1D/2D stormwater modelling to support urban flood risk management in estuarine areas: Hazard assessment in the Dafundo case study

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Abstract
Flood risk management in urban areas adjacent to the coast is essential to increase their resilience. This study aims at improving scientific knowledge of flood risk alongside estuaries, considering different hazards and integrating estuarine and urban drainage modelling. Mathematical modelling of stormwater systems is a useful tool to evaluate the susceptibility to flooding and identify potential measures to reduce flood risk. The assessment of urban drainage flooding uses a coupled 1D/2D model, applying 1D model to the underground system and 2D model for the surface component. Assessment scenarios were based on variables rainfall, estuarine water level, and degree of obstruction in sewers and at system outfalls. Estuarine hydrodynamics were simulated using the SCHISM-WWM model. A web GIS platform was developed to support urban flood risk forecast and management providing urban analysis visualisation. The main objective is to forecast flooding in the Dafundo catchment supporting definition of population warnings. This paper proposes a flood risk assessment approach, using 1D/2D coupled modelling, estuarine hydrodynamics, integrating the assessment in a forecast web platform. The novelty is supporting an integrated flood risk management in stormwater systems, particularly in estuarine areas, providing an important improvement to assess flooding occurrence, regarding flood depth, area and duration.

KEYWORDS
estuary, flood modelling, flood risk assessment, integrated platform, urban drainage

1 | INTRODUCTION

Urban areas adjacent to estuaries are particularly exposed to flood risks. Estuarine water levels often restrict the flow capacity of the urban drainage systems, a situation that can be significantly aggravated if occurrence of intense rainfall and high water levels in the estuary coincide. Severe conjoint conditions include high tidal levels together with storm surge episodes or with large freshwater discharges (Townend & Pethick, 2002). Rise in mean sea level as well as increasing frequency of extreme meteorological conditions (IPCC, 2013) are factors that...
increase the flood risk in estuarine and adjacent areas (Freire et al., 2014).

The advances in computer technology have facilitated the use of mathematical modelling to assess the complex interaction between the rainfall events and flood occurrence, assessing the potential effects of flooding (Pina et al., 2016). The coupled model between 1D network model and 2D surface runoff modelling represents a significant improvement in the overload flow modelling due to the incorporation a detailed representation of the terrain and the urban features (e.g., buildings, walls) that control flood movement through urban environments (Chang, Wang, & Chen, 2015). Modelling rainfall–runoff in urbanised areas requires consideration of the complex interaction between the sewer system and the overland surface, and the spatial heterogeneity of the urban key features (Leandro, Schumann, & Pfister, 2016). Several studies focused on the overland flow path delineation have been developed to date (Djordjević, Prodanović, Maksimović, Ivetić, & Savić, 2005; Leandro et al., 2016; Leitao, 2009). The latter authors considered the variability of building types and the spatial heterogeneity of different land surfaces in urban flood models at city scale.

The simulation process in the case of coupled 1D/2D modelling is slightly complex and computationally very demanding. The main factor that provided the improvement of the application of the dual-drainage concept, 1D/1D or 1D/2D models, has been the detailed development of Geographic Information Systems. With focus on urban flooding, the use of 1D/1D and 1D/2D coupled models has been widely investigated and implemented (Leandro, Chen, Djordjević, & Savić, 2009; Seyoum, Vojinovic, Price, & Weesakul, 2012).

In the coupled 1D/2D models, the flow in the pipe network is modelled using the 1D Saint Venant equations and appropriate approximations (kinematic wave, diffusive and dynamic wave) and the surface runoff is modelled applying the 2D Saint Venant equations (Hénonin et al., 2010). The 1D network and 2D surface runoff models are coupled through the inlets of the sewer system (manholes or surface water inlets) and the 2D surface elements. The coupling of the shallow water equation model of the surface flow with the dynamic pipe network flow model is a crucial step in from a mathematical point of view (Schmitt, Thomas, & Ettrich, 2004).

In recent years, flood risk management has been improved through information technology tools, such as real-time monitoring networks, GIS (geographical information system) and decision support systems. With regards to the urban management, the development of tools focused on the real flood simulation and flooding forecast represent an important subject under development (Bhola, Leandro, & Disse, 2018; Falconer et al., 2009; Ghanarpour, Salimi, & Hipel, 2013; Liu, Qin, Zhang, & Li, 2015). As part of this effort, the use of more accurate numerical models have contributed to the availability and improved forecasting of relevant events (Blanc et al., 2012; Rodrigues et al., 2013). The integration of these forecast systems into computational GIS-based platforms contributes to enhance emergency and routine management of areas adjacent to water bodies, in particular coastal regions (Deng, Namwamba, & Zhang, 2014; Oliveira et al., 2014). These platforms take advantage of novel technologies to provide on-line, intuitive and geographically referenced access to real-time data and model predictions to produce on-demand services (Gomes, Jesus, Rogeiro, Oliveira, & Fortunato, 2015).

The present paper aims at improving the scientific knowledge of flood risk alongside estuaries, considering the different hazards, arising from the interaction between tides, storm surges and flows in urban drainage networks, for different climate scenarios.

The Tagus estuary and its margins were selected as a study site. This article describes the evaluation of exposure to flooding in the adjacent urban area of Dafundo, the identification of potential measures to reduce risk in this area and an overview of the web-GIS platform.

2 | MODELling Urban Drainage Flooding of a study Site

The study site is located in the adjacent area of the Tagus estuary, in the Junça river catchment, at Dafundo, part of the Lisbon district, in Portugal (Figure 1). Figure 1 presents the geographical location of the Dafundo area in Portugal (a); the delimitation of the study site (b); the Dafundo upstream and downstream catchments (c).

