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RESEARCH ARTICLE

Improving the performance of stormwater detention basins by real-time control using rainfall forecasts

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Dry detention ponds are commonly implemented to mitigate the impacts of urban runoff on receiving water bodies. They currently rely on static control through a fixed limitation of their maximum outflow rate. Real-Time Control (RTC) allows optimizing their performance by manipulation of an outlet valve. This study developed several enhanced RTC scenarios of a dry detention pond located at the outlet of a small urban catchment near Québec City, Canada. The catchment's runoff quantity and TSS concentration were simulated by a SWMM5 model with an improved wash-off formulation. The control procedures rely on rainfall detection, on measures of the pond's water height, and in some of the RTC scenarios on rainfall forecasts. The implemented RTC strategies allow a substantial improvement of the pond's performance - the TSS removal efficiency increases from 46% (current state) to about 90% - while remaining safe and taking a mosquito-breeding risk constraint into account.

Keywords: dry detention pond; hydraulic stress control; rainfall forecasts; RTC; TSS removal; urban runoff mitigation.

1. Introduction

Urban areas represent a significant alteration to the natural surfaces. From a hydrologic point of view, the added impervious layer considerably increases runoff volumes and velocities (Booth and Jackson 1997, Marsalek 2005, Wenger *et al*. 2009). Downstream receiving water bodies are hence the theatre of more frequent flooding events and increased erosion, in comparison to their previous natural state (Walsh 2000). In conjunction with the carried pollutant loads washed off from the urban surfaces during rainfall events, urbanization can have significant negative impacts on downstream receiving ecosystems (Ellis and Marsalek 1996).

Numerous possibilities limiting these urban runoff drawbacks are available and are referred to as Best Management Practices (BMPs): see for example Field *et al*. (1994), Ellis and Marsalek (1996), Marsalek (2005) and Wenger *et al*. (2009) for a comprehensive review of existing techniques. The main idea behind these solutions is reducing urban stormwater volumes and velocities, in order to mimic the local natural hydrologic behaviour. In urban areas with separately sewered stormwater, a common adopted strategy (Field *et al*. 1994, Booth and Jackson 1997, Marsalek 2005) consists in implementing opened detention facilities at the outlet of the catchment, in order to manage its stormwater runoff before its release to the environment. The aim of such structures is to allow a temporary retention of the water during rainfall events, decreasing runoff velocities and volumes (by infiltration in the pond) as well as providing some water quality improvement from sedimentation. Dry detention ponds are one of these options. They are temporarily filled during rainfall events and remain dry the rest of the time (Stanley 1996, Papa *et al*. 1999). Dry detention ponds have been widely implemented in Canada (Shammaa *et al*. 2002) and the U.S.A (National Research Council 1993).

The management of dry detention ponds currently relies on static control through a fixed pre-designed limitation of their maximum outflow (Middleton and Barrett 2008), for example via a proper choice of their outlet pipe diameter. Because these ponds are designed for large storms, typically one or two hour duration rainfall events with return periods comprised between five and 100 years, one of their main drawbacks is that they generally offer almost no retention for smaller

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rainfall events (Middleton and Barrett 2008), which are by definition much more common. Furthermore, as runoff begins to discharge from the facility at the instant that it reaches the outlet, the first runoff entering a dry detention basin has a very short residence time, whereas it often carries most of the pollutants: the well-known first-flush effect (Shammaa *et al*. 2002, Middleton and Barrett 2008).

A significant water quality improvement by settling is hence achievable by increasing the retention time of the water (Papa *et al*. 1999, Vallet 2011), removing suspended solids with associated pollutants and even allowing UV disinfection during the day (Vergeynst *et al*. 2012). However, reducing the structure's maximum outflow in view of increasing the detention time would result in an increased probability of overflows during large storm events (Guo 2002, Marcoon and Guo 2004). This is not desirable given the main objective of the basin, namely smoothing the flow pattern of the larger storms (Shammaa *et al*. 2002). Flexibility is thus desired.

Real-Time Control (RTC) has a high potential for optimizing the retention time (Marsalek 2005), because it allows adopting operating strategies that are flexible and hence more suitable to adapt to the prevailing conditions than static control. For dry ponds, this would basically imply adapting the outlet opening percentage to maximize water retention time, while being able to open it completely for severe storms.

Muschalla *et al*. (2009a) developed simple Real-Time Control (RTC) strategies for an existing dry detention pond in Québec City, Canada, using a SWMM5 model. This paper follows by exploring several enhanced RTC scenarios in order to refine the environmental objectives and improve fail-safe operations. Thus, the SWMM5 model used here was improved by re-calibrating its hydrologic parameters with a longer observed flows period, by developing an improved formulation of the Total Suspended Solids (TSS) wash-off process, and by using a better representation of the dry pond's shape and infiltration process. The interest of including rainfall forecasts, in the information on which the rules rely, is also assessed since it may decrease the overflow risk through a better anticipation of the level of the security threats.

A description of our case study and available observations is provided in the following section. The methodology relative to the SWMM5 model's implementation is provided in the third section. Next, insight is given on the behaviour and weaknesses of the different RTC strategies identified so far in the literature. These results justify the methodology chosen here. Section 5 describes the performance associated with the developed RTC rules. Concluding remarks and perspectives close the manuscript.

2. Description of the case study and available data

The case study consists in a dry, grassy, on-line stormwater detention pond located at the outlet of a residential catchment in Québec City, Canada. The catchment covers 15.3 ha, comprises 264 single-family homes and 36 apartments, and accommodates 917 inhabitants. Its average slope is about 3.5%, and its average imperviousness is estimated to be about 33%. The catchment is equipped with a separate dual drainage sewer system for stormwater, which utilizes an underground sewer system as the minor conveyance and the streets as the major one. The detention pond's maximum outflow was fixed to 0.35 m^3/s.

The dry detention pond volume was designed by consultants, hired by Québec City, that used the XP-SWMM model, high-spatial resolution data on the catchment's land use and sewer system's geometry, and a 100-year return period design storm of 1-hour duration and "SEA type 2" temporal distribution (see Hogg 1985, Hogg *et al*. 1989). Calculations lead to a 3100-m^3, 1.36-m deep pond; however, the constructed one holds 4000 m^3 and is 1.65 m deep. Overflow is not allowed because it would result in the flooding of downstream roads. The urban catchment has a very fast lag time of about 15 min and a time of concentration of about 4 h. A constant base flow of about 0.0035 m^3/s is conveyed by the sewer system to the pond at all times. It originates from an upstream drained creek whose constant base flow may be provided by an underground captive aquifer. It was shown by water quality analyses that it is not due to cross-connections with the wastewater system (Vallet 2011).

Fifteen sampling campaigns have been conducted on the studied dry detention pond in the 2008, 2009 and 2010 summers by Vallet (2011). Each one lasted a few hours and consisted in the measurement of several variables including for example the catchment's rainfall depth (5-min time step), the pond's water height (time step between 2–30 min), inlet/outlet TSS concentrations (time step between 2–30 min), and flow measurements (1-min time step). TSS concentrations were determined from grab samples that allowed many pollutant concentration analyses. Composite samples were also collected at the pond's inlet for ViCAs experiments (Chebbo and Grommaire 2009) in order to characterize the Particle Settling Velocity Distributions (PSVD), which are highly site-specific and vary from rain event to rain event and even within a single event (Jacopin *et al*. 1999). From the 15 measurement campaigns, 10 were conducted with a fully opened outlet (no control cases) and five with a completely closed outlet added to the detention pond as part of the research project. The spatial heterogeneity in the TSS concentrations within the pond were also studied for the closed-outlet cases, taking supplemental grab samples at different parts of the pond. A comprehensive description of the sampled events' characteristics and collected data can be found in Vallet (2011).

The urban catchment land use and sewer conveyance system's geometrical properties are precisely known, as well as the pond's storage capacity and wet surface as a function of height.

A tipping-bucket rain gauge operated by Québec City and located less than 1 km from the dry retention pond, provided a 5-min rainfall time series from 1999 on for snow-free periods (measure of solid precipitation is locally not available).

