Improving operational management of wastewater systems. A case study

A. Pereira, J. L. S. Pinho, R. Faria, J. M. P. Vieira and C. Costa

ABSTRACT

Wastewater treatment facilities collecting wastewater from longstanding sewer networks of five municipalities in the Ave River basin (located in NW Portugal) are especially vulnerable to water inflows since they have considerable extensions of sewers installed in stream and riverbeds. TRATAVE, the company responsible for operating the system, designed and implemented a monitoring network to measure discharges along the entire drainage network and treatment facilities in order to reduce those water inflows. Several flow measurement devices were installed at strategic locations within the sewer network and integrated with a SCADA system responsible for its operation. A decision support system (DSS) is being implemented using the Delft-FEWS platform, integrating monitoring data and models. Based on monitored data and model results, an estimation of infiltration volumes during wet periods is presented. Moreover, the capabilities of the DSS are illustrated in: (i) location of manholes losses along sewer networks during wet periods; (ii) identification and location of unknown connections to the sewer network using wastewater balances; and (iii) design of a PID controller for a pumping station using on-line tank water level measurement. Acquired knowledge resulting from the DSS greatly improved the utility performance both in terms of economic revenue and environmental protection.

Key words | DSS, hydroinformatic tools, numerical modelling, optimization

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INTRODUCTION

Sewer systems are responsible for the transport of domestic and industrial wastewaters and rainwater to one or more terminal points, where they are treated before their disposal to a receiving environment (Puig 2009). The correct operation of wastewater drainage and treatment facilities is a fundamental aspect of avoiding flooding and pollutant discharges to the environment, which present considerable economic, social and environmental impacts (Joseph-Duran *et al.* 2014).

However, it is imperative to improve the operation and management performance of such infrastructures to further develop adequate digitalization methodologies for wastewater infrastructures that must be based on proper sensors and advanced hydroinformatic technologies. Mathematical modelling of wastewater systems has become a widely accepted tool and it is used for research, design, optimization, and testing of system process control (Corominas *et al.* 2010). These tools can also be used to properly solve different operational problems.

Undesirable water infiltration in wastewater drainage systems has been studied in several previous works. The processes that contribute to these inflows are diverse, specifically their entrance through manholes, infiltrations through sewer pipe joints and clandestine connections of storm waters and industrial waters to the wastewater sewer network.

The methodologies applied to solving the problem of undue inflows (Pereira *et al.* 2016, 2018) include the application of hydrodynamic models in urban environments, based on discharges data that are not measured but estimated. Several authors (Butler & Schutze 2005; Fletcher *et al.* 2013; Lowe *et al.* 2016) have developed advanced and detailed simulation models to identify the structural properties of the drainage systems that most influence the infiltration process in different meteorological scenarios.

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Gatterdam & Jonhnson (2016) described operational optimization efforts at the metropolitan sewer district of greater Cincinnati's complex sewer system for cost effectively reducing sewer overflows taking into account a framework enabled by a SCADA system. There is an increasing interest (Joseph-Duran *et al.* 2014; Pinho & Vieira 2014; Lowe *et al.* 2016) to develop and apply operational management methodologies for water resources, especially by using real time control (RTC) tools (Cembrano *et al.* 2011; Fuchs & Beeneken 2005; Puig 2009; Lowe *et al.* 2016; Van Daal-Rombouts *et al.* 2016; Pereira *et al.* 2018; Shishegar *et al.* 2018).

The meteorological conditions, namely short- and medium-term forecasts through robust models, are of extreme importance in decision-making processes and are increasingly being used (e.g. Butler & Schutze 2005; Fletcher *et al.* 2013; Joseph-Duran *et al.* 2014; Lowe *et al.* 2016) and in constant development. Nevertheless, in Portugal, the operational management of wastewaters based on advanced hydroinformatic tools is still largely unexplored and the level of knowledge still lags behind other countries.

Different hydroinformatic tools were developed (e.g. Pinho *et al.* 2011, Pinho & Vieira 2014), but stakeholders are relatively resistant to adopting these technological platforms to support and improve water management efficiency and water infrastructures' operational performance.

This research paper presents a DSS that is being implemented in a wastewater utility company, TRATAVE, responsible for the operational management of wastewater systems in Ave River basin (Portugal). The DSS is composed of the following main components: wastewater monitoring network; data-bases; models for sewerage and rivers (hydrodynamics and water quality); RTC tools; and facility reports for the presentation of the output results. Results are presented demonstrating the capabilities of the DSS in: (i) estimation of infiltration volumes during wet periods; (ii) location of manholes losses along sewer networks during wet periods; (iii) identification and location of unknown connections to the sewer network using wastewater balances; and (iv) design of a PID controller for a pumping station using on-line tank water level measurement.

METHODS

Study site

The study site is located in the Ave River basin, Portugal (Figure 1) and is focused on the wastewater drainage network and its treatment facilities. The basin consists of a dense network of rivers bounded in the north by the Cávado River basin, the east by the Douro River basin, and the south by the Leça and Douro River basins. The Ave basin has a total area of 1,469 km^2, with 247 km^2 and 340 km^2 corresponding to the basin areas of the East River and Vizela River's main tributaries, respectively.

