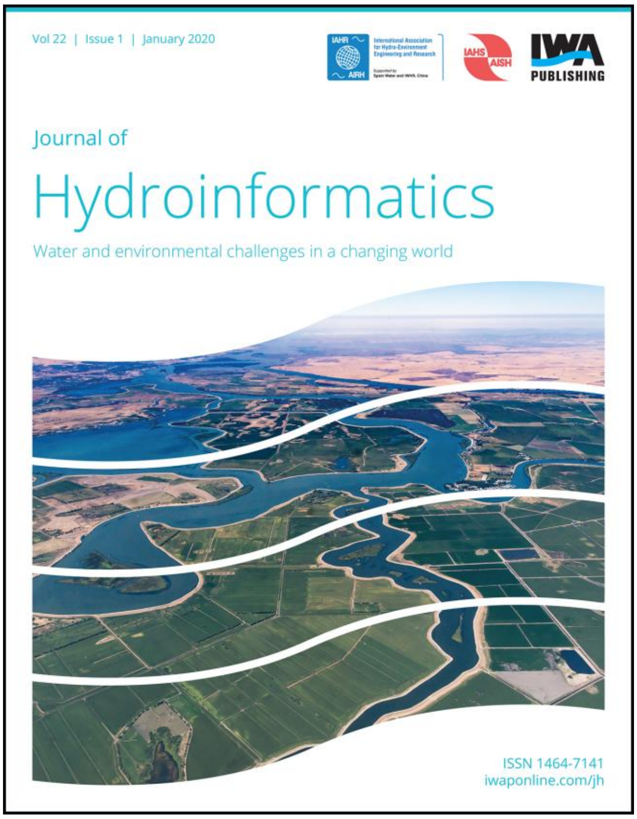
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Assessing causes and associated water levels for an urban flood using hydroinformatic tools

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ABSTRACT

Flood events are dependent on meteorological conditions but also depend on several other factors that are case specific, with relevance for reservoir operation. Hydrological and hydrodynamic models are valuable tools for understanding complex river hydrodynamics during flood events. These tools have been applied to improve understanding of the causes for an urban flood event that occurred between 9 and 11 January 2016 in the Mondego river basin, at Coimbra city (Portugal). Seven different factors that can, independently, influence the river flow at the study site were identified: three of them can be associated with the operational discharge schemes of the three upstream dams; two factors with the runoff flows from uncontrolled contributing sub-basins; another one related to discharge measurement uncertainty at a downstream dam; and finally, the seventh studied factor was sedimentation occurring in the main channel of the flooded river stretch. Hydroinformatic tools were applied in different scenarios allowing the characterization and identification of each one of the identified key factors responsible for the flood event. A proposal for a flood early warning system is presented based on the knowledge resulting from the studied flood event.

Key words | floods modelling, hydroinformatic tools, reservoirs operation

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INTRODUCTION

Regulations have been established in order to control or mitigate flood consequences since they usually are associated with severe social, economic, and environmental impacts. An EU Flood Directive (EU 2007) requires the development of flood hazard maps, which may include information on hydrological and hydrodynamic characteristics of vulnerable regions, i.e., inundated areas, river discharges and water levels. However, the occurrence of floods depends on complex hydrological processes and anthropic actions whose individual contribution to the water level rise at particular locations is hard to distinguish. High rainfall events are not the unique factor that explains the occurrence of floods. Lack or inadequate urban planning, resulting in buildings and other infrastructures being built on floodplains, is responsible for major losses (Adeloye & Rustum 2011).

Deficient design or operation of the urban drainage systems can also be a cause for urban floods. Several additional threats, like increasing of impervious areas and climate change can aggravate this problem (Hammond *et al.* 2015; Palla *et al.* 2018). Drainage systems frequently discharge into rivers that are embedded in the urban environment as a consequence of cities growing (Phong 2015). Floods are one of the main instigators of the interaction between rivers and cities, leading to artificialization of river banks, installation of defence structures and, in many other cases,

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to the construction of dams to control flood flows during extreme precipitation events (FitzHugh & Vogel 2011). Proper operational dam rules during flood events should be guaranteed to defend urban areas located near by river banks.

Methodological approaches to deal with flooding problems recommend the incorporation of decision support tools in the process to better investigate which planning options and remedial actions need to be taken at river basin scale and which operational management actions are more effectively protecting urban populations (Werner *et al.* 2004; Demir & Krajewski 2013; Henonin *et al.* 2013; Filatova 2014; Sharma *et al.* 2014; Goharian & Burian 2018). These decision support systems should be based on adequate hydroinformatic tools capable of processing, analysing and simulating the relevant hydrological data required for potential flood assessment in at-risk locations.

Uncertainty related to hydrodynamic models is usually associated with model inputs, model structure and calibration (Deletic *et al.* 2012; Efstratiadis *et al.* 2014; Dimitriadis *et al.* 2016; Papaioannou *et al.* 2016; Bellos *et al.* 2017; Teng *et al.* 2017). Nevertheless, software packages for two-dimensional simulation of water levels and flow characteristics during flood events have been found to be efficient (e.g., Stelling & Verwey 2005; Liang 2010; Tsakiris & Bellos 2014). Néelz & Pender (2010) presented a sound performance analysis consisting of the comparison of software packages in the simulation of different inundation tests. SOBEK (Deltares 2011a) was one of the evaluated software packages. This software showed the capabilities to capture the detail of the flow field for all the tests involving complex geometries of the floodplain. When applied in operational management, the computational time costs, depending on the spatial resolution, could be a restriction for some simulations. Nevertheless, capabilities to simulate operations adopted at hydraulic structures are fundamental in order to properly consider discharges at dams during flood events. The real-time control module is a quite distinctive feature of this software solution that allows simulation of complex river flow scenarios. Moreover, it includes a hydrological module, that together with the hydrodynamics (1D and 2DH) modules, constitutes an adequate solution for river flood modelling.

Pinho *et al.* (2018) have identified the operational discharge scheme at two of the upstream dams as the main cause for a flood event that occurred near the city of Coimbra (Portugal), in January 2016. Seven different factors that can, independently, influence the river flow at the study site were identified: three of them can be associated with the discharges at the three upstream dams; two factors with the runoff flows from uncontrolled contributing sub-basins; another one related to the operation of a downstream dam; and finally, sedimentation occurring in the main channel that could cause water levels to rise during flood events.

This relatively complex case study was properly monitored, thus constitutes a rare opportunity to assess the performance of a set of actual software packages for river flood and inundation modelling (Teng *et al.* 2017). Modelling of monitored historical intense inundation events at river basin scale is quite rare since floods are controlled at monitored basins and normally for inundations at uncontrolled basins the hydrometric data are not sufficient.

Application of modelling tools to anticipate inundations associated with floods or assess flood mitigation measures (e.g., Aparicio *et al.* 2009; Popescu *et al.* 2010; Schwanenberg *et al.* 2013; Gibertoni *et al.* 2014) is quite common. Moreover, development of hydroinformatic platforms for flood or inundation warnings must be based on robust models, including realistic capacity to simulate the hydrology and the river's hydrodynamics within the basin, and particularly for the flood-prone areas. These platforms are responsible for the synchronization and management of all the required data in the case of flood forecasting and automation of model running (Werner *et al.* 2012).

This paper presents a detailed description of a set of hydrological, hydrodynamic and morphodynamics models used to study that flood event. The set of available data, not only from the river system (topography, bathymetry, dam operation, etc.), but also from the flood event, such as flow, water depth and rainfall, provide a unique opportunity to validate and improve the knowledge of river floods in rivers controlled by dams. Seven different factors that influence river water levels at Coimbra city are identified and a flood forecast early warning system for the Mondego river basin is proposed, based on the knowledge acquired from the flood event study. Dam operations' auditing and improvement, and responsibility attribution for security purposes are among the potential applications of this suite of tools to flood events.

