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New Trends in Urban Drainage Modelling

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Mathematical Modelling of In-Sewer Processes as a Tool for Sewer System Design

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Abstract. The objective of this paper is to evaluate the potential impact of in-sewer processes (COD components transformation and hydrogen sulphide production) on the design of sewer systems. The tool used for such analysis is a mathematical model derived from the WATS model (Wastewater Aerobic/anaerobic Transformation in Sewers) able to describe the processes occurring in the sewer system both under aerobic and anaerobic conditions. The model is applied to three catchments with, respectively, 10,000, 50,000 and 250,000 inhabitants connected to gravity sewer systems different in terms of type (separate or combined), slope, length, travel time, wastewater temperature. The simulation results enable to assess the effect of the in sewer transformations in terms of hydrogen sulphide formation and transformation of the biodegradable organic matter that is necessary for biological nutrients removal at the WWTP.

Keywords: Aerobic/anaerobic conditions · Sewer
Wastewater transformations · Biological nutrients removal

1 Introduction

Sewer biological processes may produce a variation of carbon and nutrients from the source to the final outlet (the wastewater treatment plant). The variation of the pollutant concentrations may affect the dimension of the sewer pipes or, in other words, during the design of sewer networks biological processes should be taken into account for a more comprehensive approach.

In the light of the consideration above, this paper explores the impact of the in-sewer processes (COD components transformation and hydrogen sulphide production) on the design of sewer systems.

To achieve the above goal, a mathematical model developed in previous studies is employed. In details, the model has been applied to synthetic urban catchments with different characteristics in order to cover as much as possible the range of possible real cases occurring in engineering practice. The model results enabled to evaluate the characteristics of the sewer system that influence significantly the in-sewer processes both in terms of hydrogen sulphide production and of COD transformation.

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With regard to this latter, model outputs have been compared with the amount of biodegradable organic matter needed for biologic nutrients removal. In fact, according to Henze et al. 1999, considering typical composition of raw wastewater (Bonomo 2008; Tchobanoglous et al. 2002; Henze et al. 1996) and the standard for discharge of treated wastewater in Italy (Gazzetta Ufficiale della Repubblica Italiana 2006), about 90 mg/l of readily biodegradable organic matter are needed for phosphorus removal and approximately 425 mg/l COD are needed for denitrification. As better explained below, in this paper influent COD concentration has been assumed equal to 530 mg/l following Henze et al. 1996, in this case the organic matter available for biologic nutrients removal is hardly higher than the minimum amount calculated above (90 mg/l for P removal and 425 mg/l for N removal for a total of 515 mg/l COD) and for this reason also a limited change in COD amount and composition due to in-sewer processes can negatively influence biologic nutrients removal.

2 Methods: Model Description and Application

A previous developed quantity-quality sewer model has been employed (Calabrò et al. 2009). The model is inspired to the WATS model (Hvitved-Jacobsen et al. 1999). Similarly to the WATS (Tanaka and Hvitved-Jacobsen 1998; Bruno et al. 2003), the quantity module is dynamic and it is therefore able to consider the variability of the flow during the day while the quality module is quasi-steady (Calabrò et al. 2009). It automatically switches between aerobic and anaerobic conditions according to the local environmental conditions (presence or absence of Dissolved Oxygen). The model consists of two modules, the first module deals with the flow propagation in the sewer system, it reproduces the dynamic conditions; as matter of a fact, such module considers the variations of parameters and control variables, such as discharge, water height and velocity in space and time. On the other hand, the second module describes the in-sewer transformations according to several differential equations which are based on mass balances. As the quantity module, the quality module reproduces dynamic conditions.

The developed model has been applied to three synthetic cases with different characteristics to cover as much as possible the range of possible real cases occurring in engineering practice. The catchments present a population of respectively 10,000, 50,000 and 250,000 inhabitants and are connected to gravity sewer systems with differences in terms of type (separate or combined), slope, length, travel time, wastewater temperature. Diameter ranges have been generated using Italian Best Practice Design Rules (see CSDU 1997) and average specific water consumption. Separate and combined sewers have been considered because, during dry weather, under the same discharge, reaeration is significantly different due to the noticeable difference of the ratio between water depth and diameter.

The model parameters and the wastewater COD fractionations have been set at the same values coming from previous model applications (see Calabrò et al. 2009). Table 1 summarizes the values of the parameters used in the simulations. The simulations have been carried out considering a variation of the values of the parameter under investigation according to the range presented in Table 1 with the other parameters set at their default values. The model outputs chosen for the assessment were: COD, readily biodegradable COD (evaluated as the sum of SS and XS1) and SH2S at the outlet of the sewer.

Table 1. Parameters values considered in simulations.

