Seismic and flood hazard mapping at the local scale: Cartagena, Spain

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Abstract: In many cities, potentially dangerous geological processes such as floods and earthquakes condition urban development and the safety of their inhabitants.

The city of Cartagena (Murcia, SE Spain) is one such example. Founded in the 1st century B.C., its expansion has been clearly affected by flooded areas, which have limited its growth and have caused damage in the past. The city occupies a moderately seismic area that has suffered at least 8 earthquakes of I>VIII (MSK), whose epicentres have been less than 100 km from the city. These hazards must be evaluated and taken into account in urban planning and the management of possible natural disasters and potential catastrophic events.

In this paper, an in-depth study is presented undertaken by the Geological and Mining Institute of Spain designed to establish seismic and flood hazards for the built-up and developing areas of Cartagena. The results were used to prepare specific and integrated hazard maps at a 1/15,000 scale.

The seismic hazard map includes the seismic response of the terrain for a calculated reference earthquake, based on a deterministic and probabilistic analysis of the seismic hazard for a 100-year return period. The response was evaluated according to amplification of the seismic waves and vibration periods for each area in the study case. The vulnerability of the buildings according to their height and vibration period was also considered. The flood hazard map indicates areas that could undergo flooding (flash floods or intense rainfall) for return periods of 10, 25, 100 and 500 years. This map was based on a hydro-meteorological analysis, with hydraulic models applied to sites particularly susceptible to flood effects.

Résumé: Le développement urbain de la ville de Cartagena (Murcia, SE d'España) a été affecté par l´occurrence de processus géologiques potentiellement nuisibles le long de son histoire, comme les inondations et les séismes. Fondée au siècle I av. J.-C., (le siècle I B.C.), son expansion a été conditionnée par la présence de zones inondables, limitant la croissance et causant dangers dans le passé. La ville occupe un secteur de seismicité modérée qui a subi au moins 8 séismes d'intensité I>VIII (MSK), avec des épicentres à moins de 100 km de la ville. Ces risques doivent être évalués et considérés dans le développement urbain et dans la gestion de possibles événements catastrophiques naturels.

Dans ce travail est présentée une étude de détail effectué par l'Institut Géologique et Minier d'España pour évaluer le danger par séismes et inondations de la ville de Cartagena et son secteur d'expansion. À partir des résultats on a effectué les cartes de danger à l'échelle 1/15.000.

La carte de danger sismique inclut la réponse sismique du terrain face au séisme de référence ou calculé, sur la base des analyses déterministes et probabilistes du danger sismique pour une période de retour de 100 ans. La réponse sismique du terrain a été évaluée en fonction de l'amplification des ondes sismiques et des périodes de vibration. La vulnérabilité des bâtiments a été calculée selon sa hauteur et ses périodes de vibration.

La carte de danger par des inondations indique les secteurs inondables (par crues ou par précipitations intenses) pour périodes de retour de 10, 25, 100 et 500 ans, à partir des résultats des analyses hydrométéorologiques et les modèles hydrauliques appliqués dans les zones susceptibles d'inondation.

Keywords: geological hazards, engineering geology maps, floods, seismic hazard.

INTRODUCTION

The city of Cartagena (Murcia province, SW Spain, Figure 1) occupies an area where active geological processes have strongly conditioned the city's growth and development. The steep coastal relief that surrounds the city, the littoral conditions and its position in a seismic region of the Iberian Peninsula mean that the Cartagena area is strongly affected by natural processes, which can provoke geological risks for its inhabitants, infrastructure and buildings. The main geological hazards affecting Cartagena are floods and earthquakes.

Figure 1. Location of the study area

Detailed maps in which the hazards related to active geological processes are defined for the area occupied by the city and its expansion zones are indispensable tools for urban planning and land use projects. These maps are also essential for establishing recommendations and criteria on which to base the design and construction of buildings and infrastructure.

To this end, local geological hazard maps should indicate the spatial distribution of geological factors and processes in sufficient detail to provide engineers, town planners and architects with the information necessary to design and construct structures in harmony with the geological environment; also this type of tool is essential for gaining knowledge on natural resources targeted at land use and planning efforts.

SEISMIC HAZARD MAPPING

Methodology

To establish the seismic hazard of a zone, the characteristics of seismic activity have to be determined at the sites and adjacent areas where earthquakes could occur.

The following steps were taken to prepare the seismic response map for Cartagena:

- Seismic sources were characterised.
- Seismic hazards were evaluated and the typical earthquake defined.
- Site effects were established. The terrain was classified according to its seismic response based on geotechnical characteristics.
- Structural vulnerability was evaluated: city buildings were classified by height.
- A 1:15,000 map indicating the seismic response of the terrain was drawn up.

Seismic source characterization

Historical seismicity

For this study, an area of 200 km around the city was examined, since the effects of past earthquakes in zones outside this area have been negligible. All historical earthquakes occurring in this defined zone reported in the Earthquake Catalogue of the *Instituto Geográfico Nacional de España* (IGN, 2000), including over 3000 events, were considered.

There are no records of large historical earthquakes in the surroundings of Cartagena, although there have been several significant earthquakes 40 to 60 km outside the city: 1 earthquake of intensity X, 1 of intensity IX, 6 of intensity VIII and 15 of intensity VII (Table 1). The recent earthquake in Mula (Murcia province) of intensity VI-VII and magnitude m_b=5.0, that occurred on February 2nd 1999, was also considered.

