Methodology for risk assessment of flash flood events due to climate and land-use changes: application to the Llobregat basin

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ABSTRACT

Global change, including climate, land-use and socio-economic changes, is expected to increase the stress on the entire water cycle. In the Mediterranean region, extreme events are likely to increase due to climate change. This work, framed in the EC Seventh Framework Programme project IMPRINTS, presents a methodology to obtain future flood risk maps using climate and land-use scenarios, identifying the new potential risk zones. The implementation of this methodology is applied to the Llobregat river basin case study. Two different special report on emission scenarios are used, and although the uncertainties are high, the results obtained are coincident: an increase of flood risk is observed in the whole Low Llobregat area. The climate changes affect the basin globally, increasing the risk homogeneously within the area considered. On the other hand, land-use changes represent urban growth in the floodplains, and hence, local risk increases are found in these spots.

Key words | climate change, flood risk, IMPRINTS, land-use, Llobregat

INTRODUCTION

The work described here is part of the IMPRINTS project, included in the Seventh Framework Programme of the European Commission. The main objective of the project is to contribute to the reduction of loss of lives and economic damage through the improvement of the preparedness and the operational risk management of flash floods (FF) and debris flow generating events.

In the frame of this project, impacts of future changes including climate, land-use and socioeconomic changes, on FF risk are analysed in order to provide guidelines for mitigation and adaptation measures and to improve the application of the EC Floods Directive (CEC 2007).

The case studied here is the Llobregat River basin, with a surface of approximately 5,000 km², located in Catalonia, in the northeast of Spain. It takes its source in the Pyrenees at an altitude of 1,259 m, crosses quite densely populated areas and ends in the Mediterranean Sea, in El Prat de Llobregat, near Barcelona. Due to the rough orography of the region and the reduced size of most of the Llobregat sub-basins, the hydrologic response time of these watersheds is around a few hours. The basin presents the typical Mediterranean climate. The average annual rainfall over the region is about 600 mm and one-third of the average annual precipitation can usually fall in less than 48 h. That is why FF develop rapidly during the convective storms and suddenly inundate the terminal flood plains.

Since this is a flood risk study, which depends on flood hazard, but also on exposure and vulnerability, the case study focuses on the Low Llobregat area: a densely populated region with large cities like Cornellà de Llobregat, Sant Feliu de Llobregat or el Prat de Llobregat (Figure 1).

A changing climate brings many challenges to the whole water cycle (Brookes et al. 2010). Indeed, some researchers state that the global hydrological cycle has already been...
affected by climate change due to the observed global warming of the last decades (Vörösmarty et al. 2000; Charlton & Arnell 2011). Extreme events are expected to increase all over Europe due to global change (Dankers & Feyen 2013). Some researchers conclude that in critical regions, extreme events like floods and droughts which today have a return period (T) of 100 years, may recur every 10–50 years by 2070 (Lehner et al. 2006). In particular, FF triggered by local intense precipitation events are likely to be more frequent throughout Europe (Kundzewicz et al. 2001; Christensen & Christensen 2007).

In the Intergovernmental Panel on Climate Change’s SREX report (Managing the risks of extreme events and disasters to advance climate change adaptation) (IPCC 2012), detailed information regarding climate change and extreme events can be found. However, there is not a great deal of agreement in these results, due to the several variables and uncertainties that surround projections of future flood risk. Therefore, Kundzewicz & IAHS (2012) recommends undertaking studies at lower scales in order to properly assess the spatial variability regarding future flood risk, which is precisely the main goal of this study.

Due to the strong impacts FF currently provoke and the future ones that may appear, the development of methodologies of risk assessment of FF events is a subject of major social interest in Catalonia.

**METHODOLOGY**

**Flood risk assessment framework**

It is widely agreed that natural risks are the product of hazard and its consequences. Within this approach, risk is a function of hazard, exposure and vulnerability (Figure 2). If any one of these factors increases, the level of risk also increases. Conversely, if any one of these factors is reduced, then the risk level decreases (Crichton 1999).

This is why in order to carry out a FF risk assessment, the integration of the physical event results, such as flood inundation extent and depth, with information on flood exposure (land-use) and vulnerability of the exposed assets/people is required.

Hazard is defined as the occurrence of a hydrologic flood event with a given probability. For example, hazard can be represented by extreme river discharge and flood water depth. An extreme natural event is the driver of the hazard component.

