Demonstration system for early warning of faecal contamination in recreational waters in Lisbon

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Contents

1 INTRODUCTION

The city of Lisbon has an extended water front along the Tagus estuary, with several combined sewer overflows (CSO) in the low-lying area. The city is served by three wastewater treatment plants (WWTP), of which the Alcântara WWTP serves the largest area, with about 6000 ha. This WWTP was designed to serve 670 000 inhabitants equivalent with secondary treatment. The WWTP effluent is discharged into the Tagus estuary by the outfall that also carries the CSO discharges from the 3200 ha Alcântara combined catchment (David *et al*., 2013). The riverside downtown area is subject to flooding due to several factors, namely the low slopes, the influence of the Tagus estuary tidal level and the deposition of sediments and organic matter in the sewers. The latter factor also increases pollution from CSO due to wash-off. The stormwater and wastewater management in the city of Lisbon is closely linked to the Tagus estuary, the receiving water body for the effluents, where the water quality for recreational uses is a matter of concern. Climate change will exacerbate flooding in the downtown area and the CSO impacts in the estuary due to the expected growing magnitude and frequency of extreme rain events and sea level rise. Furthermore, increased saline water intrusion into the sewers due to sea level rise can degrade drainage infrastructures, affect gate and pump operations and reduce the efficiency of the advanced biological wastewater treatment.

To help utilities to deal with these growing problems, a pilot surveillance system for early warning of faecal contamination was deployed in the Tagus estuary for the area that receives the discharges from the Alcântara catchment outfall, the largest urban discharge point into the estuary from both WWTP treated effluent and CSO discharges. The pilot system is managed through an application of the real-time forecasting platform RDFS-PREPARED (Rapid Deployment Forecast System, Oliveira *et al*., this issue, Jesus *et al*., 2012) which includes cross-scale basin-to-estuary integrated modelling of the relevant processes. The RDFS-PREPARED platform integrates a set of scripts and programs for the automated data and model's management, the forecast engine for the numerical models, the monitoring network (David *et al*., 2013, Rodrigues *et al*., 2013), and an on-line WebGIS interface for visualization and data/predictions access, available for desktop and mobile environments (Gomes *et al*., 2013). The Alcântara urban drainage and the Tagus estuary models are coupled through soft coupling. On-line quasi-real time field data are available for models' automated and continuous validation and surveillance of the water quality in both the sewers and the estuary.

Within the PREPARED project, an existing urban drainage model was improved and updated to simulate water quality and rainfall-derived infiltration and inflow (RDII). Two alternative sources of rainfall forecast were used to force the urban drainage model: the University of Aveiro model forecasts and the Windguru internet site forecasts. The 3D hydrodynamics and water quality model ECO-SELFE (Rodrigues *et al*., 2011) was improved to simulate baroclinic circulation and faecal contamination and validated in the Tagus estuary. Synoptical field surveys were carried out to improve the water quality models validation and integration. This demo intends to assess and improve the robustness of the system forecasts and to evaluate the ability of the system to support early warnings for faecal contamination in the estuary. Since microbial faecal contamination cannot be measured by existing sensors, ammonia measured by probes and parameters measured by UV-Vis spectrophotometric probes are used as baseline parameters for continuous verification of the water quality forecasts (David *et al*., 2013, Rodrigues *et al*., this issue). On-line monitoring stations were installed in the Alcântara CSO and in the estuary. The methodology was assessed by carrying out several experimental surveys that allow the characterization of the water quality in laboratory and the search for relationships between the parameters measured by the two methods.

2 FINDINGS

According to the methodology previously described and presented in more detail in Oliveira *et al*. (this issue), this demonstration included the development of the following key activities: performing experimental surveys to calibrate the models and the sensors, and to develop relationships between the parameters; updating and calibrating the numerical models and evaluating the quality of the predictions in forecast mode; installing an on-line monitoring system for models' automated and continuous validation and surveillance of the water quality; and, integrating the models and monitoring data within the RDFS-PREPARED platform to support the prototype early warning system. The main findings are summarized below.

2.1 Field surveys

Several field surveys were carried out to synoptically characterize hydraulic and water quality parameters from the sewer and the estuary, aiming at better understanding the system to monitor, developing relationships between parameters, improving model validations and integration, and validating the methodology described above. These surveys also constituted a fundamental step to design of the on-line monitoring network and to validate and complement the on-line monitoring data.