Table 1. Main historical earthquakes occurring in the region of the study area

Intensity	Coordinates		City (Province)	Date	Distance (km)*
X	-0°42’	38°00’	Torrevieja (A)	1829	52
IX	-1º52’	37º13’	Vera (Al)	1518	86
VIII	-0°38’	38°06’	Guardamar (A)	1523	64
VIII	-1°42’	37°42’	Lorca (Mu)	1579	63
VIII	-1°42’	37°42’	Lorca (Mu)	1674	63
VIII	-1°13’	38°01’	Cotillas (Mu)	1911	48
VIII	-1°12’	38°06’	Lorqui (Mu)	1911	58
VIII	-0°50’	38°05’	Jacarilla (A)	1919	54
VII	-1°42’	37°42’	Lorca (Mu)	1674	63
VII	-0°42’	38°00’	Torrevieja (A)	1802	52
VII	-1°42’	37°42’	Lorca (Mu)	1818	63
VII	-0°42’	38°00’	Torrevieja (A)	1828	52
VII	-0°42’	38°00’	Torrevieja (A)	1837	52
VII	-0°42’	38°00’	Torrevieja (A)	1866	52
VII	-1°18’	38°06’	Ceutí (Mu)	1883	62
VII	-1°13’	37°48’	Totana (Mu)	1907	30
VII	-1°18’	38°06’	Ojos (Mu)	1908	60
VII	-0°40’	38°00’	Torrevieja (A)	1909	52
VII	-0°57’	38°34’	Salinas (A)	1916	100
VII	-1°16’	38°02’	Torres de C. (Mu)	1917	54
VII	-1°14’	38°04’	Lorqui (Mu)	1930	58
VII	-1°09’	38°10’	Fortuna (Mu)	1944	65
VI-VII	-1º49’	38º11’	Mula (Mu)	1999	97

* from the city

Seismogenetic zones: definition and characterization

A “seismogenetic zone” is a territorial unit showing homogenous seismic and tectonic features. From a standpoint of tectonics, it may be comprised of one or several source structures, and the genesis of the earthquakes produced is assumed to be homogenous in time and space.

In the south-eastern area of Spain, where the province of Murcia is located, 9 seismogenetic zones were defined, essentially corresponding to the region’s large geological-structural units and neotectonic domains. Figure 2 shows these 9 seismogenetic zones and the epicentres of the earthquakes considered in the seismic hazard evaluation. These 9 zones cover the entire 200 km area around Cartagena.

