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IMPACTS OF STORMWATER TREATMENT AND FLOW REGULATION PONDS

ON HYDROLOGY AND WATER QUALITY

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LIST OF ACRONYMS

- BMP: beneficial management practice
- C*: increased runoff coefficient
- DP: dissolved phosphorus
- EIFAC: European Inland Fisheries Advisory Commission
- EMC: event mean concentration
- EPA: Environmental Protection Agency
- ER: efficiency ratio
- Hru*: increased runoff depth
- IPCC: Intergovernmental Panel on Climate Change
- MDDELCC: *Ministère du Développement durable, de l’Environnement, et de la Lutte contre les changements climatiques*
- MIII–Al: aluminum extracted using the Mehlich-3 method
- MIII–P: phosphorus extracted using the Mehlich-3 method
- MIII–P/Al: phosphorus-to-aluminum ratio extracted using the Mehlich-3 method
- NH_3: un-ionized ammonia
- NH_4^+: ammonium
- OM: organic matter
- Pi: intercepted precipitation
- PP: particulate phosphorus
- Q: flow
- SCS: Soil Conservation Service
- SS: suspended solids
- SWAMP: Stormwater Assessment Monitoring and Performance Program
- Td: detention time
- Tl: lag time
- TN: total nitrogen
- TP: total phosphorus
- TRCA: Toronto and Region Conservation Authority
- ω: specific stream power

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INTRODUCTION

Surface water from agricultural fields flows into rivers, too often carrying with it nutrients, pesticides, heavy metals and soil particles whose concentration varies depending on inputs, soil type, cultivation methods and climatic conditions. In some cases, technology can be used to reduce such contamination. One example is stormwater treatment and flow regulation ponds that modulate water flow during peak runoff periods.

Eutrophication

Increased phosphorus loads from agricultural sources lead to degradation of freshwater aquatic ecosystems. When the maximum concentration of total phosphorus in a river exceeds 0.030 mg/L, the water may become eutrophic (Gangbazo et al., 2005). Eutrophication is the enrichment of surface waters in nutrients, generally marked by increased algae and aquatic plant production. Studies in Quebec showed that 75% of total phosphorus loadings of agricultural origin exported to streams may be concentrated in periods corresponding to as little as 6% of total gauging time (Michaud et al., 2002). In these studies, annual phosphorus exports were largely associated with peak hydrological events.

Runoff events

Climate events that cause runoff are also linked to the transport of a multitude of contaminants to streams, including nutrients, pesticides, heavy metals and suspended solids. Peak flows that occur every 1 to 1.5 years are associated with the channel-forming processes of streams. According to Brookes (1987), an erosional adjustment is likely to occur when stream power, or the rate of energy dissipation against the banks and channel bed per unit of width, exceeds 25 W m^{-2}.

The challenge of climate change

It is generally accepted that, in a context of climate change, the intensity and frequency of major precipitation events will increase at higher latitudes (IPCC, 2008). Huard (2012) reported that the frequency of extreme precipitation events is projected to increase by about 10% in the agroclimatic regions of Quebec by the year 2050. These alterations in precipitation regimes make aquatic ecosystems more susceptible to exports of contaminants and accentuate the intensity of erosion associated with runoff events.

Stormwater treatment and flow regulation ponds

Although peak hydrological events are recognized as a major cause of erosion and of transport of agricultural contaminants, few sustainable solutions with a sound basis in science have been developed so far to address this issue. This project constitutes a first attempt in Canada to analyze the effectiveness and efficiency of stormwater treatment and flow regulation ponds in attenuating peak flows in agricultural areas and improving runoff quality. To this end, three stormwater and flow regulation ponds constructed in summer 2008 at Saint-Samuel, Quebec, were instrumented in order to quantify their effects on hydrological processes and runoff quality. The specific objectives of this project were to 1) quantify the effect of the ponds on hydrological processes; 2) quantify the ponds' treatment efficiency in terms of removing phosphorus, nitrogen and suspended solids; 3) characterize the agronomic potential of the accumulated sediments; and 4) quantify the impact of measures for mitigating peak flows on the hydrological regime of small agricultural watersheds. This report deals with objectives 1 and 2. A master's thesis which is currently being written (Étienne Dupont, Université Laval) focuses on objective 3, which relates to the agronomic potential of accumulated sediments. Objective 4 was tackled in two phases: the development of criteria for the "*Design of Stormwater Treatment and Flow Regulation Ponds"* (Aquapaxis, 2011) and the evaluation of the impact of "*Integrated Rainwater Storage for a Small Agricultural Watershed"* (Genivar, 2011). More broadly, this project is ultimately aimed at enhancing biodiversity, developing a climate change adaptation tool and increasing ecological goods and services.

METHODOLOGY

Experimental design

Stormwater treatment and flow regulation ponds, location and watersheds

Stormwater treatment and flow regulation ponds are natural depressions or excavated areas designed to store flood waters temporarily. These ponds serve to modulate the evacuation of the water by holding it temporarily and then slowly releasing it into a flow channel in order to reduce the erosive force of the water. In addition to mitigating scouring in downstream areas, the ponds permit sediment deposition upstream from the structure, thereby reducing the quantities of suspended solids, nutrients and other contaminants that are exported toward streams. Very few such facilities have been installed to protect water quality in agricultural areas. In general, to maximize environmental performance, the creation of such ponds should be combined with conservation tillage practices, which help to reduce soil erosion.

In order to quantify the impact of this approach, three stormwater treatment and flow regulation ponds were established at 560 15e rang, Saint-Samuel, in the administrative region of Centre-du-Québec (Canada). Image 1 shows the three ponds established in this study.

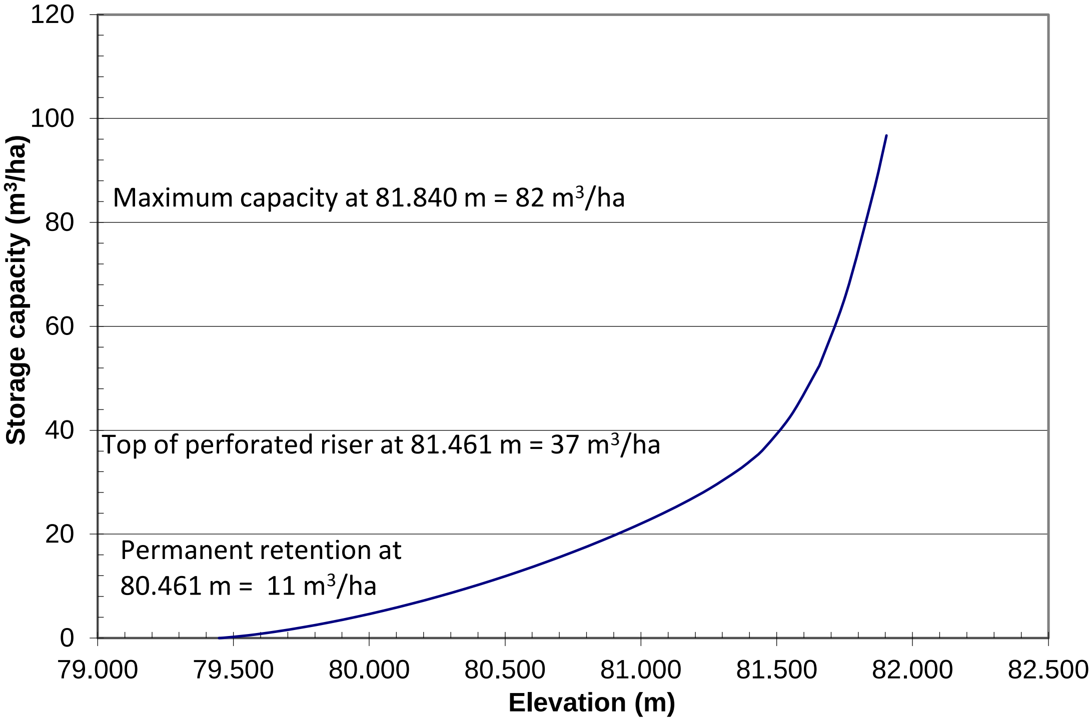
Image 1: Stormwater treatment and flow regulation ponds 1, 2 and 3, respectively

All three facilities are wet ponds, that is, they have a permanent pool of water. They are also surrounded by a grassed waterway that serves as a dry pond that temporarily stores runoff, then releases it and dries up.

The experimental site is located on a 96.8-hectare parcel of farmland divided into four drainage areas, each with a single outlet to the Nicolet River. The runoff from three drainage areas moves through three of the ponds, whereas the runoff from the fourth drainage area flows directly into the receiving stream. The experimental site, the drainage areas of ponds 1, 2, and 3, and control drainage area 4 are shown in Annex 1. These drainage areas cover areas of 36.7, 17.5, 23.1 and 19.5 hectares, respectively.

In order to characterize the experimental site properly, GPS-based surveying of the land and ponds was carried out in fall 2008. Post-processing of the data was done with TNTmip software, which permits an elevation ("Z") precision of 1.5 to 5 cm. The digital model that is generated can be used to define the dynamics of water movement and storage capacity in relation to elevation for each stormwater treatment and flow regulation pond. Annex 2 shows the hydrographic network of the study site obtained from post-processing of the GPS data. Graph 1 shows the storage capacity of pond 3 as a function of elevation. The maximum capacity of pond 3, that is, 82 m^3/ha, is less than the reference unit volumes, ranging from 200 to 250 m^3/ha for a wet pond, that are used for the design of urban and industrial stormwater ponds.

Graph 1: Storage capacity of pond 3 as a function of elevation



Soil types

The soils at the experimental site consist mainly of a loamy sand called “Terre franche de St-Jude” containing 55% to 65% fine sand to very fine sand in the B and C horizons. This type of soil is characterized by slow external and internal drainage and imperfect drainage which promotes smearing and surface runoff (Choinière, 1948). When a soil becomes smeared and compacted, it forms a hard crust at the surface which facilitates runoff. Table 1 presents the physical characteristics of the soils sampled in summer 2009. The P/Al saturation indices, i.e., the phosphorus-to-aluminum ratios extracted using the Mehlich-3 method, are 5.25% and 4.32%, respectively, for depths 0–5 cm and 5–20 cm, which is below the critical environmental threshold value for a sandy soil. The threshold value established by Pellerin et al. (2006) and adopted in the *Agricultural Operations Regulation* (Québec, 2002) is 13.1% for mineral soils containing less than 30% clay.

Table 1: Physical characteristics of soils at depths 0–5 cm and 5–20 cm

Depth	MIII–P (mg/L)	MIII–Al (mg/L)	MIII–P/Al (%)	pH	OM (%)	Density (g/cm^3)
0–5 cm	5.09	118.55	5.25	7.27	4.14	1.39
5–20 cm	3.62	121.97	4.32	6.96	4.02	1.42

Taking into account the size of the soil particles at the study site, along with storage geometry and capacity (Graph 1), pond 3 should permit adequate sedimentation of soil particles and the contaminants bound to them. The surface areas required according to equation 1 are 8, 526 and 8,467 m^2 for medium sands, medium silts and clays, whereas the mean area of pond 3 midway between the permanent pool of water and the top of the perforated riser is about 530 m^2.

Equation 1: Pond area required to capture particles of a given size

$$As = \frac{1.2Q}{Vs}$$

where:
As: pond surface area required
Vs: settling velocity for particle size (mean sand 20 x 10^{-3} m/s; mean silts 0.29 x 10^{-3} m/s; clay 0.018 x 10^{-3} m/s)
Q: flow generated by a 10-year rainfall event lasting 6 hours (0.127 m^3/s) (Aquapraxis, 2011)

Cultivation practices

The experimental site is located on a parcel of land belonging to Ferme Bergeroy S.E.N.C. The farm producer cleared and grubbed the northern part of the site in 2007. Tillage was carried out in this area in spring 2007, followed by levelling in August and September of the same year. Oats were seeded as green manure in September 2007 following this work, while soybeans were grown in 2008, the first crop year.

In the southern part of the parcel of land, the crop history prior to the installation of the ponds was as follows: 2005: corn; 2006: oats; 2007: soybeans. From the start of the project, the following succession of crops was grown: 2008: soybeans; 2009: oats; 2010: soybeans; 2011: oats and soybeans in the western part of sub-basin 1; 2012: soybeans and corn in the western part of sub-basin 1; 2013: corn.

In fall 2007, paper mill sludges that had been brought to the site in 2004 were spread over the parcel of land. Ferme Bergeroy S.E.N.C. practises reduced tillage and direct seeding; hence, only one pass of the harrow was made each year between 2007 and 2011. Ground levelling work was undertaken in fall 2011 and continued in spring 2012 (Image 2), in order to smooth out the existing levelled areas.