METHODS

Study area

Mondego river basin is a Portuguese basin with an approximate area of 6,660 km^2 characterized by a Mediterranean climate with a strong seasonal variation of flow associated with flood and dry events, with an average annual influx of about 1,213 hm^3 and 4,032 hm^3 in a dry and in a wet year, respectively. The river extends from its spring in the Serra da Estrela mountains with an altitude of 1,500 m, to the river mouth at Figueira da Foz, in the Atlantic Ocean, for 258 km. Much of its course develops in a very embedded valley, entering the area of Coimbra in an alluvium basin. The main tributaries are the rivers Alva, Dão and Ceira. In this basin, there are several dams whose operation influences the river flow characteristics near the city of Coimbra: Aguieira (the greatest storage capacity reservoir), Raiva, Fronhas and Coimbra. The water stored at Fronhas dam can be transferred to the Aguieira reservoir. Flows discharged or turbined to Raiva dam may be pumped to the Agueira reservoir (Figure 1).

Coimbra dam has a small reservoir volume (1.6 hm^3 for water level at 18.0 m above sea level (asl)) but is responsible for controlling upstream levels for river discharges up to 930 m^3/s. For higher discharges, according to this infrastructure's operational rules, its floodgates are completely opened. In this scenario, river water levels are only conditioned by the cross-section contractions caused by the bridge and mobile gate support pillars and the downstream river section.

The study focuses on the intermediate stretch of the Mondego river located between the main upstream dams and Coimbra city. The upstream dams (Aguieira, Raiva and Fronhas) are also included in the analysis developed in this work.

The river reach comprises three distinct segments. An initial segment, located downstream of Raiva dam, formed by relatively narrow river cross sections with about 80 m of surface width and a wider floodplain used for agricultural activities, both located in an embedded valley. In this segment, the longitudinal profile presents a slope of the order of 0.08%, and the river includes several small weirs along its course. The following segment, that presents a cross

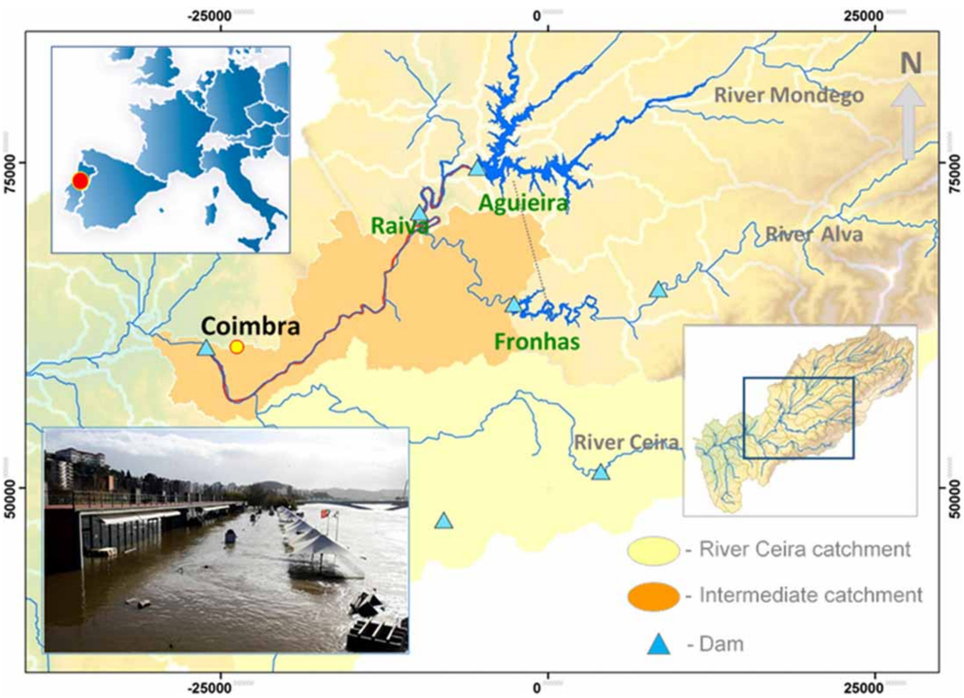

Figure 1 | Study site location, Mondego river basin with the location of the dams and photo of Coimbra inundation that occurred in January 2016 (Pinho *et al.* 2018).

section with a surface width of about 200 m under frequent river discharges, makes the transition between the initial one and the third where the river banks are artificially fixed with river walls. The top of these walls can be inundated at certain locations during flood events.

January 2016 flood event

On 11 January 2016, a severe inundation took place at Coimbra city affecting several local infrastructures. Rainfall was recorded at seven meteorological stations in the Mondego river basin during the flood event (for the period between 1 and 12 January). Hourly records were obtained from the National Water Resources Information System at the following meteorological stations: Alagoa, Maçainhas, Mangualde, Pombal, Santa Comba Dão, Sátão and Soure. Recorded daily maximum values for the flood event were compared with the historical daily maximums at each station. The recorded values on 11 January 2016 vary between 29% (Maçainhas station) and 77% (Santa Comba Dão station) of the historical maximums. A comparison between accumulated rainfall between 1 and 12 January 2016 (Figure 2) and the maximum value of the accumulated values in consecutive periods of 11 days of the historical records was also carried out. In this case, the values of accumulated precipitation were lower than the maximum historical ones for the period of the flood event. They varied from 30% (Maçainhas station) to 77% (Santa Comba Dão station) of the historical accumulated maximum values (411 mm and 424 mm, respectively).

Hourly hydrometric data were made available by the Portuguese Environment Agency (Pinho *et al.* 2018); water levels immediately upstream and downstream of Coimbra dam (Figure 1), at the upstream reservoirs (Aguieira, Raiva, Fronhas) and at Santa Clara Bridge hydrometric station located in the vicinity of the inundated area. Inflows and outflows at all the dams were also made available. Moreover, discharges near the river Ceira mouth and at Coimbra dam were estimated based on rating curves available for these locations.

The water level at Aguieira reservoir started rising on 1 January, 2016, from 117.89 m elevation until reaching a value of 120.12 m on 10 January, at midnight, around the beginning of the occurrence of the flood event. During this event, a maximum value of 124.66 m was reached (Figure 3). At Fronhas reservoir there was an increase of water level from 118.59 m (1 January 2016, 00:00) and a maximum water level of 131.94 m (12 January 2016, 06:00). This variation resulted from the storage of almost all of the reservoir inflows during the initial phase of the period under analysis. During the flood event, part of the volume was transferred to the Aguieira reservoir. At Santa Clara Bridge hydrometric station (located immediately downstream of the bridge), the water level reached 19.56 m. It should be noted that this station is located about 1,300 m upstream of Coimbra dam. The water surface elevation between these two locations was 1.55 m at the flood's peak time.