Dafundo catchment is characterised by a significant extension (89.9 ha) and a high density population, which represents a common situation in urban areas located on estuaries. The urban drainage network is prone to flooding and undue inflows from the wastewater to the stormwater drainage system; the flows discharges into the Tagus estuary through two main parallel sewers. One of the sewers is the canalised Junça River.

The main stormwater sewer follows the Junça river, which was canalised decades ago. In the lower area of the catchment, down-town of Dafundo, a relief sewer for the canalised Junça river was constructed to limit flooding problems. By then, flooding in the estuarine bordering area was significantly reduced in terms of frequency, severity and flooded area. However, flooding still occurs and further measures are required.

To study the urban flooding under the present conditions as well as for a set of scenarios, a 1D/2D coupled
model was developed. The canalised Junça River and the relief sewer were modelled in the 1D/2D coupled model to consider the current stormwater network in Dafundo downtown (Figure 2). Characterisation of the Dafundo catchment and the urban drainage system was carried out using the data from the managing utility and historical information provided by the Municipal Civil Protection and Firefighting Services. Additionally, extensive field work was carried out to verify mapping and inventory data and to select the locations for flow and rain gauging, essential for the construction and parameterization of the 1D/2D coupled model. One tipping-bucket rain gauge and six flow meters were installed in the stormwater system, at the most relevant sewers discharging into the Tagus estuary at the Dafundo beach, to obtain flow from water depth and velocity measurements (Figure 2). The time resolution adopted for the flow meters was 5 min. For the rain gauge, the time of tipping, when the bucket emptied, was registered, to reduce the sampling errors in the tipping-bucket rain gauging measurements. The monitoring period was from September 2014 to March 2015, which allowed evaluation of the influence of an equinoctial tide, of rain events with different characteristics, and, the hydraulic analysis of upstream and downstream areas.

Boundary conditions at sewers outfalls to Tagus estuary were found to be severely changed due to sediment transport in the estuary, with significant sand accumulation at the outfalls (Figure 3). The natural tidal dynamics at the Dafundo coastline promotes frequent accumulation of sediment at the outfalls. Even with frequent sand removal operations, sediment deposits are naturally re-established in two to 3 weeks.

During in situ inspections, a significant vertical drop was detected in the stormwater system. This condition limits the influence of estuarine waters in the upstream catchment, allowing segmentation of the Dafundo catchment into upper and lower areas in terms of their hydraulic behaviour. Additionally, due to the drop pipe diameter, the flow from the upstream catchment area is constricted, acting as a passive flow control to the downstream area, a factor reducing the likelihood of sewer surcharge in the lower area, which was of particular interest due to the recurrent flooding occurrence as was referred by the Firefighting Services. In terms of the urban drainage

![Geographical location of the study area](image1)

![Delimitation of the Dafundo area](image2)

![Dafundo catchment](image3)

**FIGURE 1** Location of the study site and Dafundo catchment. (a) Geographical location of the study area (CAOP 2013). (b) Delimitation of the Dafundo area (Google Maps). (c) Dafundo catchment
modelling, presence of the vertical drop allowed using a simplified model for the upper area, whereas the lower area was modelled using the 1D/2D coupled model.

3 | 1D/2D COUPLED MODEL

3.1 | Surface runoff and stormwater drainage network

The hydraulic analysis of the Dafundo upper area was carried out using a simplified, conceptual and lumped model (David & Matos, 2005; David, 2006) that represents the urban catchment as a sequence of catchments arranged in series or in parallel. This model replicates the lumped catchment response to rainfall, considering initial hydrologic losses, continuous losses through a runoff coefficient and flow propagation using a linear reservoir to generate the hydrographs at the downstream section. The setup of the conceptual model was carried out comparing the monitored and simulated water depths for the rainfall events obtained in the monitoring. Good model fit to measured data was obtained as well as an estimate of the concentration time ($t_c$), a lumped runoff coefficient ($C$) of this upper catchment and a constant dry weather base flow. Further adjustment of model parameters was carried out at the

FIGURE 2 Dafundo catchment: (1) upper area, (2) rain gauging location, (3) downtown area, and (4) flow meters location

FIGURE 3 Sand accumulation at the sewer outfalls to the Tagus estuary. (a) Junça river (left) and parallel sewer (right) September 4, 2014. (b) Junça river totally obstructed October 21, 2014
following step, the calibration of the global Dafundo model. Figure 4 presents the comparison between recorded and estimated flow discharge, based on the simplified model, for one recorded rainfall event.

The conceptual model includes regulation of the flow into the downstream catchment by a rectangular weir, thus enabling adequate simulation of catchment behaviour for high rainfall depths. The crest height of the weir is one of the model parameters adjusted during the model set-up. The resulting characteristics of the upper catchment together with their physical characteristics (total area of 87.2 ha and 78.2% of impervious area) are then used in the 1D/2D coupled model of the lower area, to generate the upstream boundary conditions as a function of rainfall.

The occurrence of storm sewer flooding at Dafundo downstream area was assessed using a coupled 1D/2D Mike Flood model. The 1D mathematical model was applied to the stormwater network using Mike Urban (DHI, 2014). The 2D overland flow model was applied to the surface runoff modelling using Mike Flood (DHI, 2014). For the latter, the computational mesh adopted was a square uniform cell sized of 1.0 m, as a compromise between the required accuracy and the simulation time step. This model calculates and represents flooding areas and water depths in the surface, relying on a Digital Elevation Model (DEM) of the study area. The DEM was developed to represent the terrain surface, based on elevation points for the whole catchment (provided by SIMAS OA, the local water utility). Higher resolution data for ground elevation around the estuary margins, were obtained from LIDAR survey (Paula, Simões, Marques, & Machado, 2014). This information produced a DEM with sufficient accuracy to represent local roads, streets and the existing singularities in the urban surface.

