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Nature-Based Solutions (NbSs) to Improve Flood Preparedness in Barcelona Metropolitan Area (Northeastern Spain)

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Abstract: This paper presents a novel study of the Nature-based Solutions (NbSs) approach to analyze and propose mitigation measures for extreme floods. The study area is the Llobregat River in Catalonia, which crosses urban areas. We have selected one section in the final stretch of 4.5 km in the Barcelona Metropolitan Area. The section has suffered several damages in the last floods (e.g., 2016, 2018 and 2019), and we propose measures to reduce flood risk. Therefore, we proposed the following three specific objectives: (a) the identification of critical areas in the river stretches; (b) the identification of NbS opportunities and utilities; and (c) the mitigation measures in concrete areas from NbSs. The effectiveness of a NbS is based on the 2D simulation of the Gloria flood event (20–21 January 2020) with HEC-RAS software (version 6.0) for the better management of stormwater, and it is influenced by design and placement aspects; however, the better use of NbSs can improve flood mitigation and enhance urban resilience.

Keywords: nature-based solution; flood events; urban flooding; mitigation measures; HEC-RAS

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1. Introduction

Floods are a natural phenomenon that have progressively gained a major role in the relationship between people and natural hazards, especially due to rapid urbanization processes and the greater exposure of the population [1–3], as has been observed in the recent floods (October 2024) in the Valencian Community (Spain) due to DANA storm in the western Mediterranean Sea. The absence of spatial planning tools, as well as management without deep technical and scientific knowledge, has led many urban areas around the world to be vulnerable to floods and suffer economic losses, damaged infrastructure and even deaths [4–6]. Thus, floods are a particularly diverse phenomenon around the world, affecting especially in those regions where there is an uncontrolled occupation of the alluvial plains and an inefficient and insufficient protection system. Moreover, the recurrence and intensity are higher because of climate change and land use changes [7]. Floods are also considered the most costly and deadly natural disaster in the world [8]. Flooding is concentrated in countries in Central and South Asia, as well as North and Central Africa, Central America and Northern Europe, with large amounts of populations at high risk due to flooding. Countries like China and India have a large number of people at risk (almost 400 million in each case), and the Netherlands and Bangladesh have more than half of their population exposed to floods [9]. The Intergovernmental Panel on Climate Change (IPCC) stated in its Sixth Assessment Report (AR6) that extreme precipitation events will become more common in Europe in the near future (consulted on 23 September 2024: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/). Furthermore, according to future urban land growth projections, natural water retention by land use is predicted to decline. As a result, the likelihood and severity of flood events are expected to rise [10].

On the other hand, the Mediterranean system is hydrologically very complex with great geographical diversity that shares patterns in relation to flooding. Episodes of torrential rains are characteristic of the ordinary and extraordinary floods of Mediterranean rivers [11]. The large amounts of heavy precipitation concentrated in a short time give rise to flash flooding, which is especially characteristic of some parts of the Mediterranean region as the Spanish coast [7,12,13]. These extreme floods caused great damage in populated and densified urban areas during the last century, particularly in those areas with no or very deficient protection measures [14]. In turn, the measures taken in a post-flood scenario have led, on many occasions, to building infrastructure along the rivers such as an artificialization, urbanization and homogenization of the river area. European administrations, following the Water Framework Directive (2000/60/EC), suggest returning river systems to a less disturbed state and trying to reset the ecosystem quality. In the last decade, several research studies on various elements of floods have been undertaken. Many researchers investigate post-flash-flood analysis through hydrological modeling and inundation mapping [15]. Furthermore, the benefits of numerical weather prediction (NWP) models and rainfall radar were leveraged, and flood forecasting and nowcasting methods were established [16]. Moreover, many studies have used multi-criteria analysis and machine learning techniques to create flood susceptibility maps [17]. On the contrary, flood exposure analysis has received a lot of interest around the world [12–14]. Flood exposure assessments of infrastructure, on the other hand, are uncommon and limited to certain regions. Large-scale techniques have primarily been carried out in the United States [18], but limited research at the national level has been carried out in Europe, taking advantage of the benefits of open access data and geospatial analysis [19]. In these areas, where critical/social infrastructure is located in inundation zones, the NbS should be an integral part of spatial and urban planning.

The protection of the natural environment is becoming increasingly important, especially in cases where damage may be irreparable. This poses a major environmental, social and economic challenge for societies trying to adapt to new living conditions as quickly as possible [20]. Supranational administration (e.g., European Commission) encourages countries to look for such solutions in their own environment trying to be sustainable in terms of their solution, and the recent approval of the Nature Restoration Law (June 2024) related to the European Union Biodiversity Strategy is a milestone in this process. Nature-based Solutions (NbSs) are defined as ecology-inspired cost-effective solutions that bring environmental, social and economic benefits and contribute to building the resilience and sustainability of a given area to specific events [21]. Generally, these solutions lead to an increase in biodiversity and environment auto-protection. Also, they used systemic, resource-efficient and locally adapted actions to vulnerable landscapes [22]. These supranational entities encourage adaptation and the search for solutions to be carried out on the basis of nature and invest in territories using these NbSs as an engine for adaptation [23]. This is even more important in densely populated areas where efforts need to be even greater to adapt through NbSs to current environmental conditions lessened [24]. Some of the functionalities of NbSs are to manage natural hazards by building resilience to climate change in order to mitigate its impact and to adapt urban infrastructures to make them more resilient [25].

Climate change may lead to an increase in extreme events such as river flooding [26,27]. Therefore, being prepared is essential to cope with this impact, mitigate it and adapt to future events. Pre-disaster preparedness discussions on Integrated Flood Management (IFM) consensus building are essential [28]. In this sense, a NbS is a good approach that is sustainable, environmentally friendly, cost-effective and sustainable over time.