In regards to the climate, the region is characterized by hot and slightly humid summers and cold and rainy winters, with the average annual precipitation reaching 1,500 mm. Its orographic characteristics, soil constitution, permeability

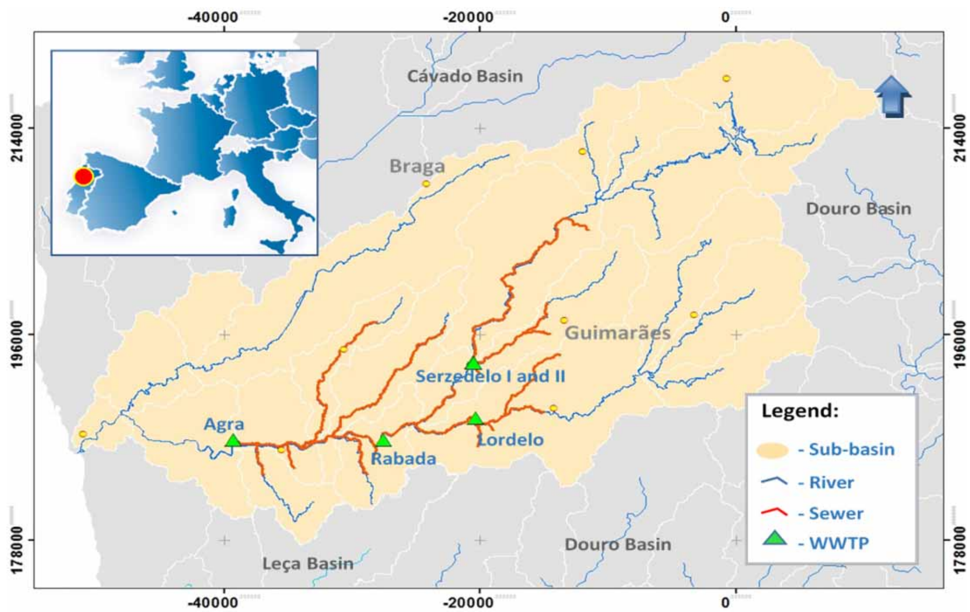


Figure 1 | Ave River basin location, main sewer network and WWTP.

and the intense precipitation that occurs during wet periods make this basin vulnerable to flooding.

The wastewater system includes 126 km of sewers and five main wastewater treatment plants (WWTP) which collect and treat the industrial (about 40% of the total wastewater volume) and domestic (about 60% of the total wastewater volume) wastewater from five municipalities: Guimarães, Vizela, Famalicão, Santo Tirso and Trofa. The drainage infrastructures are located throughout a considerable length along the Ave River riverbank and its tributaries. This characteristic, along with its vulnerability to flooding, constitute operational conditions that make the availability of reliable precipitation forecasts crucial in properly managing the wastewater infrastructures.

DSS components and data feeds

The DSS was built in a hydroinformatic environment based on a cloud server, TRATAGESC, running under Windows server 2012R2 operating system. The monitoring network was designed and installed to allow for the continuous measurement of wastewater flows at strategic locations along the drainage network supplemented with four meteorological stations located in the vicinity of the WWTP. The flow-meter data are managed by a SCADA system (PC WIN2) which was also integrated into the DSS. Microsoft database SQL Server manages measured data.

The DSS presents three main components: (i) an information component that includes all the monitoring data, infrastructure inventory, and relevant operational data; (ii) hydrological, hydrodynamic and water quality models at river basin scale and the main sewer network model; and (iii) a system that will be responsible for the analysis and processing of data to be used in the operational management of the system, which already allows the anticipation of extreme meteorological events, the operational management of the pipe network flow conditions in real time, identification of anomalies (obstructions and overflows) and detection of illegal connections.

Relevant data and models are managed using the Delft-Fews platform. Forecasting capabilities were implemented to predict intense rainy days, therefore improving the performance of the utility by taking the most adequate measures to deal with undesirable water inflow volumes that are transported to the WWTP. Forecasts are based on the implemented hydrological models and on precipitation forecasts from atmospheric models developed by NOAA (National Oceanic and Atmospheric Administration) and Meteogalicia (Spanish water resources databases).

IMPLEMENTED MODELS

River and drainage networks models

The river model (Pinho *et al.* 2011), includes Ave River and its main tributaries: Vilar do Chão, Castelões, Pequeno- left bank, Pequeno – right bank, Vizela, Selho, Ferro, Bugio, Pelhe, Pele, Sanguinhedo, Trofa, Este, Macieira, Tabuaças and Póvoa. In this river model, cross sections were established using bathymetric and topographic available data complemented with SRTM topographic data. The one-dimensional grid is comprised of 1,902 computational nodes, 18 open boundaries, 34 controlled discharges at hydraulic structures and 255 non-controlled hydraulic structures. The Ave River's channel geometry was introduced considering 1,936 cross sections. All hydraulic structures with a significant influence in the river's flows regime were included with emphasis on weirs and dams. This model was calibrated with the use of available discharge flows data (SNIRH 2017).

The sewer network model can run independently or simultaneously with the river model. Its one-dimensional grid is comprised 2,296 computational nodes, 14 open boundaries and 25 measurement stations coincident with the locations of installed sensor devices in manholes of the network. The total network length is of 126 km and its geometric characteristics were obtained through topographic fieldworks based on high precision DGPS equipment. The installed sewer pipe monitoring network covers a wide range of sensor devices which measure flows, water levels and rainfall at different locations.

Real time control of pumping stations

Wastewater systems can be controlled in real time if process variables of the system are monitored and continuously used to operate actuators. RTC algorithms consist of sets of rules that determine the control actions, which are taken in response to the current states of the sewer network (Cembrano *et al.* 2011; Joseph-Duran *et al.* 2014).

In this study, both the Sobek RTC module (Deltares 2011) and RTC-Tools (Deltares 2017) are being used, which aim at simulating various real-time control and decision support techniques applied to water resources systems. It includes feedback control strategies with triggers, operating rules and controllers as well as advanced Model Predictive Control (MPC) setups based on a combination of forecasting and optimization.

