frame. Based upon this analysis a new vulnerability map is created.

### Disclaimer

The material in this exercise is for training purposes only. The results should not be used in actual planning of the city of Turrialba as ITC does not guarantee the accuracy and precision of the input data and adequacy of methodology developed during the exercise.

The GIS software that will be used in this exercise is the Integrated Land and Water Information System (ILWIS), version 3.x, developed by the International Institute for Geo-Information Science and Earth Observation (ITC). Information: www.itc.nl

### Introduction

Very often hazard scenarios for specific locations cannot be completely depicted with the assessment of a single threatening phenomenon or event. In some cases different menacing events could onset simultaneously (or with relatively short time lag between them). For example, earthquakes can trigger landslides, floods, and even fires; hurricanes commonly bring along floods and landslides; etc. In this case, characteristics of the secondary events are dependent on the magnitude of the first one. In other cases, the sites of interest can be located in areas where different types of events can occur within certain time frame but not necessarily at the same time; for instance a town located on a flood prone and seismically active zone. Events could take place independently of each other. In both such situations a multi-hazard approach is required, and consequently a multi-hazard risk assessment.

Single hazard risk assessment methodologies are well described in the current literature. The question posed in this exercise concerns the multi hazard situation. Could the multi hazard risk assessment simply be accounted as the sum of the individual hazard risk evaluations? Or, as previously stated, should the multi hazard risk assessment have into account whether events are independent of each other to determine the total risk scenario?

**Objectives and practical application**

- To develop a methodology for a qualitative multi hazard risk assessment in an urban area
- To prepare a qualitative seismic hazard risk assessment map
- To prepare a qualitative flood hazard risk assessment map

**Expected outcomes and outputs**

- ✓ Seismic intensity maps (MMI) for earthquakes with a return period of 25, 50, 75 and 150 years.
- ✓ Seismic hazard vulnerability maps for the specified seismic hazard scenarios.
- ✓ Flood hazard maps (water depth) for the 25, 50 and 75 years return period floods.
- ✓ Flood hazard vulnerability maps for the specified flood hazard scenarios.
- ✓ Lahars hazard vulnerability map.
- ✓ Multi hazard vulnerability assessment map.

**Instructions:**

**1.1 Defining single hazard scenarios**

**Seismic hazard**

Seismic hazard scenarios can be defined using either deterministic or probabilistic approaches. In both cases available historical seismic records and geological data (neotectonics studies) are used to identify and characterize main seismic sources, relevant to the site of interest, concerning their earthquake potential. The difference between these two approaches lies in the way the seismic scenarios are defined. The probabilistic scenario is defined as the likelihood for a specified Peak Ground Acceleration (PGA) or other relevant seismic parameter value to be exceeded within a certain time frame. The deterministic approach commonly produces a worst-case scenario, defined by a controlling earthquake, without given an indication on how likely that given scenario is to occur. See http://www.regione.emilia-romagna.it/geologia/e_sism2.htm for a more detailed explanation of these methodologies

In this exercise a set of seismic hazard scenarios are drawn using a probabilistic approach for the municipality of Turrialba, Costa Rica. Expected earthquakes magnitude for return periods of 25, 50, 100 and 200 years are calculated using the frequency – magnitude relationship derived by Climent & Barquero (in process, from Badilla 2002) for the southeast of Costa Rica. The equation has been obtained through the analysis of the 1980-1996 period existing seismic records.

**Log (N) = 2,69-0,70*M (Moya, 2000) equation 1**

The seismic hazard parameters (PGA) are calculated using the attenuation law for the Central America region derived by Climent et al. (1994), assuming an epicentre distance of 50 Km and earthquake depth of 15 Km. The Climent's attenuation relation was drawn from strong motion data observed in both México and Central America. A total of some 218 such measurements have been used in the least squares derivation of this attenuation model. The Climent et al. (1994) attenuation relation is.

