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Modeling pathogen fate in stormwaters by a particle-pathogen interaction model using population balances

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Abstract

Stormwater is polluted by various substances affecting the quality of receiving water bodies. Pathogens are one of these which have a critical effect on water use in rivers. Increasing the retention time of water in stormwater basins can lead to reduced loads of pathogens released to the rivers. In this paper a model describing the behavior of pathogens in stormwater basins is presented including different fate processes such as decay, adsorption/desorption, settling and solar disinfection. By considering the settling velocity of particles and a layered approach, this model is able to create a light intensity, and particle and pathogen concentration profile along the water depth in the basin. A strong effect of solar disinfection was discerned. The model has been used here to evaluate pathogen removal efficiencies in stormwater basins considering a single class of particles with a certain settling velocity. However, it can include a population of particle classes characterized by a distribution of settling velocities in order to be able to reproduce stormwater quality and treatment in a more realistic way.

Keywords: Gujer matrix, population balance modeling, sedimentation, stormwater management

1 INTRODUCTION

For decades It is known that stormwater can cause severe flooding problems in urban areas and also affects the receiving water's quality as it contains a considerable amount of suspended solids and pollutants associated with them (trace metals, pathogens...)(Pettersson, 2002; Vaze and Chiew, 2004; Characklis *et al.*, 2005). To reduce flooding problems stormwater basins have been built in new urban developments. The present study is part of a larger project in which a new approach is developed to augment theis existing infrastrucutre with an operational strategy that improves the eco-hydraulics of the receiving water body into which it eventually discharges the retained stormwater (Pettersson, 2002; Vaze and Chiew, 2004; Characklis *et al.*, 2005). The idea behind the strategy is to operate a sluice gate at the outlet of stormwater basin on the basis of a set of rules to enhance the removal efficiency of, especially, fine particles by increasing the retention time of stored stormwater. The contribution of the work presented here is the development of a dynamic model that can support evaluating the efficiency of control rules in terms of the expected reduction of the load of pathogens discharged into the river which are critical regarding the use of the water by human.

Escherichia coli in stormwater is found in concentrations between 10^2 and 10^4 CFU (colony forming units)/100ml, 20 to 50% of which are attached to suspended solids (Muschalla *et al.*, 2009). They are present as free bacteria, in aggregates or attached to particles. The degree to which pathogens are attached to particles influences their transport and behaviour. Adsorption of pathogens to particles followed by sedimentation is an important mechanism for removal of pathogens from the bulk liquid that will eventually be discharged. The sedimentation velocity of particles and the distribution of pathogens to these particles determine the pathogens sedimentation efficiency. Jeng et al. (Characklis *et al.*, 2005; Jeng *et al.*, 2005; Krometis *et al.*, 2007) and Oliver et al. (2005) associated more than 90% of attached pathogens to particles smaller than 30 μm in stormwater. Besides, the pathogen-particle adsorption is influenced by the particle surface characteristics. Organic, clay and silt suspended matter tend to attach more pathogens than sand (2007). According to Stoke's law, the smaller and lighter (organic) particles decant slowly and thus slow down the pathogen sedimentation process. Garcia-Armisen and Servais (Guber *et al.*, 2007) observed settling rates of particle-associated *E. coli* in river water between 0 (no suspended matter) and 1,6 $m.d^{-1}$.

Decay of pathogens is a second important removal mechanism. Struck et al. (2009) predicted the pathogen concentration in retention ponds and constructed wetlands for stormwater and applied a first-order decay function that includes natural decay with temperature correction, predation, solar disinfection and a term that includes sorption, filtration and sedimentation. Natural decay is subject to many environmental conditions like conductivity, dissolved oxygen, oxygen reduction potential, pH, salinity, etc. Solar radiation causes notable pathogen decay, especially in shallow waters (2008). The pathogen-particle interaction is also important in the sense that pathogens tend to survive longer when attached to particles (Curtis *et al.*, 1992), for instance by the shielding from solar radiation and protection from predation, thus lowering the disinfection rate of attached bacteria.