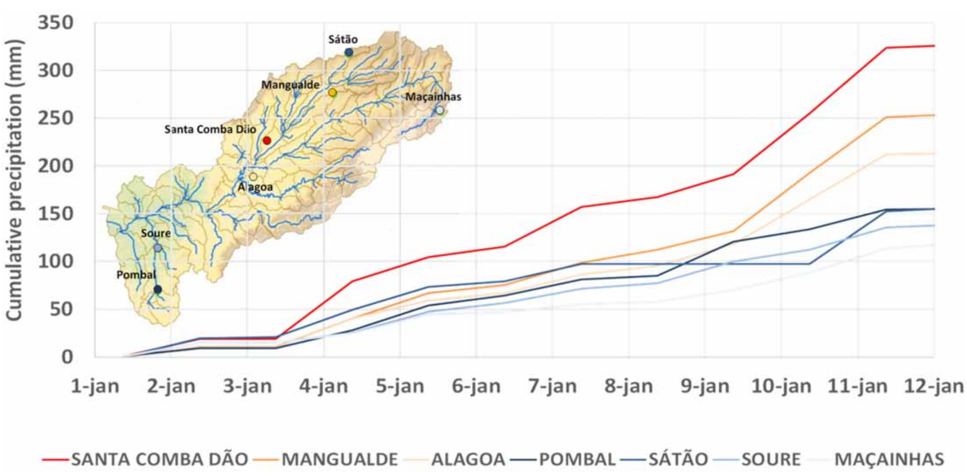

Figure 2 | Cumulative precipitation registered between 1 and 12 January 2016.

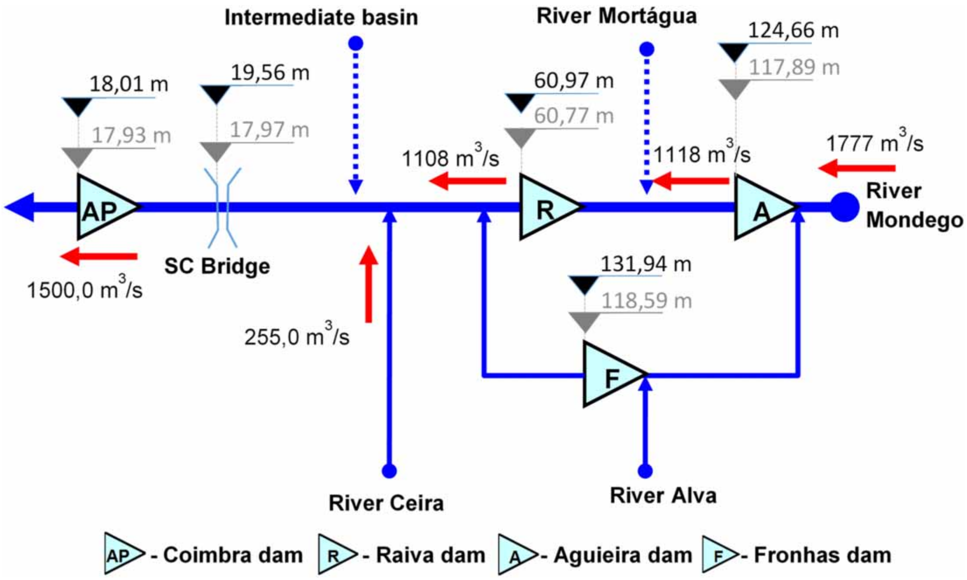

Figure 3 | Hydrometric measurements during the flood event. Water levels on 1 January (grey numbers) and maximum water levels and discharges (black numbers).

The inflow hydrograph at Aguieira reservoir presented a peak of 1,777 m^3/s (11 January 2016, 02:00). Other potential flows to this reservoir (transferred from Fronhas reservoir and/or pumped from the Raiva reservoir) are not considered in this inflow maximum value. The maximum discharge at Aguieira dam reached 1,118 m^3/s (11 January 2016, 12:00). During the initial phase of the period under analysis, the operation of the dam includes turbine and pump periods (records not included in this paper). The maximum discharge at Raiva dam reached a value of 1,108 m^3/s on 11 January 2016 at 12:00. River Ceira flows (at Ponte Conraria hydrometric station) were estimated based on the rating curve, presenting a maximum value of 255 m^3/s on 11 January 2016 at 14:00. At Coimbra dam the estimated peak flow was 1,500 m^3/s. This flow, according to information provided by the Portuguese Environment Agency, was estimated based on the original rating curves that were defined before the construction of Coimbra dam.

Hydrological, hydrodynamic and two-dimensional models

The flood event was analysed using measured hydrological data and numerical models specifically implemented for this work. The river basin hydrology was simulated by a model based on the Sacramento concept implemented with GIS support. The river and reservoirs hydrodynamics were simulated using a model implemented with SOBEK software. Two complementary local models were implemented, with the aid of RMA2 (ERDC 2013) and Delft3D (Deltares 2011b) software packages. These were used in the analysis and verification of the downstream river flow characteristics influenced by the dam pillars' constriction and in the assessment of sedimentation conditions in the inundated fluvial stretch.

Sobek river model

The Sacramento hydrological model, implemented in SOBEK software (Deltares 2011a), allows the quantification of river discharges using precipitation and evapotranspiration data as input (Singh & Woolhiser 2002). The Sacramento model conceptualizes the watershed as a soil column divided vertically into two storage zones which are filled and emptied to simulate infiltration, percolation, baseflow and interflow through the watershed. The upper and lower zones represent the infiltration capacity of shallow soils and the underlying aquifer, respectively. Runoff is computed as the net excess volume remaining from precipitation after interception and infiltration have been satisfied. Rates of infiltration and soil water volume capacities are represented with conceptual parameters which correspond closely to physical values associated with soil properties such as void space ratio and saturated hydraulic conductivities (Burnash & Ferral 2002). This model was implemented for two sub-basins (Figure 1) based on the available hydrometric and meteorological stations' data. An optimization tool (CRC 2004) was applied for the estimation of the 17 required parameter values for each sub-basin.

River and dam hydraulic structures were modelled with SOBEK software package (Deltares 2011a). It is based on a robust numerical method that allows solutions to be obtained for complex model set-ups. The governing equations are based on one- and two-dimensional version formulations of the Saint Venant equations and solved numerically by a finite difference method known as the Delft scheme (Verwey 2001). Main inputs to the model are the river stretches and associated cross sections and roughness coefficients. Different combinations of boundary conditions are allowed and a complete set of hydraulic structures can be inserted in the river schematization. The spatial discretization of the model was performed using GIS map data of the river basin. It extends from the Aguieira and Fronhas dams (upstream boundaries) to a section located downstream of Coimbra dam (downstream boundary). All the tributaries present in this intermediate reach of the Mondego river were considered in this model (Figure 4). The model was discretized by 479 calculation points, 12 open boundaries and 27 controlled discharges. Simulation of hydraulic structures was implemented applying the real-time control module. The river channel geometry was defined considering 147 cross sections, based on bathymetric surveys and Lidar data.

