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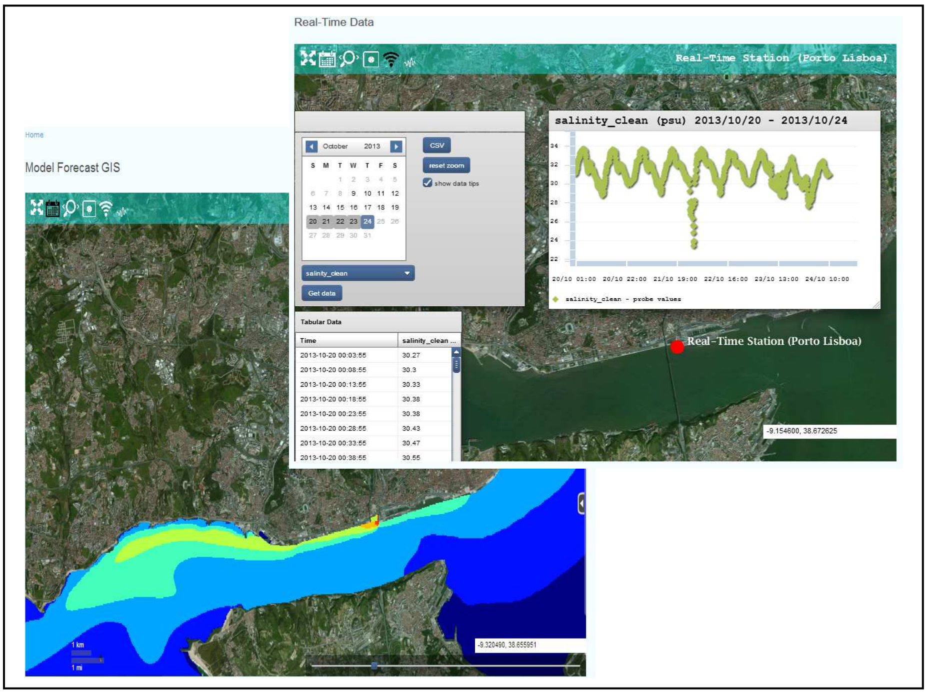
Real-time monitoring and forecast platform to support early warning of faecal contamination in recreational waters



SEVENTH FRAMEWORK
PROGRAMME

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SEVENTH FRAMEWORK PROGRAMME

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Author(s)
Anabela Oliveira, João Rogeiro, Gonçalo Jesus, André B. Fortunato, Luís M. David, Marta Rodrigues, Joana Costa, Tiago Mota, João Luís Gomes, Rafaela S. Matos

LNEC – Laboratório Nacional de Engenharia Civil, Portugal

Quality Assurance
By **Conceição David *, Luís I. Portela****

***SIMTEJO – Saneamento Integrado dos Municípios do Tejo e Trancão, S.A. Portugal**
**** LNEC – Laboratório Nacional de Engenharia Civil, Portugal**

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Contents

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1 INTRODUCTION

Controlling urban floods and managing direct discharges of effluents into receiving waters from combined sewer overflows (CSO) are two major challenges faced by urban water management utilities. Discharges from large cities can have significant environmental impacts on marginal water bodies, affecting the quality of life in general, and recreational activities in particular (Marsalek and Rochfort, 2004; David and Matos, 2005; Passerat *et al.*, 2011).

These impacts can be exacerbated by climate change. First, the growing magnitude and frequency of extreme precipitation events (Groisman *et al.*, 2005; Frei *et al.*, 2006) will increase the number and severity of the discharges. Secondly, sea level rise and the resulting increase of salinity intrusion into the sewers can degrade the performance of wastewater infrastructures, affecting gate and pump operations and advanced biological wastewater treatment procedures.

The ability to jointly manage an entire urban drainage and treatment system, towards an efficient and environmental-friendly operation of these infrastructures in a climate-change context, is often limited by the lack of reliable real-time information. Existing information systems are frequently devoted to specific parts of the network, lacking synoptic and cross-domain data. In addition, data and prediction tools are usually focused on physical variables alone. Water quality information is, at best, supported by very simple modelling approaches and limited sensors. More often, this information is sparse and not organized to provide efficient command and control procedures, taking into account climate change effects in the various domains.

Timely prediction and monitoring of environmental conditions, as well as anticipation of hazardous events, are essential parts of recreational waters management. Monitoring and forecasting platforms can provide the necessary information for safe and efficient economic activities, and the protection of valuable natural assets, including the preservation of ecosystems and recreational areas.

To this end, an innovative, real-time, coupled urban and estuarine platform was developed to support the integrated water quality management of wastewater systems, from the upstream catchment to the receiving waters. The platform efficiently integrates the monitoring and modelling of the different physical and water quality processes from the catchment to the receiving waters, at the appropriate spatial and temporal scales. It provides real-time web access to on-line hydrodynamic and water quality monitoring networks and short-term model predictions, based on a coupled modelling system that includes relevant interactions between the urban drainage system and the receiving waters, automatically compared with available on-line network data. This innovative decision support tool for urban drainage systems management is organized to provide tailor-made, automatic services to support the major operation tasks, drilled-down to the necessary details for decision support.

