Woodchip Biofilters for Treatment
of
Particulate Phosphorus in Agricultural Runoff

by

Tahina Choudhury

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences (Water)

Waterloo, Ontario, Canada, 2017

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

I completed most of the data collection, and analysis myself with the assistance of field staff. I also completed the reporting of the results.

Will Robertson designed the work, contributed to the interpretation of the results and provided revisions for the thesis.

Abstract

Woodchip filters have received attention in recent years for their ability to sustain denitrification activity across multiyear time frames. However, in most freshwater aquatic ecosystems, phosphorus (P) rather than nitrogen (N) is the nutrient considered most responsible for eutrophication. Previous studies have indicated that woodchip filters have limited ability to remove dissolved P, but P export in agricultural runoff is often dominated by particulate P (PP). Woodchip media, because of its high porosity, permeability, surface roughness and plate-like structure of the particles, could be effective for physical filtration of particulate phosphorus. In this study, woodchip filter systems were tested for treatment of PP in agriculturally impacted surface waters at five sites in southern Ontario.

Bradford Site

A woodchip filter system installed near Bradford, ON was used to treat highly turbid root vegetable wash water from a local farm and focused on the treatment of total suspended solids (TSS) and PP. The full-scale treatment system consisted of a sedimentation tank (12.3 m^3) followed by the woodchip filter (16.1 m^3) and had two stages of testing. In the initial stage, the filter media consisted of woodchips with a layer of sawdust, and in the second stage, the media contained woodchips only. The full-sale treatment system was sampled from November 2014 to March 2016 and proved effective for TSS and PP removal during both treatment stages, averaging overall removal of 99% and 91%, respectively, in the first stage, and 96% and 77%, respectively, in the second stage. During the operation of the full-scale treatment system, the sludge within the sedimentation tank was regularly monitored and was removed on two occasions. Also during this time, sludge accumulation within the top layer of woodchips required replacement of the top layer on one occasion, September 2015.

Barrie (Big Bay) Site

A woodchip filter was installed near Barrie, ON to treat particulate P in an agricultural drainage ditch adjacent to fields where row crops are grown. In this case the filter consisted of 20

m^3 of woodchips trenched in to the bottom of the stream (stream-bed filter). Stream flow was induced through the filter by placement of a gravel riffle at its downstream end. This filter was monitored from December 2014 to March 2016 and proved effective for P removal in the stream water, which had low to moderate turbidity, averaging total P removal of 58%, the majority of which was PP. Nitrate removal in the filter was modest, averaging only 1 mg/L NO_3^--N, because the filter was operated at relatively high flow rates (average hydraulic retention time of 0.4 days) such that denitrification activity was incomplete.

Keswick Site

A woodchip filter was installed near Keswick, ON to remove TSS and associated PP, as well as NO_3^--N, from a tile drain at a sod farm. The filter consisted of 36 m^3 of woodchips trenched into the subsurface near the drain outlet and was monitored intermittently from May 2014 to March 2016. Overall, geochemical parameters were not substantially changed during treatment in the filter. This was primarily because TSS, total P and NO_3^--N concentrations were relatively low at this site, averaging 20 mg/L, 24 µg/L and 3.0 mg/L, respectively, such that the woodchip filter had little opportunity to further diminish these already low values. Secondly, the tile drain unexpectedly remained dry throughout the summer and early fall months and the filter experienced freezing problem during winter. Consequently, achieving desired flow rates through the filter was problematic. Results indicated that TSS and PP values were too low and therefore this site was not well-suited for the implementation of this type of woodchip filter.

Wildwood Site

In a previous study (van Driel, 2006), a woodchip filter was installed near St. Marys, ON, in 2002, to treat NO_3^--N from an agricultural drainage tile, adjacent to a field where row crops are grown. Although extensive monitoring of the media longevity for NO_3^--N removal has been undertaken, little attention has been paid to P removal associated with this filter. During this study, in addition to NO_3^--N removal, the P removal capacity of the filter was monitored from May 2014 to March 2016, at which time the filter was 12-14 years old. Monitoring revealed that TP in the filter effluent actually increased, although the significance was low, from a mean of 29 ug/L to 83 ug/L, and this increase was dominated by SRP and not PP. There was little correlation between TP and SRP removal with hydraulic retention time (HRT), however, the relationships between these two parameters and HRT were significant. In contrast, NO_3^--N removal in the filter remained significant, decreasing from a mean of 7.2 mg/L in the influent to 2.3 mg/L in effluent. Monitoring at this site provides evidence that wood particle filters have the potential to leach low levels of dissolved phosphorus during long term operation. This could be the result of slow leaching of P associated with the sediment retained within the filter. Also, the correlation of higher SRP values with increased Fe concentrations, suggests that reductive dissolution of ferric iron solids and subsequent release of sorbed P also plays a role in the observed SRP increases. This observed occurrence of SRP leaching at this site has important implications for the long term management strategies for such filters.