**ln A = -1,687+0,553*M-0,537*ln(r)-0.00302*r+0,327*S+ln∈ equation 2**

Where

**M** is the moment magnitude
**r** is the distance to the hypocenter (from Pythagoras $r^2$ =earthquake-depth$^2$ + epicentre-distance$^2$)
**S** amplification factor, which has a value of 0 for rock site conditions and 1 for soils
**ln∈** is a term related to the error estimation factor equal to 0.75

From the previous equation we have:

***Lnarock( rock site conditions)*** = -1.687+0,553*7,7-0.537*ln(r)-0.00302*r+0.75 equation 3

***Lnasoil (soil site conditions)*** = -1.360+0,553*7,7-0.537*ln(r)-0.00302*hyp(r)+0.75 equation 4

From the previous maps it is possible to calculate

***arock*** (expected acceleration for rock site conditions) = exp(***lnarock*** )

***asoil*** (expected acceleration for soil site conditions) = exp (***lnasoil***)

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- Using equation 1 estimate the expected moment magnitude (Mw) for earthquakes having return period of 25, 50, 75 and 150 years.
- Using equations 3 and 4 calculate the PGA to expect in Turrialba corresponding to the previously estimated moment magnitudes. Assume an epicentre distance of 50 Km and earthquake depth of 15 Km.
- Taking into account the available surficial geology map for the city of Turrialba and the estimated PGA values for the different return periods prepare their related seismic hazard scenarios maps.
- Convert the PGA values into MMI values.

**Flood hazard**

A conventional flood hazard assessment requires a complete characterization of the basin's hydrological regime and detailed geomorphological mapping as basic inputs. These data were not available for Turrialba and was not feasible to rapidly acquire it. To overcome this situation and produce a flood hazard risk scenario, Badilla (2002) proposed an alternative methodology. According to the author, it would be possible to use data collected through direct interviews with the affected community to reconstruct the main characteristics of past events. That information could then be used for risk assessment purposes.

In this exercise the maps of the 1996 flood event made by Badilla (2002) will be used to generate the flood hazard scenarios required for the risk assessment. Based on the comparative analysis of local intensity precipitation records related to the 1996 flood event, Badilla (2002) hypothetically classified the 1996 rainfall as the maximum precipitation value corresponding to the 50 years return period flood (Badilla, 2002). Using this first map as reference and aided by field observations Badilla (2002) derived the 25 and 75 years return period flood hazard scenarios. These scenarios will later be used for the generation of the vulnerability functions required in the risk assessment and expected loss estimation.

The maps depicting the 25, 50 and 75 years return period flood hazard scenarios are given as equal-depth lines, so an appropriate interpolation technique should be used in order to reconstruct the flood spatial and depth distribution patterns.

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- Use the provided equal-depth flood maps to reconstruct the flood hazard scenarios for the events having 25, 50 and 75 years return period.
- Using the data on critical points (bottlenecks) try to explain the flood depth observed patterns.

**Volcanic hazard: Lahars**

The city of Turrialba is located 15 Km south east of the Turrialba volcano. Previous studies have concluded that the city of Turrialba will not be affected by any pyroclastic activity originated from the Turrialba volcano. In this exercise only the risk concerning lahars hazard is analysed. The lahars hazard map provided was prepared using PCraster.

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- Open the lahars hazard map "Lahars" and compare it against the geomorphological units map "geomorphology". What could you conclude regarding the reliability of the lahars hazard map based on the analysis of the geomorphological map?
- What can you say about the units described as "alluvial fans" and "debris avalanche deposits" in the geomorphological map concerning lahars hazard.
- Discuss the possibility of adjusting the lahars hazard map using the evidence provided by the geomorphological map. Based on your conclusions, make a decision on the lahars hazard map to be used during the risk assessment.

## 1.2 Preparing the single hazard vulnerability functions and vulnerability maps

In the previous part of the exercise the different hazard scenarios have been prepared; we will now proceed with the generation of the single hazard risk assessment maps.

The available data on elements at risk is provided in the map "Urban-DB". The main attributes described in the linked table are:

- **Use**: land use of the parcel; main categories are residential, institutional, commercial, industrial, recreational, agricultural and others
- **Material**: material and structural type of the building
- **Age:** age of the building, obtained through interviews

**Seismic hazard vulnerability functions**

In general, to create the seismic vulnerability maps the different seismic hazard scenarios are used in combination with specific vulnerability functions for the different types of buildings materials. Urban Lamadrid (2002) suggested adjusting the vulnerability functions derived by Sauter and Shah (1978) for Costa Rica to the specific type of building materials found in Turrialba. Table 1 shows the reclassification of building materials; table 2 shows the seismic vulnerability functions as defined by Urban Lamadrid (2002). The reader is invited to search for different seismic vulnerability functions and discuss the suitability of those herein presented.

