Assessment of the Flow Predictions From a Large Urban Drainage Model Forced by Distinct Spatial Resolution Weather Forecasts

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ABSTRACT

This paper assesses calibration and verification results of the Alcântara catchment model (Lisbon) and of the flow model forecasts forced by two different resolutions in Weather Forecasting: the 9 km WRF model from the Windguru website, available with just one forecast point in the catchment area, and the 5 km WRF model of the University of Aveiro, with an orthogonal grid of six forecast points. The accuracy of urban drainage model results was assessed combining statistical and graphical techniques and is substantially affected by the uncertainty in spatial rainfall distribution. Therefore, data from more rain gauges or from satellite sources would certainly improve model parameterisation and results. This study also highlighted the importance of modelling rainfall-derived infiltration and inflow (RDII) for achieving more balanced and accurate results. In forecast mode, the sewer model is significantly more accurate when forced by the University of Aveiro model forecasts than when forced by the Windguru website forecasts. Differences in results are partially attributed to the number of forecast points considered in each model and on differences in spatial resolution of the models. The comparison between predicted and observed storms was sometimes difficult and subjective due to the time lags between them.

KEYWORDS

Accuracy, RDII modelling, model predictions, surveillance and forecast systems, urban drainage, WRF models

INTRODUCTION

With the recent advances in atmospheric prediction models at regional and local level, efforts have been undertaken to apply urban drainage models for flood forecasting, for the control of combined sewer overflow (CSO) discharges and for systems operational management, with benefits for the protection of people,goods and the environment as well as for a more efficient management of energy and consumables spent in the operation of pumping stations and wastewater treatment plants.

A pilot surveillance system to support early warning of faecal contamination in estuarine waters was developed within the FP7.EU PREPARED and SIMAI projects. The WIFF platform was applied to the Tagus estuary for the area that receives the discharges from the Alcântara catchment, the largest urban catchment of Lisbon (David *et al.*, 2014).

This study aims at assessing the results from the Alcântara catchment model for calibration, verification and forecasts forced by two distinct sources of rainfall predictions. It also aims at evaluating the importance of modelling the rainfall-derived infiltration and inflow (RDII) component to improve model results. The RDII flows may be responsible for increasing CSO discharges to the receiving water bodies and for reducing the performance of the WWTP, with a consequent increase in operating costs (Zhang, 2007; Staufer *et al.*, 2012).

The analysis was carried out using statistical and graphical techniques for model results evaluation. The statistical techniques can be classified into three main categories: dimensionless (e.g., Nash-Sutcliffe efficiency coefficient: NSE), error index (e.g., root mean square error: RMSE) and standard regression. The assessment of the accuracy of hydrological model results must consider at least a graphical technique, a dimensionless coefficient and an error index (Legates and McCabe, 1999; Moriasi *et al*., 2007).

MATERIALS AND METHODS

Mathematical modelling of the Alcântara catchment with SWMM

The city of Lisbon has several catchments with CSO discharging to the Tagus estuary, which the Alcântara catchment is the largest, with 3200 ha. The mathematical model of Alcântara catchment was built in SWMM (Rossman, 2007). It only represents the main sewer network and catchments, having 114 nodes, 114 links and 35 sub-catchments. The model was calibrated based on data measured in four raingauges and three flowmeters for a period of ten months (from February to November 2012, with 36 rainfall events) and was verified for data measured in the following ten months (until September 2013, with 28 rainfall events).

To force the model in operational mode, rainfall predictions were obtained from two different sources of Weather Research Forecasting (WRF) models(Skamarock *et al.*, 2008): WRF9 km from Windguru website (http://www.windguru.cz), available with just one forecast point in the catchment area, and WRF 5 km from the University of Aveiro model (http://climetua.fis.ua.pt/-fields/continent/precip), with an orthogonal grid of six forecast points. Figure 1shows the location of the rainfall measurement and forecast points and presents model results in simulation and operational mode for a rainfall event. All the model results presented in this paper refer to the downstream flow monitoring section, just upstream the WWTP.

Mathematical modelling of the Alcântara catchment with 4S-Drainage

The RDII component was not modelled in SWMM since its calibration requires a great effort. To assess the importance of modelling the RDII component, the 4S-Drainage homemade conceptual model was used at this stage, which is much easier and faster to calibrate (David and Matos, 2005). It considers four flow components: the underground water, the subsuperficial flow and the fast and slow components of runoff.

