Floodplain Inundation Models and SAR Imagery Analysis

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ABSTRACT
Floods account for 40% of all natural hazards worldwide. In terms of inundated area, the largest floods in Portugal occur on the Lower Tagus (LT) River, causing important socioeconomical impacts. This paper focuses on the calibration of 2D-horizontal flood simulation models for the floods of 2001 and 2006 on a 70-km stretch of the Lower Tagus River, using the software Tuflow. This software provides 2D solutions based on the Stelling finite-difference that solves the full 2D free shallow water equations (SWE).

The models were based on a Digital Terrain Model (DTM) acquired in 2008 by radar techniques and on in situ measurements of water elevation in Omnias (downstream boundary condition) and discharge in Tramagal and Zêzere (upstream boundary conditions). Five dykes were introduced in the model. Steady-state flow initial conditions were guaranteed. Land cover data was retrieved from Corine Land Cover 2006 (CLC 2006) and combined with roughness Manning coefficients (n) from the literature.

Flood extent maps, derived from satellite-born Synthetic-Aperture Radar (SAR) imagery, provided the spatially distributed data for the calibration of the models. The flood extent maps obtained for each simulation were then compared with the flood extent maps derived from SAR imagery for each flood and the roughness coefficients changed accordingly. The models were also calibrated in terms of the stage at the gauging station Almourol, located 12km downriver from Tramagal. The combination of the calibration results provided the Manning coefficient values for the CLC 2006 classes of the study area. An application of these values was made for the largest flood of the 20th century (February 1979), for which no SAR imagery was available. The model was then validated in terms of flood stage marks distributed throughout the floodplain.

Keywords: Fluvial floods, Calibration of hydrodynamic inundation models, Tuflow, Synthetic-Aperture Radar (SAR) imagery, Tagus River

1. INTRODUCTION
Nowadays floods account for more than 40% of all natural hazards worldwide and half of the deaths caused by natural catastrophes (Di Baldassarre et al 2011). For example, on the last decade of the 20th century, floods alone were responsible for the loss of about 100 thousands human lives and affected more than 1.4 billion people. On the last decades, urbanization, over-populated floodplain areas and land-use change increased the probability of occurrence of floods and the potential increase of their socioeconomical impacts. This lead to the development of complex hydrodynamic models for the study, monitoring and forecasting of flood events, essential to define cost and time effective measures to counteract the floods devastating effects. With the latest developments on the
remote sensing area of Synthetic-Aperture Radar systems, which, unlike optical sensor systems are able to acquire data from the surface of the Earth and therefore maps of flood extents in day/night and in all weather conditions, a new path on flood study and prediction emerged. Therefore, on the last two decades numerical hydraulic models have been calibrated, validated and its uncertainty assessed with SAR imagery data (e.g. Bates et al 1997; Horritt and Bates 2003; Van der Sande CJ et al 2003; Horritt 2006; Pappenberger et al 2007; Schumann et al 2008; Di Baldassarre et al 2009; Di Baldassarre G et al 2011; Tarpanelli A et al 2012; Garcia-Pintado et al 2013).

Floods have been the deadliest natural disasters in Portugal in the last 100 years. In terms of inundated area, the largest floods in Portugal occur in the Lower Tagus River with records of historical flood events dating back to the 16th century, the reason why major river channels were artificially displaced in the past and dozens of dykes built (Azevêdo et al 2004). On average, the river overflows the floodplain every 2.5 years, at times blocking roads and causing important agricultural damages and subsequent economic impacts (Araújo, Pestana, Matias, Roque, Trigo-Teixeira and Heleno 2013; Pestana, Matias, Canelas, Araújo, Roque, Van Zeller, Trigo-Teixeira, Ferreira, Oliveira and Heleno 2013). The economical relevance of the area and the high frequency of relevant flood events make the LT floodplain a good pilot region to conduct systematic data-driven calibration of flood hydrodynamic models.

