Real-Time Monitoring and Forecasting System for Early Warning of Recreational Waters Contamination

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ABSTRACT

A new WebGIS platform for urban drainage management was developed based on the integration of catchment-to-receiving waters modelling and on real-time on-line monitoring networks. The platform is devoted to the surveillance and real-time decision support for urban drainage management, especially for issuing early warnings for faecal contamination in receiving waters. The water information forecast framework (WIFF) platform was deployed in the Tagus estuary forced by the discharges from the Alcântara catchment, the largest catchment of Lisbon. The system combines the 3D hydrodynamics and water quality model ECO-SELFE, that simulates circulation and faecal contamination in the Tagus estuary, forced by the Alcântara urban drainage model, built in SWMM. On-line monitoring stations were installed in the Alcântara CSO and in the estuary. Several synoptic field surveys were conducted, aiming at improving the water quality models validation and integration and validating and complementing the on-line monitoring data. These campaigns also supported the search for relations between real-time measurable variables and faecal contamination indicators. Since microbial faecal contamination cannot be measured by existing sensors, ammonia and parameters measured by UV–Vis spectrophotometric probes are used as baseline parameters for continuous verification of the water quality forecasts.

KEYWORDS

On-line water quality monitoring network, integrated urban modelling, forecast platforms, real-time management, early-warning systems, decision-support systems

INTRODUCTION

Combined sewer overflow (CSO) discharges from large cities can have significant environmental impacts on marginal water bodies, affecting the quality of life and in particular bathing and recreational activities (Marsalek and Rochfort, 2004; David and Matos, 2005; Passerat *et al*., 2011). These impacts can be exacerbated by climate change, affected through precipitation changes and sea level rise.

The Water Framework Directive (WFD, 2000) and its "daughter" directives, namely the Flood Risks Directive and the Bathing Water Management Directive, define a water management approach based on risk management, on public information and consultation through georeferenced technologies, and on the development and maintenance of monitoring, forecasting and early-warning systems. Surveillance and early-warning systems have received a great development recently, particularly to anticipate floods in urban areas (Seo *et al*., 2013 ; Thorndahl *et al*., 2013) and to predict the hydrodynamics and propagation of sea waves in estuarine and coastal areas (Jesus *et al*., 2012; Baptista, 2006). However, monitoring and forecasting processes related with water quality still involve a number of challenges to allow for reliably early warnings, particularly when involving processes with very different spatial and temporal scales as well as receiving waters with a complex environmental matrix.

A new WebGIS platform for urban drainage management was developed, based on the integration of catchment-to-receiving waters modelling and on real-time on-line monitoring networks, and their automatic comparison. The platform is devoted to the surveillance and real-time decision support for urban drainage management, in particular to support the issuing of early-warnings of faecal contamination in receiving waters, through a combination of information from predictive models and sensors. The developments of the WIFF platform (Water Information Forecast Framework) and its application to the impact assessment of Alcântara catchment, in Lisbon, in the Tagus estuary were performed aiming at the adaptation to climate change, within the FP7.EU PREPARED and SI-GeA projects.

METHODOLOGY

System requirements

The development of a surveillance and early-warning system must integrate real-time on-line monitoring networks and forecasting tools that enable the anticipation of critical events and assist decision-making to mitigate their effects. All the relevant hydraulic and water quality processes must be explicitly integrated, from the catchment to the receiving waters, at the appropriate spatial and temporal scales. Therefore, the system must incorporate, into a single platform: integrated mathematical models of the drainage network, WWTP and receiving water body; real-time data from monitoring networks; forcings for the mathematical models from oceanographic and regional atmospheric forecast models; and a system for automatic comparison between predicted and real time data (Figure 1). The system must be conceived for surveillance and decision support, being able to issue early warnings of pollution episodes, including of faecal contamination in bathing or recreational waters.

