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# Ecohydraulic-driven real-time control of stormwater basins

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Control of stormwater basins can be a competitive measure to improve the ecohydraulics of urban rivers by increasing the removal efficiency of particles and agglomerated contaminants like heavy metals and by decreasing hydraulic peak flows. In this paper, we present a simulation study that evaluates the potential of ecohydraulic-driven real-time control of stormwater basins to improve water quality and decrease hydraulic stress in the receiving water body. Nine different static and dynamic control scenarios were analysed based on a detailed hydraulic and quality model of an existing small urban catchment equipped with a stormwater basin at its outlet. Under dynamic control, an outlet valve was manipulated to increase retention time. The removal efficiency for suspended solids could be significantly increased by all control strategies and the hydraulic peaks were reduced by at least 50%. At the same time, overflow of the basin is avoided to prevent flooding. The developed dynamic control strategies proved to be advantageous as they provide significantly higher removal efficiency for suspended solids and a possible flexible adaptation to future demands. The findings of this study have been confirmed by field experiments.



## 1. Introduction

It is well known that urban stormwater has serious impacts on receiving waters including water quality degradation, flow-induced erosion, and habitat loss (Novotny and Witte, 1997; Pitt, 2002; Walsh, 2000). To limit these impacts different stormwater management strategies for maintaining or restoring the natural hydrologic functions of urbanized catchments are available, often referred to as Best Management Practices (BMP). BMPs are typically detention or retention measures to control discharge and pollutants from urban catchments (Ellis and Marsalek, 1996; Field et al., 1994; NCDENR, 2007; Villarreal and Bengtsson, 2004). In this context devices like stormwater basins and tanks but also pre-treatment devices (e.g. screens, and trash racks) and custom hydraulic controls (e.g. weirs, and orifices) are characterized as structural BMP elements. They are often complemented by non-structural BMPs which typically are passive or programmatic and comprise for example public education and participation, material source control, etc. (NCDENR, 2007; Taylor et al., 2007).

In addition to the above, real time control (RTC) technology allows updating existing systems. In general, RTC takes active influence in the flow processes of an urban drainage system. The idea is to use an (existing) infrastructure in a more flexible way, to improve its effectiveness. Hence, it can be seen as a measure to exploit an infrastructure, which is (often) designed as a static system, in a dynamic way.

In the meantime, RTC has become an accepted and mature technology (Cembrano et al., 2004; Fuchs and Beeneken, 2005; Pleau et al., 2005; Schütze et al., 2004; Seggelke et al., 2013). So far RTC is mainly applied to combined sewer systems. Applications for separate sewer system can only be found rarely (e.g. Hoppe et al., 2011) and only a few contributions are focusing on stormwater basins in separate systems (Jacopin et al., 1999; McCarthy, 1994; Middleton and Barrett, 2008).

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The objective of this contribution is to apply control strategies in stormwater management as extension to structural BMPs to further reduce the impact on local aquatic ecosystems. This is achieved by equipping stormwater basins with dynamic sluice gates or similar actuators. Our major aims are to increase the water retention time in a basin and to decrease hydraulic peaks to the receiving river. The first objective is to increase sedimentation and thus enable retention of major contaminants such as heavy metals, polycyclic aromatic hydrocarbons, phosphorous and organic compounds, which are agglomerated onto fine particles (Characklis and Wiesner, 1997; Pettersson, 2002; Rossi et al., 2005; Vaze and Chiew, 2004). The second objective focuses on reducing the hydraulic stress in the receiving river by avoiding peak discharges (Booth and Jackson, 1997; Borchardt and Sperling, 1997). The challenge resides in adjusting the basins' sluice gate to retain stormwater as long as required for sedimentation of fine particles without causing overflow of the basins and damages to neighbouring structures when the next rainfall occurs.

## 2. Methods

The analysis has been conducted in three steps. Within the first step, a model for the hydraulics and quality aspects of the urban catchment has been developed. Using this model, the second step has aimed at developing a static control of the stormwater basin by adjusting the maximum outflow of the basin. The final step has suggested a set of control rules that regulate the outflow in real time.

### 2.1. Case study

A stormwater basin from Quebec City, Canada was selected for the case study (Fig. 1). It is located in a new residential area, about 10 km north-west from the city centre in the urban district "Les Rivières". The area is equipped with a dual drainage sewer system for stormwater. Dual drainage systems utilize the stormwater sewer network and city streets as *dual* conveyance pathways. For a thorough discussion of this topic, refer to Smith (2006). The catchment comprises 264 single-family houses and some apartment complexes on the southern border. It accommodates about 920 inhabitants. The total area is 15.3 ha, 30% of which is impervious, the average slope is about 3.5%. The pervious part is mainly covered by grass; the in situ soil is predominated by fluvial deposits. The observed lag time is about 15 min with a concentration time of 4 h. All the time an average base flow of about 3.5 l/s has been recognized originating from an upstream drained creek.

Detailed data about the catchment's land use and the sewer system were available to the project because the area was constructed only one year before the study started; all relevant planning documents were thus fully accessible. A rain gauge is located less than 1 km from the stormwater basin, and rainfall data is available since 1999 at 5 min resolution. Annual precipitation is about 1230 mm including approximately 320 cm of snowfall. Quebec City's climate is classified as humid continental with warm and occasionally hot summers and severe cold winters.

The minor stormwater sewer was designed based on a synthetic rain event with 1-h duration and a 2-year return period and a 1-h, 100-year synthetic rain event for the major sewer system and the stormwater basin. The stormwater basin was designed with a retention volume of 3300 $m^3$ and a maximal water level of 1.65 m at the outlet. Table 1 summarizes the calculated stormwater flow at the system's outlets.

Fig. 1 shows an aerial photograph and the drainage network of the study site (left) and photographs of the inflow and outflow structures of the retention basin during a 3 to 5-year event.