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The forecasting engine behind the platform provides hydrodynamic and faecal contamination predictions in all components of the systems (drainage network, wastewater treatment plant and estuary), accounting for all interactions between them. Prediction models are forced by regional forecasts whenever possible, and by real-time data otherwise. The accuracy of the predictions is verified through continuous, automatic comparison with data from the innovative on-line monitoring network, including both physical and water quality sensors (Rodrigues *et al.*, 2014).

Based on the platform's data and model forecasts, an early-warning system is being proposed, supported by alert triggers both on the sewer network information and estuarine conditions. The system is being applied to the Lisbon demo, accounting for the impact of the combined sewage outfall from the Alcântara catchment on the Tagus estuary (David *et al.*, 2014).

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2 FINDINGS

2.1 Innovative methodology for real-time information system in support of early warning of CSO discharges into receiving waters

Surface waters, in particular in coastal zones, are increasingly used for recreational activities (e.g. bathing, diving, canoeing, sailing, fishing), for which good quality is required. The quality of these water masses can be severely impacted by CSO, especially those associated with large storms. The consequences on the receiving waters depend on the intensity, volume and duration of the discharges, the type of pollutants, and the dilution and regeneration capacity of the receiving water body (Marsalek and Rochfort, 2004; Chocat *et al*., 2006).

Surveillance and early-warning systems require real-time monitoring networks as well as forecasting tools that enable the early detection or even anticipation of critical events and assist decision-making to mitigate their effects. These systems have evolved significantly in the last decade, particularly in estuarine and coastal areas, to predict the hydrodynamics and propagation of sea waves (e.g. Baptista, 2006; Jesus *et al*., 2012). However, monitoring and forecasting water quality processes still face several challenges to allow for reliable early warnings, particularly when involving processes occuring at different spatial and temporal scales and receiving waters with a very complex environmental matrix (e.g., estuaries).

The accurate prediction of contamination events associated to urban discharges in receiving water bodies requires forecasting tools for all components and their interactions, from the upper basin to the estuary. Herein, a new methodology is proposed to integrate real-time data with coupled state-of-the-art models, and incorporate them within a forecast engine and webGIS platform (Figure 1). This methodology allows for the real-time automatic daily operation of the prediction procedure, supporting the issuying of alerts in the whole domain, and its continuous validation against real-time data. The system explicitly integrates the different processes involved from the catchment to the receiving waters, at the appropriate spatial and temporal scales, and takes advantages of the outputs from the innovative CSO monitoring system described in Rodrigues *et al*. (2014) for prediction and validation purposes.

2.2 Integrated modeling system for hydrodynamics and water quality in CSO and receiving waters

The coupled hydrodynamic and water quality simulation of both urban drainage and receiving water bodies poses several challenges: 1) on the adequate temporal and spatial scales for all relevant processes; 2) on the computational requirements for its use within a forecast system; and 3) on the methodology to quantify and reduce error propagation within the chain of cascade modelling. These difficulties, together with the current lack of real-time data for the validation of faecal contamination model predictions, have

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prevented the development of nowcast-forecast systems that account for all relevant processes and interactions in the integrated system.

The recent advances in continuous monitoring of physical-chemical parameters with sophisticated/new sensors (e.g. spectrophotometric probes) and its potential use to support early-warning of pollution events (Rodrigues *et al.*, 2014), together with the computational gains brought by parallel and high performance computing (Costa *et al.*, 2009) have paved the way towards a new generation of modelling systems that can overcome the challenges identified above and take advantage of recent improvements on individual model components (Rossman, 2007; Rodrigues *et al.*, 2011).

Herein, a new integrated modeling system for coupled simulation of hydrodynamics and water quality in urban drainage networks, from the catchment to the receiving waters, is presented. The modelling system implements the conceptual approach (Figure 1), accounting for the interactions between components and forced by regional atmospheric and oceanographic models.

The implementation of this modelling system implies the previous calibration and validation of each modelling component, using historical datasets, for both dry-weather conditions and storm events, while its operation requires real-time, on-line data for continuous 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, wastewater treatment plant (WWTP) if approriate for the aims, and receiving waters), to confirm both spatial and temporal accurate resolution of the relevant processes, and 2) a combination of real-time conventional and complex sensors juditiously distributed along the network. On-line monitoring stations, complemented by tailored-for-purpose field surveys, such as those described in Rodrigues *et al.* (2014), allow gathering fundamental monitoring support for the reliable use of the proposed modelling system for early-warning of faecal contamination events and other wastewater management tasks.