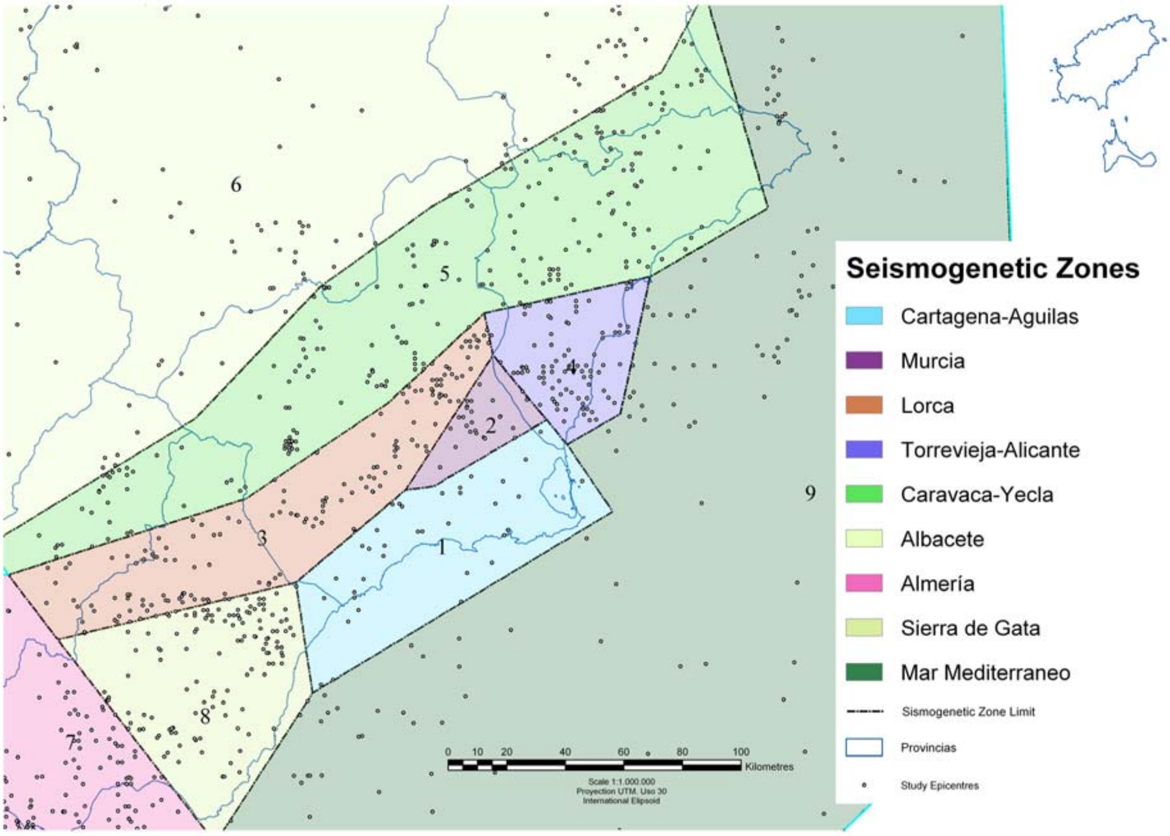

Figure 2. Seismogenetic zones in the region surrounding the study area

Each seismogenetic zone defined was characterised by the seismic intensity observed, epicentre depths, the frequency-intensity relationship and the earthquake annual rate. Intensity corresponds to the maximum destructive capacity of an event. The epicentre depth analysis indicates that earthquakes in this region are superficial, with maximum depths close to or less than 10 km. For each zone, the relationship between the number of earthquakes (N) greater than a given intensity and intensity values (I) was determined. The expression used was of the type: $\ln N = \alpha + \beta I$, where α and β are constants. Earthquake annual rate (number of events per year) were obtained directly from the Earthquake Catalogue and corresponded to the number of earthquakes/year of intensity above an established value. Table 2 provides these variables for each zone.

Table 2. Seismic characteristics of the seismogenetic zones established

Zone	Intensity			Relation Frequency -Intensity		Seismic Annual Tax	
	Maximum		Minimum	β Parameter	β Parameter	Earthquakes/year	
	Historical Period	Instrumental Period		Historical Period	Instrumental Period	Historical Period	Instrumental Period
1	V	VI	III	0.2351	0.9981	0.2808	0.8891
2	VII	VI	III	0.5663	0.9234	0.2762	0.9080
3	VIII	VI	III	0.3255	1.0017	0.6778	1.7243
4	X	VI	III	0.6257	1.1160	1.1280	0.8464
5	IX	VII	III	0.6764	1.1758	1.2265	3.8240
6	IX	VI	III	0.3380	1.2316	0.3380	2.0074
7	IX	VI	III	0.5647	1.0138	1.1464	2.7222
8	IX	VII	III	0.7225	1.5668	1.3878	2.6592
9	VI	VI	III	0.8154	0.9363	0.9087	3.5872

Seismic hazard evaluation

Seismic hazard were estimated using deterministic and probabilistic methods. The first of these methods was used to evaluate the maximum intensity expected for the study area. The probabilistic procedure allows expression of the results based on the return periods.

Background

The old building guidelines for seismic resistance, or "Norma Sismorresistente Española, PDS-1974" (IGN, 1974), assumed three types of seismicity according to the area considered: low, intermediate and high. The Cartagena area was assigned intermediate-high seismicity and intensity values of I=VIII on the MSK scale. More recent norm "Construcción Sismorresistente NCSE-94" (IGN, 1994) provide a seismic hazard map based on probabilistic criteria for a return period T=500 years. This norm distinguishes 3 areas with a basic peak ground acceleration less than 0.04 g, between 0.04 g and 0.12 g and more than 0.12 g. The city of Cartagena is ascribed a ground acceleration of 0.05 g.

Deterministic method

In the present case study, large seismogenetic features or faults coincide with the boundaries of the seismogenetic zones considered, such that the deterministic approach must be based on evaluating the seismicity of these zones, assigning to the area examined the most intense earthquake occurring in the seismogenetic province in which it is found.

Cartagena city lies in seismogenetic zone 1, where the maximum intensity reached is I=V for the historic time period. In zones close-by or further away, the maximum intensities recorded exceed I=VII and VIII. In these cases, laws of intensity attenuation with distance need to be applied to determine the maximum intensity that would reach the study area by earthquakes generated outside zone 1. Tables 3 and 4 show the attenuation laws used and the results of the deterministic analysis.

Table 3. Distance-intensity attenuation laws

Nº	Expression	Reference
1	I_0-I = 3.79 In (R+15)-11.59	Martín Martín (1983)
2	I_0-I = 3.82 In (R+25)-13.38	Martín Martín (1983)
3	I_0-I = 2.46 In (R+25)-7.40	Working Group Norma PDS (1986)
4	I_0-I = 2.38 In R-5.10	Established for this study

Table 4. Results of the seismic hazard deterministic analysis

Attenuation Law	**Origin of the earthquake**								
	Zone 1 I=V	**Zone 2 I=VII**	**Zone 3 I=VIII**	**Zone 4 I=X**	**Zone 5 I=IX**	**Zone 6 I=IX**	**Zone 7 I=IX**	**Zone 8 I=IX**	**Zone 9 I=VI**
1	V	IV	IV	VI	IV	II	I	III	V
2	V	V	V	VII	V	IV	III	V	VI
3	V	V	V	VII	V	IV	IV	V	V
4	V	IV	IV	VI	IV	III	II	IV	VI
Medium value	V	V	V	VII	V	III	II	IV	V
Determinist earthquake	I=VII								

Probabilistic method

This method consists of a probabilistic analysis in which statistical criteria are used to define the seismic hazard associated with the regional seismicity of the area around the city of Cartagena. In the analysis, the territory with seismic influence on the city was divided into zones showing the same earthquake probability of occurrence, a constant rate of events over time, and a probability of occurrence established according to a Poisson-type statistics law. For the analysis, the EQRISK program of the University of Berkeley (California) has been used, developed by R.K. McGuire. Table 5 shows the results obtained.

Table 5. Intensity values for different return periods

Attenuation Law	**Return Period (years)**				
	10	**50**	**100**	**500**	**1000**
1	3.00	4.16	4.56	5.24	5.45
2	3.94	5.06	5.47	6.24	6.47
3	3.82	5.01	5.45	6.15	6.29
4	3.00	3.77	4.17	4.95	5.08
Result	III-IV	IV-V	V	V-VI	VI

Selecting the design earthquake

Considering a mean useful life of 100 years, a valid period for most installations, Table 6 shows the probability of an earthquake of intensity IV-V, V, VI or VII occurring in the next 100 years.