Image 2: Levelling work done in fall 2011 and spring 2012

Hydrological measurements

Precipitation monitoring

Precipitation monitoring was done using a Texas Electronic TR-525M tipping bucket rain gauge (resolution: 0.1 mm per tip) located on the site. The time step used to record data was 5 minutes. The precipitation data were analyzed in order to identify rainfall events based on the following characteristics: 1) depending on the analysis, a rainfall event should produce a water depth of 1 mm or 10 mm or more; 2) rainfall events must be separated by an inter-event period of 6 hours or more.

Hydrological monitoring

Stormwater treatment and flow regulation ponds are design to reduce peak flows, attenuate scouring forces and modulate the evacuation of water. The flows/volume entering and leaving each pond, as well as those at the outlet of the control sub-basin, were monitored in order to assess the effect of the ponds on hydrological processes.

Hydrological monitoring was carried out during the growing seasons from September 2009 to October 2013. Since each pond has multiple inlets, the flows/volumes entering each pond could not be measured directly. Instead, they were determined by inverse routing, based on the values of the flows/volumes leaving each pond and the changes in the volume of the pond. The method used can be broken down into a hydraulic component and a hydrological component.

The hydraulic component considers the characteristics of the water evacuation structures and allows outflows to be defined as a function of water depth. The water evacuation structure for each of the three ponds consists of a perforated vertical conduit measuring 0.611 m in diameter, connected to a horizontal discharge pipe measuring 0.457 m in diameter. The outflows through each of the three structures comprise three distinct stages of evacuation: outflow via the holes in the perforated riser, outflow controlled by the hydraulics of flow in the riser, and the hydraulics of flow in the horizontal pipe. These discharge-pipe flow processes are described in greater depth by Haid (1999).

The hydrological component allows relationships to be established between water depth and storage area/volume. The curves show the temporal variation of water volume in each of the three stormwater treatment and flow regulation ponds by tracking changes in water depth over time. Water depth monitoring in each pond was performed using Hobo water level loggers (Onset U20-001-01) with a time step of 15 minutes. Once the outflows and the variation in volume are established, the surface runoff inflows, the interflows and the groundwater inflows can be deduced for each pond by inverse routing. A 2.5H type weir was installed at the outlet of pond 3 in order to validate the inverse routing results. Water depth was monitored inside the spillway using two Hobo water level loggers (Onset U20-001-01) with respective time steps of 1 and 5 minutes. Discharge from the control drainage basin was measured using a Greyline Stingray flow meter placed inside a culvert at the basin outlet. This instrument had a Greyline QZ02 ultrasonic sensor designed to record water levels and velocities according to a specified time interval. A time interval of 15 minutes was chosen for the recording of water levels and velocities.

Water quality monitoring

The main objective of this applied research project was to quantify the impact of stormwater treatment and flow regulation ponds on water quality. Since exports of phosphorus and other contaminants of agricultural origin into streams are primarily linked to intense hydrological events, the sampling method targets periods of heavy rainfall and snowmelt. Between 2008 and 2010, event-based sampling was done whenever more than 20 mm of rain fell in less than 24 hours. The samples were collected manually in all three ponds and at the outlet of the ponds, as well as at the outlet of the control drainage basin. The following physico-chemical parameters were analyzed in the water samples: suspended solids; electrical conductivity; pH; total nitrogen and nitrites/nitrates as well as the different forms of phosphorus, including total phosphorus, particulate phosphorus and dissolved phosphorus, molybdate reactive pintohosphorus and dissolved reactive phosphorus. During the snowmelt period in spring 2009 and 2010, daily water sampling was carried out and the above-mentioned parameters were analyzed. To gain a better understanding of phosphorus dynamics at the water-sediment interface, characterization of the bioavailability of particulate phosphorus was performed on sediment samples. These samples were collected from the bottom of the three ponds on a biweekly basis throughout the snow-free period.

In addition to this manual sampling, a more in-depth analysis of pond 3 was carried out during the growing seasons from 2010 to 2013. The sampling station for the pond consisted of two autosamplers (ISCO 6712) which were automatically triggered when the water level increased by 0.40 m relative to the level of the permanent pool. Two sampling points were used for the water quality monitoring: the inlet and outlet of the pond. Sampling was done over a 24-hour period with 6 samples taken at each sampling point. Each of the 12 one-litre samples taken consisted of a composite sample made up of eight 125-mL subsamples collected every 30 minutes during a period of 4 hours. The samples were placed on ice and sent to the Quebec government’s Centre d’expertise en analyse environnemental from 2010 to 2012 and to AAFC’s water quality laboratory in 2013. The samples were analyzed to determine the concentrations of total phosphorus – persulphate, dissolved phosphorus (<0.45 µm), total nitrogen, nitrite-nitrate, ammonia nitrogen and suspended solids (<0.45 µm), according to the following approved analysis methods: MA. 303-P 5.0, MA. 303 – N tot 1.0, MA. 104 – S.S. 1.1.

Data processing

The precipitation, water flow and water quality data were combined in order to perform the various hydrological analyses.

To properly characterize the link between precipitation and runoff, the rainfall events were analyzed to determine the water depth, the mean and maximum intensity over a 5-minute period, and the inter-event period. Increased runoff flows[1] entering pond 3 were analyzed to determine the peak flows and total volumes of increased runoff. The combined precipitation depth and runoff data were used to calculate the increased runoff coefficients.

A comparative analysis of the flows and volumes entering and leaving the pond was undertaken subsequently to characterize the impact of pond 3 on peak flows, the drawdown time of the runoff volumes and the lag time (related to the pond's detention capacity). Percent reduction in peak flow was calculated for each event retained using equation 2.

Equation 2: Percent reduction in peak flows

$$\%\ \text{reduction in } Q = \frac{(Q\ \text{inflow} - Q\ \text{outflow})}{Q\ \text{inflow}} \times 100$$

where:
Q = peak flow

The drawdown times for the outflow hydrographs were analyzed in relation to the outflow volumes and calculated by taking the difference between the maximum volume reached and the time when the outflow volume corresponded to 50%, 75%, 90% and 100% of the total volume of the outflow hydrograph. The impact on lag time was determined by analyzing the pond's detention capacity. Detention time, representing the mean delay in the flood wave due to the pond in comparison with the evacuation of water from a field, was determined for each hydrograph by calculating the time difference between the centre-of-mass of the inflow hydrograph and the centre-of-mass of the outflow hydrograph.

Lastly, the flow data were combined with the concentration data in order to determine the loads entering and leaving pond 3. These loads were divided by the corresponding volumes in order to obtain the event mean concentrations (EMC). The EMC values represent the event-based loads weighted by the volume associated with the event.

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[1] The expression "increased runoff" has been used, since part of the volume of water entering pond 3 consists of groundwater inflows.

To determine the efficiency ratio, EMC values were calculated for each event at the inlet and outlet of pond 3 using equation 3.

Equation 3: Event mean concentration (EMC)

$$EMC = \frac{\sum_{i=1}^{n} V_i * C_i}{\sum_{i=1}^{n} V_i}$$

where:
EMC = event mean concentration
V_i = runoff volume for period *i*
C_i = mean concentration for period *i*
n = total number of measurements taken during the event

The mean inlet and outlet EMCs were then calculated according to equation 4:

Equation 4: Arithmetic mean of EMCs

$$mean\ EMC\ = \frac{\sum_{j=1}^{m} EMC_j}{m}$$

where: *m* is the number of events

Lastly, the efficiency ratio was calculated for each contaminant and for all events retained, using equation 5:

Equation 5: Efficiency ratio (ER)

$$ER = \frac{mean\ inflow\ EMC -\ mean\ outflow\ EMC}{mean\ inflow\ EMC}$$

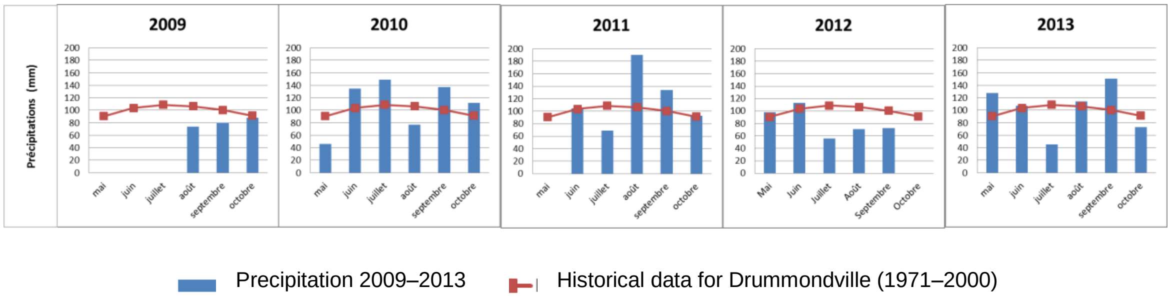
The above methodology complies with the United States Environmental Protection Agency recommendations for determining the stormwater management practices efficiency ratio (EPA, 2002). This methodology weights EMCs from all storms equally, regardless of relative storm magnitude, in order to avoid the situation where a small number of large storms dominate efficiency. The efficiency ratio is the most commonly used method to date (EPA, 2002).

RESULTS AND DISCUSSION

Precipitation characteristics

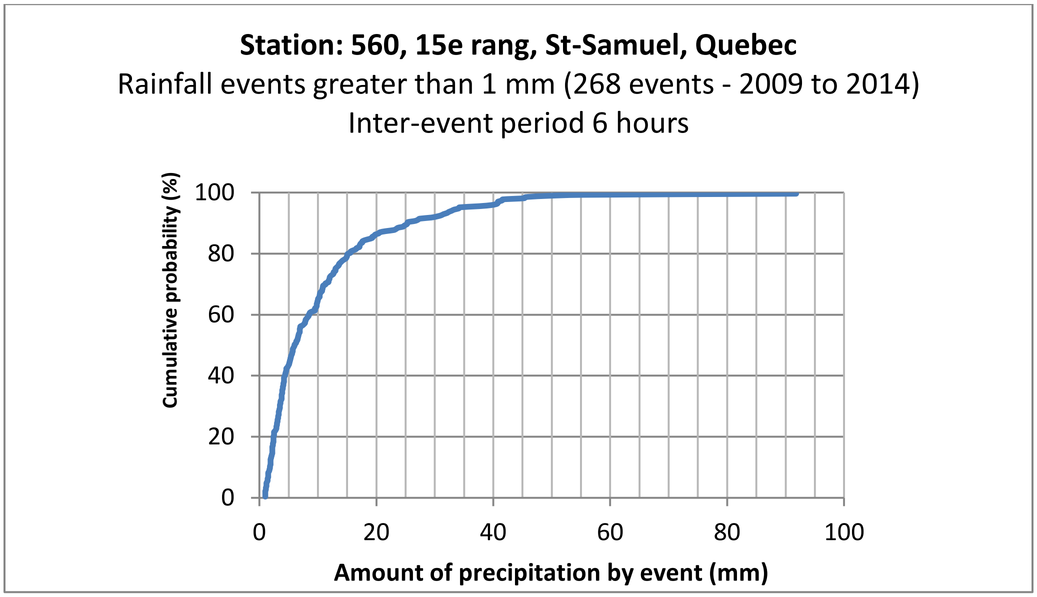
The characteristics of precipitation events are particularly important in the analysis of hydrological systems. The inter-event period, the depth of water produced, and precipitation duration and intensity can influence the observed hydrological responses. Annex 3 presents the characteristics of the rainfall events retained along with the hydrological responses measured at pond 3 as of September 2009. Graph 2 shows the monthly precipitation from 2009 to 2013 along with the historical means for the Drummondville station (Environment Canada Station No. 7022160). The year 2012 was the driest year during the monitoring period, with values slightly below historical values, whereas August 2011 was the rainiest month and stands apart from the historical mean for that month. This difference can be explained mainly by the event of August 28, 2011, the most significant event during the measurement period with a water depth of 91.8 mm.

