Using SWMM 5 in the continuous modelling of stormwater hydraulics and quality

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ABSTRACT
The use of mathematical models for urban drainage systems is well established for research and management of complex sewer systems. However, software costs still limit their use by smaller end-users and designers. The recent version 5 of SWMM for Microsoft Windows is a freeware and user-friendly program, which is easily available to students, small municipalities and companies, what may further contribute to increment its utilization as a common tool, similarly to what happened with EPANET. In addition to the general capacities of hydrodynamic models, SWMM5 also allows for continuous simulations using historical rainfall series. SWMM5 was applied in the long-term modelling of a selected urban area. Satisfactory results were obtained from the hydraulic model calibration and verification processes, but some limitations were found in the SWMM catchment hydrological description. Long-term simulations allowed to compare the benefits of different scenarios of storage and sewage treatment plant capacities for the reduction of the overflow discharges. The benefits in the reduction of the discharged TSS loads were very similar to the benefits in the reduction of the overflowed water volumes. In addition to increases in difficulties and uncertainties associated to the water quality model, no relevant benefits were obtained by its use.

KEYWORDS
Urban drainage, mathematical modelling, model calibration and verification, water quality, continuous modelling

INTRODUCTION
The use of mathematical models for urban drainage systems is well established for research and management of complex sewer systems. In Europe, MOUSE and InfoWorks are among the most used models, even if a large number of other programs have been developed. However the formers have their use restricted by software costs, which limit their use by smaller end-users and designers.

Recently, USEPA released the version 5 of the SWMM software for Microsoft Windows, which has the capability of both single-event and continuous simulation for the prediction of flows and pollutant concentrations. The SWMM5 is a freeware program, thus it is easily available to small municipalities and companies. Hence, SWMM5 use is expected to become widespread among end-users. Accordingly, universities are expected to start introducing...
students to its use, what may further increment the utilization of SWMM5 as a common tool, similarly to what happened with the EPANET use in drinking water distribution systems.

The main aim of this work was to apply SWMM5 to simulate hydraulics and water quality in a 110 ha urban area, which is divided in four catchments of different characteristics. Rainfall and hydraulic data measured at the different catchments was available for the model calibration and verification. Water quality data was available for dry weather characterisation, but only two to three rain events were sampled at each monitoring section. A digitalised 19 year-long rainfall series was available for long-term continuous modelling.

METHODS

SWMM general description

SWMM is a full dynamic wave simulation model used for single event or long-term simulation of runoff quantity and quality, primarily from urban areas. Version 5 is a complete re-write of the previous release, running under Microsoft Windows and providing an integrated environment for editing data, running hydrologic, hydraulic and water quality simulations, and viewing the results. It conceptualises a drainage system as a series of water and material flows between several major environmental compartments, namely: the atmosphere compartment, from which precipitation falls and pollutants are deposited onto the land surface compartment; the land surface compartment, which is represented by subcatchment objects; the groundwater compartment, which receives infiltration from the land surface compartment and transfers a portion of this inflow to the transport compartment; and the transport compartment, which contains a network of conveyance, storage, regulation and treatment elements. Not all compartments need appear in a particular SWMM model (Rossman, 2007).

Hydrological processes. Subcatchments can be divided into impervious and pervious areas. Losses in impervious areas are only due to depression storage while in pervious areas infiltration may also be modelled through Horton, Green-Ampt or SCS Curve Number method. Surface runoff in pervious and impervious fractions is given by the Manning’s equation. SWMM also allows to describing additional characteristics and processes within the study area, namely those related with subsurface water in groundwater aquifers and snowfall and snowmelt phenomena.

Flow routing. Flow routing in channels and pipes is governed by the conservation of mass and momentum equations for gradually varied and unsteady flow (Saint Venant) equations. The user decides on the simplification level of the equations: the steady flow routing; the kinematic wave routing; or the full dynamic wave routing.

Water quality. Runoff pollutant loads may be modelled using event mean concentrations or using buildup and washoff equations. Power, exponential and saturation functions are available for buildup. Rating curve and exponential functions are available for buildup. Different land uses inside each catchment, street sweeping, and external and dry weather inflows may also be considered.