This research thus focus on the calibration of the 2D-horizontal flood simulation model Two-dimensional Unsteady FLOW (Tuflow) for the floods of January of 2001 (with peak flow discharge in Tramagal of 4675 m³/s) and November of 2006 (with peak flow discharge in Tramagal of 3266 m³/s) on a 70-km stretch of the Lower Tagus River (see Figures 1 and 2). Tuflow was developed in 1990 and has been used since to simulated phenomena such as floods, ocean tides, tsunami inundations and to simulate flow patterns in coastal waters, estuaries, rivers, floodplains and urban areas (BMT WBM, 2010; Syme 2001; Syme et al 2004). It solves the nonconservative depth-averaged form of the 2D horizontal SWE for free-surface flow based on the algorithm developed by Stelling, using a structured grid and water as a medium (Stelling 1984, Syme 1991, Delis and Kampanis 2009). It is a finite difference method hydrodynamic model. Overall Tuflow needs as input a topographic grid of the study domain, upstream and downstream boundaries conditions, a land cover map coverage with the definition of the different land cover classes and 1D and 2D structures that constrain water flow, such as dykes and embankments.

Therefore flood extent maps, previously derived from ERS-2 SAR and ENVISAT-1 ASAR imagery were compared with the flood extent maps obtained for each simulation in order to calibrate roughness Manning coefficients. The combination of the calibration results provided Manning coefficient values of the CLC 2006 land cover classes of the study domain. These values were then used to reproduce the flood extent map for the largest flood in the 20th century: the February 1979 flood. As there were no SAR sensors operating in that area at the time, the measured stage data both in the observation gauge station (Almourol) and on flood stage marks distributed throughout the floodplain (corresponding to the maximum water level of the flood) where successfully compared with the simulation obtained values.
Figures 1 and 2: The study area: the 70-km stretch of the Tagus River between Tramagal and Ómnias and a detail of the used Digital Terrain Model (DTM).

2. DATA AND METHODOLOGY

The Digital Terrain Model used to create a 30x30m 2D mesh grid on Tuflow was acquired by radar (Interferometric Synthetic Aperture Radar) techniques by Intermap Technologies company (Intermap©) with 5m of spatial resolution and a vertical accuracy of 1m (see Figure 2). It was acquired in March-April during a dry period which allowed for a better definition of the river margins, sand banks and islets (Matias et al 2013). The CLC 2006 of 100m resolution provided the land cover information necessary to introduce in Tuflow (Figure 3). The most common land cover classes on the LT River floodplain are Permanently Irrigated Land (212), Vineyards (221) and Pastures (242).

Figure 3: Detail of the CLC 2006 of the LT River floodplain.
In-situ hourly measurements of water elevation in the hydrometric stations of Ómnias (downstream boundary condition), Almourol (observation gauge station) and Tramagal (upstream boundary condition) were available. The discharge values for November of 2006 for the Castelo de Bode dam on the Zêzere River were supplied by Energies of Portugal (EDP). There were no discharge values for this dam available for the flood of 2001. The discharge flow in Tramagal and Almourol for the flood of January of 2001 and the discharge flow in Tramagal for the flood of November of 2006 were calculated using the rating curves of Table 1. The graphics with the water levels and flow discharges for the flood of January 2001 are shown on Figure 4a and 4b.

<table>
<thead>
<tr>
<th>Gauge Station</th>
<th>h (m)</th>
<th>Rating Curve</th>
<th>From:</th>
<th>To:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tramagal</td>
<td>0.6-6.15</td>
<td>Q=53.843(h-0.6)^0.056</td>
<td>01-10-2000</td>
<td>30-09-2001</td>
</tr>
<tr>
<td>Tramagal</td>
<td>6.15-11</td>
<td>Q=94.861(h-0.6)^1.7259</td>
<td>01-10-2000</td>
<td>30-09-2001</td>
</tr>
<tr>
<td>Almourol</td>
<td>-0.5-4.58</td>
<td>Q=15.461(h+0.5)^2.434</td>
<td>01-10-2000</td>
<td>30-09-2001</td>
</tr>
<tr>
<td>Almourol</td>
<td>4.56-14</td>
<td>Q=18.511(h+0.5)^2.823</td>
<td>01-10-2000</td>
<td>30-09-2001</td>
</tr>
<tr>
<td>Tramagal</td>
<td>0-10</td>
<td>Q=69.479(h-0)^1.353</td>
<td>01-10-2006</td>
<td>30-09-2007</td>
</tr>
</tbody>
</table>

Table 1: Rating curves for the hydrometric stations of Tramagal and Almourol.