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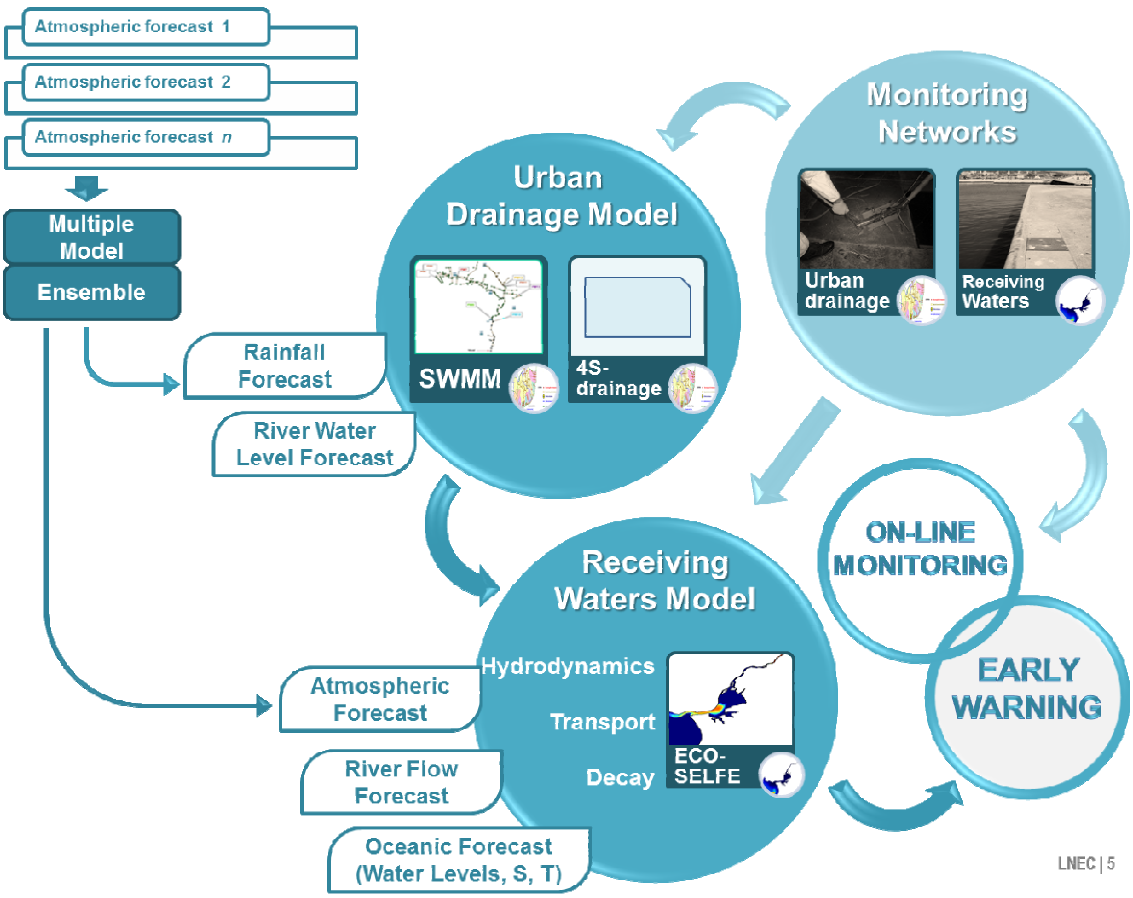

Figure 1 – Conceptual approach for real time forecasting system in support of early warning of CSO discharges in receiving waters.

The urban drainage hydraulic model is built in SWMM (Rossman, 2007), while the sewer water quality model uses relations between Total Suspended Solids (TSS) and faecal contamination indicators and takes advantage of data provided by an on-line spectrophotometric probe (Rodrigues *et al*., 2014).
The receiving waters hydrodynamics and faecal contamination are simulated using ECO-SELFE, a 3D community model which solves for circulation (SELFE, Zhang and Baptista, 2008) and faecal contamination (Rodrigues *et al*., 2011), among many other processes. The hydrodynamics and faecal contamination model is an unstructured grid three-dimensional model that allows the simulation of the time and space variation of a generic faecal tracer, accounting for bacteria die-off rate and the settling due to the attachment of the faecal bateria to the suspended sediments. The die-off rate is defined as proposed by Canteras *et al*. (1995), while the simulation of the settling of the microorganisms follows the approach proposed by Steets and Holden (2003).
Interactions between the estuary and the sewer models are included, namely the tidal water level in the downstream boundaries of the sewer model, and the flow and faecal contamination input from the drainage system into the receiving waters at all discharge points.

2.3 RDFS- PREPARED – a forecast engine for integrated urban wastewater prediction

2.3.1 *Nowcast-forecast systems for multi-scale hydrodynamics and water quality in water bodies*

Nowcast-forecast systems (NFS) are important tools to support efficient and sustainable management, as the models' predicting skills allow the anticipation of hazardous situations and the antecipation of their consequences. These systems, which started being developed in the 1990's, have shifted from research to operational tools, providing managers with short-term predictions (e.g. waves, tidal currents) and integrating both models and data, to support emergency operations and water resources management. Over the years, NFS evolved in both scope and functionality. Forecasts now include more physical variables, and are being extended to include chemical and biological variables as well (Oliveira et al., 2014). Furthermore, better functionalities are being developed to convey data and model results to the user, in order to reach a broader spectrum of users, from water body managers to the avid recreational user, using desktop and mobile platforms. Regarding water quality, in particular, nowcast-forecast systems are now emerging (bathingwater.dhigroup.comearlywarningsystem.html, www.waterman.hku.hk/beach/member/Default.aspx), but there are still few nowcast-forecast systems targeting faecal contamination issues (e.g. Viegas *et al.*, 2009).

