

A review of low-grade weirs as an agri-environmental best management practice in the Elginfield Municipal Drain watershed, Ontario, Canada

Edward DeLay and Bahram Gharabaghi

Recent algae blooms in Lake Erie are projected to worsen with continued anthropogenic climate and land use changes. Agricultural systems have evolved from being net phosphorus (P) sinks, where crop production is P-limited, to being P sources, with net P export from most farms (McElmurray et al. 2013; Scavia 2014). In 2012, the International Joint Commission established the Lake Erie Ecosystem Priority in response to growing lake-wide changes related to problems of P runoff from agricultural fields, compounded by the influence of climate change on winter hydrology and extreme rainfall event statistics (International Joint Commission 2014). These changes have resulted in impaired water quality, with impacts on ecosystem health, drinking water supplies, fisheries, recreation and tourism, and waterfront property values.

Agricultural runoff is the major source of nonpoint inputs of P in the Lake Erie basin. The basin receives 44% of the total P (TP) load entering the Great Lakes from agricultural activities, more than any other individual Great Lake in the system (Rucinski et al. 2014; Dolan and Chapra 2012). Commercial fertilizers account for the majority of agriculturally applied P in most locations. In Ohio, 84% of P applied to agricultural land in the Lake Erie basin originates from commercial fertilizers, and 16% is derived from manure (Ohio EPA 2013). Bosch et al. (2013, 2014) and Rucinski et al. (2016) have concluded that significant reductions (46% below the 2005 to 2011 baseline) in agricultural nonpoint nutrient loading are needed to reduce the incidences of harmful algal blooms and hypoxia in the western and central basins of Lake Erie. Tributary flow is expected to increase up to 17% due to climate change, as are nutrient

yields (up to 32%) in tile drained watersheds, potentially increasing P loads in the future.

The seasonal effectiveness of best management practices (BMPs) is essential in the snowbelt region of southwestern Ontario. Kepski et al. (2016) found that during winter deeper snowpacks have greater ability to store pollutants, including ions that are released in majority during the primary spring melt as an “ionic pulse.” This process is similar to a “first flush” in urban stormwater systems and was found to cause increased acidity in the surface waters of the watershed. Additionally, Jeffries et al. (1979) found that between 36% and 77% of the annual hydrogen ion (H⁺) export in runoff came within the month of April, with resulting depressions in pH present in all other sampled surface waters of their three studied watersheds in central Ontario. Similarly, Kratz et al. (1987) studied the seasonal pH variability of six lakes in northern Wisconsin and found the highest acidity values during late winter and early spring. Therefore, it is essential that new BMPs target the winter months and snowmelt events in particular for effective pollutant removal.

Asnaashari et al. (2015) and Rudra et al. (2015) analyzed historic hydrometric data in Ontario and demonstrated statistically significant trends in increasing winter streamflows due to rising winter air temperatures across the province over the latter half of the twentieth century. These temperatures have resulted in reduced snow accumulation and earlier spring snowmelt. In addition, Vasijevic et al. (2012) concluded that the two-year storm intensities in southern Ontario are increasing at a rate of 1% to 3% per year. Based on these data for the City of Waterloo, a five-year recurrence storm for the period from 1970 to 1984 is now very close in magnitude to a two-year recurrence storm for the period 1985 to 2003. Chapi et al. (2015) investigated the potential effect of these changes in seasonal precipitation patterns and the extreme rainfall events on the spatial-temporal dynamics of runoff generation areas in small agricultural watersheds in southern Ontario.

Bosch et al. (2014) concluded that common agricultural BMPs, including cover

crops, filter strips, and no-till, when implemented at levels considered feasible, were minimally effective at reducing pollutant loading. It was also concluded that agricultural BMPs will become more necessary but less effective under future climate scenarios and an “all-of-above” strategy is needed. The purpose of this study was to investigate the effectiveness of low-grade weirs as a BMP for P removal in the upper watersheds of the rivers contributing directly to Lake Erie and Lake St. Clair, in an effort to more accurately estimate the potential water quality benefits of these popular BMPs under local soil, crop, climate, and drainage conditions in southwestern Ontario.

BEST MANAGEMENT PRACTICES

BMPs are a widely used and effective approach to controlling nonpoint source pollution in the rural landscape. The application and placement of these practices in a watershed requires optimization in order to maximize economic and ecological effectiveness (Prokopy et al. 2008; Maringanti et al. 2009; Rodriguez et al. 2011; Liu et al. 2013; Smith et al. 2015; Rittenburg et al. 2015; Singh et al. 2016; Thompson et al. 2016). Stang et al. (2016) investigated water quality both pre- and post-BMP implementation in the Hog Creek and Sturgeon River watersheds in Ontario and found a 49% and 41% reduction in sediment loads in these two watersheds, respectively. Poudel (2016) studied the effectiveness of agricultural BMPs in the Coulee Baton watershed in Louisiana and concluded that these BMPs resulted in a significant decrease in total suspended solids (TSS) and soluble reactive P of approximately 56% and 82.5% respectively. Many methods, techniques, and installations are currently available for use as BMPs in the reduction of nonpoint source pollution, including compost biofilters, which were the focus of this study.