Parameter	Range of variation **(Default value)**		
Catchment Population [inhabitant]	10,000	50,000	250,000
Type	Separate, Combined		
Specific Water Consumption [m^3/in*day]	0.250	0.350	0.450
Slope [m/m]	0.0005–0.1 **(0,009)**		
Diameter [m]	0,32–1,6 (**0.32 sep.–1.6 com.**)	0.7–3.5 (**0.7 sep.–2.0 com.**)	1.3–6.7 (**1.4 sep.–4.0 com.**)
Length [km]	0–15		
Total COD [mg/l] (see Henze *et al.*1999)	530		
Most readily Biodegr. COD $S_s + X_{S1} + X_{S2}$ [mg/l]	140		
Temperature [°C]	5–25 **(20)**		

3 Results and Discussion

The simulation results are summarized in Table 2; in particular, for each of the three synthetic catchments considered, the changes in the model outputs (Hydraulic Retention Time HRT), Total COD, Readily Biodegradable COD and H2S concentration) have been reported as a function of the sewer type, diameter, slope, length and wastewater temperature. Regarding, Total COD and Readily Biodegradable COD concentration, maximum, minimum and average values normalized respect to their initial value have been reported. On the other hand, concerning HRT and H2S instead of the normalized values their actual values have been reported.

From the results analysis emerges that there is only a slight total COD variation both in dependence of the diameter, the slope, the type of sewer and the temperature. However, ss explained above, this reduction in the available COD, although moderate, could negatively influence biologic nutrients removal and should be carefully considered on case by case basis. It is also interesting that the readily biodegradable COD in correspondence of limited oxygen availability (low reaeration due to limited values of slope and velocity or excessive filling rate) or limited biological activity due to low temperature, shows an increase respect to the initial value. This effect is obviously emphasized in combined sewer where, during dry weather, the velocity is reduced. Reciprocally, a high level of hydrogen sulphide occurs in the same cases. Readily biodegradable COD reduction in smaller catchments with separate sewers and high average slopes could be high enough to reduce this component down to values non compatible with biological phosphorus removal.

Table 2. Synthesis of simulation results.

	Minimum/Maximum – Average Value at the outlet of a sewer of length equal to 15 km (normalized respect to initial values)			
	HRT [h]*	COD_{total}	$S_s + X_{S1}$	S_{H2S} [mg/l]*
	Separate Sewer			
10,000 INHABITANTS				
Diameter [m]	4.14/5.07–**4.67**	0.960/0.980–**0.973**	0.762/1.003–**0.918**	0.721/2.028–**1.469**
Slope [m/m]	2.08/12.89–**5.99**	0.943/0.973–**0.959**	0.467/0.964–**0.724**	0.019/2.424–**1.018**
Temperature [°C]	not applicable	0.955/0.974–**0.965**	0.684/1.010–**0.849**	0.118/0.949–**0.497**
Length** [km]	0.83/4.14–**1.93**	0.992/0.960–**0.982**	0.963/0.762–**0.903**	0.120/0.721–**0.303**
50,000 INHABITANTS				
Diameter [m]	2.56/3.15–**2.85**	0.986/0.993–**0.990**	0.915/1.002–**0.966**	0.028/0.663–**0.473**
Slope [m/m]	1.25/7.90–**4.00**	0.977/0.991–**0.985**	0.781/1.030–**0.908**	0.005/0.735–**0.331**
Temperature [°C]	not applicable	0.984/0.991–**0.987**	0.882/1.030–**0.954**	0.087/0.359–**0.216**
Length** [km]	0.52/2.56–**1.19**	0.997/0.986–**0.993**	0.984/0.915–**0.962**	0.056/0.289–**0.132**
250,000 INHABITANTS				
Diameter [m]	1.60/1.97–**1.75**	0.994/0.997–**0.996**	0.967/1.005–**0.985**	0.105/0.215–**0.148**
Slope [m/m]	0.34/2.13–**1.08**	0.990/0.997–**0.994**	0.917/1.027–**0.969**	0.007/0.236–**0.113**
Temperature [°C]	not applicable	0.994/0.996–**0.995**	0.954/1.018–**0.985**	0.047/0.130–**0.086**
Length ** [km]	0.32/1.61–**0.75**	0.999/0.995–**0.998**	0.994/0.969–0.**986**	0.021/0.106–**0.049**
	Combined Sewer			
10,000 INHABITANTS				
Diameter [m]	4.14/5.07–**4.67**	0.960/0.980–**0.973**	0.762/1.003–**0.918**	0.721/2.028–**1.469**
Slope [m/m]	2.18/13.93–**6.98**	0.956/0.991–**0.976**	0.766/1.211–**1.005**	0.300/3.687–**2.032**
Temperature [°C]	not applicable	0.977/0.986–**0.982**	0.993/1.101–**1.038**	0.952/2.450–**1.658**
Length** [km]	1.01/5.07–**2.37**	0.996/0.980–**0.991**	1.006/1.003–**1.008**	0.388/2.028–**0.922**
50,000 INHABITANTS				
Diameter [m]	2.56/3.15–**2.85**	0.986/0.993–**0.990**	0.915/1.002–**0.966**	0.028/0.663–**0.473**
Slope [m/m]	1.26/8.00–**4.01**	0.981/0.996–**0.990**	0.869/1.089–**0.982**	0.067/0.899–**0.497**
Temperature [°C]	not applicable	0.990/0.994–**0.992**	0.963/1.042–**1.000**	0.245/0.606–**0.416**
Length** [km]	0.63/2.91–**1.36**	0.998/0.991–**0.996**	0.996/0.979–**0.991**	0.100/0.507–**0.235**
250,000 INHABITANTS				
Diameter [m]	1.60/1.97–**1.75**	0.994/0.997–**0.996**	0.967/1.005–**0.985**	0.105/0.215–**0.148**
Slope [m/m]	0.37/2.34–**1.17**	0.992/0.999–0.996	0.944/1.051–**0.997**	0.041/0.281–**0.167**
Temperature [°C]	not applicable	0.996/0.998–**0.997**	0.988/1.022–**1.004**	0.094/0.203–**0.145**
Length ** [km]	0.37/1.83–**0.85**	0.999/0.997–**0.998**	0.999/0.995–**0.998**	0.034/0.170–**0.079**

