

Comparison Between Two Hydrodynamic Models for Flooding Simulations at River Lima Basin

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Abstract According to EU flood risks directive, flood hazard maps should include information on hydraulic characteristics of vulnerable locations, i.e. the inundated areas, water depths and velocities. These features can be assessed by the use of advanced hydraulic modelling tools which are presented in this paper based on a case study in the river Lima basin, Portugal. This river includes several flood-prone areas. Ponte Lima town is one of the places of higher flood risk. The upstream dams can lower the flood risks if part of its storage capacity is allocated for mitigating flood events. However, proper management of dam releases and the evaluation of downstream river flows should be considered for preventing flood damages. A hydrological and a one-dimensional hydrodynamic model were implemented, and at a particular flood-prone town, inundation was assessed using a two-dimensional model. The hydrological model is based on the well known Sacramento model. For this purpose, two different modelling implementations were analysed: a model based on a finite element mesh and a model based on rectangular grids. The computational performance of the two modelling implementations is evaluated. Historical flood events were used for model calibration serving as a basis for the establishment of different potential flood scenarios. Intense precipitation events in the river's basin and operational dam releases are determinant for the occurrence of floods at vulnerable downstream locations. The inundation model based on the unstructured mesh reveals to be more computationally efficient if high spatial resolution is required. A new combination of software tools for floods simulation is presented including an efficient alternative for simulation of 2-D inundation using a finite element mesh instead of a grid.

Keywords Hydroinformatics tools · River flood forecasting · Hydrodynamic model · River water management

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1 Introduction

Flood events instigate many undesirable impacts. These events can damage property, endanger human lives and are frequently associated with large economic losses. Intense water runoff causes soil erosion and concomitant sediment deposition elsewhere. The spawning grounds for fish and other wildlife habitats can become polluted or completely destroyed. Structural damage can occur in bridge abutments, shorelines, sewer lines, and other structures within flooded valleys. Waterway navigation and hydropower plants are often impaired.

Frequently, it is verified that high rainfall events are not the unique cause of flooding problems. Rather, the increased urbanisation, lax urban planning in relation to the construction of buildings in flood plains, and the lack or inadequacy of storm drainage facilities, are responsible for those losses (e.g. Adeloye and Rustum 2011; Liu et al. 2014).

Considering the social and economical importance of this problem, flood management strategies for urban and regional planning are highly required. The 2007/60/EC Directive (EU 2007) establishes a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences to human health, the environment, cultural heritage and economic activity associated with floods in the European Union.

Methodological approaches to deal with flooding problems recommend the incorporation of decision support tools in the process for better investigate which planning options and remediation actions need to be taken at a river basin scale (Demir and Krajewski 2013; Filatova 2014; Sharma et al. 2014; Sprague and Carlson 1982; Vieira et al. 2012).

Flood forecasting and flood management imply a comprehensive data collection, statistical analysis of relevant data, and implementation of hydrological and hydrodynamics models. Hydroinformatics is a new scientific branch linking informatics tools with hydraulics and environmental concepts and models (De Roo et al. 2003; Penning-Roswell et al. 2000; Pinho et al. 2004; Renner et al. 2009; Werner et al. 2004; Verwey 2005; Zagonari and Rossi 2013). The everincreasing computational resources and geographical information tools give the support for applying new methodologies in flood management ().

Land-use changes and the increasing awareness of flood effects triggered by historic flood events along the Portuguese river Lima basin (Fig. 1) advise better understanding of the hydrodynamics behaviour of this river and the establishment of adequate measures to be taken to achieve safety against new flooding events. Recent studies (Pinho and Vieira 2005; Ferreira 2010) have drawn attention to the need to predict this type of phenomena at the river basin scale.

Several software packages for two-dimensional simulation of water levels and flow characteristics during flood events revealed to be efficient (e.g. Liang 2010; Stelling and Verwey 2005; Tsakiris and Bellos 2014). Néelz and Pender (2010) presented a sound performance analysis consisting on the comparison of software packages in the simulation of different inundation tests. Sobek (WL 2005) was one of the evaluated software packages. This software showed capabilities to capture the detail of the flow field for all the tests involving complex geometries of the floodplain. However, when applied in operational management, the computational time costs, depending on the spatial resolution, could be a restriction for some simulations (Yazdi and Neyshabouri 2014).