Table 1. Types of building materials used in the definition of the vulnerability functions.

| **Building material (Sauter and Shah, 1978)** | **Reclassification Urban Lamadrid (2002)** | **Code** |
|---|---|---|
| Adobe | Discarded | |
| Low quality wood frames | Asbestos | 3 |
| Reinforced concrete without seismic design | Reinforced concrete blocks | 8 |
| Steel frame without seismic design | Metal | 4 |
| Reinforced masonry medium quality without seismic design | Mix of different materials | 5 |
| Reinforced concrete frames with seismic design | Prefabricated concrete | 6 |
| Shear walls with seismic design | Reinforced concrete on poles | 8 |
| Wooden frames dwellings | Concrete and wood, Wood | 8 |
| Steel frames with seismic design | Reinforced concrete on poles | 3 |
| Reinforced masonry high quality with seismic design | Discarded | |

Table 2. Seismic vulnerability functions for the city of Turrialba as defined by Urban Lamadrid (2002)

| **MMI** | **Selected building materials for Turrialba and percentage of damage to a specific seismic intensity.** | | | | |
|---|---|---|---|---|---|
| | **3** | **4** | **5** | **6** | **8** |
| **5** | 0.8 | 0.57 | 0.45 | 0.2 | 0.2 |
| **6** | 2.5 | 2.0 | 1.75 | 1 | 0.5 |
| **7** | 11 | 6.2 | 5.1 | 4 | 2.9 |
| **8** | 32 | 17 | 15 | 13 | 8 |
| **9** | 70 | 42 | 40 | 34 | 11 |
| **10** | 100 | 70 | 65 | 48 | 24 |

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- Analyze the seismic vulnerability functions that for the city of Turrialba are suggested by Urban Lamadrid (2002). Search on the Internet for other seismic vulnerability functions and compare them against the one herein presented. Draw your conclusions and defined a suitable seismic vulnerability function to be applied in the city of Turrialba.
- Using the existing data on elements at risk (building materials, age) prepare the seismic vulnerability maps for the previously created seismic hazard scenarios (return periods of 25, 50, 75 and 150 years).
- Reclassify the seismic vulnerability output maps into four (4) classes of expected damage: low, moderate, high and severe. Explain the criteria use to define the different value ranges assign to each damage class.

**Flood hazard vulnerability functions**

The level of damage buildings can be inflicted due to flooding events depends on several factors, such as water -depth, duration of flooding, flow velocity and sediment load. In the case of this exercise and due to the lack of suitable data, the flood vulnerability functions will be designed taking into account only the flood water –depth. Although insufficient to fully assess the expected degree of loss, the information generated can be considered as an indicator regarding the magnitude of the possible flood impact.

Following Badilla (2002) four water depth intervals are applied in the analysis of the flood hazard vulnerability. Each interval is assigned a value ranging between 0 and 1 that represents the expected degree of loss to the water depth interval. See Badilla (2002) for a more detailed explanation of the limitations of this approach.

The water depth intervals and its corresponding vulnerability value for each land use type are presented in table 3.

Table 3. Vulnerability values for each water depth intervals and land use type (Badilla, 2002)