Exposure is represented by the assets that are present on each location. This is typically expressed by statistics on

![Figure 1](https://iwaponline.com/jwcc/article-pdf/5/2/204/374992/204.pdf)

Map of the Llobregat River basin, showing the main cities and the Low Llobregat area.

![Figure 2](https://iwaponline.com/jwcc/article-pdf/5/2/204/374992/204.pdf)

The risk triangle (Crichton 1999).
population, socio-economic data on activities from different sectors and land-use.

Vulnerability is defined as the susceptibility of the exposed structures/people at contact with the damaging natural event. This factor measures the extent to which the subject could be affected by the hazard. It is normally expressed by a monetary value, although it is common to classify it into different degrees of affection according to its value.

Although exposure and vulnerability represent different concepts, the first one is commonly included in the latter by using vulnerability maps. Such maps represent the position of the assets together with their susceptibility to the hazard. Hence, the risk is finally obtained by the superposition of flood hazard and flood vulnerability maps.

Future risk assessment methodology

In order to fulfil the main goal of this paper, a methodology to assess current and future flood risk has been developed. As done in many other studies of risk (Ferrier & Haque 2003) or flood risk assessment (Camarasa-Belmonte & Soriano-García 2012), a qualitative approach has been followed, assigning different weights to the several variables, to finally produce risk maps by overlaying the hazard, exposure and vulnerability layers.

The starting point of this methodology consisted of using already existing flood hazard maps (that must be obtained using a hydrological model) and exposure maps (obtained with land-use models), in order to produce current risk maps. Combining the exposure maps with the economic values of each land-use category, the flood vulnerability maps are obtained. Finally, by overlaying these two maps in a geographic information system (GIS) tool, flood risk maps are produced. This entire process is carried out in a qualitative way and therefore, weights have to be assigned to all the considered variables. Lastly, the final risk levels will be obtained by multiplying the weights.

Given that flood hazard depends on both the intensity and probability of the extreme event, the weights from Table 1 are the ones used in this study. It is worth noting that in this case, the intensity of floods is expressed by the water depth in the river and the flood plains (more detailed information about the thresholds and the weighting function will be given in the ‘Data’ section). Therefore, flood hazard will be expressed by a set of values ranging between 1 and 9.

The same range of weights has been used to define the vulnerability levels (the vulnerability categories considered for this study are presented in Table 5). Therefore, as presented in Table 2, flood risk is given by values that oscillate between 1 and 81 in order to qualitatively express the potential damages to exposed assets. Since the flood risk maps intend to provide easy-to-read information, five different levels of flood risk can be distinguished: very low, low, medium, high and very high.

As for future flood risk, the same values as those presented in Tables 1 and 2 are used. However, several modifications will be implemented in order to represent the future situation. They are described in the following paragraphs, explaining how future changes are applied to hazard and exposure maps.

In terms of flood hazard, the same existent flood maps will be used. Nevertheless, given that hazard level depends on both the intensity and probability of the event, the latter will be modified to obtain the future hazard maps. Consequently, using climate change projections and

| Table 1 | Hazard levels and associated weights. The colours represent the low (green), medium (orange) and high (red) levels of hazard |
| --- | --- | --- | --- |
| Probability | Intensity |
| T (years) | Weight | High (3) | Medium (2) | Low (1) |
| 1 | (3) | 9 | 6 | 3 |
| ↓ | (2) | 6 | 4 | 2 |
| 500 | (1) | 3 | 2 | 1 |

Please refer to the online version of this paper to see this table in colour: http://www.iwaponline.com/jwc/toc.htm

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Risk levels and weights: very low (1–5), low (5–9), medium (9–25), high (25–45) and very high (45–81)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
<td>Vulnerability</td>
</tr>
<tr>
<td>High (9)</td>
<td>Medium (5)</td>
</tr>
<tr>
<td>High (9)</td>
<td>81</td>
</tr>
<tr>
<td>Medium (5)</td>
<td>45</td>
</tr>
<tr>
<td>Low (1)</td>
<td>9</td>
</tr>
</tbody>
</table>

Please refer to the online version of this paper to see this table in colour: http://www.iwaponline.com/jwc/toc.htm
assessing the probabilities of extreme rainfall events, the future return periods of rainfall events of the same intensity can be found. This update of the return period can be seen later in this paper, in Figure 5, represented by the black line. Finally, using a weighting function that will be described in the next section, new weights can be found so the hazard maps are finally updated (more detailed information can be seen later, and is summarized in Table 6).