There are various types of NbSs (e.g., natural systems, green infrastructure, hybrid or integrated) that can provide solutions in river areas [29,30]. Some of these actions focus on the management, enhancement and restoration of rivers and floodplains, as well as the forest ecosystem services such as recharging aquifers, sequestering carbon, stabilization of watercourses and slopes, increasing biodiversity, reducing flood risk, maintaining soil moisture and managing runoff [31–37]. Several studies have examined how these NbSs are critical for the maintenance and recovery of ecosystem services that can be affected by extreme events [38,39]. Finding the most sustainable way to adapt to extreme events is a problem for which clear and concise solutions must be found. Therefore, a lot of research needs to be carried out focusing on urban floods and the way we manage flash floods. Studies in Brazil and Greece point to NbSs as a useful, sustainable and appropriate way to intervene in the territory [40–42]. However, it is noted that the implementation and monitoring and, therefore, studies on the use of NbSs in the preparation of river areas, against flooding are still very new and still have a long way to go. Some of the measures proposed in the above-mentioned studies and based on NbSs indicate that they generally lead to a decrease in the maximum flood depth and flooded areas as well as favoring groundwater recharge in the long term potentially diminishing the risk of drought.

Regarding floods, the implementation of various types of NbSs in very different areas, both on a regional and an urban scale, is considered one of the alternatives with the greatest potential for efficiency, profitability and sustainability compared to conventional measures [43]. They include both micro-scale interventions (such as green roofs or facades on buildings) as well as other territorial scales (for example, ponds, swales or green rain gardens in cities). Although the European Floods Directive (2007/60/CE) does not explicitly mention the term NbS as it was published prior to the dissemination of this concept, throughout the implementation process of this directive there are continuous references and proposals made to opt for NbSs as measures to promote in the improvement of flood risk management.

The diversification of the structure of the riverbanks, the reconnection of secondary channels and meanders, the improvement of the connectivity of the river with the alluvial plains and the restoration of wetlands are some of the NbSs that appear to be the most suitable for improving the state of river systems as a strategy to prevent the risk of river flooding [44,45].

This type of action for the ecological restoration or renaturation of rivers and streams or the preservation of floodplains requires in-depth knowledge of the geomorphological and hydrological processes of river courses and floodplains and of the anthropic actions that affect them. This is especially important in the Mediterranean basin where the Barcelona Metropolitan Area is inserted, where ephemeral courses (ramblas, streams, ravines, etc.) make up the majority of the river network. In the Mediterranean basin, there have been several studies that have pointed out the importance and the benefits of applying such NbS measures in this kind of area [46,47].

The aims of this work are essentially three, as follows: (a) analyze the better area to install mitigation measures considering the flooding area of at least a 50-year return period and take a specific event to validate the model; (b) suggest several NbSs to reduce the flood risk; and (c) make a final proposal for the implementation of the eight chosen NbSs in the area selected in the first objective. This study highlights the importance of the NbSs as part of the sustainable measures that will help to reduce the potential risk of flooding in fluvial plains in the climate change context and areas that have been fully or partially urbanized and, therefore, have needs regarding the land management. The sections chosen in this study fulfill these conditions and, with the NbS proposed, an attempt is made to shed light on the climate change context.

2. Materials and Methods

2.1. Study Area

This work focuses on the metropolitan stretch the Llobregat River. The section chosen is located in highly populated and urbanized areas. In the case of the Llobregat section, the areas chosen are characterized by the impact of 50-year flooding, as indicated in Figure 1.

All the tributaries caused damages in such flooding, and implementing NbSs in those areas is important to decrease the impact of extreme events.

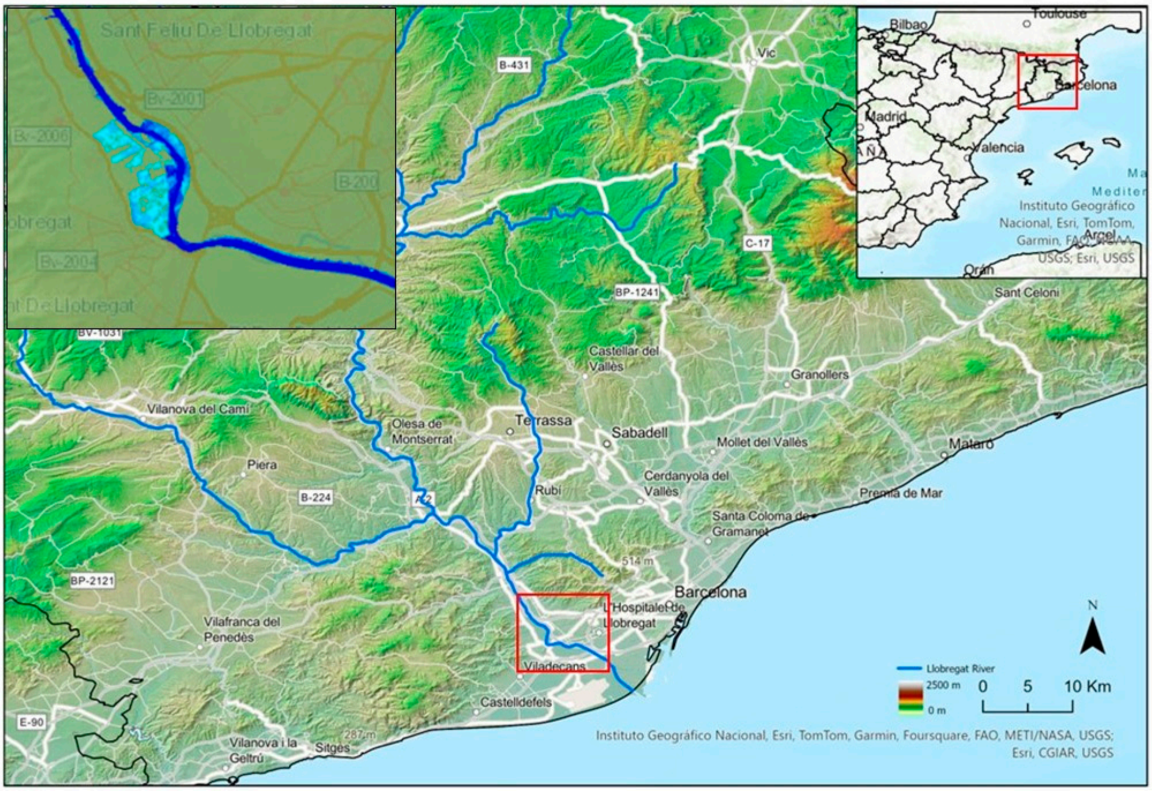

Figure 1. Map of the study area and the 50-year flood return period.

