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RESEARCH ARTICLE

Exploring forecast-based management strategies for stormwater detention ponds

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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. This study investigated the performance of several enhanced management strategies for a dry detention pond located at the outlet of a small urban catchment near Québec City, Canada. Among the enhanced scenarios studied are some previously developed real-time control (RTC) strategies, and new operating rules relying on a daily manual adjustment of the outlet gate. Both types of control make use of rainfall forecasts originating from the initial or downscaled Canadian global ensemble prediction system. Different ways of using the forecasts' ensemble spread were considered to take action. The pond performances were investigated considering three different volumetric capacities (including the existing volume). The RTC scenarios are very promising. The value of taking rainfall forecasts into account to prevent pond overflowing is demonstrated. Strategies involving only manual adjustments on a daily basis do not seem helpful.

Keywords: dry detention pond; hydraulic stress control; TSS removal; real-time control; manual control

1. Introduction

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

Numerous possibilities for limiting urban runoff impacts 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. Dry detention ponds is one of them. They are installed at the outlet of a catchment and allow a temporary retention of the water during rainfall events, decreasing runoff volumes (by infiltration in the pond) and velocities as well as providing some water quality improvement thanks to sedimentation. They are temporarily filled during rainfall events and remain dry otherwise (Papa et al., 1999; Stanley, 1996). 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 & Barrett, 2008), for example via a suitable choice of their outlet pipe diameter. Because these ponds are designed for large storms, typically 1- or 2-hour duration rainfall events with return periods of 5 to 100 years, one of their main drawbacks is that they generally offer almost no retention for smaller, more frequent, rainfall events (Middleton & Barrett, 2008). Furthermore, as runoff begins to discharge from the facility at the instant that it reaches the outlet, the first runoff has a very short residence time within the dry detention basin, even though it often carries most of the pollutants (Middleton & Barrett, 2008; Shammaa et al., 2002; Vallet et al., 2011). Note that these aforementioned drawbacks apply to ponds with the conventional design where there is only one main outlet located at their bottom. These drawbacks may be significantly reduced for more sophisticated pond designs, such as those involving the multi-level outlet concept (see Shammaa et al., 2002).

Settling has the potential of improving water quality by removing suspended solids with associated pollutants (Papa et al., 1999; Vallet, 2011). To maximize settling (or sedimentation), the retention time of water inside the pond has to be maximized. This could thus, for instance, allow UV disinfection during daylight (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 following

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large storm events (Guo, 2002; Marcoon & 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).

Real-Time Control (RTC) has the potential to maximize detention time (Marsalek, 2005) while preserving the hydraulic mitigation capacity, because it allows adopting operating strategies that are flexible and hence appropriate to the conditions that prevail over the catchment and inside the pond at a given instant. For dry ponds, this basically implies adapting the outlet opening percentage to optimize water retention time, while still being able to open it completely for severe storms.

In a previous work, Gaborit et al. (2013a) developed RTC strategies (using numerical modelling) for a dry pond located at the outlet of a small urban catchment. The strategies were promising, but due to the large capacity of the pond (able to handle more than a 100-year return period event), the control rules relying on rainfall forecasts provided no performance improvement. The forecasts' main interest consists in reducing the overflow risk (Section 2.1), while no overflow ever occurred over the simulation period with the pond's current capacity.

In order to gain insights about the pro and cons of using rainfall forecasts to manage a dry detention pond, two other (smaller) volumetric capacities for this pond are considered in this study, in addition to the original capacity. This work can thus be seen as a way to minimize a pond volume when operated under enhanced management strategies. Finally, as the implementation of RTC can be costly in practice, another management strategy is explored here in addition to the RTC strategies. It consists in a daily manual adjustment of the pond's outlet gate, based on the rainfall depths forecasted for the next 24 hours. All scenarios considered during this work were studied using numerical modelling with the SWMM5 model.

A description of the case study is given first. Next, the pond's enhanced management strategies are described in Section 3. Section 4 presents the two other capacities considered for the dry pond, while Section 5 describes the evaluation protocol followed to assess the performance of the management scenarios, and Section 6 presents the results. Concluding remarks close the manuscript in Section 7.