This paper presents a set of advanced models to simulate a complex flood-prone area. These models will be used within an operational flow forecast system under development, which implies severe computational time restrictions to deal with ensemble forecasts. Flood events at this river basin depend either on the rainfall intensity events, in the operation of two hydropower plants and on the sea level at the downstream boundary (Shahapure et al. 2010). At the river basin scale, a hydrological and a one-dimensional (1DH) hydrodynamic model were implemented. Inundation simulations at a particular flood-prone town were

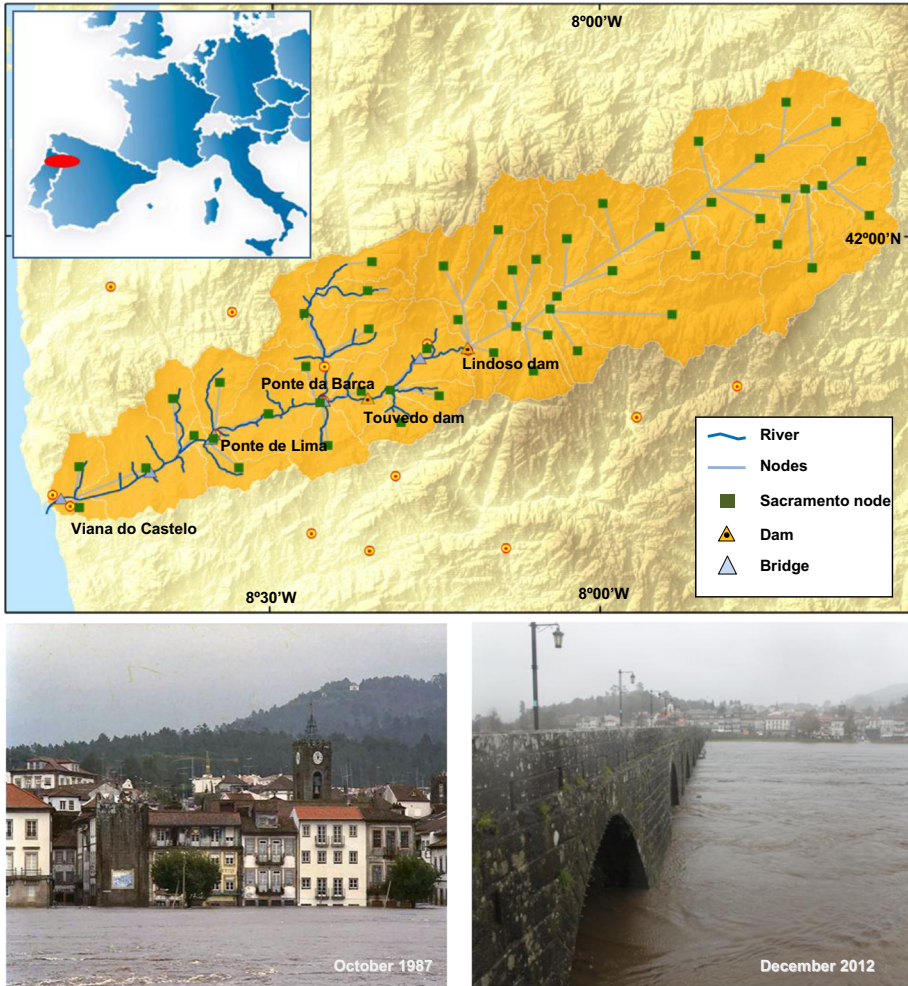


Fig. 1 River Lima basin location and floods at Ponte de Lima town

assessed using a two-dimensional model (2DH). Two different modelling approaches are analysed: (i) a 2DH model was applied to the river stretch in the neighbourhood of the town of Ponte de Lima to analyze flood-prone areas surrounding this historical town, based on a finite element mesh spatial discretization; and (ii) a 2DH model based on rectangular grids. Two main questions are evaluated. The first one concerns the computational performance of the two modelling approaches and the second one is related with the capability of each approach to correctly simulate the inundated areas.

2 Description of the Study Site

The River Lima basin (Figs. 1 and 2), located in the northern region of Portugal, has a total drainage area of approximately 2450 km². About 46.5 % of that area is located in Portuguese