This study focuses on the regional framework of the internal river basins of Catalonia (NE Spain), which extends over more than 16,000 km^2 (52% of this region) and is home to 92% of the population [48]. Several basins and sub-basins are part of this territory, but there are two main ones: the Llobregat basin (5000 km^2) and the Ter basin (3000 km^2). These two river basins feed the water uses of the metropolitan region of Barcelona. Therefore, the quantity and quality of its waters is a strategic issue for the entire Catalan territory [49]. Growing urban pressure, high demand for domestic water (amounting to some 1200 hm^3/year and 40% of total regional demand) and recurring low flows are the main environmental challenges in this area.

Llobregat River Basin

The Llobregat River is 175 km long and covers a vast geographical area from the Pyrenees to the southwest of Barcelona. The upper valley of the Llobregat is characterized by a wooded mass of pine forests and a notable presence of agricultural and livestock areas. In the central and lower part of the Llobregat valley, the vegetation that dominates is scrubbed, and there is an abundance of intensive agricultural use and increasingly populated and urbanized areas [50]. The average annual flow is 700 hm^3, with a 10 m^3/s daily discharge, and it has a regime with maxima in spring (May) and with minima in summer (August) and winter (January). It is especially important to note that there are also variable highs in autumn (October–November) that, when they occur, can cause extreme and flash floods [51,52].

The main dam that regulates the Llobregat River is located in the upper valley (La Baells, 109 hm^3). It came into operation in 1976 and was built with a double objective: regulation of the river flow and supply of water for the metropolitan area of Barcelona. The basin has two other dams, concentrated in the main tributary (the Cardener River):

Llosa del Cavall (79 hm^3) and Sant Ponç (24 hm^3). The middle valley of the Llobregat also has more than 90 small dams, built between 1850 and 1900, which have had a remarkable retention effect on coarse sediments [53]. In addition to the impacts produced by the dams in the basin, we must add a trend towards a runoff reduction, mainly due to changes in climate conditions and the increase in forested land [54]. In addition, water pollution and salinization are two persistent environmental problems in the Llobregat basin [55].

Moreover, the Llobregat delta has undergone a great transformation in recent decades. In 2004, the mouth was diverted to prevent flooding in the municipality of El Prat de Llobregat and to expand the area of logistics activities of the port of Barcelona. This intervention had a profound ecological impact on the structure and diversity of the ecosystem [56]. Furthermore, the transformations in the delta can continue with the current debate about the expansion of the Barcelona airport, as well as the growing urban pressure on the agricultural park [57].

The area chosen for this study covers an extension of nearly 4.5 km located in the lower valley of the Llobregat (Figure 1). This is a highly anthropized basin area, with a similar succession of uses between the two banks. Various communication infrastructures are combined with urban fabric, industrial areas and patches of crops belonging to the Baix Llobregat Agricultural Park. On the right bank, we find continuous urban fabric (Santa Coloma de Cervelló—8000 inh. and Sant Boi de Llobregat—83,000 inh.), discontinuous urban fabric (scattered/suburban areas near the continuous fabric), B-23 highway, railway and irrigated horticultural area. On the left bank, we can identify a succession of continuous urban fabric (Sant Feliu de Llobregat—45,000 inh., Sant Joan Despí—34,000 inh. and Cornellà de Llobregat—89,000 inh.), industrial zone (especially important in Sant Feliu), railway and A-2/B-23 highways. It is also worth noting the presence of a historic canal (Canal de la Infanta), built during the first half of the 19th century for agricultural purposes.

2.2. Methodology

The simulations in this study are conducted using the physically based semi-distributed model from the Hydrologic Engineering Center (HEC), an open-source software. This is accomplished by utilizing the River Analysis System (RAS) model packages. HEC-RAS (v6.0) stands as one of the most recognized, studied and utilized flood mapping models in both the scientific and applied literature. Given the widespread use and reliability of the HEC model highlighted in various similar studies, it was deemed appropriate to employ this tool for the measurement analysis in this case [58–62].

Specifically, the methodological process for flood simulation in this work is carried out, using version 6.0 of HEC-RAS (2D) as the essential tool for visualizing floods with and without proposed NbSs for both rivers. The HEC-RAS tool simulates hydraulic runoff through the channel (depending on morphology) to calculate the extent of the inundated region, water depth and flow velocity. It is designed to perform 1D and 2D hydraulic calculations for an entire network of channels, floodplains and other natural and artificial channels. Furthermore, HEC-RAS includes steady-state surface flow simulation to calculate water surface profiles for constant and gradually varying flow, as well as unsteady-state surface flow simulation to simulate 1D and 2D flows and combinations of unsteady flows between 1D and 2D [58].

2.2.1. Dataset Preparation

To model discharge conditions with and without NbSs using HEC-RAS, various datasets were required to facilitate simulation under different conditions. The input data include (a) terrain (elevation); (b) discharge; (c) time interval of discharge flow; and (d) Manning's roughness coefficient (n). For elevation characterization, LIDAR data (0.5 m) was employed as a base dataset for the river course. This information was obtained from the Centro Nacional de Información Geográfica (CNIG) of Spain (https://centrodedescargas.cnig.es/CentroDescargas/buscador.do; accessed on 24 April 2024), which allowed for the creation of a digital elevation model to be used as the simulation's base terrain within the software. Discharge flow data were acquired from measurements taken by the Catalan Water Agency on 30 April 2023, for the Llobregat River, during which flows exceeded the typical average characteristics for the year; in fact, this event is likely a 50-year return period. For the modelization of the discharge, we used the data from the Gloria event (20–21 January 2020), the resulting hydrograph can be observed in the Supplementary Materials (Figure S1) with a maximum discharge of 1330 m^3/s in the Sant Joan Despí gauging station, just between the two sections we have analyzed. Lastly, Manning's roughness coefficient was determined based on proposals by Chow (1959, 1994) [63,64], as well as Arcement and Schneider [65] (1989).

For the analysis of NbSs in the context of floods near Barcelona city, several flood-risk maps have been chosen. The Sistema Nacional de Cartografía de Zonas Inundables (SNCZI) mapped the potential flooding areas for a 50-year return period. We have used these maps to recognize the potential areas to apply NbSs and see what type of mitigation measures have been carried out so far. In this sense, we analyzed those areas near Barcelona city, which are affected by floods with a return period of over 50 years at the least. Figure 2 shows the flowchart we have followed to perform the analysis.

