Combined sewer overflow emissions to bathing waters in Portugal. How to reduce in densely urbanised areas?

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Abstract The current proposal for a revised European Directive concerning the quality of bathing water significantly increases the demands for the control of wet-weather discharges. A densely urbanised combined catchment was modelled for a 19-year long rainfall series in order to assess the current situation and to evaluate the benefits of potential solutions. Storage and advanced physical-chemical treatment of stormwater in the STP may significantly contribute for the reduction of the overflow volumes but reductions of the spill frequency under 2.5 spill days per bathing season are hardly obtained. This study reveals the severe strains that the local rainfall pattern may place on the control of the frequency of wet-weather discharges, pointing to serious technical, social and economical implications, at the local and at the national level, if the current proposal for a revised European Directive on Bathing Water is enforced.

Keywords Advanced physical–chemical treatment; bathing waters; combined sewer overflows; continuous modelling; water quality

Introduction
Atlantic beaches are a large fraction of the water resources in Portugal and their recreational value is of great social and economic importance. During the 20th century, there were some cases of important tourist regions that decreased their status in part due to the water quality degradation of their beaches. Currently, some countries are interdicting bathing after storms, during the period of time with increased health risk due to polluted stormwater contamination (Barro et al., 2002; USEPA, 2002; RIDHBB, 2003). The recently adopted proposal for a revised European Directive on Bathing Water emphasizes the risks of contact with, or ingestion of, faecal material originating from poorly treated sewage, sets a significantly higher health standard, and forces the public information process about water quality, health risks and the adopted management measures in order to prevent human exposure to contamination. These new practices and regulations will surely change the public perception about the health risks and will promote changes in holiday and tourist destinations, representing a new challenge for beaches management.

This study aims to evaluate the potential of building storage structures and using physical-chemical treatment in the combined sewer overflow (CSO) pollution reduction to bathing waters in Portugal. A densely urbanised combined catchment was modelled for a 19-year long rainfall series (Lisbon, 1973–91) using a simplified model. Selected catchment is located at Lisbon downtown and has a total area of 620 ha, whose 80% are impervious (550 ha). The downstream area is flat and is crossed by three combined sewer trunks that receive the flow from three upstream larger and sloped catchments. The model was hydraulically calibrated against data obtained from a calibrated hydrodynamic model (David, 2004) and is able to use water quality data obtained from a neighbour catchment (David and Matos, 2002a; David, 2002b).
Relevant EU legislation


It is the current proposal for a revised European Directive concerning the quality of bathing water (Commission of the European Communities, 2002) that, if approved, will force the adoption of stringent measures to the control of wet-weather discharges. The proposal imposes more restrictive standards and forces to the implementation of more sustainable measures by the adoption of a method where the bathing water quality assessment is established based on the 95 percentile of the microbiological data sets “obtained during the preceding three bathing seasons”. Additionally, bathing water classified as “poor” will be considered to conform temporarily, if “management measures have been undertaken during the bathing season,… the causes and reasons for non-conformity are identified; measures to prevent, reduce or eliminate the pollution/contamination are implemented and are expected to produce positive results within three years; the public is informed of the causes of the pollution/contamination and all measures undertaken”; and the classification of “poor” is not prolonged for more than three years. The improvement of the water quality classification (to achieve the “excellent quality”) is enforced by the reduction of the requirements concerning the monitoring frequency and the frequency and complexity of the compulsory “studies and analysis following classification”. To fulfil the “Excellent Quality” classification and in the “public information” process, some requirements are enlarged to waters where “other recreational activities” are practiced (“such as surfing, windsurfing and kayaking”).

“During emergency conditions, the monitoring calendar …may be suspended” but the report to be sent to the Commission “shall outline the circumstances of the emergency and, if it is weather related, the calculated return interval of any rainfall or extreme flows”. However, an emergency condition is “an exceptional condition, impacting on water quality, and which is not the result of ordinary weather conditions like rainfall or changes in the river flow that happen at regular intervals of less than five years.”