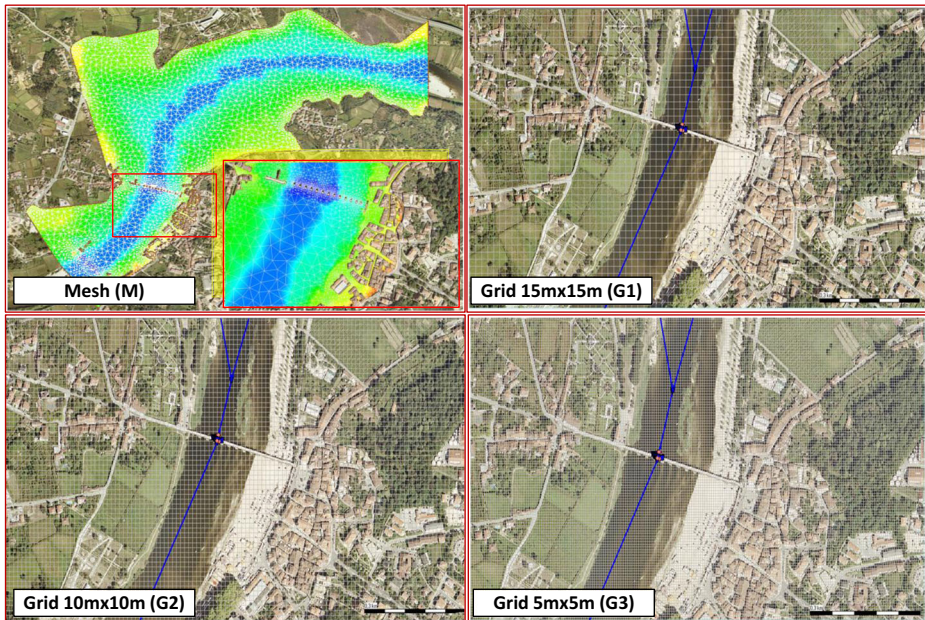


Fig. 2 Ponte de Lima town RMA2 (*mesh*) and Sobek 2DH inundation models (*grids*)

territory, while the remaining area is located in Spain. This basin has a mean elevation of 447 m with several peaks above 1300 m, an average annual precipitation in the range of 1300–4200 mm, and an average population density of 112 inhabitants/km². The largest contribution to the formation of massive floods comes from the runoff generated in its mid-section. This fact is not only due to the high rainfall events verified in that region, but also to the ability of this area to generate surface runoff and high flow velocity propagation due to low soil permeability, together with the presence of rugged and deep valleys.

Two hydropower plants (Lindoso and Touvedo dams) are in operation since 1992, and their reservoirs represent a significant storage capacity controlling the occurrence of flood events.

Ponte de Lima is a small Portuguese town with about 2800 inhabitants, located 25 km from the river mouth.

3 Methodology

3.1 Models Mathematical Formulation

Sobek (WL 2005) is a software package developed by Delft Hydraulics applicable to hydrodynamic modelling of rivers, estuaries or drainage networks. It is based on a powerful numerical method that allows obtaining solutions for complex simulations. This modelling software is based on the 1DH Saint Venant hydrodynamic equations integration by means of a finite difference scheme (WL 2005):

$$\frac{\partial Af}{\partial t} + \frac{\partial Q}{\partial s} = q_{lat} \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial s} \left(\frac{Q^2}{A_f} \right) + gA_f \frac{\partial H}{\partial s} + \frac{gQ|Q|}{C^2RA_f} - W_f \frac{\tau_{wi}}{\rho} = 0 \tag{2}$$

where,

- Q Flow discharge [m³/s]
- T Time [s]
- S One-dimensional coordinate [m]
- A_f Wetted area [m²]
- G Acceleration due to gravity [m/s²]
- H Water level above plane of reference [m]
- C Chézy's coefficient [m^{1/2}/s]
- R Hydraulic radius [m]
- W_f Superficial width [m]
- q_{lat} Lateral flow [m²/s]
- τ_{wi} Wind shear force [N/m²]
- ρ Water density [kg/m³].

Sobek software presents a graphical interface through which all pre-processing tasks are performed. The spatial discretization of the model was performed on that interface using the map of the river basin as support (in a format compatible with GIS). Moreover, a hydrological module is available for an integrated implementation of Sacramento models of the river sub-basins (WL 2005).

The two-dimensional Sobek module, based on a finite difference method and the RMA2 software (ERDC 2013) based on the finite element method, solves the 2DH form of the Saint Venant equations. The latter software can be applied for situations where flows do not exhibit significant vertical accelerations. This solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. Solved equations are (ERDC 2013):

$$h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - \frac{h}{\rho} \left(E_{xx} \frac{\partial^2 u}{\partial y^2} + E_{xy} \frac{\partial^2 u}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right) \times \frac{gum^2}{h^{1/3}} \tag{3}$$

$$\times (u^2 + v^2)^{1/2} - \zeta V_a^2 \cos(\psi) - 2h\psi \sin(\phi) = 0$$

$$h \frac{\partial v}{\partial t} + hu \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} - \frac{h}{\rho} \left(E_{yx} \frac{\partial^2 v}{\partial y^2} + E_{yy} \frac{\partial^2 v}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y} \right) \times \frac{gvm^2}{h^{1/3}} \tag{4}$$

$$\times (u^2 + v^2)^{1/2} - \zeta V_a^2 \sin(\psi) - 2h\psi \sin(\phi) = 0$$

$$\frac{\partial h}{\partial t} + h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \tag{5}$$

where,

- h Water depth [m]
- x and y Horizontal Cartesian coordinates [m]
- u and v Velocities in the Cartesian directions [m/s]
- E Eddy diffusion coefficient [Pa s]

a	Elevation of bottom [m]
n	Manning's roughness coefficient value [$m^{-1/3} s$]
ρ_a	Air density [kg/m^3]
ζ	Empirical wind shear coefficient
V_a	Wind speed [m/s]
ψ	Wind direction
ω	Rate of earth's angular rotation [s^{-1}]
ϕ	Local latitude

Pre- and post-processing of input data and results from the RMA2 simulations were performed by SMS (AQUAVEO 2009) software.