### 2.2. Models

#### 2.2.1. Hydraulic model

The hydrological and hydraulic model for the catchment including the stormwater basin is based on the standard models available in SWMM5 (US Environmental Protection Agency, 2008) using a non-linear reservoir schematisation, Manning's equation and the Horton infiltration model for surface runoff and the full de Saint

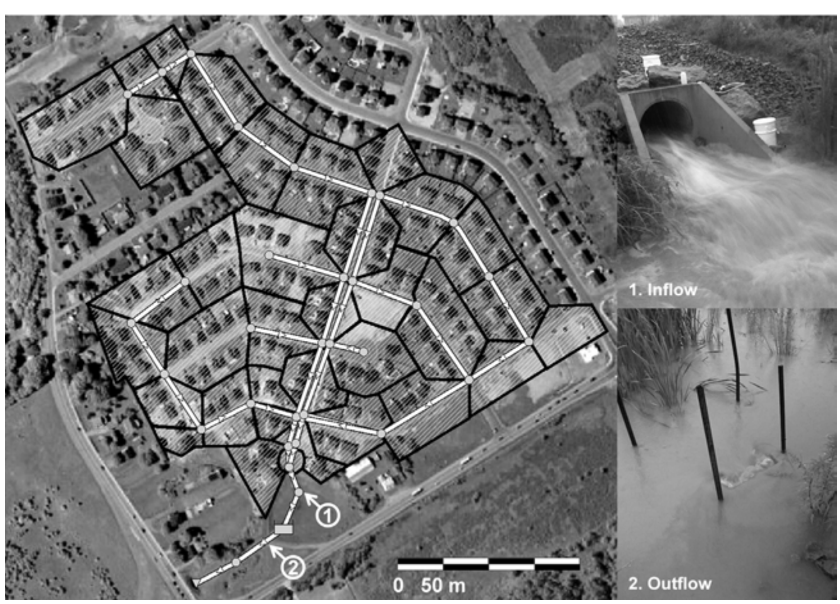


Fig. 1. Overview of the study area with structure of the SWMM model (left). The model structure is represented as follows: circles are the nodes, white lines are the links (arrows indicate the main flow direction), black outlined polygons are the subcatchments, the rectangle is the storage node used for the basin and the triangle is the outfall of the system. The right side shows the inflow (1) and outflow (2) of the stormwater basin for the August 18th 2008 rain event. Both structures are also indicated by the numbers in the left overview.

Table 1
Flow calculated for the sewer systems.

| Outlet from | Minor sewer system | | Major sewer system | Basin (controlled) |
|---|---|---|---|---|
| Return period rain event | 2 Year | 100 Year | 100 Year | 100 Year |
| Flow ($m^3/s$) | 0.72 | 0.89 | 1.89 | 0.35 |

Venant equations for flow routing in open channels and closed conduit systems. For a detailed description of the used models the reader is referred to James and Rossmann (2011).

#### 2.2.2. Quality model

The quality model consists of four sub-models: a build-up and a wash-off model for the surface runoff, a transport model for the drainage system and a sedimentation model for the stormwater basin. The water quality study was limited to total suspended solids (TSS).

For the build-up model, the exponential asymptotic build-up equation described by Alley and Smith (1981) was used (Eq. (1)).

$$\frac{dMa}{dt} = ACCU - DISP \cdot Ma \tag{1}$$

where $Ma$ is the accumulated mass (M) at time $t$, $ACCU$ is the accumulation rate (M $T^{-1}$) and $DISP$ is the dispersion coefficient ($T^{-1}$).

The wash-off was calculated according to the model developed by Metcalf and Eddy (1971) that is further described by Alley (1981) (Eq. (2)).

$$\frac{dMa}{dt} = -Ke \cdot r(t) \cdot Ma \tag{2}$$

where $r(t)$ is the runoff rate (L $T^{-1}$) at time $t$ and $Ke$ is the wash-off coefficient ($L^{-1}$).

For the transport of pollutants in the conduits a Completely Stirred Tank Reactor (CSTR) was used. It is assumed that each conduit behaves as a CSTR. The outflow concentration is equal to the concentration in the CSTR and is calculated according to Eq. (3).

$$V\frac{dC}{dt} + C\frac{dV}{dt} = Q_{in} \cdot C_{in} - Q \cdot C \tag{3}$$

where $C$ is the concentration in the effluent and in the mixed volume [M $L^{-3}$], $V$ is the water volume in the conduit [$L^3$], $Q_{in}$ is the inflow rate [$L^3$ $T^{-1}$], $C_{in}$ is the concentration of the influent [M $L^{-3}$] and $Q$ is the outflow rate [$L^3$ $T^{-1}$].

As TSS quality model for the stormwater basin, a simple scheme was developed that is formulated similar to a first-order reaction (Eq. (4)). TSS are represented by different particle size classes associated with their corresponding average settling velocities. This discretisation allows us to address smaller particle sizes separately.

$$\frac{dC_{TSS,i}}{dt} = -k_{s,i} \cdot C_{TSS,i} \tag{4}$$

where $C_{TSS,i}$ is the concentration of the $i$th TSS class in the basin [M $L^{-3}$], $k_{s,i}$ is a settling first-order rate constant for the $i$th TSS class [$T^{-1}$] that can be expressed based on the effective settling velocity of the $i$th TSS class $v_{s,i}$ [L $T^{-1}$] and the current mean water depth $h$[L] in the basin resulting in Eq. (5).

$$\frac{dC_{TSS,i}}{dt} = -\frac{v_{s,i}}{h} \cdot C_{TSS,i} \tag{5}$$

With the assumption of a completely mixed system comes that the concentration of the $i$th TSS class in the basin is equal to the concentration of the $i$th TSS class in the outflow. The concentration of TSS can be calculated by summation of all $TSS,i$ classes (Eq. (6)).

$$C_{TSS} = \sum_{i=1}^{n} C_{TSS,i} \tag{6}$$

where $C_{TSS}$ is the concentration of TSS in the basin and $n$ is the number of TSS classes used.