2. Case study and implemented model

2.1 *Case study*

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 (see Figure 1). Its average slope is about 3.5%, and its average imperviousness is estimated to be about 33%. It is equipped with a separate drainage sewer system for stormwater.

The detention pond maximum outflow was fixed at 0.35 m^3/s because of limitations imposed by the downstream sewer system. The outflow is restricted by the outlet pipe diameter and the pond's outlet is located at its bottom, in its downstream area. The pond volume was designed by consultants using the XP-SWMM model, high-spatial resolution data of the catchment's land use and the 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 led 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 of the pond is not allowed because it would result in the flooding of downstream roads. The urban catchment has a lag time of about 15 minutes and a concentration time of about 1 h. Some infiltration occurs inside the pond.

2.2 *Model*

Gaborit et al. (2013a) performed a comprehensive description of the data available and the methodology followed to implement the Storm Water Management Model (SWMM) version 5 (see Environmental Protection Agency - EPA 2008) over this small urban catchment. SWMM is widely used (Gaume et al., 1998) and is described in detail by Rossman (2008). SWMM5 allows defining control rules to manage the routing of the flow in a system. The model is able to simulate stormwater runoff and its associated Total Suspended Solids (TSS) concentrations over the urban catchment and inside the pond. The overall performance of the model was very satisfying for the hydrologic-hydraulic simulation part, and remained realistic for the TSS concentrations when compared to their observed dynamics.

However, it has to be mentioned that since a settling model is used in SWMM5, that assumes ideal conditions (i.e. no turbulence, see Muschalla et al., 2009) and because we do not represent the re-suspension effect occurring at the pond's outlet during its emptying (see Vallet, 2011), the simulated TSS removal efficiency is overestimated in a way which is hard to quantify. However, it is known that the re-suspension effect only leads to low TSS loads (Vallet, 2011) because it occurs in conjunction with low flows at the end of the emptying process.

The evaluation of the management strategies presented in this paper was always performed using numerical modelling with the implemented SWMM5 model.

Figure 1. Map of the urban catchment discharging into the dry pond studied here (tank at the bottom of the image), and SWMM5 (see Section 2.2) schematic representation of the catchment's drainage network. The images in the top right and bottom right corners respectively show the inlet (outlet of the urban area) and outlet (dug between the posts) of the pond during a rain event.

3. Enhanced management strategies

This section introduces the RTC scenarios and the manual control schemes evaluated during this work. A brief introduction to RTC is given first. The enhanced management strategies are explained next.

3.1 Overview of RTC

Schütze et al. (2004) presented an exhaustive review of RTC for urban water systems. They proposed the following definition: "An urban water system is controlled in real time if process variables are monitored in the system and continuously used to operate actuators during the process".

There are several types of RTC schemes. For example, a RTC scenario can be classified as automatic or manual if the controlled system's actuators are respectively operated automatically or manually. A scenario can thus be reactive or predictive, depending on the potential use of predictive information to perform the actions. This information can for example consist in forecasted rainfall depths or in predictions of the future system states, using simulations of the model in real-time. In the latter case, the scenario is, in addition to its other characteristics, defined as an "on-line" scheme. If no simulations are performed in real-time because all rules were pre-established, the scheme is classified as "off-line".

So far, in literature, only automatic reactive off-line RTC schemes were proposed for managing stormwater detention ponds (see Gaborit et al., 2013a for a review). In this study, we also use off-line strategies, but some are reactive and others, predictive. Here, there is but one actuator to operate: the pond outlet gate, in order to control its Opening Percentage (OP). The observed variables at our disposal consist in the catchment precipitation and pond water height. Turbidity (TSS) is not considered as it would lead to too high costs. The "eco-hydraulic" objectives of the control schemes are mainly to maximize the detention time of water inside the pond in order to improve water quality thanks to settling occurring inside the pond, and to limit the hydraulic shocks imposed on the receiving water body by performing smooth discharges of the pond. The major constraint, in this case, is that overflows of the pond are prohibited. An additional constraint taken into account in some of the RTC schemes consists of a maximum detention time of four days, in order to limit mosquito-breeding risks.

