Operational decision support system for large combined sewage systems: Lisbon/Tagus estuary case study

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ABSTRACT

Managing combined sewage systems in large cities discharging to coastal waters, often bearing recreational activities, remains a challenge. Studying the impacts of such discharges requires the development of specific models. Hydrodynamic and water quality modelling of coastal waters employs numerical methods and algorithms, leading to the design of complex models which require expert use. The use of such models as decision support tools to simulate discharge impacts and define adequate corrective measures could represent a key part in meeting this challenge. In this paper, the authors describe the work undertaken to develop an operational decision support system (ODSS) methodology aiming to enable wastewater utilities’ non-expert staff to carry out user-friendly scenario analysis based on computational fluid dynamics simulations. This article depicts the application and validation of the ODSS to the combined sewage system and the Tagus estuary of the city of Lisbon in Portugal. The ODSS was used for simulating the effects in the receiving coastal waters of a discharge caused by a scheduled maintenance operation in the sewage infrastructure. Results show that the use of such ODSS by non-expert staff increases their decision capabilities and knowledge of the wastewater utility’s contribution to reducing negative impacts of sewage discharges on the receiving water bodies.

Key words | combined sewer overflow (CSO), decision support, model, receiving waters, sewage operations

INTRODUCTION

The city of Lisbon is one of the oldest in the world. Unlike those of modern cities, the Lisbon sewage system is a combined type, in which the natural hydrological watershed coincides with the sewage network, serving a population of one million inhabitants over an area of 8,200 ha. This complex network, comprising pumping systems, inverted siphons and overflows, has a total length of approximately 774 km and the average sewer age is about 60 years. As part of its daily operation the Lisbon utility (Simtejo) needs to manage the combined sewage system (Figure 1) and wastewater treatment plant (WWTP), ensuring that the quality requirements of the treated effluent, discharged into the Tagus estuary, which has significant tidal influence, are met. One of the major challenges Simtejo faces is managing the combined sewer overflows (CSOs), which are the major contributors to water quality problems in coastal urban areas. In fact, even during small rainstorms, CSOs can seriously impair the receiving water quality, including microbiological contamination and aesthetic aspect. Although aesthetic upsets are not directly linked to human health risks, they have important socio-economic impacts on the affected area and provide important performance criteria for control technologies (National Research Council 1995). Hydrodynamic and water quality modelling tools for coastal receiving waters are generally based upon a large set of equations solved by numerical algorithms resulting in complex models. Such models require the initial specification of weather and hydrodynamic conditions and simulation settings. Wastewater end-user staff do not usually have the skills that would enable them to set those specifications and settings.

However, significant scientific and technical achievements have taken place in operational oceanography during the last decades (Le Traon et al. 2009). The latter...
led to the development of forecasting systems that can deliver high resolution metocean forecasts of great use for coastal stakeholders such as wastewater utilities. Examples of operational decision support systems (ODSSs) for wastewater systems have been reported by Suñer et al. (2007), Murlà et al. (2010) and David et al. (2013). Existing ODSSs for wastewater systems, however, do not cater for the following needs: (i) carrying out user-friendly forecast scenario analysis; and (ii) reporting with scalable key performance indicators (KPIs) based on an integrated wastewater cycle approach. The aim of the work was to develop an ODSS methodology that enables wastewater utilities’ non-expert staff to carry out user-friendly scenario analysis based on computational fluid dynamics simulations. The ODSS was designed to test the impacts of discharge scenarios in a geographic information system (GIS) environment and automatically generate KPI user-friendly reports.

MATERIALS AND METHODS

Concept

ODSS innovation lies in the link established between complex hydrodynamic and water quality modelling and the generation of discharge impact scenarios in wastewater system infrastructures (Figure 2). The application allows users to generate scenarios of simulated impacts of sewage discharges to the receiving water whether they originate from WWTP’s maintenance stoppages or other causes, without having to collate data from various sources.