The automation of pump stations is already possible using DSS. A proportional-integral-derivative controller

(PID controller) was implemented which allows operation of the upstream pump at Lordelo WWTP. The PID controller is a generic feedback controller including an optional disturbance term commonly used in industrial control systems. It is formulated by the following equations:

$$e(t) = x_{sp}(t) - x(t) \tag{1}$$

$$y(t) = y(t-1) + k_p\, e(t) + k_i \int_0^t e(\tau)\ d(\tau) + k_d \frac{d}{dt} e(t) + k_f\, d(t) \tag{2}$$

where $e(t)$ is the difference between a process variable $x(t)$ and a setpoint $x_{sp}(t)$, and k_p, k_i, k_d, are the proportional, integral and derivate gain factors, respectively. The optional feed forward term consists of a factor k_f, and an external disturbance $d(t)$. $y(t)$ is the controller output.

The proportional gain factor k_p controls according to the deviation of the process variable x to the target value (the setpoint)x_{sp}. The integral gain considers the cumulated historical deviations between setpoint and process variable. The differential gain factor controls according to the current rate of change of deviation between the setpoint and the process variable.

In order to assess the capabilities of the DSS in implementing automatic operation techniques, a PID controller was designed based on available measured data at Lordelo WWTP pumping station (Figure 8(a)). At this location, the pumps can be operated in such way that only a partial volume of the wastewater that is transported by the Vizela sewer is treated at the WWTP. The remaining wastewater can be treated, at lower costs, at the downstream Rabada WWTP.

The hydraulic model was used as a test bed for the controller implementation. In a first step, the historical measured data were used to adjust PID gains so that the PID simulated pumped discharges approximate the measured ones for a representative period of operation. This was implemented by minimizing the sum of the errors between the measured pumped discharges and simulating those by the controller. This procedure was implemented in Excel recurring to the Solver tool.

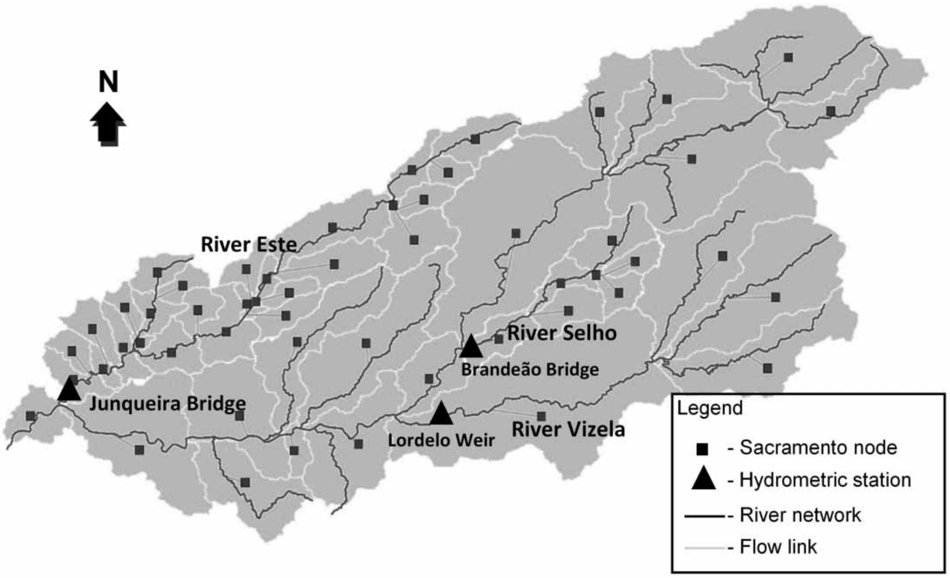
In a second phase, the PID was implemented using the RTC module of Sobek. During some wet periods, both the capacities of the pumps and the downstream sewer are exceeded and the wastewater is discharged directly to the Vizela River. The implemented model also allows for the estimation this discharge.

Hydrological model

The Sacramento hydrological model, one of the hydrological models available in the Sobek software (Deltares 2011), allows the simulation of the total instantaneous flows at the river network using as input data rainfall and evapotranspiration in the basin. In this model, the soil is divided into two main layers: (i) the upper layer in which the rapid processes occur near the surface of the soil: evaporation, percolation, surface runoff and sub-surface runoff; (ii) the bottom layer where the slow processes of the unsaturated soil occur: transpiration, recharge of the aquifer and base flow. In both layers, two sub-layers are considered: one where the water is under the effect of the surface tension (capillarity) and another where it is under the effect of hydrostatic pressure (free water).

The basin was discretized into 53 sub-basins simulated by Sacramento nodes (Figure 2). Sacramento model parameters values were obtained by a calibration procedure based on optimization algorithms, using several data sources. Historical data include hydro-meteorological data series from the Portuguese national water resources information system (SNIRH) and radar data from Meteogalicia. The first were used for the calibration of hydrological and hydrodynamic models of two sets of sub-basins. Precipitation and evaporation data at eight meteorological stations, as well as discharges at the river basins hydrometric stations for a period of 5 years (1995 to 2000) were used. This model includes 16 parameters related to the soil and surface hydrological processes. Some of these parameters can be calibrated by analysing hydrographs, others may be derived from the physiographic characteristics of the basin, and yet others must be estimated based on a trial and error analysis. It is also possible to make use of algorithms for automatic calibration based on global optimization techniques, considering different error metrics, as was the case in this work. The Rainfall Runoff Library (RRL) was used for the calibration procedure and will be applied later for integration of the MPC strategies (CRC 2004).