3.2 Enhanced management strategies

3.2.1 RTC scenarios

An overview of the RTC scenarios used in this study is presented here. All of them were developed and are explained in more detail in the previous study of Gaborit et al. (2013a). The same denomination is kept here for coherence. The general idea is to completely close the outlet when rain is detected over the catchment, in order to catch the first flushed particles. Then, as the pond water height increases and comes closer to pre-defined warning levels, the outlet gate OP is progressively increased to avoid overflow. If the pond level falls back below a given warning level, then the gate OP is reduced to maximize the water detention time in the pond. Furthermore, a minimum detention time (below which the outlet remains completely closed if no overflow risk is detected) as well as a maximum useful one are considered in the RTC schemes.

The aforementioned concepts form the "Evolved C" RTC strategy. It results from the improvement of more basic (and less effective) scenarios not explained here. The evolved D strategy is similar to the Evolved C, except for the addition of a maximum water detention time of four days, as explained above. As the water detention time comes closer to this limit, the outlet gate's OP is progressively increased to empty the pond. These "Evolved" strategies consist of automatic off-line reactive schemes.

Two other scenarios were developed, which, in addition to the rules of the Evolved D scenario, consider the information contained in rainfall forecasts to increase the pond safety regarding its overflow risk. These strategies are referred to as the "Future" scenarios, because some of their rules rely on forecasted information. They hence are automatic predictive off-line schemes. In the "Future D" strategy, forecasts are used solely to increase the safety regarding the pond overflow risk: if a pond capacity exceedance is envisioned, then a preventive emptying of the pond is performed. In the Future E strategy, in addition to the rules of Future D, the potential exceedance of the time limitation of four days with water inside the pond is evaluated. If a strong rainfall event is predicted by meteorological forecasts around the moment where the temporal limit will be reached, then a potential exceedance of this limit may occur. In this case, the emptying of the pond is performed before the incoming rainfall event. The characteristics of the four aforementioned RTC strategies are summarized in Table 3.

3.2.2 *Manual strategies*

The RTC scenarios may however be costly to implement, because they would imply automatic sensors, data acquisition systems, and a remotely adjustable outlet gate. Whereas an increasing number of combined sewer systems are already managed in real-time because they represent serious threats to the environment in case of overflows (Weyand, 2002), stormwater runoff, in the context of separate sewer systems, has not yet attracted that much attention. Moreover, it should be considered that a malfunction of the RTC system could occur, calling for a fall back to a more basic management strategy.

Given these considerations, two simple manual control strategies were envisioned for the dry pond under study. They consist in a daily manual adjustment of the outlet gate, based on the pond water height at the time of the adjustment, and the next 24-hour rainfall forecasts. According to the definition given earlier for RTC, these manual strategies cannot be classified as RTC schemes, because, they do not involve the continuous monitoring of any variable.

These manual scenarios could however be seen as manual predictive off-line management strategies.

In both strategies, the runoff volume is forecasted for a 24-hour period spanning from 12:00 to 12:00 GMT, using forecasted rainfall depths and runoff coefficients, as described in Gaborit et al. (2013a). The manual adjustment of the actuator was chosen to occur at 11:50 GMT, so just before the 24-hour forecast period available at the time of the adjustment.

Runoff volumes were forecasted for each 3-hour interval over a 24-hour period. Then, the maximum value among the 3-hour interval volumes was stored for later use, as well as the maximum values over the 6- and 12-hour intervals, and the total estimated runoff volume over the complete 24-hour period. Stormwater produced by rainfall depths accumulated over 3, 6, 12, and 24 hours was supposed to enter the pond in 2, 3, 6, and 12 hours respectively. This is to increase safety, because it is possible that a rainfall depth accumulated over a given time interval is actually brought by an event with a duration shorter than this interval. The estimated time needed for a runoff volume to enter the pond was also the timing aim when choosing an outlet gate OP to discharge this volume.

This way and in the first manual predictive strategy (named Manual 1), the outlet gate OP is chosen in order to allow the total runoff volume forecasted over the next 24-hour period to be evacuated from the pond in 12 hours. And if an excess of the pond capacity is detected with the maximum runoff volumes produced over 3, 6, or 12 hours, then the outlet gate OP is chosen in order to allow the surplus volume evacuation in a time respectively equal to 2, 3, or 6 hours.

The second manual predictive strategy is similar to the first one, except that it only focuses on evacuating the potential surplus volumes (the same way as before), including the potential surplus induced by the total 24-hour estimated runoff volume.

