Analysis of extreme flooding events through a calibrated 1D/2D coupled model: the case of Barcelona (Spain)
Beniamino Russo, David Sunyer, Marc Velasco and Slobodan Djordjević

ABSTRACT

This paper presents the results of a calibrated 1D/2D coupled model simulating surface and sewer flows in Barcelona. The model covers 44 km² of the city land involving 241 km of sewers. It was developed in order to assess the flood hazard in the Raval district, historically affected by flooding during heavy rainfalls. Special attention was paid to the hydraulic characterization of the inlet systems (representing the interface between surface and underground flows), through experimental expressions used to estimate the effective runoff flows into the sewers in case of storms. A 2D unstructured mesh with more than 400,000 cells was created on the basis of a detailed digital terrain model. The model was calibrated and validated using four sets of well-recorded flooding events that occurred in 2011. The aim of this paper is to show how a detailed 1D/2D coupled model can be adequately calibrated and validated using a wide set of sewer sensors and post-event collected data (videos, photos, emergency reports, etc.). Moreover, the created model presents significant computational time savings via parallel processing and hardware configuration. Considering the computational performances achieved, the model can be used for real-time strategies and as the core of early warning systems.

Key words | 1D/2D coupled modeling, dual drainage, sewer and overland flows calibration

INTRODUCTION

CORFU Project (COllaborative Research on Flood resilience in Urban areas; www.corfu7.eu) is an interdisciplinary project funded by the European Commission with the aim to improve the practice of urban flood risk management. In this context, eight case studies in Europe and Asia have been developed with the main objective to analyze and improve resilience of cities to flood impacts. One of the case studies is Barcelona in Spain. The average annual precipitation in Barcelona is 600 mm, but the 5-minute, 10-year design storm intensity is 204.7 mm/hour, and it is not rare for 50% of the annual precipitation to occur during two or three rainfall events. The morphology of Barcelona close to Collserola Mountain contains areas 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 (less than 1%) and several spots susceptible to flooding. This morphology produces flash floods in the lower part of the city in the case of heavy storm events. Owing to the adverse rainfall patterns, the morphological characteristics, and the high density of population and impervious surface, it is clear that drainage in Barcelona is of special relevance.

In the 1990s, a specific company responsible for the management of the Barcelona sewer system, Clavegueram de Barcelona S.A. (CLABSA), was created, and the drainage 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 cities with the most advanced management of drainage systems. However, notwithstanding the big efforts carried out in the last two decades (several sewer pipes and facilities were redesigned and improved for a 10-year return period), flooding problems still occur in the case of heavy storm events causing damage 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 collected by the sewers due to a poor surface drainage capacity.

A specific area of Barcelona, the Raval district, was selected as a case study, considering, for the whole area, a flood risk assessment based on a hazard and vulnerability evaluation. The Raval district, with almost 50,000 inhabitants in an area of 1.09 km², is one of the most densely populated areas in Europe (approximately 44,000 inhabitants/km²). The district area is highly impervious with several vulnerable elements (such as schools, hospitals, and major highways). It represents a critical point of the city where stormwater not conveyed into the sewer network and overflows from sewer manholes are stored (Figure 1). Moreover, the hydrological response time of Raval district catchment is very short (less than 30 minutes).

The literature review suggests a very wide range of methods depending on how detailed the analysis needs to be in order to give a realistic representation of the hydraulic behavior of the analyzed catchment. The methods used in research and practical applications range from very basic approaches with numerous simplifying assumptions up to very sophisticated ones with high-resolution data and time-consuming computation (Aronica & Lanza 2005; Apel et al. 2009).

Traditional 1D sewer models used by CLABSA during recent years were unable to adequately describe flooding in the Raval district and the causes producing these problems (large runoff volumes not conveyed into the sewers coming from upstream catchments). Even if it is clear that the choice between using a 1D surface network model or a 2D surface system model determines the accuracy of results and the computational time required to obtain them, when the flow overtops the curbs in the streets and it does not remain within the street profile, using a 2D model is crucial (Mark et al. 2004). Considering that Raval district is located in a very flat area and that many urban areas are occupied by pedestrian areas and squares (without curbs and preferred runoff direction), the need for a detailed coupled 1D/2D approach is evident (1D for underground sewer network model and 2D for overland flow) in order to correctly 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). Moreover, the significant information available for the Barcelona case study in terms of sewer elements (such as pipe sections, topographic data of manholes and inlets, and hydraulic performance of inlets systems), rainfall series data provided by a dense rain gauge network, water depth series provided by distributed sewer sensors, as well as the new advances in parallel processing and hardware (Kalyanapu et al. 2011; Lamb et al. 2011; Brodtkorb et al. 2012; Satra & Brodtkorb 2012; Henonin et al. 2013), have encouraged the setup and calibration of a detailed 1D/2D coupled model.