Dafundo downtown has a total area 2.7 ha and 84.3% of impervious area (Figure 5). For the downstream area

**FIGURE 4** Comparison between recorded and estimated flow discharge, based on the simplified model, for one recorded rainfall event

**FIGURE 5** Delimitation of the sub-catchments in the Dafundo downtown area
runoff model, delimitation and characterisation (length, total pervious and impervious areas) of the sub-catchments was carried out. Three categories were adopted for these areas: roads, buildings and green areas. The downstream area was divided in 68 sub-catchments, consisting of 47 roads, 15 building, and 6 green area sub-catchments, with areas ranging between 0.004 and 0.432 ha and impervious percentages between 17.5 and 100.0%. The method selected for runoff modelling was a time-area approach taking into account the catchments’ shape. By default, the shape is rectangular, with assessment in model the calibration phase. The choice of the time-area approach was motivated by its good performance, according to the monitoring measurements, and the lack of more detailed information that would be necessary to calibrate alternative hydrological approaches with a high number of specific parameters. Despite the physical basis of many models, their parameters often cannot be reliably estimated and require calibration to fit observed data (Kavetski, Kuczera, & Franks, 2006).

The stormwater system model was developed using available mapping and inventory data. The elements represented in the model were manholes, pipes and stormwater inlets. The incorporation of auxiliary elements was required. Two weirs were included to model existing blockages at the outfalls, one at the Junça river and other in the parallel sewer. The modelled network was composed by 56 manholes, 28 stormwater inlets, 3 outfalls and 87 pipes with and pipe length between 0.6 and 133.4 m and a height between 0.1 m and 1.4 m. The canalised Junça River and the parallel relief channel have maximum cross sections of 1.50 × 2.50 m and 1.20 × 1.00 m, (height × width), respectively.

The maximum sediment depth allowed by MIKE URBAN (half cross section) was also imposed in the section located immediately upstream the weir. In order to model the sediment deposition in the drainage system, a sediment depth value was considered for those pipes where data was available or collected in the field work. Both normal and sealed manholes types were included. Normal manholes allow flow entry and exit by the manhole cover; for sealed manholes, flow through the cover is not possible. Pre-defined curves were used to incorporate the geometric characteristics of the stormwater inlets (gutters or flat drains). Each curve defines the relation between the superficial and transversal area, for each component.

As indicated in the MIKE URBAN software, the runoff model (2D) and the stormwater network model (1D) were coupled together by links (stormwater inlets and normal manholes), which are the elements responsible for flow exchanges between the DEM and the stormwater network, whenever a manhole is flooding or when surface runoff enters the network. In the 1D/2D model, a square and uniform mesh with a cell size of 1.0 m was adopted. The resolution of the mesh was established as a compromise between accuracy and computational effort, taking into consideration the large number of simulation scenarios established. In a reduced number of scenarios, corresponding to those with obstruction and higher tide levels, it was required to reduce the grid size to 0.05 m to achieve convergence. The computational time for the simulations varied from 2 to 120 hr. The total number of cells in the mesh was approximately 185,000 for a grid size of 1.0 m and 75,000,000 for a grid size of 0.05 m. Despite the high number of cells, most of them are not effectively considered in the computations since they are filled by existing buildings.

The standard computational time step adopted in the 1D/2D model corresponds to 1 s. In a reduced number of scenarios, as above referred, corresponding to scenarios with obstruction and higher tide levels, a reduction of the time step to 0.1 s was required to avoid problems with convergence. It is noticed that, for the scenarios with obstruction, the sediment deposition reduces drastically the effective cross-sections in the Junça River and the relief sewer, producing high flood levels, significant flood duration and rapid wave propagation from downstream to upstream.

Inputs to the 1D/2D coupled model include tide and rainfall time series. The tidal water level was set as a downstream boundary condition to the sewer network outfalls and calculated using the coupled waves-currents hydrodynamic modelling of the Tagus estuary (Fortunato et al., 2015). The estuary water level series, used as boundary condition, were obtained through an application of the SCHISM-WWMII model (Zhang, Ye, Stanev, & Grashorn, 2016). This model was utilised to provide boundary conditions for the urban flood model and to predict the estuarine levels for different climate scenarios and return periods, at a local scale of Tagus estuary. This 2D hydrodynamic model was developed and validated for the Tagus estuary, including flood-prone areas in the southern margin of the estuary. The model was forced only by tides, storm surges and river flows (Freire, Fortunato, et al., 2016).

### 3.2 Model calibration

In the model calibration, selected model parameters were adjusted to achieve reproduction of the real system hydraulic behaviour for both upstream and downstream Dafundo catchments. The calibration was based on the hydrograph provided by the simplified model of the upper catchments and the water depths obtained in the
monitoring sites. Parameter values determined in the calibration phase are: (i) parameters of the conceptual model of the upstream Dafundo catchment (runoff coefficient, \( C \); concentration time \( t_c \); weir crest level; constant dry weather base flow); (ii) shape and concentration time for the downstream sub-catchments model; (iii) level of obstruction in the sewers.

Identification of values for model parameters resulted from comparing model results with monitoring data and historical flooding data provided by the responsible authorities.