The surplus volumes were only calculated assuming an empty initial pond (at the time of the adjustment). In the Manual 1 strategy, this is theoretically the case as the scheme is made to evacuate all of the forecasted runoff volume, even if it does not exceed the pond maximum capacity. However, as the Manual 2 scheme only aims at evacuating the potential surplus volumes, it is highly possible that the pond is not empty at the beginning of a 24-hour period. Hence the Manual 2 control scheme was accompanied by the pre-emptying of the pond, completely opening the outlet gate at 09:05 GMT, and choosing the new gate OP according to the aforementioned strategy at 11:50 GMT. Furthermore, in both manual strategies, the outlet gate was chosen never to be closed completely, first for safety considerations, but also because the base flow of 0.0035 m^3/s was not taken into account in the runoff calculations. The minimum outlet gate OP was fixed to 5%, based on trial and error after several tests.

3.2.3 Opening percentages of the outlet gate

Whether with the RTC or manual schemes, in order to choose the gate OPs based on their corresponding generated drawdown speed, simulations were performed to estimate the pond average emptying rates (in m^3/h), as shown in Table 1.

However, since the pond outflow depends on its water elevation, because of the water head, the emptying rate is actually lower for a pond which is less filled. Therefore, to associate a drawdown rate to a given gate OP (and for a given pond capacity), we supposed that the pond was filled with a water elevation equal to half of its maximum water height (Table 1) to calculate an average drawdown time. The average drawdown times could yet have been refined for each of the water depth threshold values used in the rules.

Values in the right panel (used in the rules) originate from the fitting of a linear curve to the three points of the left panel (originating from simulations).

3.3 Rainfall forecasts

Forecasts were provided by Environment Canada (EC) and cover the 3-month period of the autumn of 2010. They consist of the EC's Global Ensemble Product (GEP) that has a spatial resolution of 100 × 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 24 h for the manual strategies (as they imply a daily adjustment of the actuator) and 72 h for the RTC strategies, which allows enough anticipation time for our small urban catchment. The GEP resolution is inappropriate (Gaborit et al., 2013b) for the small catchment considered here: 15 ha (0.15 km^2). Therefore, products with a 6-km resolution were derived by Gaborit et al. (2013b) from the original GEP's rainfall forecasts' spatial disaggregation. They exploit the down-scaling technique proposed by Périca and Foufoula-Georgiou (1996). 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. (2013b). Finally, runs from a Limited Area Model (LAM) were also used. They consist of deterministic rainfall forecasts with a resolution of 2.5 km, a maximum horizon of 24 hours, one update per day (at 12:00 GMT), and a time step of one hour. It originates from the dynamical downscaling of the GEP's control run. This product is also issued by EC.

For comparison with the ensemble forecasts taken from the GEP or its downscaling, the LAM deterministic rainfall forecasts were cumulated on the same 3-h intervals as the GEP ones. The rainfall depths used in the predictive strategies were taken from the product's pixel which was closest to the small urban catchment considered here. In the rules, we used the mean of the rainfall depths forecasted by the 21 ensemble members (or different percentiles - see Results), or the unique LAM forecasted value. Table 2 summarizes the different meteorological products on which the predictive rules of the enhanced management strategies are based.

3.4 Summary of the evaluated strategies

Table 3 summarizes the different enhanced management strategies used in this study. For a comparison of the usefulness of the GEP's rainfall forecasts with that of the LAM, the Future D2 scenario was implemented. It consists in the Future D scenario, but with predictive rules considering only a maximum forecast lead-time of

Table 1. Average pond drawdown rate as a function of the initial water height and gate OP.

Opening %	Average drawdown rate (m^3/h)			Interpolated	Extrapolated	
Water height (m)	1.6	0.75	0.5	0.8	0.375	0.25
5	40.5	30.5	24.6	29.8	24.0	22.2
10	108.0	83.3	74.0	86.9	64.4	52.4
20	278.0	208.0	168.6	213.2	142.1	104.1
30	432.0	312.0	236.0	317.8	191.1	123.3
40	556.0	417.0	295.0	411.1	245.0	156.2
70	748.0	500.0	393.3	530.8	297.6	172.8
100	778.0	568.0	393.3	562.7	317.3	185.9

Table 2. Synthesis of the different rainfall forecasts used in this study.