Graph 2: Mean monthly precipitation from 2009 to 2013 compared to the historical means for the Drummondville station

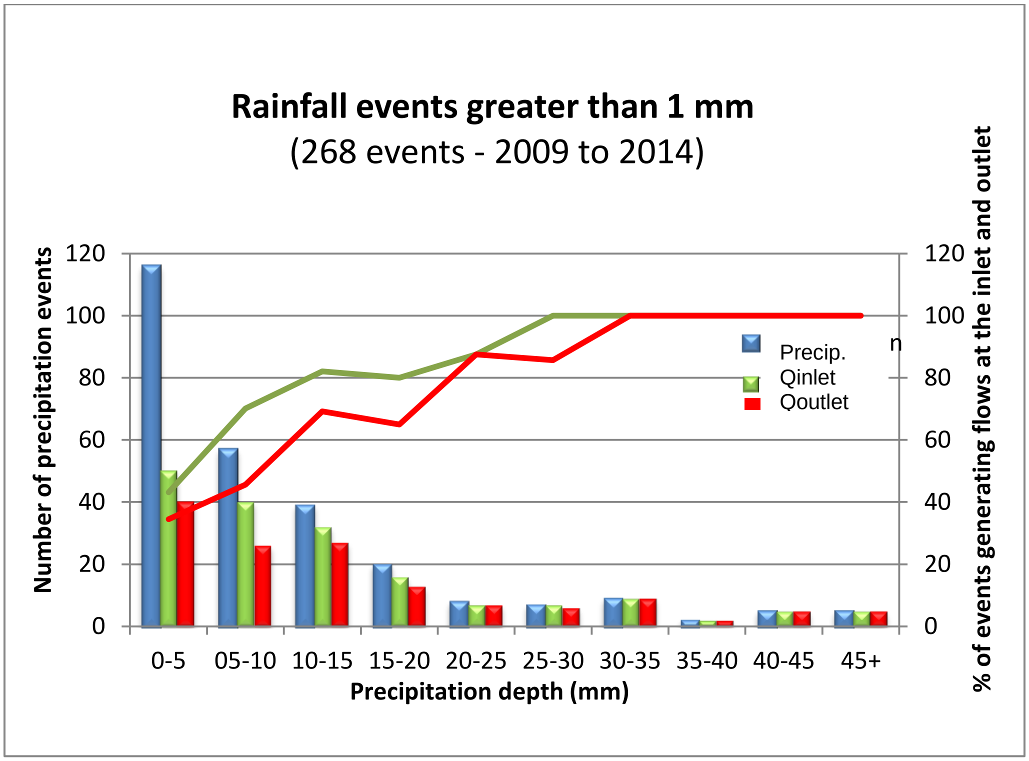


The design criteria set out in the Quebec stormwater management handbook entitled *Guide de gestion des eaux pluviales du Québec* (MDDELCC, 2011) specify that facilities should be able to treat 90% of precipitation events on average in a given area. In a study by Aquapraxis (2011), rainfall depth corresponding to 90% of annual events consists of rainfall events of 23 mm or less occurring on an annual basis at the Drummondville station. A total of 1,341 events were measured there between 1967 and 2000. During the monitoring period for this project, 90% of the 268 rainfall events generated less than 25 mm of rainfall (Graph 3). This observation indicates that the study period is representative of historical climatic conditions.

Graph 3: Cumulative distribution of precipitation measured on the study site



Graph 4: Frequency of events producing inflows and outflows



Hydrological response

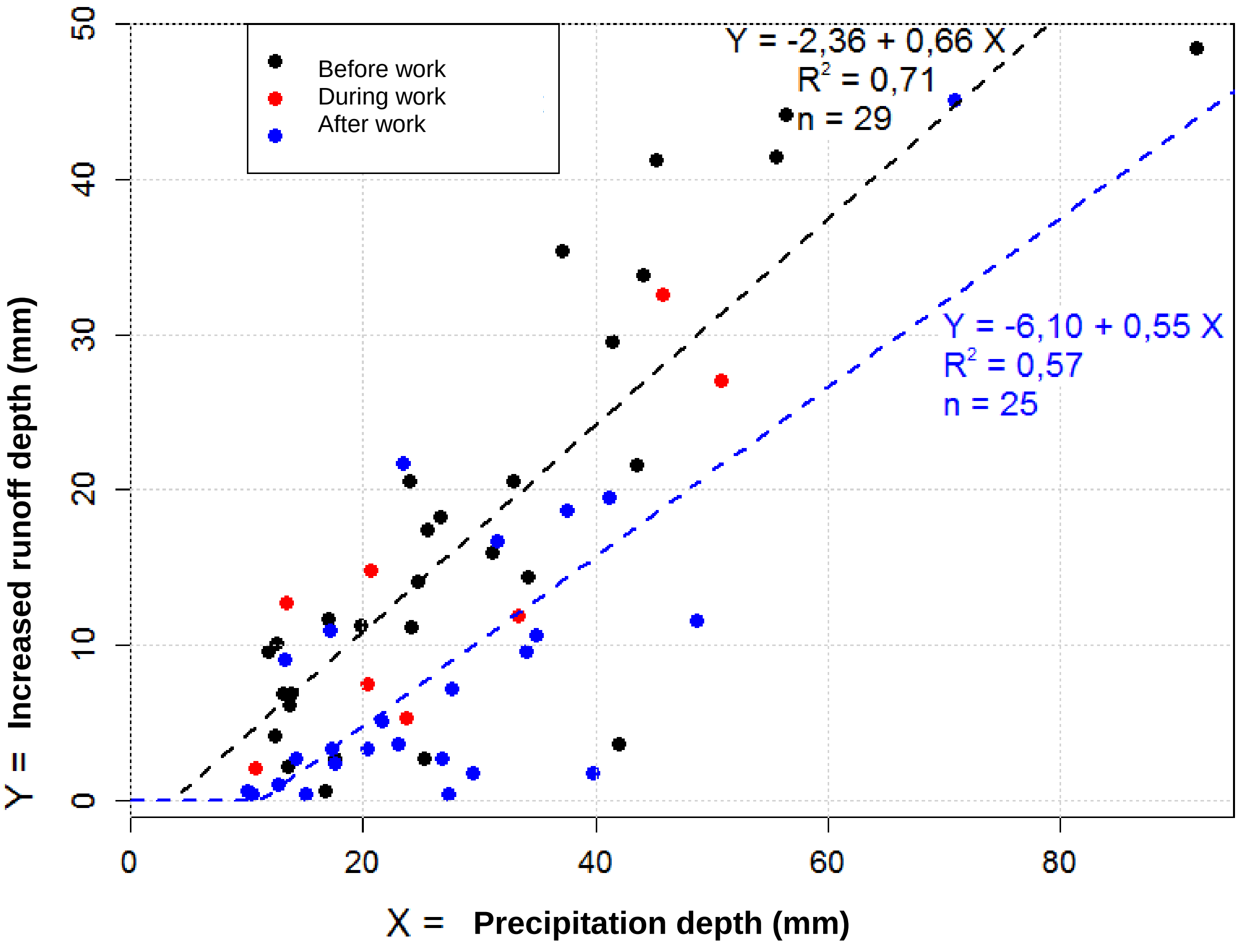
Graph 4 shows the relationships between precipitation and the inflows and discharge (outflows) at the outlet of pond 3. It can be seen that small events (1 to 5 mm) with a high frequency generate flows at the inlet and outlet in about 40% of cases. All rainfall events of 25 mm and over generate flow at the inlet, and all rainfall events of 30 mm and over generate discharge.

At the experimental site, surface runoff cannot be measured directly because of the many different points of entry into pond 3. As described in the methodology section, inflows are determined from water depth data in the pond by inverse routing. Interflows and groundwater inflows contribute to an increase in water depth in the system and therefore to the runoff coefficients obtained. Since the coefficients estimated for the study site incorporate a fraction of groundwater flow, the expression “increased runoff coefficient” (C*) was used in this report. In addition to the effect of groundwater inflow, it is important to note that the values of C* and intercepted precipitation, that is, the minimum amount of precipitation required to produce runoff (P_i), are influenced by the procedure used to select events for analysis. More specifically, only events of 10 mm and over were integrated into the analysis of hydrological response.

Graph 5 illustrates the increased runoff (Hru*) and precipitation values observed between 2009 and 2013. The effect of the levelling work done in fall 2011 and spring 2012 on C* and P_i can be seen.

The levelling work increased the threshold value of P_i from 3.6 to 11.2 mm on average. In addition, the mean value of C* estimated at the experimental site decreased by half, from 55% prior to the levelling work to 28% afterwards. Note that this decrease may be attributable to the fact that slightly larger rainfall events occurred before the work was carried out. Mean precipitation during the retained events decreased from 29.9 mm to 26.6 mm. This difference between the pre- and post-levelling precipitation is not statistically significant. Realistically, reworking of the upper soil layer during levelling may have caused a decrease in soil bulk density, thereby promoting infiltration, an increase in the amount of precipitation intercepted, and a decrease in the increased runoff coefficient. On the other hand, one must note that the land levelling work significantly increased the contaminants concentrations measured at pond 3 inlet and outlet. These observations are discussed in more depth at the “Impact on water quality” section.

Graph 5: Increased runoff depth as a function of precipitation depth



The P_i values obtained (3.6 and 11.2 mm) in this study are lower than the P_i value of 13 mm reported by Madramootoo (1988) for a small watershed on the St. Lawrence Lowlands of 8.1 km^2. The C* values estimated for pond 3 (28% and 55%) are higher than the runoff coefficients obtained in the studies by Madramootoo (1988) and Guillou (2013) for a 445-hectare agricultural micro-watershed located in the Montérégie region of Quebec. In those studies, the mean runoff coefficients were 23% and 14%, respectively. The differences between the values obtained in the present study and those reported in the literature can be attributed in part to differences in the drainage area. In fact, many studies have shown that runoff coefficient decrease when the drainage area is increase. The differences between the C* values obtained in the present study and those reported by Madramootoo (1988) and Guillou (2013) can also be explained by the differences in event characteristics, the physiography of the drainage basins, the nature of the soils and the groundwater inflows (which contribute significantly to the volumes moving through pond 3). For stormwater and flow regulation ponds that are hydraulically connected to underground flows, we therefore recommend the use of an increased runoff coefficient (C*), as this coefficient better reflects the actual volumes associated with precipitation events.

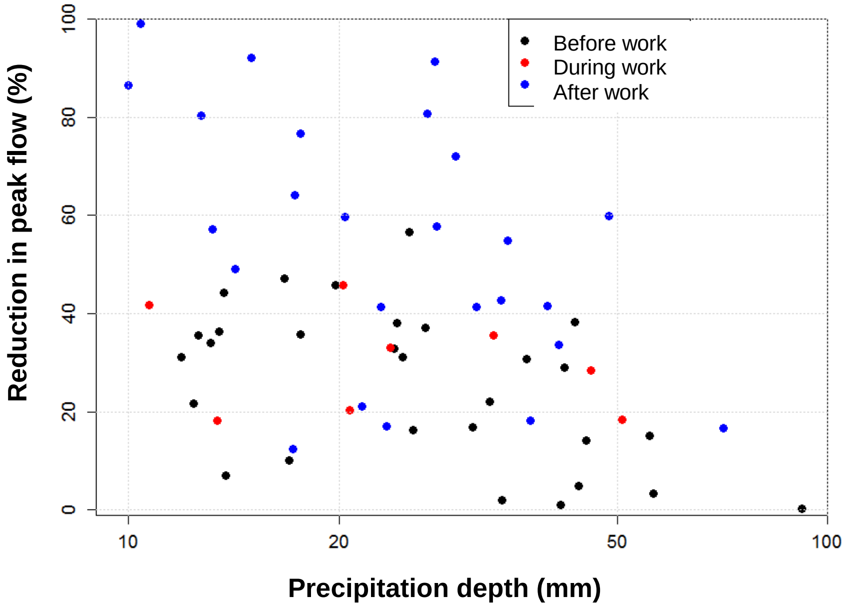
Impact on peak flows

The erosion of streambanks and the channel bed has been linked to peak flows. Morphogenetic flows (bankfull discharge) are generally considered to have the greatest influence on stream morphology and erosion processes. These flows have a return interval of 1 to 1.5 years. Since one of the main purposes of stormwater treatment and flow regulation ponds is to reduce the peak flow and thus minimize the impact on receiving streams, the design criterion for erosion control for such ponds is established based on the runoff generated by a 1-year storm event. This runoff corresponds to precipitation equivalent to 75% of a SCS Type II 2-year storm event lasting 24 h, which amounts to 36 mm for the study site (Aquapraxis, 2011).