Five surveys were undertaken in 7 sections covering the sewer system, the WWTP, the Alcântara outfall and the estuary (Rodrigues *et al*., this issue). The surveys were carried out for complete tidal cycles (13 hours) during dry- and wet-weather conditions. Hourly and synoptic determinations of several parameters were measured by probes. Every four hours, water samples were collected for laboratory analysis of physical, chemical and microbiological parameters. Additional surveys were carried out just in the sewer and estuary on-line monitoring stations.

To support the faecal contamination forecasts and early-warning, on-going research is seeking for relationships between monitored parameter concentrations and faecal bacteria concentration. Preliminary analyses showed promising relations between faecal bacteria concentrations and total suspended solids (TSS) and chemical oxygen demand (COD) concentrations in the sewer, with correlation coefficients of about 0.6, and between faecal bacteria concentrations and ammonium concentrations in the receiving waters. However, as ammonium and nitrate probes are not suited for saltwater environments, on-going research is also seeking for corrections of the probe's measurements, based on the positive correlations found between salinity and both ammonium and nitrates in the receiving waters.

2.2 Urban drainage modelling and forecast

The numerical model SWMM was applied, calibrated and validated to the Alcântara catchment. TSS and COD are simulated with exponential build-up and wash-off equations. The model uses relations between TSS and faecal contamination indicators and takes advantage of data provided by the on-line spectrophotometric probe. Results showed that, due to the large size of the catchment, the uncertainty in spatial rainfall distribution and in the flow transfers from neighbouring catchments during heavy storms significantly affects the accuracy of the model for some events. Therefore, data from more raingauges or from satellite should improve the model parameterisation and results. A conceptual RDII model was developed to provide base flow series to SWMM, to reduce the uncertainty associated with the base flow variability.

The water quality model for the sewer system aims at taking advantage of the online monitoring network developed in the scope of PREPARED. Promising results were obtained for modelling TSS and COD for most rain events, but measurements from the spectrophotometric probe

revealed complex variations of the dry-weather pollutographs related with the antecedent moisture conditions that require the development of more complex models.
To force the sewer models in operational mode, atmospheric predictions were obtained from two different sources: WRF9km from Windguru (www.windguru.cz) and WRF5km atmospheric predictions from the Aveiro University model (climetua.fis.ua.pt/fields/continent/precip). In forecast mode, a preliminary cascade modelling uncertainty analysis showed that the sewer model was significantly more accurate when forced by the rainfall forecasts from the University of Aveiro than by those from the Windguru internet site. This difference may be partially attributed to the number of rainfall forecast points used to force the model in each simulation (Figure 1). 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 predicted and observed storms was sometimes difficult and subjective due to time lags between them. The large time step for the rainfall forecasts (60 minutes) attenuates the predicted hydrographs and, consequently, underestimates the peak flows. The time step was reduced to 15 minutes for the University of Aveiro model output since April 3th, 2013.

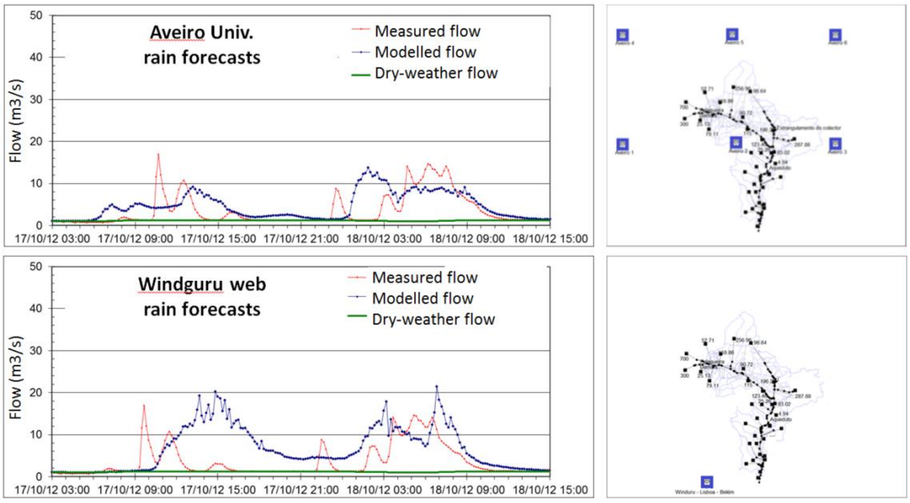

Figure 1 - Uncertainty on urban drainage prediction associated with two atmospheric forecasts.