Approach	Definition
B	Bilinear interpolation of the GEP
H	Downscaling of the GEP using a first version of a full-field generator[a]
S	Downscaling of the GEP using a second version of the same full-field generator[a]
LAM	Deterministic product issued from the dynamical downscaling of the GEP's control run

Note:
[a] See Perica and Foufoula-Georgiou (1996) for the downscaling technique, and Gaborit et al. (2013b) for the application of this full-field generator to EC's GEP.

6 hours, because LAM forecasts can only be used with such a maximum lead-time in the "Future" RTC strategies. This limitation, despite the 24-hour maximum horizon of the product, comes from the time at which its forecasts are available to the public. Finally, we evaluated another static control scenario than the actual one. Currently, the pond maximum outflow is fixed to 0.35 m^3/s (Static 1 scenario). In the Static 2 strategy, this maximum outflow was set to a lower value of 0.10 m^3/s. This new value was selected according to Table 4, which shows that with the current pond capacity and maximum outflow of 350 L/s, an outflow of 100 L/s is only reached a few tens of hours over a period of more than a thousand days. It hence seems to consist of a relatively safe maximum outflow value regarding the pond overflow risk, while fulfilling the objective of the second static scenario by reducing the original maximum outflow more than three times.

4. Volumetric capacities for the dry pond

As mentioned in the introduction, the current pond capacity is 4000 m^3, which can accommodate a one-hour duration rainfall event more severe than a 100-year return period event. Consequently, the potential benefit of the strategies exploiting rainfall forecasts remained hidden during the study of Gaborit et al. (2013a), because no pond overflow ever occurred. Therefore, two more (virtual) pond capacities were tested during the simulations. These two additional capacities were determined as follows. A one-hour duration virtual rainfall event was created based on the "SEA type 2" temporal distribution (Hogg et al., 1989), and a total depth corresponding to a return period of 2 and 5 years. Keeping the current pond maximum outflow value fixed to 0.35 m^3/s and the same curve for the wet surface as a function of height, the two volumetric capacities were chosen in order to be just able to properly deal with these virtual events. For the rainfall events with a 2- and 5-year return period, the capacities chosen after the simulations correspond to a volume of 590 m^3 and 1250 m^3, respectively, or to maximum water heights of 0.5 and 0.75 m for the pond.

For a capacity of 1250 m^3, we implemented the Evolved C, Evolved D, Future D, Future D-2, Future E, the current static, and Manual 1 and 2 scenarios. The pond with a capacity of 590 m^3 was used in conjunction with the current static, Evolved C, Evolved D, Future D-2, and Manual 1 and 2 scenarios. Such a small capacity implies a very "fast-responding" behaviour. The Future E scenario was hence not needed in such a case, because the time limitation of 4 days for water accumulated in the pond was never exceeded with the other scenarios.

5. Evaluation

The evaluation was conducted using two different simulation periods of different lengths and using several performance criteria as explained hereafter.

The many control scenarios implemented here were tested through continuous simulations performed on six consecutive summers (from 2005 to 2010, a period totalling 1030 days). This simulation was achieved by putting together the rainfall depths observed during the different summers. Over this long period, "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 (i.e. error-containing) forecasts are used, the

Table 3. Overview of the enhanced management strategies used in this study. See text of section 3.2 for further details about the different scenarios. H: pond water height; P: observed precipitation; F: rainfall forecasts.

Characteristics / Scenario	Maximum outflow (L/s)	Type	Mosquito breeding limitation	Variables used
Static 1	350	Static	No	N/A
Static 2	100	Static	No	N/A
Manual 1	350	Manual, predictive	No	H, F
Manual 2	350	Manual, predictive	No	H, F
Evolved C	350	Automatic, reactive	No	H, P
Evolved D	350	Automatic, reactive	Yes	H, P
Future D	350	Automatic, predictive	Yes	H, P, F
Future D2	350	Automatic, predictive	Yes	H, P, F
Future E	350	Automatic, predictive	Yes	H, P, F

Table 4. Performance of the developed RTC scenarios calculated with continuous simulations for the summers 2005 to 2010 and a pond capacity of 4000 m^3. See Table 3 for the scenarios. Q: outflow; Max. time excess: number of hours spent in excess of the maximum time of 4 days allowed with water accumulated in the pond. Predictive scenarios were obtained with "perfect" forecasts (see text).