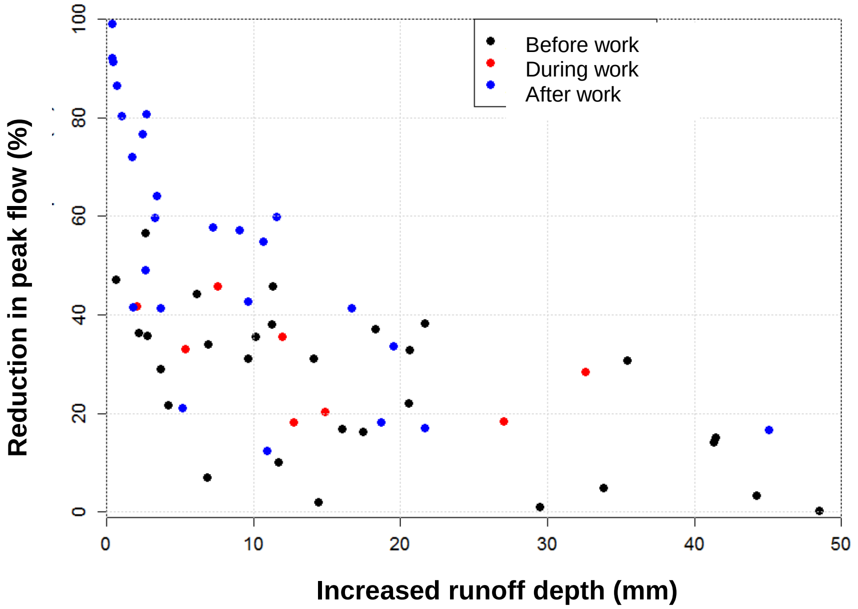
Graph 6 illustrates the reduction in peak flow estimated as a function of precipitation depth for the 62 events greater than 10 mm. Percent reduction in peak flow shows a negative correlation with precipitation depth (Kendall τ of -0.27; observed threshold = 0.002). For a given precipitation depth, the rate of reduction is generally greater for events that occurred after the levelling work was done. The mean reduction rates are 25% and 55%, respectively, for events before and after the levelling work.

Graph 7 shows that percent reduction in flow has an even stronger negative correlation with Hru* entering pond 3 (Kendall τ of -0.55; observed threshold < 0.001). The reduction rates cover almost the entire range of potential values, from about 0% for the most intense event to almost 100% for the smallest runoff values.

Graph 6: Reduction in peak flow as a function of precipitation depth for the 62 events retained



Graph 7: Reduction in peak flow as a function of increased runoff depth for the 62 events retained



Equation 6 is used to determine whether the observed reductions in peak flow can reduce erosion problems in the receiving stream. This equation established by Bagnold (1966) indicates that specific stream power is the rate of energy dissipation against the bed and banks of a stream per unit channel width.

Equation 6: Specific stream power

$$\omega = \frac{pgQS}{w}$$

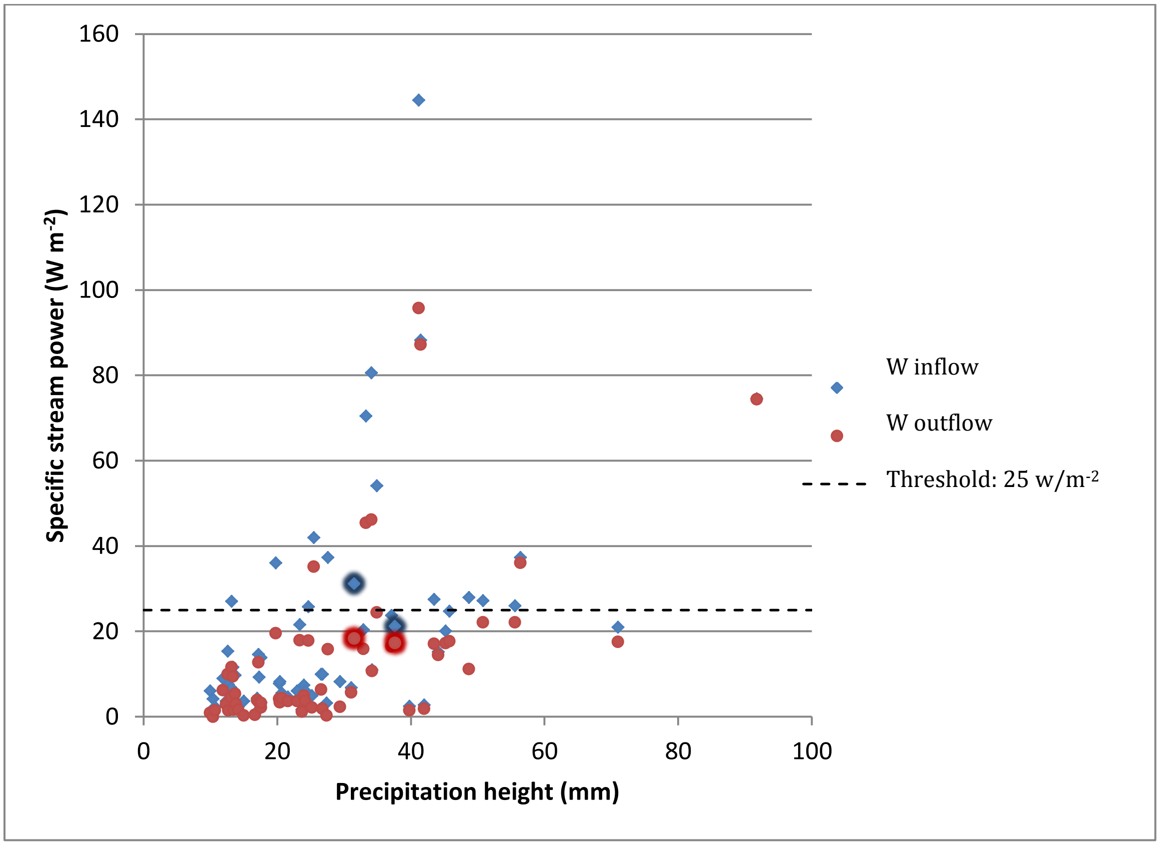
where: ω is specific stream power (W/m^2), p is the density of water (kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), Q is the flow (m/s), S is the slope of the water, and w is the channel width (m).

Thus, for a given site, when the values of S and w are constant, specific stream power is directly proportional to peak flow. According to Brookes (1987), an erosional adjustment occurs when specific stream power exceeds 25 W m^{-2}. Graph 8 illustrates specific stream power at the outlet of pond 3 calculated from the peak inflows and outflows. Peak inflows were used to represent the conditions existing prior to the construction of pond 3. The frequency of exceedance of the erosion threshold declines from 27% (17/62) when peak inflows are considered to 11% (7/62) when outflows are considered.

The event of June 2, 2012 (37.6 mm, duration 33 h) presents characteristics approaching the design rainfall associated with morphogenetic flow (SCS type II, 36 mm, duration 24 h). During this event, specific stream power reached 21 W m^{-2} at the inlet and 17 W m^{-2} at the outlet. Although not quite equivalent to the design rainfall, the event of September 21, 2013 (31.5 mm, duration 20 h) showed ω values of 31 W m^{-2} at the inlet and 18 W m^{-2} at the outlet. These points are highlighted on Graph 8.

Pond 3 is therefore likely to reduce erosion in the receiving stream by reducing the frequency of exceedance of the erosion threshold and by decreasing specific stream power below 25 W m^{-2} during events representative of morphogenetic flow (bankfull discharge). It should be noted, however, that the outflow from pond 3 is the only source of inflow to the receiving stream. In the case of facilities installed in larger drainage basins, the entire flow of the stream downstream from the structure must be used to evaluate specific stream power and the potential for reducing erosion.

Graph 8: Specific stream power as a function of precipitation depth



Impact on drawdown time

In addition to their effect on peak flows, an important characteristic of stormwater and flow regulation ponds relates to their ability to delay the evacuation of water. The design criteria for the ponds were established in keeping with two key objectives: protection of water quality and attenuation of erosion in the receiving stream. For the quality criterion, it is recommended that the volume of water captured during a 25-mm rainfall event be released over a period of at least 12 hours. The criterion related to erosion in the receiving stream stipulates that the volume associated with a 1-year rainfall event will be released over at least 24 hours (Aquapraxis, 2011). Drawdown time is defined as the period between the maximum volume reached during an event and the return to the minimum active storage volume.

To better assess storage dynamics, the drawdown times measured in this study were subdivided into four categories: the time between the maximum volume and the time when 50%, 75%, 90% and 100% of the volume has been released, known as drawdown time. The corresponding drawdown times for pond 3 are 7, 18, 28 and 42 hours. Since the outlet hydrographs show very elongated tails (10% of volume released in 14 hours on average), the category corresponding to the time at which 90% of the volume has been released has been used for comparisons with the design criteria. Therefore, the drawdown time for short duration (between 2 and 6 hours) events generating about 25 mm of rain is 24.5 hours for pond 3, which meets the design criterion set for water quality (i.e., 12 h). It should be noted that several studies related to construction sites recommend a minimum drawdown time of 24 hours for enhanced control of effluent quality (TRCA, 2006).

The event of June 2, 2012 (37.6 mm, duration 33 h), which is representative of the design rainfall event for erosion control, had a drawdown time of 14.25 hours for 90% of the volume. During more significant events, a high proportion of the runoff volume is released quickly through the top of the perforated riser, which decreases drawdown time. Pond 3 does not meet the criterion of 24 hours of retention for this 1-year event.

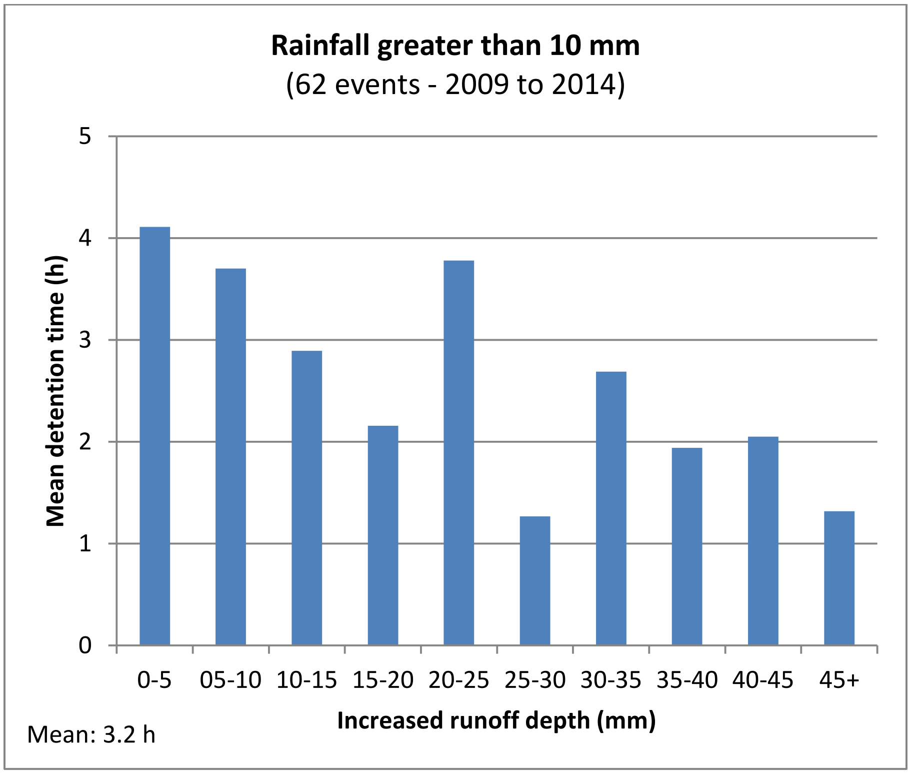
Impact of detention on lag time

As described in the methodology section, detention time corresponds to the time difference between the centre-of-mass of the increased runoff hydrograph and the centre-of-mass of the outflow hydrograph.

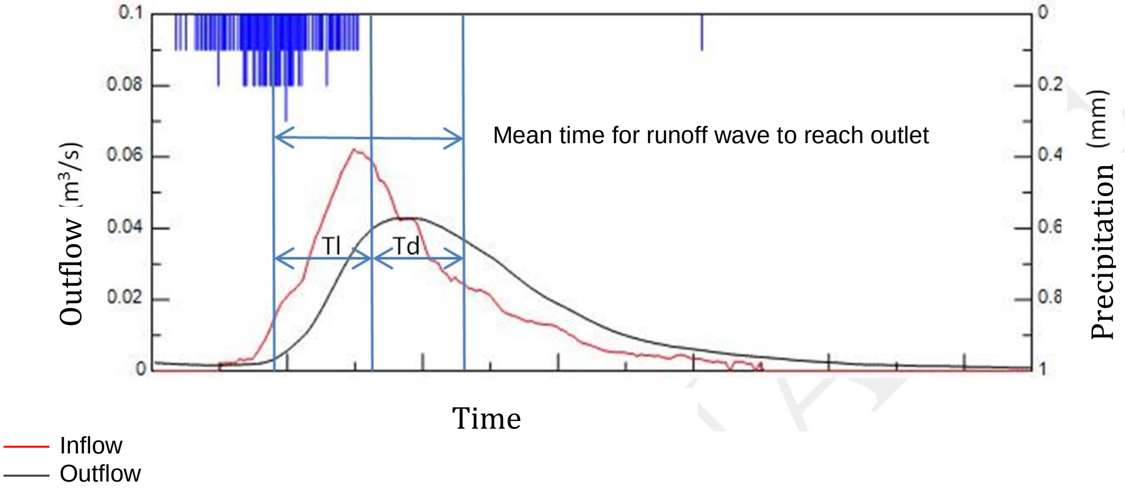
Graph 9 illustrates the mean detention time for each Hru* category. Detention time is negatively correlated with increased runoff and ranges from 4.1 hours to 1.3 hours, for an average of 3.2 hours. According to Cappuccitti and Page (2000), a detention time of 24 hours for the runoff volume generated during a 1-year return event can sufficiently attenuate release velocities so that they remain below the critical velocities causing erosion in receiving streams. The detention time for the event of June 2, 2012, which is representative of a 1-year return interval, is 2.1 hours, which is much lower than the recommended value.