2 MATERIALS AND METHODS

2.1 Model description

As mentioned above, an important *E. coli* removal mechanism is through sedimentation of the particles to which they are attached. The model presented in this paper is an extension of the more general stormwater sedimentation model of Vallet et al. (Struck *et al.*, 2008) developed in aforementioned overall project. The Vallet model allows reproducing the particles concentration gradient and the behaviour of pollutants associated to them. To describe the spatial heterogeneity it uses the layer approach adopted in wastewater treatment settler models (2010) around which a mass balance is built for both water and pollutants. In this model a population of particle classes is defined. In which for each class a different sedimentation velocity v_k is defined with an associated suspended solids mass X_k (k=1,NrOfClasses). In order to experimentally determine the fraction of each of the classes the ViCAs protocol (Takacs *et al.*, 1991) was used. It has proven to be an efficient tool to support such modelling. The information collected from ViCAs settling experiments can be used to support a pathogen population balance model. Given the sedimentation velocities and the mass balance for each particle class, the population balance model therefore allows simulating the dynamics of the pathogens along the depth of the stormwater basin.

To each of the described particle classes pathogens can sorb/desorb and their population balance allows calculating the concentration of particle-associated pathogens in each layer. Sorption and desorption of pathogens to particles is described by isotherms of the sorption equilibrium which, for low concentrations, are based on a linear partition coefficient, *K_D*. Sorption and desorption are two oppositely directed processes with the following respective rates: $k\_Sorption \cdot S\_PATH \cdot X$ and $k\_Desorption \cdot X\_PATH$ where *k_Sorption* and *k_Desorption* are respectively the sorption and desorption rate coefficients (Chebbo and Grommaire, 2009). The overall sorption/desorption process rate for each particle class is presented in Table 1 and includes the partition coefficient, *K_D*, that is equal to the ratio of the desorption to the sorption rate coefficients.

Inactivation of *E. coli* in stormwater basins is principally described by three mechanisms: (a) natural decay, (b) predation and (c) solar disinfection. These processes have been implemented for both particulate and free *E. coli* populations. Predation is often incorporated in the natural decay term because of the difficulty to measure this separately (Jacobsen and Arvin, 1996;

Lindblom *et al.*, 2006). In the proposed model the combination of predation and naturel decay is called “base decay”. Base decay of free pathogens and particle-associated pathogens is described by a first-order base mortality plus a term that includes mortality due to salinity. The whole base decay is corrected for temperature (Struck *et al.*, 2008) that is considered constant over depth in a shallow stormwater basin. Solar disinfection depends on light intensity that decreases with increasing depth due to turbidity (light extinction according to Beer’s law), another, albeit indirect, particle-pathogen interaction. In addition, at a certain depth, all free pathogens and a distinct fraction of particle-associated pathogens (F_Light_X_PATH) are assumed to be equally influenced by solar radiation whereas the remaining fraction of the particle-associated pathogens is protected from solar radiation by shielding(Mancini, 1978). A first-order mortality constant for solar disinfection, proportional to light intensity, is applied (Fenner and Komvuschara, 2005). Growth of *E. coli*, while not expected in storm water basins, is also included for generality and use in, for instance, combined sewer system models.

According to Chapra (Chapra, 1997; Struck *et al.*, 2008), the solar radiation intensity, I_0_i, at the top of each layer is calculated and used to calculate the average light intensity, I_i, over each layer:

$$I_0\_i = \left(1 - F_{I,\alpha}\right) \cdot I_{surface} \cdot \exp\left(-\sum_{i=1}^{i-1} K_e\_i \cdot H\_i\right)$$

$$I\_i = \frac{I_0\_i}{K_e\_i \cdot H\_i}\left(1 - \exp\left(K_e\_i \cdot H\_i\right)\right)$$