Catchment description

The selected modelling-area is located at Odivelas, a neighbour city of Lisbon, and has been extensively studied in previous works (David and Matos, 1999; David, 2002).
The modelling-area comprehends (Figure 1):

- a small interceptor sewer (Caneças interceptor sewer), serving some pseudo-separate catchments with a total area of 80 ha; during wet weather, the interceptor sewer surcharges and overflows to the Odivelas creek;
- a combined catchment with 22 ha (B1); at middle stream the main trunk receives the interceptor sewer referred above; downstream, there is a small storage tank having 70 m$^3$ capacity;
- two 5 ha combined catchments (B2-A and B2-B), overflowing to the same sewer outfall (B2-O).

Five sewer sections were monitored for flow and sampled at preset intervals, over dry and wet weather periods. The characteristics of the monitoring sections and their upstream catchments are described in Table 1.

**Table 1. Main characteristics of the monitored sections and upstream catchments.**

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
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<tbody>
<tr>
<td>B1-I</td>
<td>Monitoring section: interceptor sewer from pseudo-separate systems. The interceptor surcharges for wet weather; upstream there are some overflow pipes at the manholes that discharges to the Odivelas creek. Estimated area served by the interceptor: 80 ha. Interceptor sewer length: 2800 m. Interceptor sewer diameters: 300 and 400 mm. Average interceptor sewer slope: 4%. Average dry weather flow (DWF): 84 l/s, including some infiltration flow.</td>
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<tr>
<td>B1-M</td>
<td>Monitoring section: downstream to the combined catchment B1; also receives the flow from B1-I. Upstream catchment area: 22 ha. Connected impervious area: 15 ha. Total sewers length: 5400 m. Circular, egg and square sewer shapes, from 200 to 1000 mm. Average ground slope: 3.1%. Average sewer slope: 3.1%. Average DWF: 108 l/s (84 l/s from the interceptor + 24 l/s from catchment B1).</td>
</tr>
<tr>
<td>B2-A</td>
<td>Monitoring section: downstream to the combined catchment B2-A. Subcatchment area: 5.5 ha. Impervious area: 5 ha. Total sewers length: 1220 m. Sewers diameters: 300, 400 and 500 mm. Average ground slope: 4.9%. Average sewer slope: 4.1%. Average DWF: 16 to 20 l/s, including infiltration and/or underground water.</td>
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<tr>
<td>B2-B</td>
<td>Monitoring section: downstream to the combined catchment B2-B. Subcatchment area: 4.3 ha. Impervious area: 4.0 ha. Total sewers length: 870 mm. Sewer diameters: 300 mm; 450 mm downstream. Average ground slope: 2.1%. Average sewer slope: 2.1%. Average DWF: 7 l/s.</td>
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<tr>
<td>B2-O</td>
<td>Monitoring section: outlet from the combined catchment B2 (downstream B2-A and B2-B). Catchment area: 10 ha. Impervious area: 9.3 ha. Total sewers length: 2540 m. Sewer diameters: from 300 to 800 mm. Average ground slope: 3.6%. Average sewer slope: 3.0%. Average DWF: 23 to 27 l/s, including infiltration and/or underground water.</td>
</tr>
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</table>

**Model building**

Figure 1 shows the SWMM study area maps for the two models built: the Caneças pseudo-separate system and the combined catchment B1; and catchment B2 (containing catchments B2-A and B2-B). The monitoring stations and the main sewer structures are indicated in the figure.
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Catchments B1, B2-A and B2-B were modelled using 86, 34 and 17 sub-catchments, respectively. The pseudo-separate catchment served by the Caneças interceptor sewer was modelled using only two subcatchments disposed in series, due to the lack of information about the incorrect connections causing its pseudo-separate behaviour, as well as about the upstream overflow discharges to the Odivelas creek. The widths of most subcatchments were considered the square root of its area, except for the two larger subcatchments from the pseudo-separate system.

The impervious areas of each subcatchment were initially defined with basis on the soil occupation analysis. All paved and roof areas and part of the backyard areas were considered as impervious. However, this representation had to be changed due to difficulties in calibrating the model, as explained in the next section.

Week and weekend dry weather average flow patterns were determined for each monitoring section and were introduced into the models.

Hydraulic model calibration and verification

The models were calibrated for four rain events and were verified by running a complete 4-month data period, containing twenty four rain events (including those used for calibration). Good results were obtained for the combined catchments B1, B2-A and B2-B, but differences were found for some events in the interceptor sewer from the pseudo-separate system (section B1-I). These differences were due to the lack of knowledge about the incorrect connections and overflow discharges in the upstream sewer system. All the overflow sites in the upstream sewer system were conceptually represented by a unique overflow structure located downstream the upstream Caneças sub-catchment (weir and outfall B1-U, in the left side map of Figure 1). Therefore, the conceptual model from the pseudo-separate system had to be recalibrated using data from more two critical rain events.