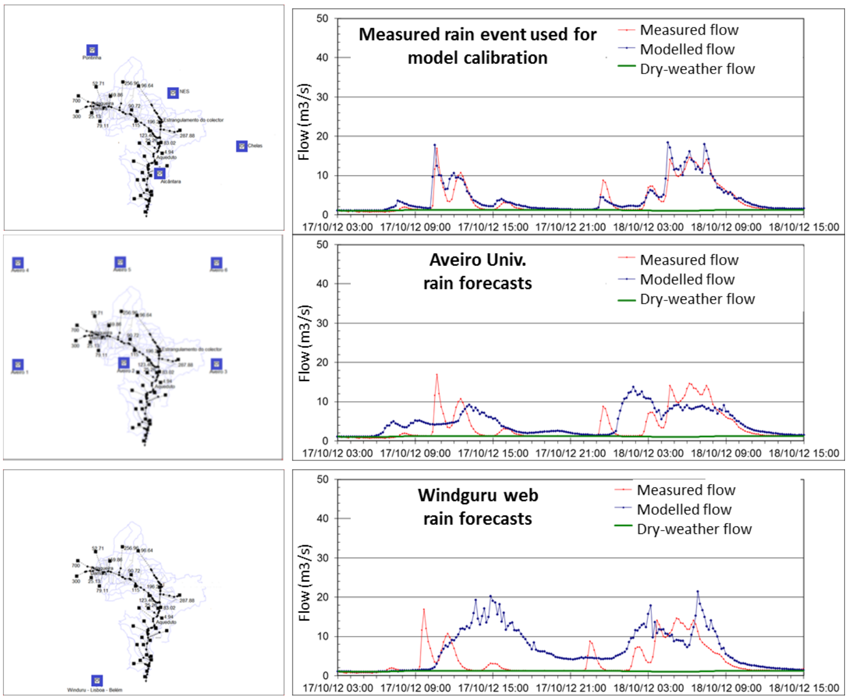


Figure 1. Location of the rainfall measurement and forecast points and SWMM results in simulation and operational mode for a rainfall event.

Techniques for assessing the quality of model results

The study was performed using statistical and graphical techniques for results evaluation. The following statistics were used: The Nash-Sutcliffe Efficiency coefficient (NSE), the Root Mean Square Error (RMSE) and the parameters from linear regression thatbetter fits the model results to the measured values (the slope, the interception and the determination coefficient).

The NSE coefficient (equation 1) has been extensively used to evaluate models performance (McCarthy *et. al*, 2011; Branger *et al*., 2013). It varies from minus infinity to the unit value, with higher values indicatinggreater model efficiency (Nash and Sutcliffe, 1970).

RMSE values depend on the magnitude of the errors of the variable analysed and are expressed in the same units of this variable. Reducing the value of RMSE corresponds to decreasing the error. A relative RMSE (RMSErel), given by the ratio between the RMSE and the mean of the observed data, provides a dimensionless result.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad (2)$$

where O_i is the i^{th}measure for thevariable being evaluated,$P_i$is thei^{th}simulated value for the variable being evaluated,$\overline{O}$is the mean of observed data for the variable being evaluated, and*n* is the total number of observations.

A graphical analysis was performed by direct comparison between the model results and the measured data for each simulation, through a bar graph ordered from the largest to the smallest measured values. The analysis is complemented by presenting the relative error of each case, determined in function of the measured values.

Aims and assessments performed

This study aims at studying:

a) the quality of model calibration and verification;
b) the quality of model predictions using the rainfall forecasts from both the Windguru and the University of AveiroWRF models;
c) the contribution of the RDII component in the quality of the model results.

For this purpose, the assessments of the quality of the results were performed for the following cases(numbered from 1 to 6):

1) Model calibration (using the first 10-month dataset);
2) Model verification (using the second 10-month dataset);
3) Forecast model with predictions from Windguru (using available 17-month dataset);
4) Forecast model with predictions from University of Aveiro (using the 20-month dataset);
5) SWMM model for the entire time domain (using the 20-month dataset);
6) 4S-Drainage model for the entire time domain (using the 20-month dataset).