2.3 Estuary modelling and forecast

The 3D coupled hydrodynamic and faecal contamination model – ECO-SELFE – was applied in the Tagus estuary. The domain was discretized with a horizontal grid with about 20000 nodes and a vertical grid with 20 SZ levels (15 S levels and 5 Z levels). The spatial resolution of the horizontal grid varies from about 1 m in the Alcântara area to 2 km in the oceanic area. Three open boundaries were considered: the Atlantic Ocean, the Tagus River and the Alcântara outfall.
The baroclinic model was validated with salinity and temperature data from 1988 covering a range of environmental conditions. Faecal contamination tracers' were validated based on the data from the PREPARD field surveys. Results showed the ability of the model to represent the main patterns observed in time and space. Differences may be partially explained by the boundary conditions imposed and by additional contamination sources that are not being considered.
The operational model is forced using faecal coliforms and *Escherichia coli* (E. coli) loads provided by the urban drainage model described in 2.2, real-time river flow data provided by SNIRH at the river boundary (www.snirh.pt), ocean elevations and three-dimensional salinity and water temperature forecasts from the regional model of MyOcean (www.myocean.eu.org) and atmospheric forecasts from the WRF 9 km for Europe (available at www.windguru.cz).

Shortwave and longwave radiation forecasts are obtained from the GFS 50 km model (available at nomads.ncep.noaa.gov).

2.4 On-line monitoring system

On-line monitoring of water quality parameters is crucial to provide a real-time integrated overview of the system behaviour and for automatic validation of the forecasts. Therefore, on-line monitoring stations were installed in the Alcântara CSO and in the estuary, close to the Alcântara catchment outfall. These stations are equipped with conventional and UV-Vis spectrophotometric probes, aiming to provide data that may characterise the pollution at these sites and may be related with faecal contamination. S::CAN UV-Vis spectrophotometric probes were installed at both stations and ammonium and dissolved oxygen probes were also installed in the estuary. Innovative structures were built in stainless steel to support and protect the probes in the measurement environment, which also use the flow lines and turbulence to maintain their stability and improve self-cleaning (Rodrigues *et al.*, this issue). Data can be accessed on-line through the RDSF-PREPARED platform (Oliveira *et al.*, this issue).
Laboratory results from grab samples confirmed the accuracy of TSS and COD measurements. Calibration with 19 samples collected in dry- and wet-weather conditions provided correlation coefficients of 0.93 and 0.86 for TSS and COD in the sewer and of 0.70 for TSS in the estuary.
Maintenance procedures were established and implemented to guarantee the safety of the sensors and the quality of the data. Three levels of maintenance procedures were carried out (Rodrigues *et al.*, this issue): automated cleaning using air compressors, periodic (weekly) cleaning and inspection, and supplementary cleaning when needed.
Data measured, transmitted on-line and stored in the WebGIS platform must be checked and processed in order to detect errors and inconsistencies and to create new series free of outliers and spurious data (Fletcher and Deletic, 2008; Lepot *et al.*, 2013). Several outliers were registered during the low flow night periods in the sewer system. Therefore, a routine with two levels of filters (outliers and dubious values) was developed for each measured parameter, also informing if dubious values occur during rainfall periods or are associated with changes in the flow hydrographs, as dubious values have to be removed manually (Figure 2). Data gaps are filled by interpolation for short dry-weather periods, but are left empty for rainy or long wet-weather periods, in order to show the lack of correct data for important periods.