The hydraulic and hydrological modules of the 1D/2D drainage system model parameters values were obtained considering selected rainfall events, with different rainfall intensities, and the corresponding water level monitored in several sections.

Parameter values obtained for the upstream catchment established are \( C = 0.23 \), \( t_c = 10 \text{ min} \) and a dry weather base flow of 20 L/s. The weir height value is 0.15 m.

Several levels of sediment in pipes were tested for scenarios of obstruction. Values of sediment deposition height are 0.20 m in sewers, around 25–30% of pipe diameter, and of 90% obstruction at the outfalls. This last model simulate the outfalls obstruction produced by the sediment deposition along the canalised Junça River and the parallel sewer.

Results show an adequate adjustment between the results of the 1D/2D model and the available field data (water depth and flow discharge). However, for events with higher rainfall intensities larger deviations were obtained, with underestimation of discharge peak flow or water depths. The error in volume varies between \(-24.5\) and \(5.5\)% while the error in peak flow discharge ranges from \(-40.6\) to \(-10.4\)%.

As already mentioned, the largest deviations were obtained for the event with higher rainfall intensities. The regulation of the upstream catchment flow by a rectangular weir was incorporated in the 1D/2D model to improve the reproduction of the hydrological behaviour for the rainfall events with higher intensities. This improved the model’s response, even though in some intense events an underestimation of volume and flow peaks was still observed.

For instance, Figure 6a,b present the comparison between the 1D/2D modelled and estimated flow discharge, based on the simplified model, for two recorded rainfall event. A significant agreement between the flow discharge modelled by 1D/2D and the estimated provided by the simplified model was achieved, either for reduced or for higher intensity rainfall events. However, the flow peaks are under calculated by the 1D/2D model regarding the estimated value.

Modelling results were validated through the historical information regarding flood occurrences reported, provided by local authorities (Figure 11b,c).

### 3.3 Assessment scenarios

The main objective of this model is to forecast flooding in the Dafundo catchment, in order to support population warnings, for a forecast horizon of 2 days. The aim was to create a set of simulations that reproduce the typical flooding in the area, for different conditions of rainfall and tide, to be included in the web-GIS based tool to support flood risk management.

Several scenarios were selected to analyse the consequences in terms of flooding extension and water depths.
over the surface. For the forecast, accumulated rainfall projection and estuarine water level, for a 3 hr period, is available at the Dafundo beach. However, a specific value of accumulated rainfall in a time interval of 3 hr can produce different consequences in terms of flooded areas and depths, depending on the shape of the hyetograph during the period. Therefore, the characteristics of the event (in terms of preceding dry weather period, maximum rainfall intensity and the variation of rainfall intensity before and after the peak) have an important role and must be taken into account. The simulated scenarios were intended to assess, for each pair of values ($x_1$, tide; $x_2$, accumulated precipitation in 3 hr), the best and worst case scenarios (as far as water depth over the surface is concerned).

The hyetograph shape was adopted based in the IDF (intensity-duration-frequency) curves of the national Decree-Law 23/95 for Portugal, for the return periods (T) of 10, 20, and 50 years. The adopted IDF curves correspond to the rainfall region of Lisbon, where Dafundo study case is located. The corresponding maximum intensities were, respectively, 56, 63, and 73 mm/hr. The shape of the rain event selected was a design rainfall pattern as shown in Figure 7. According to the Portuguese Decree-Law 23/95, this design rainfall pattern is required in studies related to stormwater drainage systems. The design rainfall pattern duration (4 hr) was selected in order to ensure that the whole Dafundo catchment contributes to the modelled drainage systems, and that the duration was both longer than the catchment concentration time (20 min) and longer than the duration of the recorded rainfall events in the Dafundo catchment.

For the corresponding generated rainfall volume, an additional uniform hyetograph was defined corresponding to the design rainfall pattern duration. Three rain events recorded in the Dafundo catchment were also simulated.

Figure 7 presents the design rainfall pattern developed by Matos (1987). These patterns are mandatory, according to the Portuguese Decree-Law 23/95 for design and studies related to stormwater drainage systems. The design rainfall pattern is based on the determination of the identified points of the $I(t)$ function, as detailed in the Figure 7. For example, the value of the function $I(t)$ for the time $t_1$ corresponds to $6/5 * I_m(4\, \text{hr})$. The $I_m$ (4 hr) corresponds to the maximum rainfall intensity for a design rainfall with a duration of 4 hr.

The tide scenarios were established taking into account both the tidal amplitude and atmospheric storm surges when extreme low pressure raises sea level. A variation of the water level of 0.5 and $-0.3 \, \text{m}$ was considered the maximum and minimum storm surge component. A maximum and minimum limits of 4.2 and 0.8 m, respectively, were considered for the tidal amplitude, based in Fortunato et al. (2015). The scenarios for tidal conditions were defined with reference to the mean sea level of 0.14 m, leading to a minimum sea level of $-2.3 \, \text{m}$ and a maximum sea level of 2.7 m, corresponding to the best and worst case scenarios, based in Fortunato et al. (2015). The tide values are referred to the topographical zero, considering that this value is 2.08 m above the hydrographic zero in the region. Ten intermediate levels of the tide were simulated.