Detention and treatment of wet-weather flows

Several measures may contribute to wet-weather pollution control. Source control measures may constitute important ways in reducing flows and pollutant loads into the sewer systems, but their implementation is often limited by the existing urban development. In densely urbanised areas, detention in the sewer system has been one of the most applied measures to reduce overflow discharges, requiring the construction of underground storage structures and, in many cases, the improving of the in-sewer storage capacity through real time control techniques. Improvement of the sewage treatment plants (STP) performance under stress conditions, such as hydraulic transients, changes in wastewater composition and prolonged periods at full hydraulic load due to the emptying of the storage structures, is also required.

Storage tanks are frequently designed to ensure a pre-treatment by settling to the overflow discharges. However, in conventional sedimentation tanks, hydraulic surface load must not exceed 10 m³/h/m² and expected suspended solids removals of 50 to 70% are highly uncertain. Higher surface loads have been obtained by addition of appropriate...
chemicals and/or equipping the structures with lamella settlers (Rietsch et al., 2003). Selection and dosage of coagulants/flocculants depends on the characteristics of the wastewater and have to be identified by experimental procedures (jar testing). The properties of the sludge and float materials generated by the coagulant are also important, given that additional efforts may be required to clean the vessels and dispose the residues for particularly cohesive materials (Averill et al., 2001). Particular attention should also be given to turbulence conditions to avoid impairing pollutant settling and scouring of deposited sludge (Marsalek et al., 2003).

Recently, in the so called “ballasted flocculation process” a flocculation aid and a ballasting agent are used to form dense microfloc particles after coagulation. The addition and recirculation of a settling carrier of colloids increases settling velocities and the allowable tank overflow rates, producing a high quality supernatant (Ding et al., 1999). Independently of suspended solids loading, the treated effluent characteristics remain almost constant. The commercial system Actiflo® consists on the addition of coagulant with the influent in a flash mix chamber to destabilize suspended and colloidal matter, followed by the addition of a polymer and recycle microsand in an injection chamber. The floc is fixed to the microsand with the polymer in a maturation chamber and the flocculated water passes through a lamellar clarifier, where the ballasted floc settles and clarified water overflows. The conceptually similar commercial system DensaDeg® uses recycled sludge as a ballast agent. Pilot and full-scale applications of microsand systems have shown reductions of up 85–95% for TSS, 60–80% for BOD and 85–95% for total P at overflow rates up to 50–100 m³/h/m². Start-up times between 10 and 30 minutes and retention times of about 10 minutes have been reported. Sludge-based systems are able to produce a much thicker sludge, but pilot applications have proven a more erratic efficiency and start-up times of up to 4 times longer than ballasted flocculation process systems (Capodaglio, 2003).

The reduction of stormwater suspended solids concentrations to 40–80 mg/l seems to allow for the effluent UV disinfection.

Recent applications upgrading the STP stormwater treatment capacity are demonstrating high-rate clarification as a promising cost-effective method for the CSO pollution abatement.

Simplified modelling description

The simplified model considers initial losses and uses a linear time-area curve to represent the stormwater propagation from the entire catchment (surface and sewers) until the storage/treatment structure. Pollutant rates may be calculated based on average mean concentrations or variable (rain dependent) build-up and wash-off equations. Their advection is also modelled by the time-area method. Mass balance equations are applied to estimate the water volumes and the pollutant loads discharged from the storage/treatment structure to the receiving water body. The reduction of the pollution loads due to sedimentation or treatment in the storage structures may also be modelled by applying a concentration reduction rate or any other treatment equation to a fraction of the overflow below a critical flow. Mix of different pollutant concentrations in the structure is not modelled.

The model was built in Visual Basic, reading and writing data in Excel worksheets. Data resulting from the hydrological model, with a time step of 5 minutes, are automatically processed in order to reduce the volume of data, by aggregating periods of consecutive “identical” flow values (differences smaller than 0.1 l/s/ha mp), and transposed to spreadsheets of an MS® Excel® workbook. The mass balance equations are automatically implemented in the workbook and statistics for several indicators are obtained for
each scenario of the stormwater treatment capacity, storage and treatment efficiencies in storage tanks. The model allows for the fast batch running of a sequence of simulations.