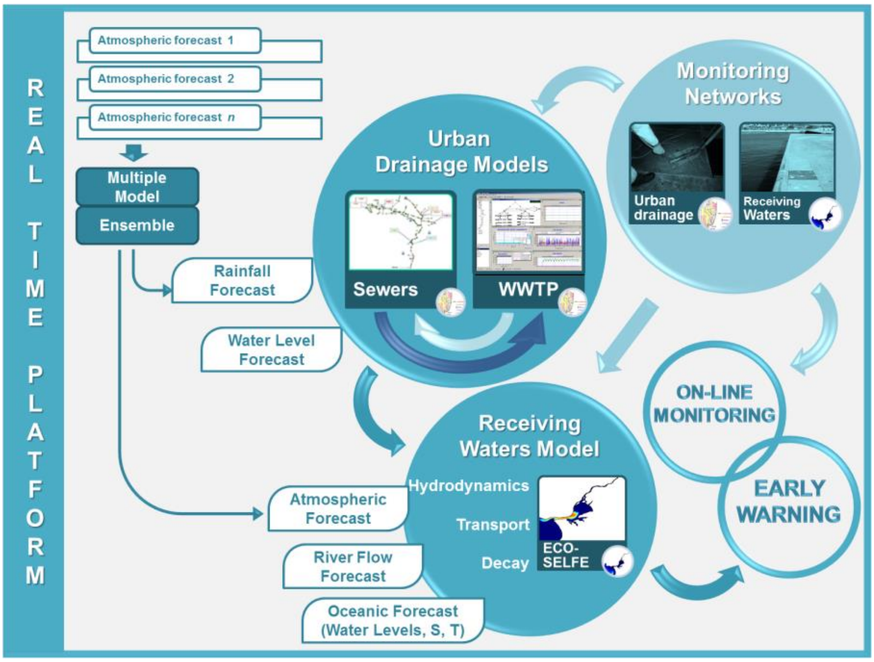

Figure 1. Conceptual scheme of the real-time monitoring and forecasting system.

Implementation challenges

The conception and implementation of this system poses several challenges that must be considered in the project planning, namely at the level of:

- integration and calibration of models with different spatial and temporal time scales;
- integration of the hydrodynamic and water quality components, particularly with respect to the faecal contamination indicators;
- need of a sufficient set of synoptic water quality data from the different sub-systems, for integrated models calibration;
- need of real-time data for automatic assessment of the forecasts;
- need of relations between real-time measurable variables and faecal contamination indicators;
- need for an efficient forecast computational structure for timely event predictions.

INTEGRATED MONITORING AND FORECASTING SYSTEM

Implementation and validation requirements

The implementation of the integrated modelling system implies the previous calibration and validation of each model component, using historical datasets, for both dry-weather conditions and storm events, while its operation requires real-time, on-line data for continuous automatic verification of the models' performance within the forecast system. Similarly, the validation of the integrated modelling system requires:

1) synoptic measurements in the several spatial compartments (catchment, sewer system, WWTP, and receiving waters), to confirm both spatial and temporal accurate resolution of the relevant processes, and
2) a combination of real-time raingauges, flowmeters and conventional and sophisticated sensors judiciously distributed along the network.

Case study: The Alcântara catchment

The integrated model and monitoring infrastructure is demonstrated herein for the impact assessment of Alcântara catchment in the Tagus estuary, an area of recreational activities. The city of Lisbon is divided in several combined catchments which discharge CSO into an extensive area of the Tagus estuary. The city is served by three wastewater treatment plants (WWTP), of which the Alcântara WWTP serves the larger area, with about 6 000 ha (Figure 3c). The WWTP was designed to serve 700 000 inhabitants equivalent. The dry-weather treatment capacity is of 3.3 m^3/s (using Multiflo® process for primary treatment and biofiltration, Biostyr®, for biological treatment) and an additional 3.3 m^3/s capacity is available for wet-weather flow (using advanced physicochemical treatment, Actiflo® process). The Tagus estuary is a mesotidal system subject to tides, wind and river flow forcings. In the discharge points, flow is bidirectional during the tidal cycle (ebb-flood) and subject to large salinity gradients.