As previously described, the combined catchment B1 receives the flow from the Caneças interceptor sewer, which was monitored at section B1-I. Therefore, the flow time series measured at section B1-I was used as input data for the calibration of catchment B1. However, the 2-minute interval flow series could not be introduced to SWMM for the whole four-month monitoring period – a output “out of memory” message have been displayed. Consequently, the four-month simulation period had to be divided in four monthly
simulations. Alternatively, the time step of the flow series would have to be increased for 8 minutes or more. This limitation is considerably minimised in the introduction of rainfall time series, because SWMM accepts the removal of the zeros from the dry instants (five years of data were imported to SWMM from the 10-minute interval Lisbon rainfall series).

As referred for the model building description, the impervious areas of each subcatchment were initially estimated based on the soil occupation by pavements and roofs. However, the runoff generated in impervious areas resulted significantly higher than the measured flows at all the calibration sections. The necessary runoff reductions could not be represented by the depression storage losses, which are the only losses used by SWMM for impervious areas. The solution found was to multiply all impervious areas by a hydrological reduction coefficient, like it is modelled by the hydrological model A of MOUSE software (from the Danish Hydraulic Institute). The hydrological reduction coefficients were calculated based on the volumetric hydrological losses and were assumed constant for each calibration sub-catchment. As very satisfactory results were obtained for all the combined catchments, and by the principle of parsimony, runoff from pervious areas was not modelled (high infiltration rates were attributed to the Horton equation coefficients). Therefore, the hydrological reduction coefficients that multiply the impervious areas were the main calibration parameters. Obtained values for the coefficients were: 0.70 for catchments B2-A and B2-B, 0.60 for catchment B1 and 0.30 for the pseudo-separate catchment B1-I. However, this methodology carries the disadvantage of not preserving the measured impervious areas nor the hydrological reduction coefficients in the model, but only their products.

Manning numbers of $n = 0.011 \, \text{s.m}^{-1/3}$ were used for overland on impervious areas and of $n = 0.014 \, \text{s.m}^{-1/3}$ for flow inside the pipes.

**Water quality coefficients adjustment**

The water quality coefficients for the exponential buildup and washoff equations were adjusted for the existing TSS data at the several monitoring sections. Data were available for three successive rain events at sections B1-I, B1-M, B2-A and B2-B, and two rain events at the outfall B2-O.

The exponential buildup equation is given by $B = C_1 \left(1 - e^{-C_2 t}\right)$, where: $B$ is the pollutant buildup mass per unit of subcatchment area (kg/ha); $C_1$ is the maximum buildup possible (kg/ha); $C_2$ is the buildup rate constant (1/days); and $t$ is the time (days). The exponential washoff equation is given by $W = C_3 \cdot q^{C_4} \cdot B$, where: $W$ is the pollutant washoff rate per unit area (kg/(hour.ha)); $q$ is the runoff rate per unit area (mm/hour); $C_3$ is the washoff coefficient; and $C_4$ is the washoff exponent.

TSS dry weather profiles were introduced into SWMM based on hourly concentrations sampled for two dry weather days at sections B1-I, B1-M, B2-A and B2-B. Initial simulations were run using default values, as well as values from the literature (Zhang and Hamlett, 2006), for the buildup and washoff coefficients, but modelled pollutographs resulted far from the measured data.

High TSS concentrations as well as pronounced first flushes were observed for both events at the outfall B2-O, contrarily to what happen in the upstream sections B2-A and B2-B. These results suggest that a significant part of the scoured material had been stored within the
downstream part of the sewer system, downstream of the CSO structures of sub-catchments B2-A and B2-B (here, sewer sections are larger, the slopes are weaker and, in addition, there are some stormwater and even domestic sewers connected to the main outfall). Modelling these processes is quite complex, require a lot of calibration data and mostly remains on the research stage. Therefore, they are empirically represented by the buildup and washoff equations in SWMM. On the other hand, the outfall B2-O was sampled four years before the upstream sections B2-A and B2-B, and the high differences on concentrations may also be attributed to any important change occurred in the catchment or in the sewers for this period.