In view of the probability of occurrence of earthquakes of intensity IV-V to VII for the next 100 years, in terms of building and structure design, an earthquake of I=VI and return period of 1000 may be considered as characteristic. For critical structures or extremely vulnerable buildings, the design earthquake would be one of I=VII.

Table 6. Earthquake probability of occurrence for different return periods

Return Period (year)	Intensity	Probability of occurrence in 100 years
50	IV-V	87%
100	V	63%
1000	VI	9.5%
> 1000	VII	< 9.5%

Accordingly, the characteristic seismic parameters (magnitude, duration and acceleration) and the response spectrum for these earthquakes must be calculated considering the intensities I=VI and I=VII on the MSK as the "calculation intensities". These values can be generally considered as slightly conservative. With respect to the magnitude, among the different intensity-magnitude correlations for Spain, some of them provide representative mean values, giving for the design earthquake of I=VI a magnitude of 4.7, while the largest earthquake expected, I=VII, would have a magnitude of 5.2. Predictions for earthquake duration are 30 s. Finally, the peak ground acceleration (PGA) estimated for the urban area of Cartagena is 0.08g.

Site effect estimation

To analyse the ground dynamic behaviour in response to the design earthquake, the seismo-geotechnical condition map of Cartagena was prepared (Figure 3). Six zones of different seismic behaviour were defined according to the lithological, hydrogeological and geotechnical characteristics of the materials present:

- Zone 1: Outcropping rock masses, with a stable response to earthquakes and no liquefaction nor seismic wave amplification phenomena.
- Zone 2: Ancient quaternary terrace and alluvial fan deposits and recent quaternary alluvial fan and glacial deposits. Slight wave amplification would be expected in the zones with greater soil depth and shallow water table.
- Zone 3: *Ramblas* and alluvial deposits, deposits of transiently active floodplains and zones of accumulating runoff. In these zones, there would be moderate wave amplification and a moderate risk of liquefaction in response to maximum earthquakes.
- Zone 4: Anthropogenic infill materials of thickness up to 8 metres. This zone would show intermediate wave amplification and an intermediate risk of liquefaction during the most intense earthquakes.
- Zone 5: Quaternary infill deposits of the *Almarjal* lagoon (an endorreic lacustrine zone): anthropogenic infill, silts, sands and muds of a depth up to 12 metres. These deposits would give rise to high wave amplification and an intermediate to high risk of liquefaction if maximum earthquakes occur.
- Zone 6: Infilling of sites reclaimed from the sea: compacted silts, sands and gravels, rocky blocks and port constructions on bay deposits. This zone would show intermediate seismic wave amplification and a high risk of liquefaction in response to the largest earthquakes, with the exception of coarse materials (breakwaters, etc.).

Part of Cartagena overlies loose soils, such as the zone occupied by the old *Almarjal* lagoon and the western zone of the historic centre. These zones harbour several public buildings, buildings of cultural value and many residential areas. Hence, an in depth study of the amplification level of the seismic signal of the characteristic (design) earthquake selected could attain in the urban area was conducted. To evaluate possible amplification effects, the linear-equivalent method Shake'91 (Idriss and Sun, 1992) was used, given its level of standardisation and the characteristic local conditions of the study area.

Each seismo-geotechnical zone was characterized by representative "type lithological columns", in which the geological materials present and their characteristic S-wave velocities were defined. The results of these amplification analyses are provided in Table 7.