In addition to accumulated rainfall and tide water level, flooding can be related to the operational conditions of the sewers, such as sediment deposition and obstruction at the outfalls. A sediment depth of 0.20 m was established as a standard condition. An additional 90% of obstruction to the cross-section was adopted at the outfalls to simulate the sediment deposition along the pipes that discharge to the estuary. In the coupled model the sediment deposition was modelled as a reduction of the sewer depth that restricts the flow to pass in the sewer bottom until the established sediment depth, thus reducing the sewer capacity. These values were selected taking into account previous field work and their effect is referred to as the operational condition with obstruction. The sediment is modelled as static. The sediment transport along the sewer network is not considered, because the major contribution for the obstruction and deposition along the pipes that discharge to the estuary is the tide.
effect. The tide facilitates the entrance of sand and sediment, creating blockage and deposition but only in the outfall sewers. Once the sediments deposition takes place, they have to be removed by the water utility.

To conclude, 9 different precipitation events, 12 tide levels, and 2 obstruction conditions were considered in the scenarios. The precipitation events considered the design hyetograph, the uniform hyetograph and real precipitation events. Table 1 presents the scenarios of rainfall events defined in the 1D/2D modelling.

The tide levels were established considering the maximum and minimum tidal amplitude and storm surge effect. Intermediate tide levels were also simulated. Table 2 presents the scenarios of tide level defined in the 1D/2D modelling.

The construction conditions were adopted based on previous field work where significant sediment deposition was observed. Considering the referred tide level, precipitation and obstruction conditions, 216 scenarios were considered with the purpose of providing information on different conditions in order to generate early warnings through the WebGIS-based tool, described in the next section.

### TABLE 1 Scenarios of rainfall events defined in the 1D/2D modelling

| Rainfall event type | Designation | $T$ (years) | $I_{\text{max}}$ (mm/hr) | $P_{\text{tot}}$ (mm) |
|--------------------|-------------|-------------|---------------------------|----------------------|
| Design rainfall    | pp_1        | 10          | 56.12                     | 57.38                |
|                    | pp_2        | 20          | 63.40                     | 66.62                |
|                    | pp_3        | 50          | 72.74                     | 79.13                |
| Uniform rainfall   | pu_1        | —           | 14.34                     | 57.38                |
|                    | pu_2        | —           | 16.65                     | 66.62                |
|                    | pu_3        | —           | 19.78                     | 79.13                |
| Recorded rainfall  | pr_1        | —           | 20.77                     | 21.02                |
|                    | pr_2        | —           | 38.27                     | 14.83                |
|                    | pr_3        | —           | 4.28                      | 7.80                 |

Abbreviations: $T$, return period; $I_{\text{max}}$, maximum rainfall intensity; $P_{\text{tot}}$, accumulated rainfall.

### TABLE 2 Scenarios of tide level defined in the 1D/2D modelling

| Mean sea level MSL (m) | Storm surge (m) | Semi-amplitude (m) | Simulated sea level (m) |
|------------------------|-----------------|-------------------|------------------------|
| 0.14                   | 0.50            | 2.10              | 2.74                   |
|                        |                 |                   | −1.46                  |
|                        |                 | 0.40              | 1.04                   |
|                        |                 |                   | 0.24                   |
|                        | −0.30           | 2.10              | 1.94                   |
|                        |                 |                   | −2.26                  |
|                        | 0.40            | 0.24              | −0.56                  |

4 | WEBGIS-BASED TOOL TO SUPPORT FLOOD RISK MANAGEMENT

To provide access to model predictions, real time data and inundation alerts, an innovative real-time WebGIS platform was developed, for enhanced support to flood risk emergency in urban and nearby coastal areas. It takes advantage of novel technologies to provide fast access to all relevant online, intuitive and geographically referenced real-time data and model predictions for urban and estuarine floods (Freire, Tavares, et al., 2016).

The WebGIS platform was created to contribute to a fast and coordinated mobilisation of emergency authorities, and other local agencies, and to a timely response to flooding events in the Tagus estuary and the nearby Dafundo downtown area. This platform aims at: integrating existing and new wireless sensor networks and accurate model forecasts (at both urban and estuarine scales); achieving a coordinated strategic planning and emergency response in urban and nearby estuarine regions; optimising the alert to local agencies, duly supported by real time monitoring and predictions of flooding.

The platform requirements were the following: (1) account for different users’ roles, providing differentiated access to dedicated products; (2) host georeferenced products from the static risk analysis and the dynamic real-time forecasts; and (3) be agile, providing fast access to the alerts and their products. Additionally, the new system should be cross-platform, that is, it was built in a way that it is automatically and transparently adaptable to any device with a data connection, providing access to emergency information anywhere.

The development and conceptualization of the platform have taken into account past developments in this area. For instance, Fahland, Gläber, Quilitz, Weibleder, and Leser (2007) developed a web platform integrating GIS and spatial databases. In Kulkarni, Mohanty, Eldho,
Rao, and Mohan (2014), a WebGIS is presented addressing risk management related issues, providing authenticated users access to queryable information, depending on their authorization level. Building on these experiences and in similar work developed in the scope of past projects (David et al., 2013; Oliveira et al., 2014), LNEC has been developing and applying a suite of Web platforms denoted as WIFF—Water Information Forecast Framework (Oliveira et al., 2014) to provide access to real time information to decision makers. These platforms provide full access to real time sensor data and model predictions and, at the same time, are a repository of past information available at each deployment site to the relevant end-users.

The platform is organised around the two levels of study (estuarine and urban areas), mapped for early warning, forecast and risk assessment (Figure 8).

For urban flooding simulation, a scenarios matrix, based on scenarios results, was constructed in function of the total volume of the rainfall, estuarine water level and operational conditions. The platform shows the results for simulated conditions similar to the forecast conditions, namely, the total volume of the rainfall level (obtained using the precipitation model WRF 9 km from Windguru) and estuarine water level (calculated through the coupled waves-currents hydrodynamic modelling of the Tagus estuary).