3. SWMM5 model implementation

The open-source Storm Water Management Model (SWMM) version 5 (see Environmental Protection Agency - EPA 2008) was implemented to simulate the runoff volume and quality exiting the small urban catchment, including its dry detention pond. SWMM5 is a continuous, semi-distributed, hydrologic (for the surface runoff generation calculation), hydraulic (for the runoff conveyance into open channels/closed conduits) model. It mainly relies on a conceptual/empirical representation of the processes for the hydrologic part and on a physical formulation (conservation) for the hydraulic one. SWMM is widely used (Gaume *et al.* 1998) and is described in detail by Rossman (2008). The runoff quality was here simulated using the SWMM5 build-up/wash-off representation of the phenomena. The dry detention pond was simulated as a non-linear, completely mixed reservoir, described by a storage curve (representing the area as a function of the height). SWMM5 also allows defining control rules to manage the routing of the flow in the sewer conveyance system.

3.1. *Hydrologic calibration*

The SWMM5 model was here implemented using the Horton infiltration method for the sub-catchments, the full dynamic wave routing model (keeping the inertial terms of the equation), time steps of 5 min for the hydrologic part and of 10 s for the hydraulic one. Only parameters of the sub-catchments (hydrologic part) were calibrated to match the observed flows.

Due to some problems associated with the pond's inflow measuring sensor, hydrologic parameters of the urban sub-catchments were calibrated using flow values measured at the outlet of the dry detention pond with the outlet gate completely opened. Because the shape of the pond is precisely known, this procedure should not affect the values found for the sub-catchments' hydrologic parameters.

The "BlueM.opt" optimizer (Muschalla *et al.* 2009b) using the "Hooke and Jeeves" algorithm (Hooke and Jeeves 1961) and the Nash-Sutcliffe criterion of the flow rates (Nash and Sutcliffe 1970) as objective function, were selected for calibration. Since the infiltration in the pond is negligible when the outlet is opened, due to a very short detention time for most events, it was deemed preferable to first calibrate the hydrologic parameters with outflow measurements taken with the outlet fully opened and then to calibrate the pond's infiltration parameters with the campaigns performed with the outlet closed. This can produce infiltration of about 4 L/s. Calibration was based on outflow values taken from 13 to 19 July 2010 (1-min time step), while validation was performed on observations from 27 to 30 September 2009. Initial and final values of the parameters are given in Table 1. This table contains a relatively low value for the depth of the depression storage on impervious surfaces, as well as a high value for the percentage of impervious areas without any depression storage. This could be due to an under-estimation of the areas covered with impervious surfaces in the catchment, which the calibration procedure compensated for by the aforementioned parameters' values. The calibrated parameters led to Nash-Sutcliffe values reaching 0.98 and 0.91 respectively for the calibration and validation periods (Figures 1 and 2). Not considering the long dry periods of the calibration period however led to a Nash value of 0.94. The bias existing in Figure 2 can be partly explained by the constant base flow value of

Table 1. Values of the calibrated SWMM5 hydrologic parameters.

Values	Slope (m/m)	N_imper	N_perv	S_imper (mm)	S_perv (mm)	perczero (%)	Maxr (mm/h)	Minr (mm/h)	Decay (1/h)	Drytime (days)
Initial	0.02	0.013	0.25	0.5	5	0	76.2	12.7	4	7
Calibrated	0.035	0.026	0.47	0.24	0.77	73.8	75.3	1.69	7.22	2.08

Notes: N_imper and N_perv: Manning's coefficients for impervious and pervious surfaces; S_imper and S_perv: depths of depression storages on impervious and pervious areas; perczero: percent of impervious area with no depression storage; Maxr, minr, and decay: maximum and minimum rates and decay constant for the Horton infiltration curve; drytime: time for a fully saturated soil to completely dry.

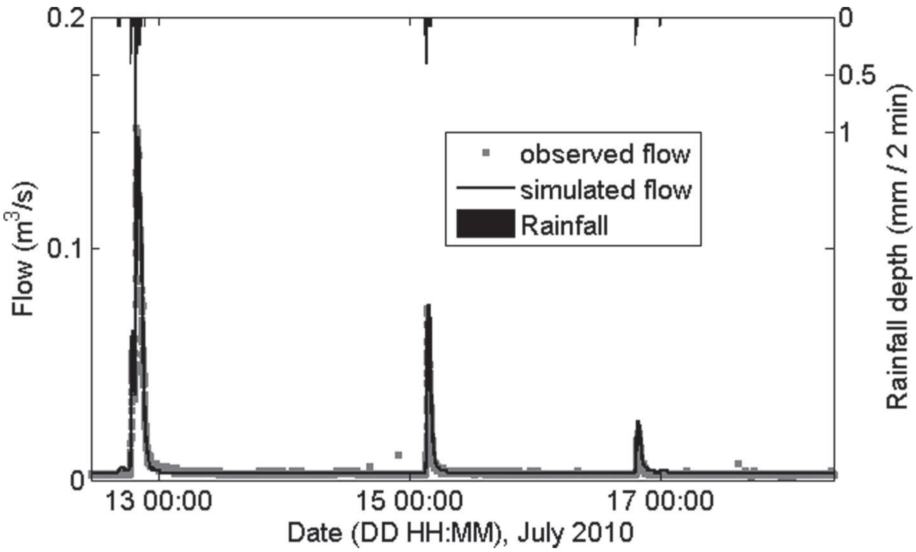

Figure 1. Observed and simulated pond's outflow with fully opened outlet (calibration period).

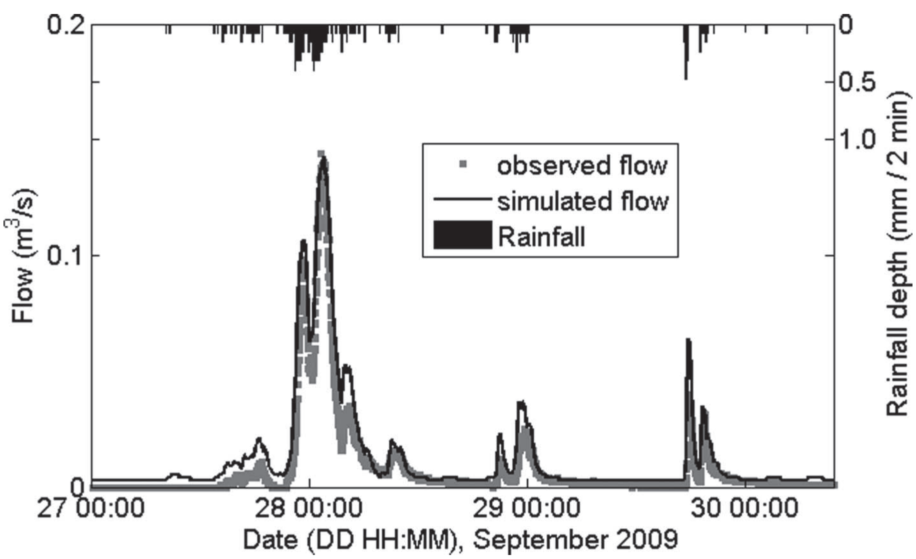

Figure 2. Observed and simulated pond's outflow with fully opened outlet (validation period).

0.0035 m^3/s used in the SWMM5 model, which is supposed to be actually less at the end of a summer period, as in Figure 2.

Next, the pond's simulated water heights were matched to the ones observed when the outlet was closed, by adjusting the pond's Green-Ampt infiltration (Green and Ampt 1911) parameters (Table 1). Figure 3 illustrates the simulated and measured water heights for the validation period. Evaporation was fixed to 2 mm/day, but tests were performed with values ranging from 0–4 mm/day. This resulted in insignificant changes in the simulated pond's water heights even for a closed outlet, which sometimes involved water detention of more than 5 days.

