6TH INTERNATIONAL CONFERENCE ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

FLOOD RISK ASSESSMENT OF CLIMATE CHANGE IMPACTS USING A DETAILED 1D/2D COUPLED MODEL. APPLICATION TO BARCELONA CASE STUDY

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ABSTRACT: In a context of high uncertainty about hydro-climatic variables, the development of updated methods to assess climate change impacts, is as important, if not more important, than the provision of improved climate change data. This paper shows the results achieved in the Barcelona case study in two interdisciplinary projects funded by the European Commission in the framework of the 7th FP (CORFU and PREPARED projects). A detailed 1D/2D coupled model, simulating surface and sewer flows was developed for the Barcelona case study using Infoworks ICM version 3.5 by Innovyze. Special attention was paid to the hydraulic characterization of the inlet systems (representing the interface between surface and underground flows) using experimental expressions. The 2D domain covers 44 km^2 of the city land involving 235 km of sewers, while 2D mesh counts more than 400,000 cells. Sewer and overland flow modelling was calibrated and validated using data regarding 4 critical rainfall events occurred in 2011. Modelling speeding-up strategies focused on parallel processing, hardware advances and a specific code based on fast graphic processing units (GPU), allow to obtain simulation results of the developed model with very short computational times (3-4 minutes). In this context, real time strategies and early warning systems could be activated on the basis of the result of the developed coupled model. Once the coupled model was calibrated, it was used to assess the flood risk in the Raval District, (historically affected by flooding problems during heavy storms) for current and future scenarios. For the future scenarios, climate change inputs were defined. Specifically, in order to quantify the impacts of climate changes on the Raval District for the horizon 2050, 4 CO2 emission scenarios (A1B, A2, B1 and B2) were considered and a sea rise of 0.20 m were considered.

Key Words: Flood Risk, Climate Change, 1D/2D Coupled Model.

1. INTRODUCTION

This paper shows a methodology carried out to assess the flood risk impacts due to climate change in a critical district of Barcelona in terms of pedestrian and vehicular safety.

Barcelona, with a population of more than 1,600,000 inhabitants within its administrative limits on a land area of 101.4 km^2, is located in Catalonia, on the Northeast coast of the Iberian Peninsula, facing the Mediterranean Sea, on a plateau limited by the mountain range of Collserola, the Llobregat river to the south-west and the Besòs river to the north east (Figura 1). The average population density of the city is 15,985 inhab./Km^2, which approximately becomes 19,200 inhab./Km^2 if the forest area of Collserola mountain is not considered. The yearly average rainfall in Barcelona is 600 mm, but the maximum intensity in 5 minutes corresponding to a return period of 10 years is 204.7 mm/h and it is not rare that 50% of the annual precipitation occurs during two or three rainfall events. The morphology of Barcelona presents areas close to Collserola mountain with high gradients (with an average of 4% and maximum values of 15-20%) and other flat areas near to the Mediterranean Sea with mild slopes (close to 0-1 %) and several spots susceptible to floods. This morphology produces flash floods in the bottom part of the city in case of heavy storm events. Due to the adverse rainfall patterns, the morphological characteristics and the high density of population and impervious surface, it is clear that drainage in Barcelona has special relevance. In the nineties sewer system management of the city was transformed in order to be more effective against floods and water pollution. With two main tools – hydraulic regulation and real time control – Barcelona is nowadays one of the leading cities in the advanced management of drainage systems. However, notwithstanding the big efforts carried out in the last two decades, flooding problems still occur in case of heavy storm events, causing damages to assets and people in some critical points of the city. These flooding problems are produced by sewer floods and by the runoff that is not discharged into the sewer systems due to a poor surface drainage capacity.

In this paper, the methodology to assess the flood risk in a critical area of Barcelona, the Raval District, is shown. The Raval District, with almost 50,000 inhabitants in an area of 1.09 km^2 is one of the most densely populated areas in Europe (approx. 44,000 inh./km^2). The district area is highly impervious with several vulnerable elements (such as schools, hospitals, emergency highways, etc.). It represents a critical point of the city where stormwater not conveyed into the sewer network and overflows from sewer manholes are stored. Moreover, the hydrological response time of Raval District catchment is very short (less than 30 minutes). Traditional 1D sewer models are unable to adequately describe flooding in the Raval District and the causes producing these problems, so there is a need for a coupled 1D/2D approach in order to take into account surface flows coming from upstream catchments and the interactions between the two drainage layers (known, respectively, as 'major system' formed by streets, sidewalks, squares, etc. and 'minor system' formed by the sewer network). For this reason a coupled model able to provide realistic simulations of the flooding produced by heavy storm events was developed. Through this model is now possible to elaborate hazard maps on the basis of the local estimation of the flow parameters (flow depth and flow velocity). Once model setup was finished, climate change inputs were defined. It is common to consider adapting stormwater systems to climate change by adding simple uplift factors to rainfall intensities and then assessing whether or not the existing system can cope or not, or where flood perimeters increase or not (Arnberg-Nielsen, 2012). In this case, uplift factors and sea rise were considered.