After a sensitivity analysis of the coefficients, these were iteratively adjusted through a series of simulations for the events. The same values of the calibration coefficients were assumed for all sub-catchments of each monitoring catchment. For some calibration sections, more than one combination of coefficients was found to adjust the modelled pollutographs to the measured concentrations. The adjustment was concluded when satisfactory results were obtained using the same values for three calibration coefficients in all the catchments, and only one coefficient characterise each catchment, as presented in Table 2. Figure 2 compares measured and modelling results at the pseudo-separate monitoring section (B1-I) and at the outfall of the combined catchment B2 (B2-O). For both cases, the wet weather TSS concentrations significantly exceeded the raw sewage TSS concentrations, showing the importance of the buildup, washoff and transport processes. However, even if acceptable results were observed, the number of available events was not enough to allow a full calibration of the 4 empirical coefficients of each water quality model. Accordingly, the obtained outputs underline the models uncertainty, whenever the number of event’s data is not enough for calibration.

Table 2. Values obtained for the empirical water quality coefficients.

<table>
<thead>
<tr>
<th></th>
<th>Buildup equation</th>
<th>Washoff equation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_1$</td>
<td>$C_2$</td>
</tr>
<tr>
<td>B1-I</td>
<td>132</td>
<td>0.08</td>
</tr>
<tr>
<td>B1-M</td>
<td>160</td>
<td>0.08</td>
</tr>
<tr>
<td>B2-A</td>
<td>80</td>
<td>0.08</td>
</tr>
<tr>
<td>B2-B</td>
<td>65</td>
<td>0.08</td>
</tr>
<tr>
<td>B2-O</td>
<td>450</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figure 2. Modelling results at sections B1-I (pseudo-separate) and B2-O (combined).
CONTINUOUS MODELLING FOR THE ASSESSMENT OF WET WEATHER DISCHARGES

Modelling results may be seen or exported in the form of reports, tables, hydrographs, longitudinal profiles and other graphs, for several parameters at nodes or links, such as water depths, heads, flows, volumes, flooding and pollutant loads. SWMM5 also provides statistics (mean, peak, total, duration and inter-event time), histograms and the frequency plots of the variables for annual, monthly, daily or event-dependent periods.

Continuous simulations were carried out in order to evaluate the potential benefits of the existing 70 m$^3$ storage tank (located downstream catchment B1) in the reduction of wet weather discharges. A digitalised 19-year long rainfall series was available for continuous modelling, but, as previously referred, only 5-year long sets could be introduced to SWMM due to computer memory limits. This limited number of years is a constraint for the SWMM statistical analysis, but results from successive 5-year long simulations may be exported and analysed together outside SWMM, in an Excel spreadsheet for example.

For the pseudo-separate and combined catchment B1 model, each 5-year long simulation took 16 hours to run with the full dynamic wave routing, using an AMD 2.0 GHz, 2 GB of RAM computer. Due to the long time of the simulations and taking into consideration the academic objective of this work, continuous simulations were run only for the 5-year period from 1977 to 1982, which includes the average and the wettest years of the available 19-year period.

Figure 3 gives an example of some statistics provided by SWMM for the flow at the CSO outfall B1-O, for the current situation. SWMM annual statistics are calculated with respect to civil years, while the data was introduced by hydrological years (starting on October 1st).

In order to evaluate the potential benefits of the existing 70 m$^3$ storage tank, simulations were run for the current situation and for the scenario without any storage tank. For both
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Simulations, flows discharged from each one of the three outfall sewers from catchment B1 (B1-O, B1-I and B1-U) were exported to external files. The results were analysed together in an Excel worksheet. Figure 4 compares the total volume discharged from the three outfall sewers for the two simulated scenarios, for each one of the five simulated hydrological years and for the annual average. Flooding volumes are also indicated. A threshold value of 220 l/s was used for the maximum flow draining to the sewage treatment plant (by the interceptor sewer) in the B1-O CSO structure, which corresponds to the double of the dry weather flow.

![Figure 4. Annual overflow volumes from the three outfall sewers, for the current situation and for the scenario without any storage tank.](image)

Modelling results, illustrated in Figure 4, show that the existing 70 m$^3$ tank allows to reducing the overflow discharged in B2-O of about 16% (from 14% to 20%), which corresponds to approximately 8% of the volume discharged by the whole catchment (from 7% to 11%).

New simulations were carried out assuming the hypothetical construction of storage tanks upstream each one of the three outfall sewers (B1-O, B1-I and B1-U). The following two storage scenarios were simulated:

- 70 m$^3$ in B1-O; 30 m$^3$ in B1-I; and 160 m$^3$ in B1-U, totalising 260 m$^3$;
- 140 m$^3$ in B1-O; 60 m$^3$ in B1-I; and 320 m$^3$ in B1-U, totalising 520 m$^3$.