Regarding future exposure, a model to simulate urban growth is needed in order to obtain the future maps. Once the future scenarios have been implemented into the model, maps with the same resolution as the current ones are obtained for the future situation. Then, using the same vulnerability classification, exposure maps are transformed to vulnerability ones.

Again, overlaying the future hazard and vulnerability maps, the future risk maps for different scenarios can be obtained. For both climate and land-use changes, several future scenarios can be simulated with this methodology, though it is worth noting that for each variable they will be implemented differently. In the case of climate, projections of emissions of all relevant species of greenhouse gases will be used as driving forces to run climate models. On the other hand, urban growth models are driven by the narrative ‘storylines’ that describe alternative futures. These two different types of future projections are included in the emission scenarios from the Special Report on Emission Scenarios (SRES) of the IPCC (Nakićenović & Swart 2000). Thus, scenarios from this report will be the ones used, in order to be consistent with the future situations projected.

In order to properly see the differences between future and current situations, the flood risk maps have to be subtracted. The risk level obtained at each cell for the current situation is deducted from the values of the future scenarios. Then, using the values presented in Table 3, the maps showing the risk increases can be represented, allowing proper identification of the critical areas presenting major changes. In Figure 3, a scheme representing the methodology that has been presented can be seen.

**DATA**

In order to carry out this FF risk assessment, data describing the Low Llobregat area hazard, exposure and vulnerability are required, both for the current and future situations. In the next sections, details of the different datasets used are described.

**Hazard data**

The hazard level produced by a flood is expressed in terms of its intensity and probability. Although the damage that a flood can produce depend on many variables (e.g. water depth, flow velocity, duration of inundation, sediment concentration, etc.), the approach that has been used in this study only takes into account water depth. This is so because not only it is probably the most relevant factor to express the intensity of floods, but it is also a variable easy to model and assess.

Considering this, in the work presented here, the hazard level produced by a flash flood event on a precise spot will depend on the return period of this event (which expresses its probability), and the water depth of the flood (expressing the intensity).

In order to obtain these data, hydrologic and hydraulic models must be applied to a digital elevation model of the studied area. Since this was not the intention of this study, the flood maps developed by ACA (Catalan Water Agency) in the frame of the PEFCAT Project (River Area Planning in Catalonia) have been used (ACA 2008).

In the frame of this project, raster maps in GIS format have been created with a 1 × 1 m spatial resolution for the Llobregat basin, presenting the flood depth at each cell. The model used to produce such maps was MIKE-11 (DHI 2009). The calibration was carried out using data from five different river gauges in the Llobregat basin, within the 1996–2002 period. Special attention was paid
to properly represent the rain events that occurred on December 18 1997 and June 10 2000, which created flood problems in different zones of the studied area.

The return periods that were simulated in the frame of the PEFCAT project were 10, 50, 100 and 500 years. This information gives a clear idea of the extension of floods that often occur in this region. In Figure 4 the Low Llobregat area with the flood plains for a 500 year return period event can be seen.

As the goal of this task is to determine future risk scenarios, it will be crucial to transform these existent hazard maps into future hazard maps. To do so, future climate scenarios created in a previous task of the IMPRINTS project (Cabello et al. 2011) will be used. Next, there is a short explanation of the data used for this purpose.

For the whole Llobregat basin, the Servei Meteorològic de Catalunya (SMC) provided high-resolution climate data for the 1971–2100 period (Barrera-Escoda & Cunillera 2014). These data were obtained by means of a dynamical downscaling, nesting the MM5 mesoscale model into the ECHAM5/MPI-OM global simulations developed for the IPCC-AR4 (IPCC 2007). The control period is 1971–2000 and the future projections cover 2001–2100 for Catalonia. Two emission scenarios from the SRES of the IPCC (Nakicénovic & Swart 2000) have been considered: A2 and B1. The output data have a spatial resolution of 15 × 15 km, and a temporal resolution of 6 h.