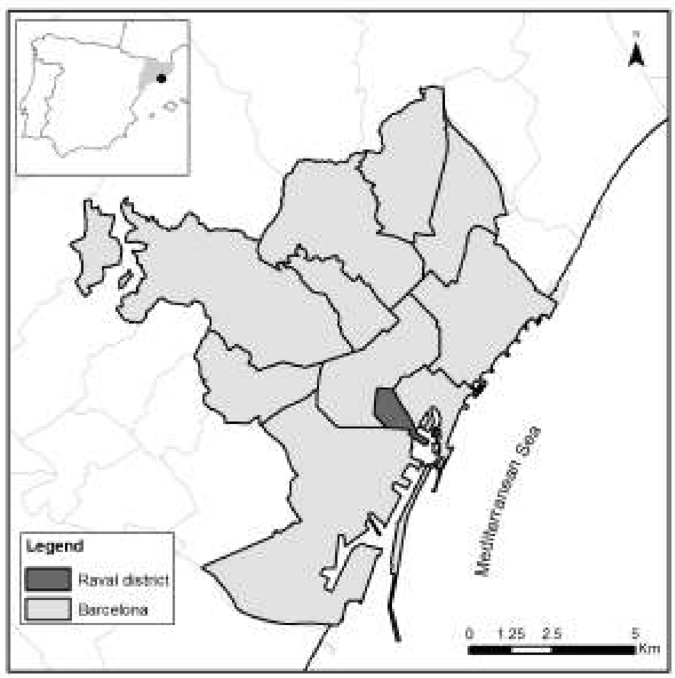

Figure 1: Location of Raval District in the Barcelona context. In the upper part of the figure, on the right, the location of Barcelona respect to Catalonia and Spain.

2. METHODOLOGY

2.1 1D/2D Modelling setup

Currently, a 1D/2D coupled model (2D for the analysis of the hydraulic behaviour of the '*major system*' formed by streets, sidewalks, squares, etc. and 1D for the analysis of the '*minor system*' formed by the sewer network), represents a powerful tool to describe, in a very realistic way, the hydraulic behaviour of urban areas suffering flooding problems due to the excess of runoff not conveyed by the drainage networks (Obermayer *et al*., 2010; Leandro *et al*., 2009).

Urban areas present a very complex topography due to the presence of elements such as buildings, sidewalks, roadways, gutters, walls and banks. When a storm event occurs in our cities, generally, runoff produced in roofs and terraces is directly conveyed to the underground sewer networks, while runoff produced in roadways, parks, squares, etc. circulates over the urban surfaces up to reach the inlet structures of the drainage systems. Moreover, due to relatively low roughness of the surfaces in urban areas, stormwater runoff is characterized by low flow depths (less than 15-20 centimetres) and high flow velocities (up to 3-4 meters per second). In this context, it is crucial to have a detailed Digital Terrain Model (DTM) with high resolution. For this study, a specific DTM model was provided by the Catalan Institute of Cartography. This DTM presents a resolution of 1 m^2 obtained by a LIDAR flight with a density of 1.33 points/m^2 and a precision of 15 cm in terms of ground elevation.

Dual drainage modelling cannot be adequately represented without a careful consideration of hydraulic efficiency of surface drainage structures (inlets, transversal grates, etc.). In fact the possibility to characterize hydraulically all the connections (manholes and drain inlets) between surface and underground systems allows to improve the estimation of surface and pipe flows during a storm. The consideration, at the same time, of the surface flow and its interaction with sewer flow is commonly known as '*dual drainage modelling*', with flow components on the surface and underground (Leandro *et al*., 2009). In order to achieve this objective, the hydraulic performance of the most common inlets present in the Raval District was analysed using experimental expressions recently proposed by Gómez and Russo (2009; 2011). Moreover a clogging factor of 50% was uniformly applied to all inlet types and all geometric configurations in order to take into account possible reduction of the hydraulic efficiency due to blockage of grated inlet void areas during storm events (Gómez and Russo, 2013).

The software Infoworks ICM (version 3.5) by Innovyze (following ICM) was adopted to assess flood hazard in the Raval District during storm events. ICM solves complete 2D Saint Venant equations in a finite volume semi-implicit scheme with Riemann solver (Alcrudo and Mulet-Martí, 2005). ICM combines a number of distinctive features as the analysis and prediction of potential flood extent, depth and velocity, and the modelling of the interaction of surface and underground systems in a fully integrated environment. Moreover it allows the creation of multiple surface unstructured meshes that optimizes modelling flexibility and accuracy. In order to take into account potential overland flow coming from Raval District upstream catchments, the coupled model involved a total area of 44 km^2 with 3625 nodes, 234 Km of total pipe length and 6 storage facilities with a total capacity of 170,000 m^3. In the bottom part of the city, and particularly, in the Raval District, main and secondary networks were simulated to achieve detailed results in the most critical points. A 2D unstructured mesh covered the whole analysed domain with more than 400,000 cells (Figure 2). Parks and other green areas were represented in the same 2D mesh, through "2D infiltration zones" characterized by their specific hydrological, physical and geometric parameters, while buildings were represented as void areas (Figure 2). Rainfall falls on the cells of the 2D domain where Horton's method is applied to estimate infiltration losses before that rainfall-runoff transformation and propagation phenomena occur. The rainfall fallen on the roof and terraces of the buildings is directly conveyed to the sewers after applying reservoir model for the rainfall runoff transformation. Further information about the features of the model and, above all, the interactions between 1D and 2D layers is available in Russo *et al*. (2012). Rainfall data come from 11 rain gauges and Thiessen polygon method was used to assign the rainfall to the analysed area. Due to the recent significant changes of the Barcelona sewer system (new infrastructure such as pipes and tanks were built in the past few months and regularly work now), 4 rainfall events (3 for calibration and 1 for validation of the model) occurred in 2011 were selected with the main characteristics shown in the Table 1.