3.2 Models Implementation

Model construction was supported by a GIS tool and databases, which were implemented to support this project. Aerial photos, topographical and bathymetric data, river flow discharges, and water levels for the river Lima basin were collected and processed to be used in the implementation of the models.

The modeling system consists in a 1DH hydrodynamic model of the river network, hydrological models of the upstream and lateral basins, and two alternative 2DH hydrodynamic models for simulation of flood inundations in the surroundings of Ponte de Lima town (Fig. 3).

Sub-basins Sacramento models are connected with the river network introducing the produced runoff into the river canals. The 2DH inundation models at the downstream flood prone city are coupled with the 1DH model via the open boundaries. Results obtained at those locations for the 1DH model are used to define the open boundary conditions of the 2DH inundation models.

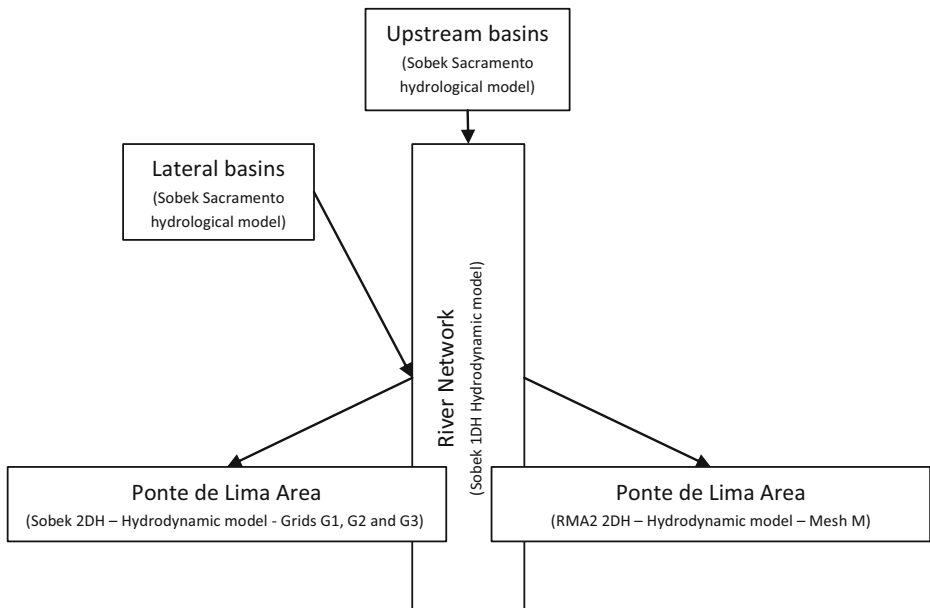


Fig. 3 Modelling system used to simulate floods at river Lima basin, consisting on hydrological Sacramento models, 1DH hydrodynamic river network model and two alternative 2DH models for flood inundation simulation

The 1DH hydrodynamic model of the river Lima extends from the river mouth at Viana do Castelo to the upstream Spanish basins located upstream Alto Lindoso dam (Fig. 1). Sacramento nodes of each sub-basin simulating rainfall-runoff to the main river stretches were implemented and connected to the hydrodynamic model of the main river and tributaries. Hydraulic structures nodes were used to simulate the main reservoirs, hydraulic structures at dams (turbines and spillways) and weirs located along the rivers. At the downstream open ocean boundary tidal water levels were assumed.

2DH models were implemented in Sobek (2D module) and RMA2 for Ponte de Lima surrounding areas. In the case of the RMA2 model, a unique unstructured mesh was generated considering larger elements within the floodplain inundated areas and high resolution discretization (small elements) in the potentially inundated building areas (Fig. 2, mesh M). Rectangular grids used in the spatial discretization presented some limitations representing complex geometries such as those associated with building areas. A balance between spatial resolution and computational efficiency must be found for each case. Three different versions of the Sobek 2DH models were implemented: 15 m, 10 m and 5 m squared grid resolutions (Fig. 2 Grids G1, G2 and G3, respectively).