This paper shows the main results and features concerning the creation and the calibration of a detailed 1D/2D coupled model able to provide realistic simulations of flooding produced by heavy storm events in the Raval district and the elaboration of hazard maps on the basis of the local estimation of the flow parameters (flow depth and flow

Figure 1 | Typical gradients and morphology in Barcelona. The circles in both images indicate the location of Raval district.
velocity). In particular, the model was calibrated and validated using a wide set of rainfall time series, water depth time series coming from a distributed sensors network, and post-event collected data (videos, photos, emergency reports, etc.). Moreover, speeding-up strategies focused on parallel processing and hardware advances were implemented in the model, reaching very high computational performances. All these aspects demonstrate that 1D/2D detailed and realistic models can be developed and calibrated on the basis of collected sensors and field data and can be used for real-time strategies and as the core of early warning systems in complex and vulnerable urban areas like Barcelona.

MATERIALS AND METHODS

General aspects for the creation of a coupled 1D/2D urban model

Several authors have published interesting papers treating the need for coupled approaches (modeling of the surface and sewer flows at the same time) to represent adequately urban flooding caused by sewer overflows (Phillips et al. 2005; Lipeme Kouyi et al. 2008; Leandro et al. 2009; Obermayer et al. 2010) and carry out a realistic flood risk assessment (Kandori & Willems 2008). Currently, a 1D/2D coupled model represents a powerful tool to describe, in a very realistic way, the hydraulic behavior of urban areas suffering flooding problems due to the excess of runoff not conveyed by the drainage networks. However, in order to ensure good and detailed results, it is not sufficient to have a technologically advanced tool for the calculation concerning hydrological and hydraulic processes, but several other aspects must also be carefully considered, such as the following:

- Detailed topographic data able to reproduce complex urban morphologies.
- Methodologies able to take into account flow interchanges between the two layers of drainage (surface and underground layers).
- Rainfall and flow/flow-depths records for the adjustment of the model parameters in the calibration phase and for the results validation.
- Time series of the operations carried out by the sewer devices (variable sluices, pumps, etc.).

These aspects were considered for the creation of the 1D/2D coupled model of the Raval district. Sewer flow was represented by full 1D Saint Venant equations, while surface flow concerning overland flow on streets, sidewalks, squares, and other pervious and impervious areas was simulated by full 2D Saint Venant equations. Flow exchanges occur between manholes and the cells of the mesh depending on the flood type. The software used for the creation of the model was version 3.5 of InfoWorks ICM by Innovyze (2012).

Topographic data

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 until it reaches 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 (often less than 15–20 cm) and high flow velocities (up to 3–4 m/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 m² obtained by a LIDAR (laser imaging detection and ranging) flight with a density of 1.35 points/m² and a precision of 15 cm in terms of ground elevation. This DTM was also improved using data concerning CLABSA territorial system (for example, positions and elevations of manholes, inlets, etc.).

Characterization of the hydraulics of surface drainage systems

The need to estimate the hydraulics of the surface drainage structures and to model them through a coupled 1D/2D approach is clear. Moreover, the possibility to characterize hydraulically all the connections (manholes and drain
inlets) between surface and underground systems allows the estimation of surface and pipe flows during a storm to be improved. The consideration, at the same time, of the surface flow and its interaction with sewer flow are commonly known as ‘dual drainage modeling’, with flow components on the surface and underground (Djordjevic et al. 1999) (Figure 2).

To achieve this objective, the hydraulic performance of the inlets present in the Raval district was analyzed using experimental expressions proposed and implemented by Gómez & Russo (2009, 2011), Gómez et al. (2011) and by Russo et al. (2013). Specifically, all the inlets located in the Raval district (more than 2,600 units of almost 50 different types) were classified in groups represented by eight inlet types previously studied by Gómez & Russo (2011) (Figure 3). The hydraulic efficiency of these grated inlets was analyzed according to the specific type and several geometric parameters of the location (longitudinal and transverse slopes, gutter section, width of the roadway, etc.). Finally, hydraulic efficiency of each grated inlet was compared to the performance of the Barcelona 1 inlet (the top right one in Figure 3) in order to obtain specific weighted efficiency coefficients. Hydraulic efficiency of each type of grate was estimated as follows:

\[ E_i = E_{Barcelona1} \cdot c_{wei} \]  

where, \( c_{wei} \) is the specific weighted efficiency coefficient for the type grate \( i \) (from 1 to 8); \( E_{Barcelona1} \) is the hydraulic efficiency of the grated inlet Barcelona 1 (where efficiency is defined as the ratio between the flow captured by the grated inlet and the flow circulating in the gutter); and \( E_i \) is the hydraulic efficiency of the grated inlet type \( i \).

Combining street geometric configurations and the types of grates \( c_{wei} \) range varies from 1 to 2.1.

Once the hydraulic performance of each inlet was estimated through empirical expressions, a further efficiency reduction was applied using a clogging factor of 50% that 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 et al. 2013).