Compost Biofilters. Organic woody compost was shown to be effective in the removal of TSS, and can be used as a biofilter when placed inside a photodegradable mesh sock (Finney et al. 2010, 2011). These flexible biofilters are available in a variety

Edward DeLay is a consulting engineer with RJ Burnside and Associates, Limited, in Stratford, Ontario, and a graduate student in the School of Engineering at the University of Guelph, in Guelph, Ontario, Canada. Bahram Gharabaghi is a professor of water resources engineering in the School of Engineering at the University of Guelph, Guelph, Ontario, Canada.

of diameters and can be oriented and/or stacked to accommodate individual field geometries. The application of these biofilters as a check dam can lead to increased filtration due to increased ponding time. The removal efficiency of the filters was found to increase with the number of socks installed in series. The 200 and 450 mm (7.9 and 17.7 in) diameter biofilters had removal efficiencies ranging between 34%, 48%, and 60% and 69%, 84%, and 95% for sequences of 5, 10, and 15 filters, respectively. It was noted that removal efficiencies decreased over time. Removal efficiencies of clay particles versus fine and coarse silt particles were noted as 30%, 50%, and 80%, respectively. Finney et al. (2010) promoted an alternative BMP for the treatment of stormwater runoff, which in many cases is not meeting provincial water quality guidelines. An installation of compost biofilters located adjacent to Highway 8 at Kitchener, Ontario, was monitored during 18 storm events over a period of two years. The study found that the biofilter installation was responsible for lower TSS in the stormwater runoff by 42% to within provincial water quality guidelines.

Low-Grade Weirs (Compost Bio-Check Dams). Kröger et al. (2013) and Littlejohn et al. (2014) studied low-grade weirs, a series of low-grade check dam structures installed within agricultural drains and a common BMP in the lower Mississippi alluvial valley. These low-grade weirs result in increased hydraulic residence time, decreased flow velocities, and increased trapping of sediment-bound nutrients within the drain, reducing the nutrient loads moving downstream. They concluded that low-grade weirs can be a viable BMP in agricultural landscapes as these sediment-focused BMPs will have an impact on particulate-bound nutrients, such as total inorganic P, providing up to a 45% load reduction.

Tiessen et al. (2011) studied the effectiveness of two small dams and reservoirs in reducing TSS, total nitrogen (TN), and TP loading from headwater agricultural land in south-central Manitoba between 1999 and 2007 and found that the reservoirs acted as sediment sinks during snowmelt periods and sources during summer rainfall events. Additionally, these watersheds were dominated by (greater than 70%) the dissolved forms of both N and P; however,

the dam and reservoirs effectively achieved a mean removal efficiency of over 71% of sediment, 17% of TN, and 10% of TP.

Baker et al. (2016) studied the ability of low-grade weirs to reduce nutrients in drainage ditches in paired watersheds with and without weirs. The annual sediment and P concentrations were lower in systems with weirs, indicating that weirs have the potential to effectively slow water allowing for retention of sediment. Kröger et al. (2013) also reported that sediment and P were effectively retained behind weirs. However, with an average 50 cm (19.7 in) depth of sediment accumulation behind weirs one year after construction, they cautioned that yearly maintenance would be necessary to ensure optimal sediment and P reductions (Kröger et al. 2013).

Municipal Drains. Municipal drainage systems are infrastructure owned and maintained by municipalities and are the receiving bodies from private lands used primarily for agriculture. Currently in Ontario, there are approximately 44,000 km (27,340 mi) of municipal drains established under the *Drainage Act, R.S.O. 1990*. These drains can carry water, sediment, P, and other pollutants toward downstream receiving bodies, typically rivers and lakes. Common drainage design for both open and piped municipal drains focuses on removing water from the landscape as quickly as possible. BMPs and P-reducing methodologies could enhance the efficacy of these drainage systems and riparian areas that are managed under the *Drainage Act, R.S.O. 1990*. In addition to their primary purpose, municipal drains could provide an opportunity to further control nutrient loading in agricultural production areas. In Ontario, the establishment or improvement of a municipal drain is carried out under the direction of a professional engineer or Ontario land surveyor in accordance with the *Drainage Act, R.S.O. 1990*, and this provides an excellent opportunity for enhancement of the drain in promoting pollutant retention. Working closely with landowners on a variety of BMPs under the control of rural municipalities should result in improved nutrient management in these communities.