These observations can, however, be placed in perspective by comparing the mean detention time of pond 3 with the physical characteristics of its drainage basin and, more specifically, the lag time. The lag time (Tl) of a watershed is defined as the mean time it takes the runoff wave to reach the outlet. This parameter corresponds to the time interval between the centre-of-mass of storm precipitation and the centre-of-mass of the resulting runoff (Ponce, 1989). Graph 10 illustrates the lag time of the drainage basin (Tl) and the detention time (Td) in pond 3. This example shows that the lag time added to the detention time corresponds to the average time it takes the runoff wave to reach the outlet of the stormwater treatment pond.

Graph 9: Mean detention time as a function of increased runoff depth



Graph 10: Graphical representation of lag time (Tl) and detention time (Td)



The mean Tl for 7 simple events is 3 hours 24 minutes for pond 3, and the mean Td is 2 hours 42 minutes, which gives a mean time to outlet of 6 hours 6 minutes. Since estimated runoff is influenced by groundwater flows, lag time is likewise influenced by those flows. Since interflow and groundwater inflow are slower than surface runoff, the centre-of-mass values calculated for inlet hydrographs are displaced toward the end of the events, which results in an increase in Tl. As described by Sheridan (1994), the theoretical Tl values calculated for the drainage basin of pond 3 using the methods of Nash, Capece and SCS, are presented in Table 2: the average is 3 hours 18 minutes, which is very close to the observed mean value. It can thus be concluded that pond 3 is capable of nearly doubling the mean time it takes the runoff wave to reach the outlet. This conclusion is drawn from the observed Tl (3 hours 24 minutes) added to the observed detention time (2 hours 42 minutes).

Table 2: Theoretical lag time for drainage basin 3

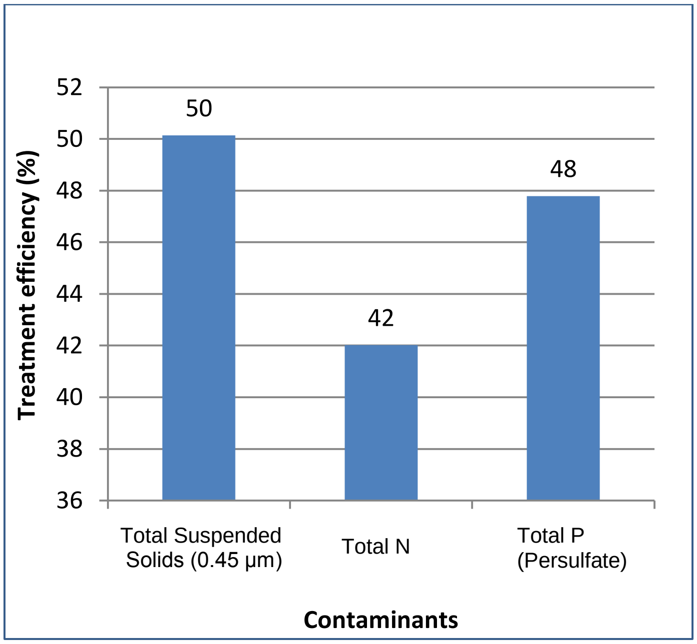
Lag Time (Tl)	
Method	**Calculated Values (h)**
Nash (1959)	4.60
Capece et al. (1988)	3.23
SCS (1972)	1.94

Impact on water quality

Runoff associated with rainfall events is one of the most important sources of water contamination. A stormwater treatment and flow regulation pond is a beneficial management practice (BMP) which is designed mainly to treat runoff in order to reduce the impact on receiving ecosystems. The treatment (removal) efficiency of the present BMP (pond 3) was evaluated for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP).

Detailed results per event are presented in Annex 4. Graph 10 illustrates the mean treatment efficiency rates estimated using equation 4, that is, 50%, 42% and 48% for TSS, TN and TP, respectively (*n* = 20, 11, 14). One must note that removal efficiencies are even higher for these three contaminants when estimated with the sum of all loads methodology (EPA, 2002). These results are not discussed in this report since a small number of large storms, where loads and reduction rates are high, dominate treatment efficiency.

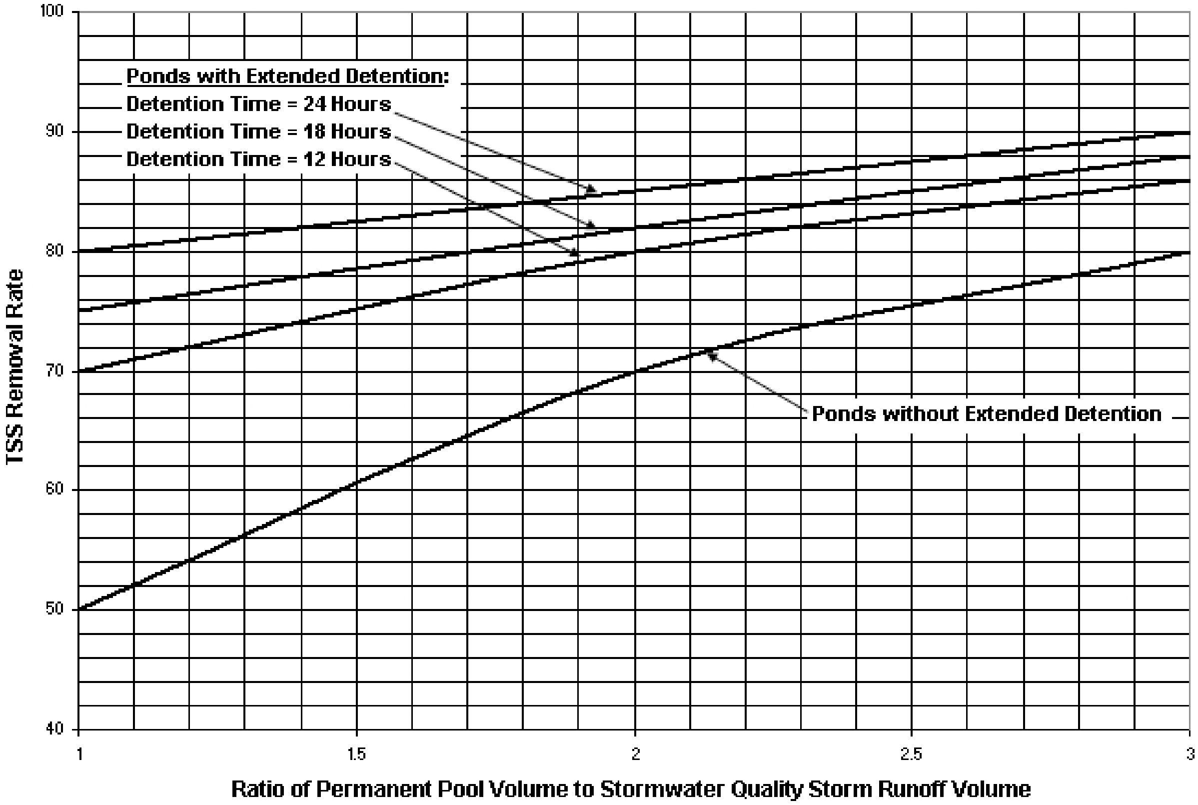
Graph 11: Treatment efficiency for weighted contaminant loads



Suspended solids

In 2004, the Government of the State of New Jersey published a graph that can be used to estimate the potential for treating total suspended solids in a wet pond as a function of the ratio of permanent pool volume to the volume associated with the quality criterion (Graph 12). Using the mean C* measured at the site (44% for the 62 events), the volume of the quality criterion corresponds to 25 mm x 0.44 x 23.1 ha = 2,541 m^3 and the volume of the permanent pool corresponds to 11 m^3/ha (Graph 1) x 23.1 ha, that is, a volume of 254 m^3. Based on Graph 12, the rate of reduction for a pond without extended detention and a ratio of 0.1 should be lower than 50%. The treatment efficiency of pond 3, i.e., 50% (Graph 11), exceeds the standards established by the State of New Jersey. This performance can be attributed to the detention time, which falls between the 12-hour curve and the curve without detention, and to the procedure used to select precipitation events. This procedure targets heavy rainfall events generating high inflow concentrations, for which the rates of reduction are generally higher. Despite the high efficiency ratio, the treatment performance of pond 3 could be increased further by extending the detention time or increasing the volume of the permanent pool (Graph 12).

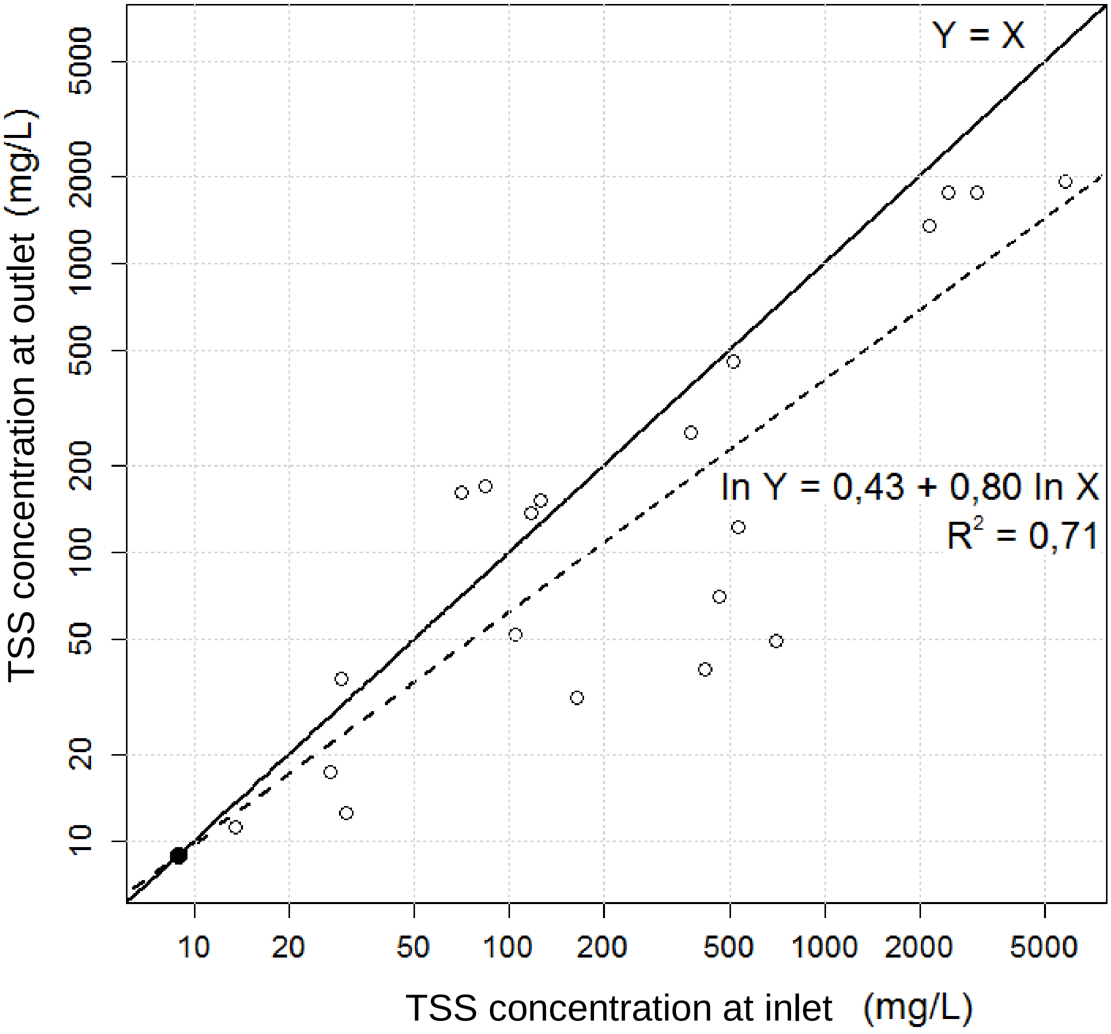
Graph 12: Rates of reduction of total suspended solids for wet ponds (adapted from New Jersey, 2004)



Although the mean efficiency ratio for suspended solids was 50% (Graph 11), it varied greatly among events, ranging from 92% to negative values (i.e., mean outflow concentration exceeding mean inflow concentration) for 5 of the 20 events retained (Annex 4). Graph 13 presents the TSS concentrations at the inlet and outlet of pond 3 for these 20 events. It should be noted that the four highest inlet and outlet concentration values come from the first four events of 2012: the first three occurred during the levelling work and the fourth a few weeks later.