The basin itself acts as a homogenous system. A tank model, which allows multiple in and outflows, was thus used (Eq. (7)). Eq. (4) is used in the tank model to account for sedimentation processes.

$$V\frac{dC}{dt} + C\frac{dV}{dt} = \sum_i Q_{in,i} \cdot C_{in,i} - \sum_j Q_j \cdot C - V\sum_i k_{s,i} \cdot C_{TSS,i} \tag{7}$$

where $C$ is the concentration in the effluent and in the mixed volume [M $L^{-3}$], $V$ is the water volume in the basin [$L^3$], $Q_{in,i}$ is the inflow rates [$L^3$ $T^{-1}$], $C_{in,i}$ is the corresponding concentrations of the influents [M $L^{-3}$] and $Q_j$ is the outflow rates [$L^3$ $T^{-1}$].

### 2.3. Model application and calibration

#### 2.3.1. Application

For the hydraulic model data on geography, land use, and geometry of the sewer systems was available in high spatial resolution and quality. This enabled us to develop a detailed model to adequately characterize the expected hydraulic behaviour of the catchment.

The quality model faces the problem that the particle size distribution (PSD) is highly site-specific and varies from rain event to rain event and even within a single event (Jacopin et al., 1999). As a consequence, this study uses two different approaches for the classification of the TSS classes and their associated settling velocities $v_{s,i}$. addressing the variability of the particle size distributions. First, settling velocities for different particle sizes, as provided by Marshall Macklin Monaghan Limited (1994), are used (abbreviated hereafter as MMML). These velocities have been estimated from stormwater particle size distributions, which were compiled in the NURP (Nationwide Urban Runoff Program, (US Environmental Protection Agency, 1983)) study. It should be noted that these settling velocities (see Table 2) are much lower than settling velocities calculated by Stokes' Law. Stokes' Law assumes ideal settling conditions and spherical particles. Neither of these assumptions normally holds in experimental studies. Second, settling velocity classes are used (Table 3). These classes were obtained from a measurement campaign accompanying this study following the ViCAs protocol (Chebbo and Gromaire, 2009). The basis of this protocol is to measure the cumulative mass settled at the bottom of a column over time. A mathematical treatment of the data allows extracting the fraction corresponding to each settling velocity. All together 12 samples have been taken at the inlet of the basin in the period 14 May to 18 September 2009. An average event regarding the settling velocity distribution (SVD) has been selected for this study (sample 21 August 2009 (1); Fig. 2).

#### 2.3.2. Calibration

The model for the as-is state was developed and the hydraulic behaviour was analysed. The simulation results are within a realistic range compared to the observed hydraulic behaviour of the stormwater basin. The simulated water levels correspond well with the observed water levels during the conducted measurement campaign. The simulated retention effect and the inflow and outflow hydrographs of the stormwater basin correspond with the expected physical behaviour. In addition, simulated outflow

Table 2
Average settling velocity for different particle size ranges and fraction of total mass based on MMML.

| Size fraction $i$ | Particle size range (lm) | Average settling velocity of particles in size fraction $i$, $v_{s,i}$ (m/h) | Average settling velocity calculated by Stokes' law (m/h)[a] | Fraction of total mass contained in size fraction $i$ (%) |
|---|---|---|---|---|
| 1 | $x$ 6 20 | 0.009 | 0.150 | 20 |
| 2 | 20 < $x$ 6 40 | 0.047 | 0.751 | 10 |
| 3 | 40 < $x$ 6 60 | 0.092 | 1.951 | 10 |
| 4 | 60 < $x$ 6 130 | 0.458 | 7.69 | 20 |
| 5 | 130 < $x$ 6 400 | 2.135 | 66.4 | 20 |
| 6 | 400 < $x$ 6 4000 | 19.8 | 6064 | 20 |

[a] Assumed water temperature 10 °C; assumed particle density 1.5 (kg/m$^3$) as reported e.g. by Kayhanian et al. (2008) and Takamatsu et al. (2010).

Table 3
Settling velocities ranges, settling velocities and fraction of total mass inputted to the basin's quality model. All values are based on the 21 August 2009 observations.

| Velocity fraction $i$ | Settling velocity range (m/h) | Used settling velocity in velocity fraction $i$, $v_{s,i}$ (m/h) | Fraction of total mass contained in velocity fraction $i$ (%) |
|---|---|---|---|
| 1 | <0.019 | 0.002 | 31 |
| 2 | 0.019–0.062 | 0.019 | 11 |
| 3 | 0.062–0.140 | 0.062 | 10 |
| 4 | 0.140–0.262 | 0.140 | 8 |
| 5 | 0.262–0.568 | 0.262 | 9 |
| 6 | >0.568 | 0.568 | 31 |

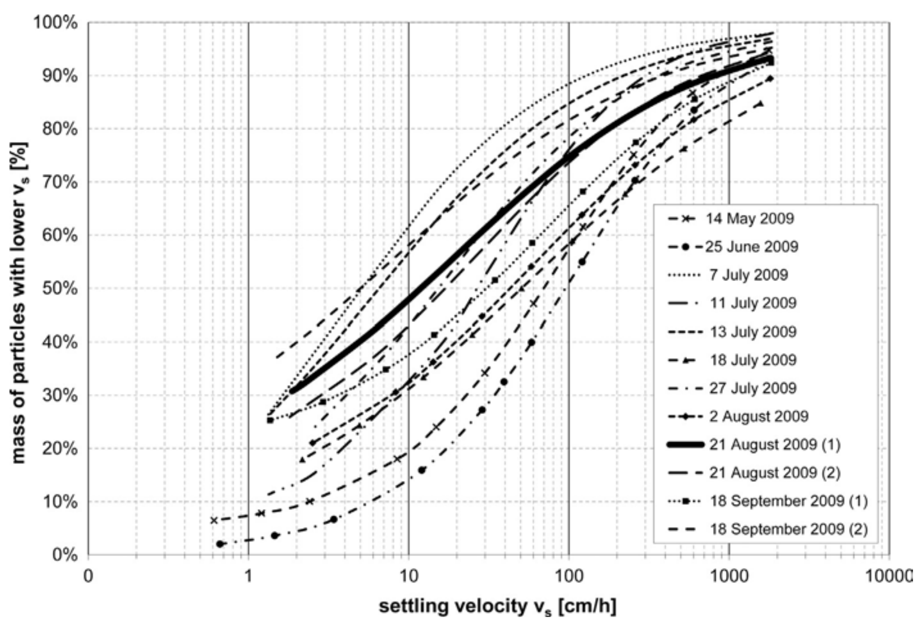


Fig. 2. Settling velocity distribution of the 2009 water samples, following the ViCAs protocol (Berrouard, 2010).