Creation of the 1D/2D coupled model

Dual drainage modeling cannot be adequately represented without a careful consideration of hydraulic efficiency of
surface drainage structures (inlets, transversal grates, etc.) and an adequate representation of the urban topography (buildings, streets and sidewalks, curbs, etc.). Therefore, a powerful informatics tool is necessary to simulate all the hydrological and hydraulic phenomena involved during heavy storm events. As mentioned, a 2D simulation is better suited than a 1D simulation for modeling flows through complex geometries (such as urban streets and buildings, road intersections, and other transport infrastructure). The same happens in open ground, where either source or direction of flow is not predefined. In urban areas, the situation is exacerbated further by the presence of sewer networks, in which flows can both enter and exit the system during flood events. It is clear that modeling such complex systems requires coupled 1D and 2D engines to provide accurate results.

The software InfoWorks ICM by Innovyze (2012) (from here on ‘ICM’) was adopted to assess flood hazard in the Raval district during storm events. ICM solves the complete 2D Saint Venant equations in a finite volume semi-implicit scheme (Godunov 1959) with a Riemann solver (Alcrudo & Mulet-Martí 2005). ICM combines a number of distinctive features such as the analysis and prediction of potential flood extent, depth and velocity, and the modeling of the interaction of surface and underground systems in a fully integrated environment. Moreover, it allows the creation of multiple surface unstructured meshes that optimize modeling flexibility and accuracy.

To consider surface and sewer flows coming into the Raval district from upstream catchments, an extended area was considered in the study. Only main sewers were considered for these catchments, while main and secondary networks were taken into account for Raval district. The final model considered a total area of 44 km² with 3,874 nodes, 241 km of total pipe length, and six major storage facilities with a total capacity of 170,000 m³ (Figure 4).

A 2D mesh covered the whole analyzed domain with 403,822 triangles. The mesh was created using Shewchuk

Figure 4 | The final model of the Barcelona case study. The circle highlights the high density of pipes and nodes corresponding to the main and secondary networks of the Raval district.
The meshing algorithm (Shewchuk 1996). The algorithm enables creation of an irregular mesh based on the main parameters: average mesh size, the maximum cell size, and the minimum angle. In this case, these parameters were fixed to 25 m², 100 m², and 25°, respectively, even if for narrow streets and complex topographies (e.g., in the Raval), the cell size decreases significantly to adapt the mesh to the 2D domain. The ground level for a mesh element is calculated by sampling the ground model within the 2D triangles making up the element and then taking the average of the sample point levels.

The number of sample points for each triangle is determined by sub-dividing the triangle until the minimum element area or, when using a gridded ground model (a ground model made up of gridded data, such as LIDAR data), the ground model resolution is reached. The sample points are the centroids of the resulting triangles. So, for the proposed model, the terrain data were integrated into the model through the mesh cells, even if 48 break lines/walls were defined and introduced during the 2D meshing to reproduce urban elements as walls, banks, etc.

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 (Figure 5), while buildings (formed by roofs and courtyards) were represented as void areas (Schubert & Sanders 2012). Spatial rainfall distribution was applied to 2D domain and sub-catchments containing roofs and courtyards according to Thiessen polygons method (Thiessen 1911). For each 2D element and each sub-catchment, ICM checks in which rain gauge region (if any), the centroid of the element, is located and applies the rainfall profile accordingly. Runoff produced in the building areas was estimated considering an approximation of single non-linear reservoir (whose routing coefficient depends on surface roughness, surface area, ground slope, and catchment width) and directly conveyed into the sewer network. This follows in accordance with the local practice in Barcelona, where roofs, terraces, and courtyards (approximately corresponding to 50% of the whole analyzed domain) are directly connected to the underground sewers.

ICM allows the hydraulic characterization of inlets and the consequent possibility to carry out 1D/2D simulations according to the dual drainage concept previously explained. The inlet effect in the model is to limit the flow rate from the surface into the manhole, or vice versa. This can lead to the situation (as occurs in reality) where there is surface flooding while there is available capacity in the below-ground system.

Nodes are used in 2D simulations to model the exchange of flow between the sewer system and a 2D

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**Figure 5** | Flexible unstructured mesh with triangular cells representing the streets and pervious areas (shown with shadows) of the city. Building areas (with roofs and courtyards) are excluded by 2D domain. 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.
Gully 2D: exchange of water between the 2D manhole and the meshed area (Figure 5). Surcharging of a manhole results in an inflow to the 2D mesh element in which it resides. Calculation of flow exchange between the manhole and the mesh depends on which ‘flood type’ is chosen as follows.

- **2D**: exchange of water between the 2D manhole and the mesh is calculated using weir equations assuming a weir crest level at the node ground level and crest length equal to the node shaft circumference. A flooding discharge coefficient equivalent to the weir discharge coefficient is specified for the node. The weir equations used in the model assume rectangular full width weir with thin plate that extends the full width of the channel. For free discharge, ICM uses the governing model equation based on the Kindsvater and Carter equation as follows:

\[ Q = C_d \sqrt{gBD_u^{3/2}} \]  

(2)

where, \( Q \) is the discharge (m³/second); \( C_d \) is the discharge coefficient; \( g \) is the acceleration due to gravity (m/second²); \( B \) is the width of the weir (m); \( D_u \) is the upstream depth with respect to the crest (m).