The assessments of the quality of the results were performed to the volumes and peak flows. However, in the case of prediction models (cases 3 and 4) only the volumes were studied, since hourly forecasts are provided by the atmospheric models, leading to large attenuation of peak flows (the time step was reduced to 15 minutes for the University of Aveiro model output since April 2013, the last 6 months).Despite this limitation, peak flows have less relevance for modelling CSO discharges than the volumes. Therefore, additional assessments were performed for the predicted volumes only considering the most significant set of events (measured rainfall exceeding 10 mm or measured peak flow exceeding 10 m^3/s).

RESULTS

The graphical analyses are shown in Table 1. For each of the 6 cases described in the section above, the lower graph (with red and blue bars) compares the modelled results with the measured data and the upper graph (with light green bars) gives the relative errors with respect to the measured values. The statistical results assessing the accuracy of the modelled volumes and 10-minute peak flows are shown in Table 2 and Table 3, respectively. Table 4 presents the statistical results for the additional assessments performed for the predicted volumes only considering the larger events. The titles, abbreviations and symbols in the headers of the tables have the following mean: Case – casedescribed in the section above; n – number of rainfall events; Mean – mean of the measured data; RMSE and NSE – statistics described above; Slope, Int. andR^2 are respectivelythe parameters slope, interception and determination coefficient ofthe linear regression; RMSErel – RMSE relative to the measured mean; i95 –confidence interval at 95%, which corresponds to2xRMSE for unbiased estimators.

Table 1. Graphical results of volumes and peak flows

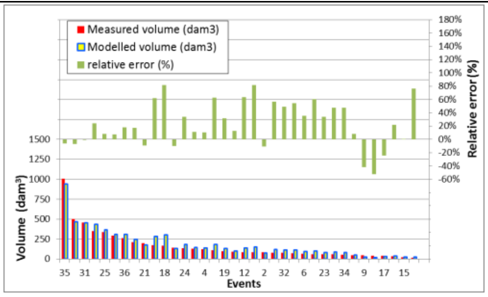
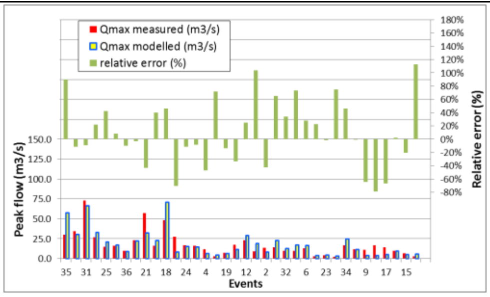
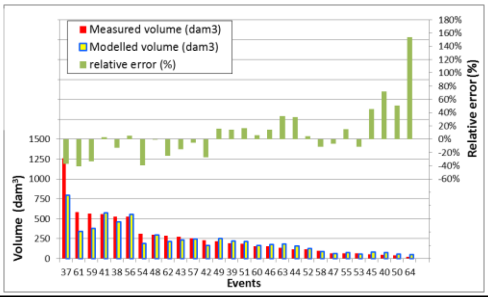
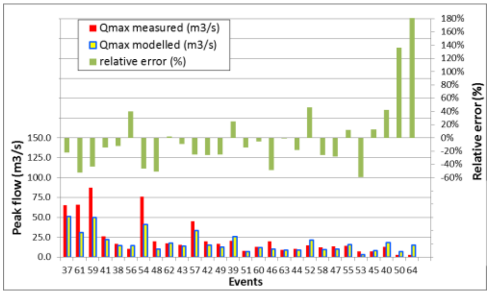
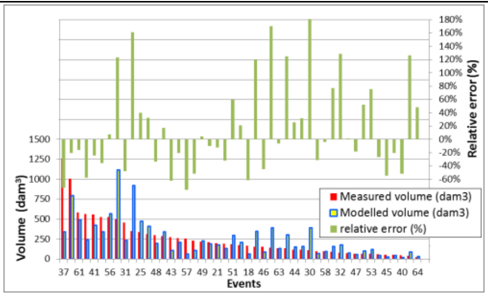
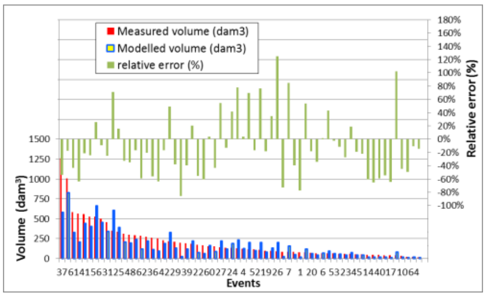
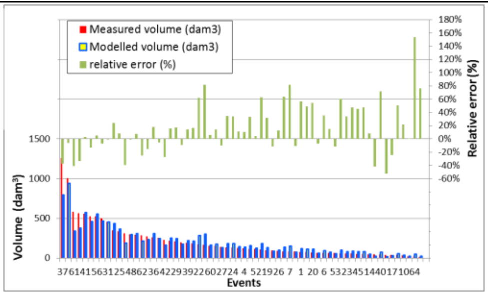
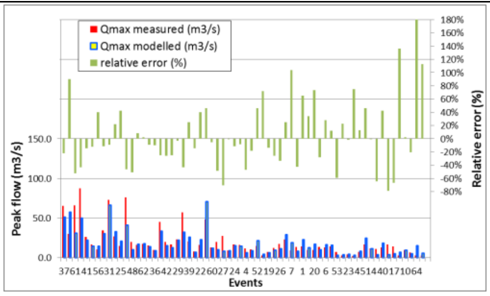
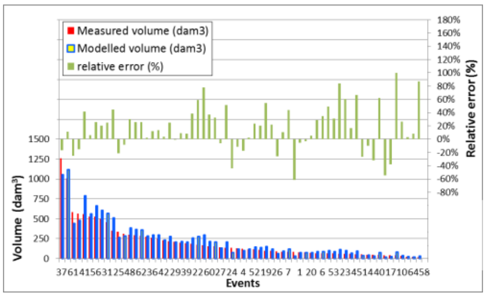
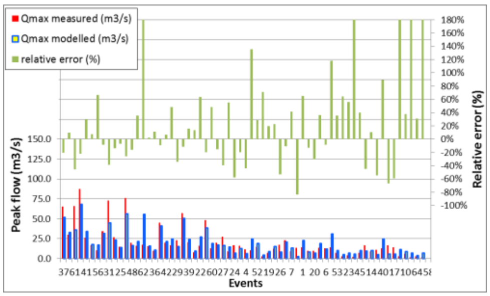
Case	Volume	Peak flow
1		
2		
3		Not considered
4		Not considered
5		
6		