The relationship between the logarithm of total suspended solid concentrations at the inlet (SS_{in}) and the outlet (SS_{out}) can be expressed by a linear equation (Graph 13, dashed line).

Graph 13: Total suspended solids (TSS) concentrations at the inlet and outlet of pond 3 for the 20 events retained



The efficiency ratio is therefore dependent on the inflow concentration and can be estimated by $1-\frac{e^{a}}{SS_{\text{in}}^{1-b}}$, with *a* = 0.43 and *b* = 0.80 (Graph 13). Treatment efficiency increases with increasing inflow concentration. For example, for an inflow concentration of 100 mg/L, the outflow concentration should be 62 mg/L on average (efficiency ratio = 38%), whereas for an inflow concentration of 1,000 mg/L, the outflow concentration should be about 390 mg/L on average (efficiency ratio = 61%). In addition, according to the above equation, the efficiency ratio should be negative for inflow concentrations below $e^{\frac{a}{1-b}}$, that is, about 9 mg/L (Graph 13, solid line). This value can be seen as an approximation of the *irreducible* pollutant concentration reported by Scheuler (2000). The values presented in Table 3 summarize the irreducible concentrations, that is, concentrations below which treatment in a wet pond becomes ineffective.

Table 3: Irreducible effluent concentrations

Contaminant	**Scheuler (2000)**	**Pond 3**
Total suspended solids	20 to 40 mg/L	9 mg/L
Total phosphorus	0.15 to 0.2 mg/L	0.2 mg/L
Total nitrogen	1.9 mg/L	2 to 4 mg/L

Several studies found similar relationships between the inflow and outflow concentrations of stormwater ponds; however, according to TRCA (2006), effluent quality is influenced to a greater extent by inflow/outflow volumes and peak flows. Pond volume was much greater in the TRCA study (2006) than in the present study, which explains the lower correlation obtained in that study between inflow and outflow concentrations. In addition, as stated in SWAMP (2005) the efficiency ratio is a biased indicator of performance, as it varies with inflow concentrations. Thus, although major reductions can be achieved, effluent quality may continue to have a negative impact on receiving ecosystems.

To assess the potential for impacts on aquatic receiving ecosystems, the volume-weighted event contaminant loads (or the event mean concentration, EMC) can be compared to the corresponding established environmental guideline values. Table 4 presents the environmental guideline limit values chosen for this comparison along with the frequency of exceedance.

Table 4: Number of exceedances of environmental guideline limit values at the inlet and the outlet of pond 3

Environmental thresholds	Impact	# of observed exceedances (EMC)	
		inlet	outlet
Total suspended solids[1]		***n*** = 20	
<25 mg/L	Very low risk	1	3
25–80 mg/L	Low risk	4	6
80–400 mg/L	Moderate risk	6	6
> 400 mg/L	High risk	9	5
Total phosphorus[2]		***n* = 14**	
<4 µg/L	Ultra-oligotrophic	0	0
4–10 µg/L	Oligotrophic	0	0
10–20 µg/L	Mesotrophic	0	0
20–35 µg/L	Meso-eutrophic	0	0
35–100 µg/L	Eutrophic	3	2
>100 µg/L	Hyper-eutrophic	11	12
30 µg/L[3]	Prevention of eutrophication	14	14
Nitrate		***n* = 10**	
10 mg/L[4]	S/O	0	0
13 mg/L[2]	Chronic toxicity	0	0
550 mg/L[2]	Acute toxicity	0	0
Nitrite[2]			
60 µg/L	Toxicity evaluated in salmonid populations	2	6
Ammonia nitrogen[2]		***n* = 5**	
19 µg/L (NH_3)	Chronic toxicity	5	5

[1] Threat to fish and their habitats according to the EIFAC (1965)
[2] CCME, guideline for the protection of aquatic life
[3] MDDELCC, criterion for the prevention of eutrophication
[4] MDDELCC, maximum acceptable concentration defined for drinking water

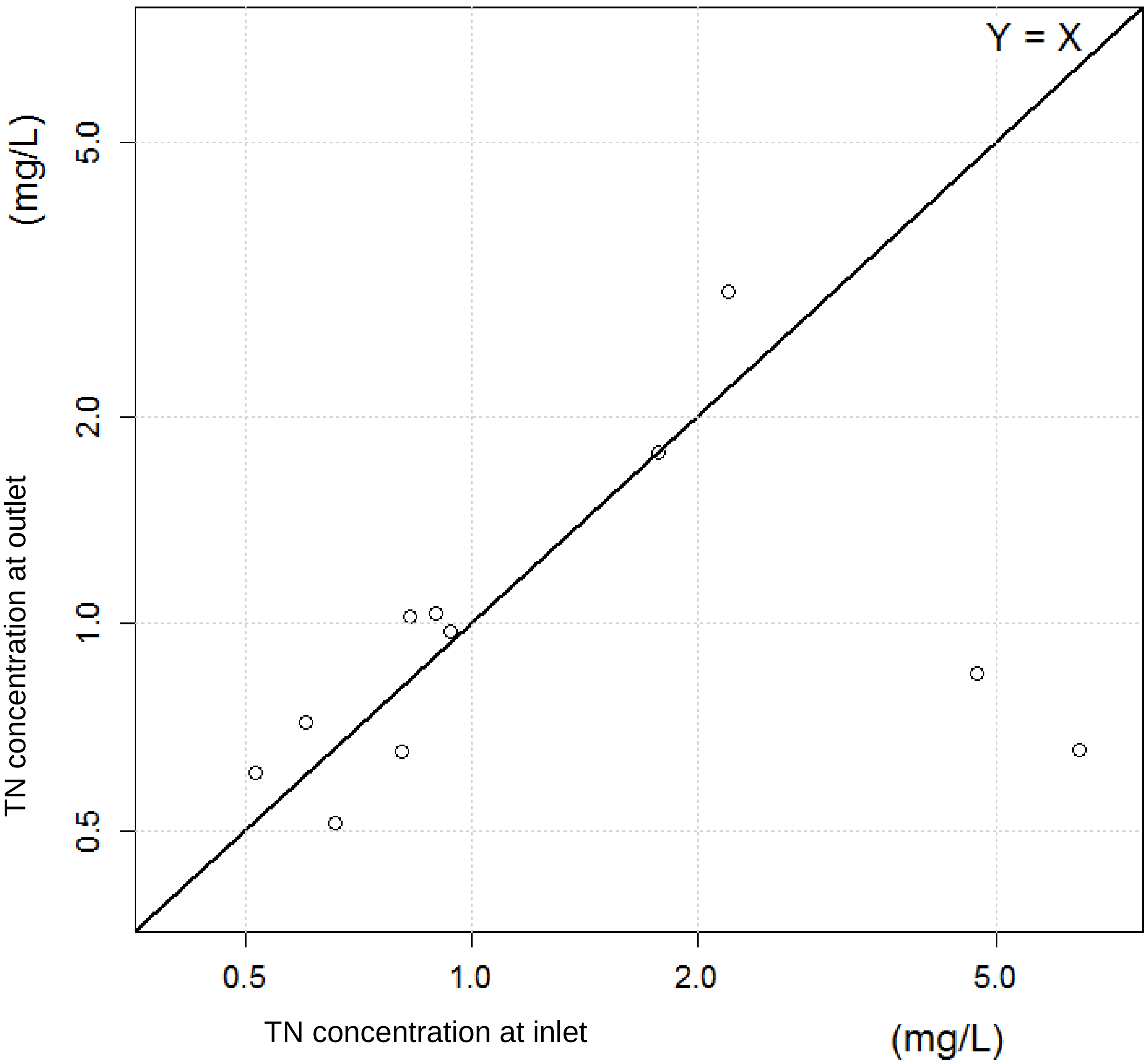
The water quality criteria for suspended solids established by the European Inland Fisheries Advisory Commission (1965) are often exceeded. Effluent quality is therefore likely to have an adverse impact on fish and their habitats. However, the level of risk ranges from moderately high in the absence of a pond to moderate at the outlet of pond 3. With respect to the observed exceedances, no assumption was made concerning a dilution effect in the receiving stream, since it is an intermittent creek supplied solely by pond 3. The impact on aquatic fauna and flora could be evaluated at the next Strahler stream order level. In the case of pond 3, the next order corresponds to the Nicolet River, which has an annual mean discharge of 33.3 m^3/s. Since the flow rates in pond 3 are two to three orders of magnitude lower than the mean discharge of the Nicolet River, it is unlikely that pond 3 would have an impact, either positive or negative, at that scale. To maximize the potential impact on the quality of aquatic ecosystems, stormwater treatment and flow regulation ponds should be constructed in an integrated manner at the small agricultural watershed scale.

Nitrogen

The small number of rainfall events ($n = 11$) makes it difficult to estimate the efficiency ratio for total nitrogen. In most cases, the inflow concentrations are too small to detect a treatment effect (Graph 14). Only the two events with higher total nitrogen concentrations at the inlet (4.71 and 6.45 mg/L) show high efficiency ratios, that is, 82% and 90%, respectively. For the other events, excluding one event with a ratio of -47% (mean concentrations at the inlet and outlet of 2.20 to 3.03 mg/L, respectively), the efficiency ratio is about 0 ± 25%. These results suggest that the irreducible concentration level lies between 2 and 4 mg/L, which is close to the value reported by Scheuler (2000) (Table 3). The mean efficiency of 42% estimated for all the events taken together (Graph 11) should therefore be interpreted with caution.

The environmental criteria for nitrogen encompass nitrate, nitrite and ammonia nitrogen. The concentrations measured at the study site combine nitrite and nitrate in a single value. The measured nitrite/nitrate concentrations do not exceed the nitrate guideline limit for the protection of aquatic life (Table 4). There are 6 exceedances of the guideline limit for nitrite; however, here again, the measured concentrations combine nitrate and nitrite. Therefore, it is impossible to determine the actual number of exceedances for nitrite. All measured concentrations of ammonia nitrogen exceed the guideline limit for the protection of aquatic life; however, this guideline value varies widely with the characteristics of the outflows. The toxicity of ammonia nitrogen is higher at higher pH values and higher temperatures. For example, at a pH of 10 and a temperature of 20^{o}C, the toxicity threshold for total ammonia nitrogen is 0.020 mg/L, because un-ionized ammonia (NH_3), which is more toxic, is dominant. By contrast, at a pH level of 7 and a temperature of 15^{o}C, ammonium (NH_4^+), a less toxic form of nitrogen, predominates, and the threshold is 5.74 mg/L. Under these conditions which are more representative of effluent, the ammonia nitrogen concentrations do not exceed the environmental threshold. It should be noted that the number of events with measured ammonia nitrogen concentrations is very low, that is, 5 events. Furthermore, this toxicity threshold applies to long-term exposures (chronic toxicity), whereas the sampling in this study was conducted during rainfall events likely to generate appreciable concentrations of contaminants but only for a short time period.