In the optimization approach for model calibration, initial values of model parameters were defined, resorting to their typical range obtained from literature (Anderson *et al.* 2006) and from their soil characteristics (Koren *et al.* 2000). These first values are very dependent on the selected events, and on the basin in question. The Sacramento model's performance was assessed using different metrics: Nash Sutcliffe Model Efficiency (NSE), Root Mean Squared Error (RMSE), a bias parameter computation based on the difference between the sum of simulated discharges and



Sub-basin	NSE	BIAS	RMSE	MAE	R^2	Average sim.	Average obs.
(-)	(-)	(m^3/s)	(m^3/s)	(m^3/s)	(-)	(m^3/s)	(m^3/s)
River Este	0.7	1.9	3.6	2.6	0.8	6.9	8.8
River Selho	0.8	0.2	1.1	0.6	0.8	1.6	1.8
River Vizela	0.7	0.8	0.3	2.4	0.7	27.6	28.0

Figure 2 | Hydrological model discretization for Ave River basin and the performance for the validation simulation.

the sum of observed ones (BIAS), and Mean Average Error (MAE). The algorithms of global optimization that presented more satisfactory results were the Rosenbrock Single Start and the Pattern Search Single Start (Lewis et al. 2000) using as the primary objective the Nash Sutcliffe Model Efficiency (NSE) and as secondary the Root Mean Squared Error (RMSE) as error functions to be minimized. The obtained metrics are presented in Figure 2.

RESULTS AND DISCUSSION

The information and modelling components of the DSS have already been implemented. The analysis component is still under development and will be fully implemented with the integration of MPC strategies.

Estimated infiltrated discharges water inflows

Considering hourly measured precipitation and discharge data for the period between 1/10/2015 to 30/8/2018, in four main sewers (Nespereira, Ave, Vizela FD4 and Vizela FD6), the daily average discharges for dry and wet periods were calculated.

As seen in Figure 3, the value of wastewater discharges transported to the WWTP increases during wet days, namely in the Ave and Nespereira sewers, with the Vizela sewers being less sensitive to infiltration in comparison.

This infiltration is quite problematic since all the WWTP were designed to receive domestic and industrial effluents with low volumes of infiltrated stormwater. These results are caused by a significant number of clandestine stormwater connections to the wastewater drainage network, in addition to direct infiltration at manholes and pipes. Less urban areas, such as the Vizela sewage infrastructures, are less susceptible to infiltration.

The typical hourly flows during dry weather conditions were obtained for the main sewers (Figure 4). The importance of the received industrial effluents is very clear from the obtained typical flow patterns for the different days of the week: there is an almost constant lower flow on Sundays. This value rises on Mondays beginning early in the morning. Tuesdays, Wednesdays, Thursdays, and Fridays present an hourly flow variation with identical patterns, but with a general increase in average values. On Saturdays, the flow continuously decreases throughout the day.

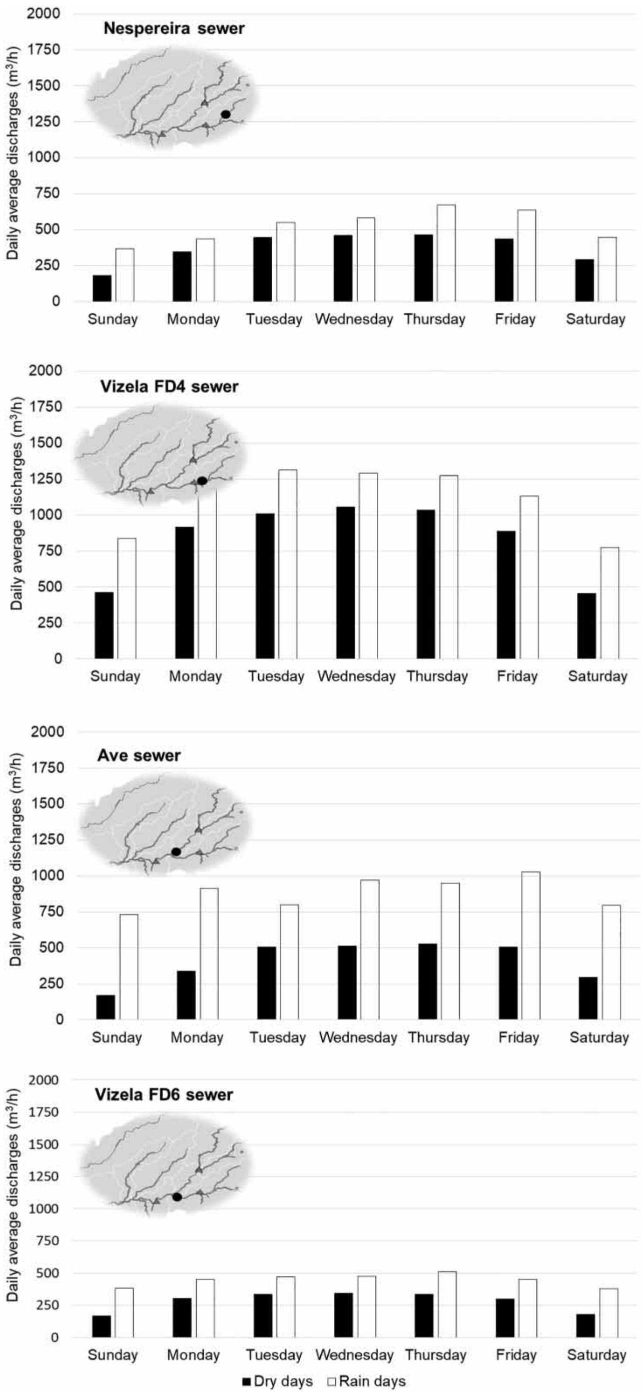


Figure 3 | Weekday average wastewater discharges during dry and rainy periods.