3.2. *Runoff quality calibration*

After the hydrologic calibration of the urban catchment's and pond's parameters, the TSS concentrations measured at the pond's inlet were matched. Runoff quality simulation was limited here to the TSS, in accordance with the objective of this study, namely to gain insights on the potential interest of the proposed RTC strategies, which aim at maximizing the detention time of water in the pond in order to increase the TSS removal efficiency through sedimentation. A simple non-linear and homogeneous reservoir was thus exploited focusing on the settling processes present in

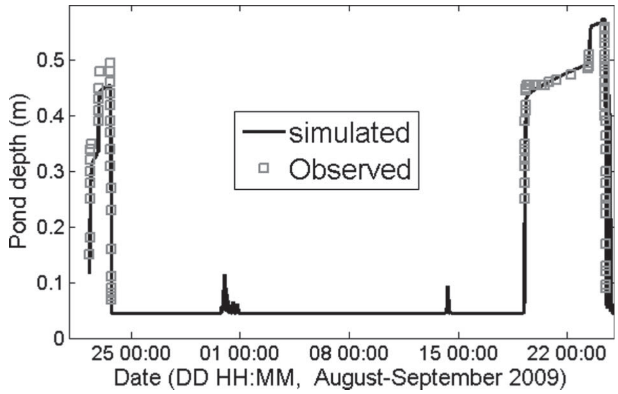

Figure 3. Observed and simulated pond's water heights during campaigns performed with the outlet closed (validation period).

the dry detention pond. It was therefore not possible to simulate other treatments such as pathogen removal by UV disinfection or dissolved pollutant removal by plant uptake. Thus, the spatial heterogeneities existing in the TSS concentrations inside the pond as well as the possible re-suspension of settled particles were not taken into account here but were identified and modelled by Vallet (2011). However, particular attention was given to the simulation of the TSS concentration entering the pond, as described below.

First, identical land use was considered for all subcatchments. The selected build-up function consists in the following power function (Huber and Dickinson 1988, Roesner *et al.* 1988):

$$B = \mathrm{Min}\left(C1, C2\ t^{C3}\right) \tag{1}$$

where B is the pollutant build-up (mass per unit area), $C1$ is the maximum possible build-up (mass per unit area), $C2$ is the build-up rate (mass per unit area per day), t is the antecedent dry period length, and $C3$ is an exponent.

The wash-off function that was initially considered is the following power function (Huber and Dickinson 1988, Roesner *et al.* 1988), which is called the "exponential wash-off" function in the SWMM5 model:

$$W = E1\ q^{E2}\ \mathrm{B} \tag{2}$$

where W is the pollutant wash-off (kg/ha/h), $E1$ is the wash-off coefficient, $E2$ is the wash-off exponent, q is the runoff rate (mm/h), and B is the pollutant remaining build-up (kg/ha). Possible values for the parameters of the different SWMM5 build-up/wash-off functions can be found, for example, in Tsihrintzis and Hamid (1998), Pitt *et al.* (2005), Gironas *et al.* (2009) or Hossain *et al.* (2010).

Equation (2) implies that pollutant wash-off begins as soon and lasts as long as there is some build-up available for this pollutant and there is some runoff occurring. However, it was hypothesized by Yalin (1963) that a particle is washed-off by (and carried with) the runoff only when the flow is high enough to initiate its motion, which was supported by Novotny and Chesters (1981) and observed by Pitt *et al.* (2005). This could not be confirmed in our case study because ViCAs analyses (used to determine the PSVD) were conducted with composite samples. But the phenomenon seems to be partly supported by Figure 4: the first accumulated particle class (with settling velocities between 0 and a given threshold, see Table 3) is activated by the first flow peak and hence the second flow peak (at 17:30 on Figure 4) of similar magnitude as the first one did not generate any TSS pulse. Then, subsequent flow peaks with higher magnitudes than the first two ones are able to move particle classes of higher settling velocities. Hence, a modified version of the SWMM5 wash-off function was implemented to take into account a runoff magnitude threshold below which the associated pollutant class is not washed-off, and above which wash-off occurs. This modified version follows:

$$W = E1\ q^{E2}\ B\ C \tag{3}$$

where

$$C = 1 - (1/(1 + (q/d)^{e})) \tag{4}$$

with d the threshold runoff value associated to the particle class considered, and e a parameter describing the smoothness degree of the C versus q curve. The e value was here set to 100, which results in a C versus q curve with an abrupt change between no wash-off and a complete wash-off around the chosen d threshold runoff rate. The $E2$ parameter value of Equation (3) was fixed to 1 because optimal values for this parameter as found by Hossain *et al.* (2010) or by manual calibrations in our case study were generally close to 1 (between 0.8 and 1.5). This thus allowed a reduction in the number of parameters to be manually calibrated.

The strategy consisted in simulating TSS concentrations using six different particle classes, each one possessing its own set of parameters (manually calibrated) for the build-up and wash-off functions. The first four classes' parameters were calibrated using the event depicted on Figure 4 (using one different particle class to simulate each of the four TSS concentration peaks of the event), and parameters of the last two classes were defined using two other events involving higher maximum runoff values than the

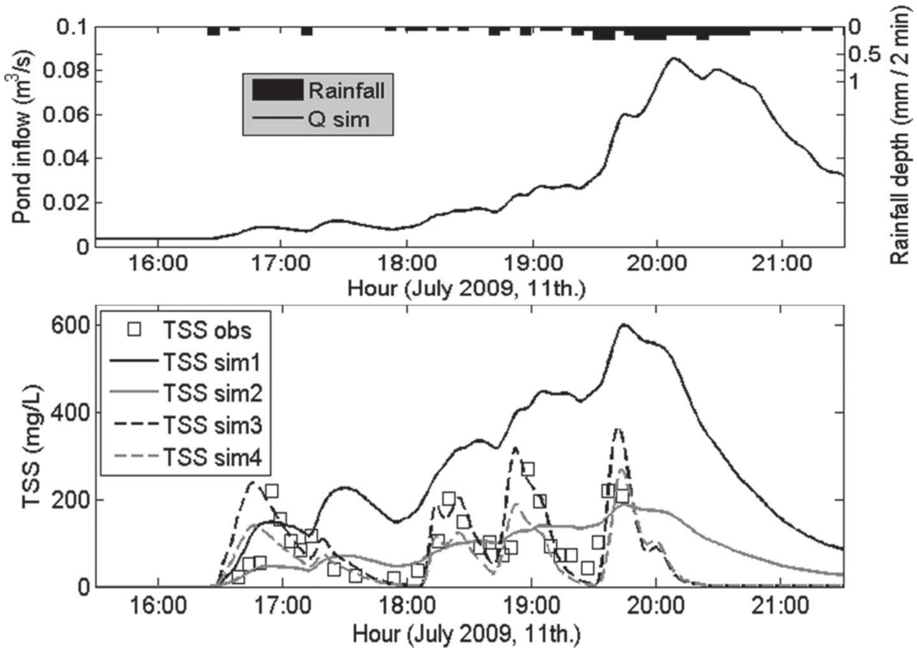

Figure 4. Observed (TSS obs) and simulated (TSS sim) TSS concentrations at the pond's inlet (calibration period). The corresponding pond's inflow (Q sim) is represented on top of the graph. See text for details.

event of Figure 4. Parameters calibrated this way led to the TSS concentration simulation named "TSS sim3" on Figures 4, 5 and 6. The runoff quality parameters found this way for each TSS class were then refined to achieve an overall satisfying TSS concentration simulation for all measured events of 2009 and 2010, leading to the TSS simulation called "TSS sim4" on Figures 4, 5 and 6. "TSS sim4" corresponds to the simulation finally chosen to perform the RTC tests, with values of the associated runoff quality parameters compiled in Table 2. TSS concentrations simulated (TSS sim4) for this urban area's outflow remain in the range of 0 to 1500 mg/L, which is in agreement to TSS concentration magnitudes observed by the NURP (EPA 1983) and Pitt *et al.* (2005) for residential areas. According to simulations performed on six consecutive summer periods (see Section 5), an average TSS load of 380 kg/month (equivalent to 300 kg/ha/year) is washed-off from this 15.3 ha urban catchment during snow-free periods. This order of magnitude is in agreement with those found by Taebi and Droste (2004), and by Charbeneau and Barrett (2008), with TSS load values found by these authors for similar catchments ranging from 400 to 800 kg/ha/year. It is obvious, when looking at Figures 4, 5 and 6, that the modified wash-off formulation led to an improvement of the TSS concentration simulation's performance when comparing it to simulations with the original wash-off formulation of Equation (2), one particle class, and two possible parameter sets originating from manual calibrations on two different periods of the summer of 2009 (Table 2): calibration on June 2009 (period P1) led to the simulation "TSS sim1" of Figures 4 to 6, and calibration on August and September 2009 (period P2) to the "TSS sim2" simulation shown on the same Figures. For unknown reasons, smaller values were obtained for build-up parameters (Table 2) when calibrating on the second part P2 of the summer of 2009. However, because values obtained this way using the first part of 2009 were adapted to observations of 2010, this period P1 as well as observations of 2010 were given more importance when calibrating the parameters of the 6 particle classes using the modified wash-off formulation of Equation (3). This concept involving threshold cut-off values in the particles' wash-off process of the SWMM5 model may represent an interesting future research topic. Using for example the runoff velocity on the local impervious surface of a sub-catchment as a cut-off variable in Equation (4) instead of the average runoff over the entire sub-catchment could lead to more general (and hence transferrable) parameter values.