In the scope of PREPARED, LNEC's Rapid Deployment Forecast System (RDFS-PT, Jesus *et al*., 2012), based on the deployment of a generic forecasting platform (Baptista, 2006), adaptable to any geographical location, and customizable for coastal applications, was extended to the integrated modelling system (Rodrigues *et al*., 2013). The extension included hydrodynamics and faecal contamination in urban drainage and receiving waters, as described above, and is denoted as RDFS-PREPARED. The system integrates the set of coupled numerical models that run automatically and daily in a high-performance environment, following the sequence and constraints defined above in the innovative methodology for early-warning of receiving waters. Each forecast of the coupled urban and receiving waters modelling system is forced by external atmospheric and regional circulation forecasts (atmospheric model prediction at a 9 km scale for precipitation in the sewer model and for wind, air temperature and other air variables for the estuary model; ocean model prediction – MyOcean – for the water level, temperature and salinity at the ocean boundaries for the estuary model), and by extrapolation of data and climatology for riverine boundary conditions. This strategy ensures a natural adaptation to variability in climate-dependable variables and is built in a modular way that allows the easy update of individual components.

2.3.2 *Physical Architecture of RDFS- PREPARED*

The physical architecture of RDFS-PREPARED comprises several computer servers, clustered around a central file server. This central file server provides archival storage for model outputs, access to model data, and tools for managing the forecasts. Every day each computer server runs one or more forecasts (depending on its capacity). The interaction between physical components and the location of files, web and database servers, as well as how users can connect to RDFS through a web browser are shown in Figure 2.

The RDFS-PREPARED execution process runs daily, starting forecasts execution scripts and products generation, among others, and interacting with the database in order to get the location of the forecast systems and remotely transfer the products files to the central node.

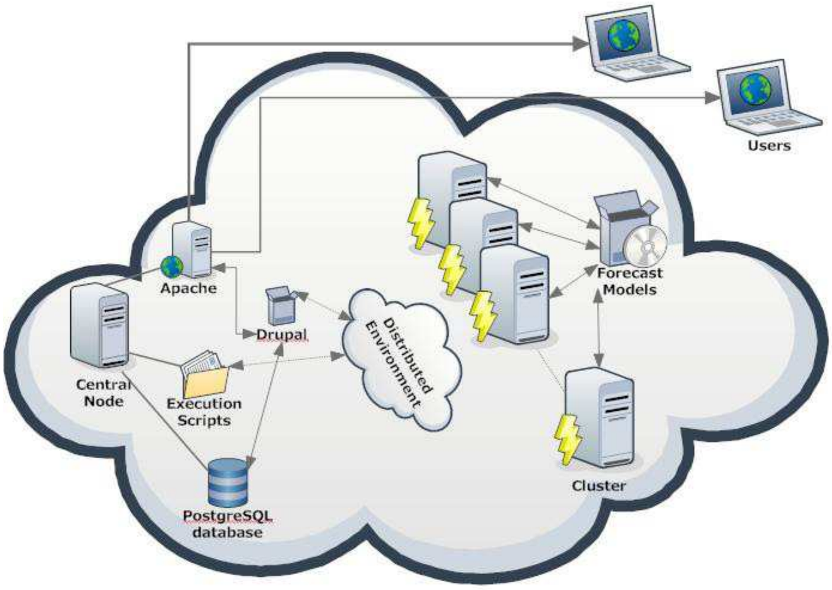

Figure 2 - RDFS-PREPARED physical architecture.

2.3.3 *Technologies and Interface of RDFS- PREPARED*

RDFS-PREPARED runs on the Linux operating system, and its core is composed by a set of Perl scripts, scheduled on crontab, which prepare and launch the simulations for each forecast model. The RDFS-PREPARED main process begins by setting up the environment of the current day, which involves creating the folder structure that will contain all information required to run the simulations, including the preparation scripts. These scripts interact with a PostgreSQL database to retrieve input data to force the models. Simulation requirements include the results of the previous run (and/or other forecast models simulation results in the ensemble mode), forecasts from regional atmospheric and oceanographic models, and data from field sensors.

A cascade modelling approach is used, forced by external regional models. Each model is fed by the outputs of the previous model, customized for each model format.

Models output results are then processed in the forecast engine, using visualization tools such as VisTrails or the matplotlib library, to generate

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automatically model forecast products and data/model comparisons, to be included in the WebGIS platform.

2.4 Real-time monitoring and forecast WebGIS platform in support of early warning of faecal contamination

2.4.1 Introduction

A new intelligent web 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 platform is conceived in a user's service-oriented architecture, providing an on-line access to both real-time model predictions and data-derived products, at different levels of detail and complexity. It is built in a modular and generic way, including both quick access products and a Web Geographic Information System (WebGIS). This WebGIS allows not only the visualization of the PREPARED network monitoring information, but also spatial data from other sources, that can be easily expanded in the future for new data sources. Services are automatically provided in the platform for comparison between model predictions and these data, granting robustness and long-term evaluation to the whole system to the end-users.

2.4.2 Concepts, technology and services

The RDFS-PREPARED platform is a customized deploy of Drupal, a PHP-based Content Management System (CMS), which is used to access model metadata, status and products (Figure 3).