These data were previously used to assess changes in the probability of occurrence of extreme events for the future periods in the whole Llobregat basin (Cabello et al. 2011). This study conducted a classical extremes assessment (Hurkmans et al. 2010; Zhu et al. 2012), fitting a distribution to annual maximum series. In this case, the function used was the Generalized Extreme Value (GEV) distribution (Jenkinson 1955), and the precipitation data was studied at a daily level. The intensity–return period (I-T) relationships showed that the SMC model data is indeed able to represent the extremes in the studied area.

Therefore, in this case there was no need to apply a bias correction (Lenderink et al. 2007) to the precipitation series. In cases where some differences between the control and

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**Figure 4** Low Llobregat area, showing the flood plains for a 500 year return period event.
the observations were found, such correction should have been undertaken. A multi-linear interpolation based on the relationships of the two datasets in the control period should be done. Then, in order to properly represent the seasonal variability, this correction should be made month by month. Once relationships are found for the historical series, they should be applied to correct future data.

Since flash flood events always have a duration of 6 h or shorter, and given that the climate change data was provided at this precise temporal resolution, it has been decided to use this duration to develop the I-T curves (Figure 5). Additionally, the flood hazard maps produced in the PEFCAT project (ACA 2008) were also created by implementing design hyetographs of 6 h in most of the modelled sub-basins. Therefore, the use of this duration to study the future flash flood risk is consistent with both the flash floods definition and the data used.

As will be explained in the next section, exposure data are available for every year until 2040. Hence, the current situation is going to be represented by year 2000, whereas the future scenario will be showing the situation in 2040.

In order to be consistent with this, and taking into account that using the GEV functions requires a certain amount of data, it has been decided to use the following 30 year periods to assess precipitation extremes: from 1986 to 2015 for the current situation and from 2026 to 2055 for the future one.

As has been mentioned previously, the return periods of the hazard maps included in the PEFCAT project reach the value of 500 years. Because of that, the GEV distributions fitted to these periods imply an extrapolation of the high return periods (Figure 5).

Although undertaking such extrapolation might imply uncertainties, this is the only way that this future assessment can be done. As has been explained in the previous section, these relationships between future and current extreme precipitation are used to transform the current flood hazard maps into future ones.

As explained in the methodology section, flood hazard depends on the intensity and the probability of a given flood event. This issue was already considered in the Catalan Flood Emergency Plan INUNCAT (GENCAT 2006). In this plan, the intensity was defined in terms of flood depth, being 0.3 and 1.2 m, the thresholds between low, medium and high intensity (Table 1). The weights assigned to each of these categories will be 1 (low), 2 (medium) and 3 (high).

Since this classification of intensity is going to remain the same for current and future scenarios, the climate change scenarios will be affecting the probability part of hazard. As can be seen in Figure 5, the conversion of current extreme precipitation into the future one can be done in two different ways: (1) increasing the intensity by keeping the return period constant; or (2) decreasing the return period by keeping intensity constant.

The first approach would require running a hydrological model to obtain new water levels and their associated floodplains. On the other hand, the second approach (represented by the black lines in Figure 5) only involves the assignment of new return periods to the same flood maps. In this case, the water level maps developed in the frame of the PEFCAT project can be used as long as they are assigned new return periods.

Since the approach followed requires the update of the original return periods, a weighting function has been developed in order to assign a new value to each one of the current ones. Considering that the I-T curves are better represented in a semi logarithmic way, a lineal function considering these axes has been used to define weights. In addition, as boundary conditions, it has been assumed that a return period of 1 year will have the maximum weight (3), whereas the 500
year return period events will have a weight equal to 1:

\[
\text{weight (T)} = a + \frac{b}{C_1 \ln(T)}
\]

\[
\text{weight (1)} = 3
\]

\[
\text{weight (500)} = 1
\]

Solving Equation (1), the weighting function is obtained (Equation (2)). This function will be used to define the several weights of the current hazard maps (with T equal to 10, 50, 100 and 500 years), as well as the ones for the future hazard maps:

\[
\text{weight (T)} = 3 - 0.741 \cdot \ln(T)
\]

Combining the weights defined by Equation (2), as well as the ones previously shown for the intensity, the hazard levels are defined as can be seen in Table 1.