The sedimentation process in the pond was simulated using the Camp model (Fair *et al.* 1954, EPA 1986) for dynamic settling, but assuming ideal settling conditions (no turbulence in the pond). This chosen dynamic settling model is further described by Muschalla *et al.* (2009a) and is defined in the SWMM5 model by the following equation:

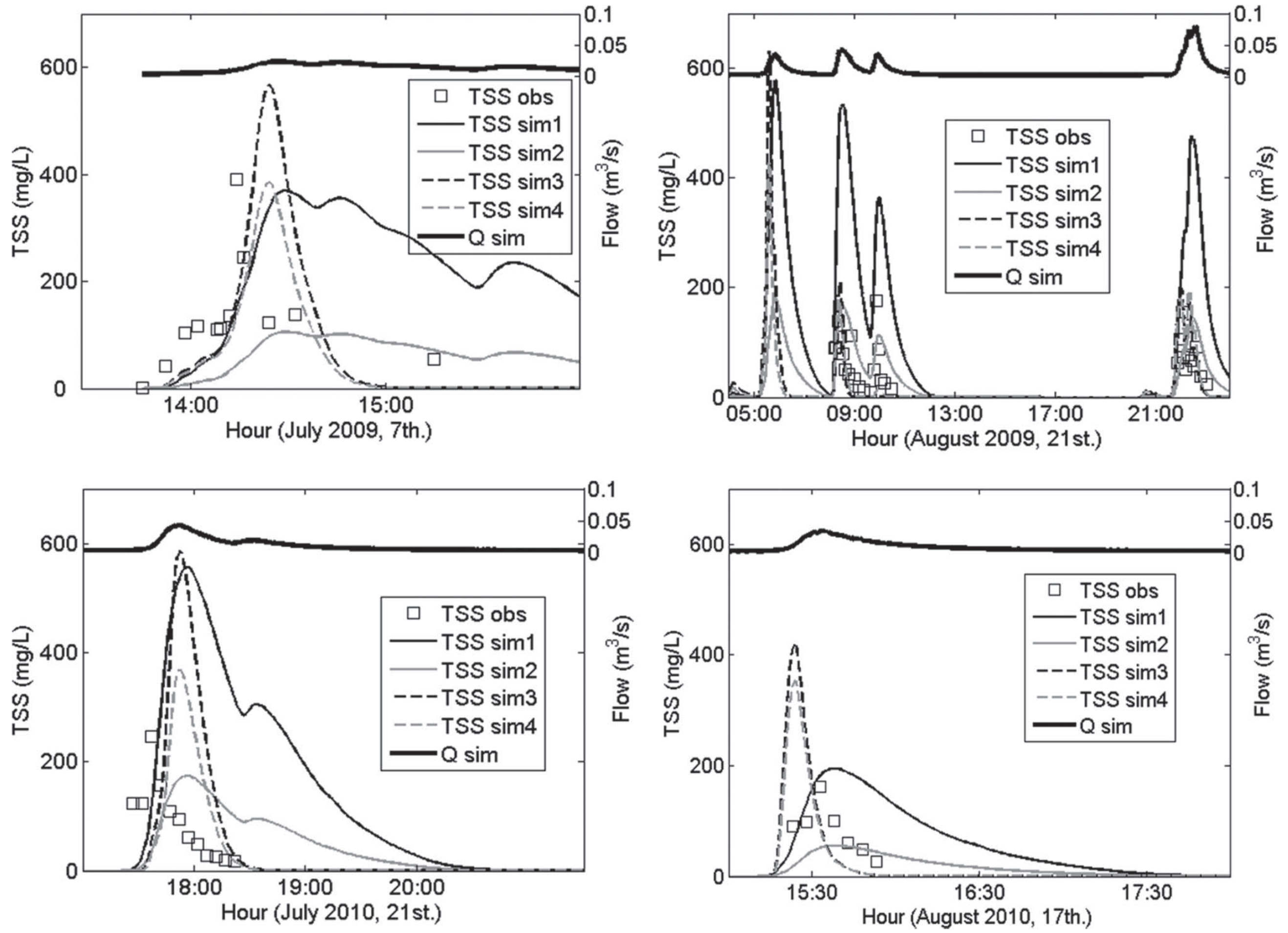

Figure 5. Observed (TSS obs) and simulated (TSS sim) TSS concentrations at the pond's inlet (validation period). The corresponding pond's inflow (Q sim) is represented on top of the graph. On the graph of the top right corner, TSS sim3 and TSS sim4 are merged for the main TSS concentration peak. See text for details.

$$C(t+\Delta t)_{\text{final}} = C(t+\Delta t)_{\text{initial}} \exp(-vs/[(H(t) + H(t+\Delta t))/2]\Delta \text{t}) \quad (5)$$

where C is the TSS concentration for a given class (mg/L), vs is the settling velocity associated to this class (m/s), H is the water height in the pond (m), and $\Delta\ t$ is the hydraulic time-step (10 s in this study).

The sedimentation process in the studied pond was simulated using the same six TSS classes defined in the wash-off representation. A settling velocity was attributed to each class (Table 3), based on the average percentage of the TSS that it represented (calculated from the continuous simulation of the implemented model on the summers of 2009 and 2010) and using the PSVD originating from the Ministry Of Environment and Energy (see MOEE 1994), who derived it from the National Urban Runoff Program (NURP) performed by the United States Environmental Protection Agency (US EPA) – see EPA (1983). Given typical measurement errors and variability, the average PSVD derived from the ViCAs analyses performed in our case study is quite similar to the one reported by MOEE (1994), see Table 3. This confirms the PSVDs used here to attribute settling velocities to each of the six simulated particle classes.

4. Selected RTC methodology

4.1. Existing RTC strategies for dry detention ponds

Although RTC has already been studied extensively for combined sewer systems (see for example Jorgensen *et al*. 1995, Weyand 2002, Colas *et al*. 2004, Butler and Schütze 2005, Wan *et al*. 2006, and Breinholt *et al*. 2008), only a few studies focused on the potential benefit of the implementation of RTC for dry detention ponds in the context of separate sewer systems. More precisely, four studies have been