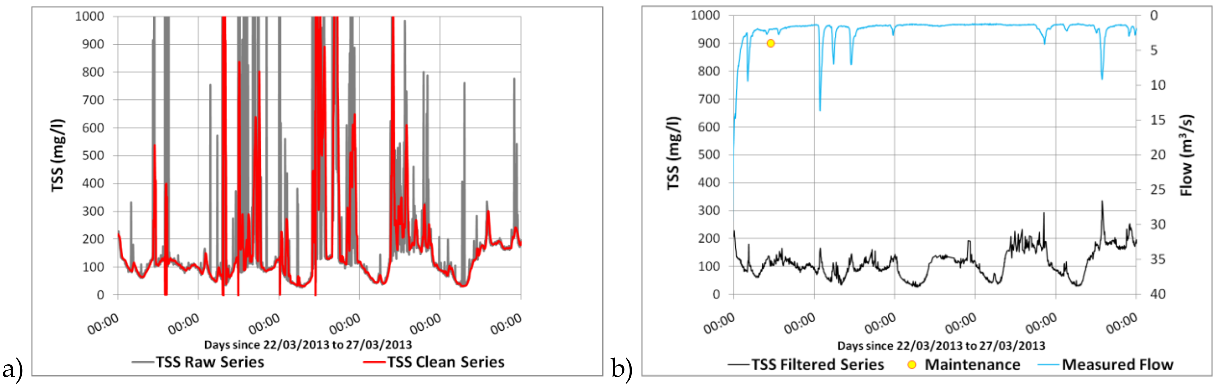

Figure 2 – TSS monitoring during a rainy period and comparison between a) data provided by the S::CAN spectrophotometric probe and b) data stored after processing and treatment.

The monitoring network provides on-line water quality data to feed the WebGIS platform and to support the surveillance and early-warning of faecal contamination events. Besides assessing the impact of the Alcântara catchment outfall on the estuary, this platform also contributes to the global monitoring of the Tagus estuary, which is currently poorly monitored.

2.5 RDFS-PREPARED platform to support early warnings

The RDFS-PREPARED platform was customized for the Alcântara catchment integrated analysis. It entails the real-time hydrodynamic and water quality forecasting of the integrated system Alcântara outfall – Tagus estuary and the monitoring network outputs (Figure 3)

The platform deployment was conceived in a service-oriented framework:

- For the estuarine hydrodynamic predictions, specific products were developed for two types of access: quick view (for fast access, for instance under low-speed internet connections or in an emergency) and GIS-supported maps (allowing several GIS capabilities and high resolution) - Figure 3.
- For data analysis within the platform, both tabular and graphical displays are available, allowing for a user selection of the period of analysis (Figure 3). Several operations (such as zoom and the identification of the values as the mouse slides over the data points) are implemented over the graphical tool. Further analyses are possible outside the interface by a simple exporting option in csv format.
- Automatic model/data comparisons are implemented for the available on-line data and can easily be expanded in the future as other sources of real-time data become available

Given the importance of accessing real-time data in mobile devices in case of emergencies and also as a support tool for daily checking the status of the network, a mobile application was developed to access the WWTP and Alcântara dock stations' historical records. This current version of the app will be later extended for data and forecast map products.