Graph 14: Total nitrogen (TN) concentrations at the inlet and outlet of pond 3 for the 11 events retained



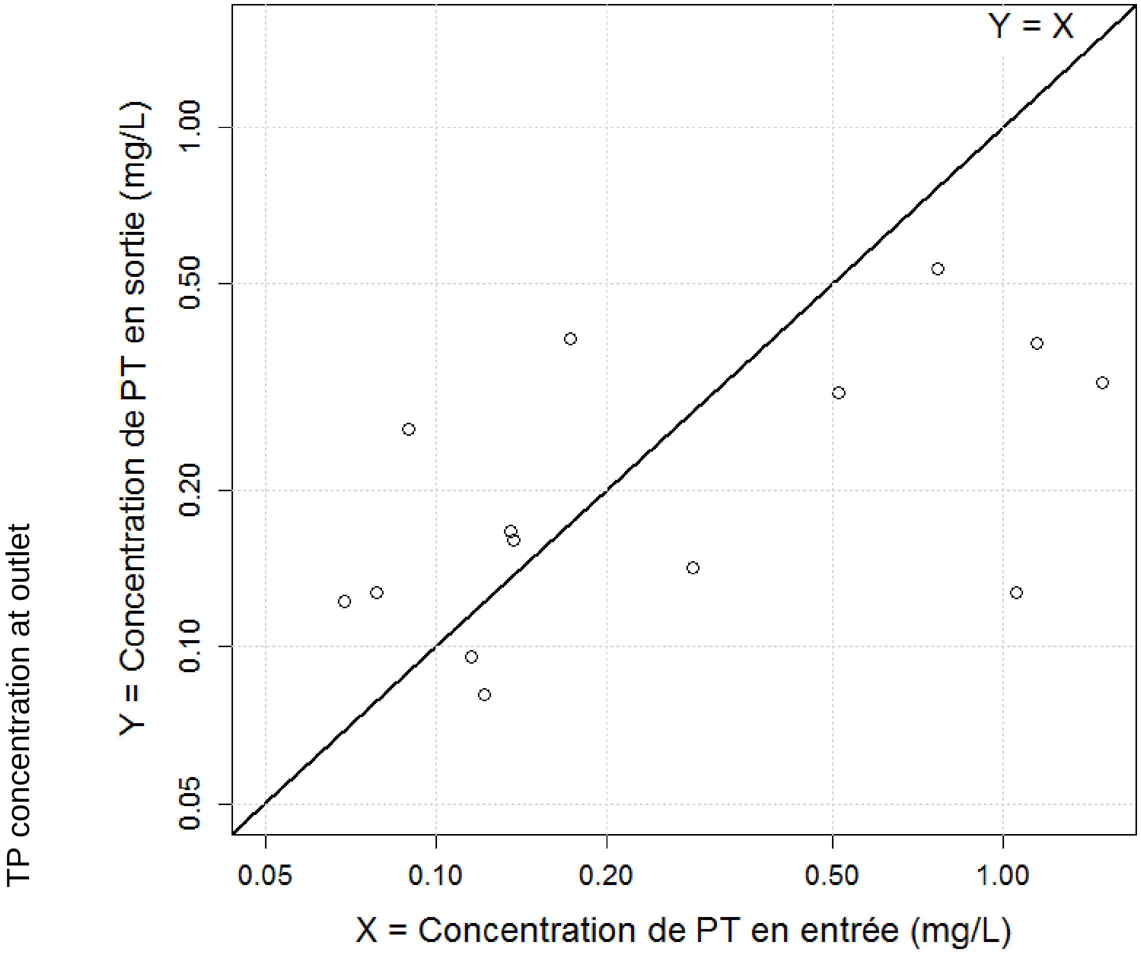
Phosphorus

As illustrated in Graph 11, the mean removal efficiency for total phosphorus is 48%. In addition, Graph 15 shows the correlation between inflow and outflow concentrations of total phosphorus. At the event level, removal efficiency increases with an increase in the incoming concentration; however, not enough data are available (*n* = 14) to properly estimate the relationship between these two variables. The six events with the highest mean inflow concentrations, ranging from 0.28 to 1.49 mg/L, all gave efficiency ratios greater than 30%. The three events with mean inflow concentrations ranging from 0.28 to 1 mg/L gave a mean efficiency ratio of 40%, whereas the three events with mean inflow concentrations greater than 1 mg/L gave a mean efficiency ratio of 78%. For seven of the eight events with mean inflow concentrations below 0.18 mg/L, the efficiency ratio is lower than 30% and it is negative in most cases. These results suggest that the irreducible concentration level is about 0.2 mg/L, which corresponds to the upper limit reported in Scheuler (2000) (Table 3).

The removal efficiencies for TP are of the same order of magnitude as those for TSS and point to a strong dominance of particulate phosphorus relative to dissolved phosphorus. This hypothesis was validated during the rainfall events of fall 2008 and during the snowmelt period in spring 2009. Graph 16 illustrates the dominance of particulate phosphorus observed in ponds 1, 2 and 3 as well as in the control drainage basin. Particulate phosphorus accounts for more than 80% of the measured phosphorus concentrations.

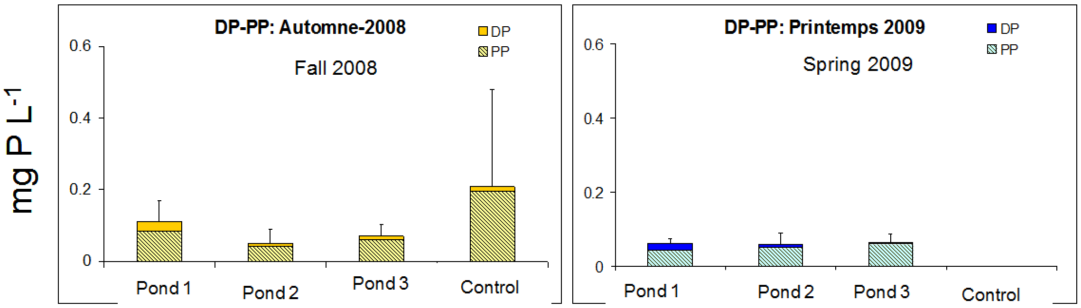
In all cases, the quality of the water discharged from pond 3 exceeds the total phosphorus criterion for the prevention of eutrophication. The inflows show concentrations similar to those found in hyper-eutrophic waters. Despite an efficiency ratio of 48%, the effluent (outflows) likewise present the characteristics of eutrophic to hyper-eutrophic water. Note that the criterion for the prevention of eutrophication (0.03 mg/L) is lower than the irreducible concentration level of 0.15 to 0.2 mg/L. It is therefore unlikely that the environmental criterion, which was established for rivers, will be met at the outlet of a stormwater treatment pond. The exceedances observed in this study are not assumed to undergo a dilution effect in the receiving water body, as it consists of an intermittent stream supplied solely by pond 3. As mentioned in the section on suspended solids, the impact on the aquatic ecosystem should be evaluated at the next Strahler stream order level. To maximize the potential impact on the quality of aquatic ecosystems, stormwater treatment and flow regulation ponds should be developed in an integrated manner at the small agricultural watershed scale, in order.

Graph 15: Total phosphorus (TP) concentrations at the inlet and outlet of pond 3 for the 14 events retained



Graph 16: Particulate and dissolved phosphorus (PP and DP) concentrations in ponds 1, 2 and 3 and at the outlet of the control drainage basin in fall 2008 and spring 2009

TP concentration at inlet



CONCLUSION

To support the development of sustainable agriculture in Quebec, it is necessary to find solutions that can help reduce pollutant exports to aquatic ecosystems and mitigate erosion problems in receiving bodies of water. Stormwater treatment and flow regulation ponds are natural depressions or excavated areas designed to store flood waters temporarily in order to reduce peak flows downstream and permit settling out of contaminants. This type of beneficial management practice has been used in urban settings for a number of years, but very few, if any, such ponds have been constructed in agricultural areas. It is essential to quantify the effectiveness of stormwater treatment and flow regulation ponds under the agroclimatic conditions characterizing Quebec, before deploying this type of BMP in agricultural areas.

This study focused on three agricultural stormwater treatment and flow regulation ponds constructed at St-Samuel (Quebec, Canada) in 2008. Detailed analyses of pond 3 showed the following:

- Peak flows from 62 precipitation events were reduced by 38% on average.

- Pond 3 is likely to reduce erosion in the receiving stream by reducing the frequency of exceedance of the erosion threshold and by decreasing specific stream power below 25 W m^{-2} during events representative of bankfull discharge. It should be noted, however, that this conclusion applies to the intermittent stream for which pond 3 is the only source of inflow.

- Drawdown time, which corresponds to the interval between the peak volume and the time at which 50%, 75%, 90% and 100% of the runoff volume has been evacuated, was 7, 18, 28 and 42 hours, respectively. The measured drawdown times are in keeping with the recommendations for the protection of water quality, but do not meet the criteria for the prevention of erosion in a receiving stream.

- The mean time it takes the runoff wave to reach the outlet doubled with a detention time of 3.2 hours. This average detention time is much lower than the recommended time of 24 hours which generally attenuates release velocities so they remain below the critical velocities causing erosion in receiving streams.

- Removal efficiencies measured using the efficiency ratio method were 50%, 42% and 48%, respectively, for total suspended solids, total nitrogen and total phosphorus (*n* = 20, 11, 14). These mean efficiency rates should, however, be interpreted with caution.

- The correlation analysis revealed the presence of threshold concentrations below which removal efficiency is nil. The irreducible concentrations of suspended solids, total nitrogen and total phosphorus were about 9 mg/L, 2 to 4 mg/L and 0.2 mg/L.

- In general, removal efficiency increases when the inflow loads, weighted by the event-based volume, are greater.

- The levelling work done by the producer in fall 2011 and spring 2012 is likely the reason for the large amounts of sediment exported in 2012. The rate of reduction in peak flows increased from 25% before this work to 55% after it. It would be interesting to see whether levelling continues to have a beneficial effect on peak flows over the coming years.

- In spite of the high efficiency ratios for TSS, TN and TP, the outflow concentrations exceeded the environmental criteria for the protection of aquatic life in the case of TSS, and the criterion for the prevention of eutrophication in the case of TP. No dilution effect was considered for the receiving environment.

- To maximize the potential impact on the quality of aquatic ecosystems, stormwater treatment and flow regulation ponds should be developed in an integrated manner at the small agricultural watershed scale.

These findings indicate that stormwater treatment and flow regulation ponds are an efficient method for reducing peak flows at farm level and for improving runoff quality. In order to improve the environmental performance of the agriculture sector, such ponds should be established in conjunction with conservation tillage practices that reduce soil erosion.

Finally, since climate change scenarios project an increase in the frequency and intensity of extreme hydrological events, stormwater treatment and flow regulation ponds could have a beneficial effect on water quality as soon as they are installed, while their effect on the environment will increase as the impact of climate change increases.

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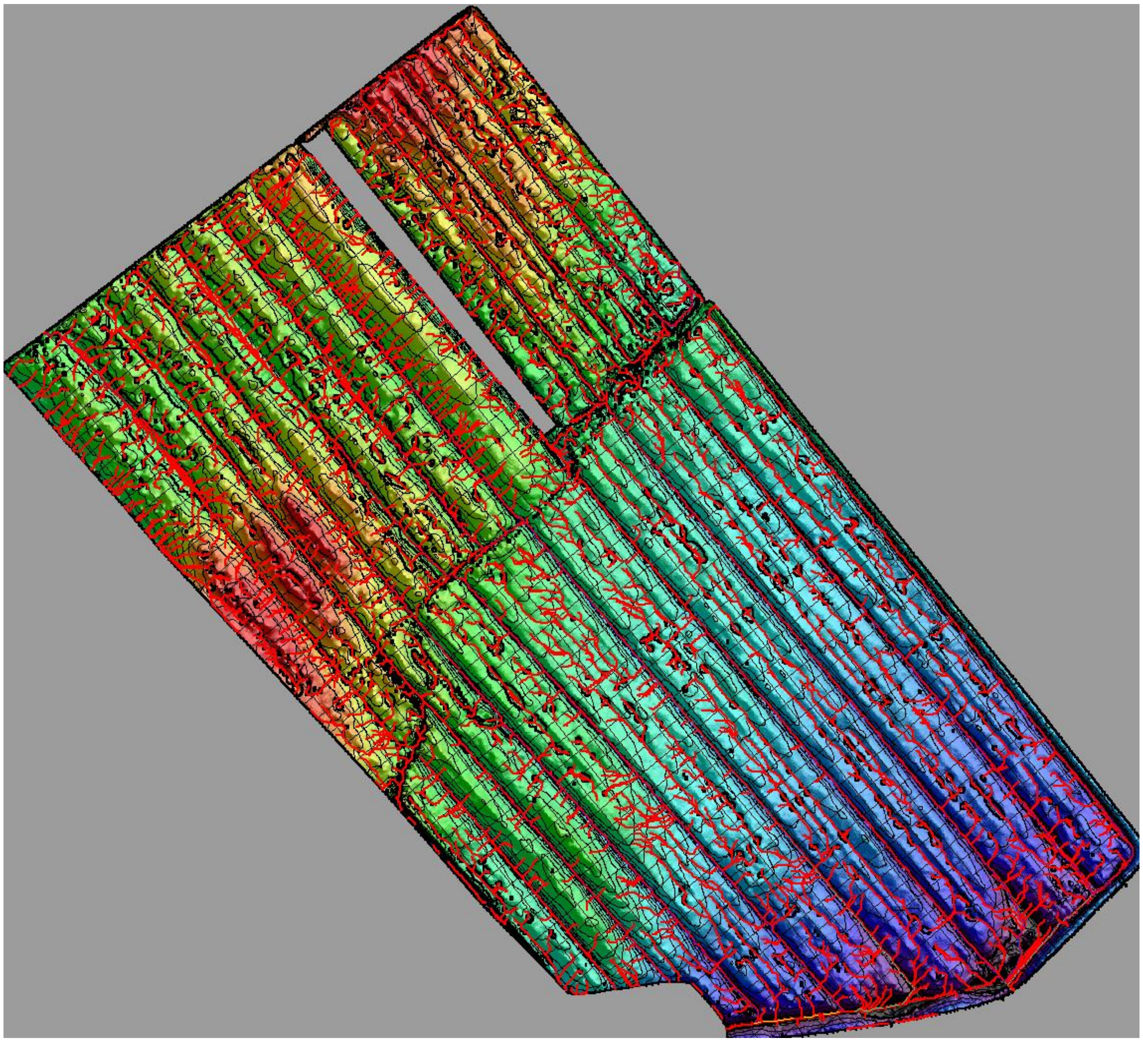
ANNEXES

Annex 1: Experimental site showing the four watersheds

Annex 2: Hydrographic network of the experimental site



Annex 3: Hydrological characteristics of the events measured at pond 3 during the growing seasons from 2009 to 2013.