Integrated modelling system for hydrodynamics and water quality in the sewer, WWTP and receiving waters

The numerical model SWMM (Rossman, 2007) was applied, calibrated and validated to the Alcântara catchment. TSS and COD are simulated with empirical equations. The model uses relations between TSS and faecal contamination indicators and takes advantage of data provided by the on-line spectrophotometric probe. The uncertainty in spatial rainfall distribution was found to significantly affect the accuracy of the model for some heavy storms, due to the large size of the catchment. Therefore, additional raingauges or rainfall satellite data should improve model parameterisation and results. A conceptual RDII model is being implemented to reduce uncertainty (Mota *et al*., 2014).

The WWTP hydraulic model was built in SWMM and was calibrated using operation data. A simplified semi-empirical model was developed for water quality simulation (TSS, COD and *Escherichia coli*) through the different WWTP components, for dry- and wet-weather conditions. In spite of the simplified WWTP model, the water quality transformations in the borders with the sewer model are adequate for the project purpose.

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. The spatial resolution of the horizontal grid varies from about 1 m in the Alcântara area to 2 km in the oceanic area. Nine open boundaries were considered: the Atlantic ocean, the Tagus river, the Alcântara outfall, and six other discharges in the water front Algés – Alcântara – Terreiro do Paço. The hydrodynamic 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 PREPARED FP7 project field surveys (David *et al*., 2013). Results showed the ability of the model to represent the main patterns observed in time and space. Differences may be partially explained by boundary conditions imposed and by additional contamination sources that are not being considered (Rodrigues *et al*., 2013).

Interactions between the sewer model, the WWTP and the estuary are done through soft coupling, namely the tidal water level in the downstream boundaries of the sewer model, and the flow and faecal contamination input from the CSO into the receiving waters at all main discharge points. The integrated system was validated in several field surveys, carried out to synoptically characterize hydraulic and water quality parameters from the sewer and the estuary. Six surveys were undertaken over 2012-2014 in 7 sections covering the sewer system, the WWTP, the Alcântara outfall and the estuary. The surveys were carried out for complete tidal cycles (13 hours) during dry- and wet-weather conditions, and included hourly and synoptic determinations of several parameters, measured by probes, and 4-hour water sampling, for laboratory analysis of physical, chemical and microbiological parameters.

Real-time monitoring network

On-line real-time field data are available for models' automated and continuous validation and to support the surveillance and early-warning of faecal contamination events. The monitoring system from SIMTEJO (the WWTP and main interceptors' utility) allows for the transmission of on-line data from four raingauges and some flowmeters installed throughout the sewage network, including the WWTP. Two on-line monitoring stations were installed in the Alcântara CSO and in the estuary, close to the Alcântara catchment outfall. These stations, as well as some stations within the WWTP, 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 (Figure 2). External on-line monitoring networks in the estuary complement these data sources.

a)
b)

Figure 2. Water quality monitoring stations: a) in the sewer (WWTP inlet); b) in the estuary.

Data provided by field surveys have also been crucial to validate and complement the on-line monitoring data. To support the faecal contamination forecasts and early-warning, on-going research is searching for relationships between monitored parameter concentrations and faecal bacteria concentration. Preliminary analyses showed promising relations between faecal bacteria concentrations and TSS and COD concentrations in the sewer (with determination 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, corrections for their measurements are also being studied based on the positive correlations found between salinity and both ammonium and nitrates in the receiving waters (Rodrigues *et al*., 2014).

Real-time forecast system for integrated modelling

48 hour forecasts are managed within the WIFF platform (denoted as RDFS-PREPARED platform in David *et al*., 2013). The real-time forecast system automatically provides predictions everyday for the integrated sewer, WWTP and estuary dynamics. Two sources of atmospheric predictions were used in operational mode to force the models: WRF 9 km from Windguru (http://www.windguru.cz) and WRF 5 km from the Aveiro University model (http://climetua.fis.ua.pt/-fields/continent/precip). The sewer model results are evaluated in Mota *et al*. (2014). The forecast system integrates a set of scripts and programs for the automatic management of models and data, the forecast engine and an online WebGIS platform for access to predictions and real-time data, available at desktop and mobile environments (Oliveira *et al*., 2014). WIFF's physical architecture includes several computer servers and a shared file server. This central file server provides archival storage for model outputs, access to model results, and tools for managing the forecasts.