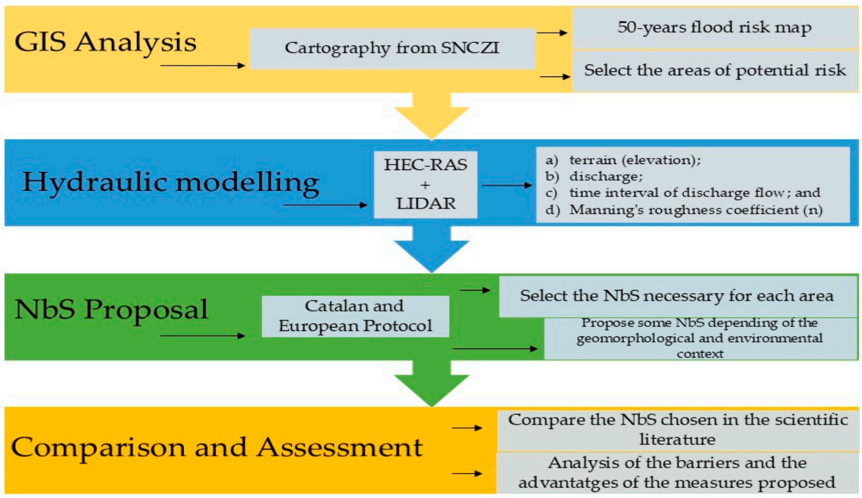

Figure 2. Flowchart with the three steps followed and the data and dataset used in the process of areas and NbS selection.

2.2.2. Hydraulic Modeling (With and Without NbSs)

For the simulation of NbS proposals in both rivers, a 2D flow area was added, outlining the assumed flood domain boundary by drawing a polygon using the point cloud (LIDAR) as the background layer in the geometric data editor of the program. Subsequently, a calculation grid is automatically created within the boundary layer with a calculation point spacing (CPS) of 1 m $\times$ 1 m. This results in a total of 161,884 cells for the Llobregat River, with an average size of 25.90 m^2. Boundary conditions lines are drawn along the outer boundary of the 2D area to determine upstream and downstream flood limits, and, in this case, the limit with the delta plain of Llobregat River. High-water conditions for both rivers are located north of the polygon's starting point, while low-water conditions are located where the river connects with the ocean.

The primary land use and land cover categories, based on Chow (1959) [63], Chow et al. (1994) [64] and Arcement and Schneider (1989) [65], were classified into seven categories, each assigned Manning's roughness n values: agriculture (0.07), urbanization (0.2), forests (0.035), grasslands (0.045), channels (0.03) and NbSs, representing the implementation of medium vegetation with a land use change assigned a Manning's roughness n value of 0.08.

Within the unsteady-state flow data editor of the software, for the upstream flow, the flow hydrograph for April 20–21 January 2020, was assigned with a 1 h interval, filled with the corresponding flow data for the river (Figure S1). For the downstream case, a normal depth necessary for the accurate simulation of flow inflow and outflow from the river was assigned. The energy gradient (EG Slope) to distribute the flow along the upstream boundary line for each time step is established based on the terrain slope in the vicinity of the upstream end of the surface flows [61,62].

Before running the model, various parameters in the unsteady flow analysis editor of the program were adopted. For unsteady 2D flood calculations in HEC-RAS, the diffusion wave equation is set as the default option. To prevent model stability issues, the calculation time interval is set to 0.1 s, considering the Courant–Friedrichs–Lewy condition [62,66]. Lastly, the initial conditions time is set to one hour due to the travel time of the first flood wave between the two ends of the inundation. In this way, the model is initiated to generate a simulation for each river, allowing measurement and analysis, based on specific breakpoints of flood depth and velocity behavior, both in the absence of NbSs and with strategically placed NbSs.

2.3. Application of NbSs

We have identified the main areas in order to develop the new NbS proposal: from Sant Feliu de Llobregat to Sant Boi de Llobregat (S-S) is the section chosen in the Llobregat River. The S-S transect is 4.5 km long and the river passes through urban, agricultural and industrial areas and, therefore, they have to be managed in order to decrease flood risk. As can be seen in Figure 1, there are several flooding areas with a 50-year period: these areas are the ones we have chosen to apply to the NbS, considering them the most affected section by extreme floods.

Given the importance of the public administration in this type of study and in the implementation of the NbS, the choice of the measures that are proposed to be implemented has been based on the NbS that it considers. On the one hand, the 2020 protocol action was published by the Catalan regional administration (Generalitat de Catalunya). On the other, the measures were taken from UNEP/DHI, IUCN and TNC, "Green Infrastructure: Guide for Water Management" and TNC: "Beyond the Source" (https://portals.iucn.org/library/sites/library/files/documents/EPLP-089-Es.pdf accessed on the 21 December 2022). The first protocol tried to add some NbSs in areas affected by urbanization and where the natural landscape is affected. However, most of the measures keep being infrastructure changes. They added information regarding several NbSs, which could be used in specific areas. Therefore, we have used all the information related to our study area to apply new NbSs in our stretches and adapt them to the measures already existing. On the other hand, at the European level, they mention the measures strictly related to the mitigation of flood risk. Therefore, the eight measures that the "Green Infrastructure: Guide for Water Management" and TNC: "Beyond the Source" consider to be the most effective mitigation of floods have been chosen. Similarly, to corroborate these eight measures, we have verified at a scientific level that all of them have been used or proposed beforehand in areas comparable to the Barcelona Metropolitan Area. They are the following:

- Strategic protection for terrain (including buying properties close to the river plain): trying to protect all the land influenced by the banks of the rivers and being able to adapt it to apply different measures;
- Revegetation (including reforestation and forest conversion): applying plantations of native riverside vegetation and introducing fauna typical of the study area;
- River shore restoration (including shore corridors): eliminating impervious land near rivers and trying to create green corridors around them;
- River reconnection and floodplain: recreating natural flood areas eliminating currently anthropized areas and incorporating tributaries in a more natural way;
- Works on flood deviation: applying measures so that the deviations of the channels are the least aggressive, through natural channels or creation of natural meanders;
- Wetlands restoration recovery: eliminating or minimizing the areas with anthropized vegetation due to the installation of nearby industrial areas to favor the typical riverside and delta green spaces in the case of the Llobregat River;

- Green areas (increase bio-retention and infiltration): incorporating highly natural areas with the elimination of rural dirt roads and the installation of areas of meadows and green paths;
- Sustainable urban drainage system: related to the previous one, eliminating rural dirt roads and channeling of rivers and tributaries to favor a more natural bed and thus favor fluvial erosion–sedimentation processes.