For submerged flow, the equation is as follows:

\[ Q = C_d \sqrt{gBD_u(D_u - D_d)^{1/2}} \]  

(3)

where, \( D_d \) is the downstream depth with respect to the crest with \( D_d \) greater than zero (m).

For more information see BS3680 (Part 4A) (BS 1981).

- **Gully 2D**: exchange of water between the 2D manhole and the mesh is calculated using a specific ‘head/discharge relationship’.

In the proposed model, the manholes present either flood type 2D or ‘Gully 2D’. Specifically, the manholes outside of the Raval district were characterized as with a ‘2D’ flood type. In this area, only the main network was considered for the model, and consequently, inlet system capacity was neglected (flow interchanges occur through manholes regardless of inlet system capacity). In this case, a flooding discharge coefficient of 0.5 was adopted according to several papers that suggest this value to characterize the interaction between surface and sewer flows (Leandro et al. 2007, 2009; Djordjević et al. 2013). The hypothesis done may overestimate or underestimate the runoff entering the Raval district in the case of flows intercepted through 2D nodes using weir equations that are significantly different from the captured flows by the inlets. This can occur due to the difference in terms of discharge coefficients between a weir and an inlet and the limited number of 2D node (manholes) with respect to the real number of inlets placed upstream the Raval district.

The manholes inside the Raval district were characterized through a ‘Gully 2D’ flood type. In this case, several curves ‘head vs. discharge’ (Figure 6) were elaborated in order to take into account the hydraulics of the inlets located in the Raval district according to the cited methodology (Gómez & Russo 2011). These curves represent two possible situations: the first one considering flow exchange from 2D surface to 1D sewer due to a ‘positive’ head gradient (i.e., when water level on the surface is above the water level in the manhole (Figure 7, left)); and the other one representing flow exchange from 1D sewer to 2D surface due to a ‘negative’ head gradient (i.e., when piezometric head in the manhole is above the water level on the surface due to high pressure in the manhole (Figure 7, right)). In the first case, the experimentally derived expressions were used to estimate intercepted flow while, in the second case, a discharge coefficient of 0.5 was used according to the previous considerations. Specifically, according to Gully 2D node definition, circulating flow is determined through a 2D approach on the basis of flow depth and flow velocity.
calculated in the cell of the mesh, while captured flow is determined on the basis of specific head/captured discharge tables. These tables were elaborated off-line applying Gómez & Russo’s (2011) methodology that relates inlet hydraulic efficiency to flow depth upstream of the inlet and the approaching discharge.

As mentioned, flow interchanges were simulated through manholes (nodes) although they occur through the inlets too. ICM allows a manhole to be treated as a set of inlets defining the ‘number of equivalent inlets’ \( n_{eq} \) for each Gully 2D. \( n_{eq} \) is a scaling factor used to multiply the discharge values of the head/discharge tables that for this model were calculated using the following equation:

\[
n_{eq} = \sum_{i=1}^{8} C_{wei} \cdot n_i
\]

where, \( n_{eq} \) is the integer number of equivalent inlets associated with a Gully 2D node; \( n_i \) is the number of inlet with type \( i \) (\( i = 1, \ldots, 8 \)) associated with a Gully 2D node.

Head/discharge tables for the inlet Barcelona 1 were defined for several geometric conditions and were related to each Gully 2D node.

To determine the number of inlets associated with each Gully 2D node, the ‘micro-catchments’ were defined as the portion of the 2D surface (containing grated inlets) related to each Gully 2D node. As shown in Figure 8, micro-catchments covered the 2D domain formed by streets, squares, parks, and other green areas excluding buildings that were directly connected to sewer systems. These micro-catchments were defined generating overland flow paths through GIS tools according to the following steps:

- Generation of a Digital Surface Model considering the height of the building in order to achieve the effective flow paths.
• Definition of ‘potential micro-catchments’ using ArcGIS Spatial Analyst and Watershed Delineation (ArcGIS v.10).
• Definition of ‘final micro-catchments’ through a specific tool created by Aqualogy Urban Drainage Direction to associate each ‘micro-catchment’ with the Gully 2D node with the lowest level inside it. In case no Gully 2D node is found inside the micro-catchment, its area and limit are merged to the downstream micro-catchment.

The hypothesis is made that flow interchanges occur only through the cells where this element (Gully 2D) is placed, assuming for this point all the interception capacity due to the equivalent inlets of the micro-catchment discharging into the Gully 2D node. It is clear that the model will be more realistic when micro-catchment size is small.

2D domain of the Raval district was divided into 432 micro-catchments with approximately 3,000 equivalent inlets. It means that for each micro-catchment, an average of seven equivalent inlets were associated.