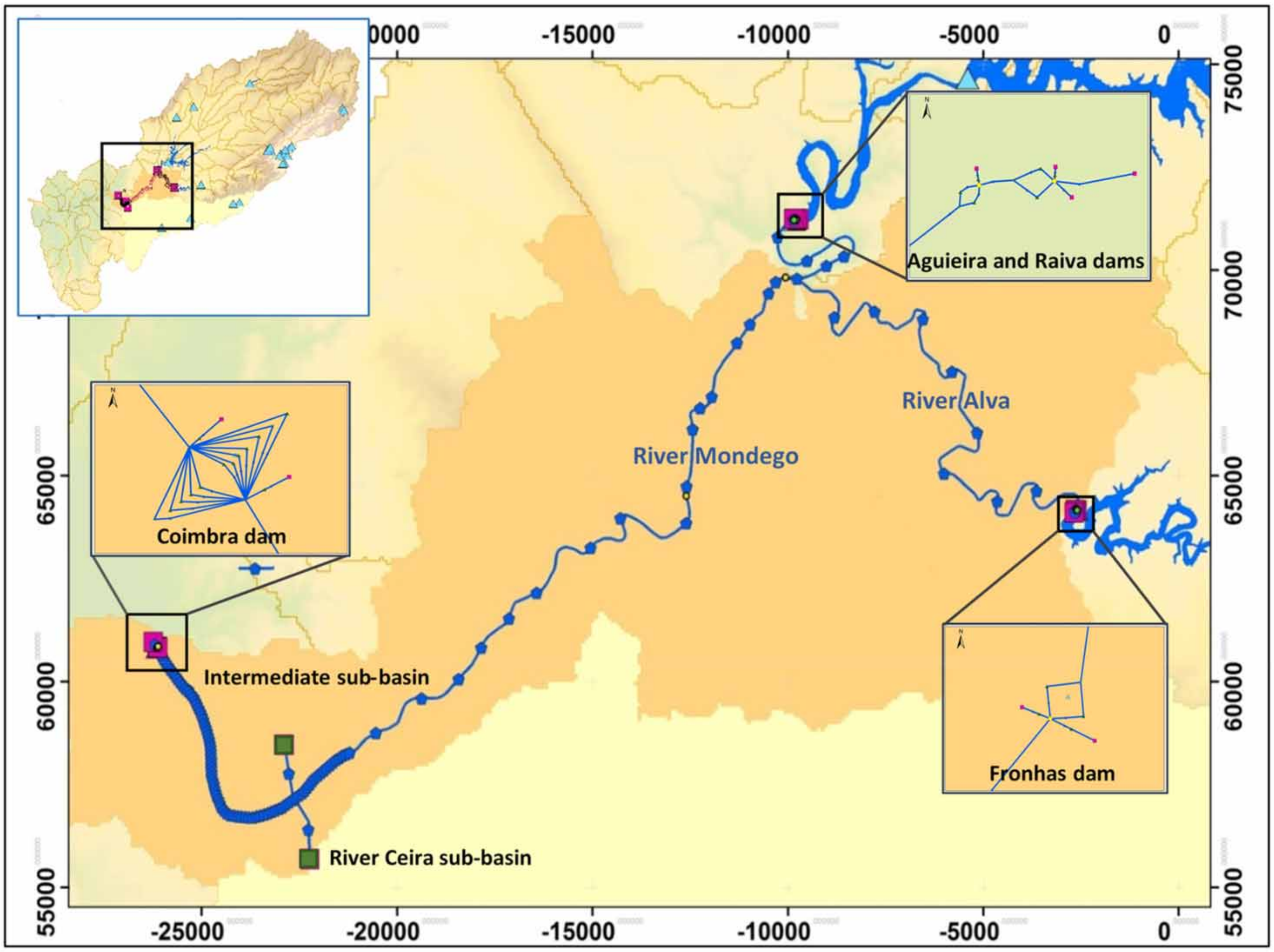

Figure 4 | Mondego river model implemented in SOBEK software, including Coimbra, Aguieira, Raiva and Fronhas dams and hydrological models of Ceira and intermediate sub-basins.

Hydraulic structures at dams were modelled in order to consider all discharges that occurred during the flood event at the upstream reservoirs. They include flood gates, bottom outlets and turbines that were discretized through orifice or pump nodes. Water levels within the river stretch under analysis depend on the operation of the upstream dams, hydraulic structures and on the operation of the Coimbra dam floodgates. Thus, the real-time control module available in SOBEK software, was crucial to define reliable hydrodynamic scenarios to analyse the observed inundation conditions.

RMA2 local model

Water discharges at Coimbra dam are estimated based on rating curve and measured water levels. This rating curve (Figure 5) was defined before the construction of the dam so that, in the case of extreme events, all of its gates should open. However, the river cross-section contraction resulting from the dam pillars could modify the flow characteristics at this stretch. A local hydrodynamic model for the verification of the flow characteristics during flood events at Coimbra dam was implemented using RMA2 software. This software, based on the finite element numerical method, solves the shallow water equations in unstructured meshes, that are suitable for discretization of the river geometry at the dam cross section. The domain was discretized with an unstructured mesh with 6,839 quadratic triangular elements and 14,076 nodes. Bathymetry was defined based on the geometric characteristics of the dam and the river bathymetry downstream (Figure 5).

Delft3D local morphodynamic model

Considering the uncertainty of flood water levels arising from the lack of an updated bathymetry of the river stretch near the city of Coimbra (the most recent bathymetric survey was completed in 2008), a two-dimensional morphodynamic model was implemented with Delft3D software (Deltares 2011b). For this work, the 2DH version of the

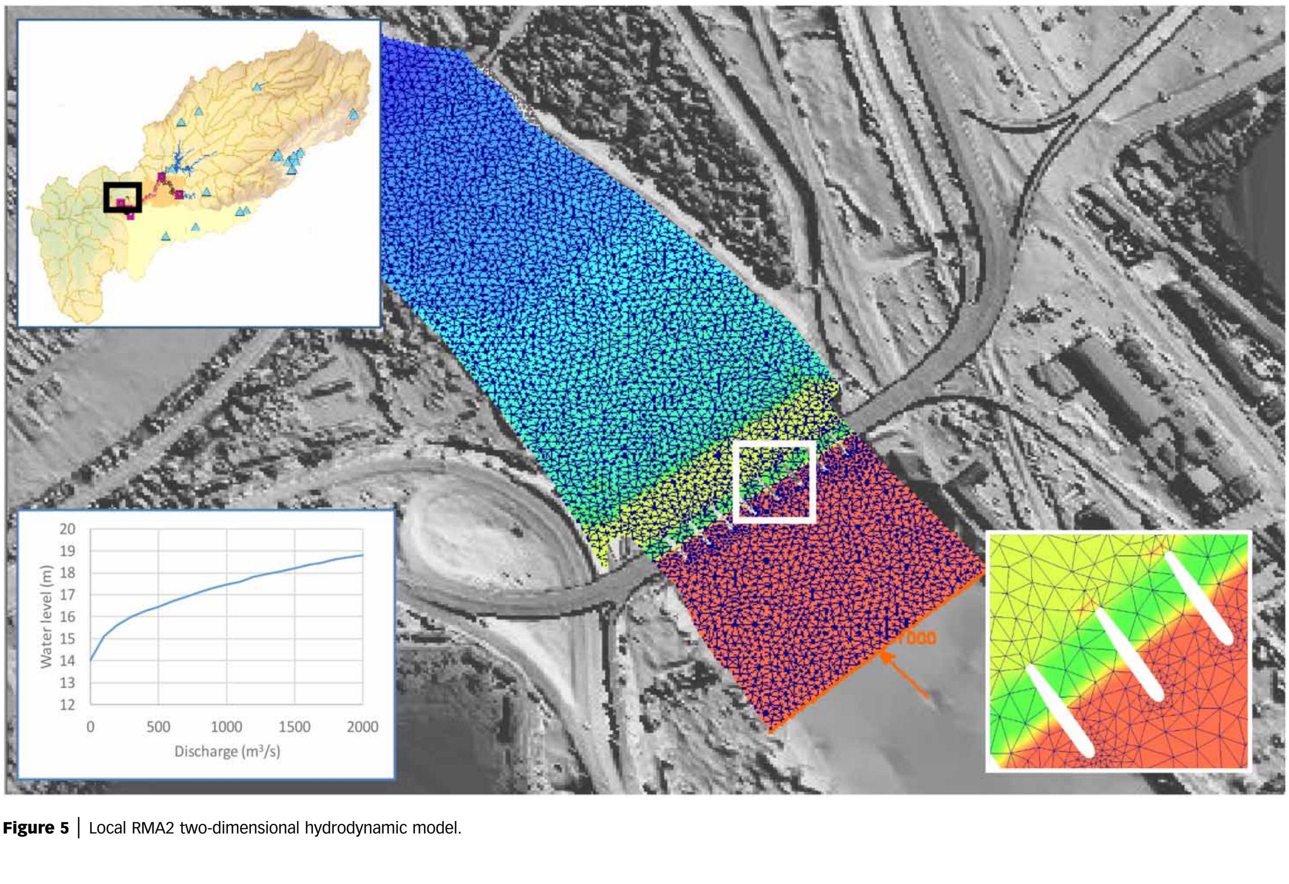

Figure 5 | Local RMA2 two-dimensional hydrodynamic model.