where $I_{surface}$ is the incoming solar radiation intensity (w.m^{-2}); H_i is the height of layer i (m); the term $\left(1 - F_{I,\alpha}\right)$ accounts for the fraction of the incoming light penetrating the water surface (-). The global extinction coefficient over the i^{th} layer, K_e_i (m^{-1}), increases linearly with the total suspended solid (TSS) concentration (mg.L^{-1}) that added to a constant extinction coefficient due to water, $K_{e,water}$: $K_e\_i = K_{e,X} \cdot TSS\_i + K_{e,water}$. Note that the population balance over the particle classes allows calculating the TSS concentration in each of the layers. Finally to represent the diurnal variation of the light intensity $I_{surface}$ was describe by the following equation: $I_{surface} = Max(\frac{I_{max}}{3} + \frac{2.I_{max}}{3}.\sin(\frac{3\pi}{2} + 2\pi.t); 0)$ where I_{max} is the maximum light intensity during the day period. This equation allows reaching Imax at noon with a sinusoidal pattern for the rest of the day during the simulation time.

Also originating from wastewater treatment modelling, the Gujer matrix approach to present the physico-chemical and biological processes in a system (previously known as Petersen matrix, (Henze *et al.*, 1987)), is adopted here to concisely present decay, (de)sorption and growth. Table 1 represents the Gujer matrix for a system with 2 particle classes (*NrOfClasses*=2), but it can be observed that it is easy to augment the matrix for a larger number of classes. Please note as well that in this matrix no reference is given to the layer in the stormwater basin to which it applies. In fact the mass balance of each layer contains such Gujer matrix to calculate the conversions processes taking place, next to the transport processes (mixing, advection and sedimentation). Again, augmenting the stormwater basin model with more layers is straightforward.

Table 1 : Gujer matrix representation of the population particle-pathogen interaction model

	State variables					
Process	**S_path**	**X_1**	**X_2**	**X_path_1**	**X_path_2**	**Process rate**
Growth Of S_path	+ 1					μ_S_path . S_path
Base decay of S_path	- 1					((b_S_path + K_Salt_path . S_Salt) . θ_T20_path$^{(T - 20)}$) . S_path
Disinfection of S_path	- 1					α_Light_path . I . S_path
Growth of X_path_1				+ 1		μ_X_path_1 . X_path_1
Growth of X_path_2					+ 1	μ_X_path_2 . X_path_2
Base decay of X_path_1				- 1		((b_X_path_1 + K_Salt_path . S_Salt) . θ_T20_path$^{(T - 20)}$) . X_path_1
Base decay of X_path_2					- 1	((b_X_path_2 + K_Salt_path . S_Salt) . θ_T20_path$^{(T - 20)}$) . X_path_2
Disinfection of X_path_1				- F_Light_X_path_1		α_Light_path . I . X_path_1
Disinfection of X_path_2					- F_Light_X_path_2	α_Light_path . I . X_path_2
Sorption of S_path on X_1	- 1			+ 1		k_Sorption_1 . (S_path . X_1 - X_path_1 / K_D_1)
Sorption of S_path on X_2	- 1				+ 1	k_Sorption_2 . (S_path . X_2 - X_path_2 / K_D_2)

μ_S_path : growth rate of soluble pathogens (0 d^{-1})
b_S_path : decay rate of soluble pathogens (0.8 d^{-1})
K_Salt_path : salinity influence factor (0.02 d^{-1} ppt^{-1})
S_Salt : salt concentration (0 ppt)
θ_T20_path : temperature correction (1.013)
T : temperature (10°C)
α_Light_path : proportionality constant for influence of light (0.006 m^2 W^{-1} d^{-1})
I : light intensity (W m^{-2}) (variable with the depth of water)
μ_X_path_1 : growth rate of pathogens adsorbed on X_1 (0 d^{-1})
μ_X_path_2 : growth rate of pathogens adsorbed on X_2 (0 d^{-1})
b_X_path_1 : decay rate of pathogens adsorbed on X_1 (0.4 d^{-1})
b_X_path_2 : decay rate of pathogens adsorbed on X_2 (0.4 d^{-1})
k_Sorption_1 : sorption rate coefficient of soluble pathogens on X_1 (0.58 m^3 g^{-1} d^{-1})
k_Sorption_2 : sorption rate coefficient of soluble pathogens on X_2 (0.58 m^3 g^{-1} d^{-1})
K_D_1 : sorption equilibrium coefficient for pathogens adsorbed on X_1 (0.005 m^3 g^{-1})
K_D_2 : sorption equilibrium coefficient for pathogens adsorbed on X_2 (0.005 m^3 g^{-1})
F_Light_X_path_1 : fraction of pathogens adsorbed on X_1 exposed to light (0.95)
F_Light_X_path_2 : fraction of pathogens adsorbed on X_2 exposed to light (0.95)