Calibration and validation processes

Calibration is the procedure for ensuring an acceptable level of confidence in a model’s ability to accurately represent the real system. It refers to the whole process of ensuring that a model behaves as similar to the real system as possible. The main undertaking in calibration process is the adjustment of model parameters in order to minimize the differences between simulated results and observed measurements.

For urban surface runoff models, it is recommended that at least three events are used (DHI 2002). The use of more events in the calibration would increase the overall reliability of the model. From the available data, some are used for parameter estimation (calibration) while others must be kept for model validation.

The comparison of simulations against observations may be done in many ways and on different aspects, i.e., focusing on different qualities of the data in the comparison. Having different measures of comparison helps constrain and improve the parameter adjustment. In hydrological modeling, calibration is generally performed using continuous flow records. For flood models, important criteria are peak flows and depth levels, timing of peaks, and also total volumes when the model is also used for the development of flood storage structures and general water management.

The central step in the calibration process is the iterative adjustment of model parameters in order to match model results with observations. The complexity of the process depends on the number of calibration parameters being adjusted, and its transparency is determined by the character of the calibration parameters and the modeling concepts being applied. The parameters that are adjusted in calibration are generally the ones that cannot be directly assessed from field data. Calibration may be understood as an optimization process involving one or several simultaneous objective functions. These objective functions represent in one form or another formalized measures of deviation between measurements and simulations. In manual calibration, these measures are used with visual observations in the evaluation of the goodness-of-fit simulations to observations. Common numerical performance measures were used in the calibration and validation of the 1D/2D Raval model (Madsen et al. 2010).

Calibration with statistical analysis generally calculates root mean squared error as a statistical measure of deviation between measured and simulated time series.

\[
\text{RMSE} = \sqrt{\frac{\sum_{j=1}^{n} (\text{Meas}_j - \text{Sim}_j)^2}{n}}
\]  

(5)

where, RMSE is the root mean squared error; Meas\(j\) is the measured (observed) flow depth at time \(j\); Sim\(j\) is the simulated flow depth at time \(j\); \(n\) is the number of time steps in the calibration/validation period.

Another statistical measure of deviation used in the statistical analysis was the coefficient of determination as follows:

\[
R^2 = \frac{\left(\sum_{j=1}^{n} (\text{Meas}_j - \overline{\text{Meas}}) \cdot (\text{Sim}_j - \overline{\text{Sim}})^2\right)^2}{\left(\sum_{j=1}^{n} (\text{Meas}_j - \overline{\text{Meas}})^2 \cdot \sum_{j=1}^{n} (\text{Sim}_j - \overline{\text{Sim}})^2\right)}
\]

(6)

where, \(R^2\) is the coefficient of determination; \(\overline{\text{Meas}}\) is the mean value of the measured (observed) flow depths during the calibration/validation period; \(\overline{\text{Sim}}\) is the mean value of the simulated flow depths during the calibration/validation period.
of the simulated flow depths during the calibration/validation period.

Finally, peak error (PE) and time to peak error (TPE) are expressed as follows:

\[
PE = |\max (\text{Meas}_j) - \max (\text{Sim}_j)|
\]

\[
TPE = t\{\max (\text{Meas}_j)\} - t\{\max (\text{Sim}_j)\}
\]

RESULTS AND DISCUSSION

Sensitivity analysis

1D/2D coupled models in urban areas represent an innovative technique to analyze the hydraulic behavior of critical streets during heavy storm events. The available literature does not yet provide extensive reference on the importance and influence of all parameters involved in hydrological and hydraulic processes.

According to the results of a study developed by Sheffield University (Shepherd et al. 2011) concerning the routing parameters in a 2D domain using InfoWorks CS, the extent of the flooded area is relatively insensitive to mesh density and surface roughness, while the modeling of buildings has however been shown to have a significant effect on flood depths.

For the Barcelona coupled model, sensitivity analysis was carried out in order to study the influence of Manning roughness (range from 0.013 to 0.020 second/m\(^{1/3}\)) on the surface flow. Results do not show strong dependency of the surface flood extension to this parameter, although seem to influence the sewer hydrographs strongly (this parameter plays an important role in the flow velocity of the surface runoff, and its adjustment allows to reduce peak time error).

The sensitivity of the model toward discharge coefficient was also analyzed. Literature on this parameter suggests using values ranging from 0.5 to 0.7 (Leandro et al. 2007, 2009; Djordjević et al. 2013). Two different simulations with these extreme discharge coefficients showed that at global scale, no change is detected for perimeters of the flooded areas, while at micro-scale (considering cells where flow interchanges occur) maximum differences in terms of flow depth ranged from 4 to 9%. It is useful to remark that discharge coefficients variation only affects flow interchange through the surcharged 2D nodes located outside the Raval district. As previously explained, for the nodes located in the Raval, Gully 2D node type was selected, and their hydraulic performance was estimated through checked experimental expressions (Gómez & Russo 2009; Russo et al. 2015).