In the weirs located upstream the storage tanks, two scenarios were considered for the flows draining to downstream, to the sewage treatment plant:

- flows of two times the dry weather flow ($Q_{STP} = 2 \times Q_{DWF}$), resulting 220 l/s in B1-O, 165 l/s in B1-I, and 140 l/s at B1-U;
- flows of four times the dry weather flow ($Q_{STP} = 4 \times Q_{DWF}$), resulting 440 l/s in B1-O, 230 l/s in B1-I, and 280 l/s in B1-U.

Figure 5 presents the average annual overflow volumes for the four scenarios referred above and also for the two following scenarios:

- no storage tanks and flow draining to the STP only controlled in B1-O (as currently) for a threshold value of two times the dry weather flow (220 l/s);
- no storage tanks and flow draining to the STP only controlled in B1-O for a threshold value of four times the dry weather flow (440 l/s).
Figure 5. Average annual overflow volumes for six simulated scenarios.

Results presented in Figure 5 show that the overflow discharges for the scenarios having a total storage capacity of 260 m$^3$ are significantly lower than those for the no storage scenarios, for both situations of the flows draining to the STP. The reductions were of 39% and of 46%, respectively for Q$_{STP}$ = 2Q$_{DWF}$ and for Q$_{STP}$ = 4Q$_{DWF}$. However, for the scenarios doubling the total storage capacity (V = 520 m$^3$), reductions were only ca. 7% higher.

Increasing the flows draining to the STP from 2 to 4 times the dry weather flow, the overflow discharges are reduced on 41% for the no storage scenario, and on 48% for the two simulated storage scenarios.

A similar analysis was done to comparing the overfl owed TSS loads for the six simulated scenarios and very alike results were obtained for the benefits from increasing storage or the threshold values of the Q$_{STP}$. Therefore, in addition to increases in difficulties and uncertainties associated to the water quality model, no relevant benefits were obtained by its use, at least within the scope of the present study.

**CONCLUSIONS**

The recent version 5 of SWMM for Microsoft Windows is a freeware and user-friendly program, which is easily available to students, small municipalities and companies, what may further contribute to increment its utilization as a common tool, similarly to what happened with EPANET.

In addition to the general capacities of hydrodynamic models, SWMM5 also allows for continuous simulations using historical rainfall series and provides several statistics for the results. Result data series may also be easily exported, allowing the treatment of the data by external software. However, there are limitations to import long time series into SWMM5, which may be necessary to define the boundary conditions, due to computer lack of memory. A maximum of about thirty days data could be loaded to SWMM5 from a 2-minute interval inflow time series. This limitation is considerably minimised in the introduction of rainfall time series, because SWMM accepts the removal of the zeros from the dry instants. Five years of data could be imported to SWMM from the 10-minute interval Lisbon rainfall series.
Using an AMD 2.0 GHz, 2 GB of RAM computer, SWMM5 took 16 hours to run a 5-year long simulation with the full dynamic wave routing, for a model having 90 catchments, 160 nodes, 170 conduits and water quality parameters for one pollutant substance. The selection of the kinematic wave method of routing would decrease the time of computation, but backwater and surcharge could not be correctly calculated.

The impervious areas of each subcatchment were initially modelled based on the soil occupation by pavements and roofs. However, the only losses used by SWMM for impervious areas are the depression storage losses, which were not enough to allow the necessary flow reductions for model calibration. Very satisfactory results were obtained multiplying all impervious areas by a hydrological reduction coefficient (constant for each calibration subcatchment) and annulling runoff from pervious areas, like it is modelled by the hydrological model A of MOUSE software (from the Danish Hydraulic Institute). This methodology, based on the principle of the parsimony, carries the disadvantage of not preserving the measured impervious areas nor the hydrological reduction coefficients in the model, but only their products.

For the present case study, continuous modelling allowed to compare the benefits of different scenarios of storage and sewage treatment plant capacities for the reduction of the overflow discharges. The benefits in the reduction of the discharged TSS loads were very similar to the benefits in the reduction of the overflowed water volumes, showing that, in addition to increases in difficulties and uncertainties associated to the water quality model, no relevant benefits were obtained by its use, at least within the scope of the present study.

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REFERENCES