	Precipitation					Increased Runoff				Effluent		Hydrology		
Start date of event	Inter-event period	Water depth	Duration*	Mean intensity	Volume	Peak flow	Volume	Runoff depth	Increased runoff coefficient	Peak flow	Volume	Reduction in peak flow	Detention time	Drawdown time (100%)
(mm/dd/yyyy hh:mm)	(d)	mm	(h)	(mm/h)	(m^3)	(m^3/s)	(m^3)	(mm)		(m^3/s)	(m^3)	(%)	(h)	(h)
9/27/2009 5:45	0.01	43.5	97	0.45	10049	0.19	4997	21.6	0.50	0.12	5070	38	4.5	85
10/7/2009 4:40	0.01	24.0	99	0.24	5544	0.05	4764	20.6	0.86	0.03	4924	33	6.9	111
10/22/2009 0:20	0.01	37.1	70	0.53	8570	0.16	8184	35.4	0.96	0.11	8322	31	1.9	84
10/31/2009 11:25	0.62	12.6	7	1.87	2911	0.11	2342	10.1	0.81	0.07	2499	36	3.7	63
4/16/2010 16:50	0.29	24.2	74	0.33	5590	0.04	2593	11.2	0.46	0.03	2716	38	5.7	99
5/8/2010 10:40	1.75	13.8	34	0.41	3188	0.02	1581	6.8	0.50	0.02	1683	7	4.1	71
5/15/2010 2:35	0.00	13.5	7	1.98	3119	0.02	509	2.2	0.16	0.01	550	36	5.2	44
6/20/2010 7:10	0.52	25.2	6	4.09	5821	0.03	617	2.7	0.11	0.02	617	57	4.2	27
6/24/2010 2:35	1.04	17.6	7	2.43	4066	0.02	632	2.7	0.16	0.02	663	36	4.3	31
6/26/2010 17:05	0.42	13.7	16	0.84	3165	0.07	1412	6.1	0.45	0.04	1419	44	3.7	29
6/28/2010 3:50	0.77	12.4	50	0.25	2864	0.03	974	4.2	0.34	0.02	1058	22	4.4	46
7/9/2010 14:20	3.33	34.2	14	2.49	7900	0.08	3322	14.4	0.42	0.07	3316	2	2.9	37
7/13/2010 16:55	0.49	25.5	8	3.06	5891	0.29	4033	17.5	0.69	0.24	4027	16	1.7	30
7/19/2010 8:05	1.44	24.7	21	1.19	5706	0.18	3258	14.1	0.57	0.12	3266	31	2.0	33
7/24/2010 22:25	0.99	41.5	2	26.20	9587	0.61	6816	29.5	0.71	0.60	6771	1	0.6	23
9/24/2010 2:15	0.02	16.7	57	0.29	3858	0.01	146	0.6	0.04	0.00	232	47	9.9	42
9/27/2010 18:40	1.32	31.1	37	0.84	7184	0.05	3702	16.0	0.52	0.04	3645	17	2.7	29
9/30/2010 9:15	0.05	45.2	28	1.64	10441	0.14	9538	41.3	0.91	0.12	9704	14	2.5	78
10/6/2010 16:45	1.08	17.0	27	0.62	3927	0.03	2701	11.7	0.69	0.03	2843	10	4.0	77
10/15/2010 7:10	7.47	55.6	59	0.94	12844	0.18	9582	41.5	0.75	0.15	9652	15	1.7	83
5/26/2011 13:40	1.92	26.6	73	0.37	6145	0.07	4227	18.3	0.69	0.04	4305	37	3.2	52
6/23/2011 11:35	8.33	42.0	49	0.86	9702	0.02	846	3.7	0.09	0.01	837	29	4.1	22
6/25/2011 18:55	0.26	13.1	34	0.38	3026	0.05	1601	6.9	0.53	0.03	1688	34	4.2	58
6/29/2011 0:25	1.81	19.8	10	1.95	4574	0.25	2614	11.3	0.57	0.14	2596	46	2.2	23
8/28/2011 11:15	1.15	91.8	18	5.15	21206	0.52	11200	48.5	0.53	0.51	11148	0	0.7	31
9/4/2011 4:15	0.99	56.4	52	1.09	13028	0.26	10216	44.2	0.78	0.25	10239	3	2.0	62
9/13/2011 14:35	2.38	32.9	6	5.13	7600	0.14	4745	20.5	0.62	0.11	4710	22	1.8	29
9/15/2011 3:40	0.01	11.9	31	0.39	2749	0.06	2218	9.6	0.81	0.04	2305	31	3.7	38
9/29/2011 6:35	2.01	44.1	146	0.30	10187	0.11	7818	33.8	0.77	0.10	7952	5	2.2	87
10/14/2011 8:55	9.02	45.8	63	0.72	10580	0.17	7524	32.6	0.71	0.12	7442	29	3.2	58
10/20/2011 6:10	0.26	13.4	28	0.49	3095	0.08	2940	12.7	0.95	0.07	3136	18	4.0	73
11/14/2011 21:40	0.45	10.7	9	1.16	2472	0.02	473	2.0	0.19	0.01	620	42	7.5	62
11/24/2011 13:35	4.17	20.7	140	0.15	4782	0.04	3429	14.8	0.72	0.03	3584	20	2.9	46
4/21/2012 11:20	0.98	50.8	95	0.54	11735	0.19	6249	27.1	0.53	0.15	6328	19	1.9	70
5/8/2012 7:20	3.39	23.7	74	0.32	5475	0.01	1234	5.3	0.23	0.01	1293	33	5.5	51
5/15/2012 14:10	1.33	20.3	35	0.58	4689	0.05	1741	7.5	0.37	0.03	1805	46	4.3	63
5/29/2012 18:30	0.50	33.3	11	3.17	7692	0.49	2762	12.0	0.36	0.31	2735	36	1.9	25
6/2/2012 5:25	1.01	37.6	33	1.12	8686	0.15	4321	18.7	0.50	0.12	4192	18	2.1	25
6/25/2012 19:15	0.37	34.1	12	2.78	7877	0.56	2217	9.6	0.28	0.32	2140	43	1.5	18
6/26/2012 14:05	0.28	14.2	36	0.40	3280	0.02	616	2.7	0.19	0.01	713	49	4.3	38
7/16/2012 20:55	0.98	26.8	18	1.48	6191	0.07	621	2.7	0.10	0.01	603	81	2.4	30
8/5/2012 17:00	2.15	15.0	6	2.53	3465	0.03	89	0.4	0.03	0.00	41	92	3.5	22
8/11/2012 20:05	0.91	41.2	26	1.58	9517	1.00	4512	19.5	0.47	0.66	4481	34	0.7	25
9/30/2012 9:45	0.74	39.8	40	1.01	9194	0.02	419	1.8	0.05	0.01	353	42	4.6	25
10/6/2012 5:00	1.03	23.0	16	1.47	5313	0.04	852	3.7	0.16	0.03	853	41	3.6	32
5/10/2013 23:25	15.95	27.4	16	1.73	6329	0.02	105	0.5	0.02	0.00	37	91	3.4	12
5/22/2013 20:55	0.00	71.0	84	0.84	16401	0.15	10418	45.1	0.64	0.12	10426	17	1.9	43
6/11/2013 4:15	0.93	21.6	28	0.77	4990	0.03	1187	5.1	0.24	0.03	1171	21	3.6	33
6/24/2013 1:20	0.00	27.6	18	1.54	6376	0.26	1663	7.2	0.26	0.11	1592	58	2.9	24
6/28/2013 5:50	1.29	17.3	16	1.09	3996	0.06	783	3.4	0.20	0.02	771	64	3.7	28
8/2/2013 13:55	0.49	10.4	2	5.20	2402	0.03	85	0.4	0.04	0.00	2	99	1.2	2
8/3/2013 6:15	0.60	12.7	6	2.15	2934	0.05	238	1.0	0.08	0.01	169	80	2.6	14
8/9/2013 1:45	0.76	10.0	5	2.03	2310	0.04	154	0.7	0.07	0.01	97	87	2.9	15
8/13/2013 20:10	0.49	17.6	14	1.27	4066	0.10	562	2.4	0.14	0.02	522	77	3.3	25
8/22/2013 7:40	4.85	29.4	22	1.32	6791	0.06	401	1.7	0.06	0.02	352	72	3.4	24
9/2/2013 7:50	1.90	48.7	22	2.24	11250	0.19	2673	11.6	0.24	0.08	2639	60	1.4	30
9/12/2013 2:50	0.04	34.9	20	1.74	8062	0.37	2460	10.7	0.31	0.17	2417	55	1.7	20
9/13/2013 17:00	0.74	17.2	18	0.95	3973	0.10	2525	10.9	0.64	0.09	2589	12	2.4	25
9/21/2013 22:40	5.63	31.5	20	1.57	7277	0.22	3859	16.7	0.53	0.13	3850	41	2.6	34
10/7/2013 16:00	0.83	20.4	4	4.80	4712	0.06	764	3.3	0.16	0.02	738	60	3.7	23
10/18/2013 1:55	0.78	13.2	18	0.74	3049	0.19	2091	9.1	0.69	0.08	2104	57	3.6	29
10/31/2013 13:30	3.15	23.4	21	1.09	5405	0.15	5007	21.7	0.93	0.12	5026	17	1.9	48
Moyenne	**1.72**	**28.3**	**34**	**1.88**	**6529**	**0.14**	**3099**	**13.4**	**0.44**	**0.10**	**3122**	**38**	**3.2**	**42**

*The duration of precipitation includes all tips of the basket that occur during a given event. Therefore, tips that occur toward the end of the event extend the total duration of precipitation.

Annex 4: Water quality of events measured in pond 3 during the growing seasons from 2009 to 2013.

Start of Event (mm/dd/yyyy)	Runoff Volume (m^3)	TSS Concentration (EMC)			TN Concentration (EMC)			TP Concentration (EMC)		
		Inflows (mg/L)	Outflows (mg/L)	Efficiency ratio (%)	Inflows (mg/L)	Outflows (mg/L)	Efficiency ratio (%)	Inflows (mg/L)	Outflows (mg/L)	Efficiency ratio (%)
7/19/2010	3258	30.5	12.5	59	0.94	0.97	-4	0.14	0.16	-17
7/24/2010	6816	27.1	17.4	36	0.66	0.51	22	1.06	0.13	88
5/26/2011	4227	164.5	31.4	81	0.90	1.04	-15	0.12	0.10	17
9/13/2011	4745	13.5	11.2	17	0.83	1.02	-23	0.09	0.26	-195
10/14/2011	7524	29.2	36.6	-25	0.51	0.61	-18	0.08	0.13	-63
4/21/2012	6249	5749.6	1920.6	67	1.78	1.77	0	0.77	0.53	30
5/15/2012	1741	2137.5	1351.4	37	0.81	0.65	19	0.51	0.31	40
6/2/2012	4321	2469.8	1760.0	29	4.71	0.85	82	1.49	0.32	78
8/11/2012	4512	3029.2	1748.0	42	6.45	0.65	90	1.15	0.38	67
10/6/2012	852	83.5	168.4	-102	0.60	0.72	-19	0.07	0.12	-77
6/28/2013	783	530.5	121.9	77	2.20	3.03	-38	0.28	0.14	50
8/3/2013	238	514.8	456.5	11	-	-	-	-	-	-
8/9/2013	154	70.4	161.7	-130	-	-	-	0.17	0.39	-126
8/13/2013	562	376.4	258.1	31	-	-	-	0.12	0.08	33
8/22/2013	401	125.6	150.1	-20	-	-	-	0.14	0.17	-24
9/2/2013	2673	117.7	136.4	-16	-	-	-	-	-	-
9/21/2013	3859	418.6	39.5	91	-	-	-	-	-	-
10/7/2013	764	104.1	52.0	50	-	-	-	-	-	-
10/18/2013	2091	702.1	49.4	93	-	-	-	-	-	-
10/31/2013	5007	461.1	70.4	85	-	-	-	-	-	-
Mean	**3039**	**858**	**428**	**50**	**1.85**	**1.07**	**42**	**0.44**	**0.23**	**48**

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