Calibration of the model

Once sensitivity analysis was terminated, calibration and validation processes were carried out. CLABSA Exploitation and Maintenance Department provided rainfall data for the calibration of the 1D/2D Raval model. Spatial rainfall distribution was applied considering rainfall data coming from 11 rain gauges of CLABSA network (Figure 4). Owing to the recent significant changes of the Barcelona sewer system (new infrastructure such as pipes and tanks were built in the period 2008–2010), only rainfall events in the year 2011 were selected. According to the literature, three storm events were selected for the calibration process, while another one was selected for validation. The main characteristics of these events are shown in Table 1.

<table>
<thead>
<tr>
<th>Date event</th>
<th>Cumulative rainfall (mm)</th>
<th>Maximum rainfall intensity in 20 minutes (mm/hour)</th>
<th>Maximum rainfall intensity in 5 minutes (mm/hour)</th>
<th>Event used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 March 2011</td>
<td>54.1</td>
<td>69.6 ((T = 1))</td>
<td>98.4 ((T = 0.5))</td>
<td>Calibration</td>
</tr>
<tr>
<td>07 June 2011</td>
<td>26.8</td>
<td>24.3 ((T = 0.2))</td>
<td>49.2 ((T = 0.2))</td>
<td>Calibration</td>
</tr>
<tr>
<td>19 July 2011</td>
<td>45.9</td>
<td>95.1 ((T = 5))</td>
<td>135.6 ((T = 2))</td>
<td>Calibration</td>
</tr>
<tr>
<td>30 July 2011</td>
<td>30.4</td>
<td>105.9 ((T = 8))</td>
<td>140.4 ((T = 2))</td>
<td>Validation</td>
</tr>
</tbody>
</table>

The maximum values and the return periods \(T\) in parentheses refer to one of the 11 rain gauges of CLABSA network.
Flooding reports and 29 water level gauges located in manholes and conduits of the analyzed domain were used for the calibration/validation processes (Figure 1). Specifically, flow-depth series calculated by the model were compared to flow-depth series recorded by the water level gauges.

Several ultrasonic flow meter gauges were installed in the Barcelona sewer network during the last years. Specifically, one of these flow meters is located inside the domain of analysis of the 1D/2D Raval model, but it has been operating since November 2011, so its data were not used for the calibration/validation processes.

The 1D/2D coupled model was calibrated mainly on the processes related to urban surface runoff and flow propagation. Regarding the areas directly connected to underground sewers, the following standard parameters in rainfall–runoff models were adjusted in the calibration:

- **Hydrological losses.** Specifically, wetting and storage losses were considered for impervious areas, while for pervious areas infiltration losses were taken into account using Horton’s equation (Horton 1933).

- **Surface roughness coefficients.**

- **In the sewers, the continuous friction loss and the head losses due to turbulence at singularities of the network (entrances of storage tanks, jumps, etc.).**

For the 2D overland flow, the adjusted calibration parameters were as follows:

- **Hydrological losses.**

- **Routing parameters (cells size, cells roughness coefficients, and representation of the area excluded by 2D domain).**

The parameters related to 2D overland flow play an important role in the calibration process, and they were selected through a sensitivity analysis presented in the previous section.

Some of the results concerning several sensors located in the Raval district (P-AV65 and BR-CL205) and upstream from it (P-FW147, P-DS44, P-YD, and P-IV35.1) (Figure 9) are shown in Figures 10–16 and summarized in Table 2.

Specifically in Figures 10–13, calibration results concerning four monitored manholes in Parallel Avenue of the Raval district (P-AV65 and BR-CL205) and Diagonal

Figure 9 | Locations of the sewer facilities and surface points used for the calibration and the validation of the model.
Avenue upstream from the Raval district (P-FW147 and PDS44) are shown. In Figures 14 and 15, calibration results for the monitored Urgell storage tank (P-YD) and Diagonal pipe (P-1V35.1) both located upstream Raval district are shown.

Validation data of all these sewer facilities are shown in Figure 16.

Statistical analysis according to a previous section was carried out by calculating all the parameters previously described. A summary of this analysis is shown in Table 2.

In general, results show a good agreement between measured (observed) and simulated values. For less extreme events differences seem to increase. For the sewer features located in the Raval district, this behavior
could be explained considering the clogging coefficient used to limit the flow intercepted by the inlet. As said, a uniform coefficient equal to 0.5 was applied to all the inlets irrespective of the rain event. During extreme events, inlet blockage phenomenon is more frequent with respect to rainfall with minor intensity. Nevertheless, in all cases, the temporal evolution is very similar in the measured and simulated series and allows adequate matching of intermediate peaks.