The original RDFS-PT (Jesus *et al.*, 2012) only provided a static interaction with the model forecast products, lacking the means to localize them geospatially and to display other detailed information besides the products. This shortcoming was solved through the inclusion of GIS support for the generated products and to provide a more interactive and intuitive user interface (UI) for their visualization. In order to overcome those needs, Web Map Services (WMS) support have been added to the RDFS-PT, using Geoserver map server, allowing geospatial placement of products, as well as model output query capabilities.

The WebGIS was developed in Flex, using the OpenScales library to handle geospatial information. This WebGIS is built in a modular and generic way, allowing the visualization of RDFS-PREPARED data and also spatial data from other sources.

The deployment of RDFS-PREPARED products in Geoserver is automatic. It is done daily via a set of Perl scripts, which convert TIFF products into GeoTIFF, and a user-agent script that deploys these data into Geoserver. WMS layers are then served by Geoserver and displayed in the WebGIS, projected on top of a Bing Map Layer. This interface allows the user to intuitively manipulate existing products, offering, among others, zooming capabilities and a slider which allows easy navigation through model simulation results in a given interval (Figure 4).

Custom products are automatically generated for each model, depending on the complexity of the simulations and on the variables simulated. Examples of such products are the images and animations of isolines of water levels, velocities, salinity, water temperature and faecal indicators. The user can iterate over the results from one time step to the next, and also observe comparisons between model outputs and field sensor data.

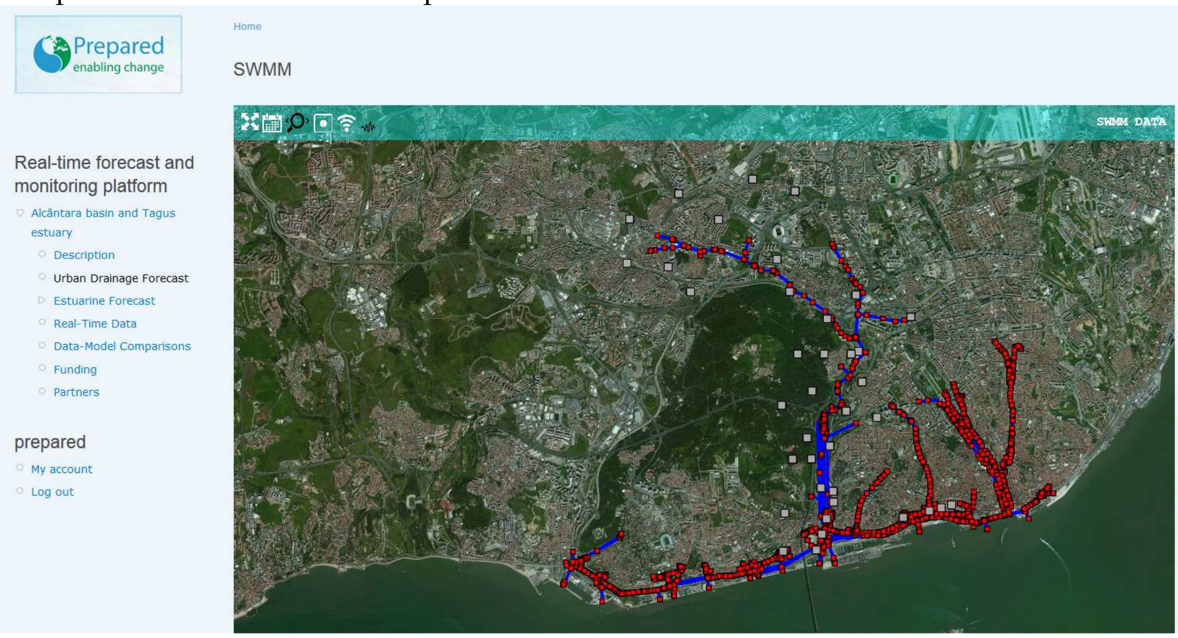


Figure 3 - RDFS-PREPARED interface, showing the urban drainage model. Red dots are the model nodes, sewer network links are shown in blue and the grey dots represent the contributing basins for the Alcântara CSO.

The new UI also provides access to real-time data (Figure 4). Data is transmitted from the monitoring stations to a central server through remote mobile communications, Circuit Switched Data - CSD or General Packet Radio Service - GPRS. The transmission occurs at given time intervals. Once at LNEC's central server, the sensor data is analyzed and stored into a persistent storage system. Data files are then parsed by a set of Perl scripts that verify if any alerts should be activated, and insert the data into a PostgreSQL database. These Perl scripts have been developed in a generic and modular way, using config files, providing future adaptation of the scripts to different types of measurement data, as well as functionalities additions to the process. The data are available via requests to Java SOAP Webservices which query the database.