REAL-TIME WEBGIS PLATFORM TO SUPPORT EARLY WARNINGS

An interactive and flexible computational GIS-based platform is developed to provide on-line, intuitive and geographically-referenced access to real-time data and model predictions, and to produce on-demand services in support of routine management of water bodies. This platform is intended for the daily use of water management entities and is available at each deployment site to the relevant end-users. The enhanced interface is based on a previous deployment using Drupal, a PHP-based Content Management System (CMS) used to access model metadata, status and products. To allow for geospatial placement of monitoring and forecast products, as well as model output query capabilities, map server support (Geoserver) providing Web Map Services (WMS) have been added to the WIFF. A WebGIS was developed in Flex, using the OpenScales library to handle geospatial information. This WebGIS is being built in a modular and generic way, to allow future inclusions of new models, sensor networks and services required by water body authorities and emergency agents. The requirements analysis of this platform was developed in close cooperation with the WWTP utility, to promote its usefulness for management purposes.

The WIFF platform was customized for the Alcântara catchment integrated analysis. Figure 3 illustrates the information from three menus: a) "Estuarine Forecast GIS", where the faecal concentration forecasts in the estuary were selected; b) "Real-Time Data", showing the location of the on-line water quality stations and the access to the data, in table and graphs and; c) "Urban Drainage Forecast". Table data may be saved into external files for offline analyses.