All of these NbSs are basic to develop correct strategies in order to better manage flood risk and, in the Llobregat River basin as well.

In order to apply the proposal in the study area, a GIS analysis has been carried out. We have developed two maps (two in the S-S and one in the M-S section) where the NbSs are represented in two groups. Moreover, the measures have been mapped in the points where they are more necessary following the actual state of the river management, according to local administration and PNOA aerial photographs. The selection of the different NbSs in each area has been carried out following the extensive literature related to flood mitigation and NbSs, and the measures that can be better adapted in each area.

3. Results

3.1. Llobregat River Basin

In the section chosen to apply the NbS, different measures have been carried out in recent years focused on reducing the risk of flooding to the population. Some have been aimed at alerting people not to access flood-prone areas during extreme rain periods and others towards the partial channeling of the river. These measures, although they have not been unsuccessful, are far from the Sustainable Development Goals and the European Union directives on land management to mitigate the risk of flooding. Of the eight NbSs identified in this work, four are proposed in this 4.5 km transect. The Generalitat de Catalunya updated the Emergency Plan for Floodable Areas (INUNCAT) in 2021. The document describes the damage suffered by municipalities throughout the Catalan territory due to flooding, so we have based the measures on the sections that they considered more damaged and in the 50-year return period flood map.

The NbS measures that are proposed to be implemented in the study transect are the following: revegetation (including reforestation and forest conversion), river reconnection and floodplain, works on flood deviation and wetlands restoration recovery. We have selected two areas in the Llobregat River where the NbSs chosen can be implemented (Figure 3). These areas are some of the most affected during flood events, as can be seen in Figure 1, where the 50-year return period is shown.

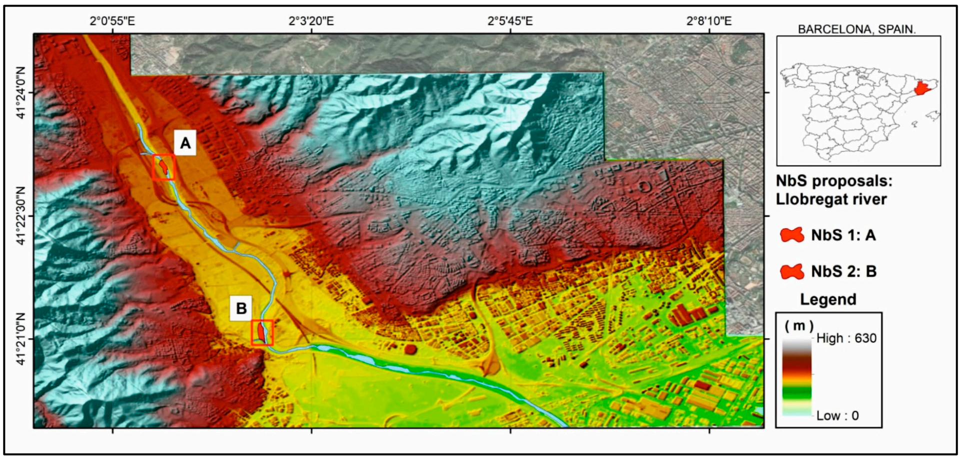

Figure 3. Location of Nature-based Solutions (NBSs) for the Llobregat, based on local configuration.

We proposed the implementation of the so-called "river reconnection and floodplain" and "works on flood deviation". The implementation of the reconnection of the tributary with the main river and managing it so that there is an active flood plain would be the objective of the implementation of this NbS. Here, the important thing is to permeabilize the soil and install green paths. Another solution could be the installation of wooden walkways through a low area and the naturalization of the path, making it floodable in periods of torrential rain. This type of NbS has been implanted in different parts of the Mediterranean with positive results [58,67].

The second area chosen to implement a NbS. In this case, it can be observed how a tributary connects with the Llobregat River through a watertight channel (B). In addition, in the same area, an asphalt parking lot is located in the floodable area of the channel. For this area, following the parameters established in different studies [58,68], the most effective NbSs are "works on flood deviation", applying a natural meander between the tributary and the Llobregat River, with a natural "revegetation" and "wetlands restoration-recovery", will restore delta vegetation with natural wetlands. Then, the proposal established here is the diversion through meanders once the passage passes under the road infrastructure for the possible flooding of the adjacent crop fields so that the channel would provide nutrient-rich sediments to improve the soil quality [69]. Subsequently, a wetland restoration and recovery of the connection with the river would be carried out, so that the native fauna and flora can proliferate and recover the natural landscape of the river [68]. This re-nature of the land includes a third NbS, the revegetation of the land in the park area or at least the implantation of a land or herbaceous vegetation park. In this way, infiltration in that area will improve and the soil will have a greater water retention capacity, reducing the runoff generated during episodes of torrential rain.

Other NbSs that could be implemented in both cases are a "revegetation (including reforestation and forest conversion)" focus on the channel in order to change the runoff dynamic and the soil dynamic; and "river reconnection and floodplain", installing a natural meander and creating connection between the main river channel and the tributary trying to take profit from the natural vegetation and the dynamic erosion–sedimentation. An improvement in the infiltration and permeability of the soil would be necessary and for this, a revegetation based on reforestation would be a good decision, thus reducing the runoff that reaches the river, without sediment as a consequence of the canalization. Therefore, the land would gain water retention capacity and infiltration [68]. The second of the measures aims to create a more natural connection of the tributary to the river and generate a flood plain that benefits the adjacent agricultural land [69]. In this way, infiltration would again improve and a flood area would be formed for the channel that would provide nutrients to improve soil quality.

3.2. Flood Simulation

Figures 4 and 5 illustrate the outcomes of the simulation for the river segments, based on two parameters that enable the observation of flow behavior and characteristics: (a) water depth and (b) flow velocity. The results indicate that the inundation depth in the analyzed area reveals, for the case of the Llobregat River (sheets A1 and B1), maximum values of 4.26 m and 3.75 m without the presence of NbSs. In sheets A2 and B2, the depth reaches maximum values of 4.21 m and 4.62 m with the presence of NbSs.

Regarding the flow velocity, the results demonstrate that the velocity in the flooded area reveals, for the Llobregat River case (sheets C1 and D1), maximum values of 0.67 m/s and 0.18 m/s without a NbS. In sheets C2 and D2, the velocity reaches maximum values of 0.40 m/s and 0.13 m/s with a NbS.