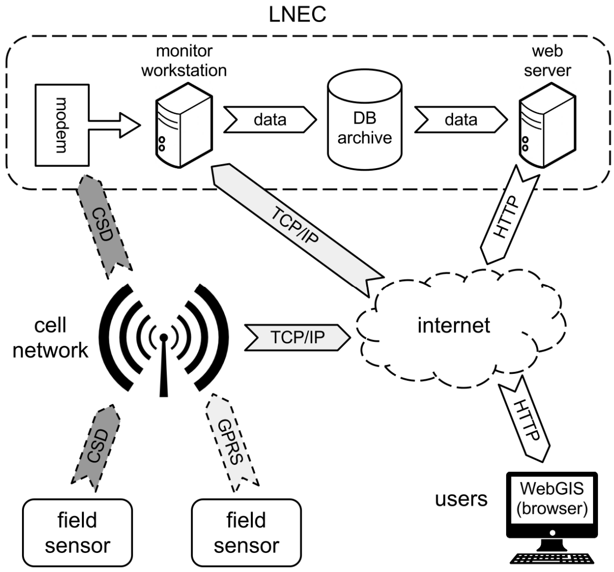


Figure 4 - RDFS-PREPARED data handling procedure.

In the WebGIS, users are able to choose which sensor data to access, as well as the time interval
and parameter monitored. These data are made available to the user in a simple way through line charts, tabular data and CSV files (Figure 5, Gomes *et al.*, 2013).

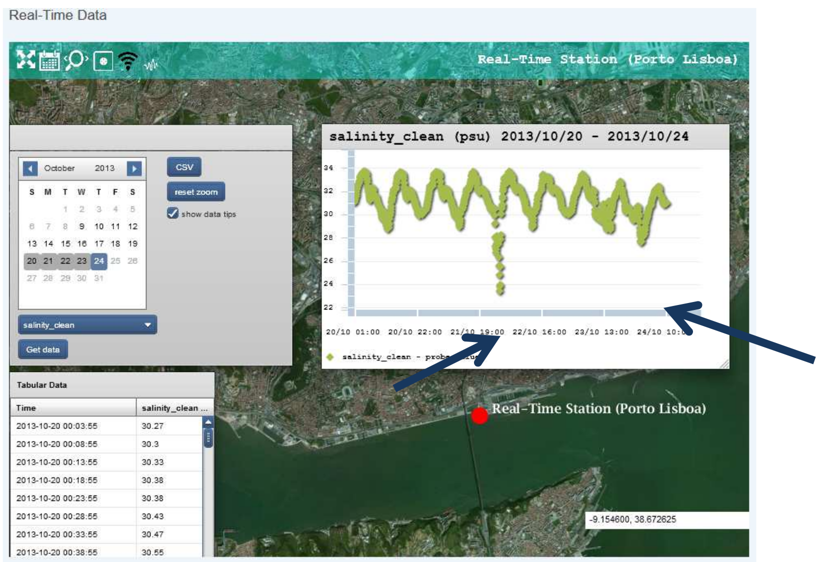


Figure 2.5 –RDFS-PREPARED platform applied to the Lisbon Demo: automatic monitoring data handling at a monitoring station.

The platform also provides access to several model prediction products, both for the urban drainage and estuary model (Figure 6). High resolution, zoomable layers, integrated within a GIS, are available for the hydrodynamic and faecal contamination variables.
For a quick analysis of the simulations, a fast-access product is available,

allowing for automatic and manual time visualization (Figure 7). Probing at the model results at user-specified locations (Figure 8), as well as automatic data/model comparison, constitute the remaining model products (Figure 9).

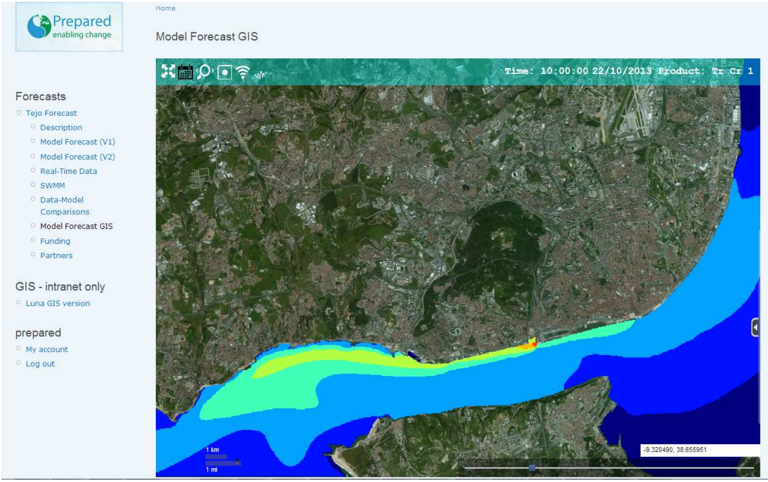
b) 

Figure 6 –RDFS-PREPARED platform applied to the Lisbon Demo: GIS model prediction layers for faecal coliforms.