hydrographs coincide well with the measured ones, for two distinct periods (see Fig. 3).

The surface runoff quality model for TSS was calibrated with TSS values measured at the basiń s inlet during the 18 August 2008 rain event (total rainfall 36.8 mm, average intensity 0.19 mm/min, maximum intensity 1.52 mm/min). The basin's quality model for the TSS fractions was validated in two ways. First, the two sets of settling velocities were directly used with the formulated model. The simulation results were confronted against the 18 August 2008 TSS measurements at the basin's outlet. Second, the average settling velocity distribution obtained from the 2009 measurement campaign was used to simulate the ViCAs experiment with the formulated model.

The TSS inflow concentration is well captured for the precipitation event. In addition, the order of magnitude for the simulated outflow concentration fits well (Fig. 4). However, the figure also shows that the settling velocity distribution has a considerable influence on the simulated TSS concentrations and the removal efficiency. Furthermore, the formulated TSS quality model for the basin is able to reproduce the laboratory experiment that was conducted to derive the settling velocity distributions.

### 2.4. Control strategies and rules

The developed control strategies are based on the following objectives and constraints:

- Increase retention time in order to decrease TSS loads and agglomerated contaminant loads to the receiving water by capturing sediments within the stormwater basin.
- Decrease hydraulic peak impacts by limiting the maximal outflow of the stormwater basin.
- Avoid overflows of the stormwater basin to prevent flooding or damage to infrastructure.

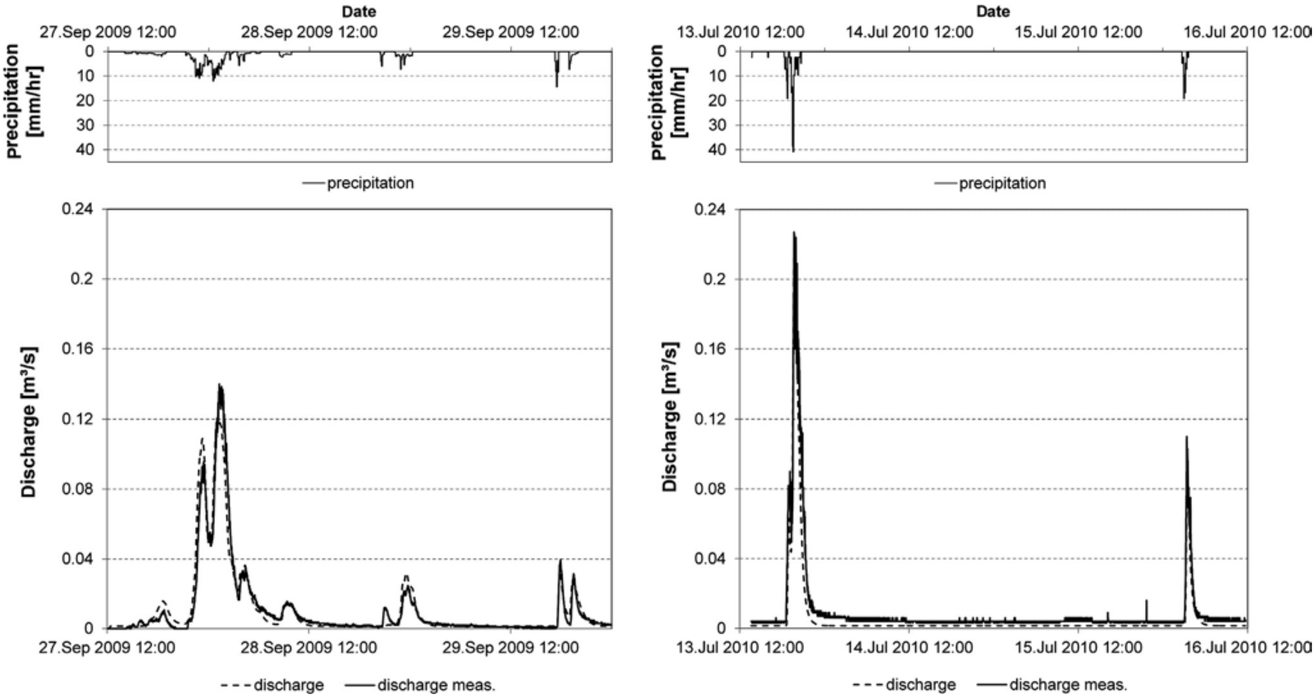


Fig. 3. Comparison between simulated (discharge) and measured (discharge meas.) outflow of the stormwater basin for two independent measuring periods in September 2009 and July 2010.

- Consider the length of aquatic life stages of mosquitoes as limiting factor for the time span water can be stored in the basin (for possible mosquito control strategies in constructed wetlands see e.g. Knight et al. (2003)).