Table 2. Statistical results of the analyses of modelled volumes

Case	description	n (-)	Mean (dam^3)	RMSE (dam^3)	NSE (-)	Slope (-)	Int. (dam^3)	R^2 (-)	RMSErel (%)	i95 (dam^3)
1	Calibration	36	162.3	45.4	0.94	0.94	33.4	0.96	28.0	90.9
2	Verification	28	265.6	112.3	0.81	0.65	60.5	0.89	42.3	224.7
3	Windguru	47	254.4	216.5	0.21	0.55	109.5	0.34	85.1	432.9
4	Aveiro Univ.	64	207.5	129.3	0.67	0.64	37.3	0.7	62.3	258.7
5	SWMM model	64	207.5	81.8	0.87	0.75	51.2	0.89	39.4	163.5
6	RDII model	64	207.5	69.2	0.91	0.99	26.0	0.92	33.4	138.4

Table 3. Statistical results of the analyses of peak flows

Case	description	n (-)	Mean (m^3/s)	RMSE (m^3/s)	NSE (-)	Slope (-)	Int. (m^3/s)	R^2 (-)	RMSErel (%)	i95 (m^3/s)
1	Calibration	36	17.8	9.4	0.60	0.92	1.9	0.68	52.9	18.8
2	Verification	28	23.3	13.1	0.65	0.51	6.3	0.84	56.1	26.2
5	SWMM model	64	20.2	11.2	0.64	0.64	5.2	0.66	55.2	22.4
6	RDII model	64	20.2	10.0	0.72	0.66	6.2	0.72	49.7	20.0

Table 4. Statistical results of the analyses of predicted volumes for the larger events

Case	description	n (-)	Mean (dam^3)	RMSE (dam^3)	NSE (-)	Slope (-)	Int. (dam^3)	R^2 (-)	RMSErel (%)	i95 (dam^3)
3	Windguru	22	426.5	298.1	-0.29	0.43	179.8	0.17	69.9	596.1
4	Univ. Aveiro	23	420.6	206.0	0.36	0.59	65.1	0.54	49.0	412.0

DISCUSSION

Quality of the results for model calibration and verification

In general, the model calibration gives acceptable results for both variables: volume and peak flow. For the volumes (Table 2), the NSE coefficient and the regressionslope and determination coefficient are all above 0.94. The interception value of the regression line and the RMSE are relatively reduced when compared with the mean of measured values, revealing a quite satisfactory adjustment regarding the size of the catchment. For the peak flows (Table 3), besides the results for NSE, slope and R^2 are not too low, they are far from the unit value, indicating a merely satisfactory adjustment of the model for peak flow. Graphs from Table 1 show that the calibration performed lead to conservative volumes for most storms.