Surface flow gauges are not common in urban drainage complicating calibration and validation processes regarding overland flow. In this case, flooding parameters provided by the model (perimeter of flooded areas, flow depths of the overland flow, etc.) were compared to observed data.
Table 2 | Statistical parameters related to calibration and validation processes for all the sewer facilities used in this study

<table>
<thead>
<tr>
<th>Code</th>
<th>Type of sewer facility</th>
<th>Location</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>Measured peak level (m)</th>
<th>Simulated peak level (m)</th>
<th>PE (m)</th>
<th>TPE (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 March 2011</td>
<td>P-AV65</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.86</td>
<td>0.185</td>
<td>2.500</td>
<td>1.081</td>
<td>1.419</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>BR-CL205</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.93</td>
<td>0.353</td>
<td>2.710</td>
<td>1.133</td>
<td>1.597</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-FW147</td>
<td>Manhole Francesc Macià Square (upstream from Raval)</td>
<td>0.87</td>
<td>0.179</td>
<td>1.130</td>
<td>1.018</td>
<td>0.112</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-DS44</td>
<td>Manhole Diagonal Avenue (upstream from Raval)</td>
<td>0.62</td>
<td>0.232</td>
<td>1.050</td>
<td>1.708</td>
<td>-0.658</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-YD</td>
<td>Storage tank Urgell Street (upstream from Raval)</td>
<td>0.95</td>
<td>0.336</td>
<td>8.589</td>
<td>8.560</td>
<td>0.029</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-IV35.1</td>
<td>Pipe Diagonal Avenue (upstream from Raval)</td>
<td>0.92</td>
<td>0.785</td>
<td>3.770</td>
<td>2.094</td>
<td>1.676</td>
<td>0</td>
</tr>
<tr>
<td>07 June 2011</td>
<td>P-AV65</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.84</td>
<td>0.100</td>
<td>1.290</td>
<td>0.747</td>
<td>0.543</td>
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<tr>
<td></td>
<td>BR-CL205</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.90</td>
<td>0.232</td>
<td>1.630</td>
<td>0.624</td>
<td>1.006</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-FW147</td>
<td>Manhole Francesc Macià Square (upstream from Raval)</td>
<td>0.86</td>
<td>0.219</td>
<td>0.660</td>
<td>1.314</td>
<td>-0.654</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-DS44</td>
<td>Manhole Diagonal Avenue (upstream from Raval)</td>
<td>0.96</td>
<td>0.085</td>
<td>0.650</td>
<td>0.829</td>
<td>-0.179</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-YD</td>
<td>Storage tank Urgell Street (upstream from Raval)</td>
<td>0.48</td>
<td>0.171</td>
<td>1.579</td>
<td>1.143</td>
<td>0.436</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>P-IV35.1</td>
<td>Pipe Diagonal Avenue (upstream from Raval)</td>
<td>0.93</td>
<td>0.614</td>
<td>1.380</td>
<td>1.476</td>
<td>-0.096</td>
<td>20</td>
</tr>
<tr>
<td>19 July 2011</td>
<td>P-AV65</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.93</td>
<td>0.108</td>
<td>2.070</td>
<td>2.117</td>
<td>-0.047</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>BR-CL205</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.96</td>
<td>0.382</td>
<td>3.490</td>
<td>1.488</td>
<td>2.002</td>
<td>0</td>
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<tr>
<td></td>
<td>P-FW147</td>
<td>Manhole Francesc Macià Square (upstream from Raval)</td>
<td>0.86</td>
<td>0.222</td>
<td>3.380</td>
<td>2.321</td>
<td>1.059</td>
<td>0</td>
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<tr>
<td></td>
<td>P-DS44</td>
<td>Manhole Diagonal Avenue (upstream from Raval)</td>
<td>0.95</td>
<td>0.125</td>
<td>3.160</td>
<td>2.606</td>
<td>0.554</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-YD</td>
<td>Storage tank Urgell Street (upstream from Raval)</td>
<td>0.96</td>
<td>1.417</td>
<td>12.229</td>
<td>14.237</td>
<td>-2.008</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P-IV35.1</td>
<td>Pipe Diagonal Avenue (upstream from Raval)</td>
<td>0.94</td>
<td>0.683</td>
<td>4.850</td>
<td>3.325</td>
<td>1.525</td>
<td>5</td>
</tr>
<tr>
<td>Validation event</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 July 2011</td>
<td>P-AV65</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.96</td>
<td>0.156</td>
<td>3.950</td>
<td>4.114</td>
<td>-0.164</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>BR-CL205</td>
<td>Manhole Parallel Avenue (Raval)</td>
<td>0.93</td>
<td>0.307</td>
<td>4.420</td>
<td>4.108</td>
<td>0.312</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-FW147</td>
<td>Manhole Francesc Macià Square (upstream from Raval)</td>
<td>0.89</td>
<td>0.259</td>
<td>3.210</td>
<td>3.141</td>
<td>0.069</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-DS44</td>
<td>Manhole Diagonal Avenue (upstream from Raval)</td>
<td>0.94</td>
<td>0.166</td>
<td>3.160</td>
<td>2.606</td>
<td>0.554</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P-YD</td>
<td>Storage tank Urgell Street (upstream from Raval)</td>
<td>0.98</td>
<td>0.976</td>
<td>11.770</td>
<td>12.138</td>
<td>-0.368</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>P-IV35.1</td>
<td>Pipe Diagonal Avenue (upstream from Raval)</td>
<td>0.92</td>
<td>0.306</td>
<td>4.940</td>
<td>3.585</td>
<td>1.355</td>
<td>10</td>
</tr>
</tbody>
</table>
collected in the post-events emergency reports of policemen and firemen, amateur videos, and photos recorded during the selected storm events (Figures 17 and 18). In this way, it is possible to compare overland flow depth to reference elevation of objects located on the surface (walls, cars, urban furniture, etc.). The locations of sewers and surface points used for calibration and validation of the model are shown in Figure 13. Moreover, it is possible to observe the good agreement between the historically flooded areas of the Raval and the results, in terms of flow-depths map, of the model for a synthetic design storm with a return period of 10 years and duration of 1 hour (Figure 19).