Figure 2. On the left, the network modelled in Barcelona case study. The red circle highlights the high density of pipes and nodes corresponding to the main and secondary networks of the Raval District. Shadowed areas represent the pervious areas. On the right, flexible unstructured mesh with triangular cells representing the streets and pervious areas (shown in red) of the city. On the bottom-right corner of the figure, it is possible to see the narrow streets of the Raval District involved in the 2D mesh.

Table 1. Events selected for calibration and verification of the model

Date event	Cumulative rainfall	Maximum rainfall intensity in 20 minutes	Maximum rainfall intensity in 5 minutes	Function of the event
	(mm)	(mm/h)	(mm/h)	
15/03/2011	54.1	69.6	98.4	Calibration
07/06/2011	26.8	24.3	49.2	Calibration
19/07/2011	45.9	95.1	135.6	Calibration
30/07/2011	30.4	105.9	140.4	Verification

Flooding reports and 29 water level gauges located in manholes and conduits of the analysed domain were used for the calibration/validation processes. Specifically, flow depth series calculated by the model were compared to flow depth series recorded by the water level gauges. Calibration results are shown in Russo *et al*., 2013.

2.2 Climate change inputs considered for the flood hazard assessment of future scenarios

In order to quantify the impacts of climate changes on the Raval District for the horizon 2050, 4 CO_2 emission scenarios (A1B, A2, B1, and B2) were considered. Through spatial and temporal downscaling techniques, coefficients of climate change were deduced (Figure 3) and applied to Barcelona synthetic project storms for the most pessimistic A1B scenario and the horizon 2050. Further information about spatial and temporal downscaling is available in Rodríguez *et al*. (2013).

Climate change coefficient can be defined as the ratio between the rainfall intensity with a return period *T* and a duration *d* for a future climate scenario $(I(T/d)_{Future}$ and the corresponding rainfall intensity in the present climate $(I(T/d)_{Present}$ (Arnberg-Nielsen, 2012):

$$c_f = \frac{I(T,d)_{Future}}{I(T,d)_{Present}} \quad (1)$$

For this case, the considered future scenario (horizon of 2050 and emission scenario A1B), rainfall intensities of the project storms with return periods of 1, 10 and 100 years were upgraded with factors of 8, 12 and 15% respectively, while a sea rise of 0.2 m was considered.

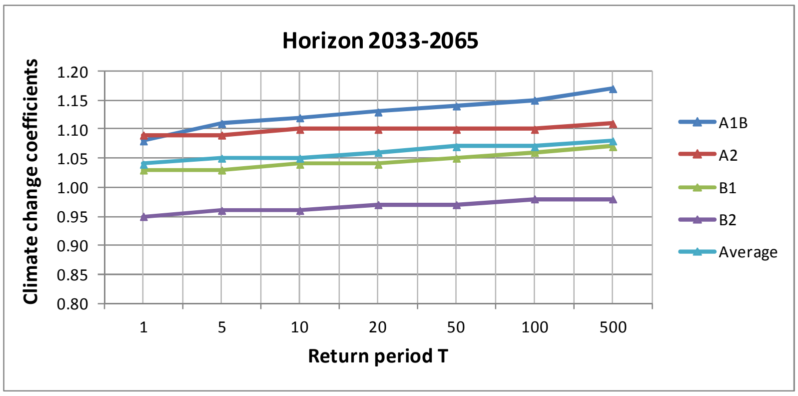

Figure 3. Climate change coefficients for the horizon 2033-2065. It is possible to observe that emission scenarios A1B, A2, B1 show an increase of rainfall intensities, while B2 scenario shows small decreases.

3. RESULTS

3.1 Flood risk assessment

3.1.1 Pedestrian circulation

Once the model was calibrated, hazard maps related to flow depths, velocities and the combination of both flow parameters were generated for different return periods (T = 1, 10 and 100 years). Thresholds for flood hazard mapping were raised from a specific study about hazard criteria in flooded streets during heavy storm events (Russo *et al.*, 2013). According to this study, high hazard conditions were defined for velocities above 1.9 m/s and flow depths above 10 cm, while for moderate hazard, 1.5 m/s and 6 cm were considered as thresholds. Hazard maps for current and future scenarios were elaborated obtaining the results shown in the Figures 4 and 5. It is possible to observe that the relative increases of the areas affected by high hazard are always greater than the rainfall increases. In fact, the results show that these increases are 15%, 34% and 23%, respect to the increments of 8%, 12% and 15% in terms of rainfall caused by climate change coefficient.