2.2 Model implementation and simulations

The model has been implemented in the WEST modelling and simulation software (MOSTforWATER, Kortrijk, Belgium)

3 SIMULATION RESULTS AND DISCUSSION

In order to illustrate the pathogen dynamics induced by the different processes involved in the model, two specific simulations have been run with a single particle class. The initial concentrations have been set to 10^3/100mL for free *E. coli*, 0 for particle-associated *E. coli* and 163 mg/L for the TSS (average concentration observed during sample campaign). The simulations have been conducted for two different settling velocities. The first one has been set at 1.6 m/d according to Garcia-Armisen and Servais (2009) for particle-associated *E. coli* at a particle concentration of 163 mg TSS/L. The second velocity has been set at 0.3 m/d which is the smallest velocity measured by the ViCAs experiments (Vallet *et al.*, 2010). Other parameters have been taken from the literature and are presented in the Table 2. Finally the light intensity has been chosen for a typical summer day in Québec, considering the maximum value as the double of the average referred by Natural Resources Canada (2010). Simulations were run with a water height of 1.5 m and duration of 4 days. This duration has been set in order to see the effect of diurnal variation of the light and not to exceed the maximum residence time define in the overall project (Muschalla *et al.*, 2009).

Table 2 : Parameter's values used for simulations (a: Chapra, 1997 ; b: Struck *et al.,* 2008 ; c: Vergeynst, 2010)

Symbol	Description	value	unit
b_{SPATH}	decay rate of soluble pathogens	0.8^a	j^{-1}
b_{XPATH}	decay rate of pathogens adsorbed on X	0.4^c	j^{-1}
K_{Salt}	salinity influence factor	0.02^a	$j^{-1}.ppt^{-1}$
θ_b^{20}	temperature dependency coefficient	1.013^b	-
μ_{SPATH}	growth rate of free pathogens	0^c	j^{-1}
μ_{XPATH}	growth rate of pathogens adsorbed on X	0^c	j^{-1}
α_{Light}	proportionality constant for influence of light	0.006^b	$m^2.W^{-1}.j^{-1}$
$F_{light\ XPATH}$	fraction of pathogens adsorbed on X exposed to light	0.95^c	-
K_D	partition coefficient for pathogens adsorbed on X	0.005^c	$m^3\ g^{-1}$
$k_{sorption}$	sorption rate coefficient of soluble pathogens on X	0.58^c	$m^3.g^{-1}.j^{-1}$
I_{max}	Maximum light intensity during the day	480	$W.m^{-2}$
$F_{I,\alpha}$	light reflection factor at the surface of water	0.28^c	-
$K_{e,X}$	extinction coefficient due to TSS	0.55^a	$m^{-1}.g.TSS^{-1}$
$K_{e,water}$	extinction coefficient due to water color	0.05^b	m^{-1}
T	temperature	15	°C
S_{salt}	salinity influence factor	$0,1^c$	ppt

Figure 1 presents the results of the simulation with the two settling velocities 1.6 m/d (left) and 0.3 m/d (right). For each simulation light intensity (a,b), free *E. coli* concentration (c,d) and attached *E. coli* (e,f) are presented. The results are shown for the first layer (or surface), layer 5 (middle), layer 9 (bottom) and layer 10 (sediment layer).