Delft3D modelling suite was selected, which is able to accurately simulate the hydrodynamics and morphodynamics during flooding events. This numerical model solves depth-averaged free surface flow equations, taking into consideration several processes such as bed friction, turbulence, supercritical and subcritical flows, density effects related to horizontal temperature and salinity gradients, and drag forces created by vertical structures.

This model was discretized with a high spatial resolution grid (~5 m × 5 m). The model was set up to analyse the river bed morphology between 2001 and 2008 (Figure 6). During this period the river showed a sedimentation tendency, registering the formation of sediment bars that reached 1 m above the bed level of 2011 at several places.

The simulation period was artificially defined based on extreme events that took place in the period of analysis. From March 2001 to January 2008, the following occurrences were registered according to the average daily flow data: flow of 500.0 m^3/s in 4 days, flow rate of 700.0 m^3/s in 2 days and river flow of 900.0 m^3/s in 2 days. The sediments of the bed are composed of coarse sand. In the adopted simulation a characteristic dimension of 2 mm was considered.

Model calibration

Hydrological model

The hydrological model was calibrated for the river Ceira sub-basin based on hydrometric station data available at the downstream river reach before the river mouth and in the recorded rainfall data registered during the flood event. The Sacramento model parameter values were obtained using an optimization tool. A Nash–Sutcliffe efficiency coefficient value of 0.71 was obtained for this event (Figure 7(a)). The same Sacramento parameter values were adopted for the intermediate sub-basin.

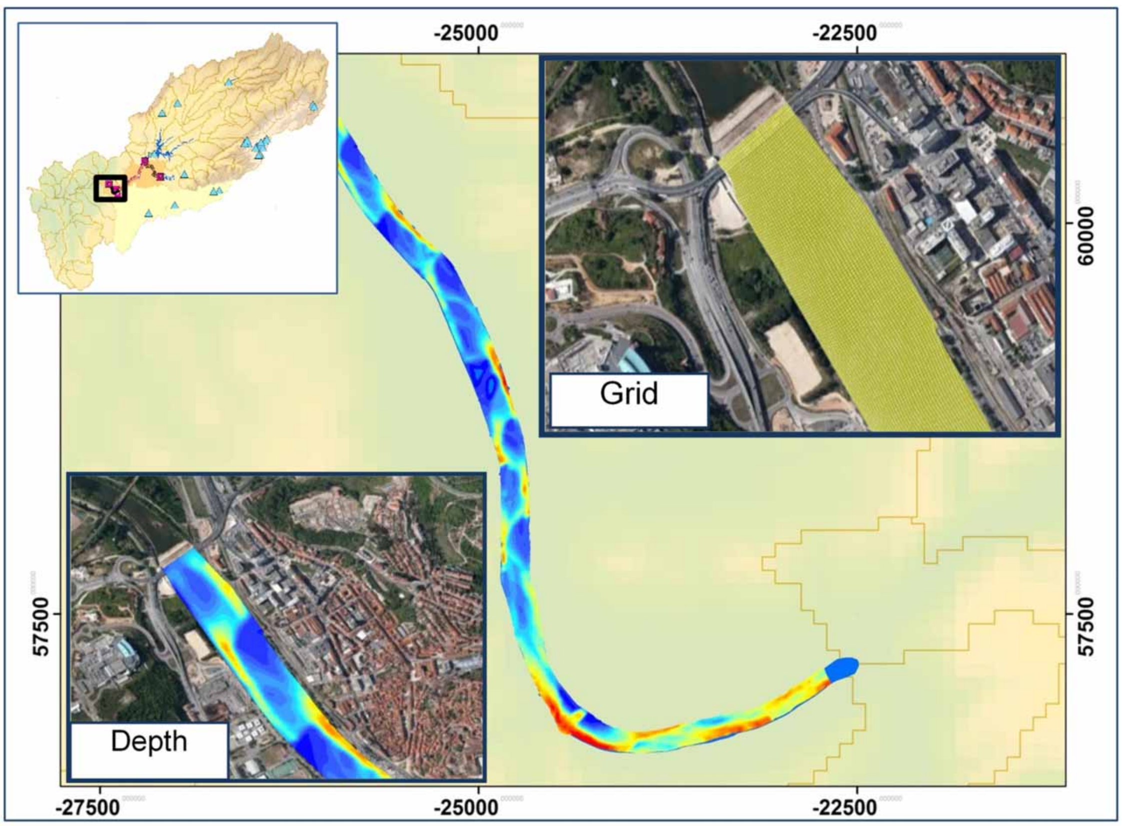

Figure 6 | Local Delft3D two-dimensional morphodynamic model.