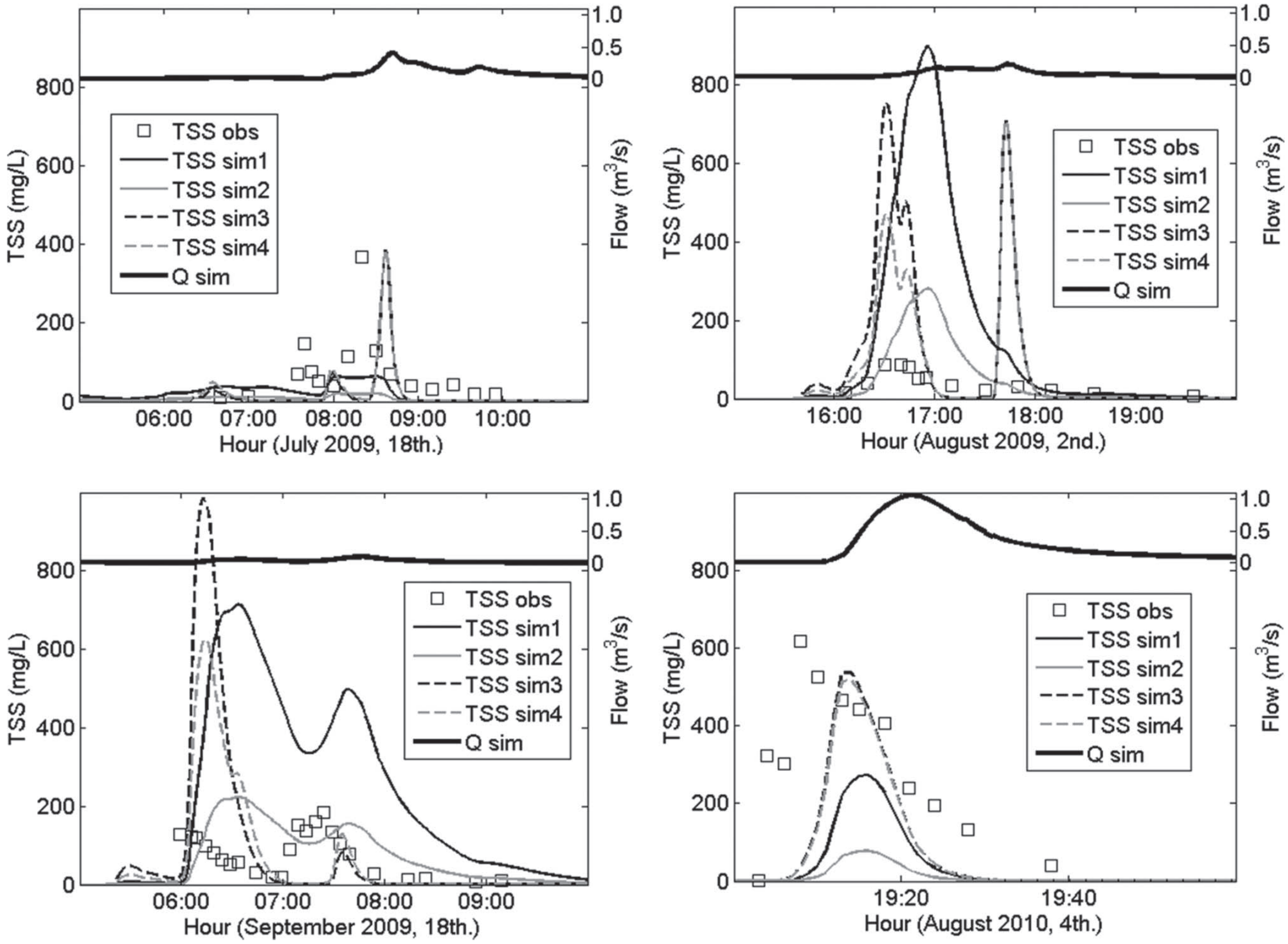

Figure 6. Observed (TSS obs) and simulated (TSS sim) TSS concentrations at the pond's inlet (validation period). The corresponding pond's inflow (Q sim) is represented on top of the graph. See text for details.

Table 2. Calibrated values for parameters of Equations (1) to (4). P1: values obtained from calibration on June 2009; P2: values obtained from calibration on August and September 2009.

		Build-up					Wash-off		
		C1 (kg/ha)		C2 (kg/ha/day)		C3	E1	E2	d (mm/h)
		P1	P2	P1	P2				
Equation (2) used for wash-off, 1 particle class	Class 1	16	5	7	2	0.7	0.5	1.5	n/a
Equation (3) used for wash-off, 6 particle classes	Class 1	0.3	n/a	0.1	n/a	0.3	30	1	0.01
	Class 2	0.5	n/a	0.2	n/a	0.3	30	1	0.3
	Class 3	0.5	n/a	0.2	n/a	0.3	30	1	0.5
	Class 4	0.8	n/a	0.3	n/a	0.3	5	1	0.94
	Class 5	1	n/a	0.4	n/a	0.3	50	1	1.45
	Class 6	13	n/a	5	n/a	0.3	5	1	5

identified so far, which based on the definitions given by Schütze *et al*. (2004) could all be classified as automatic local (or global) reactive control schemes derived from heuristic rule approaches. They all rely on the control of the pond's outflow or outlet opening percentage. The proposed RTC strategies involve various degrees of complexity in their decision trees.

Table 3. Particle Settling Velocity Distributions (PSVD) according to MOEE (1994) and (ViCAs UL:) analyses performed by Vallet (2011), used to attribute settling speeds to the six simulated TSS classes.

Settling velocity (cm/h) of particle class		MOEE's PSVD (cumulative %)	VICAS UL's PSVD (cumulative %)	Simulated particle classes' cumulative mass percentage		Settling velocity attributed (cm/h)
	0			TSS1	5.61	0.0
	0.5			TSS2	14.24	0.5
Mean	0.91	20	23.38	TSS3	22.24	0.9
Maximum	2.80					
Mean	4.7	30	32.42	TSS4	29.86	4.7
Maximum	6.9					
Mean	9.1	40	48.62	TSS5	38.57	9.1
Maximum	27.4					
Mean	45.7	60	69.00			
Maximum	129.6					
Mean	213.5	80	88.08			
Maximum	1096.7					
Mean	1980.0	100	92.62	TSS6	100	746.4
Maximum	2360.3					

Middleton and Barrett (2008) used a very simple RTC strategy of an off-line dry detention pond by defining a fixed residence time for the stormwater to be detained in the pond: as soon as runoff enters the basin in this framework, the outlet valve is closed and is opened 12 hours later until the pond is completely drained. This approach seems interesting for an off-line pond for which the maximum inflow can be fixed and known, but seems too simple for an on-line pond (for which the inflow is highly variable), because in such a case the filling of the pond can be very rapid during large storm events. Consequently, this approach, if applied to an on-line pond, would either result in a detention time that would not be optimal (Vallet 2011), or create a high overflow risk during high rainfall events.

Jacopin *et al.* (2001) defined control rules of a pond's outlet based on the pond's inflow and water height measurements: in their study, when the inflow becomes higher than a threshold, the outlet gate is closed. Then, the pond fills until a predefined water height is reached and maintained, with the outlet gate being completely opened or closed (on/off strategy) to maintain this water height until the inflow becomes less than the chosen threshold, which is an indication to begin the drawdown of the pond. The authors mentioned the idea of choosing between the aforementioned control scheme and another one aiming at maintaining the maximum hydraulic capacity in the pond at all times, depending on the anticipated or measured magnitude of the current rainfall event. This approach is interesting, but the following comments can be made. Aiming to maintain a unique predefined water level can be problematic for two reasons: first, if this level is low, a significant hydraulic capacity will be unused (non-optimal solution). If it is too high, the maximum hydraulic capacity may be used, but it could cause overflow safety issues: if the rainfall event is a strong one, emptying the pond only when this elevated level is reached may be too late to avoid overflow. Second, maintaining a defined water height by using an on/off (or two-point) actuator such as a completely opened or completely closed gate could imply oscillations of the gate position, possibly resulting in a rapid wear and tear of the actuator. Finally, drawing down the pond as soon as the inflow becomes low enough (i.e. as soon as the rain event has passed in systems with a rapid lag time) may not result in a long enough detention time for the settling to occur optimally.

Muschalla *et al.* (2009a) defined simple rules based on the current raining intensity of the system and on the measured detention pond water height. In this study, the outlet gate is closed as soon as it rains, opened to 20% if a given warning water height level is reached and it is still raining, and fully opened until the pond is completely emptied if a second warning level is reached. In addition to these rules, they used and compared two maximum residence time limitations: one based on a maximum detention time's usefulness after which no significant TSS removal can be achieved anymore, and one using a maximum detention time of 3.5 days to avoid mosquito breeding issues. These simple rules allow exploiting a high percentage of the pond's maximum hydraulic capacity while using a pre-warning level to increase safety relative to overflows and can provide a long detention time, but they are not free from problems. The complete gate's opening performed if the second warning level is reached will not be decreased during the drawdown process, which could result in an induced hydraulic shock in the receiving water body and can furthermore cause a high degree of TSS re-suspension.