A historical event occurred on the 23–24 March 2006 has been used for the calibration of the 1DH river network model. Available data for a second historical event occurred on the 15th November 1987 was used to calibrate the RMA2 2DH model. Obtained Manning's roughness coefficient value was also used in the 2DH Sobek models. Moreover, for these calibration simulations the hydrological models were used to compute the runoff for each sub-basin.

Calibration parameters values are maintained constant for the three simulations used to analyze the performance of the 2DH inundation models. In these simulations precipitation and reservoirs discharges are tuned in order to achieve three different steady-state values of discharges at Ponte de Lima town: $400 \text{ m}^3/\text{s}$, $1000 \text{ m}^3/\text{s}$ and $3200 \text{ m}^3/\text{s}$.

3.3 Performance Assessment of 2DH Models

The assessment of the performance of the 2DH models was carried out using a quantitative assessment considering three different flood peak discharges (FPD) and using four models versions. For the RMA2 model, since an iterative numerical model is used for time integration, a steady-state solution was achieved in a single time step. In the case of the Sobek models, the average computation time (CPU time) per time step of integration was computed for each simulation that was long enough to achieve a steady dynamic solution. These CPU times were used to compare the performance of the different model versions.

Obtained inundated areas for 2DH models were computed. They were also qualitatively analyzed to assess the performance of the models simulating inundations in built areas.

4 Model Calibration

Model calibration is an important procedure to ascertain the model accuracy for further practical applications. Data from flood events registered in the river Lima basin from the years of 1987 and 2006 were used for calibration of the 2DH and 1DH model, respectively.

4.1 1DH Model Calibration

The flood event that occurred on the 23–24 March 2006 served as calibration data, using records from two locations: the flood hydrograph at Ponte da Barca (Fig. 4); and water levels

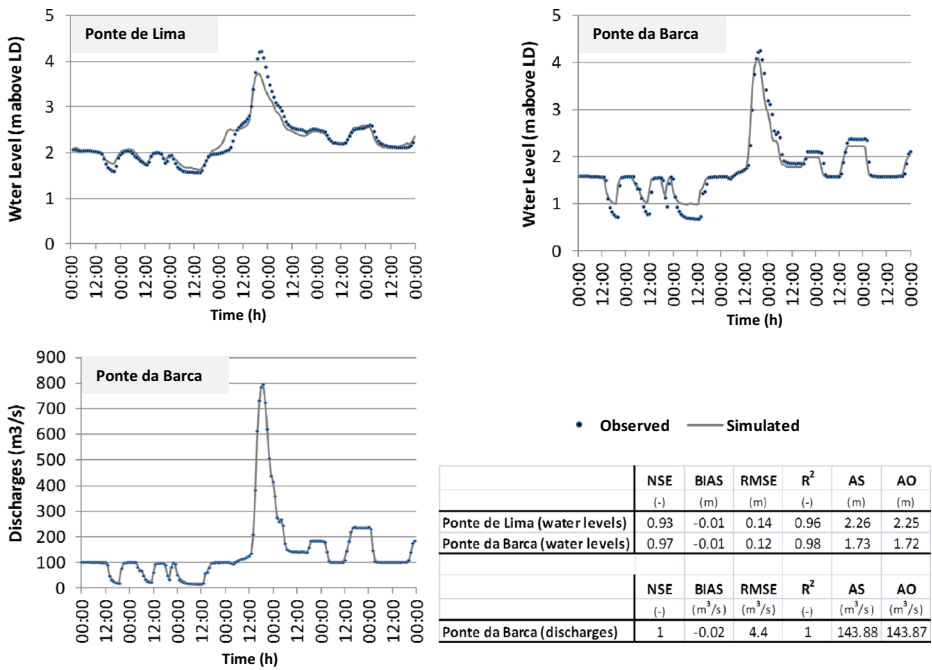


Fig. 4 1DH model calibration results: water levels at Ponte Lima and Ponte da Barca (upper panels); discharge at Ponte da Barca (left bottom panel); and computed metrics (right bottom panel)

at Ponte da Barca and Ponte de Lima. A 7 days simulation period with a time step of 15 min was performed for calibration purposes.

The calibration procedure was developed in order to obtain the flood hydrograph resulting from rainfall data collected in 18 meteorological stations, flows coming from 30 tributaries and discharges from Alto Lindoso and Touvedo dams. Appropriate discharge coefficients for hydraulic structures were adopted as well as Manning’s values for the river reaches.

Results presented in Fig. 4 reveal a good model performance simulating this event as can be inferred from the different computed metrics: Nash-Sutcliffe (NSE), bias (BIAS), root mean squared errors (RMSE), correlation coefficient (R²), average simulated (AS) and average observed (AO).