| Landuse type or category | Vulnerability values | | | |
|---|---|---|---|---|
| | <10 cm | 10-50 cm | 50-100 cm | 100-150 cm |
| Residential | 0.15 | 0.35 | 0.50 | 0.80 |
| Elementary education | 0.02 | 0.30 | 0.45 | 0.60 |
| High education | 0.02 | 0.30 | 0.50 | 0.70 |
| Fire brigade and Police | 0.00 | 0.10 | 0.40 | 0.50 |
| Red Cross | 0.00 | 0.15 | 0.50 | 0.70 |
| Government office | 0.00 | 0.25 | 0.60 | 0.80 |
| Bank/Financial | 0.00 | 0.15 | 0.45 | 0.60 |
| Doctor's practise | 0.00 | 0.15 | 0.40 | 0.60 |
| Hospital | 0.01 | 0.08 | 0.15 | 0.20 |
| Rehabilitation Centre | 0.05 | 0.25 | 0.50 | 0.65 |
| Elderly's rest house | 0.05 | 0.10 | 0.35 | 0.60 |
| Church, com. centre | 0.00 | 0.05 | 0.20 | 0.30 |
| Cemetery | 0.20 | 0.30 | 0.35 | 0.40 |
| Water tank | 0.00 | 0.00 | 0.05 | 0.05 |
| Water treatment plant | 0.01 | 0.20 | 0.30 | 0.35 |
| Hotel, rest., bar | 0.01 | 0.30 | 0.50 | 0.85 |
| Commercial | 0.10 | 0.40 | 0.60 | 0.80 |
| Work shop/garage | 0.00 | 0.10 | 0.30 | 0.50 |
| Warehouse | 0.00 | 0.20 | 0.40 | 0.50 |
| Gas station | 0.00 | 0.20 | 0.40 | 0.60 |
| Industrial | 0.00 | 0.20 | 0.40 | 0.60 |
| Empty area | 0.00 | 0.00 | 0.00 | 0.00 |
| Sport fields and parks | 0.00 | 0.05 | 0.10 | 0.15 |
| Gymnasium and stadium | 0.00 | 0.15 | 0.25 | 0.30 |
| Swimming pool | 0.10 | 0.40 | 0.55 | 0.70 |
| Parking and bus station | 0.00 | 0.01 | 0.05 | 0.05 |
| Agricultural field | 0.00 | 0.05 | 0.10 | 0.20 |
| Forest | 0.00 | 0.00 | 0.00 | 0.00 |
| Grassland | 0.20 | 0.30 | 0.40 | 0.50 |
| Green house / Garden | 0.30 | 0.45 | 0.50 | 0.55 |
| Farm | 0.01 | 0.10 | 0.20 | 0.25 |
| Dairy farm | 0.01 | 0.10 | 0.20 | 0.25 |
| Farm for crop | 0.30 | 0.45 | 0.50 | 0.55 |

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- Using the information on water depth intervals and flood vulnerability values provided in table 3 create flood hazard vulnerability maps for each of the previously defined flood hazard scenarios (25, 50 and 75 years). Bear in mind that some of the land use types could be grouped together into a single category to ease the analysis.
- Reclassify the flood vulnerability output maps into four (4) classes of expected damage: low, moderate, high and severe. Explain the criteria use to define the different value ranges assign to each damage class.

**Lahars hazard vulnerability functions**

The case of the volcanic hazard is different from the previously analysed. Lack of sufficient data prevent us from having lahars hazard maps depicting the characteristics of their spatial distribution regarding thickness, composition, speed, etc. Instead only a map indicating areas susceptible of being affected regardless of the event's impact magnitude is available. Therefore using a conservative approach only a very simple vulnerability function could be defined: all elements at risk within the lahars affected areas are assigned a vulnerability value of 1, i.e completely destroyed or severely affected.

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- Prepare the lahars vulnerability map.

### 1.3 Multi hazard vulnerability (risk) assessment

As stated in the introduction, the main objective of this exercise is to prepare a multi hazard risk assessment using the example of the city of Turrialba. Multi hazard risk assessment methodologies have been discussed by different authors (Badilla et al, 2002 http://www.adpc.ait.ac.th/audmp/rllw/themes/th1-westen.pdf; Geoscience Australia & Bureau of Meteorology http://www.ga.gov.au/pdf/GA1486.pdf among others). The reader is invited to review the methodologies discussed in the mentioned documents before continuing with the exercise.

The methodology for preparing a multi hazard risk assessment suggested in this exercise comprises the following steps:

- ✓ Individual hazard vulnerability maps are combined into a single global vulnerability map (cross operation). Keep in mind differences in hazard scenarios, i.e. return periods.
- ✓ The output map is analysed and further subdivision is made between those areas exposed to a unique hazard and those areas exposed to two (2) or more hazards for the specified time frame of analysis.
- ✓ The final multi hazard vulnerability map will be defined as follows:
  - The vulnerability in those areas subjected to a single hazard is defined by the vulnerability corresponding to that specific hazard
  - The one representing the larger expected damage determines the vulnerability in those areas subjected to more than one type of hazard. For instance, if the classes low seismic hazard vulnerability and high flood hazard vulnerability overlap in a certain area, the global vulnerability of that area is defined as high, provided that the same time frame is considered.

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- Using the methodology herein introduced and taking into account the different hazard scenarios previously defined, prepare the multi hazard vulnerability map for the city of Turrialba. Pay attention to the return period assigned to the volcanic hazard!
- Discuss the results explaining advantages and limitations of this approach.
- Would you propose a different methodology?