The simplified model performance was checked against the results obtained from the MOUSE hydrodynamic model for a complete rainy year, for 3 different scenarios of storage (8, 30 and 50 m³/ha), without and with downstream tide sinusoidal influence (David, 2004).

**Results and discussion**

**Modelling conditions**

The average annual rainfall for the 19-years series is 690 mm. Based on the prototype catchment, the following modelling parameters were considered:

- impervious area = 550 ha;
- time of concentration = 30 min;
- initial losses = 1.5 mm (10% losses and an average annual runoff of 620 mm);
- a reference value for the STP hydraulic capacity of 3 times the average dry-weather flow, resulting an average stormwater treatment capacity ($q_{STW}$) of 1.5 l/s/ha_{imp}.

Overflows annual distribution for the no storage scenario

For a stormwater treatment capacity of $q_{STP} = 1.5$ l/s/ha_{imp}, corresponding to a typical STP hydraulic capacity of three times the average dry-weather flow, and assuming no additional storage in the sewer system ($V_s = 0$), the following monthly, bathing season and annual statistics of spill frequency and volume are presented in Figure 1: average, median and percentiles 5, 25, 75 and 95.

Figure 1 illustrates an important annual variation of the overflow discharges. Average values of 59 spilling days per year and 6 spilling days per bathing season are expected. In a whole year analysis, the median and average values of the overflow volumes are very close (4,500 m³/ha/year = 450 mm/year, 74% of runoff) and the coefficient of variation is only 0.3 (not presented in the figure). However, for the bathing season, the magnitude of overflowed volumes differs substantially, having a coefficient of variation of 1.1 and values of 170 m³/ha for the median, 330 m³/ha for the average and 880 m³/ha for the percentile 95.

These figures approximately correspond to the current scenario of discharges in many beaches at the north side of the Greater Lisbon region, where wet-weather discharges are the main cause for non compliance with the current bathing water Directive.

**Storage and treatment scenarios**

The model allows for the fast batch running of a sequence of several scenarios of STP hydraulic capacity and of storage and treatment in tanks. Giving a value for the STP hydraulic capacity and an equation for the treatment efficiency in tanks, the model is able to determine the storage needs for any pre-established objective of spill control. Figure 2 presents curves of equal bathing season’s spill frequency (left) and of equal bathing season’s spill volume (right) for different scenarios of STP hydraulic capacity ($q_{STP}$) and storage capacity in tanks ($V_s$). No treatment in storage tanks was considered.

Eight scenarios where highlighted in Figure 2, corresponding to four storage capacities ($V_s$): 0, 12, 24 and 36 m³/ha_{imp} and two stormwater STP treatment capacities ($q_{STP}$): 1.5 and 6.0 l/s/ha_{imp}. These stormwater treatment capacities correspond to STPs designed to treat 3 and 9 times the average dry-weather flows, respectively (a conventional one and another using high-rate clarification and disinfection).

For a conventional STP ($q_{STP} = 1.5$ l/s/ha_{imp}) and assuming no additional storage, 77% of the runoff is discharged and the spill frequency during the bathing season reduces from 7.0 rainy days to 5.7 spill days. For this STP hydraulic capacity, storage capacities
of 12, 24 and 36 m$^3$/ha$\text{imp}$ decrease the spill volume for 59, 49 and 40% of the runoff, respectively. The spill frequency reduces to 3.7, 2.8 and 2.5 days per bathing season, respectively.

Increasing the STP capacity for $q_{\text{STP}} = 6.0$ l/s/ha$\text{imp}$ and assuming no additional storage, 47% of the runoff is discharged (~30%), the same value that would be obtained by a storage capacity of 36 m$^3$/ha$\text{imp}$ for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$. The spill frequency reduces to 4.0 spill days, corresponding to a storage capacity of 9 m$^3$/ha$\text{imp}$ for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$. The benefits of increasing the storage capacity are less relevant for $q_{\text{STP}} = 6.0$ l/s/ha$\text{imp}$ than for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$, but still contribute for important reductions of the CSO volumes, especially for the smaller storage capacities (storage capacities of 12, 24 and 36 m$^3$/ha$\text{imp}$ decrease the spill volume for 35, 28 and 33% of the runoff, respectively; the spill frequency reduces to 2.5, 2.1 and 1.6 days per bathing season, respectively).