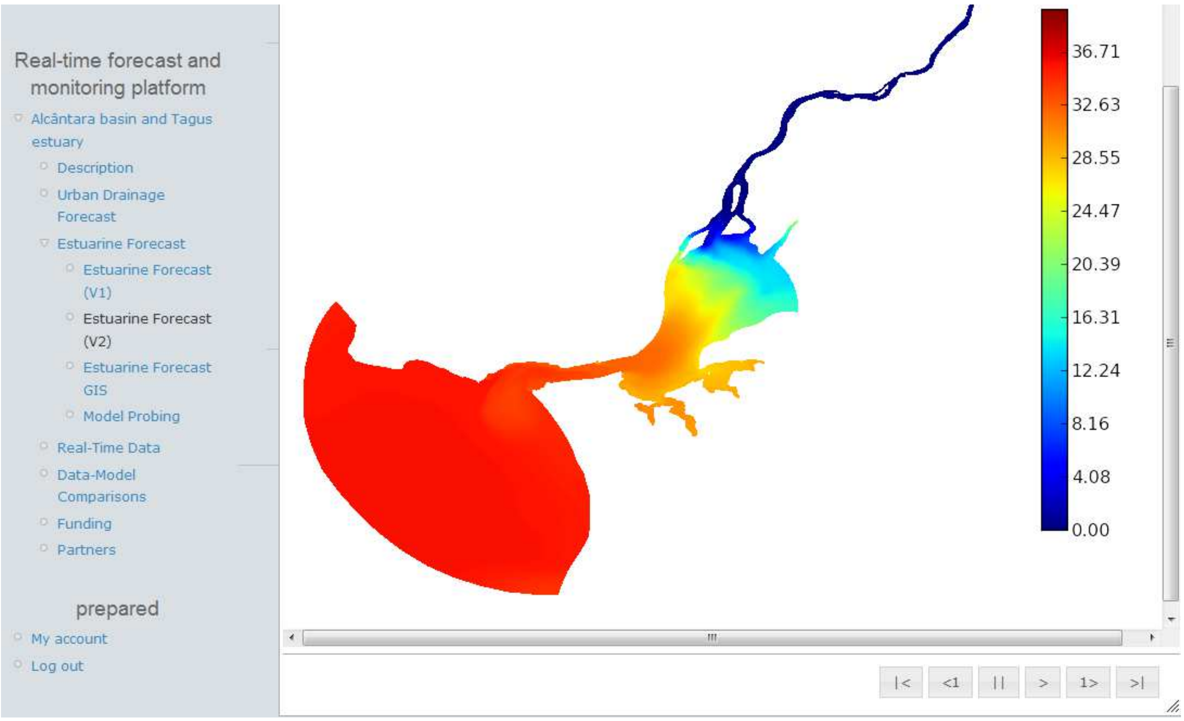


Figure 7 –RDFS-PREPARED platform applied to the Lisbon Demo: fast-access salinity model prediction.

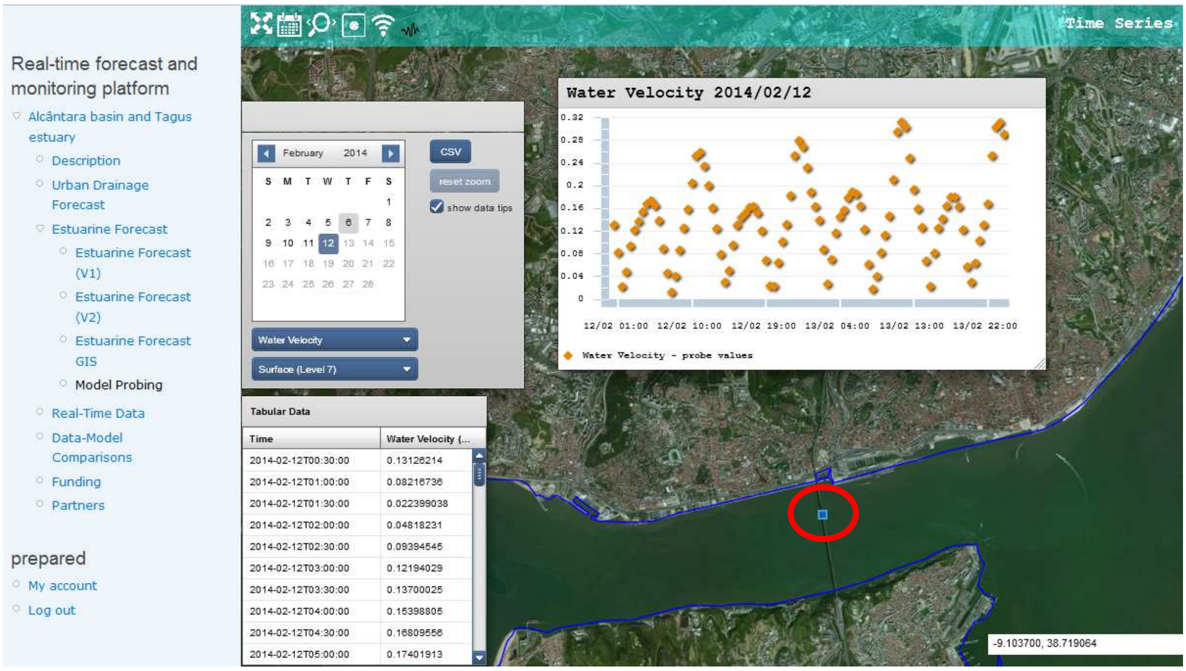


Figure 8–RDFS-PREPARED platform applied to the Lisbon Demo: probing at velocity predictions near the discharge.