4.2 Two-Dimensional Models Calibration

The flood event that occurred on the 15th November 1987 served as calibration data using records from the town of Ponte de Lima town. During this flood event, a peak flood discharge of 3120 m³/s was registered and a water level of 1.80 m was measured at St. Paulo Tower. For this calibration considering a constant Manning’s value of 0.04 m^{-1/3} s, the simulated water level at St. Paulo Tower was 1.81 m. The same manning value was adopted for all the 2DH models versions.

5 Results and Discussion

The study of river Lima flood conditions at the town of Ponte de Lima was performed considering the effect of ocean open boundary (tides), dam releases, and rainfall over the river

basin throughout the discharges of its tributaries. Results of the simulated scenarios for river Lima basin (1DH model) and for a critical region in the neighbourhood of Ponte de Lima are presented (2DH model).

5.1 Simulated Scenarios Using the 1DH Model

Estuarine tidal water levels were used as downstream boundary conditions: spring tide (1.849 to -1.849 m), average tide (1.275 to -1.275 m), and neap tide (0.700 to -0.700 m).

Touvedo and Alto Lindoso dams releases with maximum turbinated flow of $250 \text{ m}^3/\text{s}$, were considered for three operational situations: the maximum turbinated flow combined with 1/3 of the maximum flow discharged by floodgates; the maximum turbinated flow combined with 2/3 of the maximum flow discharged by floodgates; and the maximum turbinated flow combined with the maximum flow discharged by all floodgates. These combinations correspond to the three possibilities of operating floodgates at Touvedo dam. In all the scenarios, the bottom outlets of both dams were considered closed. All simulations were performed with the stored water in Alto Lindoso and Touvedo dams at average water levels of 324 and 46 m, respectively, except for the simulations considered in scenarios S4.1, S4.2 and S4.3, which were performed with the dams at maximum flood water level (339 m).

These considered scenarios are summarised in Table 1.

5.2 Simulated Scenarios Using the 2DH Model

The scenarios simulated using the 2DH model were defined considering the open boundary severe water levels (spring tides) obtained with the 1DH model for Ponte de Lima town location, taking into account the worst river flows conditions. River discharges and water levels at Ponte de Lima's weir were used to define the different simulations. Another scenario was also adopted considering a 50-year return period for the peak discharge of the flood (ARHN 2012).

Table 2 presents the characteristics of these flood simulations scenarios.

Table 1 Flood simulation scenarios performed with 1DH model

Scenarios	Tidal conditions	Touvedo dam		Alto Lindoso dam	
		Turbinated flow [m^3/s]	Open floodgates / water level	Turbinated flow [m^3/s]	Open floodgates/ water level
S1.1	Spring	250	1 in 3 / 46 m	250	2 in 6 / 324 m
S1.2	Average		1 in 3 / 46 m		2 in 6 / 324 m
S1.3	Neap		1 in 3 / 46 m		2 in 6 / 324 m
S2.1	Spring		2 in 3 / 46 m		4 in 6 / 324 m
S2.2	Average		2 in 3 / 46 m		4 in 6 / 324 m
S2.3	Neap		2 in 3 / 46 m		4 in 6 / 324 m
S3.1	Spring		3 in 3 / 46 m		6 in 6 / 324 m
S3.2	Average		3 in 3 / 46 m		6 in 6 / 324 m
S3.3	Neap		3 in 3 / 46 m		6 in 6 / 324 m
S4.1	Spring		3 in 3 / 46 m		6 in 6 / 339 m
S4.2	Average		3 in 3 / 46 m		6 in 6 / 339 m
S4.3	Neap		3 in 3 / 46 m		6 in 6 / 339 m

Table 2 Simulation scenarios for 2DH model

Scenarios	Hydraulic parameters in Ponte de Lima's weir	
	Discharges [m ³ /s]	Water level [m]
S_1987 (Calibration)	3120	7.25
S1	765	4.25
S2	1169	4.99
S3	1834	5.80
S4	3219	7.40
S _{RP50}	3805	7.86

5.3 Results from 1DH Model

Figure 5 depicts the results obtained for discharges and water levels at the town of Ponte de Lima for the simulated scenarios.

As expected, Alto Lindoso dam presents high discharge capacity. When the spillway discharges are open and the water level rises from 324 m to the maximum water level (339 m), the discharge will rise from about 1300 m³/s (scenarios S3.1, S3.2 and S3.3) to 3200 m³/s (scenarios S4.1, s4.2, s4.3). Predictions of intense rainfalls and a responsible reservoir water release policy are crucial to avoid inundations at Ponte de Lima, since for relatively low river discharges (around 800 m³/s) the river banks start being inundated at the town of Ponte de Lima (water levels at Ponte de Lima's weir greater than 4 m). Since a considerable area of the basin is not controlled by reservoirs, even if no water is spilled from the dams, the occurrence of floods can be expected during intense rainfall events.