Finally, these hazard maps were crossed to vulnerability maps of the Raval District in order to obtain flood risk maps concerning pedestrian safety during heavy storm events. In this case, vulnerability considers general people density (D), density of people with critical age (C) (less than 15 years old and more than 65), density of foreign people (F) and presence of critical buildings (such as hospitals, schools, etc.). Hazard assessment was carried out for each cell of the 2D domain in the Raval, while vulnerability and risk assessment was carried out for each census area of the district due to the availability and the format of data provided by local administrations.

Results of simulation in terms of hazard for pedestrian circulation show that the maximum increase (more than 30%) of areas affected by high hazard conditions due to climate change effects concerns return period of 10 years (this is the design period commonly used in Spain for new sewer system facilities). For the maximum return period analyzed, areas presenting high hazard conditions change from 44% for the current scenario to 56% for the future scenario.

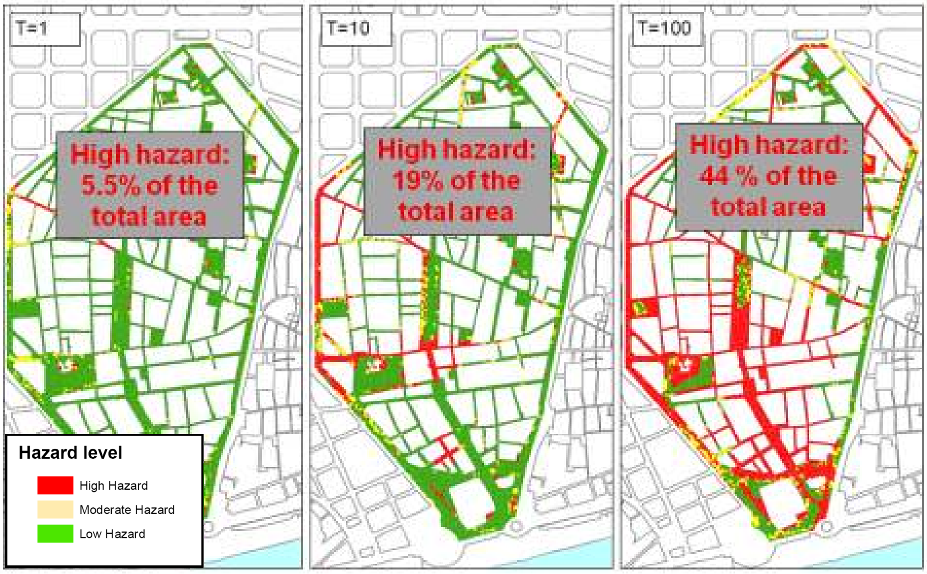

Figure 4. Hazard maps of the Raval District for return periods of 1, 10 and 100 years.

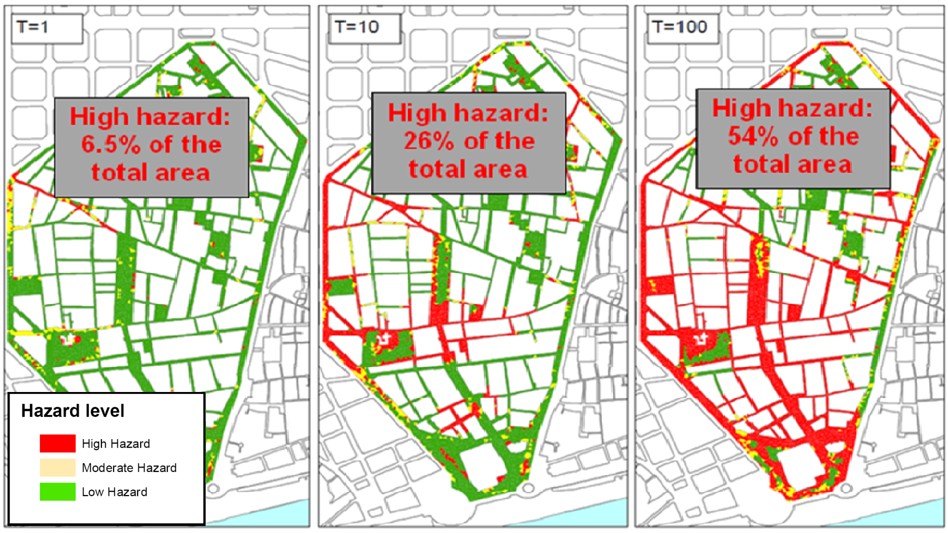

Figure 5. Hazard maps of the Raval District for synthetic storms for return periods of 1, 10 and 100 years upgraded through climate change coefficients.

In order to evaluate the population data for the future scenarios the following demographic forecasts, provided by the municipal and regional institutes of statistical sciences, were taken into account:

- For the horizon of 2050, in Catalonia vulnerable people with “critical age” (less than 15 years and more than 65) will increase from 32.6 % to 41.35 % for a medium scenario (increasing factor of 1.26 due to people ageing).