**Exposure data**

As stated initially, exposure is represented by the assets that are present on each location, which is typically represented by land-use maps. Urban land-use changes were simulated using the MOLAND cellular automata (CA) model. The CA model comprises several factors that drive land-use dynamics in a probabilistic approach. Barredo et al. (2003, 2004) defined the process of urban land-use dynamics as a probabilistic system. The probability that a place in a city is occupied by a given urban land-use type at a given time step is a function of accessibility, suitability, zoning status and the neighbourhood effect measured for each specific land-use type at each specific time step.

SRES scenarios A2 and B1, the same ones as for the climate projections, have been implemented in the Llobregat basin, specially focusing in the region surrounding the city of Barcelona. The scenarios produced cover a period until 2040. The set-up of the meta-narrative descriptions is considered to be the first step in climate change land-use modelling studies (de Nijs et al. 2004; Solecki & Oliveri 2004; Regnster & Rounsevell 2006). One storyline is produced for each scenario describing the drivers that they represent.

The second step for the implementation of the scenarios is to quantify the demand for urban land-use for each meta-narrative. In the present study, a similar approach to that of Solecki & Oliveri (2004) and Barredo & Gómez Delgado (2008) is followed.

As an example of this approach, a part of the A2 scenario storyline is presented. This scenario is considered a pessimistic future with a lot of dependence on fossil fuels and high CO₂ emission levels (Nakićenović & Swart 2000). Consequently, an increased dependence on automobiles can be assumed, which will lead to more scatter and diffuse urban growth patterns. Therefore, in such a scenario, urban nuclei in peripheral areas will grow more than the urban areas closer to the core cities.

CORINE land-use datasets (EEA 1995) have been used as input data into the model. This European-wide dataset creates the possibility of modelling large European areas using a single implementation of the model.

Before the implementation of the scenarios, the model has been calibrated by using datasets from 1990 and 2000 for the Llobregat basin. Thus, the simulation period for the scenarios is 2000–2040.

With all this, it is possible to obtain raster images with a spatial resolution of 100 × 100 m, having each of these cells a land-use type assigned (Table 4 and Figure 6). In addition to the urban land-use categories that can be seen in the figure, eight rural classes are also modelled, obtaining the total amount of 17 land-use categories.

As can be seen from Table 4 and Figure 6, the two scenarios used in this study project a considerably large increase of the urban areas. Considering that the damage of floods in urban areas is much larger than the damage to rural areas,

| Hectares in the whole Llobregat basin of urban land-use in 1990 and 2000 as obtained from CORINE datasets, and in 2040 B1 and A2 simulated with the Moland model |
|---|---|---|---|---|
| | 1990 | 2000 | 2040 B1 | 2040 A2 |
| Continuous urban fabric | 19,570 Ha | 20,129 Ha | 21,023 Ha | 22,812 Ha |
| Discontinuous urban fabric | 22,494 Ha | 23,743 Ha | 25,741 Ha | 29,738 Ha |
| Industrial or commercial | 7,994 Ha | 11,206 Ha | 16,345 Ha | 26,624 Ha |
the exposure of the whole studied domain is projected to increase.

In addition to the economic consequences, the fact that the urban areas increase also has an impact on the hazard part of the risk equation. In urbanized areas, rainfall cannot infiltrate into the soil. Instead, water fallen on rooftops and pavements quickly runs off, leading to an increase of the flow volumes and peak discharges (Moscrip & Montgomery 1997), which obviously increases the intensity and frequency of floods (Field et al. 1982).

In order to properly represent such changes, the new land-use parameters in the hydrological model would need to be introduced to run it again. Nevertheless, as has been stated previously, the methodology created here is based on the use of existent flood hazard maps. Consequently, the hydrological changes caused by the increase of urban areas will not be considered in this study.

Vulnerability data

Vulnerability is the susceptibility of the exposed structures/people at contact with the damaging natural event. In order to obtain this variable for the Low Llobregat area, a monetary value has been assigned to each one of the different land-use types.

This classification is based in the total economic value of exposed assets for each land-use class in Spain. This value represents the cost of replacement, which follows the principle that ‘Old goods which are damaged during a flood are substituted by new, more productive or better performing ones’ (Penning-Rossell 2005).

Although these values lead to an overestimation of the actual damages of the event (Merz et al. 2010), this is not an issue here. Considering that vulnerability will be used as a qualitative variable defined by several weighs (Table 5), the

<table>
<thead>
<tr>
<th>Vulnerability class and weight</th>
<th>Cost of replacement</th>
<th>Example of land-use class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>9</td>
<td>301–500 €/m²</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>151–300 €/m²</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>21–150 €/m²</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6–20 €/m²</td>
</tr>
<tr>
<td>Very low</td>
<td>1</td>
<td>&lt; 5 €/m²</td>
</tr>
</tbody>
</table>
precise economic values are not required as long as the land-use classes are correctly identified.