Products related with urban flooding are available in two ways:

- as static results, through access to all flooding maps from the matrix of scenarios. The user can select the interval of water level in the estuary and the precipitation range over a three-hour period and examine the maximum and minimum flooded area contour, as well as the corresponding water depths.
- as dynamic products, through the construction of a forecast sequence for a period of 48 hours starting at midnight every day. At 3-hr slots, the maximum water level and the predicted precipitation are used to select the adequate result from the matrix of scenarios (Figure 9). A script runs through the 48-hr period to build the sequence and show it in the interface. A script runs through the 48-hr period to build the sequence and show it in the interface. The information flow scheme behind this forecast sequence is shown in Figure 10. If flooding is not bound to occur in the selected period, a message is displayed on the screen (Figure 9).

The generation of early warning at selected locations in the Dafundo area is under construction, accounting for the different assets at stake in each location. This early warning module will be provided within the forecast sequence dashboard.
RESULTS

For the operational condition without obstruction, flooding presents a reduced dependence on the tide level at the Tagus estuary. The tide level only acts as a restriction in term of the duration of flooding, but the flooded area and the water depths do not change. For the scenarios of low precipitation and uniform intensity, a significant area in the main street in downtown Dafundo is flooded, but the maximum water depths over the surface are low. For the operational condition without obstruction, the greatest water depths are obtained for a return period of 50 years; although the flooded area is quite large, the water depths are below 10 cm. For the higher intensity scenarios, such as the ones corresponding to the design rainfall, the eastern locations in the study area also flooded. For the maximum rain intensity studied, the main central avenue, a very important traffic route in greater Lisbon, is also flooded, but still with low water depths (Figure 11a).

For the operational condition with obstruction, the tide level has a greater influence on the system. The water depths in the flooded area, for the highest simulated tide levels and for the rainfall event with greater intensity, are three times greater than those corresponding to the simulations without obstruction, mainly due to the reduced outfall capacity to the Tagus estuary. The flooded area reaches even further into

FIGURE 9  Urban flooding forecast: snapshot of three consecutive 3-hr periods

FIGURE 10  Urban flooding: workflow of information to produce model forecasts: connection with estuarine forecasts through water level and precipitation prediction

5 | RESULTS
eastern areas, and goes all the way up to almost 30 cm (Figure 11b). Additional sediment and obstruction rates were simulated to reproduce aggravated conditions, but generally the same results were obtained.

The results were confirmed with the historical data (Figure 11c and Figure 11d) in terms of extension and depth of the flooded area. As Figure 11c shows, the main historical flood records in these area correspond to the same locations of the flooded areas obtained by the 1D/2D model, presented in Figure 11a,b. Moreover, Figure 11d allows to visualise that the water depths, based on flooded records, are not higher than the kerb. In this sense, the maximum water depth ($T = 50$ years), for the operational condition without obstruction, below 10 cm looks in accordance with the historical records. An overall good model performance was obtained, allowing to identify the main technical shortcomings of the stormwater drainage system.

In the downtown Dafundo area, flooding occurs historically. Clearly, this benefited from the relief sewer running alongside the stormwater main sewer (Figure 11a). Nevertheless, flooding still occurs occasionally, usually due to simultaneous heavy rainfall and high tides occurrences. Flooding is more serious when associated with obstruction either in the stormwater network or in the outfalls to the estuary. In order to study flooding occurrence in this area, the integrated 1D/2D model results confirmed that without these operational problems, the occurrence of flooding is almost independent of tidal levels. Regarding the extension of flooding areas, it can be quite relevant although the water depths over the surface are always low. Even though tide affects the duration of flooding, its severity depends just on precipitation.

Potential measures to reduce the risk in the estuarine area of Dafundo have been identified, such as reviewing the stormwater system maintenance plan, studying solutions to reduce the frequency of deposition in the system outputs, along with the implementation of population warnings in the WebGIS platform. The results were incorporated into a results integration platform that enables flood prediction to be performed, allowing flood warnings to be made in places which experience the more severe consequences.
6 | DISCUSSION

The 1D/2D mathematical modelling in estuarine urban areas represents an adequate tool that provides the required information to analyse the flooding occurrence and to contribute to support flood risk management. The coupling between the runoff model (2D) and the stormwater network model (1D) was ensured by links (stormwater inlets and normal manholes), which are the elements responsible for flow exchanges between the DEM and the stormwater network. Related to the 1D/2D mathematical model and estuarine level integration, this is ensured through the definition of the tide water level series as a downstream boundary condition to the sewer network outfalls. The tidal water level was previously calculated using the coupled waves-currents hydrodynamic modelling of the Tagus estuary. The appropriate integration between the mathematical model and the tidal levels allow to achieve an adequate reproduction of the real conditions in the Dafundo downtown area through the 1D/2D coupling model.

Regarding the model calibration, first, the C coefficient, the concentration time, the weir crest level and the dry weather base flow were determined in the conceptual model of the upstream Dafundo catchment. Second, the shape and concentration time for the downstream subcatchments model were determined. Lastly, the level of obstruction in the sewers was established taking into consideration the previous field work. The calibration achieved an adequate match between the results of the 1D/2D model and the available field data. Likewise, modelling results showed an adequate reproduction of the historical flood occurrences.

A proper definition of a set of scenarios to be studied is an important modelling step and should consider the objectives of the study. A set of scenarios was analysed which together reproduce the typical conditions of the local flooding in the area. The joint assessment of the tide level, rainfall events and operational conditions provided a best knowledge of the mechanism that influence the flooding occurrence and existing limitations in the stormwater drainage systems.