- A specific study about population growth indicates a growth factor of 0.98 up to 2021. No reference was found up to 2050, so it was decided to consider for the future scenarios the same value as for the baseline scenario).

- Finally no data concerning foreign people evolution was found so no change was supposed for the future scenarios.

Once data were available for the current and future scenarios, the following thresholds were defined in order to assess the vulnerability of each census area. Specifically for the human vulnerability related to the people density, thresholds were deduced from the average density of Barcelona (16000 inhabitants per Km^2) and the definition of the National Institute of Statistics of urban area defined as a group of minimum 10 houses in a distance less than 200 m (equivalent to 1273 inhabitants per Km^2). The other defined thresholds are shown in Table 2. Three vulnerability indexes were defined according to the 3 first data types and for the final vulnerability index, the average value between C, D and F was computed and in case there was any critical building in the census area, a 0.5 value was added. The final vulnerability level was achieved according to the formulations proposed in the Table 3..

Applying the described methodology, human vulnerability maps were obtained for the current and future scenarios. In these maps, the different vulnerability levels (high, moderate and low vulnerability) of census areas were represented using, respectively red, yellow and green colours (Figure 6). Moreover the presence of critical buildings (schools, hospitals, etc.) was also shown in the same map.

Table 2. Thresholds to assess human vulnerability according to different criteria.

Vulnerability index	C % people age < 15 or > 65 years old	F % of foreign people	D People density
1 (low)	≤ 33%	≤ 33%	≤ 1273
2 (medium)	33% < X ≤ 50%	33% < X ≤ 50%	1273<X≤16000
3 (high)	> 50%	> 50%	> 16000

Table 3. Formulation to compute the total vulnerability index.

Vulnerability level	Formulation *
Low	(D+C+F)/3 < 1.5
Medium	1.5 < (D+C+F)/3 < 2.5
High	D+C+F)/3 > 2.5
*In case there is a critical building is in the census area, a value of 0.5 must be added to the average value of (D+C+F)/3.	

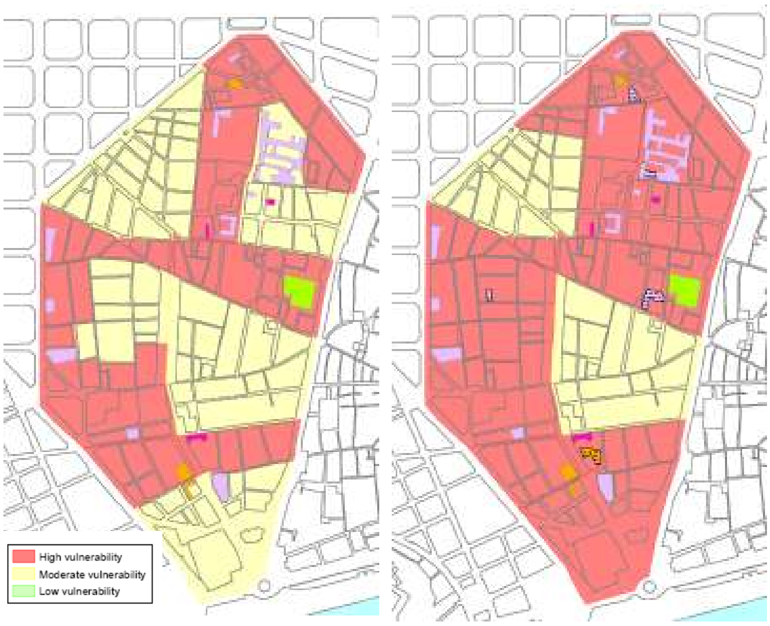

Figure 6. Human vulnerability for the current and future scenarios.

For the flood risk assessment related to pedestrian, the general methodology based on the risk matrix was implemented obtaining the risk for current and future scenarios. The risk was defined for each census area and represented with the same range of colours previously described (Figure 7). In order to define the risk level of each census area a statistic treatment of the risk of the cells was carried out. The risk level of each census area was assumed equal to the maximum risk level of the cells, as long as they represented at least a 15% of the total cells located in the same census area.

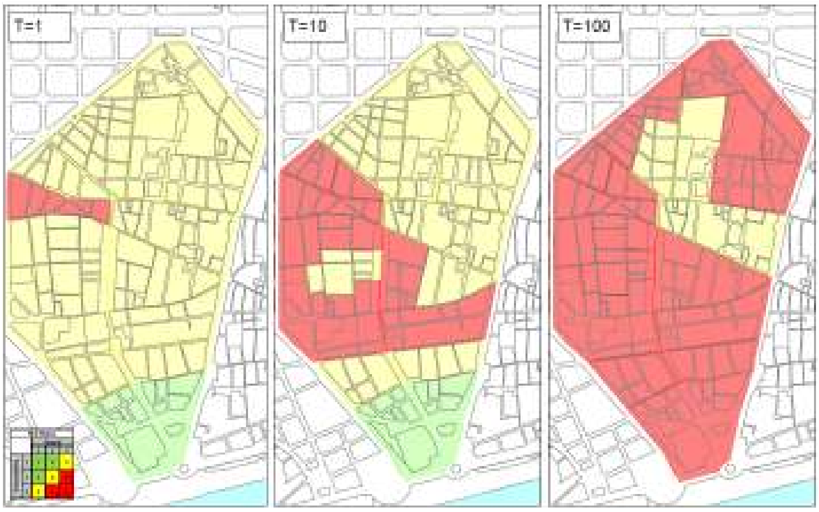

Figure 7. Risk maps for pedestrians related to the current scenario for several return periods T.