RESEARCH SITE

The site for this study was located northeast of Elginfield, Ontario, near the intersec-

tion of Stonehouse Line and Observatory Road. The Upper Thames Regional Conservation Authority (UTRCA) uses the site as a pilot test facility for various BMP research. The upstream contributing watershed for the Elginfield Municipal Drain is approximately 20 km² or 1,978 ha (8 mi² or 4,888 ac), including several tributaries, involving multiple land uses and practices (figure 1). The entire site is conventionally farmed for this region and includes corn (*Zea mays* L.), soybean (*Glycine max* [L.] Merr.), and wheat (*Triticum aestivum* L.) crop rotations. A small field at the corner of the site is very flat, facilitating controlled drainage, and is typically no-till planted. The larger portion of the field to the north is conventionally tilled with a disk harrow.

Background Water Quality. The UTRCA produces a report card every four years for the Medway Creek watershed, the outlet of the Elginfield Municipal Drain. Since 1996, average TP concentrations have steadily declined, from 0.17 mg L⁻¹ to 0.12 mg L⁻¹ in 2010. However, this exceeds the Ontario Ministry of the Environment and Climate Change's (MOECC's) provincial surface water guideline of 0.03 mg L⁻¹ for TP.

PROJECT OBJECTIVES AND DESIGN

The objective of this project was to determine the effectiveness of a low-grade weir BMP for P and sediment removal associated with artificial rural drainage, focusing on municipal drainage systems, with the aim of reducing nutrient loading from rural areas to streams and lakes. The scope of the study includes the evaluation of compost biofilter check dams, which were installed in sets of three at three locations within the channel of the Elginfield Municipal Drain, as shown in figure 2.

Each weir was composed of a 4 to 6 m (13 to 20 ft; varying dependent on channel width) length of 300 mm (11.8 in) diameter compost biofilter (supplied by Filtrix Canada Inc., Brantford, Ontario) staked to the channel floor. The purpose of multiple rows of the biofilter "speed-bumps" was to slow the velocity of the incoming flow and encourage sedimentation at these locations upstream of the check dam, including the sediment bound P (SBP). The socks were covered with a depth

of approximately 200 mm (7.9 in) of 100 to 200 mm (3.9 to 7.9 in) diameter river stone as protection during larger storm events and snowmelt periods, as shown in figure 3.

The performance of this BMP was assessed for control of sediment and P in stormwater runoff from June of 2015 to September of 2016, over 21 site visits. Three sampling locations in the study included upstream (Station 3) and downstream (Station 1) of the site within the channel, and at a point within the study reach (Station 2) as shown in figure 2.

Water grab sampling and/or visual inspection was completed for each installation approximately every 14 days during the spring, summer, and fall months as well as a general site inspection, in addition to sampling following storm events and periods of snowmelt when possible. A summary of all sampled channel water is presented in figure 4. Bathymetric surveys of the channel bed were completed to estimate the mean annual sediment and P removal efficiency of the bio-check dams.

MEAN MONTHLY DISCHARGE

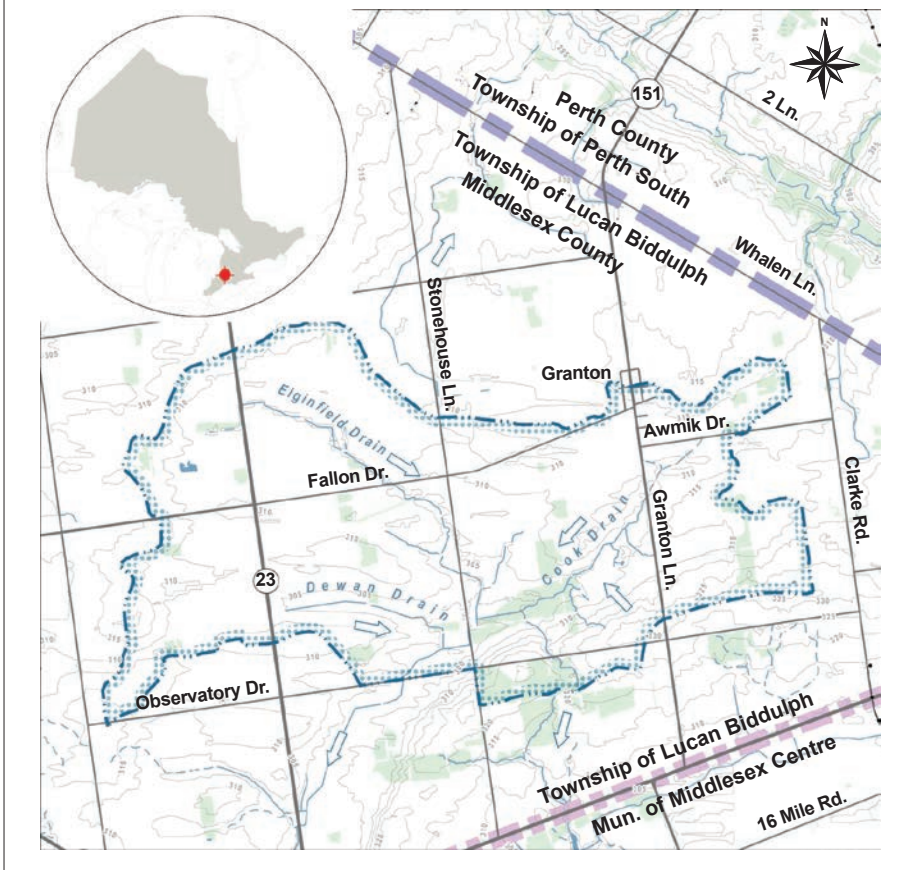
Streamflow monitoring was conducted within the channel at the Observatory Line crossing using two HOBO water level data loggers complete with vertical standpipes. Water levels were recorded in October and November of 2015 and again from April to September of 2016. Additional monitoring was conducted at the upstream end of the study reach over the summer of 2016 as shown in figure 2.