The incorporation of the operational conditions in 1D/2D mathematical modelling represents an important issue as it is a common situation in stormwater drainage systems, especially in estuarine areas, and it is suitable to be applied for other types of obstruction, such as the presence of roots, or for reduction in the network capacity. The obstructions lead to a significant decrease of the hydraulic capacity of the system and intensify the associated flood magnitude, frequency and duration. The incorporation of the operational conditions helps to improve the stormwater drainage management, contributing to a better understanding of the weaknesses of the network and of maintenance requirements.

Since the 1D/2D mathematical modelling allows to identify the hydraulic limitations of the surface water inlets, it may also be applied for planning surface maintenance practices that may be assessed and compared.

7 | CONCLUSIONS

The assessment of flooding occurrence in the urban area of Dafundo, adjacent to the Tagus estuary, was carried out based on a coupled 1D/2D model and considering the water level in the estuary as a boundary condition from a hydrodynamic model. Inspections were carried out in the stormwater system, rainfall and hydraulic variables were monitored and information on the operational condition of the system and flooding historical records were collected. The main objective is to forecast flooding in the Dafundo catchment and to support definition of population warnings. A set of simulations that reproduce the typical flooding in the area, for different conditions of rainfall and tide, to support flood risk management, based on the web-GIS based tool, were simulated.

The integrated 1D/2D model results confirmed that without operational problems regarding high levels of sediment deposition, the occurrence of flooding is almost independent of tidal levels. With regard to the extent of flooded areas, it can be significant although the water depths over the surface are always low. Even though tide affects the duration of flooding and its severity depends just on precipitation.

These results allowed to identify potential measures to reduce the risk in the estuarine area of Dafundo such as reviewing the stormwater system maintenance plan, studying solutions to reduce the frequency of deposition in the system outfalls, along with the implementation of population warnings in the WebGIS platform.

In essence, the incorporation of the operational conditions in 1D/2D mathematical modelling represents an important issue as it is a common situation in stormwater drainage systems, especially in estuarine and coastal areas. The incorporation of the operational conditions is also suitable to be applied for other types of obstruction, such as the presence of roots, or for reduction in the network capacity.

The proposed approach considers new aspects based on the utilisation of 1D/2D integrated modelling, providing an important improvement to assess flooding occurrence and contributing to support an appropriate flood risk management in stormwater drainage systems.

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DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES
Bhola, P. K., Leandro, J., & Disse, M. (2018). Framework for offline flood inundation forecasts for two-dimensional hydrodynamic models. Geosciences, 8(9), 346.
Blanc, J., Hall, J. W., Roche, N., Dawson, R. J., Cesses, Y., Burton, A., & Kilshy, C. G. (2012). Enhanced efficiency of pluvial flood risk estimation in urban areas using spatial–temporal rainfall simulations. Journal of Flood Risk Management, 5(2), 143–152.
Chang, T. J., Wang, C. H., & Chen, A. S. (2015). A novel approach to model dynamic flow interactions between storm sewer system and overland surface for different land covers in urban areas. Journal of Hydrology, 524, 662–679.
David, L. M., & Matos, J. S. (2005). Combined sewer overflow emissions to bathing waters in Portugal. How to reduce in densely urbanised areas? Water Science and Technology, 52(9), 183–190. https://doi.org/10.2166/wst.2005.0315
David, L. (2006). Descargas de excedentes de sistemas de drenagem urbana - estudo referenciado em resultados experimentais obtidos em Portugal. (PhD Thesis), Technical University of Lisbon, 304 p. Lisbon, Portugal.
David, L. M., Oliveira, A., Rodrigues, M., Jesus, G., Póvoa, P., David, C., ... Matos, R. S. (2013). Development of an integrated system for early warning of recreational waters contamination. In J.-L. Bertrand-Krajewski & T. D. Fletcher (Eds.), Novatech 2013. France: GRAIE, Lyon.
Deng, Z. Q., Namwamba, F., & Zhang, Z. H. (2014). Development of decision support system for managing and using recreational beaches. Journal of Hydroinformatics, 16(2), 447–457.
DHI (2014). Mike Flood. 1D-2D Modelling. User Manual. MIKE BY DHI Software, Danish Hydraulics Institute Harsholm, Denmark.
Djordjević, S., Prodanović, D., Maksimović, Ć., Ivetić, M., & Savić, D. (2005). SIPSION—simulation of interaction between pipe flow and surface overland flow in networks. Water Science and Technology, 52(5), 275–283.
Fahland, D., Gläber, T.M., Quilitz, B., Weibleder, S., & Leser, U. (2007). HUODINI – Flexible Information Integration for Disaster Management, Proceedings ISCRAM2007, 2007, pp. 255–138.
Falconer, R. H., Cobby, D., Smyth, P., Astle, G., Dent, J., & Golding, B. (2009). Pluvial flooding: New approaches in flood warning, mapping and risk management. Journal of Flood Risk Management, 2(3), 198–208.
Fortunato, A.B., Tavares da Costa, R., Rogeiro, J., Gomes, J.L., Oliveira, A., Li, K., Freire, P., Rilo, A., Mendes, A., & Rodrigues, M. (2015). Desenvolvimento de um sistema operacional de previsão de níveis temporais na costa Portuguesa, VIII Congresso Sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa, Associação Portuguesa dos Recursos Hídricos, pp.15.
Freire, P., Tavares, A., Oliveira, A., Cardoso, M.A., & Pires, P. (2014). An integrated approach for flood risk assessment in estuaries. 3.as Jornadas de Engenharia Hidrográfica, Instituto Hidrográfico, Lisboa, Portugal.
Freire, P., Fortunato, A. B., Rilo, A., Li, K., Costa, R., Oliveira, A., ..., Dias, J. (2016). Project MOLINES: Modelling flood in estuaries. From hazard to the critical management. Final Report. LNEC Report 250/2016—DHA/NEC. R&D Hydraulics and environment. National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal.
Freire, P., Tavares, A. O., Sá, L., Oliveira, A., Fortunato, A. B., dos Santos, P. P., ... Pinto, P. J. (2016). A local-scale approach to estuarine flood risk management. Natural Hazards, 84(3), 1705–1739.
Ghanbarpour, M. R., Salimi, S., & Hipel, K. W. (2013). A comparative evaluation of flood mitigation alternatives using GIS-based river hydraulics modelling and multicriteria decision analysis. Journal of Flood Risk Management, 6(4), 319–331.
Gomes, J., Jesus, G., Rogeiro, J., Oliveira, A., Costa, R., & Fortunato, A. (2015). Molines—Towards a Responsive Web Platform for Flood Forecasting and Risk Mitigation. Proceedings of the 2015 Federated Conference on Computer Science and Information Systems, pp.1183–1188.
Hénolin, J., Russo, B., Roqueta, D. S., Sanchez-Diezma, R., Domingo, N. D., Thomsen, F., & Mark, O. (2010). Urban flood real-time forecasting and modelling: A state-of-the-art review. In Proceedings MIKE by DHI Conference (p. P028).
IPCC (2013). Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. BouROP, A. N. N. X. A. X. V. B. X. P. P. M. A. M. M. L. M. C. B. W. P. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, pp. 1535.
Kavetski, D., Kuczera, G., & Franks, S. W. (2006). Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory. Water Resources Research, 42(3), 49–68.
Kulkarni, A. T., Mohanty, J., Eldho, T. I., Rao, E. P., & Mohan, B. K. (2014). A web GIS based integrated flood assessment modeling tool for coastal urban watersheds. Computers & Geosciences, 64, 7–14. https://doi.org/10.1016/j.cageo.2013.11.002
Leandro, J., Chen, A. S., Djordjević, S., & Savić, D. A. (2009). Comparison of 1D/1D and 1D/2D coupled (sewer/surface) hydraulic models for urban flood simulation. Journal of Hydraulic Engineering, 135(6), 495–504.
Leandro, J., Schumann, A., & Pfister, A. (2016). A step towards considering the spatial heterogeneity of urban key features in urban hydrology flood modelling. Journal of Hydrology, 535, 356–365.
Liu, Q., Qin, Y., Zhang, Y., & Li, Z. (2015). A coupled 1D–2D hydrodynamic model for flood simulation in flood detention basin. *Natural Hazards, 75*(2), 1303–1325.