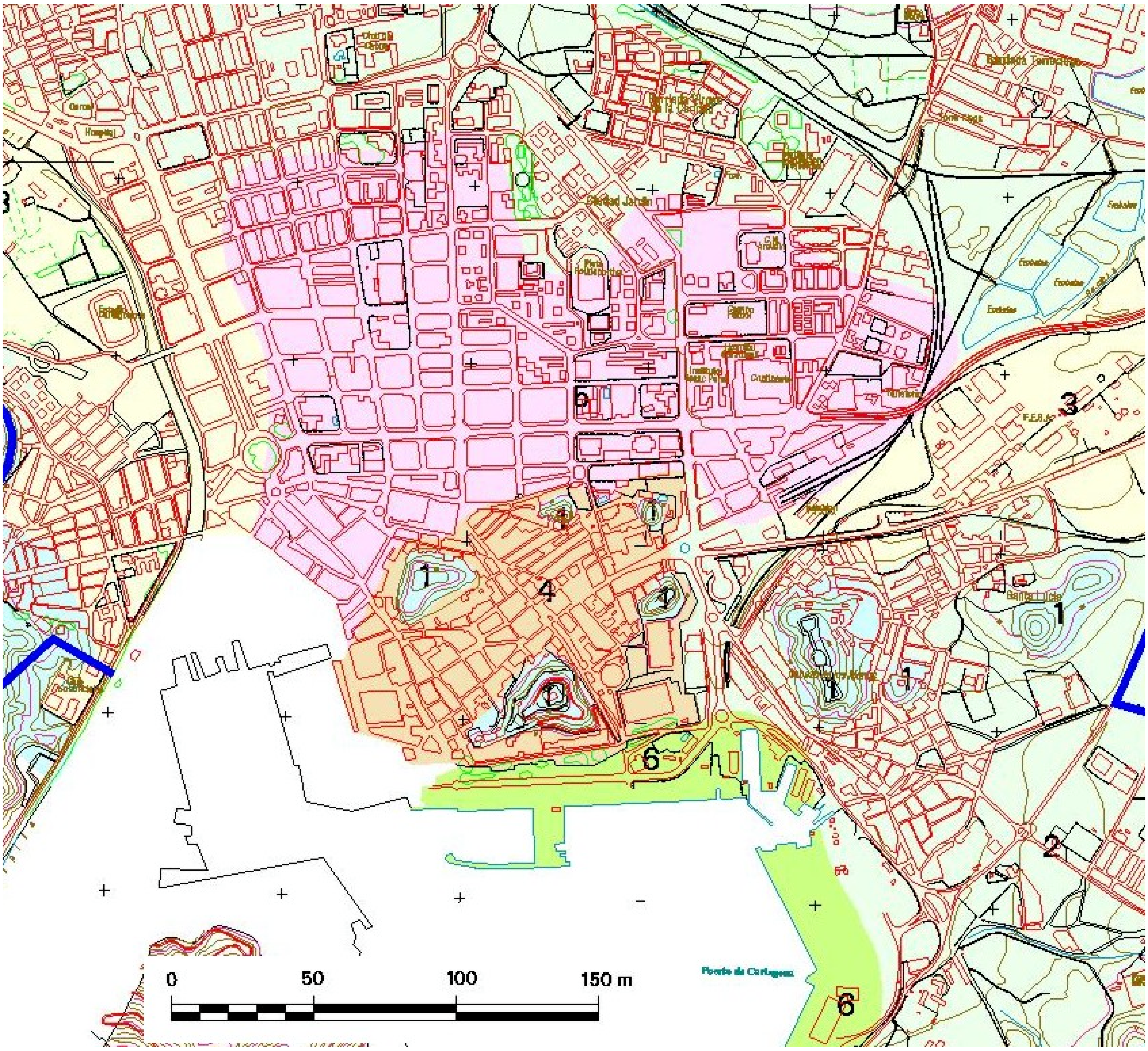

Figure 3. Detail of the seismo-geotechnical map of Cartagena. Original scale 1:15,000

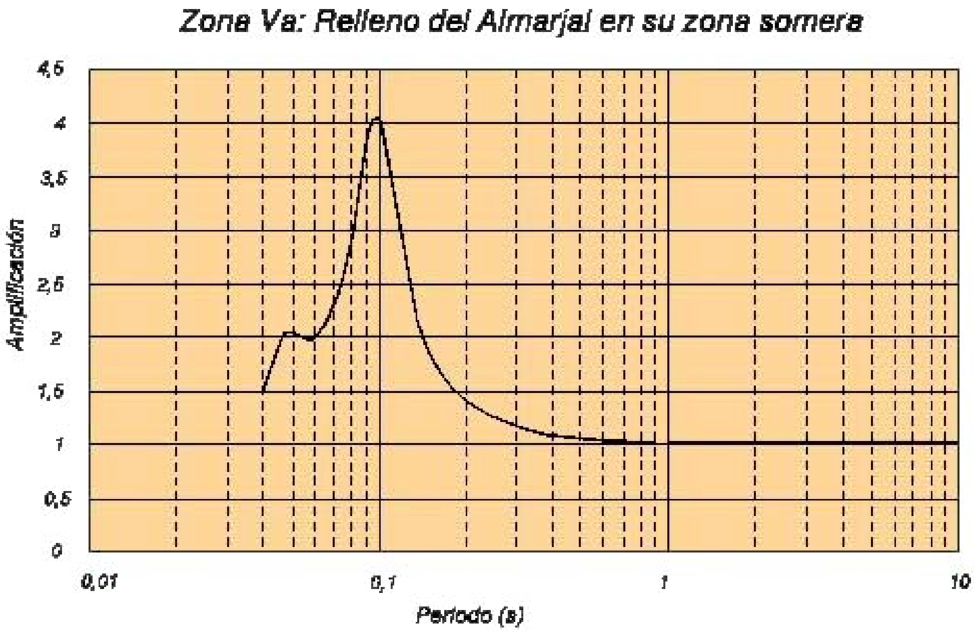

Figure 4. An example of the results of the amplification analysis. Zone V_a

Table 7. Zoning of Cartagena's built-up area according to the expected peak amplification

Area	Earthquake characteristic maximum amplification	
Area I_a	1	Very Low
Area I_b	1,06	Very Low
Area II	2,03	Moderate
Area III	2,02	Moderate
Area IV_a	1,9	Moderate
Area IV_b	1	Very Low
Area V_a	4,04	Very High
Area V_b	2,22	Moderate
Area V_c	3,2	High
Area VI	1,22	Low

Vulnerability analysis: classifying the city's buildings by height

In order to estimate the degree of seismic vulnerability of Cartagena's buildings, the number of floors of the buildings present in each seismo-geotechnical zone, were determined, defined in the urban area. Building height is a determining factor for the degree of damage produced by an earthquake. The displacement provoked by the arrival of the wave is a function of its propagation period and of the building's resonance period, which in turn depends on its narrowness (base to height ratio). Building heights were determined by interpreting 1:3500 aerial photographs. Subsequently, the relative percentages of each type of building defined in the classification scheme provided in Table 8, were calculated.