The river discharge values for the affluent of the Tagus River Zêzere for 2001 were calculated by subtracting the flow discharge in Almourol by the flow discharge in Tramagal, displaced by one hour (the approximate water time travel between the two gauge stations):

\[ Q_{Zêzere}(t) = Q_{Almourol}(t) - Q_{Tramagal}(t-1) \]  


All model runs had the same boundaries and were simulated using steady-state flow initial conditions. The initial water level for all study domain was 0 m.

Flood extent maps (Figure 5a and 5b) were derived from ERS SAR and ENVISAT ASAR imagery, by a manual delimitation approach (Roque D et al 2013a, 2013b). These were compared with the simulated flood extent maps. Also the observed and simulated water level values in Almourol were compared. The roughness coefficient values were adjusted accordingly. Since there were no
roughness coefficient values defined for the study area, the initial roughness coefficient map used in the simulations was based on the CLC 2006 classes, crossed with roughness coefficient values in the literature for other study areas (e.g. Chow 1959; De Roo 1999). Different strategies were used (see Table 2): A) maintain all classes with the n literature values, except the most common classes on the study area, for which the n values were increased and decreased to extreme values (according to the classification level 1 of the CLC 2006); B) Increase and decrease all classes literature Manning values by the same percentage; C) with all Manning coefficient values higher 30%, maintain class 212 (Permanently Irrigated Land) with the value 0.015 (solely ran for the flood of January of 2001); D) use the literature Manning coefficient classes values; E) Maintain the Manning coefficient equal for all classes (0.50).

Different measures of the similarity between simulated and imaged flood extents (overall accuracy, kappa coefficient and omission and commission errors) were derived from confusion matrices using the software ENVI. A final roughness coefficient map for the study domain for both floods was chosen.

The chosen roughness coefficient values were used to perform a simulation for the February 1979 flood for which no SAR imagery was available. The validation of the obtained flood extent was made by comparing the observed and simulated water levels at Almourol gauge station and at undated flood stage marks spread throughout the floodplain. This flood stage marks were observed after the 1979 flood and correspond to the highest water level of the inundation.

Figures 5a and 5b: ERS-SAR image acquired during the flood of January of 2001 and manual delimitation of the flooded area (in blue) (left) and ASAR Wide Swath image acquired during the flood of November 2006 and manual delimitation of the flooded area (in blue) (right).

3. RESULTS AND DISCUSSION

Table 2 shows the calibration results for the simulation performed for the January 2001 flood and the measures of similarity between the simulated and the SAR image flood extents. Figure 6 shows the flood extents resulting from the decrease of 30% (in blue) and from the increase of 15% (in orange) of the roughness coefficients values for the 2001 flood. Note that the increase of the Manning coefficient values decreased the flooded area.
Table 2: Calibration results for the 17 simulations performed for the January 2001 flood, and measures of similarity between simulated and SAR image flood extents. The hyphen means that the literature values were used.

The omission errors represent the percentage of pixels classified on the SAR image as flooded that do not appear as flooded on the simulated flood extent image. The commission errors represent the percentage of pixels classified as flooded on the simulated image that are non-flooded on the SAR image. The strategy for choosing the best combination of roughness coefficients for the CLC 2006 classes of the study domain was a multicriteria approach: combine the visual interpretation, the Almourol observed and simulated water level time-series and the measures of similarity. One took into account that it was a priority to have low omission errors as these results may be used to produce hazard maps.

Therefore for the flood of January 2001, the best simulated result was obtained when the Manning coefficient value was changed individually for the class 212 to n=0.20. For this case the omission (15.93%) and commission (24.63%) errors are relatively low, and the overall accuracy is high (96.15%). The kappa coefficient is also relatively high (0.77). Figure 7 shows the omission and commission errors for this best case. In Figure 8 one can observe that the pace of the simulated water levels in Almourol is similar to the observed one, although delayed by 2 to 5 hours.

The same calibration process was repeated for the November 2006 flood. Comparing the results from both floods, one concluded that an increase of 15% in the Manning coefficient values for all classes resulted in the best measures of similarity between simulated and imaged flood extents (Table 3). The chosen simulation flood extents are thus presented in Figures 9 and 10 and the final roughness coefficient values for the CLC 2006 classes on Table 4.
Figures 6 and 7: Flood extents resulting from the decrease of 30% (in blue) and from the increase of 15% (in orange) of the roughness coefficients values for the 2001 flood. Omission and commission errors for the best case of the flood of 2001.