Finally, McCarthy (1994) also developed a RTC procedure for dry detention ponds. As Jacopin *et al.* (2001), their framework requires the pond's inflow and water height to be measured in order to adjust the pond's outflow either to predefined design release rates or to zero. In their control strategy, the default position of the outlet valve is closed. If a certain first warning level is reached, the outflow is adjusted to a design release rate. If a second warning level is reached and the inflow exceeds the outflow, then the outflow is increased but in a way that it remains lower than the inflow in order not to imply a pond's behaviour that would correspond to an overflow case (even if such an action may favour an overflow). If no warning arises, then the gate remains closed unless a required detention time has been reached. This control strategy is close to the one proposed by Muschalla *et al.* (2009a), except that it does not rely on the rain and water height measurements, but on the measurement of the inflow, outflow, and water height values. This framework also allows a long detention time of water, a varying degree of safety relative to the pond's overflow as in the work of Muschalla *et al.* (2009a), but in addition, it involves a systematic discharge smoothing when the pond's water height comes back below the second warning level. Wear and tear thus does not seem to be a problem in this case, because McCarthy (1994) uses a system originally made to maintain a target outflow value, which is designed to perform high-frequency actuator adjustments. Furthermore, McCarthy (1994) proposed additional control loops, which allow detecting an eventual outlet clogging and resolving it by gate oscillations, automatically adjusting the defined threshold warning level and retention time values during the system's functioning to increase its performance and, finally, a simple coordinated management of several detention ponds by avoiding their simultaneous discharge if their combined effect results in a downstream flow judged too high for the receiving water body. In such a case, the discharge priority is given to the pond with the lowest estimated remaining time before its overflow. Consequently, despite being the oldest study identified so far, it is the most sophisticated one.

Based on the aforementioned findings about urban impacts on receiving water bodies and on the problems identified in the already proposed dry detention ponds RTC strategies, several important objectives seem obvious to take into consideration to develop enhanced RTC strategies for a dry pond's management:

- Maximize the detention time of the water while avoiding any overflow.
- Runoff has to be retained in the pond as soon as it starts entering it, in order to deal with a possible first-flush effect.
- When discharging the pond, a smooth drawdown should be performed if there is no need to hurry, in order to minimize the hydraulic shocks induced to receiving water bodies and to minimize re-suspension.
- Avoid mosquito breeding by limiting the detention time to 3 or 4 days, which further helps recovering the pond's maximum hydraulic capacity when the dry time becomes significant, consisting in increasing the chances of retaining the next rain event with large TSS loads. Furthermore, after a certain detention time, there is almost no more possible improvement of the water quality induced by settling.
- Minimize the number of gate operations in order to prevent the rapid wear and tear of its actuator, by limiting instabilities in the rules' conditions.

The RTC methodology should therefore aim at progressively fulfilling more and more of the aforementioned objectives, by following a simple to more complex rules' philosophy while developing them. Finally, because technical problems are more likely to occur with velocity sensors (as experienced during the measurement campaign) than with water height sensors, it has been chosen not to develop rules relying on flow information, but strictly on measurements of rain intensity and on water heights in the pond.

4.2. Proposed RTC strategies

The threshold values used in the decision-trees presented in this section result from trial-and-error. The rules' structure was chosen first and the involved thresholds were next refined looking at several criteria detailed later in the Results section. The gate's opening percentages were selected to allow a wide variety of possible discharge flows, based on an analysis of the pond's drawdown time when completely filled and as a function of different opening percentages of the gate (Table 4).

In the SWMM5 model, control rules are associated to a corresponding priority order, used to choose between two different control actions to be performed when system states lead to simultaneous but contradictory pre-defined resulting actions. The rules are presented here (Figures 7 and 8) in decreasing order of priority.

The first three real-time control objectives mentioned earlier were first taken into consideration in order to evolve control from a "basic" scenario to the "evolved A" one, as depicted in Figure 7. The "evolved A" scenario allows diminishing the pond's outflow during drawdown, as soon as the water height falls below some warning levels. Conditions of the rules related to the pond's overflow safety thus depict some dead bands in their involved level threshold values to limit their instability. The "evolved A" case asks for more rules than the "basic" one in order to avoid abrupt changes in the gate's opening percentage, which would result in hydraulic shocks induced to the receiving river.

Rules specifying minimum and maximum detention times were considered next, leading to the "evolved B" scenario (Figure 7).

Table 4. Influence of the gate's opening percentage on the studied pond's drawdown time.

Gate's opening percentage	Drawdown time from full state (water height = 1.6m)	Average drawdown speed (m/d)	Maximum outflow (m^3/s)
5	4 days	0.4	0.02
10	3 days	0.53	0.045
20	14h	2.4	0.11
30	9h	4.27	0.2
40	7h	5.5	0.26
70	5h	7.68	0.35
100	5h	7.68	0.35

Considering a minimum detention time (here 30 hours) is justified by Vallet (2011), who noticed that there is an accumulation of first-flush Suspended Solids (SS) near the outlet of the basin during its filling, and that it takes about 20 h for the TSS concentrations in the pond to significantly decrease and become homogeneous. In the rules, the minimum detention time's condition is associated to a pond's water height limitation above which the rule is not taken into account. This is done to prevent closing the outlet gate in the dead bands of the rules looking at the overflow safety. The minimum detention time thus starts to be looked at only 30 min after the end of the last rain event. The lag time of the basin being 15 min, this value of 30 min is selected in order to prevent the outlet gate from being closed when the runoff volume of the last rain event has not yet reached the detention basin.

The maximum (useful) detention times also follow Vallet (2011) who noticed that almost no more quality improvement is achieved beyond 40 hours of retention (settling). Hence, it is preferable in such a case to smoothly empty the pond in order to recover its maximum hydraulic capacity.

The "evolved C" scenario is a modification of the "evolved B". In the "evolved B" strategy, a rainfall event is detected when the rainfall of the last 5 min is greater than 0, resetting the dry time to 0. In order to prevent closing the outlet gate for negligible rainfall

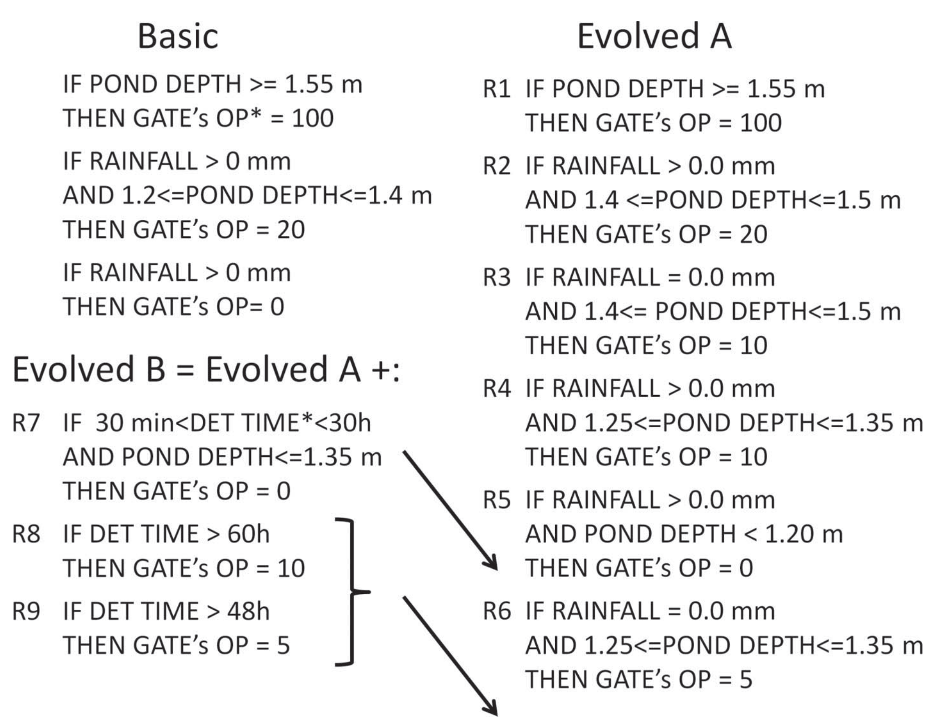

Figure 7. Rules of the first three developed RTC scenarios. OP = opening percentage; DET TIME = detention time.