The light intensity is following a sinusoidal pattern from the sunrise to the sunset. Light intensity is maximum at the surface. Along the four days of simulation the light intensity in deeper layers increases as the suspended solids settle out. This increase in light intensity is slower in deeper layers for the larger distance to travel. In the first simulation maximal light intensity in all layers is attained after two days when all particles are settled out (Figure 1a) whereas in the second simulation (Figure 1b) light penetration remains negligible due to the slowly settling particles. Notice that the light never reaches layer 10 where sediment accumulates. Because simulations have been run with one particle class, the light intensity is strongly correlated with the particle settling velocity. In a real stormwater there will be a distribution of particle settling velocities then the behaviour of the light intensity will probably reach the deeper layers faster. The hypothetical cases presented here are to emphasize the behaviour of variables.

Instantly, the attached and free bacteria fractions reach sorption equilibrium at 45% of the total *E. coli* being attached to particles. Then, the attached pathogens settle with the particles (Figures 1 e,f). In the first simulation, the attached *E. coli* concentration at the bottom of the basin (Figure 1e, X_PATH(10)) increases during the first day, because of the accumulation of settled particles with attached bacteria, but then decay takes over. The same dynamics can be observed in the second simulation although it happens much slower due to the slower particle settling velocity. The effect of solar disinfection on particle-associated *E. coli* cannot be observed except for the surface layer in the second simulation (Figure 1f, X_PATH(1)). Solar disinfection of *E. coli* attached to slow settling particles plays here a more important role.