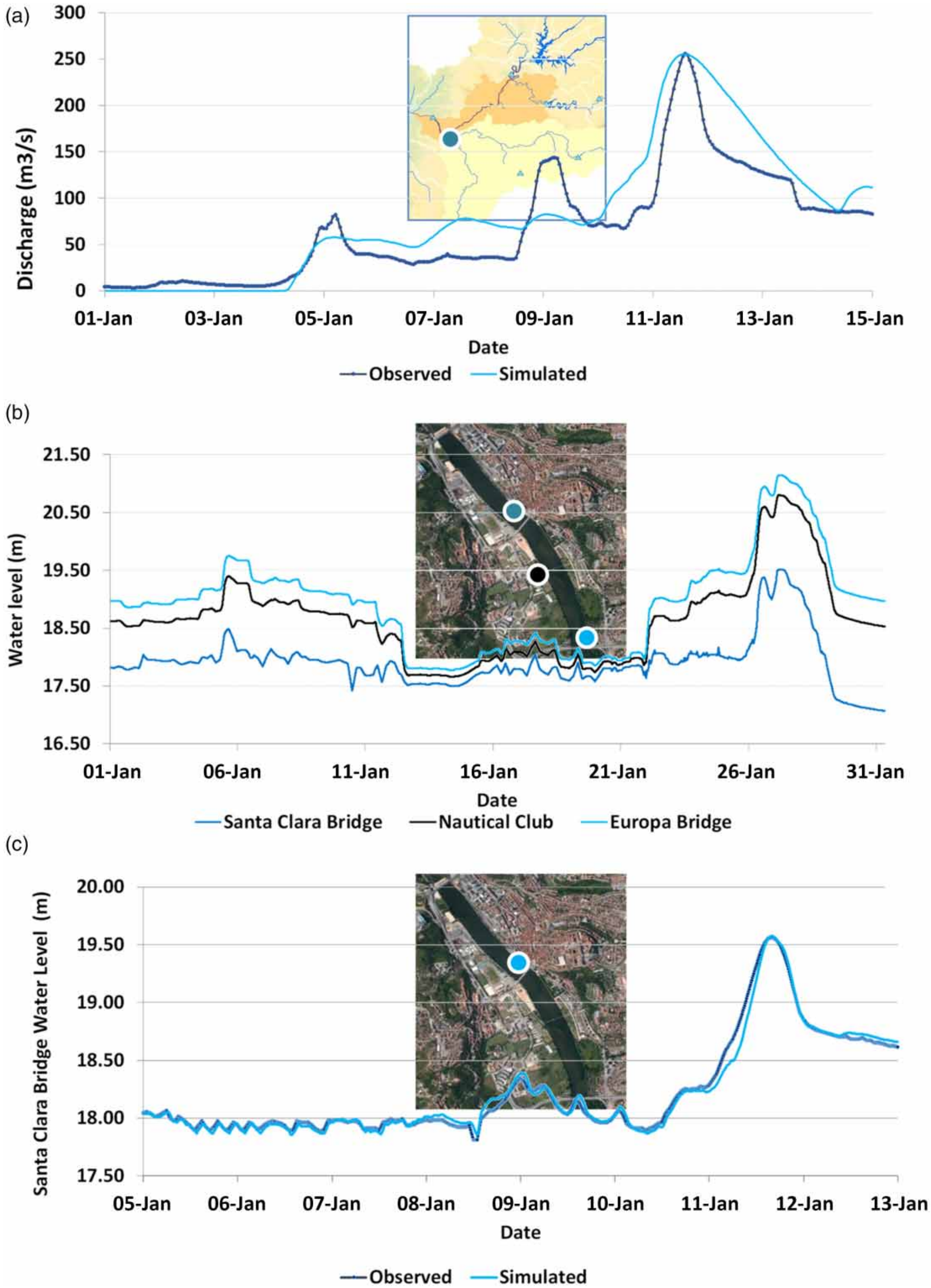

Figure 7 | Model calibration results: (a) comparison between the observed flow rates registered at Ponte de Conraria hydrometric station and flow rates simulated by the hydrological model; (b) 2001 flood water levels results at three different locations; (c) measured and simulated water levels at Coimbra dam for the January 2016 flood event.

River model

The one-dimensional hydrodynamic model was calibrated and validated considering the observed water level information registered at Santa Clara Bridge hydrometric station. This station has a location within the domain under study. Two different flood scenarios were defined in the calibration procedure: (i) in the first one the Manning roughness values were defined in order to approximate the simulated values to the ones registered at three locations

Table 1 | Comparison between water levels obtained by Sobek model simulation of 2001 flood event and water levels obtained by Santos *et al.* (2002)

Water level, 1DH model (m)			Water level, Santos *et al.* (2002)		
Santa Clara Bridge	Nautic Club	Europa Bridge	Santa Clara Bridge	Nautic Club	Europa Bridge
19,51	20,80	21,10	19,50	20,86	21,05

for the 2001 flood event and using available bathymetric data for 2001; (ii) in the second scenario the hydrological conditions of the January 2016 flood were adopted together with the bathymetry of 2008.

In Figure 7(b), results regarding water levels are presented. They were obtained for three different study locations: Santa Clara Bridge, Nautic Club and Europa Bridge. Maximum water levels are depicted in Table 1 and compared with the ones obtained in a study of the 2001 flood at the Mondego river (Santos *et al.* 2002).

The differences found result from the uncertainties (Dimitriadis *et al.* 2016) associated with different geometric discretization, techniques and modelling parameters and a possible approximation on the exact site location used for the comparison. The order of magnitude of the differences found is compatible with the accuracy that is intended for the present work. It should also be noticed that the morphological variations that occur associated with the flood events with the magnitude of the simulated flood event (flood peak river flow around 2,000 m^3/s) may present a higher order of magnitude than the differences found, which can be reflected in water levels. Only hydrodynamic and morphodynamic coupling modelling may allow the evolution of the flood levels to be simulated more rigorously. Thus, only a bathymetric survey prior to the floods of 2001 could allow an integrated analysis of the evolution of the morphology and water levels during this event.

Results of water levels at Santa Clara bridge for the 2016 flood event simulation, considering all the relevant variables of the fluvial system, are presented in Figure 7(c). For this event the following metrics (Willmott 1982; Krause *et al.* 2005) were obtained: (i) Nash–Sutcliffe efficiency coefficient value of 0.98; (ii) statistical bias of 0.026 m; (iii) root mean square error of 0.057 m; and (iv) scatter index of 0.003. In this simulation, the opening sequence of the Coimbra dam floodgates, the discharged and turbinated flows in the upstream dams, the contribution of Ceira river and the intermediate basin flows estimated with the hydrological model, were considered. The quality of the obtained results is explained by the application of the appropriate calibration parameter values and by considering, in an explicit way, the opening sequence of the floodgates whose operation was defined with time series controllers.

A comparison between observed and simulated water levels registered at the upstream reservoirs included in the 1DH model for the January 2016 flood event is shown in Figure 8. The reservoirs were modelled considering the respective characteristic curves (volume – surface area) defined, considering the historical hydrometric information registered in their respective hydrometric stations. In Figure 8, also considered are the flow rates associated with the controllers of the simulated hydraulic structures. The results obtained for the calibration of the hydraulic structures indicate that the model simulates almost perfectly the operational aspects of the upstream dams.

Local models

For the local two-dimensional hydrodynamic model, a Manning coefficient of 0.01 $m^{-1/3}$ s and an eddy diffusion coefficient of 20 m^2/s were adopted. For the downstream morphodynamic model a value of 0.05 $m^{-1/3}$ s for roughness and 1 m^2/s for both the horizontal eddy viscosity and diffusivity were adopted.

RESULTS AND DISCUSSION

Results in terms of water level change at Coimbra city are presented in Table 2 for each one of the seven identified factors: (i) discharges of upstream Aguieira and Raiva dams; (ii) discharges at upstream Fronhas dam; (iii) river Ceira sub-basin flows; (iv) intermediate sub-basin flows; (v) operation of floodgates at Coimbra dam; (vi) uncertainty associated with river discharge measurements at Coimbra; and (vii) sedimentation at the downstream stretch.

The influence of each one of these factors was analysed based on different simulation scenarios applying the SOBEK model. The Mondego river flow discharge at Coimbra city is the result of the contribution of the river