Table 8. Building classification by number of floors

Type	Floors number	Dominant period vibration (s)
1	1-2	0.1 a 0.3
2	3-5	0.3 a 0.6
3	≥ 6	> 0.6

Seismic response map

Using the information described above, a map of the seismic response of Cartagena was prepared at a scale of 1:15,000. This map indicates the areas whose response to the design earthquake could be greater, given their potential for wave amplification due to the site effect and the presence of vulnerable buildings (Figure 5 and Table 9).

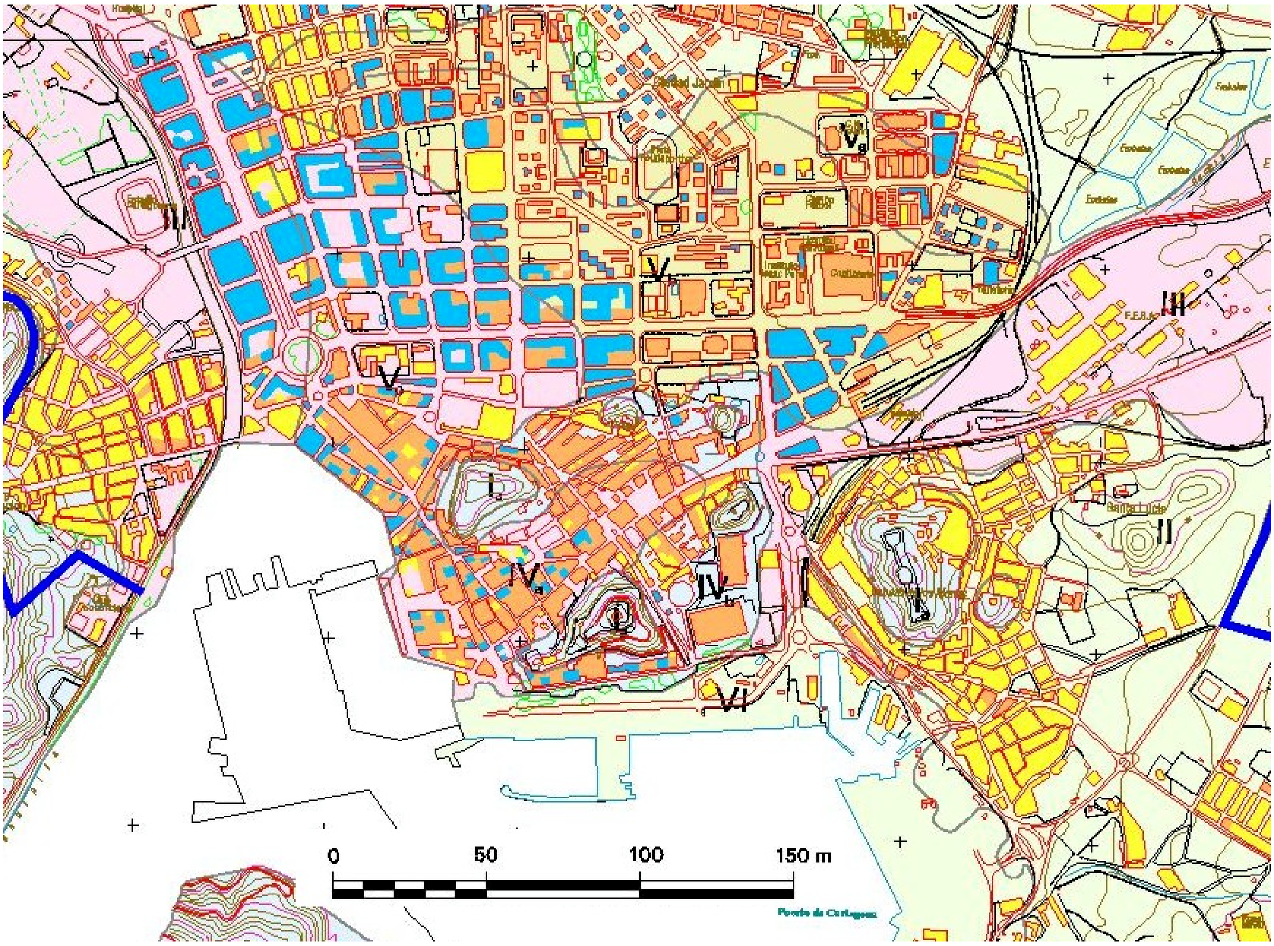

Figure 5. Detail of the seismic response map for Cartagena. Original scale 1:15,000

Table 9. Key to the Cartagena seismic response map

Area	% Buildings			Transference functions relations		Vulnerable building types	Seismic response (amplification)
	Type 1	Type 2	Type 3	Maximum amplification	Period (s)		
I_a	100	0	0	1 (very low)	-	None	Very low
Ib	95	5	0	1,06 (very low)	0.04	None	Very low
II	78	17	5	2.03 (moderate)	0.043	None	Low
III	79	3	18	2.02 (moderate)	0.25	1	Moderate-high
IV_a	20	50	30	1,9 (moderate)	0.37	2 1 3	Moderate-high
IV_b	40	50	10	1 (very low)	-	None	Very low
V_a	27	51	22	4,04 (very high)	0.095	1	Moderate
V_b	13	48	39	2,22 (moderate)	0.07	1 2	Moderate
V_c	19	34	47	3,2 (high)	0.3	2 3 1	Moderate-high
VI	90	10	0	1,22 (low)	0.45	2 3	Low

FLOOD HAZARD MAPPING

Floods historical record of Cartagena

Floods are the natural hazards that have caused most economic and human losses in the history of Cartagena. Documented records in this city date back to the end of the XVI century, although this estimate is not too precise because of the difficulties in registering events in those times and the lack of development of flood zones such as in the present.