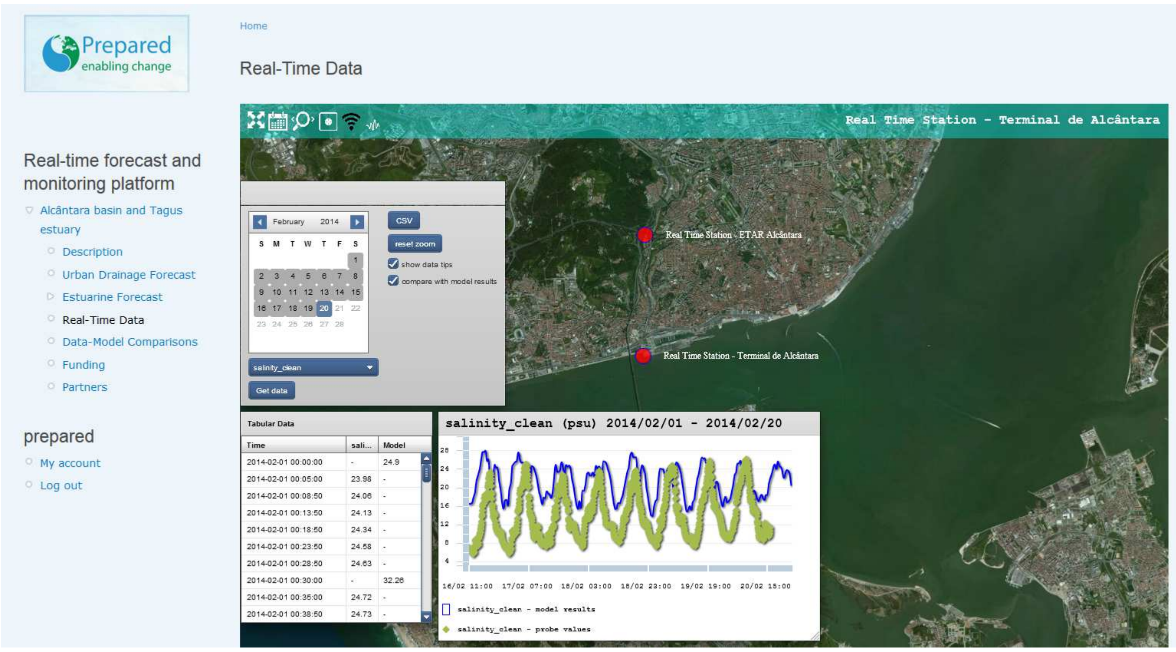


Figure 9 –RDFS-PREPARED platform applied to the Lisbon Demo: model/data comparison at the APL terminal station.

3 CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

A new urban drainage management platform is presented, conceptualized to account for all relevant components in an integrated system (catchment, sewers, WWTP and receiving waters) and their interactions in a changing climate context. It is based on the innovative integration of catchment-to-receiving waters, real-time predictive modelling and real-time on-line sensor networks, covering physical and water quality monitoring in the sewer and receiving water systems (Rodrigues *et al.*, 2014). This WebGIS platform is devoted to support urban drainage systems and their receiving waters, in particular the issuing of early-warnings of faecal contamination in receiving waters, through a combination of information from predictive models and sensors.

The WebGIS platform provides several custom-tailored services, designed to support the management of sewer systems, such as the analysis of reliability of information, based on automatic model / data comparison and the access to both real-time and historical data sets. Services are accessible in desktops in both quick-view and WebGIS schemes, to allow for fast or detailed decision making, and are currently being ported to mobile environments. The application of the platform to Lisbon's largest basin and its receiving water body – the Tagus estuary – is already providing valuable, real-time information for sustainable and energy-efficient stormwater and wastewater management (David *et al.*, 2014). Results have shown the usefulness of this tool to support proactive management and short-term planning, which reduces operation and maintenance costs.

3.2 Recommendations

The RDFS-PREPARED platform can have a considerable role in the support of urban drainage management in Lisbon and other large cities, both for everyday wastewater utility management and for contamination event risk management. Given its generic nature and flexible technological approach, it can be continuously adapted 1) to more accurate modelling tools and new sensors, and 2) to account for improved knowledge on climate change impacts on cities' drainage of storm- and wastewater fluxes.

However, there are still several research lines that need to be pursued, for reliable early-warning systems. Examples include:

- Uncertainty should be properly accounted for in all components of the cascade modelling behind the forecast system. While uncertainly has been thoroughly investigated (Bertrand-Krajewski *et al.*, 2003), the integrated approach proposed herein poses new challenges;
- The strong dependency of the proposed methodology on both operating monitoring and modelling tools creates the need for deviating values/fault analysis and new methodologies for fault-

compensation methods throughout the cascade modelling system. While some research is already ongoing on the monitoring network in estuaries (e.g. Jesus *et al.*, 2013), automatic fault detection and the establishment of fault compensation models in these complex environments remains to be done;

- The implementation and maintenance of the supporting monitoring network constitutes a significant cost in this system. Efforts towards the development of low-cost sensors and efficient maintenance procedures are required.
- There remains significant room for improvement of the modelling system, including better representation of the relevant processes and the coupling between the different models.

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