Flow data from a water office of Canada monitoring gauge near the mouth of Medway Creek at the Thames River in London, Ontario, were used to create additional flow data for the Elginfield Municipal Drain watershed using a drainage area weighted average. Using this process, the Medway Creek flow data were scaled for the months of December of 2015 to March of 2016. Cumulatively, these data were later used to determine sediment and P loading for the watershed.

The average monthly flows for the monitored reach of the Elginfield Municipal Drain from October 2015 to September 2016 are shown in figure 5. Increased flow and TP loads were observed between mid-January and mid-April of 2016 and were responsible

Figure 1

Project site located adjacent to the northwest corner of Stonehouse Line and Observatory Drive on the Elginfield Municipal Drain within the Medway Creek Watershed (Source: RJ Burnside and Associates, Limited).



for the majority of streamflow, sediment, and nutrient loading over the study period.

It is worth noting the deposited sediments behind the bio-check dams during the July of 2015 to February of 2016 monitoring period, as shown in figure 3. Figure 6 depicts the channel bottom surveys, to quantify changes in sediment deposition depth that indicate approximately 10 cm (3.9 in) of sediment was deposited in the channel in one year, with the majority deposited following the snowmelt in January of 2016.

NUTRIENT AND SEDIMENT LOADS

Total Phosphorus. Total P values exceeded the Provincial Water Quality Guideline of Ontario (PWQO) value of 0.03 mg L⁻¹ in 52 of 63 total samples (mean TP concentration of 0.097 mg L⁻¹ with sd of 0.091 mg L⁻¹), indicating the need for installation of agricultural BMPs to reduce TP values by a minimum of three- to fourfold.

Baker et al. (2014) studied three Ohio tributaries of Lake Erie's western basin, the Maumee, Sandusky, and Cuyahoga rivers, having flow weighted mean TP concentrations of 0.418, 0.421, and 0.300 mg L⁻¹, respectively—three to four times our sampled concentrations. The rivers' flow weighted mean dissolved reactive P (DRP) concentrations were 0.073, 0.071, and 0.044 mg L⁻¹, respectively.

Sediment Bound and Dissolved Phosphorus. The fraction of TP in dissolved (TDP) versus SBP forms was roughly 60% TDP and 40% SBP.