### References

**Badilla Coto, E.,** Flood hazard, vulnerability and risk assessment in the city of Turrialba, Costa Rica. ITC Msc Thesis 2002.

**Urban Lamadrid, R.G.** Seismic hazard and vulnerability assessment in Turrialba, Costa Rica. ITC Msc Thesis 2002.

UNESCO - ITC. Capacity Building for Natural Disaster Reduction (CBNDR) Regional Action Program for Central America (RAPCA). Estudio preliminar de amenazas naturales en la cuenca del rio Turrialba, Canton Turrialba, Costa Rica, Centro América. July 2000

### Materials

| Basic data/map name | Format | Description | Comments |
|---|---|---|---|
| Phototur | Raster | Color aerial photography Turrialba (ortho?) | |
| Turritm | Raster, image list | Satellite images covering Turrialba river basin | Landsat ? Bands 3,4,5 |
| Contourlines | Segments | 20 m interval contour lines Turrialba river basin | |
| Reg_rivers | Segments | Rivers Turrialba basin | |
| Rivers | Segments | Detail rivers in the urban area of Turrialba city | |
| T_towns | Points | Location of urban centers in the Turrialba river basin and surroundings | |
| Streets_Turrialba | Segment | Roads Turrialba city | |
| Roads | Segments | Roads Turrialba river basin | |
| Bridges | Points | Location and type of bridge, though not technical aspects included | |
| Pstations | Points | Location of meteorological stations | |
| Locations | Points | Important places in Turrialba city | |
| Neighborhoods | Points | Labels wards Turrialba city | |
| Geomorphology | Polygons | Geomorphology map, Turrialba city | |
| Turegeomo | Polygons | Regional geomorphology map Turrialba area, | Covers middle and lower Turrialba river basin, source? |
| Geomcuenc | Polygons | Geomorphology Turrialba basin, R. Mora Universidad de Costa Rica | |
| Scarps | Polygons | Scarps Turrialba area | Used in the analysis of seismic topographic effects |
| Surficial-geol | Polygons | Surficial geology Turrialba city | Used in the analysis of seismic local effects due to soil conditions |
| Sub-catchments | Polygons | Sub-catchments in the Turrialba river basin | |
| Landcover_reg | Polygons | Land cover/use Turrialba river basin | Derived from? Year ? |
| **Vulnerability data/map name** | **Format** | **Description** | **Comments** |
| Urban-DB | Polygon | Cadastral map Turrialba city and some basic attributes | Data on hazards is derived from field observations. |
| City88 | Polygon | Extension of the city by 1988 | From aerial photo-interpretation? |
| City98 | Polygon | Extension of the city by 1998 | From aerial photo-interpretation? |
| Bridges | Points | Location and type of bridges, Turrialba city | No structural neither construction material data |
| Roads_mat | Point | Some information about roads cover material | |
| Structure_cost | Table | Estimated cost types of construction material | Cost in Costa Rican Colons, CRC |

| Risk | Table | Land use class and content's cost | Cost in Costa Rican Colons, CRC |
|---|---|---|---|
| **Flood Hazard data/map name** | **Format** | **Description** | **Comments** |
| Criticalpoints | Points | Critical points flood hazard: bottlenecks | |
| Depth96 | Segments | Depth 1996 flood, defined as the 50 years return period flood | Derived from field observations (Badilla, 2003) |
| Depth75 | Segments | Depth 75 years return period flood | Derived from field observations (Badilla, 2003) |
| Depth25 | Segments | Depth 25 years return period flood | Derived from field observations (Badilla, 2003) |
| Detailed_Floodhazard | Polygons | Flood hazard Turrialba city map derived from geomorphological interpretation | |
| Reg_Floodhazard | Polygons | Flood hazard Turrialba basin, derived from the reclassification of the 1:50000 geomorphological map | |
| **Seismic Hazard data/map name** | **Format** | **Description** | **Comments** |
| Quakes | Point | Derived from the seismic catalogue table "quakes" | Seismic parameters are given. This data it's not necessary but can be used as general background information |
| Quakes | Table | Seismic catalog | |
| **Volcanic Hazard data/map name** | **Format** | **Description** | **Comments** |
| Crater | Point | Location of the crater of the Turrialba volcano | |
| Lahar | Polygons | Lahars hazard | Created in PCRaster |