For the control strategy, two different approaches were pursued, a static and a dynamic control. The static control aims to adjust one optimal maximal outflow of the stormwater basin. The resulting optimization problem can be solved using the maximum outflow of the stormwater pond as decision variable and the maximum peak flow and the TSS load in the effluent of the stormwater basin as objective functions. Values for both objectives are obtained by means of long-term simulations involving a series of rain events of different intensity. For the dynamic control strategy, different rules must be derived. In our case, the rules are:

(1) If a runoff event occurs, close the outlet of the stormwater basin completely to store the water as long as possible and guarantee maximum removal efficiency.
(2) If a certain water level in the stormwater basin is reached and it is still raining or starts to rain again, open the outlet to a predefined maximum set point to prevent hydraulic stress in the recipient water.
(3) If a predefined maximum water level in the pond is reached, open the outlet completely to avoid overflow.

This basic set of rules was updated by introducing a mosquito prevention control rule:

(4a) If the stormwater is stored longer than 80% of the aquatic life span of mosquitoes, computed from the time when the basin starts to fill, open the outlet only up to a predefined maximum set point to prevent hydraulic stress in the recipient.

Also, a "free up storage volume" rule was introduced that aims at an optimal utilization of the available storage volume by releasing stormwater if no further settling (e.g. over 99%) is expected.

(4b) If the stormwater is stored longer than the maximum time span needed to retain 99% of the finest particle fraction, starting from the time where the filling of the basin ends, open the outlet only up to a predefined maximum set point to prevent hydraulic stress in the recipient water.

Note that rule 4a and 4b are alternatives since rule 4b demands longer periods to store stormwater than the aquatic life cycle of mosquitoes can permit.

### 2.5. Scenarios

Long-term simulations (1st July–16th August 2008 – 47 days) are performed to analyse the original state and the potential of static and dynamic control to achieve the aims discussed above. For all scenarios, the removal efficiency for *TSS* and all *TSS,i* fractions is calculated based on the *TSS* and *TSS,i* mass flowing in and out of the stormwater basin using the quality model as defined in Eqs. (4)–(7). The removal efficiency is calculated according to Eq. (8). Each simulation is performed twice, first using the particle size fractions based on MMML (Table 2) and second using the settling velocity classes derived from the measurement campaign (Table 3).

$$\text{Removal efficiency}_i = \left(1 - \frac{M_{TSS,i,out}}{M_{TSS,i,in}}\right) \cdot 100 \qquad (8)$$

where *removal efficiency*$_i$ is the removal efficiency for the *i*th TSS fraction [%], $M_{TSS,i,in}$ is the total mass flowing in the stormwater basin during simulation [M], $M_{TSS,i,out}$ is the total mass flowing out of the stormwater basin during simulation [M].

*Original state*. For the original state, the maximum outflow of the stormwater basin is set to 350 l/s (~75 l/(s * ha)).

*Static control (5 scenarios)*. Five scenarios are simulated to analyse the static control, each with a different maximum outflow rate between 30 l/s and 150 l/s (~6 l/(s * ha) and ~33 l/(s * ha)).

*Dynamic control (3 scenarios)*.

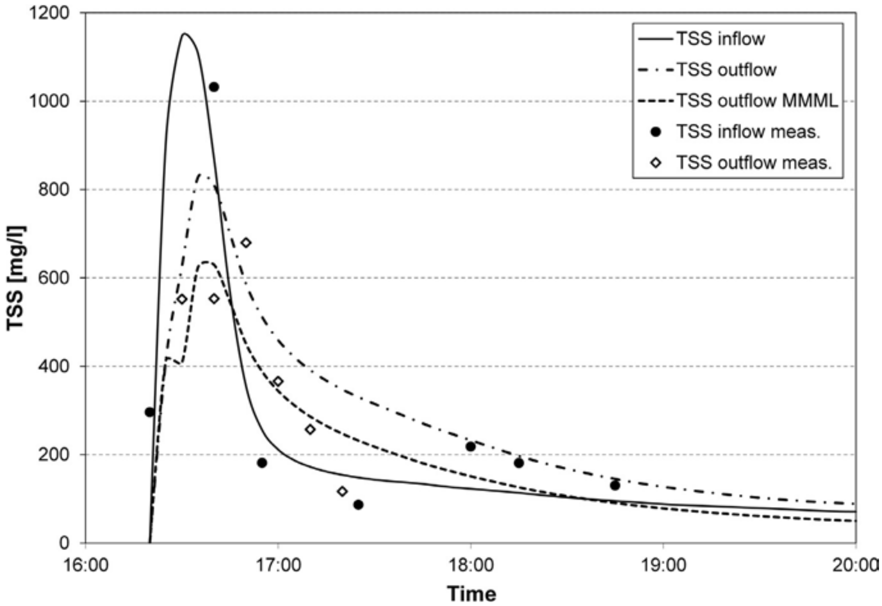


Fig. 4. Simulated and measured TSS concentrations for the inflow and outflow of the stormwater basin on August 18th 2008. TSS inflow – simulated TSS inflow concentration, TSS outflow – simulated outflow concentration using SVD obtained from measurement campaign, TSS outflow MMML – simulated outflow concentration using SVD described in Marshall Macklin Monaghan Limited (1994), TSS inflow meas. and TSS outflow meas. – TSS concentrations for inflow and outflow obtained from measurement campaign.

(1) Dynamic scenario 1: rules 1–3 (dyn. control basic)

The maximum water level for rule 2 is set to 1.2 m, the maximum outflow to 200 l/s; for rule 3, the maximum water level is set to 1.4 m.

(2) Dynamic scenario 2: rules 1–3, 4a (dyn. control mosq.)

For rule 4a, the allowed time span to store water after beginning of filling is set to 4 days (aquatic life cycle of mosquitoes is between 4 days and a month depending on the species and temperature).

(3) Dynamic scenario 3: rules 1–3, 4b (dyn. control sett.)

For rule 4b, the time span needed for best possible TSS removal was set to 4.5 days after the end of inflow to the basin (average settling time for the smallest TSS fraction is ∼4 days for a water depth of 1 m using the values from Table 2).

Table 4 provides a detailed overview of the applied control rules for all scenarios.