5.4 Performance Assessment of 2DH Models

Figure 6 depicts results of CPU time per time step, obtained for the 2DH models. For low flow conditions (FPD=400 m³/s), all the three grids perform better than the RMA2 model. This situation is inverted for the other two analyzed flood peak discharges, where the RMA2 model becomes less computationally expensive than the G3 grid. Analyzing the flood maps presented

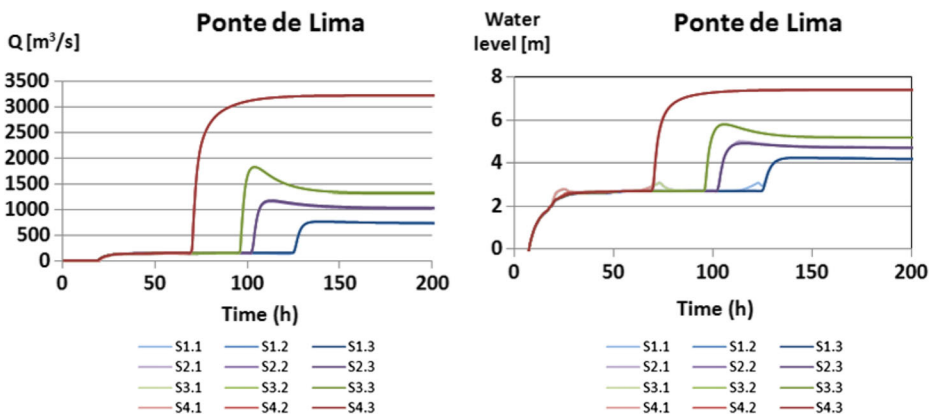


Fig. 5 Simulated discharges (left) and water levels (right) at Ponte de Lima weir, for simulated scenarios presented in Table 1

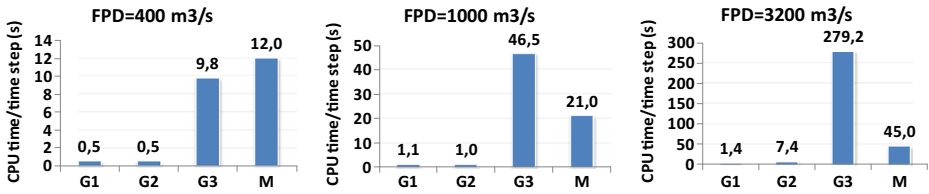


Fig. 6 2DH models performance assessment results: CPU times per time step, considering different FPD, obtained for Sobek 2DH models (grids G1, G2 and G3) and RMA2 2DH model (mesh M)