Avon Site

In a previous study (Robertson and Merkley, 2009) a woodchip filter, of the same design as the Big Bay stream-bed filter, was installed at the headwaters of Avon River, near Stratford, ON. The filter was designed to treat NO_3^--N in a drainage ditch, adjacent to fields where row crops are grown.. The filter has been monitored extensively in previous studies for NO_3^--N removal, but P removal received little attention. During the current study, both the NO_3^--N and P removal capacities of the filter were monitored during the period May 2014 to November 2015. During this monitoring period there was a consistent problem with inadequate flow rates (< 4 L/min) through the filter and secondly, there was an observation of very dissimilar chloride values in the filter influent and effluent. This indicated that the woodchip media had likely become substantially impermeable due to sediment accumulation in the pore space, such that the filter effluent was apparently dominated by incoming groundwater flow, rather than flow originating from the stream. Consequently, the filter is no longer functioning as designed.

This study has demonstrated that woodchip filters are a cost effective and low maintenance method for the removal of particulate P from agricultural waters under appropriate conditions. The study also demonstrates design options, flow conditions and maintenance requirements for the newly installed and older (> 10 years) filters for effective nutrient removal.

Acknowledgements

This thesis would not have been possible without the help and support of many people. I would like to thank my family and friends for their love, moral support, and for always reminding me to keep going and to stay focused.

I would like to thank Darryl Finnigan, Bulent Mutus and Craig Merkly for their efforts during our collaborations, which included their academic and technical inputs to the project.

This thesis has been advised by Dr. William D. Robertson, whose mentoring, teaching, and above all, patience is greatly appreciated. Will, thank you, for your extensive guidance and effort contributed to this thesis. I also want to thank you for presenting me with opportunities to showcase this project. Whether it be through poster presentations or publications, you have truly provided me with great guidance throughout this whole process.

I want to thank my committee members, Sherry Schiff and Barry Warner, for providing me with the constructive criticism and guidance in completing this thesis.

Finally, I would like to thank all the lab technicians and field staff that have contributed to the completion of this thesis, including Richard Elgood. Richard, thank you for guiding and teaching me all the things that you have these past few years.

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1. Introduction

Agriculture is a potential source of nitrate (NO_3^-) and phosphorus (P) loading to aquatic ecosystems in Southern Ontario. Fertilizers are routinely applied to increase crop yields, and this has the potential to impact surface water and groundwater quality due to nutrient loading. Concentrations of NO_3^- and P can potentially exceed water quality guidelines for the protection of aquatic life in water bodies. Excessive N and P loading alters the chemistry and physical characteristics of aquatic ecosystems which can adversely impact important organisms. Phosphorous is considered the nutrient most responsible for eutrophication in freshwater ecosystems (Dillon and Rigler, 1974; Schindler, 2006). Studies have also shown a strong relationships between P loading and harmful cyanobacterial blooms in freshwater ecosystems (Schindler, 1977; Smith and Schindler, 2009) Eutrophication also has the potential to affect human health through increased loading of pathogens from manure application, and from increased rates of transfer and replication of pathogens (Wilson *et al*., 1996; Smith and Schindler, 2009). Leaching and subsurface drainage are dominant pathways for the transportation of these nutrients into groundwater and surface waters.

1.1 Nitrate

Nitrate (NO_3^-) is an anion that is essential for plant growth and protein production, and acts as a source of N (Canadian Fertilizer Institute, 2016). In subsurface conditions in younger soils, it typically does not sorb onto aquifer materials and is most stable under aerobic conditions. Under anaerobic conditions, NO_3^- undergoes denitrification, a process where NO_3^- is reduced to nitrogen gas (N_2; Figure 1). This process requires the presence of an electron donor, such as organic carbon or sulphide minerals, and is usually a microbially mediated process in groundwater (Buss et al., 2005). Nitrogen fertilizers that are primarily used in Canada are anhydrous ammonia, urea, nitrogen solution, ammonium nitrate and ammonium sulphate (Source: Agriculture and Agri-Foods Canada, 2013). In 2012, nitrogen fertilizers were the largest nutrient used in agricultural production, accounting for 75% of total fertilizer use in Canada (Figure 2; Agriculture and Agri-Foods Canada, 2013). From 2008 to 2012, the usage of nitrogen increased by an annual growth rate of 7.7 %, where urea fertilizers represented the largest volume (Agriculture and Agri-Foods Canada, 2013). Excess nitrate application has the potential to leach into subsurface drainage systems (tile drains) or leach from the soil zone and impact groundwater and surface water bodies. Figure 3 illustrates the various N sources, pathways and chemical processes that can occur in the subsurface. Globally, nitrate has been a major source of groundwater and surface water contamination (Freeze and Cherry, 1979; Exner and Spalding, 1985; Mueller and Helsel, 1996; Hunt et al., 2004; Buss et al., 2005).