Case study description

In this article, the authors describe the application of the ODSS in Simtejo, the wastewater utility of Lisbon. The application was carried out by staff lacking expert modelling skills but using state-of-the-art hydrodynamics and water quality modelling tools. The assigned staff were to plan and schedule treatment system stoppages, in order to enable the performance of maintenance work, while causing a minimum impact on the receiving water body in the Tagus estuary. The Simtejo wastewater utility is responsible for collecting, treating and disposing of wastewater from 1.5 million inhabitants located to the north of the Tagus estuary, in the Lisbon Metropolitan area. In 2014, the utility treated a total wastewater volume of 135 million m³. Ninety-seven per cent of Simtejo’s treated wastewater is discharged in the Tagus Estuary. Estuarine ecosystems are often the source of goods and services for the surrounding population. These comprise recreational navigation, tourism and leisure,
fisheries, marine farming and salt production. The Tagus estuary supports these and other uses, such as bivalve production (in certain zones) and plays an important role in the increasing tourist attraction to the city of Lisbon. It was assumed that indicators of faecal pollution are associated with CSO. As the statutory indicator of faecal pollution, the presence of *Escherichia coli* directly influences the assigned quality of the water body and could be used for CSO pollution assessment (Passerat et al. 2011). Figure 3 illustrates the *E. coli* concentration geometric mean, calculated per year, for the northern, southern, middle and mouth estuary zones. The geometric mean is the statistical measure used, by regulatory agencies and utilities, for gauging bacteria concentration. As depicted in Figure 3, there has been a decrease in *E. coli* concentration from 2004 to 2012. This trend matches the increase in the number of users connected to the sewage system. Furthermore, data accruing from point samples carried out under different tidal conditions suggests that, depending on the tidal situation, bacterial concentration might change by one log (lower concentration during flooding and higher during ebbing). This means that planning stoppages for maintenance shutdowns in pumping stations, CSO diversion structures, and WWTP, while taking into account the dynamics of the receiving water bodies, might significantly lessen the effects of the discharges on water quality.

The Tagus estuary is one of the largest estuaries in Europe, with a total area of approximately 368 km² and an average volume of around 2,700 hm³. The width varies between 2 km in the mouth’s channel and 17 km in the upper zone, and the average and maximum depth are about 10 m and 40 m, respectively. The tidal propagation distance in the Tagus estuary is approximately 80 km. The intertidal zone occupies a total area of 146 km², mainly composed of tidal flats (64%) and salt marshes (13%). The Tagus estuary is mainly tidal driven with a semi-diurnal regime with an average tidal range of approximately 2 m in Cascais. The main source of fresh water into the estuary is the Tagus River, with flow rates varying typically between 50 and 2,000 m³ s⁻¹, showing strong seasonality, though this is smoothed out by dam releases. The smaller rivers Sorraia and Trancão, the other two estuarine tributaries, contribute with a mean discharge of 59 m³ s⁻¹ and 6 m³ s⁻¹, respectively (Campuzano et al. 2012). The inflow of fresh water plays an important role in hydraulic residence time within the estuary. However, it is only when the extreme values of the Tagus river flow (>2,000 m³ s⁻¹) are met that fresh water has a significant impact over currents and sea level variability. The Tagus estuary currents have significant maximum velocities (0.5–1.5 m s⁻¹). The Tagus estuary is characterized by intense and oscillatory currents rendering this water body capable of diluting pollutants quite efficiently.

### Hydrodynamic and dispersion model MOHID

Hydrodynamic forecasts are computed employing the MOHID (Modelo Hidrodinâmico) model. This model has been successfully used in several numerical studies carried out along the Tagus estuary in the past few years (Vaz et al. 2015). A complete description of the model can be found in Martins et al. (2001), with a downscaling approach described in Vaz et al. (2015). Three domains were nested to properly represent the tidal forcing at the sea boundary of the Tagus estuary. The three domains cover the entire West Iberian coast, part of the Portuguese coast and the Tagus estuary and part of the nearest coast. A 4-month dynamic simulation period was also used for validating the tide propagation in the Tagus estuary model, along with the tidal components obtained from harmonic analysis of the water level results and tide gauge data from estuary sampling points. In addition, the velocity tidal model components were validated with the currents’ field data presented by Neves (2010). The ODSS hydrodynamic forecast uses a tide prediction based on harmonic constants of water level and velocity. This is an efficient approach to forecasting currents and sea levels in marine environments where currents are forced mainly by astronomical tides such as in the case of the Tagus estuary. A Lagrangian (particle tracking) model was used to simulate the dispersion of the faecal pollution indicator in the receiving water body. The wastewater plume is discretized using a cloud of particles, where each particle is characterized by a position in space (x, y, z) and time (t), and a volume and a concentration of the faecal indicator. Particles are emitted with a
frequency equal to the flow divided by the particle volume (Leitão et al. 2012).

The faecal concentration indicator (total coliforms, faecal coliforms (FC) or E. coli) is assumed to have a constant decay rate of T90 (time that the faecal indicator concentration takes to decrease one order of magnitude due to mortality) in hours, with typical daytime and nighttime values (T90 for E. coli) of 3 hours and 12 hours, respectively (Canteras et al. 1995).