## 3. Results and discussion

### 3.1. Original state

The simulated TSS removal efficiency for the original state varies between 59.9% using the SVD according to MMML and 41.5% using the SVD measured at the stormwater basin. All values are

Table 4
Overview of applied rules for all examined scenarios.

| Rules | | Original state | Static scenarios | Dynamic scenario 1 | Dynamic scenario 2 | Dynamic scenario 3 |
|---|---|---|---|---|---|---|
| R0a | SET OUTFLOW = 350 l/s | X | | X | X | X |
| R0b | SET OUTFLOW = 30 l/s, 60 l/s, 90 l/s, 120 l/s, 150 l/s[a] | | X | | | |
| R1 | IF RAINFALL > 0 mm/h<br>AND WATER DEPTH < 1.2 m<br>THEN SET OUTFLOW = 0 | | | X | X | X |
| R2 | IF RAINFALL > 0 mm/h<br>AND 1.2 m ≤ WATER DEPTH < 1.4 m<br>THEN SET OUTFLOW = 200 l/s | | | X | X | X |
| R3 | IF RAINFALL > 0 mm/h<br>AND WATER DEPTH ≥ 1.4 m<br>THEN SET OUTFLOW = 350 l/s | | | X | X | X |
| R4a | IF WAT. ACC. TIME ≥ 4 days<br>AND BASIN's WATER DEPTH < 1.2 m<br>THEN SET OUTFLOW = 70 l/s | | | | X | |
| R4b | IF DETENTION TIME ≥ 4.5 days<br>AND WATER DEPTH < 1.2 m<br>THEN SET OUTFLOW = 70 l/s | | | | | X |

OUTFLOW = maximum outflow at the stormwater basin's outlet, RAINFALL = indicator if it currently is raining in the basin's catchment, WATER DEPTH = current water depth in the stormwater basin, WAT. ACC. TIME = time spent with water accumulated in the basin (water accumulation time), DETENTIN TIME = detention time after the end of inflow to the basin.
[a] One fixed value, depending on scenario.

Table 5
Simulated removal efficiency for TSS and TSS fractions for both SVDs using the model for the as-is state of the stormwater basin, analysis for period from 1st July to 16th August 2008.

| | TSS fraction $i$ (small to large) | | | | | | TSS |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| *MMML* | | | | | | | |
| TSS inflow (kg) | 999 | 499 | 499 | 999 | 999 | 999 | 4994 |
| TSS outflow (kg) | 921 | 383 | 322 | 290 | 78 | 6 | 2001 |
| Removal efficiency (-) | 7.7% | 23.2% | 35.4% | 70.9% | 92.2% | 99.4% | 59.9% |
| *Measured* | | | | | | | |
| TSS inflow (kg) | 1548 | 549 | 499 | 400 | 449 | 1548 | 4994 |
| TSS outflow (kg) | 1529 | 482 | 361 | 221 | 186 | 144 | 2923 |
| Removal efficiency | 1.2% | 12.2% | 27.7% | 44.6% | 58.7% | 90.7% | 41.5% |

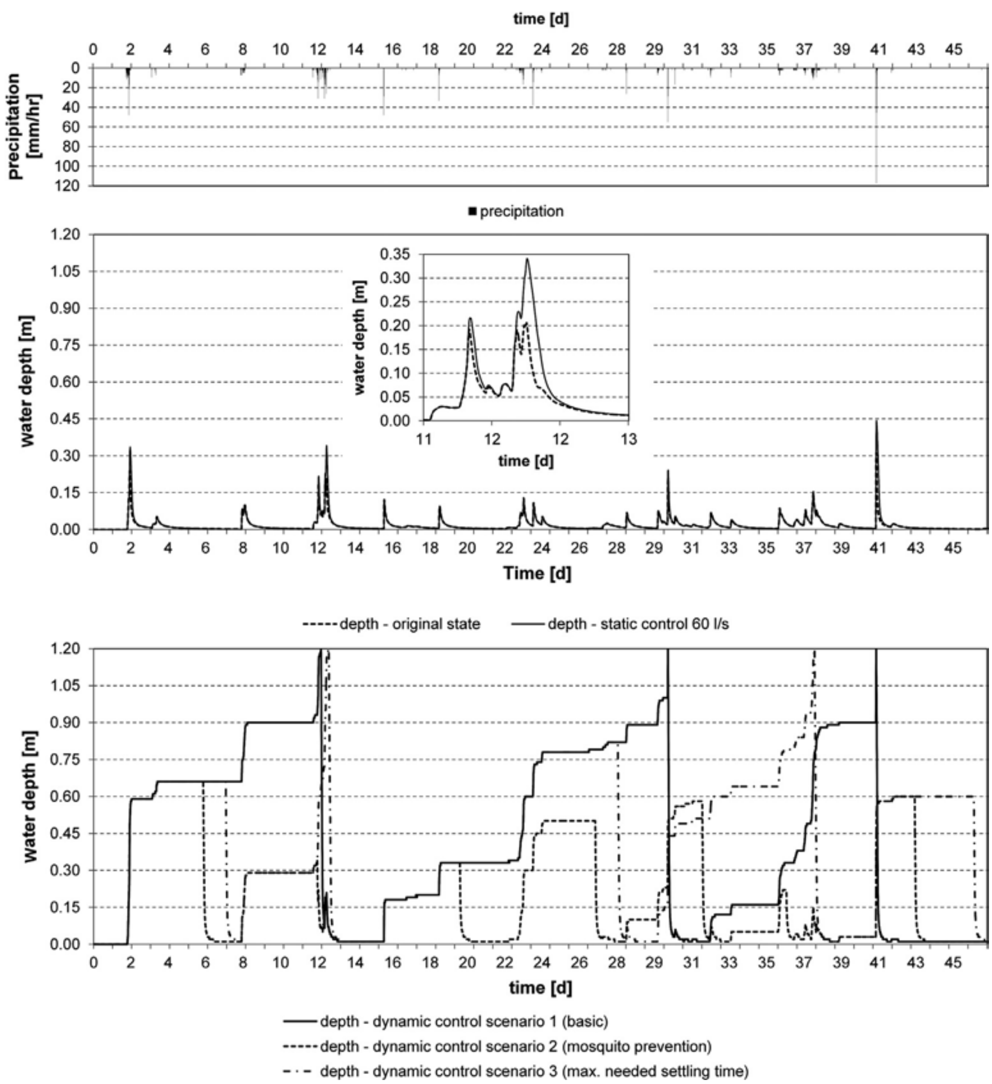


Fig. 5. Hydraulic behaviour (water depth) of the stormwater basin for all control strategies and the original state for the period from July 1st to August 16th 2008. Upper panel: precipitation time series; middle panel: water depth for the original state and the static control with 60 l/s maximum outflow; lower panel: the resulting water depth for the three dynamic control strategies.