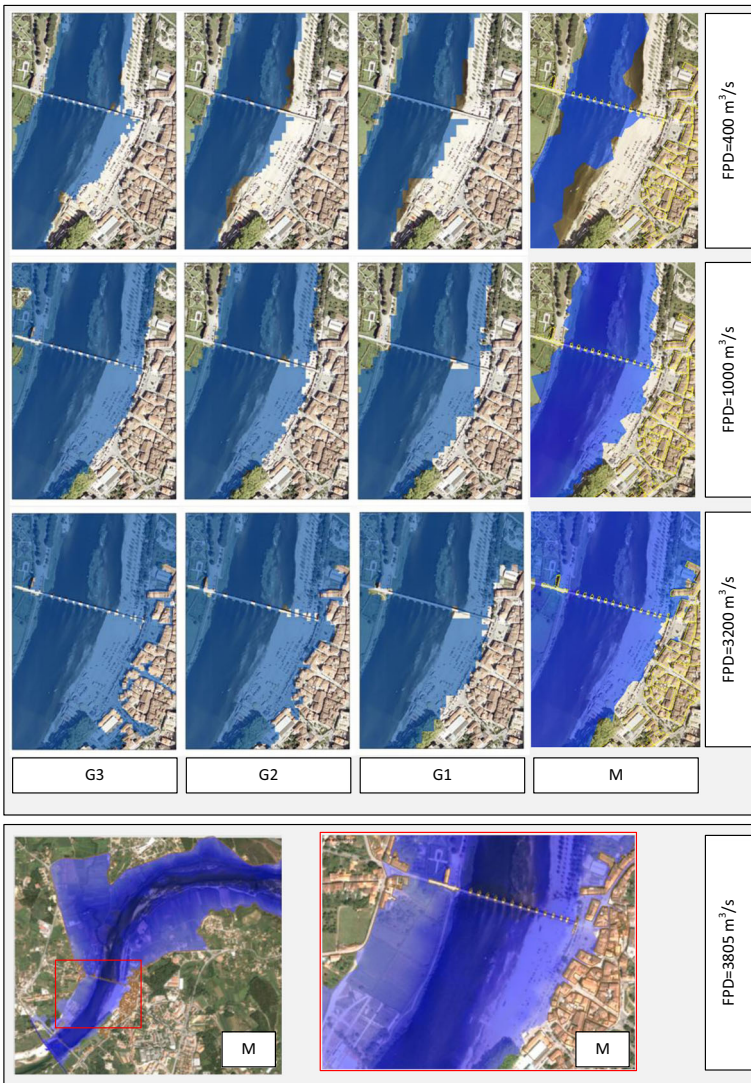


Fig. 7 Inundation maps within building areas obtained for different FPD using Sobek 2DH models (grids G1, G2 and G3) and RMA2 2DH model (mesh M)

Table 3 Ratios between the flood inundation areas obtained for the different grids and the inundation area obtained with the 2DH mesh

FPD (m ³ /s)	Grid/Mesh			
	G1	G2	G3	M
400	0.83	0.84	0.96	1.00
1000	0.88	0.91	0.97	1.00
3200	0.95	1.02	1.05	1.00

at Fig. 7, it is clear that the G3 grid resolution it is not sufficient to accurately represent the narrow streets in the building areas since they are narrower than 5 m.

The ratios between the flood inundation areas obtained for the different grids and the inundation area obtained with the RMA2 2DH triangular mesh are presented in Table 3.

As the grids spatial resolutions increase the inundated areas approach the area obtained with the RMA2 model for FPD of 400 and 1000 m³/s. Differences between results are attenuated for FPD of 3200 m³/s.

RMA2 model could be used as an efficient alternative to simulate inundations when the expected computation time of Sobek models becomes prohibitive to be used in a forecast system.

5.5 Results of the 2DH Model

From the obtained results, it can be concluded that scenario S_{RP50} showed the most critical effects related to inundations at Ponte de Lima's historical center as can be seen in Fig. 6.

In this scenario, the results obtained for the water levels immediately upstream and downstream of the Medieval Bridge were 11.92 and 8.96 m respectively, whereas the water level recorded in S. Paulo's Tower was 2.26 m. These results show that this scenario originates a critical flood situation at downtown Ponte de Lima, with a water level above the one calculated in S4 scenario and still greater than that registered in 1987 flood event (1.80 m). Figure 7 presents the flooded areas, comprising the historical center of Ponte de Lima, evidencing a severe impact in the upstream area of the Medieval Bridge.

With regard to the impact of tides in the Ponte de Lima's weir discharges, it can be concluded that the tide influences flow conditions, but only when the river discharges are lower than 150 m³/s, while having no influence during flood events. However, the tide level is of greater influence to the water levels verified downstream Ponte de Lima town during these events.

6 Conclusions

Results obtained with the 1DH hydrodynamic model of the river Lima basin showed that this model constitutes an adequate tool for the simulation and determination of flood characteristics and of the influence of different hydraulic structures and natural processes, such as the case of tidal level in river flow conditions during normal and extreme events.

Regarding Touvedo and Alto Lindoso dams operating conditions, it was concluded that water releases have an important effect upon the occurrence of floods in the town of Ponte de Lima, as these present a remarkable effect in river water levels and discharges at this location. These changes are also noticeable for scenarios where only turbinated discharges are considered, since water levels at Ponte de Lima are dependent of the hydropower generation

schedules. It can therefore be concluded that Alto Lindoso and Touvedo dams are the most important structures for flood control in the river basin due to its large water storage capacity.

A two-dimensional model based on an unstructured mesh revealed to be more computationally efficient if high spatial resolution is required. If inundation details are necessary in the building area, rectangular grids are not appropriate to carry those simulations in an operational environment, given its narrow streets, since these require prohibitive computational times.

The results obtained in this work clearly show that there is a high flooding risk in the surrounding areas of the Medieval Bridge, which includes most of the historic center of the town of Ponte de Lima.

This fact confirms that the applied hydroinformatic tools are of great interest for the prediction and management of flood events in urban areas. Although in this work the 2DH model was used to study in more detail the area surrounding the town of Ponte de Lima, these tools may be applied to the study of flood situations in other locations within the river Lima basin. The implemented models showed to be efficient for the simulation of flood events and could be used as a base model for the implementation of a flow forecast system at this river basin to support early warning and water management decisions during flood events.

A new combination of software tools for floods simulation was presented. This modelling system was implemented for a specific Portuguese river basin where the most important hydropower plant is installed. A computationally efficient alternative for simulation of 2-D inundation using a finite element mesh instead of a grid, where complex geometries (like in urban areas) imply high spatial resolution, was demonstrated.

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