Using the measured discharge data and subtracting the derived average hourly data for dry weather conditions, it was possible to estimate the infiltrated discharges along the network. To assess the correlation between hourly measured wastewater discharges and precipitations, the cumulative values of precipitation (Serzedelo precipitation gauge stations) and infiltrated discharges (Vizela sewers) were considered (coefficients of determination of 0, 92). Figure 5 presents these cumulative values for an intense rain event that took place in January 2016. This same relation can be seen in a scenario that occurred in January 2018 where the infiltrated volumes were lower since it corresponds to a less intense precipitation event.

The infiltration starts at the very beginning of the rain event, mostly by entering through shaft manholes and also unlicensed stormwater connections. When the first precipitation event ends, the infiltrated flow continues to rise, which can be associated with infiltrations along pipe joints. However, the entrance of stormwater into the wastewater drainage networks should be the main reason for the rapid increase in wastewater discharges during rain events. During the first event, the added volume of rainwater that was transported reached one million m^3 (which represents a treatment cost of about 270,000 €, considering the current unit treatment cost), and about 200,000 m^3 transported in the second event (54,000 € for treatment costs). If, in the first case, the network does not have the capacity to transport the total volumes to WWTP and they are discharged directly to the river (representing an environmental cost), in the second case these volumes are treated at WWTP. Part of these volumes is measured and the associated cost must be accepted by the municipalities that are clients of the utility responsible for the system.

Detection of illegal discharges

The main sources of wastewater at Ave River basin are the textile industries that require large volumes of water for industrial dyeing processes.

To increase the performance of the system in terms of detecting illegal connections, normalization of the industrial discharges profiles over the weekdays was carried out, together with redundant water balances at different locations in the drainage network. This approach allowed for a more assertive surveillance.

Figure 6(a) depicts the results of a comparison between the normalized typical hourly flow patterns during Tuesday, Wednesday, Thursday and Friday, and the corresponding normalized flows measured at an illegal connection. The difference between the measured illegal discharges (dots) and the typical patterns (lines) is very clear. These differences reach values of about 100 m^3/hour. After a field inspection, an illegal bypass to the measurement pipe was detected. Figure 6(b) shows another anomaly that occurred during Sunday and Monday mornings. In this case, the industrial