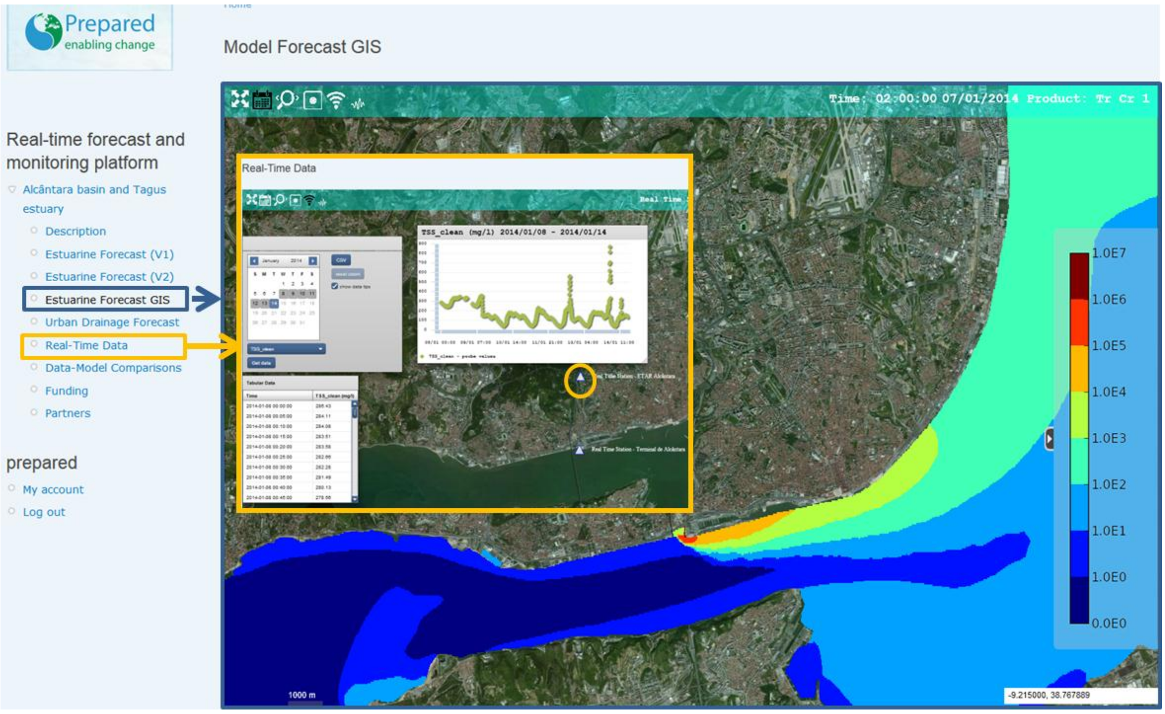

Figure 3 – Global view of interface, showing faecal concentration forecasts and the location of the PREPARED network stations

3 CONCLUSIONS AND RECOMMENDATIONS

The real-time forecast and monitoring network platform developed in the scope of WA4 – tasks 4.3.4 and 4.3.5 was demonstrated in the Lisbon site to support early-warning of faecal contamination events in the receiving waters of the major CSO outflow (Alcântara catchment).

The numerical model SWMM was applied, calibrated and validated for the Alcântara catchment. TSS and COD are simulated with exponential build-up and wash-off equations. The model uses relations between TSS and faecal contamination indicators and takes advantage of data provided by the on-line spectrophotometric probe. The major sources of errors and uncertainties were assessed and overcome whenever possible. In particular, the model's accuracy is significantly affected by the quality of the rainfall predictions and, to a lesser extent, by the rainfall-dependent inflow and infiltration. The current model results from successive improvements made by the LNEC and the SIMTEJO teams, running on servers of both institutions.

A coupled 3D baroclinic circulation and faecal contamination model was developed for the Tagus estuary and validated against existing and new data. The model is forced by elevations, salinity and temperature forecasts at the ocean boundary, river flow at the Tagus river boundary, and by atmospheric inputs. The water quality model is fed from the Alcântara catchment model. The modelling system was included in a forecast engine to produce 48-hour predictions. The coupled circulation-water quality model (ECO-SELFE) provides accurate forecasts of the circulation and the faecal contamination in the Tagus estuary.

A forecast WebGIS platform was implemented in Lisbon, hosting the integrated use of the Alcântara urban drainage and the estuary models for real-time 48 hour predictions, automatically validated against on-line data (from the PREPARED network and other sources).

An on-line water quality monitoring network was implemented and validated through tailor-made field campaigns. Experimental research has required complex logistics and involvement of equipment, materials, labs and multidisciplinary teams from both SIMTEJO and LNEC. The monitoring network data are used to feed the integrated WebGIS platform and to support the surveillance and early-warning of faecal contamination events. Data are measured by conventional and UV-Vis spectrophotometric probes in the Alcântara CSO and in the estuary, close to the Alcântara catchment outfall. Laboratory results from grab samples confirmed the accuracy of TSS and COD measurements from the spectrophotometric probes. A routine was developed to detect errors and inconsistencies and to create new series free of outliers and spurious data. The operational use of the Lisbon demo platform has already contributed to a better knowledge of the impact of the Alcântara catchment outfall. Besides assessing the impact on the estuary of the Alcântara catchment outfall, this platform also constitutes an important asset for the global monitoring of the Tagus estuary. Thanks to its innovative nature and user-oriented services, supported by both high-accuracy models and real-time data, the platform has been used by SIMTEJO to enhance sewer and WWTP operation, aiming at more sustainable and energy-efficient wastewater management and planning adaptation to climate change. Preliminary results were already presented by SIMTEJO at ENEG2013, the main Portuguese conference for the water utilities.

The platform for management of CSO discharges in receiving waters demonstrated for Lisbon and the Tagus estuary has the potential for a wider application to other cities and other receiving water bodies. Its application only depends on the availability of modelling studies on the sewer network and receiving water bodies and on the availability of real-time data for its validation. Indeed, the platform is of generic nature and can be easily adapted for other sites.

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