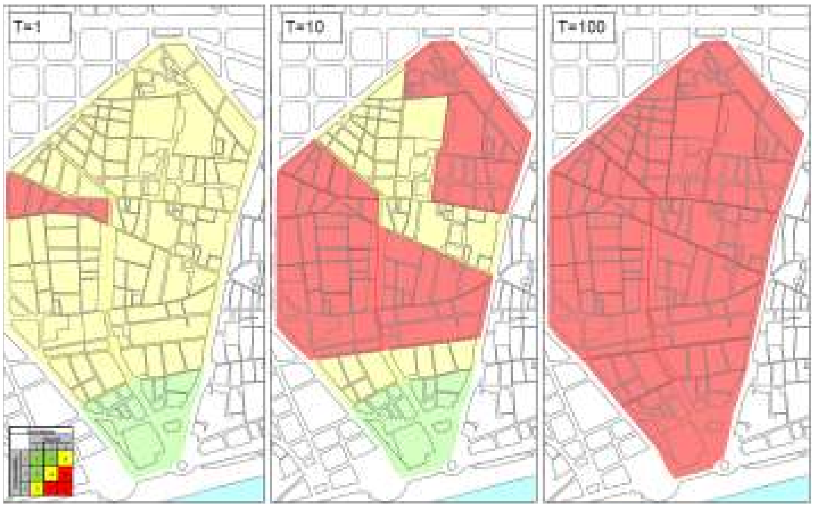

Figure 8. Risk maps for pedestrians related to the future scenario for several return periods T.

In the Figures 7 and 8, it is possible to observe that climate change effects increase the number of census areas affected by high flood risk. This situation is exacerbated for high return periods.

3.1.2 Vehicular circulation

A similar procedure to the one defined for pedestrian circulation was proposed for the risk assessment related to vehicular circulation. Stability criteria for stationary vehicles were defined to create vehicular traffic hazard maps. These criteria were deduced by a report developed by Engineers Australia contracted by Water Research Laboratory: "Appropriate safety criteria for vehicles" (Shand *et al*. 2010)

(Figure 9). Using these hazard criteria and the results of the models for the current and future scenarios, the hazard maps for vehicular circulation were elaborated (Figures 10 and 11). Traffic vulnerability was obtained through intensity of vehicular traffic data in the Raval district provided by the Traffic Department of Barcelona Municipality. Thresholds were decided based on the average values of the traffic flow in Barcelona streets (Figure 12). The vulnerability map for vehicular circulation is presented in Figure 12. Due to the great uncertainties of the future policies regarding the vehicular traffic in the Raval District, and considering the absence of specific information concerning the forecasts for the horizon of 2050, the same map was considered for the several future scenarios. In fact traffic conditions changes in this District are mainly caused by political decisions to convert a street in pedestrian or change the traffic direction, decisions which are difficult to predict. Many streets of these critical areas present very low vehicular flow intensity as shown in the following vulnerability section concerning traffic circulation (Figure 12). Moreover, it is possible to observe that no significant increase of the vehicular flood hazard is appreciated due to the effect of climate change.

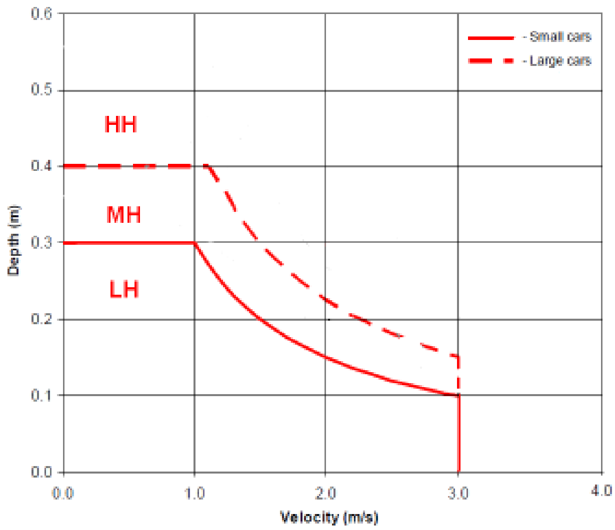

Figure 9. Hazard criteria for vehicular used in Barcelona case study (HH: high hazard; MH: moderate hazard; LH: low hazard).