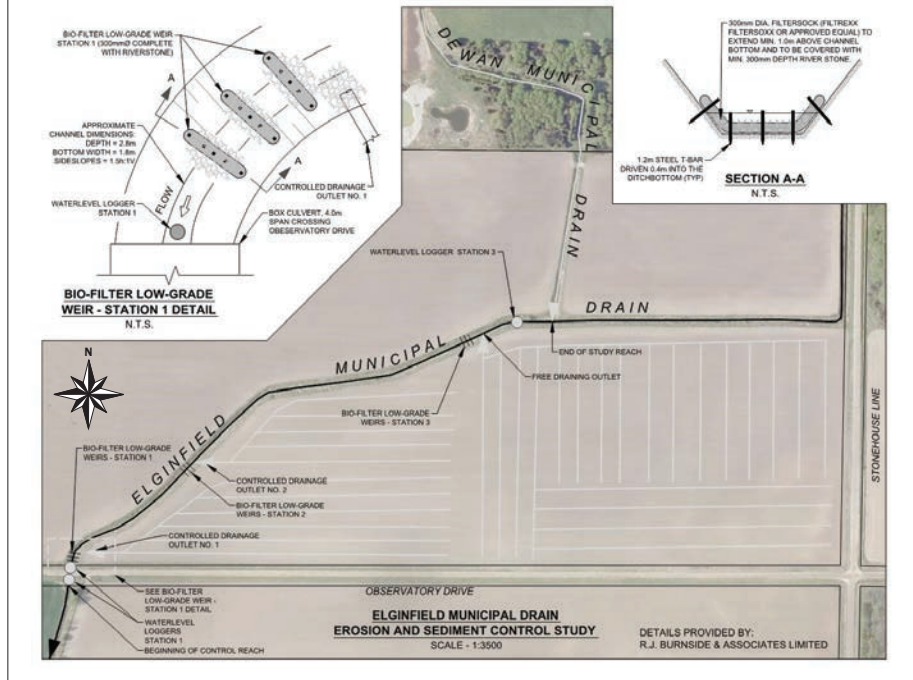
Total Nitrogen. Total N in runoff had a mean concentration of 4.46 mg L⁻¹, with sd of 3.67 mg L⁻¹, which was below the MOECC PWQO value of 10 mg L⁻¹.

SITE OBSERVATIONS

Winter of 2016 included significant snowfall and periods of increased temperature leading to extensive snowmelt, particu-

Figure 2

Plan of the existing research site layout and low-grade weir installation details (Source: R) Burnside and Associates, Limited).



larly in January of 2016 when near bank full flow was observed. Spring of 2016 was again typical leading into an abnormally dry and hot summer. Similar to the summer of 2015, the channel was stagnant; however, the low-grade weirs were able to retain water in the channel versus the previous year, and the overall appearance of vegetation in the channel bottom was increased.

The free draining tile outlets along the north and west bank were running water during most site visits. They may be a large contributor to sediment in the channel and/or stirring up the existing loosely bound sediment within the ditch and may be a cause of elevated levels of TSS and TP at Station 2 as observed in the majority of samples.

At this site, the particular soil and topographic characteristics led to a majority of the precipitation infiltrating into the ground, and when coupled with an adequate subsurface tile drainage system, the number of observed runoff events was very low. This observation was confirmed by the DRAINMOD model, which, when calibrated to climatic data for the spring and summer of 2015, showed a very close correlation to the observed data for drainage outflow.

Channel System Controls and Unknowns. Flow in the channel itself was sustained over the entire sampling period; however, during the summer months the channel was stagnant. In general, there were fluctuations in the parameters from water samples taken throughout the sampling period. Even within the 500 m (1,640 ft) study reach of channel, many unknown factors may have contributed to the variations in the sampling results along the reach, such as soil erodibility in the channel and multiple drainage outlets from the northwestern channel bank. Therefore, it is not possible to compare individual sampling results without consideration of the complex boundary conditions of the system.

With this in mind, the channel was also surveyed periodically in order to measure the amount of sediment capture following the installation of the weir structures. The major deposition event of the study period came during the largest snowmelt in January of 2016. A subsequent survey of the channel confirmed this observation and showed that roughly 10 cm (3.9 in) of material was deposited in the study reach. This event contained the highest con-

centrations for TSS, TP, SBP, and DRP as sampled in this study.

AVERAGE WATERSHED SEDIMENT LOADS

Annually, the contributing watershed of the Elginfield Municipal Drain produced a load of approximately 110 t (121 tn) of sediment at a rate of $60 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (54 lb $\text{ac}^{-1} \text{ yr}^{-1}$), a load of approximately 540 kg (1,191 lb) of TP at a rate of $0.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (0.27 lb $\text{ac}^{-1} \text{ yr}^{-1}$), and a DRP load of approximately 350 kg (772 lb) at a rate of $0.2 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (0.18 lb $\text{ac}^{-1} \text{ yr}^{-1}$).