Scenario / Criterion	Static 1	Static 2	Manual 1	Manual 2	Evolved C	Evolved D	Future D	Future E
TSS removal (%)	46.0	52.5	58.4	65.4	91.1	87.8	86.9	87.8
Q > 0.06 m^3/s (h)	251.4	329.6	172.2	172.8	31.3	216.5	207.0	222.5
Q > 0.15 m^3/s (h)	66.1	0.0	17.8	95.3	5.4	11.3	22.6	22.2
Q > 0.20 m^3/s (h)	21.4	0.0	8.6	41.1	5.4	6.1	6.8	6.4
Overflows (h)	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0
Max. time excess (h)	0.0	0.0	0.0	0.0	0.0	16.5	16.5	0.0

enhanced management strategies were tested with the original (i.e. bi-linearly interpolated) and spatially disaggregated GEP's forecasts for the 3-month period of the autumn of 2010, for which meteorological forecasts were made available to us by EC.

Criteria used to evaluate performance are the following: 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, and the number of hours spent exceeding the maximum 4-day "mosquito-breeding" limit. The number of hours spent with the pond outflow greater than the thresholds of 0.06, 0.15, and 0.20 m^3/s provides information about the efficiency of hydraulic shock or "erosion force" mitigation. Such outflow thresholds cannot be directly linked to a gate OP because the pond outflow depends on the pond water height. However, reaching an outflow greater than 0.20 m^3/s was generally only possible with the outlet fully opened, i.e. for emergency situations.

6. Results/discussion

Results for the current capacity of 4000 m^3 clearly show the superiority of the RTC strategies (Evolved and Future scenarios) over the current static one: the TSS removal efficiency is increased, the hydraulic shocks are reduced, and no overflow occurs (see Table 4).

We refer to Gaborit et al. (2013a) for more details about the performances obtained for this pond. We will now focus on results obtained for the smaller pond volumes.

For a volume of 1250 m^3, the Future D, D2 and E scenarios depict TSS removal efficiencies lower than those of the Evolved strategies (Table 5). When looking more precisely at the control actions taken, these deteriorations can be explained by false alarms that resulted in useless preventive discharges of the pond with sometimes quite important OPs of the outlet gate. Since these false alarms occurred even with perfect forecasts, the rules defined in the "Future" scenarios may be too conservative (a safety margin was taken into consideration when choosing the threshold rainfall depth values used in the rules), but in this context this was judged preferable than not being safe enough.

The benefit of rainfall forecasts lies in improved safety regarding overflow, as depicted in Table 5. Note that the minimum achievable overflow duration is equal to the value of the current (Static 1) scenario, because this scenario consists of a permanent complete opening of the outlet gate.

The Future E scenario also fulfilled its aim of avoiding any excess of the four-day limit with water accumulated in the pond, compared to other scenarios that include the mosquito constraint (Evolved D, Future D / D2). Finally, the Manual 1 and 2 strategies do not compete with the automatic RTC scenarios. They indeed only lead to a marginal improvement of the pond TSS removal efficiency while almost not improving its hydraulic mitigation capacity, compared to the static scenario (Tables 4 and 5).

As can be seen in Table 6, a decrease in the pond capacity is logically accompanied by a decrease in the TSS removal efficiency.

Table 5. Performance of the developed RTC scenarios calculated with continuous simulations for the summers 2005 to 2010 and a pond capacity of 1250 m^3. See Table 3 for the scenarios. Q: outflow; Max. time excess: number of hours spent in excess of the maximum time of 4 days allowed with water accumulated in the pond. Predictive scenarios were obtained with perfect forecasts.

Scenario / Criterion	Static 1	Static 2	Manual 1	Manual 2	Evolved C	Evolved D	Future D	Future D2	Future E
TSS removal (%)	49	50	56	61	86	84	77	79	78
Q > 0.06m^3/s (h)	251	312	176	190	153	137	142	152	140
Q > 0.15m^3/s (h)	66	0	45	66	38	35	40	43	40
Q > 0.20m^3/s (h)	21	0	21	22	38	35	19	20	19
Overflows (h)	0.5	18.6	0.5	0.5	4.8	4.1	0.5	0.5	0.5
Max. time excess (h)	0	0	0	0	3079	17	17	17	0

Table 6. Pond performance calculated with continuous simulations for the summers 2005 to 2010, as a function of the capacity considered, for the Evolved C and D scenarios.