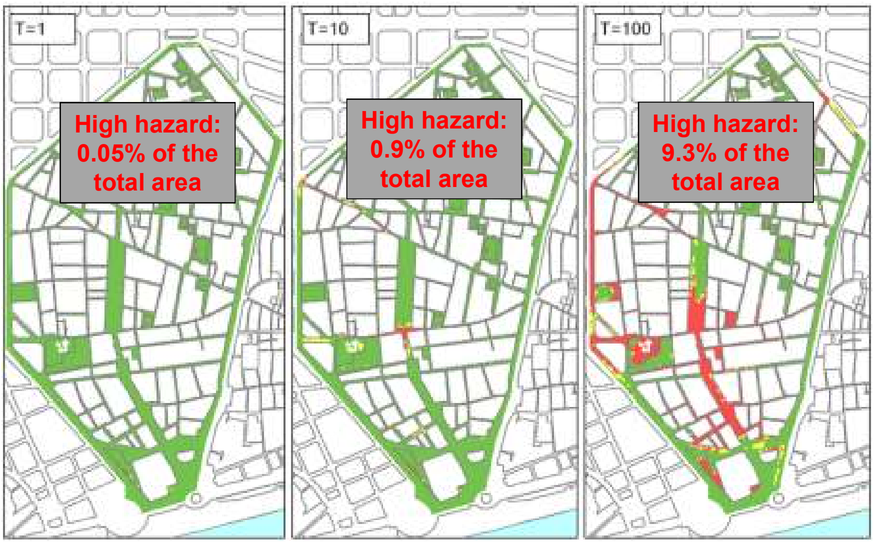

Figure 10. Hazard maps concerning vehicular circulation for the current scenario.

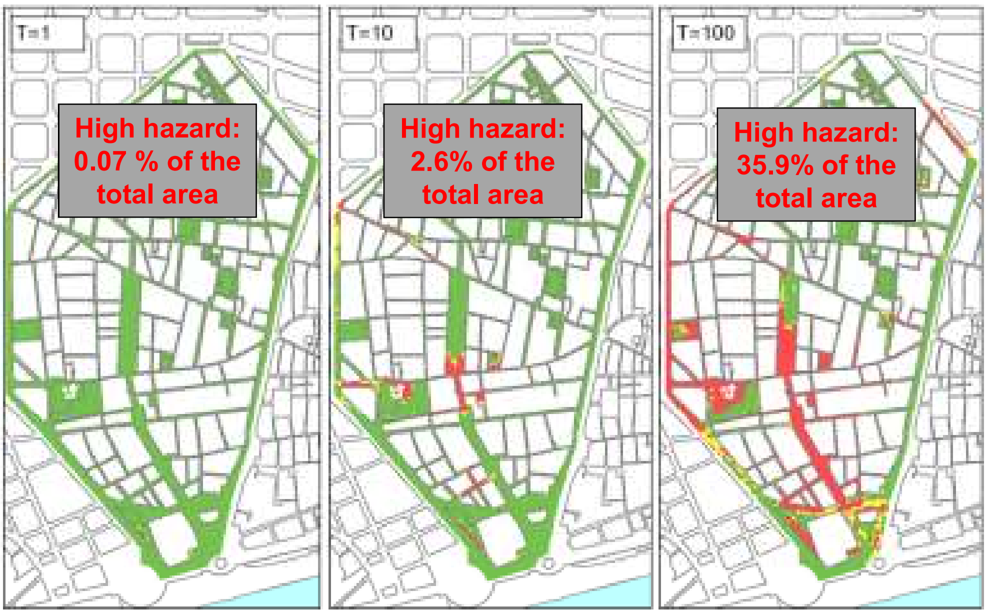

Figure 11. Hazard maps concerning vehicular circulation for the future scenario.

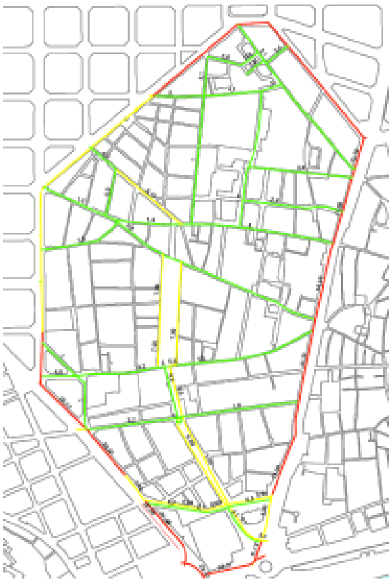

Figure 12. Vehicular vulnerability map for the baseline and future scenarios based on traffic intensity (shown values express vehicular flow intensities (VFI) x 1000 in 24 hours). Vulnerability level was defined as los if VFI < 5000, moderate if 5000 < VFI < 10000 and high if VFI > 10000).

As applied with the human risk, a matrix combining hazard and vulnerability data for vehicular circulation was implemented for the assessment of vehicular traffic flood risk. The objective of this step was to determine the risk level of the street on the basis on the hazard levels of each cell and the vehicular flow intensity of each traffic lane. Crossing these data, risk maps for vehicular circulation were obtained for the current and future scenarios considering the selected return periods (T = 1, 10 and 100 years) (Figures 13 and 14). These maps present few differences due to the similarity of the hazard maps concerning these scenarios. For this type of risk, it is possible to observe that no significant increase of the vehicular flood risk is appreciated due to the effect of climate change.