**COMPUTATIONAL SETTING**

Historically, 1D/2D coupled models were considered too computationally demanding, so their use was restricted to those parts of the catchment where overland flow pathways could be multi-directional or could not be easily defined.
Figure 18 | Validation results for the crossroad between Diagonal Avenue and Casanova Street: comparison between the profile representing surcharged pipes provided by ICM software and a photo taken during the event of 30 July 2011. Specifically, the maximum piezometric level corresponding to the photographed surcharged manhole was 46.6 cm.

Figure 19 | On the left, the Barcelona drainage master plan remarking the historical flooded areas inside the analyzed domain is shown. On the right, a hazard map in terms of maximum flow depths (represented through shadowed areas progressively more intense) achieved through the 1D/2D coupled model for a storm with a return period of 10 years and historical flooded areas are shown.
Conversely, the required high-resolution topographic data for detailed simulations in urban areas are increasingly available from airborne altimetric LIDAR. Their wider application in large areas is limited by computational power and the performance of hydraulic modeling software. Recent research has focused on the following different techniques to reduce computation time of software models: dynamically adaptive grids, spatially varying timesteps, and simplified approximations for the physic phenomena considering kinematic and diffusive wave approximations (Liang et al. 2008; Sanders 2008). The first options showed a relative computational time saving but introduced new criticisms and challenges. The latter, even if they may allow faster computations, neglect significant aspects of flow.

In the past decade, modeling speeding-up strategies have focused on parallel processing and hardware advances (Pau & Sanders 2006; Sanders et al. 2010). More recently, specific codes based on fast graphic processing units (GPUs) usually dedicated to games and advanced computer graphics have been developed and used in fluid mechanics (Lamb et al. 2011; Henonin et al. 2013). Combining these features, it is possible to create hydrodynamic models capable of fully exploiting GPUs and CPUs with very promising performance in terms of computational time (Kalyanapu et al. 2011; Brodtkorb et al. 2012; Satra & Brodtkorb 2012).

All these new advances were used in the Barcelona coupled model and a computational analysis was carried out considering the following hardware configurations for a specific simulation of 3 hours, with storm duration of 1 hour:

1. Workstation with 64-bit operating system (Windows 7) and 2 Gb of RAM memory.
2. Virtual server in a blade system with 64-bit operating system (Windows 7), 2 Gb of RAM memory, and 4 CPU Intelxeon in order to exploit the software capacity to support full multi-core processing.
3. Workstation with 64-bit operating system (Windows 7), 2 Gb of RAM memory, 4 CPU Intelxeon for multi-core processing, and a specific GPU card that plays an important role during the treatment of the 2D calculations.

The results of this analysis showed that run time varies from several days (6–7 days) for Configuration 1, to several hours (5–6 hours) for Configuration 2 and a few minutes (3–4 minutes) for Configuration 3.

It is clear that, since simulations can be carried out in few minutes, real-time strategies and early warning systems could be activated on the basis of the results of this coupled model continuously running.

CONCLUSIONS

A detailed 1D/2D coupled model was developed to study the hydraulic behavior of 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 km² of the city area involving 241 km of sewers, while 2D mesh counts more than 400,000 triangular cells.

Calibration and validation of the model were based on a wide range of field data (rainfall and flow-depth time series, amateur videos and photos, and post-event reports provided by firemen and police) related to four heavy storm events that occurred in 2011. The results obtained show that it is possible to reproduce the effects of urban floods in the Raval district with a high level of detail.

The calibrated model can be used to assess flood hazard and risk and to estimate the economic losses produced during storm events. In this way, this could be a useful tool to design new infrastructures with clear objectives in terms of flood risk and economic loss reduction.

Moreover, speeding-up strategies focused on parallel processing and hardware advances allowed very high computational performance. Specifically, the coupled model is capable of fully exploiting GPUs and CPUs with very promising performance in terms of computational time saving with a run time of 3–4 minutes for complete simulations.

The results obtained demonstrate that it is possible to develop and calibrate 1D/2D detailed and realistic models on the basis of collected sensors and field data and use them for real-time strategies and early warning systems in complex and vulnerable urban areas like Barcelona.

ACKNOWLEDGEMENTS

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