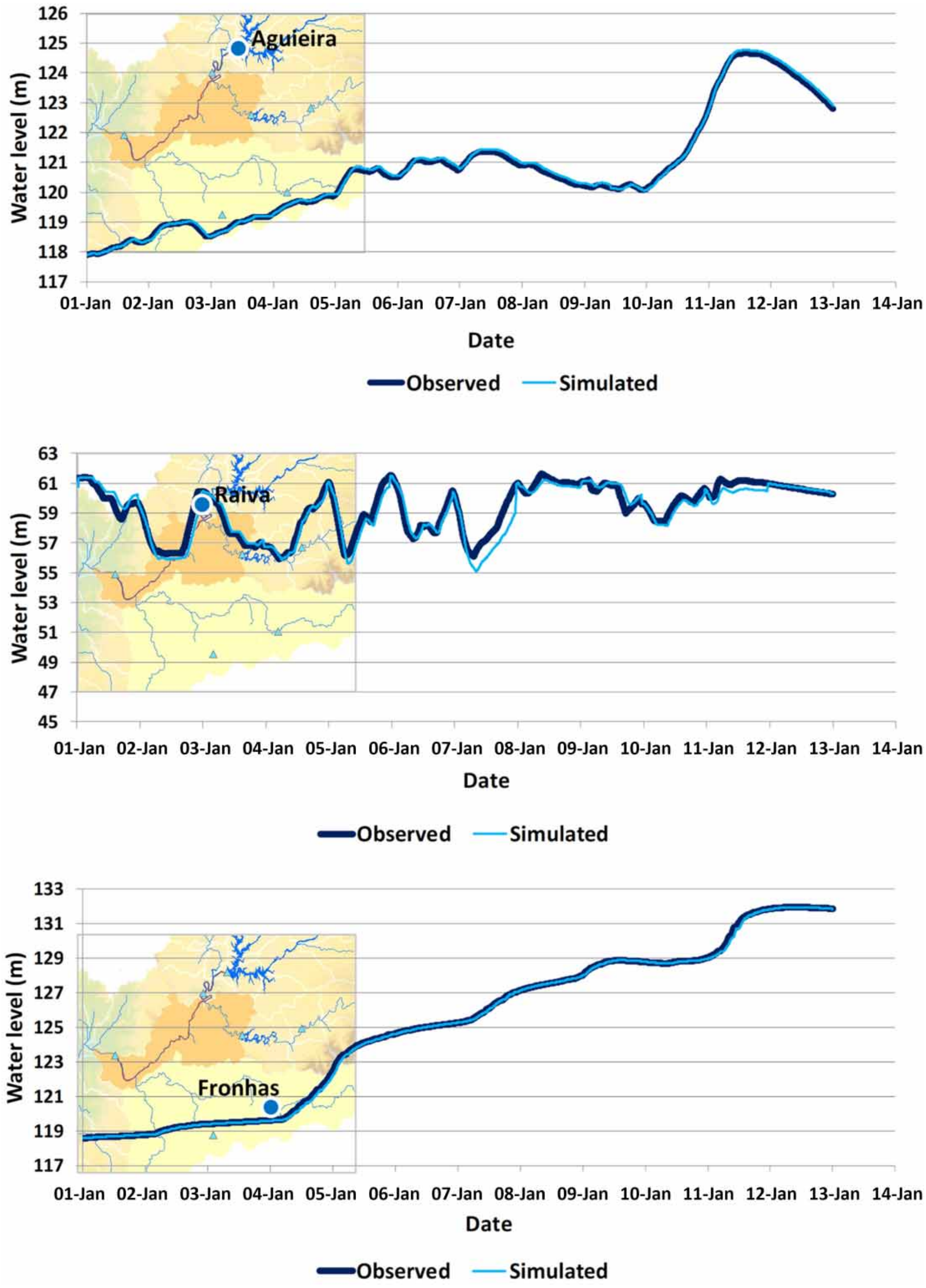

Figure 8 | Calibrated water level model results at upstream reservoirs.

Ceira, the intermediate sub-basin and from the upstream dam's discharges. The water level variation at Coimbra city was quantified to analyse the effect of factors (i) to (iv). In each one of these scenarios all the conditions that took place during the flood event were considered with the exception of the one that is being analysed in the corresponding scenario (considered with a null contribution). The variation in terms of water level at Coimbra city was registered and is presented in the first four rows of Table 2. It is clearly demonstrated that the discharges that

Table 2 | Simulated river water level variations according to different factors affecting inundations in Coimbra city

Inundation factors		Water level variations at Santa Clara bridge (m)
(i)	Absence of upper Aguieira and Raiva dam discharges	−1.36
(ii)	Absence of upper Fronhas dam discharges	−0.10
(iii)	Absence of River Ceira sub-basin flow discharge	−0.36
(iv)	Absence of intermediate sub-basin flow discharge	−0.12
(v)	Operation of gates at Coimbra dam: one gate closed	+0.20
(vi)	Uncertainty associated with river discharge measurements at Coimbra dam	±0.10 to 0.20
(vii)	Estimated sedimentation occurred in a period of 8 years	+0.50

result from the operation of the Aguieira and Raiva dams were the main cause for the water level rise and associated flood at Coimbra. This way, if a different discharge schedule was adopted during the flood event the inundation would be avoided or its impact mitigated.

During the flood event, all the Coimbra dam floodgates were opened as the river flow discharge increased. This operation is automatically implemented with a PID controller at the dam. If any of these gates were kept closed the effect of this operation (factor (v)) would imply an increase of +0.20 m in the water level at Coimbra city according to simulated results.

Regarding factor (vi), uncertainty associated with river discharge measurements at Coimbra dam, free-flow (flow with all gates opened) was simulated using the two-dimensional local model of the dam river stretch (Figure 5). It was verified that the measured upstream and downstream water levels during the flood event are compatible with the values obtained by the model when considering river discharges identical to those reached during the event, and it was possible to verify that the pillars' constriction is not responsible for a significant increase in the water level at this location. Indeed, for high river discharges (above 900 m^3/s) water levels at the dam seems to be conditioned by a downstream constricted river section. This way, variations in the relationship between levels and flows are expected due to the method used to estimate the discharges. This depends on the maintenance of geometric conditions and roughness of the river bed at the present time identical to those for which the water velocity measurements, that served as the basis for its definition. Two simulations with the SOBEK model were performed, considering in one of them all measured flows discharged during the flood event (dams) and estimated with the hydrological model (sub-basins), and in the other, omitting the contribution of the intermediate sub-basin that is the sole sub-basin which is dependent on the estimated discharges based on the rating curve. Obtained differences are in the order of 100 m^3/s. It turns out that, for each level obtained in this section, different flow rates may occur depending whether the estimation is made during the ascending or descending branch of the flood event. Flow variations of the order of 100 m^3/s estimated in the dam imply variations of the order of 0.10 m to 0.20 m at Santa Clara Bridge. Thus, we can say that this is the order of magnitude in the water level measurements at Santa Clara Bridge resulting from uncertainty associated with discharge estimated at the downstream Coimbra dam.

For the last analysed factor, (vii), the available data from two bathymetric surveys in a time interval of seven years (2001 and 2008) were used. A simulation with the local morphodynamic model was implemented. It should be noted that in the period between 2001 and 2008 there were no floods (river discharges below 900 m^3/s). Results obtained with the morphodynamic model for a simulation defined for the analyzed period (2001 to 2008) show similar patterns of bed morphology to those derived from the surveys analysed (Figure 9).

It should be noted, however, that similar values of sedimentation may occur during intense flood events. In a simulation involving a river discharge of 1,500 m^3/s and the same sediments, deposition values of the order of 0.70 m are reached in the locations identified in Figure 9, in a short time interval (few hours). Once the order of magnitude of the morphological variations occurring in the period between 2001 and 2008 was confirmed, and in order to estimate the influence of eventual bed level variations on water levels measured at Santa Clara Bridge, a simulation with the SOBEK model was defined, maintaining the river bed roughness parameters and inducing a

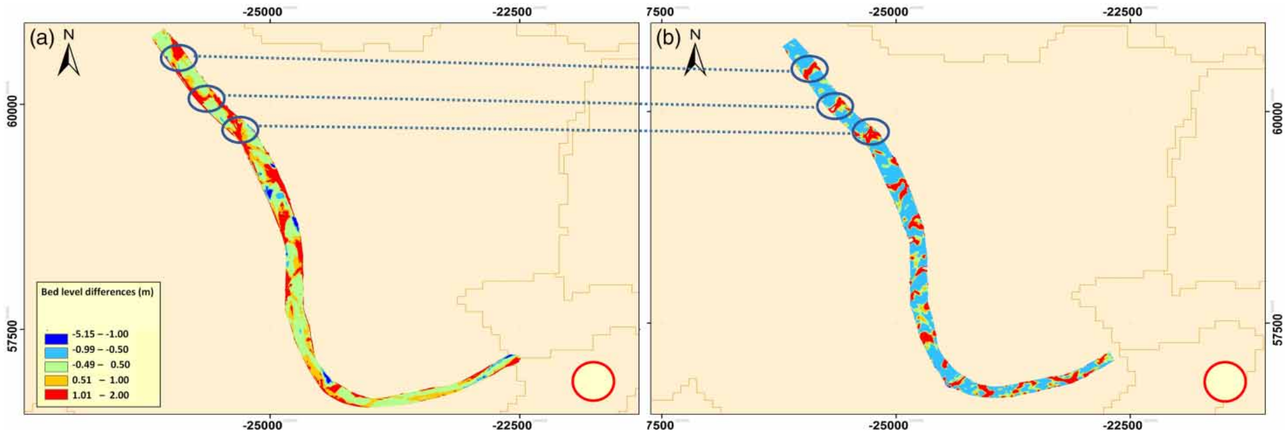

Figure 9 | Morphodynamic model results: (a) bed level differences between 2008 and 2001; (b) Delft3D model results for cumulative bed level change.

bathymetric variation similar to the one that occurred between 2001 and 2008. From the simulated results an increase of water level at Santa Clara bridge of 0.50 m was obtained, for this extreme and unlikely scenario since it is expected that the river bathymetry tends to an equilibrium profile in the absence of intense floods and under an almost constant fluvial discharges regime.