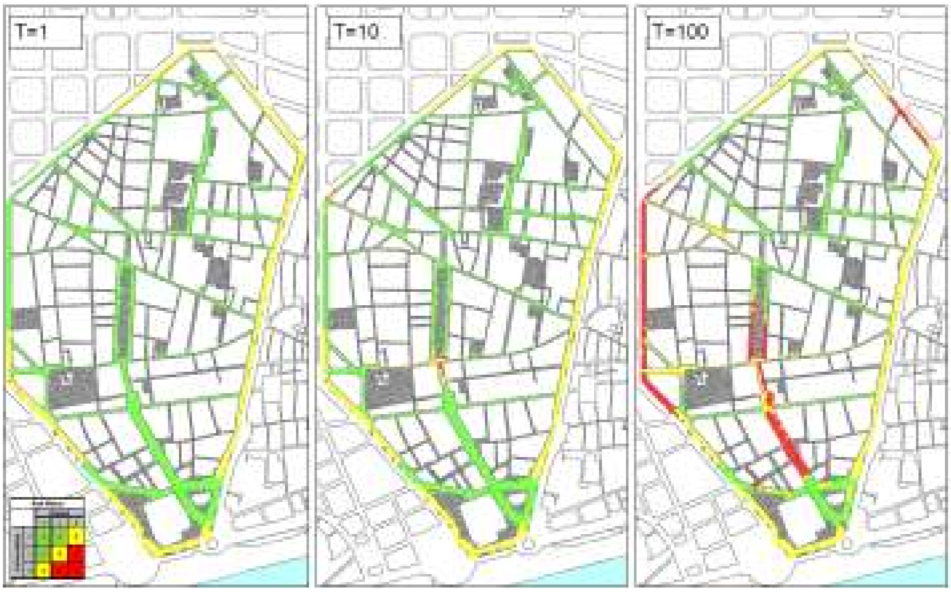

Figure 13. Risk maps for vehicles related to current scenario for several return periods T.

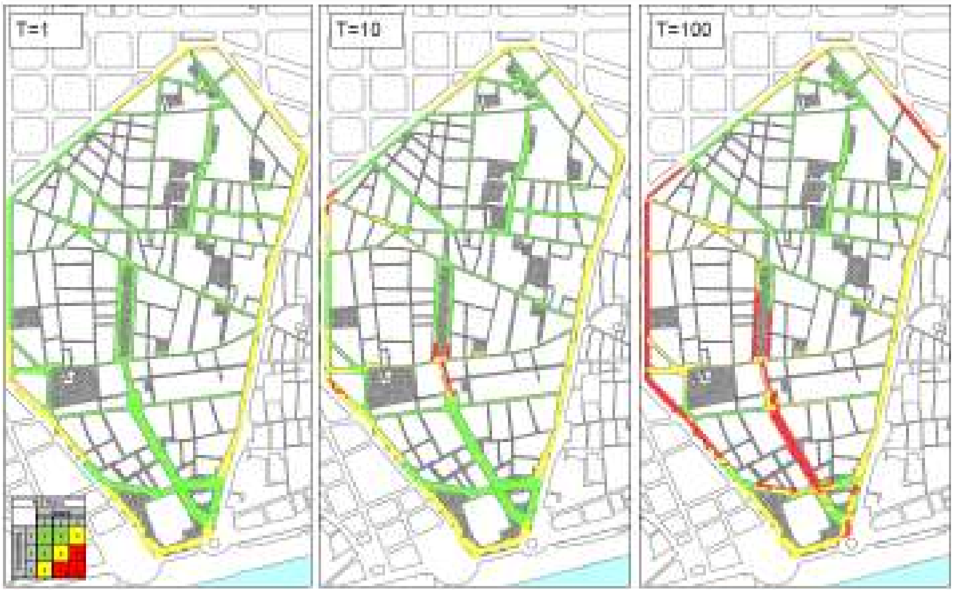

Figure 14. Risk maps for vehicles related to the future scenario for several return periods T.

4. CONCLUSIONS

A detailed1D/2D coupled model was developed to assess flood risk in a critical area of Barcelona (Raval district). The interface between the two drainage layers was characterized through empirical expressions related to hydraulic performance of surface drainage systems. The 2D domain covers 44 km^2 of the city land involving 235 km of sewers, while 2D mesh counts more than 400,000 cells.

Calibration and validation of the model were based on sewer and surface data related to 4 heavy storm events occurred in 2011. The obtained results show that it is possible to reproduce the effects of urban floods in the Raval District in a more realistic way than traditional 1D sewer flow simulations.

Flood hazard maps concerning specific hazard criteria related to pedestrians and vehicles were elaborated for current and future scenarios. For the future scenarios, climate change coefficients achieved through specific spatial and temporal downscalling techniques were used.

A specific methodology to assess flood risk for pedestrian and vehicular circulation was proposed and a comparison between current and future scenarios was done in order to assess climate change impacts.

5. ACKNOWLEDGMENT

The authors thank the CORFU (Grant Number 244047) and PREPARED (Grant Number 244232) projects, which are being funded by the EU FP7, whose support is gratefully acknowledged.

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