In this case, the information on vulnerability was derived from the EC Joint Research Centre’s database of flood-damage functions (Huizinga 2007). As the total economic value has been used, only the maximum values of these functions have been taken into account. Then, the several land-use types have been sorted and grouped in terms of their vulnerability level, and different weights have been assigned to each of them (Table 5). The information contained in this table has been used as input in the risk mapping exercise of this work.

As can be seen from Table 5, five different weights ranging from 1 (very low) to 9 (very high) have been assigned to different land-use classes. As explained in the methodology section, these values have been chosen in order to be consistent with the weights of flood hazard (Table 1).

By using the values presented in Table 5, each land-use class is given a vulnerability level, and so the exposure maps can be transformed into vulnerability maps. These maps present at the same time the location and the economic extent of the damage that may occur in each spot.

As vulnerability is expressed in terms of weights, the monetary information is no longer needed. Therefore, no inflation has been considered to define the vulnerability of the future maps produced by the Moland model.

At this point, as summarized in Figure 7, all data have been presented and all the variables to assess flood risk have been defined and have a weight assigned. Then, by overlaying the different datasets risk maps can be obtained. This will be done via a GIS platform, by multiplying the different weights for each cell.

RESULTS AND DISCUSSION

The first step to assess flood risk consists on the climate data analysis. The increase of intensity for a certain return period and the new return period assigned to the previous intensity have been calculated from the intensity-return period curves, such as the one presented in Figure 5. As described in the methodology section, the new return periods from Table 6 (which correspond to the A2 scenario) are used in order to obtain a new weight, and hence update the hazard level of each cell.

Although the maps and tables that are shown correspond to the most extreme situation (i.e. the A2 scenario), it is important to remember that the study considered projected changes in climate and land-use for both A2 and B1 scenarios.

A2 scenario considers a regionalized world that focuses on economic growth, whereas B1 takes into account a globalized world that puts stress in preserving the environment. In general, A2 results tend to be more severe than B1 ones.

In this study, three combinations of climate change and land-use projections have been used: A2–A2; B1–B1; and A2 for climate and B1 for land-use. This third configuration has been considered because, while climate is affected by global dynamics, land-use is usually locally managed either by national, regional or local governments. Therefore, an A2 scenario for climate can coexist with a B1 scenario for land-use, meaning that even if climate changes may be
more severe, local land-use management policies are implemented in a more sustainable way.

Using these future climate data, new hazard maps have been obtained. In combination with the future vulnerability maps, risk maps for each future configuration considered have been obtained (Figure 8(b)). Of course, using the same methodology current risk maps have also been developed (Figure 8(a)).

Since the main goal of this work was the assessment of changes in flood risk, current and future maps have been compared. Using the colour coding described in Table 3 and subtracting the weights of the current risk maps to the future ones, the potential risk changes can be identified (Figure 8(c)).

It is worth noting that risk maps are not directly linked to a certain return period, but they present the maximum risk level of each cell associated to the highest return period available. This means that in the case of the current situation, the map evaluates the risk up to a 500 year return period precipitation event, because this is its initial flood map associated. Nevertheless, future scenarios present a return period considerably lower.

Figure 8 shows that the A2–A2 scenario presents a considerable risk increase. Although this increase is spread all over the area, there are some specific locations where changes are more localized. Strong and intermediate changes appear in the mid part of the area which corresponds to a densely populated and industrial zone. The model projects urban, industrial and commercial growth in this area leading to an increase of exposure and hence, vulnerability and risk.

As stated before, scenario B1 is more moderate than A2, for both the future climate extremes and the future exposure maps. Consequently, the combinations B1–B1 and A2–B1 present smaller risk increases than the A2–A2 results. This can be seen in Table 7, which presents the areas corresponding to each risk level and scenario. In the specific case analysed here, the Low Llobregat area, the scenario chosen has proved to make an important difference in both the cases of urban land-use and climate changes.