**ODSS user interface design**

A non-expert modelling user wishing to perform scheduled maintenance operations in the sewage infrastructure with the support of the ODSS should (i) indicate which part of the treatment system is going to be temporarily shut down (WWTP and/or pumping station by-pass), (ii) characterize the discharge (location, flow volume and quality parameters) and (iii) state the planned day, hour and expected duration of the shutdown (Figure 4). The model boundary conditions are automatically defined by the ODSS using the best available data in the database (Figures 2 and 4). Choosing the best time frame for a sewage infrastructure stoppage, resulting in discharging untreated wastewater into the environment, does not come as an obvious decision to make. To overcome this difficulty the authors developed a report, to provide operational teams with straightforward KPIs which enable them to estimate discharge impacts under different tidal and solar radiation (night/day) conditions. The ODSS runs automatically 12 simulation scenarios based on possible tide combinations for day and night period of the expected day and for the closest neap and spring tides (Figure 4). The night/day scenarios take into account the important effect of solar radiation on faecal concentration mortality.

For the simulations presented in this paper the ODSS database was loaded with six WWTPs, 18 pumping stations, 39 CSO diversion infrastructures and one river/stream. Moreover, the faecal concentration indicator used was FC.

**Scenario reporting for shutdown-scheduling decision support**

Scalable KPIs, based on an integrated wastewater cycle approach, were defined in order to convert the simulated results into information for the utility operation staff. The KPIs are calculated for the focal areas (virtual monitoring boxes) selected through a statistical analysis of FC and time frames in which the concentration exceeds a pre-defined limit (Viegas et al. 2012) and comprise (i) KPI faecal concentration (CFU/100 mL) of contaminated area: percentile,
specified by the user, of the instantaneous FC (CFU/100 mL) geometric mean of contaminated area in each virtual monitoring box, (ii) KPI % contaminated area: percentage of FC (CFU/100 mL) of contaminated area in each virtual monitoring box and (iii) KPI duration of contamination: time frame within which the geometric mean of FC (CFU/100 mL) of contaminated area rises above the specified limit (e.g. 2,000 CFU/100 mL). Average concentration in each virtual monitoring box could be defined as the product of KPI FC of contaminated area by the KPI % contaminated area.

RESULTS AND DISCUSSION

One of the examples used to illustrate the current study entailed an emergency stoppage that had to be performed in the Agências pumping station, a large and critical component of the Lisbon sewer system, located in a downtown tourist area. The initial scheduled day was 15 August 2013 with an expected 3-hour duration, and the question raised was ‘What would be the most suitable timing for the maintenance operation?’ Tables 1 and 2 show the outputs of the ODSS KPI report which provides information to choose the most adequate time for a discharge with minimum impact on the receiving water body. These tabular reports complement the transient dispersion maps generated on the map view of the GIS FC simulator (Figure 5) whereby KPI values are presented per scenario and per monitoring box or per group of selected boxes. In Tables 1 and 2 the columns correspond to four scenarios (possible tide combinations for day and night period), namely night period/high-tide, night period/low-tide, day period/high-tide and day period/low-tide. Each scenario contains three columns showing the above-mentioned KPIs. The KPI faecal concentration (CFU/100 mL) of the contaminated area (first column in each scenario) also relates to water quality criteria, in which the darkest colour means poor quality and the lightest means the best quality. The width of shading for a particular value represents the magnitude of the value compared with the other values of the same column. Table 1 shows the detailed results for the predicted shutdown date. Each line shows the results per monitoring box and in the top line shows the average result for the selected monitoring boxes (average of the selected monitoring boxes). In Table 2 each line depicts the average results of the selected monitoring boxes for the following situations: shutdown date, closest neap (18 August 2013) and spring (12 August 2013) tides. Choosing the best timing for a shutdown based on these quantitative reports requires the decision maker to take into account and

<table>
<thead>
<tr>
<th>Quality Class</th>
<th>FC (CFU/100 mL)</th>
<th>Night period</th>
<th>Day period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>≤ 2,000</td>
<td>Fecal concentration (CFU/100 mL)</td>
<td>% Contaminated area</td>
</tr>
<tr>
<td>Soft</td>
<td>≤ 200</td>
<td>8.1×10^5</td>
<td>0.69%</td>
</tr>
<tr>
<td>Coarse</td>
<td>≤ 2,000</td>
<td>4.8×10^5</td>
<td>1.26%</td>
</tr>
<tr>
<td>Soft</td>
<td>≤ 200</td>
<td>8.4×10^5</td>
<td>1.39%</td>
</tr>
<tr>
<td>Coarse</td>
<td>≤ 2,000</td>
<td>2.5×10^5</td>
<td>0.46%</td>
</tr>
<tr>
<td>Soft</td>
<td>≤ 200</td>
<td>5.1×10^5</td>
<td>0.15%</td>
</tr>
<tr>
<td>Coarse</td>
<td>≤ 2,000</td>
<td>2.2×10^5</td>
<td>0.24%</td>
</tr>
</tbody>
</table>

Table 1 | Scenario reporting – KPI table for the expected shutdown date

<table>
<thead>
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<td>2.2×10^5</td>
<td>0.24%</td>
</tr>
</tbody>
</table>

Table 2 | Scenario reporting – average FC (CFU/100 mL) of selected boxes’ KPIs resulting from the simulation of the shutdown discharges carried out in the spring and neap tides nearest to the predicted shutdown date
weigh up the following issues: (i) which is the most critical parameter, i.e. faecal concentration, the extent and duration of the FC contamination; and (ii) whether the emphasis should be put on the average analysis of all selected monitoring boxes or whether a specific box should be regarded as more important than the remaining ones.