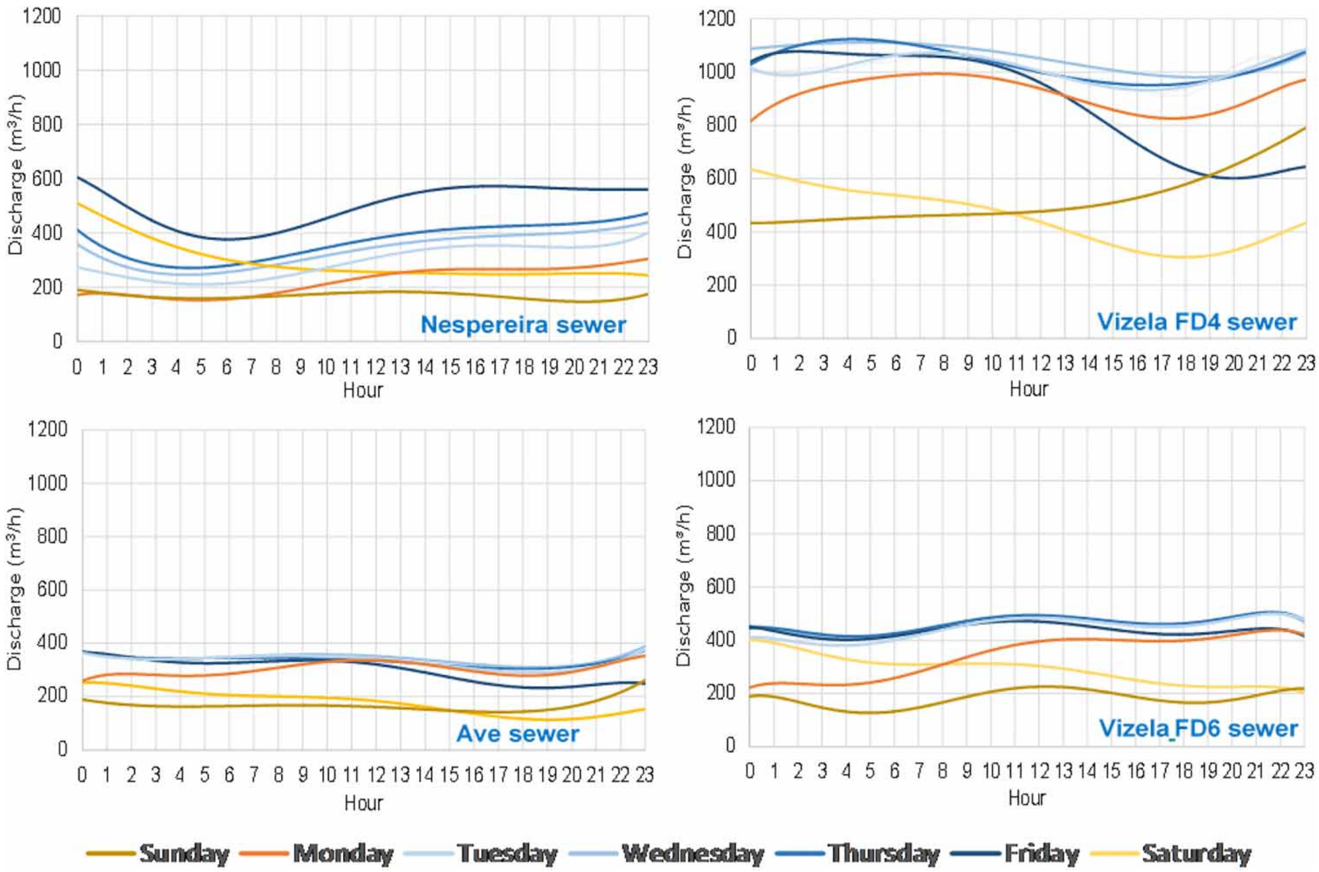


Figure 4 | Hourly average wastewater discharges during the different days of the week.

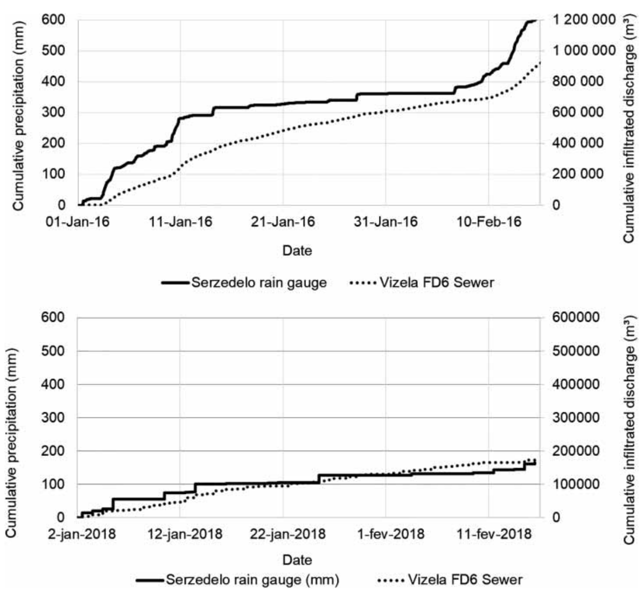


Figure 5 | Cumulative precipitation and infiltrated discharges estimation during two intense rain events at the Vizela FD6 sewer.

company was discharging, during the weekend, wastewater stored in a reservoir (5,000 m³) throughout the week, using a bypass to the measurement device.

The applied methodology, based on the on-line measurement of discharges and systematic comparison with the historical derived discharge flow patterns over the weekdays, allowed the identification of several frauds. After correction of illegal connections at this sub-system, there was an increase in the billed wastewater volumes of 55.81%, which represents 7.81% of the unbilled volumes of the entire network. During the period of the DSS installation (4 years) the correction of about 15 anomalies led to a decrease of unbilled flows in the order of 16%, resulting in a financial benefit and representative increase in the utility's economic performance.

Drainage network overflows analysis

The correction of illegal inflows to the drainage network and proper estimation of infiltrated rainwater provided the

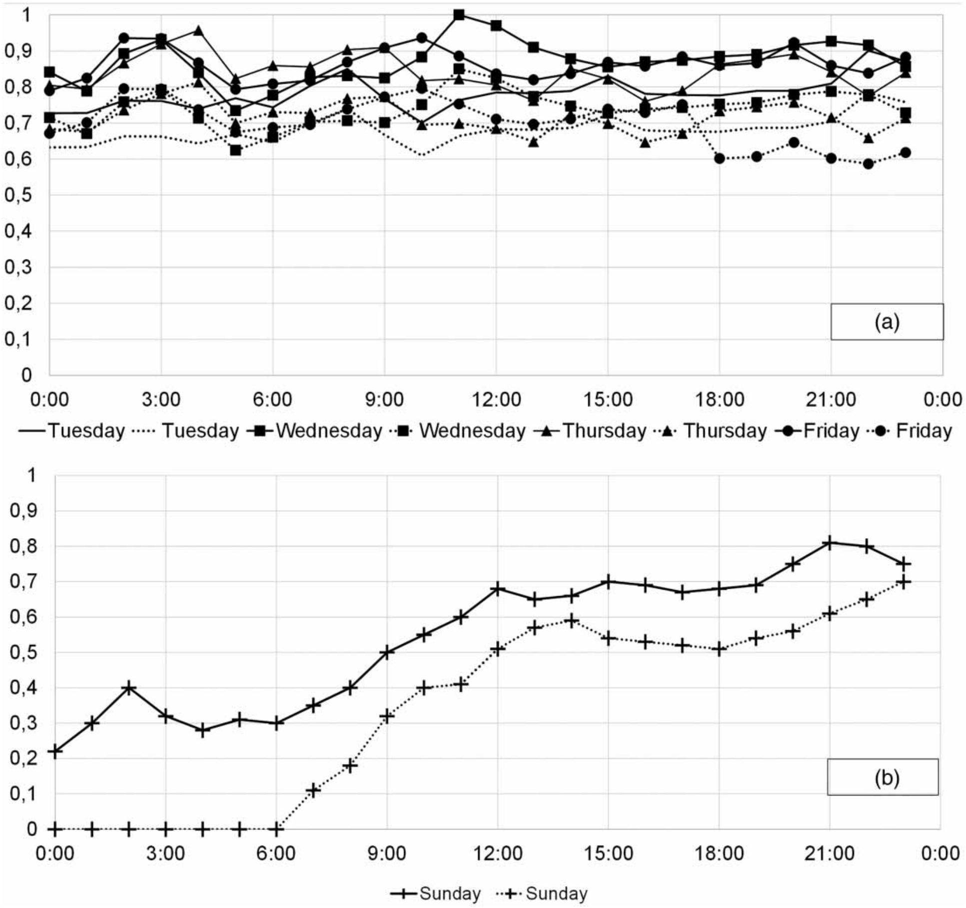


Figure 6 | Detection of illegal connections based on normalized hourly discharge data.

necessary conditions to properly simulate the discharges and water levels through the pipe network using the hydrodynamic model. This model was applied to analyse the most vulnerable manholes that overflow during intense rain events and decide the most adequate locations to install overflow discharges and avoid overflows in urban areas.