Figure 8: Observed and simulated water levels in Almourol for the best case of 2001 (class 212 with n=0.20) and for other simulations.

Table 3: Measures of similarity for the best case of the flood simulations of 2001 and 2006.

<table>
<thead>
<tr>
<th>Flood</th>
<th>overall accuracy (%)</th>
<th>k coefficient (%)</th>
<th>omission (%)</th>
<th>commission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-01-2001</td>
<td>95.74</td>
<td>0.75</td>
<td>16.46</td>
<td>27.37</td>
</tr>
<tr>
<td>25-11-2006</td>
<td>95.60</td>
<td>0.78</td>
<td>8.09</td>
<td>29.08</td>
</tr>
</tbody>
</table>

Figure 9 and 10: 2001 and 2006 simulated flood extents resulting from the increase of 15% in the Manning values and comparison with the manual delimitation of the SAR image.
The values of Table 4 were then used to simulate the flood of February 1979 of peak flow discharge in Tramagal of $11042\text{m}^3/\text{s}$ (Figure 11). Due to the lack of information of the date and time of the maximum flood extent, one chose 11/2/1979 at 21:00. This corresponds to 11 hours after the peak flow discharge in Almourol and 6 hours before the highest water level in Ómnias. These approximate time differences occurred for the 2001 and 2006 floods as the study domain was the same, corresponding to the maximum flood extents.

Validation was made by comparing observed and simulated water levels at Almourol gauge station and at flood stage marks spread throughout the floodplain. These correspond to the maximum water level observed during the 1979 flood (Figure 12). Note the accordance between the observed and simulated water levels at the flood stage marks. The water stage marks simulated values that are
more distanced from the observed ones, are those located near dykes, where the water constraints can cause more instabilities in the model (e.g. stage marks 5 and 7).

![Figure 12](image.png)

**Figure 12:** Comparison between the maximum observed and maximum simulated water level values for the flood stage marks of the study domain. The flood stage marks number increases upriver.

4. **CONCLUSIONS**

This study constitutes the first time that, for a Portuguese river, a hydrodynamic numerical model is successfully calibrated and validated using SAR imagery. One saw that Tuflow software successfully models floods flow on the floodplain area, despite of the large size of the study domain (a 70-km stretch of the LT River). Furthermore this was accomplished by using 2D mesh grid cells of 30x30m, that is, grids with low resolution, corroborating the findings of Dottori *et al.* (2013) that for reliable flood predictions too much detail in the data is not always necessary.

Therefore one concludes that the methodology applied for the calibration and validation of the flood models was adequate for the present case. Namely, the comparison of the observed and simulated water level at a gauge station located within the study domain and the comparison of the flood extent areas retrieved for SAR imagery with the simulated flood extents. This was also the first time roughness coefficient values specific for the LT River region were obtained. The roughness coefficient values obtained in this research can hereafter be applied as reference values on hydraulic simulations on the Lower Tagus River region.

Furthermore the findings show that the roughness coefficient values matter: small changes in one land cover class Manning coefficient value may significantly alter the simulation results. In sum, one was able to find a best case roughness coefficient values for the Corine Land Cover 2006 classes on the Lower Tagus River area and successfully applied it to the largest flood of the 20th century. Nevertheless one needs to safeguard the following: *n* depends on the flow peak discharge of each flood; there are errors associated with the DTM, as it was collected in 2008 and the floods occurred in 2001 and 2006; the SAR images have different resolution, which can introduce errors on the delimitation; and the calibration of *n* allows to compensate for other uncertainties on the simulation process.

This study has contributed to the flood hazard mapping in the Tagus River Basin on the scope of the European Directive 2007/60/EC.
References


Roque D et al (2013b) OBIA flood delimitation assisted by threshold determination with PCA. Photogrammetric Engineering and Remote Sensing (conditionally accepted with minor revision).


ACKNOWLEDGMENTS

This research was supported by the Portuguese Foundation for the Science and Technology (FCT) through project RIVERSAR (PTDC/CTEGIX/099085/2008). SAR imagery was provided by the European Space Agency (ESA) through category-1, project 9441. The National Water Resources Information System (SNIRH) and the Portuguese Environmental Agency (APA) are acknowledged for making the hydrometric data available.