within the range of reported TSS removal efficiencies in the literature for this type of stormwater basin (Middleton and Barrett, 2008). The different total removal efficiency for the SVD according to MMML and the measured SVD is justified by the different total mass contained in the size fractions and settling velocity fractions, respectively. A summary of the simulated in- and outflow TSS loads (including fractionation) as well as the removal efficiency for the original state of the stormwater basin are given in Table 5.

### 3.2. Static control

The hydraulic characteristics of the basin are not considerably changed when comparing the static control to the original state (evolution of water depth for original state and static control 60 l/s in the middle panel of Fig. 5). However, the design goal of the basin (retention of a 1-h, 100-year rainfall) is no longer reached under the static control scenarios resulting in undesired more frequent emergency overflows. Note also that the reduction of the maximum outflow to very small values (e.g. 15 l/s) is not feasible as such small outflows provoke operational problems such as clogging and time consuming emptying of the basin (∼61 h for 15 l/s maximum outflow, ∼2 h for the original design).

TSS retention for static control is computed for maximum outflow discharges between 30 and 150 l/s (Figs. 6 and 7). It is obvious that reducing the maximum outflow will increase the retention time in the basin and therefore increase TSS retention. The static control improves the overall TSS removal efficiency by between 1% and 15% using the SVD according to MMML and by between 1% and 8% using the measured SVD. The removal efficiency for the smallest particle size fractions (TSS1 and TSS2) increases from 0.5% up to 12% and from 1% to 17% respectively for maximum outflows of 150 and 30 l/s using the SVD according to MMML and from 0.1% to 1.0% and from 0.5% to 14% using the measured SVD.

### 3.3. Dynamic control

The three dynamic control strategies perform better than all static control strategies. They improve the overall TSS removal efficiency using the SVD according to MMML by between 26% and 30% and the removal efficiency for the smallest particle size fractions TSS1 and TSS2 by 48–58% and by 51–60% respectively (Fig. 6). Using the measured SVD the overall TSS removal efficiency increases from 24% to 29%, the removal efficiency for the smallest particle size fractions TSS1 and TSS2 from 19% to 22% and from 53% to 63% (Fig. 7).

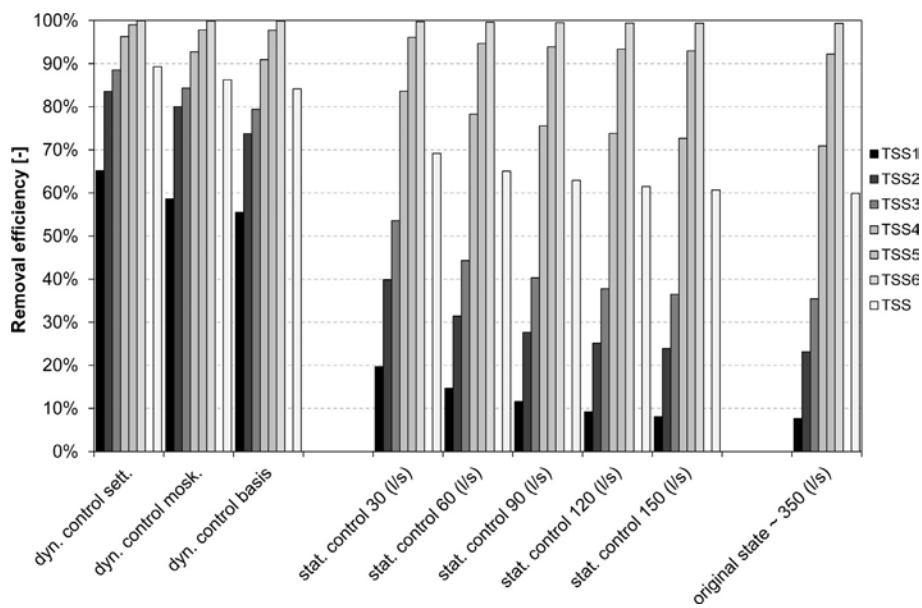


Fig. 6. TSS removal efficiency for all control strategies and the original state using SVD according to MMML. TSS1 is the TSS fraction with the smallest particle size.