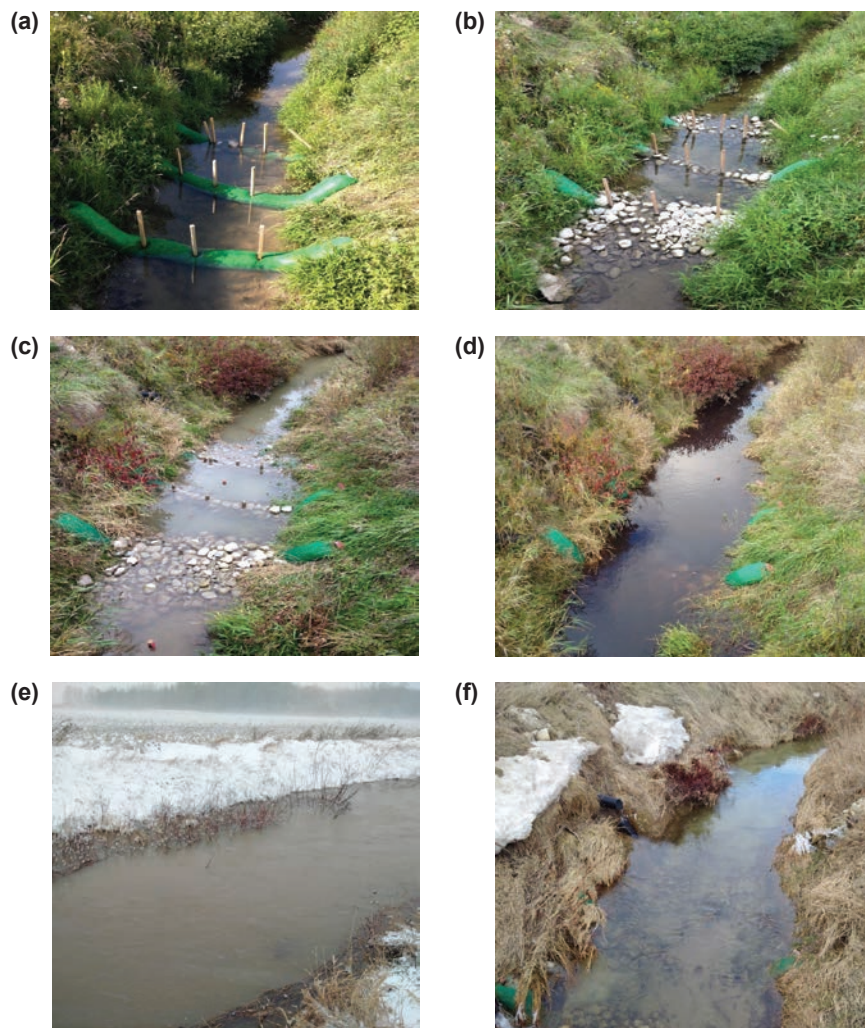
A report prepared by MOECC (2012) compared current stream loading to historical rates from the "Pollution from Land Use Activities Reference Group" (PLUARG) study of the 1970s and 1980s. The findings of the MOECC report indicated a minimum sampled TP annual loading of 0.20 kg ha^{-1} (0.18 lb ac^{-1}) in the Blyth Brook of northern Huron County, Ontario, and maximum value of 1.89 kg ha^{-1} (1.69 lb ac^{-1}) found in the Little Ausable River of southern Huron County, annually. The average TP loading value from their study was approximately 0.92 kg ha^{-1} (0.82 lb ac^{-1}), annually. By comparison, during the PLUARG study annual TP loading in the Blyth Brook and Little Ausable River were 0.16 and 0.77 kg ha^{-1} (0.14 and 0.69 lb ac^{-1}), respectively, or an increase of 2.5 times for the Little Ausable River and 1.3 times for the Blyth Brook.

Calculated TP loading in the Elginfield Municipal Drain of $0.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (0.26 lb $\text{ac}^{-1} \text{ yr}^{-1}$) is 1.5 times higher than the minimum value in Blyth Brook from the 2012 study. This rate is 6.3 times lower than the maximum value from the 2012 study, found in the Little Ausable River. Additionally, calculated loadings are below the MOECC report average rate.

Similarly, a minimum sampled total sediment annual loading of 60 kg ha^{-1} (53.6 lb ac^{-1}) was found in the Blyth Brook and maximum value of 520 kg ha^{-1} (464 lb ac^{-1}) found in the Little Ausable River. The average TSS loading value was approximately 235 kg ha^{-1} (210 lb ac^{-1}) annually. During the PLUARG study, TSS loading in the Blyth Brook and Little Ausable River were found to be 60 and 200 kg ha^{-1} (53.6 and 178.6 lb ac^{-1}), respectively, or an increase of 2.6 times

Figure 3

The low-grade weir structure (compost bio-check dam) as shown from weir installation in the summer of 2015, through snowmelt and sediment deposition during the winter of 2016: (a) July of 2015, (b) August of 2015, (c) October of 2015, (d) November of 2015, (e) January of 2016, and (f) February of 2016.



for the Little Ausable River and no increase for the Blyth Brook.

In comparison to calculated loading, the Elginfield Municipal Drain sediment loading of approximately $60 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($53.6 \text{ lb ac}^{-1} \text{ yr}^{-1}$) is equal to the rate in the Blyth Brook, which also supports a high quality trout fishery.