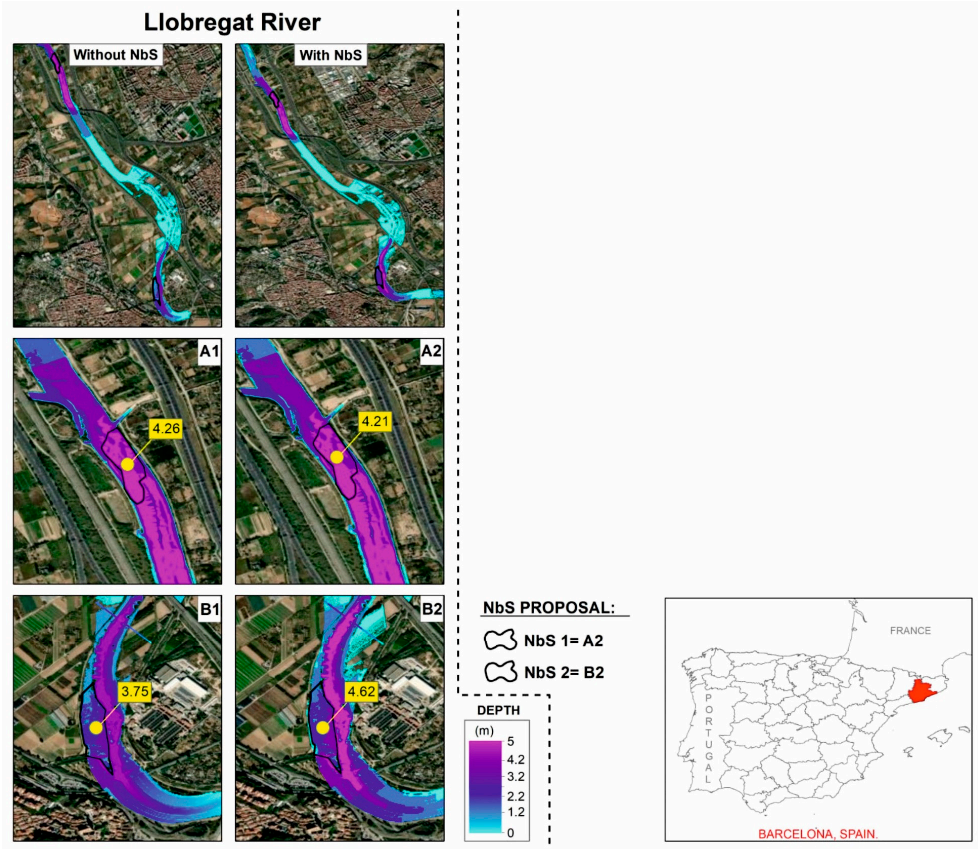

Figure 4. Flood simulation results with water depth for the Llobregat with and without NbSs.

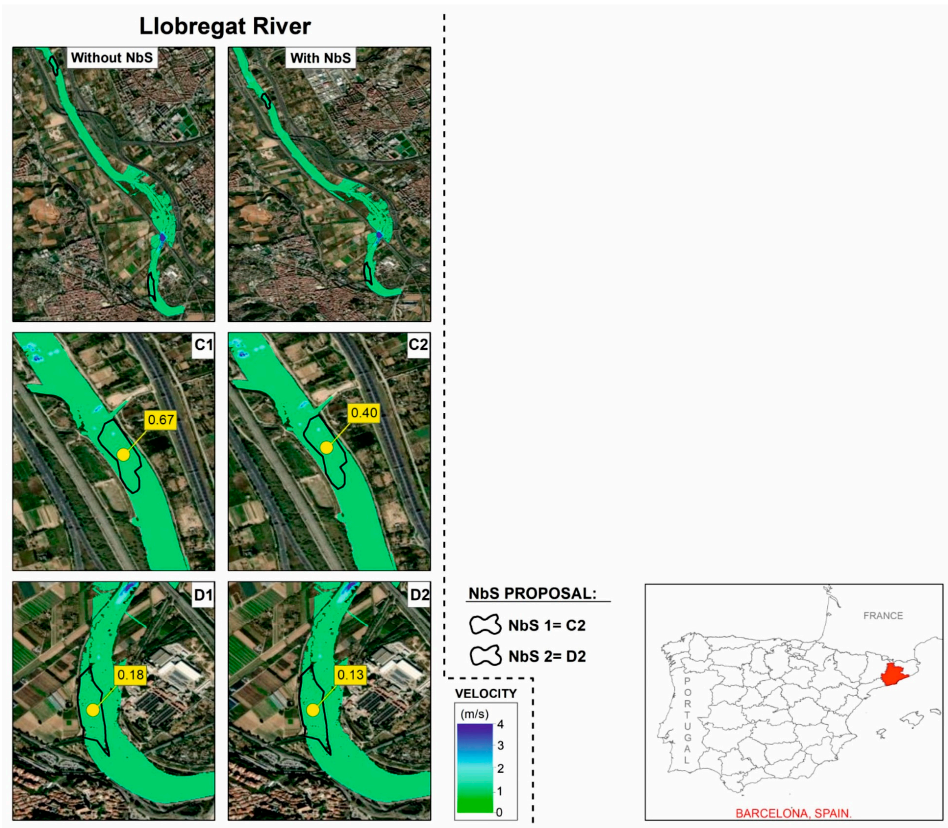

Figure 5. Flood simulation results of flow velocity for the Llobregat with and without NbSs.

According to the comparison of results based on comparative results with general patterns, the results obtained in the simulation of this work show great consistencies with patterns exhibited in previous studies on the dynamics of flows in river systems. As an example, the reduction in flow velocity in the presence of NbSs is aligned with results that stand out in other works where the incorporation of a NbS fulfills important functions, affects the dissipation of energy and favors a more homogeneous and controlled flow [70–72]. In particular, it has been observed that natural structures not only act as a physical barrier, but also redistribute water velocities, reducing the effects on sensitive areas and thus increasing the resistance of river systems [72]. Likewise, the depth values obtained in the simulations are within the range of variability indicated in recent studies of a similar nature developed in the Mediterranean basins [42,58].