These figures put in evidence a declining efficiency with the increase of both the storage and the STP hydraulic capacity. For a conventional STP, a storage capacity of 20 m$^3$/ha$\text{imp}$ would be required to reduce the spill frequency bellow 3.0 spilling days per bathing season (for half). For a STP designed to treat 9 times the average dry-weather flow, a storage capacity of 6 m$^3$/ha$\text{imp}$ would reduce the spill frequency to 3.0 spilling days and the overflowed volume to 40%.

Figure 3 compares the average cumulated values of spill volume, number of spill days and spill duration, ranked by decreasing values of the spill intensities, for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$ (left side) and for $q_{\text{STP}} = 6.0$ l/s/ha$\text{imp}$ (right side). Figure 4 compares the same indicators for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$ and $V_s = 24$ m$^3$/ha$\text{imp}$, assuming no treatment in the storage tanks (left side) and treatment of 50% of the overflow fraction under 20 l/s/ha$\text{imp}$ (right side). Treated overflow fraction ensures a retention time of 20 minutes in the 24 m$^3$/ha$\text{imp}$ storage tanks.

An increase of the STP stormwater treatment capacity corresponds to a translation of the number of spill days and spill duration curves to the left side of the graphic (Fig. 3). Overflow volumes decrease due to the reduction of the overflow intensities. Cumulated spill volume and duration curves for the scenario $q_{\text{STP}} = 6.0$ l/s/ha$\text{imp}$ and $V_s = 0$ (Figure 3, right) are very similar to the curves for $q_{\text{STP}} = 1.5$ l/s/ha$\text{imp}$ and $V_s = 24$ m$^3$/ha$\text{imp}$ (Figure 4, left), but the curve of the cumulated spill days is higher, specially for the
low spill intensities. For the both scenarios, the most improvement of all indicators occurs for the lower spill intensities.

For spill intensities higher than approximately 40 l/s/ha (15 mm/h), curves are similar for all the scenarios and cumulated values became very low. An inflow of 40 l/s/ha (15 mm/h) would correspond to a retention time of 10 minutes in a 24 m³/ha imp tank.

Settling in storage tanks (Figure 4, right) may contribute for important reductions of overflowed pollution, even for the higher intensities. However, it is important to stress that the total spill frequency and volume are unchanged (graphic just presents the number of “untreated” spill days) and that, in spite of a significant reduction of suspended solids, microorganism concentrations remain almost invariably high.

Conclusions

Wet-weather discharges are the main cause for some beaches located at the Great Lisbon’s region does not comply with the current bathing water Directive. The current proposal for a revised European Directive concerning the quality of bathing water significantly increases the demands for the control of wet-weather discharges. Among other relevant aspects, the proposal establishes a five year return period for the occurrence of weather related exceptional conditions impacting on water quality.
A densely urbanised combined catchment was modelled for a 19-year long rainfall series in order to assess the current situation and to evaluate the potential benefits of increasing the sewer system storage capacity, the STP stormwater treatment capacity and combinations of both measures.

The calibrated simplified model allows for the fast batch running of a sequence of several scenarios of STP hydraulic capacity and of storage and treatment in tanks, producing statistics and graphics that allow more cost effective decisions at the planning level. Monthly, seasonally and annual statistics for some indicators can be promptly obtained for each scenario.

For the current situation, an average of 5.7 CSO discharges are expected to occur per bathing season, in average, corresponding to 77% of the runoff. Presented results shows that storage and advanced physical-chemical treatment of stormwater in the STP may significantly contribute for the reduction of the overflow volumes but reductions of the spill frequency under 2.5 spill days per bathing season are hardly obtained.

Settling in conventional sedimentation tanks may contribute to important reductions of overflowed pollution, but the microorganism concentrations remain almost invariably high.

This study reveals the severe strains that the local rainfall pattern may place on the control of the frequency of wet-weather discharges, pointing to serious technical, social and economical implications, at the local and at the national level, if the current proposal for a revised European Directive on Bathing Water is enforced.

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