The model's performance was almost perfect (coefficient of determination of 0.95), in simulating water levels as presented in Figure 7(a), for a 1 month simulation with one-hour time resolution data.

For sewer model calibration, field data were collected to estimate pipes roughness coefficients. These data included simultaneous measurements of flow velocities and water levels. These field results were also used to estimate correct correlations to then estimate water flow discharges from measured water levels. In Table 1, the pipe roughness and stage-discharge relationship obtained at monitoring stations are presented.

Simulations involving other periods corresponding to intense rain events were carried out to identify vulnerable pipes/manholes (Figure 7(b)) and alternative locations for discharges were also tested in the model. These alternatives showed a significant improvement in the discharge conditions. Thus, temporary wastewater tanks could be a feasible solution which is under evaluation.

Automatic control of pumping stations

Besides the improvement in the wastewater transport facilities that results from the knowledge that arises from the developed DSS, automated control of pumping stations is also starting to be evaluated using the hydrodynamic model. Currently, there are two different options in managing infiltrated discharges: (i) creating temporary wastewater storage reservoirs and (ii) distributing the incoming flows to different WWTP. This last possibility can be implemented while the pumping station is functioning. The system's configuration permits the incoming wastewater volumes at the Lordelo WWTP to pump or divert downstream.

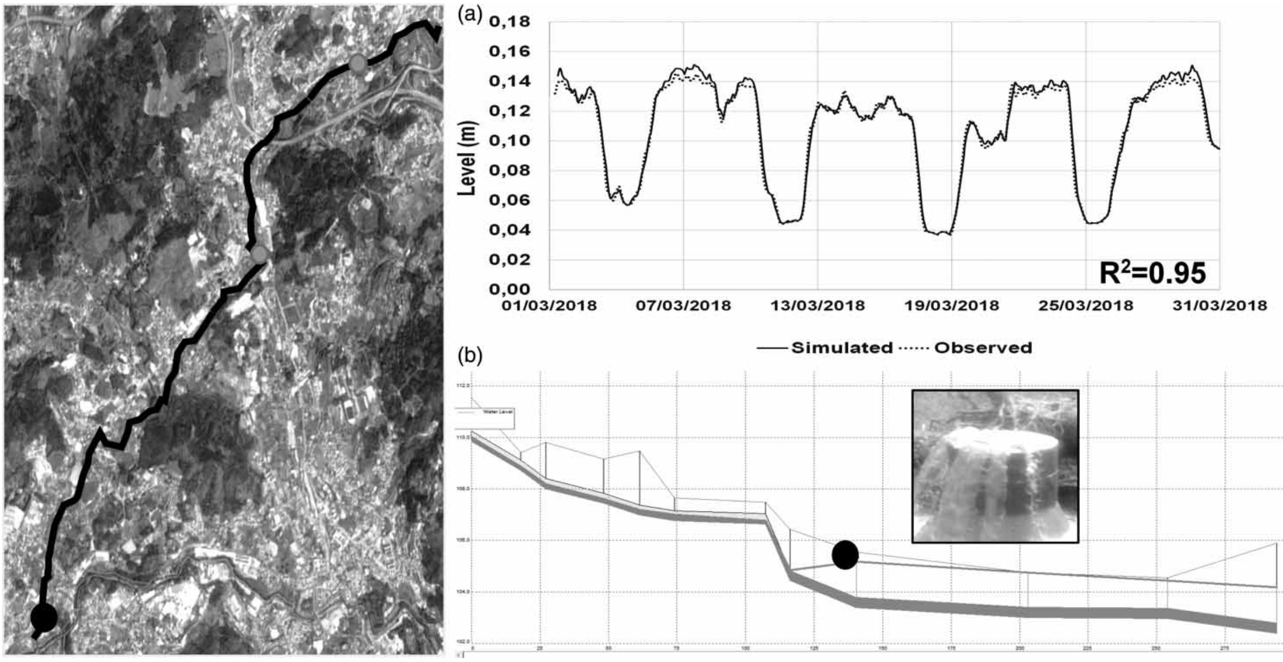


Figure 7 | Sewer network hydrodynamic model: (a) measured versus simulated water levels and (b) identification of manholes with overflow.