3.3. River Management Tools

The management of river measures that have been taken in many cases are related to the construction of infrastructures near rivers, emergency barriers when there is a flood or the implementation of an emergency flood warning system. In addition, because of climate change, flood events are becoming more recurrent. Therefore, adaptation to climate change is a key element toward resilience, developed through an operational framework that allows local planners to define approaches and practical strategies for action [73]. Therefore, it is fundamental to understand the dynamic of the whole system and to develop frameworks that recognize the multiple values of NbSs and their co-benefits for society since they represent a valuable tool for decision-making. In this sense, the success of a NbS is dependent on factors and conditions involved in the process of flood risk management. For instance, the implantation of large infrastructure to reduce flooding risk and the industrialization process caused severe land contamination at thousands of brownfield sites abandoned around the world due to the high cost of remediation and there are risks related to the interactions with these areas to revert the pollution [74]. So, the frequency with which the NbS paradigm is positively bandied about in many disciplines is diverse, as well as the criticism.

In some ways, the necessity of a scientific and practical transitional path is printed on NbS demand, such as those applied at the urban scale, which emphasizes multifunctionality in terms of ecological services, and that includes, first of all, strategic protection for terrain river, trying to buy the properties near the river banks, and then shore restoration, river reconnection with floodplains, wetlands restoration or recovery and establish green areas or sustainable urban drainage system. All of these NbSs will contribute to adapting and mitigating the effects of climate change in the river environment, as well as reduce flooding risk in urban and peri-urban areas.

Depending on the level of risk, which in our study areas is high, political decisions and funding, a suitable combination of measures should be adopted to mitigate rising flood risk driven by urbanization, but also climate change [75]. Conventional engineering solutions alone, as has been stated before, are often not enough for flood control, so NbS has been applied in flood management in recent years [76]. By using flexible and cost-effective solutions that mimic natural processes, NbS has the potential to build urban resilience and provide a number of ecosystem services associated with environmental, social and economic benefits [77].

3.4. Barriers and Challenges

In the described context, we find that the main difficulties when carrying out the planned measures respond to the inherent complexity of the administrative management of basins and rivers in Spain. The identified interventions can be applied from a technical point of view, and they are positive from an ecological perspective, but their management and social acceptance can generate problems in the short and mid-term. Nevertheless, these initial barriers could also represent an opportunity to deepen the knowledge of NbSs in

Spain and their application in zones of highly transformed and urbanized landscapes such as the Barcelona Metropolitan Area.

Knowledge gaps and multifunctional governance can represent the first barrier. NbS measures require scientific and technical knowledge on the part of the administration that carries them out, and adequate coordination is necessary between all the partners involved. In this pursuit, the Catalan Water Agency would need constant cooperation from the local administrations (municipalities and consortiums). All the stakeholders involved must be aware of the importance and need for green infrastructure to plan and manage metropolitan river spaces. The complexity of the division of competences between multilevel public administrations can be more easily managed if there is a clear awareness to apply NbS measures.

Furthermore, another identified barrier is the lack of political support and public acceptance. The measures described may imply regulation changes that could affect specific users. For this reason, it is important that the administration propose a public participation process for NbS measures. This process can contribute to analyzing impacts, learning about the social dynamics of the affected spaces and avoiding further conflict. This process can become a challenge through the co-creation of NbS measures between administration, technical professionals, scientists, users and society. Beyond technical and scientific knowledge, it is important that the citizens of the municipalities involved have access to information on these measures promoted from the political sphere. Citizens in general must understand that the application of these measures entails an increase in the quality of life in their urbanized environments.

Last but not least, a financial support strategy is required. The provision of specific budgets for NbS measures and public–private partnerships may be actions to consider, especially in the case of the Llobregat River. Anticipation can be a key factor in order to plan the measures and, eventually, adapt them to the budget. The main challenge in this regard may be to carry out satisfactory monitoring and evaluation of the measures and their practical results.

3.5. New NbS Measures

To apply NbSs, some issues related to the governance, citizen involvement or what type of funding they will have must be considered. The three aspects are interrelated since, depending on the level of custody of the territory (municipal, intermunicipal, regional or national), some NbSs or other mitigation measures may be designed. Also, a key aspect in flood risk management is citizen participation, since risk perception is equally crucial once the necessary mitigating measures are installed.

Eight NbSs have been chosen for this study. All of them are directly related to river management, from revegetation to installing fully sustainable urban drainage systems. This group of measures is considered in the governance plan of the *Generalitat de Catalunya* [78] and that is why what is proposed in this study is in line with some of the Sustainable Development Goals, promoted by the European Union, as well as the objectives set by the competent administration in these two sections.

The eight measures can be divided into the following two groups: (1) those related to the local flora and fauna of the rivers, and (2) the NbSs that deal with the management at the structural level of the river. The first group includes revegetation with flora and the installation of native fauna, creation of green areas, installation of sustainable urban drainage system and restoration of wetlands. The second group is made up of the formal procurement and acquisition of private properties close to the river, the restoration of corridors along the river banks and carrying out work on the diversion of high flows and river-floodplain reconnection.

Some of the data related to flood damage are described in Table 1. Table 1 shows the flood damage that occurred in all the municipalities that are within the section of the Llobregat River studied. As can be seen, the economic damage during the last decade reached almost EUR 1 million, the number of people affected was almost 15,000 and the number of people injured and damaged buildings was 56 and 17, respectively. These data give rise to the formulation of new measures against the consequences of flooding in the Llobregat River. In this case, they are produced by torrential rains in an urbanized context. The proposed NbS can help to mitigate the risk of flooding, in addition to recovering the river ecosystem.

Table 1. Damage of the floods during the last decade according to the Catalonia government.

Town	Economic Damage (EUR)	People Affected	People Injured	Buildings Damages	Length Flooded (km)
Sant Feliu de Llobregat	275.129	4968	9	3	1
Santa Coloma de Cervelló	50.177	918	14	3	2
Sant Joan Despí	291.101	7386	8	5	1
Cornellà de Llobregat	22.764	36	17	4	0
Sant Boi de Llobregat	145.872	1173	8	2	2
TOTAL	785.043	14.481	56	17	6

4. Discussion and Conclusions

Mediterranean rivers are generally characterized by a precipitation-dependent flow [79]. When this precipitation is torrential, it can cause flooding in the areas surrounding the rivers. These areas often coincide with urbanized and human-occupied areas [80]. Therefore, there is a constant concern to prepare for these events in the best possible way [81]. Historically, one of the most widely used tools for river management is the creation of infrastructures (e.g., flood fords, cross drainage works, levees, siltation and gully covers) [82,83]. Mapping, stakeholder's forum and spatial and urban planning are also essential when determining priority areas for intervention and areas of special interest to protect [84,85]. These infrastructures may have been effective in the past, but they are not adapted to today's flood protection needs and characteristics [86,87]. In addition, many of these works turn out to be unsustainable and environmentally unfriendly, and, therefore, over the years, there has been a shift towards the use of green infrastructure that protects the environment [88,89]. NbSs are emerging as a sustainable alternative to these tools and infrastructures due to their adaptability, durability over time and environmental friendliness [90].