Baker et al. (2014) also reported pollutant loadings for three Ohio tributaries of Lake Erie's western basin: the Maumee, Sandusky, and Cuyahoga rivers. For the Maumee River between sampling in 1991 and 2012, an increase in TP and decrease in TSS loading was reported, from 1.23 to $1.44 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (1.10 to $1.19 \text{ lb ac}^{-1} \text{ yr}^{-1}$)

and 0.65 to $0.52 \text{ t ha}^{-1} \text{ yr}^{-1}$ (580 and $464 \text{ lb ac}^{-1} \text{ yr}^{-1}$), respectively. The Sandusky River was sampled in 1991 and 2012, reporting increases in both TP and TSS loading, from 1.06 to $1.91 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (0.95 to $1.71 \text{ lb ac}^{-1} \text{ yr}^{-1}$) and 0.57 to $0.75 \text{ t ha}^{-1} \text{ yr}^{-1}$ (509.01 to $669.75 \text{ lb ac}^{-1} \text{ yr}^{-1}$), respectively. Similarly, the Cuyahoga River was sampled in 1991 and 2012, reporting increases in both TP and TSS loading, from 1.09 to $1.55 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (0.97 to $1.38 \text{ lb ac}^{-1} \text{ yr}^{-1}$) and 0.94 to $1.51 \text{ t ha}^{-1} \text{ yr}^{-1}$ (839.42 to $1,348.43 \text{ lb ac}^{-1} \text{ yr}^{-1}$), respectively. By comparison, mean TP and TSS loadings calculated for the Elginfield Municipal Drain watershed

were approximately one-third and one-tenth of these values, respectively.

IMPLEMENTATION, MAINTENANCE, AND POTENTIAL FOR APPLICATION

Further evaluation of the effectiveness of the proposed BMPs at sediment capture is required to determine the optimal location to install these BMPs and, also, the various sediment and P retention capabilities that are possible over time. Additionally, maintenance of these BMPs would be essential to retaining their performance in this respect. Also, further research on the time of year for the maintenance to occur and be in compliance with existing environmental regulations is essential.

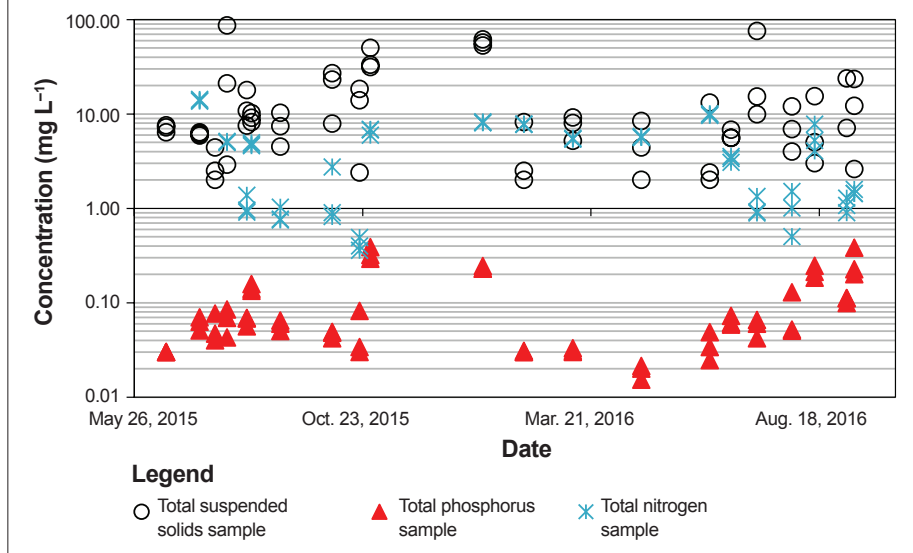
Through the use of the *Drainage Act, R.S.O. 1990*, BMPs such as low-grade weirs and others could be utilized by engineers in drainage reports as another tool to combat TSS and TP loading in municipal drains across Ontario. Once made part of the drain under the report, these structures and other environmental measures would be protected under the *Drainage Act, R.S.O. 1990* and the corresponding municipal bylaws and could not be modified unless by another engineer's report. For this reason, these BMPs are an excellent choice for addressing problems in the municipal drainage system. Application of BMPs to rural Ontario also means that rigorous field testing in a variety of conditions would be necessary and that improvements to the effectiveness, cost, and functionality of these BMPs would take place over time following their mainstream use and implementation.

Also, when maintenance would be required in the future, it would be completed by the municipality under the *Drainage Act, R.S.O. 1990*, which would again be set out in the drainage report. In this way, the required maintenance and any special provisions associated with it would be accounted for by the municipality and would be assessed back to the contributing landowners under the same report and bylaw. This is currently a very common practice in rural Ontario and would be well-suited for application to these new BMPs.