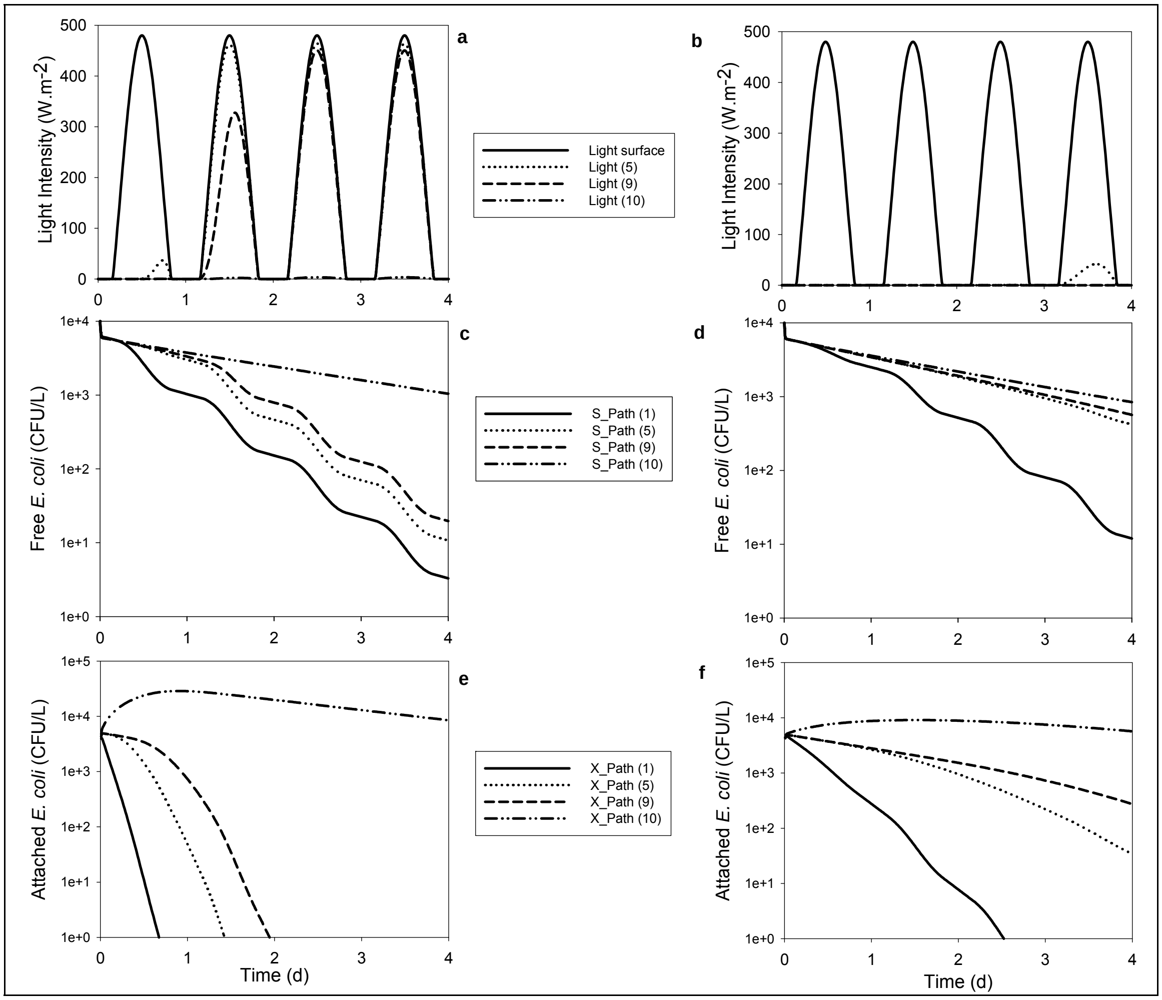

Figure 1 : Simulation results of the particle-pathogen interaction model for the conditions encountered in the Chauveau stormwater basin studied in Quebec City (Muschalla et al., 2009) Left: simulation considering homogenous suspension of particles with a settling velocity of 1.6 m/d and Right: simulation considering homogenous suspension of particles with a settling velocity of 0.3 m/d. Parameters shown are Light (a, b), free (c, d) and attached (e, f) *E. coli* for layer 1, 5, 9 and 10

The removal of free *E. coli* (Figures 1c,d) increases as the particulate concentration decreases, which leads to increasing disinfection. Without radiation, at night, the removal of free pathogens is only caused by base decay. This increase in solar disinfection takes longer to occur in the deeper layers and for slower settling particles because the particles take longer to settle out, leading to lower light intensities. This phenomenon is visible in the wave shape of the concentration profiles. The importance of the solar disinfection in this model can be seen from the decrease of free bacteria in the deeper layers (figure 1c,d S_Path(5) and S_Path (9)). As soon as a higher light intensity reaches subsurface layers (during the second day) the pathogens concentration begin to decrease faster than under simple decay, as occurring in the bottom layer (layer 10).

The present model has shown the ability to reproduce different phenomena occurring in a stormwater basin as decay, ad/desorption to particles and disinfection by solar radiation. The settling model allows reproducing the spatial heterogeneity as function of water depth. It must be stated that no calibration has so far been performed. In that respect it is important that measurements are made of the different pathogen fractions (free and attached) and a study is underway to develop an appropriate protocol. However, the model has been set up with parameters found in the literature and can therefore be used to provide realistic information that supports the development of management strategies for the stormwater basin. For example, on figure 1 it can be seen that the effect of solar disinfection is depending on the retention time of the water in the basin and even with a settling velocity of 1.6 m/d influence of light in the deepest layers requires a minimum residence time of 2 days. This means that the retention of the water in the stormwater basin by introducing valves on the outlet can be a strong improvement in term of water quality. Also results are strongly influenced by particle settling velocities and it should be mentioned that the disinfection results will probably be different for a heterogeneous influent. Actually when applying a distribution of particle classes the TSS dynamics in the stormwater basin will change and with it the solar disinfection effect. Hence, introducing different particle classes that can interact is a further important step in the model development. The goal of further work will be to use the pathogens' removal to further optimize the parameter of the RTC rules to optimally manage the stormwater basin (Muschalla et al., 2009).

4 CONCLUSION

This paper has presented a new model to describe the behavior of pathogens in stormwater basins. Different processes as base decay, solar disinfection, settling, sorption and desorption to suspended solids have been implemented. The dynamics of the concentration of pathogens is well represented, as shown on figure 1, and the importance of particle settling and solar disinfection are illustrated. This model is easy to use and modify and it accounts for a population of particles characterized with a distribution of different settling velocities. The development of this dynamic population balance model contributes to evaluating the efficiency of introducing real time controlled valves on stormwater basins in terms of the reduction of the load of pathogens to the river.

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