*Actual value; **Value at 3 km/Value at 15 km –Value at 7 km.

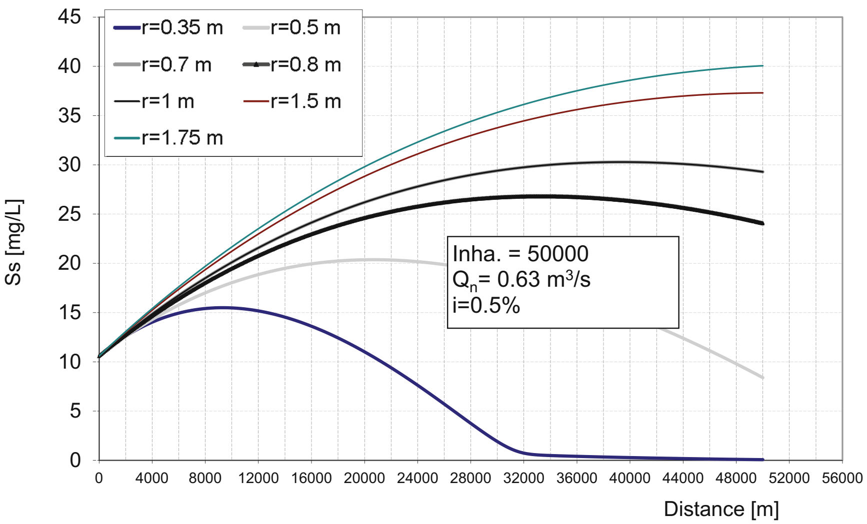

Fig. 1. Variation of the COD along the sewer

Referring to the type of sewer, the change in readily biodegradable COD concentration is higher for separate sewer and, on the other hand, combined sewers are generally affected by higher levels of hydrogen sulphide. The wastewater temperature shows, as it could have been expected, a significant impact on in sewer processes. The model results analysis clearly shows that the most significant in sewer processes take place in the smallest of the three synthetic catchments tested that is also the one showing the highest HRTs. In most cases the dependence of the outputs with the various parameters tested seems linear but it has to be outlined that if sewer length is increased the trend could be very different. In Fig. 1 a variation of the carbon along the sewer is reported.

4 Conclusions

The model results showed that the most significant results of in sewer processes in gravity sewers are hydrogen sulphide production and COD modification in terms of increase or decrease of readily biodegradable substrate. The most significant in sewer processes take place in the smallest of the three synthetic catchments tested that is also the one showing the highest HRTs. The in sewer processes are almost negligible for modest travel time and for sewer length lower than 3 to 5 km; conversely, their impact is stronger if sewer length is around 10/15 km and HRT is of several hours.

At the end it is important to underline that since wastewater composition is highly variable, and, as discussed above the available biodegradable organic matter is often slightly sufficient for biologic nutrients removal, the possible negative influence of in-sewer processes on this process should be evaluated on case by case basis since it cannot be excluded beforehand. For this reason reliable models are needed to foresee such cases and to avert possible problems with an appropriate design of sewer systems or at least to adopt appropriate countermeasures (e.g. change in WWTP lay-out, adoption of chemical P removal, use of additional carbon sources).

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