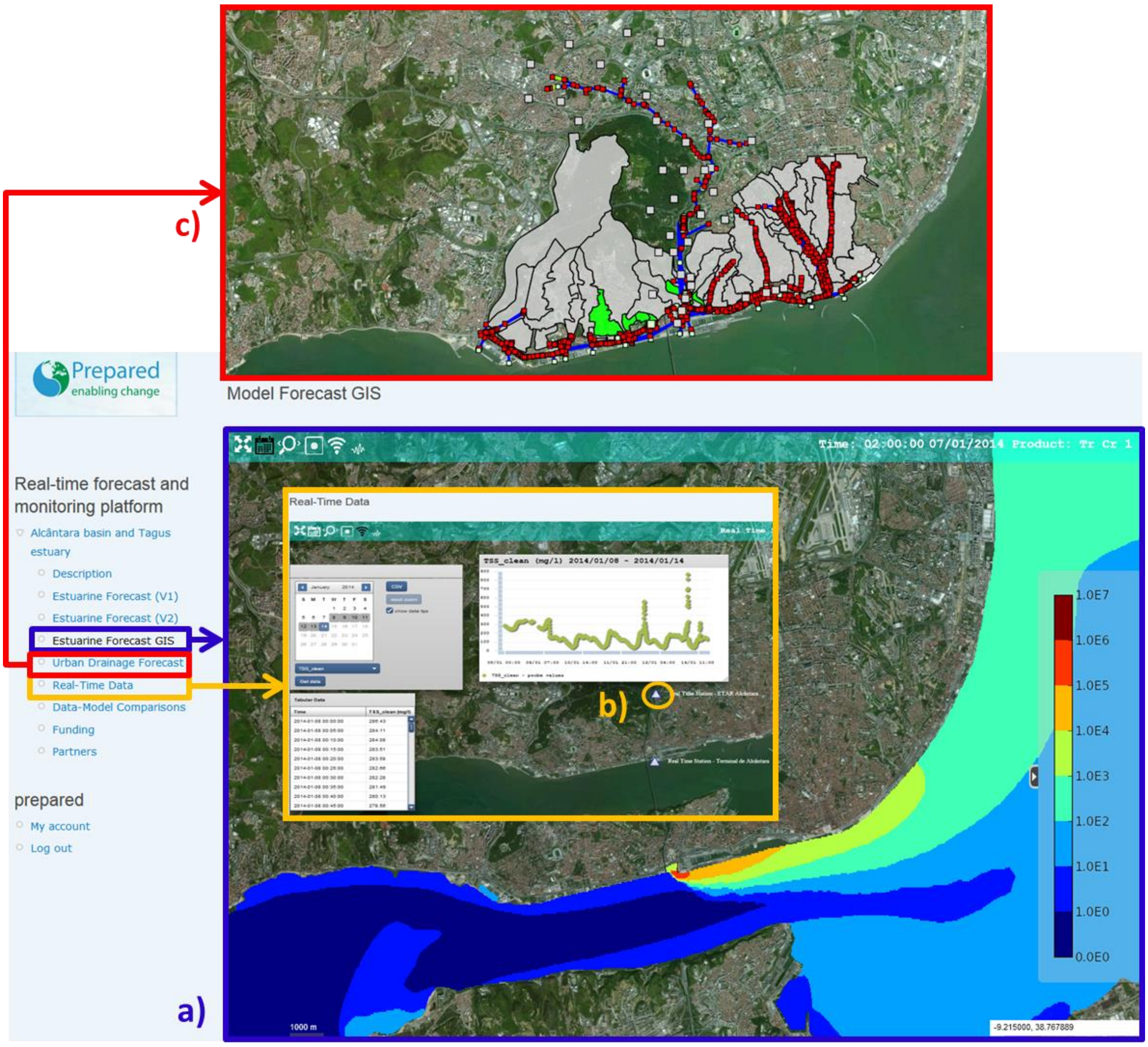

Figure 3. WIFF interface showing: a) faecal concentration forecasts in the estuary; b) the access to data from the on-line water quality stations and; c) the urban drainage network.

CONCLUSIONS

A new WebGIS platform for urban drainage management was developed, based on the integration of catchment-to-receiving waters modelling and on real-time on-line monitoring networks, and their automatic comparison. The platform is devoted to the surveillance and real-time decision support for urban drainage management, in particular to support the issuing of early-warnings of faecal contamination in receiving waters, through a combination of information from predictive models and sensors. This innovative decision support tool for urban drainage systems management is organized to provide tailor-made, automatic services to support the management of the receiving water bodies and the operation of the urban drainage infrastructure (WWTP and drainage network).

The WIFF platform was implemented in Lisbon, hosting the integrated use of the Alcântara urban drainage, WWTP and the estuary models for real-time 48 hour predictions, automatically validated against on-line data (from the PREPARED network and other sources). Two on-line real-time monitoring stations were installed to measure physical and chemical parameters in the sewer and the estuary. S::CAN UV-Vis spectrophotometric probes were installed at both stations and ammonium and dissolved oxygen probes were also installed in the estuary. Data are available on-line for continuous automatic verification of the models' performance and to support the surveillance and early-warning of faecal contamination events. Experimental surveys were carried out during dry- and wet-weather conditions aiming at getting synoptic water quality data from the different sub-systems for integrated models calibration, validating and complementing the on-line monitoring data, and searching for relations between real-time measurable variables and faecal contamination indicators. Results indicate UV-Vis spectra are reliable for TSS and COD estimation in urban drainage systems. Promising relations were found between faecal bacteria concentrations and TSS and COD concentrations in the sewer and between faecal bacteria concentrations and ammonium concentrations in the receiving waters. The major sources of errors and uncertainties were assessed and overcome whenever possible. In particular, the sewer model's accuracy is substantially affected by the quality of the rainfall predictions and, to a lesser extent, by the rainfall-dependent inflow and infiltration. A conceptual RDII model is being implemented and the potential use of satellite or radar rainfall forecasts may also contribute to improve the predictions.

This WebGIS platform is of generic nature and 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.

ACKNOWLEDGEMENTS

This study was co-funded by the Seventh Framework Programme, through Project PREPARED (FP7-ENV-2009-1 Grant Agreement nº 244232), by the *Fundação para a Ciência e Tecnologia* (FCT), through Project SIMAI (PTDC/AAC-AMB/102634/2008), and by the QREN, under *Fundo Europeu de Desenvolvimento Regional* (FEDER), within COMPETE - *Programa Operacional Fatores de Competitividade*, through the Project SI-GeA (Project n.º 23053). The third author is co-funded by FCT grant SFRH/BPD/87512/2012.