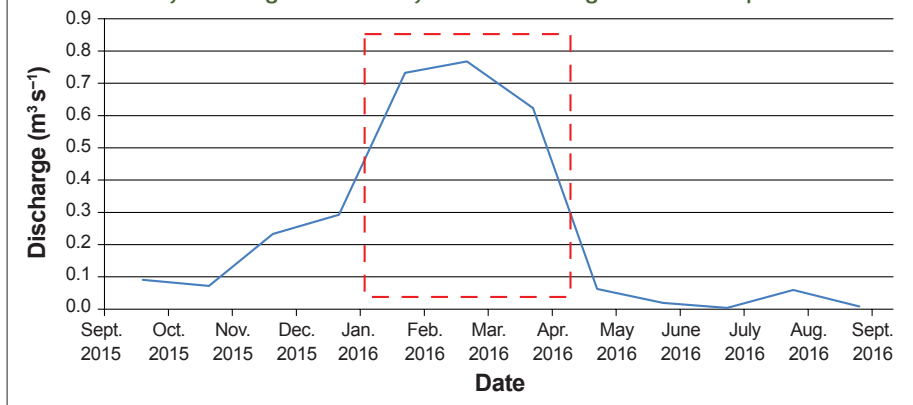
Previous studies on low-grade weirs showed that they can be effective at reducing concentrations of TSS and TP when

Figure 4

Summary of all sampled ditch runoff quality parameters.

**Figure 5**

Mean monthly discharge in the study reach of the Elginfield Municipal Drain.



applied and maintained correctly; however more research must be done in this regard in an Ontario context. Additionally, a comprehensive monitoring program should also be implemented to document the various successes and challenges associated with this approach.

In summary, low-grade weirs showed promise for use with municipal drains in Ontario. A series of compost bio-check dams installed within the municipal drain would serve as “speed bumps” promoting the slowing of channel flow velocities to enhance removal of sediments and associated nutrient deposition upstream of the check dams. The check dams were effective in sediment removal throughout the year; however, they were particularly effective during the winter and early spring

snowmelt events. Additional testing of the in-channel compost bio-filter check dam would be optimized with a smaller contributing watershed. Furthermore, limited input from tile drainage systems or a combined system outlet would increase the ability to track pollutant sources.

The application of this BMP was successful in this particular case. However, the specific land uses and practices used within this watershed in addition to climatic inputs were observed to have a large effect on the collected data. This was particularly evident in the limited amount of surface runoff and was exacerbated by the heavily tiled fields studied, which encouraged infiltration versus overland runoff. This points to the need for a targeted approach to BMP application for individual areas

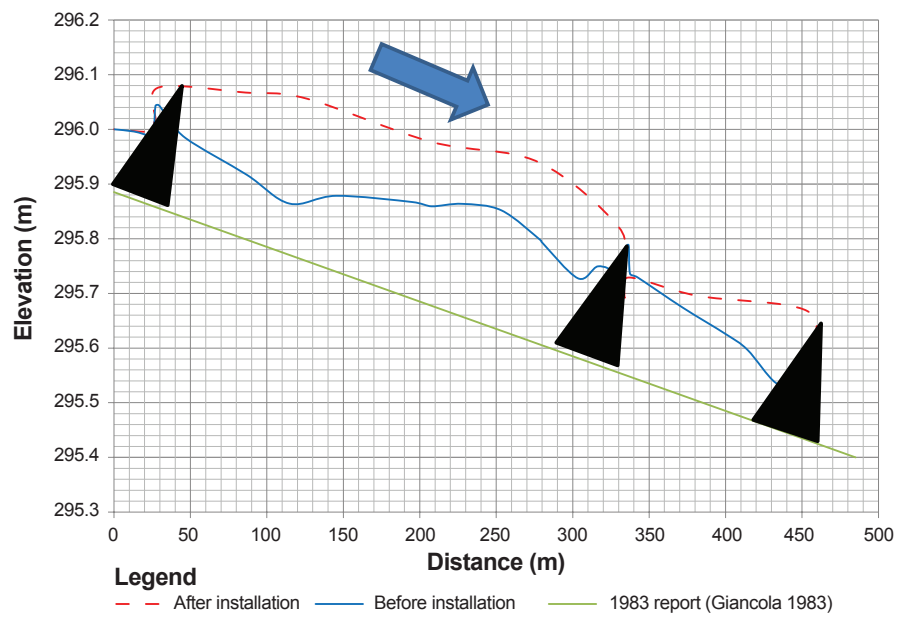
requiring water quality improvement and the pathways currently utilized. A water balance approach would achieve this objective in the planning stage of BMP implementation. In this way, the chosen BMPs could be applied for maximum benefit; using an optimization technique or selection program would achieve this. Finally, more research in the application of these BMPs in agricultural watershed is required in the context of the climate of southwestern Ontario.

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Figure 6**The channel bottom as surveyed before and after the weir installations.**

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