The results presented here are subject to a certain amount of uncertainties, and therefore must be taken with care. The data and the methodology used, as well as the several assumptions that have been made in the creation of the future scenarios, contain different types of uncertainties. This study does not intend to assess them, even though, the reader must keep in mind that they exist and further work regarding this subject should focus on this issue. For example, including more future scenarios or presenting the results on a

Table 6 | Intensities and return periods (T) of daily precipitation values for the 1986–2015 period and A2 scenario from 2026 to 2055

<table>
<thead>
<tr>
<th>T (years)</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{1986-2015}$ (mm/h)</td>
<td>6.84</td>
<td>8.42</td>
<td>9.00</td>
<td>10.34</td>
</tr>
<tr>
<td>$I_{A2,2026-2055}$ (mm/h)</td>
<td>8.67</td>
<td>10.92</td>
<td>11.92</td>
<td>14.17</td>
</tr>
<tr>
<td>Increase of I (%)</td>
<td>26.83</td>
<td>29.70</td>
<td>32.41</td>
<td>37.09</td>
</tr>
<tr>
<td>Future T (years)</td>
<td>3.10</td>
<td>8.79</td>
<td>13.19</td>
<td>34.05</td>
</tr>
</tbody>
</table>

Figure 8 | Risk maps for (a) year 2000, (b) future A2–A2 scenario (2040) and (c) its difference.
probabilistic way could be two simple ways to improve the quality of the results obtained.

CONCLUSIONS

The work described in this paper consists of the flash flood risk assessment in the Low Llobregat area. In order to do that, future scenarios of climate and land-use have been defined, and a methodology to assess future risk has been created.

Although only two scenarios of a regional climate model have been used, the general trend presented by them is that risk will increase in the whole Low Llobregat area due to the effects of climate change. For the considered scenarios and due to the methodology used (in which a single uplift factor is applied to modify existent flood maps), climate changes will raise the probability of occurrence of extreme rainfall events over the whole basin. On the other hand, there are risk changes affecting localized areas due to urban and industrial growth in the floodplains.

Regarding climate change, A2 and B1 scenarios present very different results in this area, being the first one much more extreme in terms of rainfall intensities. Regarding land-use projections, scenario A2 presents rapid urban growth with low infilling, whereas B1 represents a slower growth of the city extension, which is in turn becoming denser due to the infilling increase. Because of that, A2 land-use shows higher urban and industrial growth in the plains, leading to higher exposure, and hence, vulnerability and risk.

The simplified methodology implemented in this work is able to identify those new zones of high potential risk where adaptation measures should be implemented. It must be noted though that the results presented in this report may have large uncertainties associated. Further work should be dedicated to the assessment of these uncertainties, trying to quantify and reduce them when possible.

ACKNOWLEDGEMENTS

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REFERENCES


Table 7 | Affected flood areas with their corresponding risk level for all the studied scenarios. The relative increase compared to the year 2000 is also presented

<table>
<thead>
<tr>
<th>Risk level</th>
<th>2000 Area (Km²)</th>
<th>2040 A2-A2 Area (Km²)</th>
<th>Relative increase (%)</th>
<th>2040 A2-B1 Area (Km²)</th>
<th>Relative increase (%)</th>
<th>2040 B1-B1 Area (Km²)</th>
<th>Relative increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>13.37</td>
<td>2.07</td>
<td>-84.52</td>
<td>4.30</td>
<td>-67.84</td>
<td>8.04</td>
<td>-39.87</td>
</tr>
<tr>
<td>Low</td>
<td>5.58</td>
<td>6.20</td>
<td>11.11</td>
<td>10.15</td>
<td>81.90</td>
<td>6.48</td>
<td>16.13</td>
</tr>
<tr>
<td>Intermediate</td>
<td>8.67</td>
<td>1.85</td>
<td>-78.66</td>
<td>1.58</td>
<td>-81.78</td>
<td>6.15</td>
<td>-29.07</td>
</tr>
<tr>
<td>High</td>
<td>2.60</td>
<td>14.12</td>
<td>443.08</td>
<td>10.78</td>
<td>314.62</td>
<td>9.01</td>
<td>246.54</td>
</tr>
<tr>
<td>Very high</td>
<td>1.50</td>
<td>7.48</td>
<td>398.67</td>
<td>4.91</td>
<td>227.33</td>
<td>2.04</td>
<td>36.00</td>
</tr>
</tbody>
</table>


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