The measures proposed in this analytical and proactive study focused on two river stretches located in the Barcelona Metropolitan Area (NE Spain) are preliminary and specific with the aim of creating precedents in the application of NbSs in the river basin. The benefits of these measures have been demonstrated in different studies in areas with similar characteristics [85,86]. In this way, the fact of having chosen areas affected by more or less recurrent floods (50 years) will allow us to observe the real effectiveness in a relatively short time frame.

The results of the hydrodynamic simulation obtained in this study reaffirm the capacity and benefits that NbSs can have in mitigating risks associated with floods. Regarding depth, for example, the maximum values with NbSs show slight variations compared to the scenarios without the presence of NbSs. This, considering the nature of the Llobregat River could be strongly related to the capacity of NbSs to reduce the localized accumulation of water, favoring a uniform redistribution in the flow [91]. Although the maximum depth values do not show a uniform decrease, this aspect could be indicative of a behavior tending towards a more homogeneous distribution in the flow, avoiding dangerous concentrations at specific points [92]. Such conditions open a dimension for future studies to investigate how the spatial configuration of NbSs can influence risk reduction and ecological restoration in basins of this nature. Now, in terms of flow speed, there are great contrasts between the different scenarios. There is a marked reduction in maximum velocities when NbSs are implemented, indicating a decrease in the destructive potential of fast-flowing waters. The reduction in maximum velocities by more than 60% with the incorporation of NbSs not only translates into an immediate reduction in the risk to infrastructure and human life, but also into benefits on sedimentation that can favor long-term ecosystem resilience [91].

Adaptive management, an approach that facilitates decision-making with long-term monitoring under uncertain conditions [90], could provide guidance on long-term NbS monitoring to maintain flood mitigation efficiency. Via long-term monitoring by adaptive management, the implementation of NbSs can be sufficiently considered for the long-term planning of flood risk management [93]. The flooding of upstream fields, also called "making space for water" [94], such as some of the measures proposed here, is now a common practice, e.g., in lowland Britain, to prevent flooding of adjacent or downstream urban areas [95]. However, NbS strategies based on control flooding require more space than conventional gray infrastructures, and the land needed is often owned by private individuals [96], an issue of administrative complexity that needs to be addressed properly. Allowing specific land to flood is a particularly effective measure in flood risk control, so economic compensation to the owners of these agricultural plots must be provided in exchange for flooding of their land [97]. Using flood-tolerant land is more cost-effective than disaster relief economic impact. In the Stroud Frome catchment in the UK, the use of floodplain areas or flood storage, as well as NbS strategies to increase soil infiltration and resistance to flow by slowing the water, have proven to be cost-effective [77].

In many cases, NbSs are valued solely for the ecological value and protection they provide, but it is also necessary to make cost–benefit assessments from an economic point of view. In this respect, there is a consensus that a NbS implies a significant investment but the benefits over time are high, as individuals value co-benefits such as leisure, aesthetics, food and materials and the setting that provides more space for nature in the river basin [39].

On the other hand, a NbS also acts as a measure to mitigate the effect of climate change [98]. The NbS perform as catalysts to maintain or increase the contributions that nature can have to humans, in the context of climate change [99]. The proposals we have made in this study, in addition to mitigating the risk of flooding in the selected sections, would also be beneficial to mitigate some effects of climate change [100], and they would increase ecosystem services along the entire river bank [101]. The damages caused by floods in the last 100 years have shown that the role played by the NbS to mitigate them is essential. The experience that the implementation of these measures has entailed has shown that ecosystem services can be both ecologically and economically beneficial for society in terms of natural disasters [101]. In addition to providing these direct mitigation benefits, ecosystems can also help vulnerable communities, especially those who depend on natural resources, to better adapt and become more resilient to the adverse effects of climate change, including extreme weather events and climate-related disasters.

Furthermore, an example of a good point to start for the application of NbSs is the return period maps (50 years) shown in Figure 1. As can be seen, in the area studied, the area flooded is quite large. Thus, in the context of climate change with the consequent increase in torrential precipitation events [24], urban flooding will be increasingly catastrophic in non-managed areas [27,67]. Proper land management to reduce the risk of flooding is considered essential in urban planning in riverside areas.

This study presents several proposals to mitigate the risk of flooding in urban areas, historically affected by significant river floods, since the NbSs have emerged as effective means to respond to such challenges for the international community, these measures will be very useful in our study context. The identified and proposed measures can be taken by stakeholders and planners with the aim of providing benefits and building resilience. NbSs have been shown to be sustainable and environmentally friendly solutions [58,67], to the detriment of the historical and traditional solutions based on the construction of large infrastructures, which, although they temporarily reduce the risk, during extreme episodes, can cause more economic damage. From this perspective, NbS represents an opportunity to rethink human intervention in nature and reorient it towards corrective and restorative management.

Further research on the execution process and social adaptability and acceptance is needed, especially from a quantitative approach that provides a concrete and detailed vision of the applicability, replicability and possible consequences of the measures from an ecological, technical and engineering perspective. Our study is framed within a general proposal, which also needs to be approached from a systemic and multifaceted perspective that considers all the factors involved. Although the measures could be technically and scientifically correct, the implementation gap can be a significant barrier if social, regulatory and economic issues are not correctly adjusted. The multi-level governance and legal framework may not easily adapt to the urgency of NbS action. For this reason, it is necessary to deepen the processes of communication, information, participation and co-creation among all the stakeholders involved: administrations, scientists and society. In this way, awareness about the benefits of NbS measures in highly urbanized areas will increase, as well as the citizen's perception of healthy, aesthetic and safe places.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology11120213/s1, Figure S1: Hydrographs of 20th–21st January, 2020, for the Llobregat river.

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