Table 10 lists the main historical flood events and the available data on these floods. The main cause of flooding is the existence of *ramblas* or water channels crossing the city centre and the deficient drainage capacity of urban areas during intense rainfall. Since the XIX, for which there is a greater wealth of historical references, floods have recurred, such that over intervals not surpassing 7-12 years, the city of Cartagena has always been affected by floods. Of particular note is period between 1915 and 1919, during which the city suffered a flood practically each year.

Figure 6. Flood occurring on September 29, 1919 ("Riada de San Miguel")

Table 10. Main historical floods occurring in Cartagena

Date	Cause	Adverse consequences	Water level
Jan 1595	Benipila stream flood		
21 Oct 1604	Heavy rain	Broken bridges and buildings, flooded streets	2,1 m
25 Nov 1694 Santa Catalina storm	Sea storm	Waves surpassed the sea wall and the old town was flooded. Structural damage to several buildings.	
Oct 1704	Benipila stream flood	Almarjal zone and the city flooded. Several deaths.	4 "varas"
27 Sep 1767	Sea storm	Streets flooded. 3 deaths.	
1790	Tsunami: Orán earthquake	Flooding of the docks. Several fishermen on boats in the port fell into the sea.	
Sep 1858	Benipila stream flood	City flooded.	
Nov 1869	Benipila stream flood	Almarjal zone and city flooded.	
Sep 1885	Benipila stream flood	Almarjal zone, several streets, Santa Lucía church and crops flooded.	1 m
Nov 1889	Heavy rain	Houses flooded.	
Nov 1894	Heavy rain	Several streets flooded.	
Mar 1895	Heavy rain	Several streets flooded.	
5 Sep 1906	Benipila stream flood	Several streets flooded.	1 m
27 Nov 1908	Heavy rain	Many streets flooded.	
27 Nov 1908	Heavy rain	Basements flooded.	
Oct 1915	Benipila and Canteras stream floods	Many streets flooded.	
17 Sep 1916	Heavy rain	Almarjal area flooded.	
Nov 1917	Benipila stream flood	Water flooding the basement and lower part of the town.	
29 Sep 1919 Riada de San Miguel	Benipila and Hondón stream floods	Almarjal area and streets in the lower part of the old town. 20 people dead and several missing.	3,2 m
May 1923	Heavy rain	Artillería Park and several streets flooded.	
29 Oct - 2 Nov 1923	Heavy rain	Arsenal and adjacent streets flooded. Railway service cut.	
13 Nov 1926	Benipila stream flood		
Sept 1931	Heavy rain	Almarjal zone flooded.	
20 Oct 1939	Benipila stream flood	Intense flood in the La Concepción district.	
11 Sep 1941	Sta Lucía and Hondón stream floods	Full flood. Industrial and railway losses. Streets of the Santa Lucía district flooded.	
21 Oct 1948	Benipila stream flood	Industrial and business quarter losses. 73 l/m^2 fell in 11 hours.	
20 Nov 1953	Benipila and Hondón stream floods	The streams Hondón and Lazarillo flooded.	0,8 m
19 Oct 1972	Heavy rain	Ensanche district streets flooded (old Almarjal zone).	3m
Sep 1989	Heavy rain	Ensanche district streets flooded (old Almarjal zone).	
3 Feb 1993	Heavy rain		

Analysing threshold amounts of intense rainfall producing local floods

Distinguishing between floods caused by flash processes or by intense rainfall is complex, since these two factors are usually related. Both causes should nevertheless be differentiated, so that the effects on the city area of Cartagena can be analysed separately. The aim of this analysis was to evaluate the hazards associated with these processes, which can give rise to catastrophic events, whether in the form of flooding of the streams or of runoff that is not channelled in urban areas. Zones occupied by cities are characterized by a low infiltration capacity, which aggravates the situation further in the case of intense rainfall, as the water can not be evacuated by the collector network.

There are many past records of intense rainfall in the study area, many of them provoking floods in the city. Through an analysis of peak daily rainfall series and those of past floods, thresholds can be established, or the minimum limits that would give rise to the occurrence of floods in the city. These criteria are based on rainfall and historical records and are limited by their own extension in time. However, they constitute useful information for estimating the rainfall thresholds that could provoke significant runoff.

There are three weather stations in the study area – Cartagena HE (011), Cartagena Castillo (012) and Cartagena Puerto (013)– with data for the period 1968-1998. Other meteorological stations with data for periods shorter than 20 years were excluded, but a further station was considered with good records outside the basin, El Algar (016), with data for the period 1968-1995.

From rainfall series and by applying a SQRT-max type distribution function and the maximum likeness adjustment method, different return periods were obtained for the different stations. Table 11 provides a summary of these results.

Table 11. Maximum daily rainfall versus return period for four weather stations in the Cartagena area

Return period (years)	Maximum daily rainfall (period 1968-1998)			
	station 011	station 012	station 013	station 016
2	50	42	51	61
5	72	63	72	90
10	87	77	86	109
25	106	95	103	133
50	120	108	116	151
100	134	121	129	169
200	148	133	142	187
500	166	150	159	211

Table 12 compares maximum daily rainfall values and the record of floods in the urban area aimed at identifying the lowest rainfall values producing substantial runoff in the city. The minimum rainfall values found to produce floods in the city area were around 80–90 mm, corresponding to return periods of 15-20 years.