As expected, the statistical results for volume and peak flow in verification are lower than results in calibration. For example, the relative RMSE increases in volume from 28% to 42% (Table 2). During the verification period less rain events occurred, but there were higher volumes and peak flows generated. During the verification period there were six events with volume exceeding 500 dam^3 while in calibration period there were only one (Table 1). The graph for volumes in verification (case 2 in Table 1) shows that the model underestimates the larger storms and overestimates the small events. All higher peak flows are underestimated. These differences of results are attributed to the spatial variability of rainfall, to the influence of the RDII component and even to flow transfers from neighbouring catchments during heavy storm events.

Quality of the results for forecast model

In general, the results using theUniversity of Aveiroforecasts are substantially better than the results using the Windguru forecasts. For example, the NSE for University of Aveiro is 0.67 and for Windguru model is 0.21 (Table 2). Some statistics obtained for the model forced by the Windguru forecasts reveal weak predictions. This difference in results may be partially attributed to the difference in the number of points considered for each atmospheric model, six for the University of Aveiro forecast model, distributed over the catchment, and just one for Windguru model in Belém, near the Tagus estuary. The difference in spatial resolution of the two models, 5 km for the University of Aveiromodel and 9 km for the Windguru model, may also contribute to the difference in the quality of forecasts.

Table 1shows that resultshave no trends for both atmospheric models. However, for University of Aveiro it is apparent that the model is conservative for intermediate volume events and for large and small volumes the model does not reach the measured volumes.Substantially weaker results were obtained for the assessments considering only the larger events (Table 4). The general volume underestimation for the larger events may be partially explained by the influence of RDII component, which is not being modelled.

Both rainfall forecast models predicted storms that did not occur and failed to predict some typically small or median size events. The comparison between the predicted and the observed storms was sometimes difficult and subjective due to the time lag between the predicted and the real occurrences.

Contribution of RDII consideration in the quality of the model results

The results highlight the importance of modelling the RDII component for model improvement. The NSE coefficient increases from 0.87 to 0.91 for the volume and from 0.64 to 0.72 for the peak flow. The linear regression line is significantly closer to the 45° line for the volume and the determination coefficient increases for both variables. The RMSE associated to the volume decreases 15%, from 81.8 dam^3 to 69.2 dam^3, and the RMSErel reduces 6 %, from 39.4 % to 33.4 % of the mean observed volume (Table 2 and Table 3).

These results were achieved through a better balance of errors in volume between the largest and smallest events. Both models tend to overestimate volumes, but while the SWMM underestimates the major storms, the RDII is more balanced in overestimation and underestimation of volumes and also leads to smaller relative errors(Table 1).

CONCLUSIONS

The accuracy of urban drainage model results was assessedcombiningdifferent statistical and graphical techniques. Due to the large size of the catchment, the uncertainty in spatial rainfall distribution and probably in flow transfers from neighbouring catchments during heavy storms significantly affects the accuracy of the modelcalibration and verification. Therefore, in addition to the four raingauges used for model validation, data from more raingauges or from satellite would certainly improve model parameterization and results.

In forecastmode, the sewer model is significantly more accurate when forced by rainfall forecasts from the University of Aveiro WRF model than by forecasts from the Windguru website. Differences in results are partially attributed to the number of rainfall forecast points used to force the model. Six forecast points within the Alcântara catchment area are provided by the University of Aveiro model, while a single forecast point is used from the Windguru internet site, located near the estuary. This different spatial resolution may be particularly relevant for this specific case due to the spatial variability of the rainfall distribution. The spatial resolution of each atmospheric model by itself (5 km and 9 km) may also contribute to the different quality of forecasts. Both rainfall forecast models predicted storms that did not occur and failed to predict some typically small or median size events.The comparison between the predicted and the observed storms was sometimes difficult and subjective due to the time lags between them.

Theanalyses highlight the importanceof modellingthe RDIIcomponent for achieving more accurate and balanced resultsbetween the largest and smallest events. The potential use of satellite or radar rainfall forecasts may also contribute to improve the model predictions.

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