Evolved D = Evolved C + : (examples)

R10 IF WAT. ACC. TIME* > 3.65 d
THEN GATE's OP = 100

R11 IF WAT. ACC. TIME > 3.56 d
THEN GATE's OP = 30

R12 IF WAT. ACC. TIME > 3.47 d
AND POND DEPTH <= 1.5 m
THEN GATE's OP = 20

Between R1 and R2 (Fig. 7)

Future D = Evolved D + : (examples)

IF P 3h* > 30 mm
AND POND DEPTH >= 0.63 m
THEN GATE's OP = 100

IF P 3h > 20 mm
AND POND DEPTH >= 1.17 m
THEN GATE's OP = 100

IF P 6h > 25 mm
AND POND DEPTH >= 1.40 m
THEN GATE's OP = 100

IF P 12h > 35 mm
AND POND DEPTH >= 1.35 m
THEN GATE's OP = 35

IF P 24h > 35 mm
AND POND DEPTH >= 0.99 m
THEN GATE's OP = 20

Future E = Future D + (examples) :

IF 60h < WAT. ACC. TIME < 63h
AND P 21 to 45h* > 6 mm
AND P 12h < 3 mm
THEN GATE's OP = 25

IF 63h < WAT. ACC. TIME < 66h
AND P 18 to 42h* > 6 mm
AND P 24h < 3 mm
THEN GATE's OP = 15

Figure 8. Rules of the "evolved D" strategy and examples of rules of the RTC scenarios relying in addition on forecast information; WAT. ACC. TIME = time spent with water accumulated in the pond (water accumulation time); P xxh = total rainfall depth forecasted over the next xx hours; Pxx to yyh = total rainfall depth forecasted between the next xx and yy hours.

depths, scenario "evolved C" considers a rainfall event only when the following conditions are fulfilled: if rainfall of the last 5 min is greater than 0.3 mm (more than one rain bucket tip), rainfall of the last 10 min is greater than 0.4 mm, or rainfall of the last 25 min is greater than 0.6 mm. This refinement still allows a sufficiently rapid closing of the outlet to catch the first-flush runoff. It thus contributes to a reduction in the number of operations applied to the gate, because it decreases the frequency of oscillations between the rainy and dry status of the system. Following the same logic, the minimum detention time (assumed equal to the dry period) was reset to 0 in the "evolved C" scenario only when the rainfall depth of the last 25 min was greater than 0.6 mm.

To prevent mosquito breeding, accumulation of water in the pond was limited to 4 days (Santana *et al.* 1994, Knight *et al.* 2003) in the "evolved D" scenario. Hence, rules were added (Figure 8) to the decision tree of the "evolved C" scenario, by adding them directly before or after level safety based rules with the same resulting gate's opening percentages. The water accumulation time in the pond is initialized as soon as the water level exceeds 0.055 m and stops when it falls below 0.045 m.

Figure 9 depicts an example of the pond's water height, outflow and TSS load discharge evolution under the rules of the "evolved D" scenario, compared to its behaviour with the current static control. Operations applied to the gate are depicted on the top row of Figure 9 via the identification of their corresponding rule's condition fulfilling moment.

4.3. *Accounting for rainfall forecasts*

Rainfall forecasts may provide the necessary information for decreasing overflow risk. Forecasts used here were provided by Environment Canada (EC) and cover the 3-month period of the autumn of 2010. They consist of their Global Ensemble Product (GEP) that has a spatial resolution of 100 x 70 km (7000 km^2 at mid-latitudes), 21 members, two updates per day, a 3-h time step, and a maximum prediction horizon of 240 h. The maximum horizon used in this study is 72 h, which allows enough anticipation time for our small urban catchment. The GEP resolution is inappropriate for the small catchment considered here (Gaborit *et al.* in press): 15 ha (0.15 km^2). Therefore, products with a 6-km resolution derived from the original GEP's rainfall forecasts' spatial disaggregation, as performed by Gaborit *et al.* (in press) and exploiting the downscaling technique proposed by Périca and Foufoula-Georgiou (1996), were used here. Further information on the downscaling methodology, the different meteorological products available to the project and their quality can also be found in Gaborit *et al.* (in press).

The extrapolation in time of radar rainfall maps allows rainfall nowcasts up to a 6-hour horizon (see for

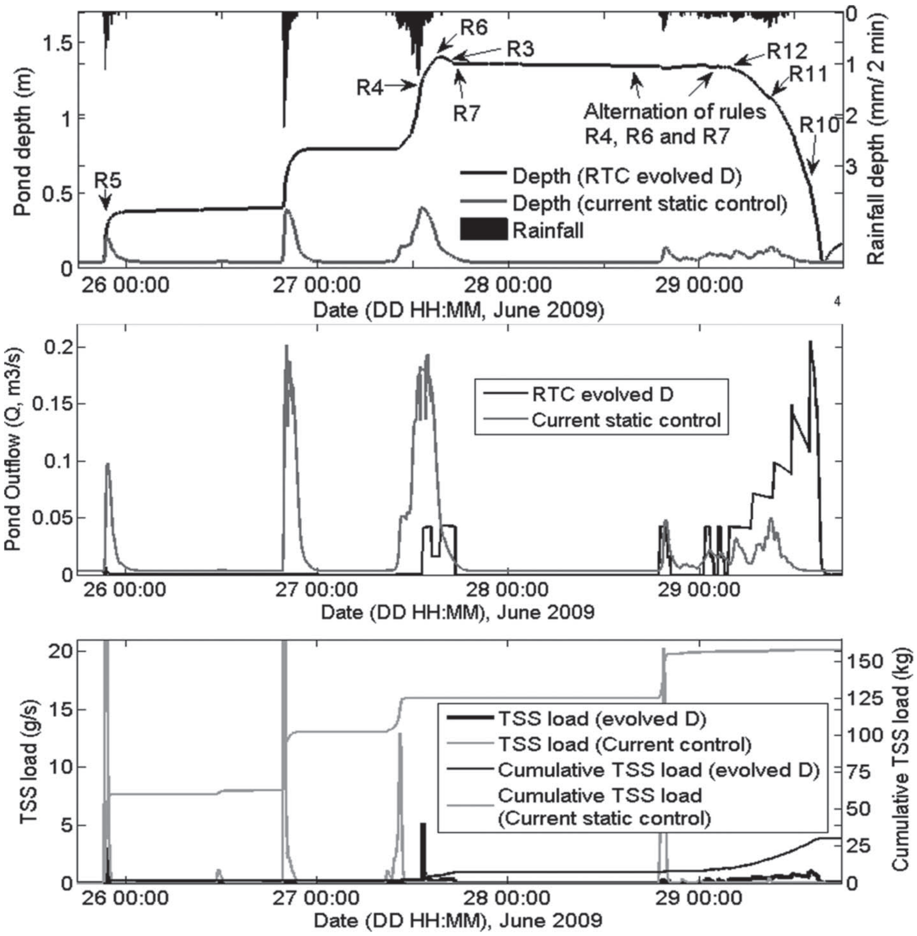

Figure 9. Example of simulated water heights (top row), outflows (middle row) and TSS discharges of the pond, with the current static control (maximum outflow limitation of 0.35 m^3/s) and the "evolved D" RTC strategy. Explanations of the rules are given in Figures 7 and 8.

example Pierce *et al.* 2004). It would be interesting to test such procedure in the context of the study. Nowcasts could also be coupled with the available rainfall forecasts (i.e., originating from meteorological models) if longer lead times are needed (Bowler *et al.* 2006).

The meteorological forecasts are used for anticipating the pond's hydraulic capacity. At any given time, the current pond water level and its remaining volume capacity are measured. The future incoming volume of runoff is calculated based on the rainfall forecasts and associated runoff coefficient. This coefficient has been defined as a function of the duration and volume of rainfall implied in the event based on a few (but varied) observed rainfall events and their associated simulated runoff volumes (taking the constant base flow into account). It was found to vary between 35% and 61%. Then, if a hydraulic capacity excess is forecasted, the gate's opening percentage is calculated on the basis of the volume to be evacuated and the time remaining before the predicted overflow will occur.

The forecasts taken into consideration at each given time consist in the total rainfall depths predicted over the next 3, 6, 12, and 24 h. The rainfall depth forecasted over a given horizon was supposed to fall with a duration equal to half of the horizon length and hence respectively fixed to 1, 3, 6, and 12 h. This way, if a fraction of the incoming runoff volume has been underestimated because of an overestimation of the rain duration, it will be corrected when the rainfall volume will be included in the shorter horizon forecasts.

The time left before a forecasted overflow occurrence coincides with its associated rain event duration. This relies on the principle that if no hydraulic capacity warning has been issued by the 3-hour horizon forecast, we have at least 3 hours to discharge the pond if a security warning is caused by the 6-hour horizon forecast, and so on.