	Pond capacity for the Evolved C scenario			Pond capacity for the Evolved D scenario		
	$4000\,m^3$	$1250\,m^3$	$590\,m^3$	$4000\,m^3$	$1250\,m^3$	$590\,m^3$
TSS removal (%)	91	86	73	88	84	72
Q > $0.06 m^3/s$ (h)	26	153	128	202	137	126
Q > $0.15 m^3/s$ (h)	5	38	67	9	35	66
Q > $0.20 m^3/s$ (h)	5	38	1.7	6	35	1.7
Overflows (h)	0	4.8	17	0	4.1	16
Max. time excess (h)	4078	3079	2000	26	17	0

Since for this smaller pond volume, the emergency levels are reached faster during a storm event, the water has to be released sooner and less time is available for sedimentation. Yet it is noteworthy that there is no large difference between the TSS removal efficiencies attained for the pond capacities of 4000 and $1250\,m^3$. When the pond capacity decreases, its potential to reduce the hydraulic shocks on receiving water bodies is altered, leading to an increase in overflows. In Table 6, the number of hours with the pond outflow being greater than $0.2\,m^3/s$ decreases when moving from a 1250 to a $590\,m^3$ capacity, but this due to the fact that water leaving the pond by the emergency spillway in case of overflows was not taken into account in the outflow value computation (which is based solely on the outlet pipe flow value).

The enhanced management strategies using real rainfall forecasts were evaluated with the simulations performed over the three-month summer period of 2010, for which the forecasts provided by EC were available. However, it turned out to be difficult to differentiate between the different meteorological products (see Section 3.3), because the performances of the RTC scenarios were often very close, even for the pond volume of $590\,m^3$ (see Table 7). We remind that in the rules, we used the mean of the rainfall depths forecasted by the 21 ensemble members, or simply the deterministic LAM value.

Differences can nevertheless be noticed between perfect forecasts and real forecasts. Compared to perfect forecasts, the downscaled or original GEP led to a better TSS removal efficiency (Table 7). This can be explained by the fact that the real rainfall forecasts missed some events. Therefore, some alerts issued using the perfect forecasts did not occur when using the real ones, leading to a longer water detention time. However, the hydraulic shocks mitigation capacity of the Future scenarios with real forecasts remain nearly the same as those with perfect forecasts, because the reactive rules of all Future scenarios are the same and can handle the misses of the real forecasts. In Table 7, one can see that using real forecasts with the Future D2 strategy leads to a performance deterioration, compared to the Evolved D scenario, which is only reactive.

Furthermore, rather than using the average of the 21 members of the ensemble products (i.e. original or downscaled GEP, see Section 3.3) as being the deterministic interpretation of the ensemble 21 possibilities to be used in the rules, different percentiles were tested for considering the deterministic rainfall depth values forecasted by an ensemble product. The mean, median, and 30% and 70% percentiles of the ensemble members were compared. The results are consistent in the sense that using the 70% percentile (in comparison to using the median or the 30% percentile) led to a decrease of the TSS removal efficiency and to a diminution of the hydraulic shocks mitigation capacity because more overflow alerts were issued. However, it led to a slight increase of the safety regarding overflows (Table 8). Note that using the mean of the ensemble members generally led to a performance close to the 70% percentile for the downscaled H and S rainfall forecasts.

Table 7. Performances of the RTC scenarios with simulations performed from July to October 2010 with perfect and real forecasts and a pond capacity of $590\,m^3$.

Criterion / Scenario	Static 1	Evolved D	FD2_PO	FD2_BM	FD2_HM	FD2_SM	FD2_LAM
TSS removal (%)	43	69	57	68	67	67	62
Q > $0.06\,m^3/s$ (h)	18	7	14	13	13	13	14
Q > $0.15\,m^3/s$ (h)	5	4	5	4	4	5	6
Q > $0.20\,m^3/s$ (h)	0.1	0.3	0.0	0.2	0.0	0.3	0.3
Overflows (h)	1.1	1.3	1.1	1.3	1.3	1.3	1.3
Max. time excess (h)	0	0	0	0	0	0	0

Notes: FD2: Future D2 scenario (section 3.2); PO: perfect forecasts. The letters B, H, S and LAM refer to the rainfall forecasts used (see Table 2). The letter M refers to the fact that we used here the mean of the ensemble members, for the ensemble forecasts.