Table 12. Rainfall records from weather stations in the Cartagena area for several historic floods

Station	Flood date and rainfall record in mm				
	19-10-1969	19-10-1972	21-02-1985	07-09-1989	03-02-1993
Cartagena 011	98	114	105	68	145
Cartagena 012	80	86	97	23	107
Cartagena 013	108	103	105	58	130
Cartagena 016	60	75	160	100	137

Flood hazard

For the study of flood hazards due to overflowing of the streams running through the city (locally known as *ramblas*), a hydrometeorological and hydraulic analysis was undertaken. The former involved determining discharges foreseen for different return periods (10, 25, 100 and 500 years). In the hydraulic analysis, the water levels reached in the river channels of the study area were estimated from the discharges established in the first analysis.

To establish the levels reached by the water in the channels, the U.S. Army Engineer Corp hydraulic model HEC-2 was used, which allows flow analysis in a stationary regime. Once the maximum flood discharge had been determined using hydrometeorological methods (Temez 1987), the level corresponding to this discharge was estimated, and applied to several selected cross-sections.

The flood hazard map obtained shows the bands or zones of territory that would be affected by floods with discharges corresponding to the different return periods (Figure 7). The map also includes the zones in which intense local rainfall would provoke flooding as well as the city's particularly susceptible points to flood effects, such as main streets and evacuation routes, which run the risk of being cut, or buildings of historical interest that could be damaged. In addition, the map shows zones affected by floods in the past for which there are references, and protection works against flooding conducted in the city that are still functional today, such as channeling of the *ramblas*, or rainwater collectors.

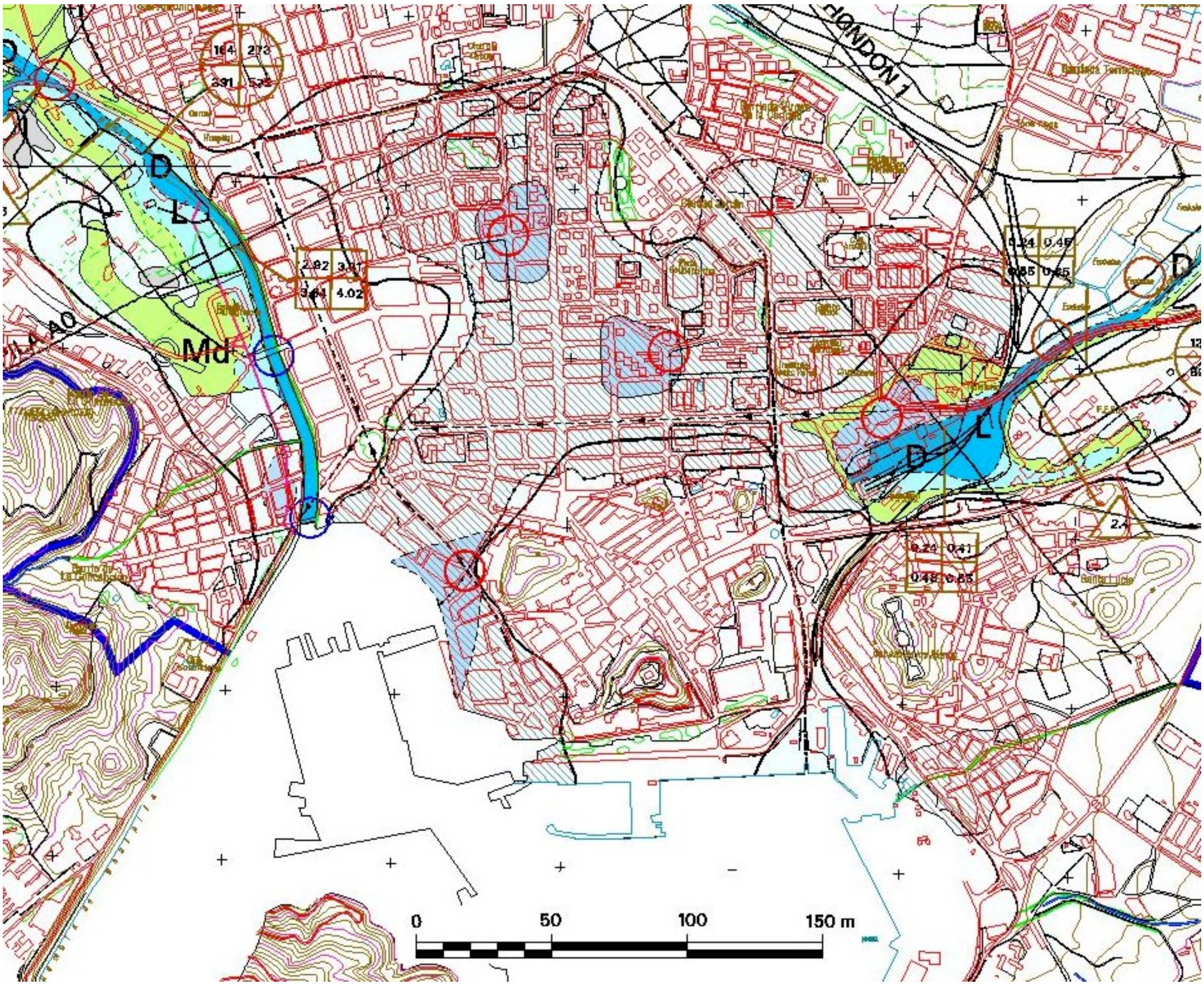

Figure 7. Detail of the flood hazard map for Cartagena. Original Scale 1/15,000

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