Leitao, J. P. C. (2009). Enhancement of digital elevation models and overland flow path delineation methods for advanced urban flood modelling. PhD thesis. In *Imperial College London*. London: UK.

Matos, R. (1987). *Métodos de análise e de cálculo de caudais pluviais em sistemas de drenagem urbana. Estudo referenciado em dados experimentais de bacias urbanas portuguesas*. Collection LNEC—I&D—Hidraulic thesis. Vol. 1.

Oliveira, A., Jesus, G., Gomes, J. L., Rogeiro, J., Azevedo, A., Rodrigues, M., ... Den Boer, S. (2014). An interactive WebGIS observatory platform for enhanced support of integrated coastal management. *Journal of Coastal Research, 70*(sp1), 507–512.

Paula, T. J., Simões, N., Marques, J. A., & Machado, F. M. (2014). Zonas inundáveis e quantificação do risco de inundação em meios urbanos: Estudo em Coimbra. *Revista Eletrónica de Gestão e Tecnologias Ambientais (GESTA)*, 2(1), 9–19.

Pina, R. D., Ochoa-Rodriguez, S., Simões, N. E., Mijic, A., Marques, A. S., & Maksimović, Č. (2016). Semi-vs. fully-distributed urban stormwater models: Model set up and comparison with two real case studies. *Water, 8*(2), 58. https://doi.org/10.3390/w8020058.Rodrigues

Rodrigues, M., Costa, J., Jesus, G., Fortunato, A. B., Rogeiro, J., Gomes, J., Oliveira, A., & David, L. M. (2013). Application of an Estuarine and Coastal Nowcast-forecast Information System to the Tagus Estuary. Proceedings of the 6th SCACR–International Short Course/Conference on Applied Coastal Research (Lisboa, Portugal), pp. 10.

Schmitt, T. G., Thomas, M., & Ettrich, N. (2004). Analysis and modeling of flooding in urban drainage systems. *Journal of Hydrology, 299*(3), 300–311.

Seyoum, S. D., Vojinovic, Z., Price, R. K., & Weesakul, S. (2012). Coupled 1D and noninertia 2D flood inundation model for simulation of urban flooding. *Journal of Hydraulic Engineering, 138*(1), 23–34.

Townend, I., & Pethick, J. (2002). Estuarine flooding and managed retreat. *Philosophical Transactions of the Royal Society A Mathematical Physical and Engineering Sciences, 360*(1796), 1477–1495.

Zhang, Y., Ye, F., Stanev, E. V., & Grashorn, S. (2016). Seamless cross-scale modeling with SCHISM. *Ocean Modelling, 102*, 64–81.

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