The KPI results for the simulated scenarios on the scheduled day (15 August 2013), taking into account the average of the selected boxes, indicate that the most suitable timing for the shutdown is at the nearest high-tide during the night period (4:30). This scenario (top line in Table 1) shows the lowest FC concentration ($8.1 \times 10^3$ CFU/100 mL), the smallest percentage of area affected (0.69%) and the shortest duration of the contamination event (3.69 hours). Regarding individual box results (Monitoring box no. 1, 2, 4, 5, 25 and 26 in Table 1), a detailed analysis was carried out for Monitoring box 4, since it encompasses a waterfront promenade in which tourists can be near to the water. Results for FC concentration ($5.9 \times 10^3$ CFU/100 mL) and duration period (7.6 hours) in this individual box are better at the low-tide during the day period (15 August 2013 10:45). When the ‘average of the selected boxes’ scenario is compared with Monitoring box 4 scenario the respective KPIs show little variability, making it difficult to pick the best option. Therefore it would still be better to choose the scenario with the best outputs, namely the ‘average of the selected boxes’, given that this occurs at night when no tourist crowding is expected at the riverfront (top line in Table 1). Moreover, Table 2 shows the average FC (CFU/100 mL) of selected boxes’ KPIs resulting from the simulation of the shutdown discharges carried out in the spring and neap tides nearest to the predicted shutdown date. This analysis reveals that the most suitable timing for the shutdown coincides with the nearest neap-tide (18 August 2013) on the diurnal low-tide (14:15).

Figure 5 shows a map of FC dispersion near the selected boxes (GIS FC Simulator). With this feature it is possible to see, for example, the animation of one of the less favourable scenarios, simulated by the ODSS (Figure 5), that corresponds to the nearest low-tide during the night period (14 August 2013 22:20).

The time saved with scenario analysis done with ODSS compared with the same analysis performed by a modelling expert is approximately 5 days (2 hours versus 5 days). However, the KPI results that support the definition of the virtual monitoring boxes can be further improved, by allowing for its size to be changed to accommodate the study’s specific goals. Results of the ODSS implementation study described thus far firmly indicate that the use of this tool can greatly help the wastewater utility to simulate the outcomes of emergency and planned short- and long-term operations. In addition, a set of field validation measurements needs to be carried out, namely FC concentration and velocity profiles. Given the complexity involved in the validation of FC results this will imply executing complex field surveys, ideally using tracers.

CONCLUSIONS

A complex hydrodynamic model can be used to support the decision-making of operational wastewater utility staff. The
functionalities included in the developed ODSS, such as KPI reporting, represent a valuable asset for end-users since they transform complex and highly variable modelling results in time and in space into objective information and knowledge. The outputs of the ODSS capacitate wastewater utilities to take better informed decisions, based on scientific criteria, aiming to minimize the negative effects of discharges on the receiving water bodies without aggravating discharges. In the current study, the analysis reveals that the most suitable timing for the shutdown of Agências pumping station coincides with the nearest neap tide (18 August 2013) on the diurnal low-tide (14:15) of the initial scheduled day (15 August 2013). The time saved with scenario analysis done with ODSS compared with the same analysis performed by a modelling expert was approximately 5 days (2 hours versus 5 days). The ODSS’s implementation revealed some limitations in its proposed methodology. Global KPIs are calculated using the weighted averages of the values found in the selected monitoring boxes. This method proved to be simplistic because the KPIs, thus reckoned, showed too little variability across scenarios. One way to facilitate the decision-making process would be to set up a scenario classification system based on the sensitivity of each monitoring box. For example, a monitoring box including a bathing area and a protected fishing zone must be apportioned greater weight than one comprising a sea port. Overall, it may be concluded that the ODSS should be further developed to integrate: (i) sewer and WWTP dynamic models which will broaden boundary conditions; (ii) a dynamic weather forecast radar to enable real-time CSO management; and (iii) ecosystem services providing a deeper understanding of the implications between healthy ecosystems’ sustainable management and the attainment of economic goals. Furthermore, a set of field validation measurements needs to be carried out.

REFERENCES


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