Table 8. Performances obtained with the Future D scenario, a capacity of 1250 m^3 and simulations performed from July to October 2010.

	PO	BM	B_30	B_50	B_70	HM	H_30	H_50	H_70	SM	S_30	S_50	S_70
TSS removal (%)	75	77	78	77	78	77	79	79	76	77	79	77	77
$Q > 0.06 m^3/s$ (h)	10	6	4	7	8	7	6	8	7	7	8	4	9
$Q > 0.15 m^3/s$ (h)	4	2	2	2	2	2	3	2	2	2	3	2	2
$Q > 0.20 m^3/s$ (h)	2	2	2	2	2	2	3	2	2	2	3	2	2
Overflows (h)	0.0	1.1	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.0	1.1	1.1	1.0
Max. time excess (h)	0	0	0	0	2	0	0	0	0	0	0	0	0

Notes: PO: perfect forecasts. The letters B, H and S refer to the rainfall forecasts used (see Table 2). The letter "M" denotes performances obtained considering the mean of the ensemble members, and the values 30, 50 and 70 respectively correspond to using the percentiles 30, 50 and 70% of the ensemble members.

The enhanced management strategies developed here can be transferred to other dry ponds, provided that the constants and thresholds involved in the rules are refined. The rules may be refined too, depending on the local pond configuration or its associated management objectives' priorities. Testing of improved static strategies for dry ponds such as the multi-level outlet concept (see Shammaa et al., 2002) would be interesting because they are less costly to implement than RTC. Finally, the use of radar nowcasts, in conjunction with forecasts issued by meteorological models for longer lead-times, seems to present a lot of interest, too. This was not tested here, but radar nowcasts, which can issue rainfall depth predictions for lead-times comprised between 2 and 6 hours (see, for example, Dolcine et al., 2001; Moore et al., 2005; Pierce et al., 2004; Pleau et al., 2005), could be more than enough for managing a dry pond located at the outlet of such a small urban catchment as the one of this study.

7. Conclusions

This work proposed enhanced management strategies for a dry detention pond. While the strategies considering a daily manual adjustment of the pond outlet gate led only to a slight improvement of its performances, scenarios relying on an automatic adjustment of it (the RTC scenarios) performed much better.

The automatic reactive control schemes implemented here increased the pond TSS removal efficiency from 46% (current state) to between 70% and 90%, depending on the pond volumetric capacity considered. The rules allow maximizing the detention time of water, while minimizing the hydraulic shocks to receiving water bodies as well as overflows. A constraint relative to a maximum time of 4 days with water in the pond was respected to avoid mosquito breeding issues. Taking perfect rainfall forecasts into consideration further reinforces the safety of the management strategies. However, results obtained here indicate that no additional improvement is gained for the predictive scenarios over the purely reactive schemes when using real forecasts, because of the error they contain. But this statement is based only on the three-month period of the autumn of 2010, and more testing is needed to confirm this conclusion.

Such predictive strategies are interesting because they allow considering forecasted information without requiring an on-line implementation of the model (i.e. no simulation has to be performed in real-time). Based on these results, there seems to be a strong potential in the implementation of (automatic) RTC scenarios to manage dry detention ponds. No meteorological product considered here was clearly better than the others, nor has any clear optimal manner to estimate a deterministic rainfall depth value from ensemble forecasts emerged, from the view point of the pond performances reached using such forecasts. Taking the mean of the ensemble members seems to be a good choice, in our case study. Finally, automatic RTC scenarios are interesting to implement because they allow a minimization of the pond detention volume. Here, a volumetric capacity equal to half of the one designed may be sufficient, if accompanied with enhanced management strategies such as the RTC scenarios described in this study. This represents a significant advantage in dense urban areas where saving space is an important issue.

Disclosure statement

No potential conflict of interest was reported by the authors.

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