The aforementioned philosophy was translated in the SWMM5 control rules' using the following methodology: if the incoming runoff volume forecasted by a rainfall forecast is greater than the pond's maximum volume minus the current volume and minus the volume of water which can be discharged by a gate's opening of y% in the remaining time, then the gate will be opened at the next higher threshold percentage. However, the rules were written in SWMM5 using forecasted rainfall depths (instead of predicted volumes) and maximum water level heights instead of the current pond volume plus the volume which can be discharged with a given gate's opening. More precisely, this was done using rainfall forecasts with four different possible horizons, eight different rainfall depth thresholds from 0 to more than 40 mm (with increments of 5 mm), and four different possible gate opening percentages of 10, 20, 35, and 100%. The number of rules of the "Future D" scenario created this way is equal to 80, compared to 18 for the "evolved D" scenario.

An example of some rules considering rainfall forecast information is given in Figure 8. Such a methodology (with threshold values) had to be used in lieu of performing precise calculations at each time step to define the volume to be discharged and the rate at which to perform that task. This is due to the fact that the SWMM5 control rules system does not allow performing any additional calculation. Hence, performing precise calculations instead of using threshold values would either imply significant modifications of the SWMM5 source code or developing a dialog between the SWMM5 model and an external program, which is beyond the scope of this paper.

Finally, a "Future E" scenario was implemented, in order to anticipate potential excesses of the limitation of 4 days with water in the pond to limit mosquito-breeding risks. It is indeed possible that a strong rainfall event occurs when the limit of 4 days with water in the pond is approaching. To prevent such situation, the depth of forecasted rainfall over the 24 h period around the moment of expected limit is considered. If it is higher than a defined threshold (fixed to 6 mm), then there is a risk of exceeding the time limitation of 4 days. In this case, the rainfall depth for the next 24 h is estimated. If it is below another threshold (fixed to 3 mm), then there is no significant rainfall forecasted for this period, and hence the pond is emptied over the next 24 h. If there is no "room" for drawdown in the next 24 h, then it is investigated for the next 12 h. Of course, a preventive emptying is performed only if there is already water in the pond when a rainfall event is forecasted around the expected time limitation of 4 days. Examples of such rules are given in Figure 8.

5. Results

The many control scenarios implemented here were tested through continuous simulations performed on six consecutive summers. This simulation's continuity was achieved by putting together the rainfall depths observed during the different summers. Perfect forecasts derived from observed rainfall series were used for the strategies relying on forecast information. Then, to evaluate the performance deterioration in case real, error-containing forecasts are used, these "Future" scenarios were tested with the original and spatially disaggregated GEP for the 3-month period of the autumn of 2010. The criteria calculated to evaluate a scenario's performance consist in the global TSS removal efficiency, the number of hours spent with the outflow higher than three selected thresholds, the number of hours with the pond overflowing, the number of hours spent exceeding the maximum "mosquito-breeding" limit with water present in the pond, and finally the number of operations applied to the gate. Tables 5 and 6 present the objective criteria calculated with simulations performed on the six consecutive summers and the 3 months of 2010, respectively.

Table 5. Performances of the developed RTC scenarios, calculated with continuous simulations on the summers 2005 to 2010.

	Static 1	Static 2	Basic	Evolved A	Evolved B	Evolved C	Evolved D	Future D	Future E
TSS removal (%)	48	52	89	92	93	91	88	87	88
$Q > 0.06 m^3/s$ (h)	251	330	442	49	31	26	202	207	223
$Q > 0.15 m^3/s$ (h)	66	0	26	8	6	5	9	23	22
$Q > 0.20 m^3/s$ (h)	21	0	23	8	6	5	6	7	6
Overflows (h)	0	4	0	0	0	0	0	0	0
Max. time excess (h)	0	0	21581	22883	7754	4078	26	16	0
Number of operations	0	0	15798	954	1371	873	2285	3986	3836

Notes. Static 1: current static control (maximum outflow of 0.35 m^3/s); Static 2: static control with a maximum outflow of 0.10 m^3/s; Q: outflow; Excess of max. time: number of hours spent in excess of the maximum time of 4 days allowed with water accumulated in the pond. Future scenarios were here performed with perfect forecasts.

Table 6. Same as Table 5 but with simulations performed from July to October 2010.

	Evolved D	FD_PO	FD_BM	FD_HM	FD_SM	FE_PO	FE_BM	FE_HM	FE_SM
TSS removal (%)	85	85	84	84	84	85	84	84	84
Q > 0.06m^3/s (h)	23	29	25	24	25	32	29	25	27
Q > 0.15m^3/s (h)	0	1	1	1	1	1	1	1	1
Q > 0.20m^3/s (h)	0	0	0	0	0	0	0	0	0
Overflows (h)	0	0	0	0	0	0	0	0	0
Excess of max. time (h)	0	0	0	0	0	0	0	0	0
number of operations	458	595	256	358	204	289	251	424	206

Notes. FD: Future D scenario; FE: Future E scenario; Forecast products used (using the mean of the ensemble members at the 6-km resolution): BM: Global Ensemble Product (GEP) bilinearily disaggregated; HM and SM: E1 and E2 GEP spatial disaggregation strategies (Gaborit *et. al*, submitted) relying on the method of Périca and Foufoula-Georgiou (1996); PO: perfect forecasts.

The results clearly show the superiority of the more evolved control strategies over the simpler ones. Enhanced RTC rules allow increasing the TSS removal efficiency considerably (from 46% with the current static control to about 90% for the different evolved scenarios), decrease the hydraulic shocks induced to the receiving river while remaining safe from the overflow point of view, and minimize the number of operations applied to the gate. Taking into account the mosquito constraint deteriorates the TSS removal efficiency and increases the number of hours with outflows greater than 60 L/s compared to other control strategies. This is due to the discharge performed when the time limit of 4 days approaches and could probably be further optimized by starting the drawdown of the pond earlier but in a slower manner.

The pond volume is too large to illustrate the potential benefit of rainfall forecasts in the rules to improve its safety regarding overflow. The static control scenario with a maximum outflow of 100 L/s indeed causes only 4 hours of overflow on more than thousand simulated days. This large volume thus prevents us from identifying significant differences in the objective criteria calculated with the different meteorological products (Table 6). Table 5 nevertheless indicates a small increase in the number of hours with outflow larger than 0.15 m^3/s for the "Future" scenarios compared to the "evolved" ones. When looking more precisely at the control actions taken, this increase can be explained by false alarms that resulted in useless preventive discharges of the pond with sometimes quite important opening percentages of the outlet gate. Since these false alarms occurred even with the perfect forecasts, the rules defined in the "Future" scenarios may hence involve a too high safety level, but in this context this is preferable than being not safe enough.

Finally, the "Future E" scenario, which was created to prevent exceeding the time limit of 4 days with water in the pond, successfully achieved its implementation objective as can be seen in Table 5, compared to other scenarios including the mosquito constraint (Evolved D, Future D).

6. Conclusion

This work proposed enhanced RTC scenarios of a dry detention pond. The many different strategies revealed a high potential of improvement of the pond's performance, mainly by increasing its TSS (and associated pollution) removal efficiency from 46% (current state) to about 90% in all implemented RTC strategies. The rules indeed allow simultaneously maximizing the detention time of water, while minimizing the hydraulic shocks induced to the receiving water bodies and preventing overflow. A constraint relative to a maximum time of 4 days with water accumulated in the pond was thus respected to avoid mosquito breeding issues. Taking rainfall forecasts into consideration can further reinforce the safety of the management strategies, even if meteorological forecasts are, of course, not error-free. Such strategies are interesting because they allow a consideration of forecasted information without requiring an on-line implementation of the model (i.e. no simulation has to be performed in real-time in this case). It is envisioned to use a dry pond designed for smaller return period events, which asks for an increase in the frequency of potential overflow situations, to draw more precise conclusions about the pros and cons of the (scenarios considering) different rainfall forecast products. Because such sophisticated scenarios rely on automatic sensors, data acquisition systems and remotely controlled actuators, they may be too costly for implementation in practice. Other scenarios are currently being tested, which rely only on one (manual) adjustment per day of the pond's gate opening, relying only on the pond's depth at the time of the adjustment and on rainfall forecasts.

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