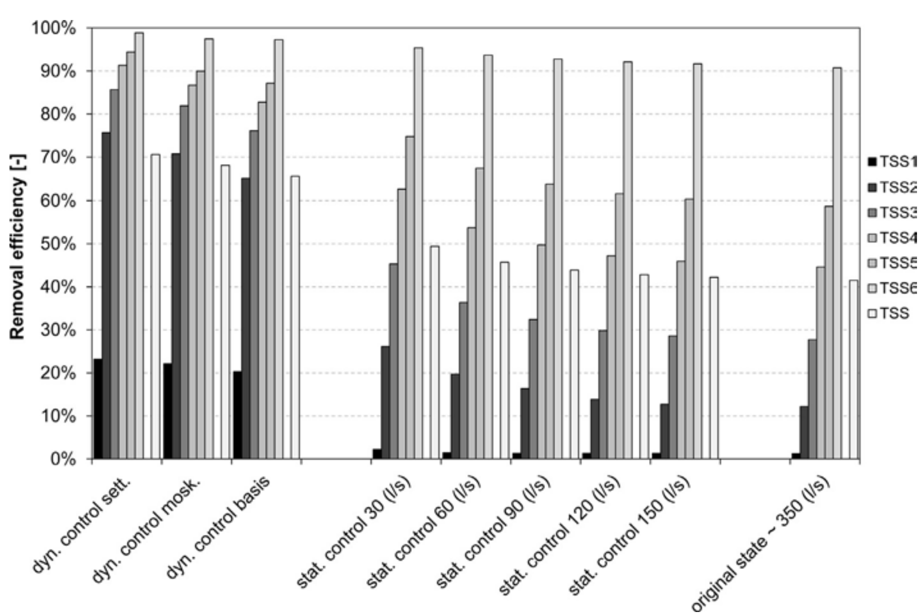


Fig. 7. TSS removal efficiency for all control strategies and the as-is state using the SVD obtained from the 2008 measurement campaign. TSS1 is the TSS fraction with the smallest particle size.

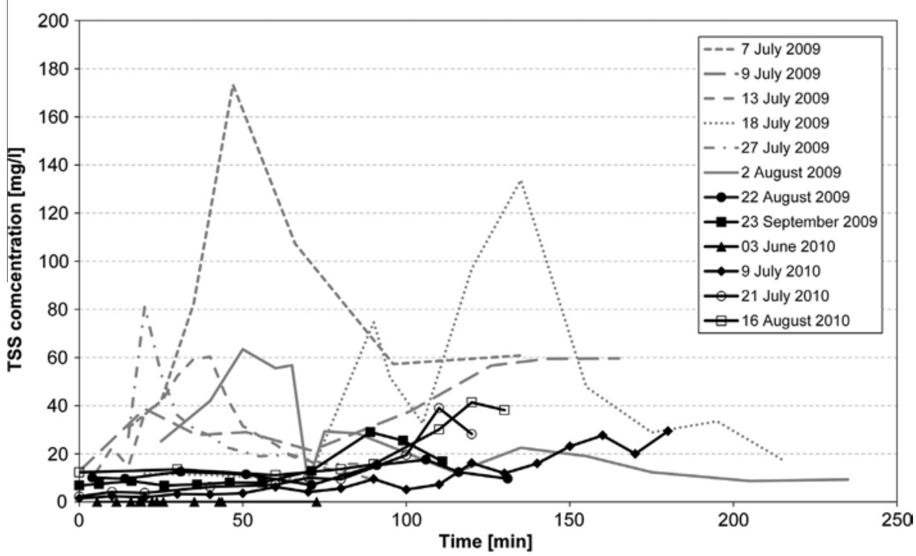


Fig. 8. Comparison of TSS outflow concentrations at the basin's outlet for normal operational conditions and after closing the basin between 30 and 135 h. TSS outflow concentrations of the stormwater basin during normal operational conditions in grey (events between 7 July 2009 and 2 August 2009) and after opening the closed basin in black (events between 22 August 2009 and 16 August 2010). (Carpenter et al., in press).

One notes that the two extended strategies (4a) and (4b), which limit the maximum retention time in the basin, perform better than the basic dynamic control rule that allows an unlimited retention time. This at first sight unexpected result can easily be explained by the fact that an unlimited retention time leads to situations where a new rainfall event starts when the basin has not yet emptied (lower panel, Fig. 5). If the remaining storage capacity is too small, the stormwater has to be released to the receiving water body without sufficient time for an effective particle removal. Such situations are identified for the basic dynamic control strategy on day 12, 30, and 41 (lower panel in Fig. 5).

Nevertheless, the two best performing dynamic control strategies have conflicting objectives. On the one hand, the "free up storage volume" strategy results in the best removal efficiency for TSS. On the other hand, this strategy provides good conditions for reproduction of mosquitoes, reducing the quality of life of residents or even introducing a health risk. The aquatic life cycle of mosquitoes can be breached by the "mosquito control" strategy but with a slight decrease of the TSS removal efficiency.

The three dynamic control strategies demand equipment that is more complex and requires more maintenance compared to the static control (i.e. higher costs). In return, the system is more flexible and the basin can be operated as dual-purpose facility: fulfilling the original design criteria for hydraulic retention and flood protection and allowing an optimized operation for pollutant control. In addition, the system becomes adaptable to future demands, e.g. under climate change.

The presented simulation study has been validated by an extensive field experiment (Vallet, 2011). For this, the stormwater basin has been closed during six independent rainfall events for a time span between 30 and 135 h (average closing time 75 h). After opening the basińs outlet again, the outflow TSS concentration has been measured. Comparing these measurements with outflow concentrations measured during normal operational conditions confirms the results of the presented simulation study (see Fig. 8).

## 4. Conclusion

The simulation study showed that real-time control (RTC) of the outlet sluice gate proves to be an effective solution for reducing the suspended solids discharge and hydraulic stress in an urban river. In all studied scenarios, the controlled basin enabled removal of fine particles and associated contaminants such as heavy metals, leading to concentrations much lower than for the current basin without control. The removal efficiency for TSS could be increased from 41.4% to 70.6% and from 59.9% to 89.3% using the SVD according to MMML and the measured SVD respectively – an improvement of 70% and 49%. For the different TSS classes (from coarse to fine) an improvement between 9% and 1780% using the SVD according to MMML and 1% and 750% using the measured SVD could be reached by the best performing dynamic control strategy. At the same time, hydraulic peaks could be reduced considerably.

The dynamic control of the outlet proved advantageous over the static control, as dynamic control results in a higher TSS removal efficiency, allows a multipurpose operation of the basin and a flexible adaptation to future demands. It also became clear that the design of the dynamic control rules results in a multi-objective optimization problem, for which environmental aims and social impacts (e.g. removal efficiency against mosquito control) are conflicting. Finally, in a parallel experimental study, simulation results were confirmed.

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