Obtained results for the factors influencing water levels at Coimbra city show that for the January 2016 flood event, the factor that had the greatest impact on the Mondego river water level at Coimbra (Santa Clara bridge) was the discharges at Raiva and Aguieira dams.

Several operational scenarios of the upstream dams were simulated with the calibrated SOBEK model. In one of those scenarios it was assumed that the discharges at Aguiera dam were limited to 670 m^3/s when the reservoir water level reached 120.12 m. In this case, the maximum water level will be 125.25 m (instead of 124.66) and instead of a water level of 19.56 m at Santa Clara bridge, it would have been 18.94 m. In this scenario the river discharges at Coimbra dam would be 1,090 m^3/s.

A more secure situation would be achieved if the initial water level at Aguieira reservoir had been 117.00 m (as established by the dam operating rules during flood events) and the dam discharges were limited to 670 m^3/s. In this case, the maximum water level would be 122.78 m and the water level at Santa Clara bridge would remain the same as the simulated in the previous situation.

Another scenario considered that the water level at Aguieira dam at the beginning of the flood event should be 117.0 m and discharges were limited to the maximum capacities of its turbines (450 m^3/s). In this case, the water level at Coimbra city would be 18.5 m (much lower in comparison with the maximum registered level of 19.36 m during the flood event).

Operation and early warning system

Results showed that flood control and dam operations are too complex, but the use of adequate tools can improve the understanding of the phenomena and help the decision-maker to manage these extreme situations.

Organizations responsible for flood management at Mondego river basin base their decisions on measured precipitation data, discharges observed at dams and hydrometric stations along with precipitations forecasts. A hydrological model is also available. However, this model was implemented about two decades ago and needs to be updated. The emergency plan for floods of Coimbra municipality specifies an alert for water levels based on criteria that result from recorded precipitation values, measured river flows at Coimbra dam and river discharges of Ceira river.

These approaches are not based on forecasts of hydrological and hydrodynamic models and thus, it is not possible to predict the water levels in the fluvial system that result from the operation of the dams and precipitation events with the appropriate accuracy and detail. They do not allow flood events to be foreseen with the desired anticipation and accuracy. Indeed, according to the current

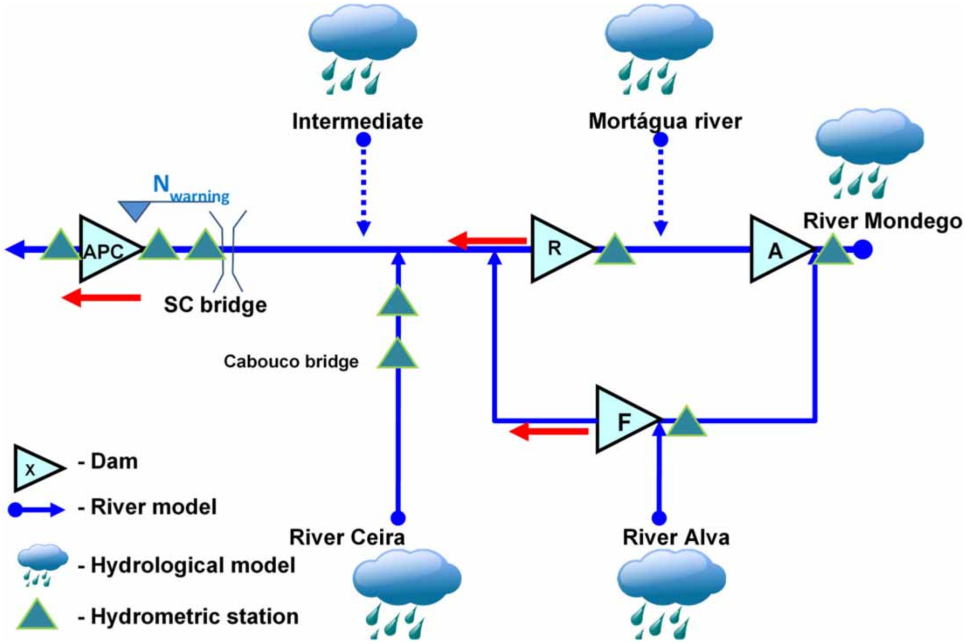

Figure 10 | Conceptual scheme of Mondego river basin flood early warning system.

predictive capacity of the most advanced technologies, limited to 1 or 2 days, the use of this type of technology considerably increases the capacity to plan operations to minimize the impacts of floods.

In an artificial system such as the Mondego river, operational rules should be clear and preferably monitored through technological platforms that facilitate and integrate relevant information and are shared by all stakeholders in the decision-making process. They should include communication tools with automatic early warnings. An early warning flood forecasting system for the Mondego river basin should include a hydrological and hydrodynamic modelling of the main sub-basins and rivers, as identified in the conceptual scheme proposed in Figure 10.

The hydrological models should consider diversified sources of precipitation forecasts and should be implemented with techniques that allow efficient assimilation of monitored data. Hydrodynamic models should be integrated with hydrological models to allow water level forecast at locations vunerable to flood. The models should also consider the simulation of the operating rules of the hydropower plants through methodologies based on real-time control techniques.

CONCLUSIONS

The results obtained showed that the applied hydroinformatic solutions constitute an excellent instrument to analyse a complex system under the influence of different hydraulic structures and natural hydrological processes during a flood event in a river basin.

The key factors responsible for inundations that occurred at Coimbra city were analysed through a comprehensive and state-of-the-art set of modelling tools. It was concluded that for the January 2016 flood event, the upstream dam discharges were a determinant for the water levels verified at the city. Before the beginning of the flood event the reservoir water levels were not limited to a maximum of 117.0 m, as recommended in the established operational rules, and this fact was crucial for the difficulties verified in accommodating the inflows to the reservoir during the flood event.

Even considering the water levels observed in the reservoir of the Aguieira dam during the flood event, based on simulated operational alternatives, the flood event that occurred in January 2016 could have been minimized if another operating scheme had been adopted.

In an artificial river system such as the Mondego river basin, operational rules should be clear and preferably monitored through technological platforms that facilitate and integrate relevant information and are shared by all stakeholders in the decision-making process. They should include communication tools with automatic warnings and preferably based on forecast models.

The current hydroinformatic technologies allow substantial improvement of flood forecasting capabilities with the implementation of a decision support system for the Mondego river basin that allows the use of precipitation forecasts from a variety of sources, uses models with the potential to simulate hydraulic structures and their respective controllers and that also can allow the efficient assimilation of monitoring data.

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