The authors would like to thank to Prof. António Melo Baptista and Prof. Joseph Zhang, from CMOP, for making the SELFE model available, to Prof. Alfredo Rocha (University of Aveiro and CESAM) for the atmospheric forecasts, to the Instituto Geográfico Português and to the Administração do Porto de Lisboa for making the tide gauges data available on-line, and to INAG for making the water levels available through SNIRH. The authors also thank to Eng. António Frazão for all the support from Simtejo, and all colleagues that collaborate in the field surveys.

REFERENCES

Baptista A.M. (2006). CORIE: the first decade of a coastal-margin collaborative observatory. Oceans'06, Boston, MA.

David L.M. and Matos J. S. (2005). Combined sewer overflow emissions to bathing waters in Portugal. How to reduce in densely urbanised areas?. *Wat. Sci. & Tech*., 52(9), 183-190.

David L.M., Oliveira A., Rodrigues M., Jesus, G., Póvoa P., David C., Costa R., Fortunato A.B., Menaia J., Frazão M. and Matos R.S. (2013). Development of an integrated system for early warning of recreational waters contamination. In: Bertrand-Krajewski J.-L. and Fletcher T.D. (eds). Proc. of Novatech 2013, GRAIE, Lyon, France, CD-ROM.

Jesus G., Gomes J., Ribeiro N.A., Oliveira A., 2012. Custom deployment of a Nowcast-forecast information system in coastal regions. Proceedings of Geomundus 2012.

Marsalek J. and Rochfort Q., (2004). Urban wet-weather flows: sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. *Journal of Toxicology and Environmental Health*, Part A, 67(20-22), 1765-1777.

Mota T., David L.M., Rocha A., Jesus G., Oliveira A. (2014, submitted). Assessment of the predictions from a large urban drainage model forced by WRF atmospheric models. Proc. of 13th ICUD, Sarawak, Malaysia.

Oliveira A., Jesus G., Gomes J.L., Rogeiro J., Azevedo A., Rodrigues M., Fortunato A.B., Dias J.M., Tomas L.M., Oliveira E.R. Alves F.L. and den Boer S. (2014). An interactive WebGIS observatory platform for enhanced support of coastal management. In: Green, A.N. and Cooper, J.A.G. (eds.), Proc. 13th Int. Coastal Symp., Durban, South Africa, *J. of Coastal Research*, Special Issue No. 66, ISSN 0749-0208.

Seo D., Lakhankar T., Mejia J., Cosgrove B. and Khanbilvardi, R. (2013). Evaluation of operational national weather service gridded flash flood guidance over the Arkansas red river basin. *J. of the American Water Resources Association*, 49(6), 1296-1307. doi: 10.1111/jawr.12087

Thorndahl S. and Rasmussen, M.R. (2013). Short-term forecasting of urban storm water runoff in real-time using extrapolated radar rainfall data. *J. of hydroinformatics*, 15 (3), 897-912.

Passerat J., Ouattara N.K., Mouchel J.M., Vincent R. and Servais P. (2011). Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. *Water Research*, 45(2), 893-903.

Rodrigues M., Costa J., Jesus G., Fortunato A.B., Rogeiro J., Gomes J., Oliveira A. and David L.M. (2013). Application of an estuarine and coastal nowcast-forecast information system to the Tagus estuary. Proc. of the 6th SCACR – Int. Short Course/Conference on Applied Coastal Research, Lisboa, Portugal.

Rodrigues M., David L.M., Oliveira A., Fortunato A.B., Menaia J., Costa J., Mota T., Rogeiro J., Jesus G., Morais P., Palma J. and Matos R.S. (2014). Deliverable 4.3.4 - On-line monitoring of CSO: sewer and receiving waters. PREPARED Project. Deliverable 2013.043.

Rossman L.A. (2007). Stormwater Management Model User's Manual, Version 5.0. U.S.