Table 1 | Sewer network model: pipe roughness and stage-discharge relationship

Monitoring station (Id)	Roughness coefficient (Manning) ($m^{1/3}s$)	Stage (x)–discharge (d) relationship $d = ax^2 + bx$ x (m)–d (m^3/h) a	b	R^2 (−)
1	0.0123	7,422.50	−303.08	0.8585
2	0.0132	7,492.60	−375.86	0.9916
3	0.0113	23,040.00	150.12	0.9971
4	0.0115	−958.22	2,129.70	0.9109
5	0.0112	5,659.60	710.19	0.9868
6	0.0134	9,239.80	596.94	0.9987
7	0.0128	4,289.60	394.01	0.9966
8	0.0130	20,167.00	−737.24	0.9705
9	0.0132	7,058.10	698.10	0.9246
10	0.0130	15,806.00	−356.05	0.9902
11	0.0120	16,400.00	156.42	0.9737
12	0.0136	3,111.30	−545.39	0.9839
13	0.0125	4,133.90	525.56	0.9799
14	0.0130	4,448.20	−66.12	0.9027
15	0.0128	5,891.40	631.52	0.9186
16	0.0113	6,131.20	398.34	0.9061
17	0.0130	15,022.00	30.03	0.9748
18	0.0127	12,262	1,820.7	0.9972

A PID controller was designed to automate the operation of the Lordelo pumping station based on the intake water level measurements. Figure 8 depicts the implementation of a PID controller for the Lordelo WWTP pump station (Figure 8(a)) and the results of pumped discharges (Figure 8(b)), water intake water level (Figure 8(c)) and wastewater diverted to the downstream WWTP (Figure 8(d)). These results shows that the automation is close to the manual procedures.

Ongoing research is focused on the development of advanced model predictive control (MPC) strategies to support operational management decisions in this complex system. This support includes precipitation forecasting and consequently the infiltrated flows, the installed storage and treatment capacity, and, finally, the impacts of different transport/treatment alternatives on the receiving waters, assessed by the river water quality model.

CONCLUSION

A relatively complex transport and treatment system is being used as a living laboratory to support research on proper operational control techniques to deal with infiltration of stormwater in sewer networks. A DSS was implemented with the use of a specific monitoring network and advanced

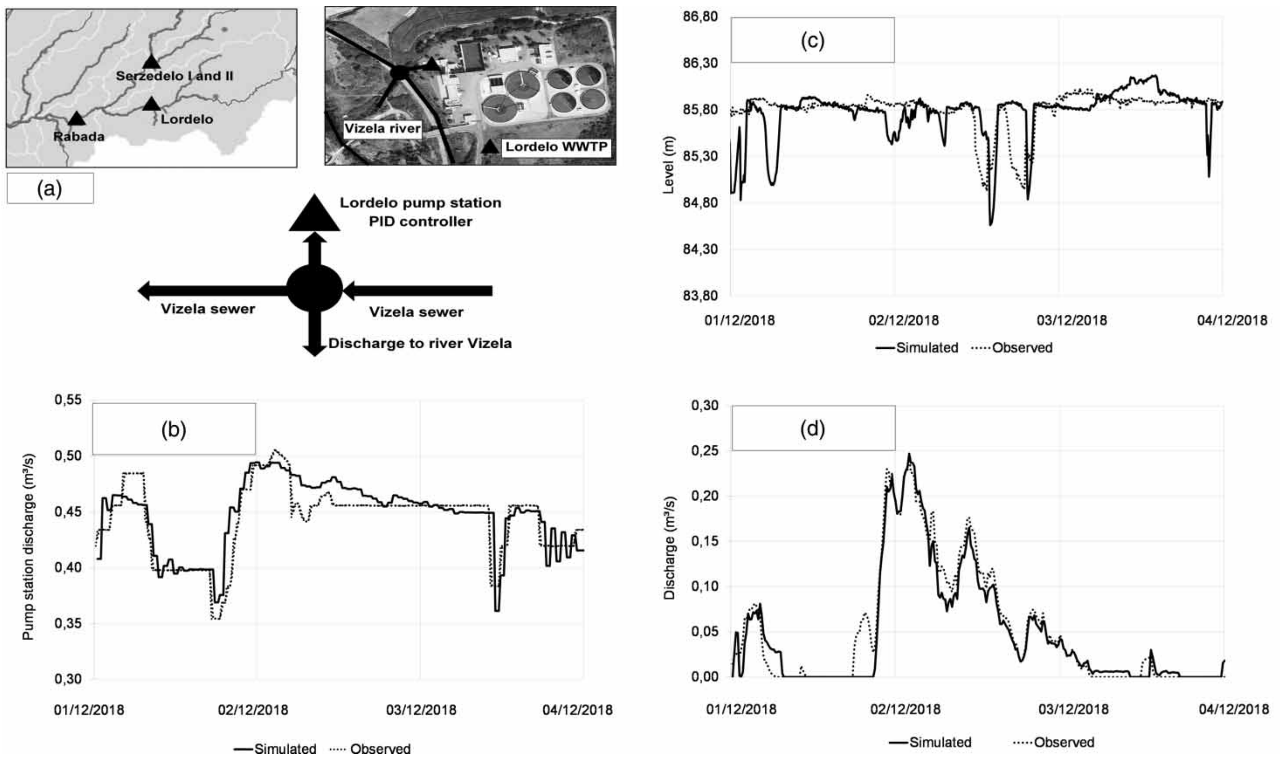


Figure 8 | Results of PID controller against manual operation.

hydroinformatic tools, including the Delft-FEWS platform and integrated hydrological, hydrodynamic and water quality models. Infiltration stormwater volumes can double the dry-weather wastewater flows. Cumulative precipitation presents a strong correlation with estimated infiltrated water volumes and is being used to assess different operational management strategies to properly transport, store and treat collected wastewaters during wet periods.

The adopted methodology for estimating infiltrated discharges also allowed for a more assertive surveillance of illegal connections. Moreover, automatic control through a PID controller has proved to be an extremely valid option for the automation of the operation of pumping stations. The implemented DSS presents all the relevant components adequate for the implementation of MPC, including different meteorological forecasts, enabling an adequate environment to deal with uncertainty.

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