Geology and soil types are factors that affect the transport and leaching of NO_3^- in an agricultural setting. Nitrate is not limited by solubility constraints and due to its anionic form (NO_3^-), it is the stable form of dissolved N in oxidizing groundwater (Freeze and Cherry, 1979). Nitrate is mobile in environments where groundwater flows through fractured rock or very shallow groundwater in highly permeable sediment because of the higher dissolved oxygen concentrations often associated within these hydrogeologic environments (Freeze and Cherry, 1979). Soil type investigations have shown that, given a source of organic C, bacterial denitrification often occurs. In a soil column experiment, Gilbert et al. (1979) showed > 80% N-removal by denitrification during low infiltration rates, but at higher infiltration rates, C enrichment was required to maintain the same removal rates. Coarse, permeable soils, such as sandy soils, allow enhanced leaching of NO3- to the groundwater zone (Baker et al., 1989; Goss et al., 1998) whereas clayey soils have been shown to restrict N leaching (Hubbard et al., 2004).

1.2 Phosphorus

Phosphorus is a naturally occurring element that is essential for seed, fruit and flower production (Canadian Fertilizer Institute, 2016). Phosphate is a moderately soluble compound that is an important nutrient for plant and algae growth, where orthophosphate is the simplest form of phosphate (PO_4^{3-}). Anthropogenic activities, such as intensive agriculture, often result in increased P loading to waterbodies causing chemical imbalances in aquatic ecosystem. Nitrate and phosphorus are both nutrients that can stimulate eutrophication of water bodies, however, P is usually considered the limiting factor for algae growth in freshwater ecosystems (Dillon and Rigler, 1974; Schindler, 2006). Increased algae growth can lead to the development of anoxic conditions within the waterbody. Like nitrate, fertilizer use is a source of P (main forms are as

$H_2PO_4^-$ and HPO_4^{2-}; Rivard et al., 2016) in an agricultural setting. The tile drainage systems of agricultural fields are potentially a source of P (and N) transport into streams and lakes. Total P (TP) concentrations, in agricultural runoff, include P in the form of soluble reactive P (SRP) (or dissolved P) and particulate P (PP).

Soluble reactive P is one of the soluble forms of P, often referred to as orthophosphate, which is often rapidly up taken by plants— Phosphorus in this form often becomes depleted. Irrigation practices and rainfall can increase the mobility of soluble P and during low flow periods, there is the potential for the slow release of P.

Particulate P is the non-soluble form of P. It is primarily the organic P associated with the organic debris that comprises part of the suspended sediment load in streams. Particulate P is not directly available for plant uptake, however, this material can be converted to orthophosphate under certain conditions and subsequently dissolved. Application of P fertilizers promotes adsorption of phosphate anions onto soil particles, causing P enrichment in surface soils. Soil particles with elevated P then have the potential to erode into adjacent waterbodies during runoff events. In agricultural runoff, the total phosphorous load is often dominated by particulate P (Sharpley et al., 1992; Kronvang, 1992; Beauchemin et al., 1998; Vanni et al., 2001; Gentry et al., 2007; Choudhury et al., 2016), making it an important component to target in remediation efforts.

1.3 Biofilter Construction and Use

The use of constructed wetlands and biofilters has gained popularity in recent years for control of nutrient export from agricultural lands. Woodchips have become one of the medium types promoted for use in biofilters because the medium has demonstrated an ability to remain effective in field applications across multiyear time frames while requiring little maintenance (Schipper and Vojvodic-Vukovic, 2001; Moorman et al., 2010). The principle focus of most woodchip filters has been the control of NO_{3^-} export because the medium provides a source of slowly soluble labile C that can promote denitrification (Schipper *et al*., 2010b).

To date, many of the woodchip bioreactor studies have focused on low turbidity water, such as agricultural tile drainage or pretreated wastewater, which necessarily focused on SRP and NO_3^--N (Robertson *et al.*, 2005; Schipper *et al*., 2010a). Even novel approaches, such as the use of zeolite and biochar as biofilter amendments to facilitate P removal, have focused on SRP (Ibrahim *et al.*, 2015; Bock *et al.*, 2015). However, the source water available for treatment in woodchip bioreactors in many of our agricultural landscapes is highly turbid, with particulate P contributing 38 to 95% of the TP loads in several studies (Sharpley *et al.*, 1992; Kronvang, 1992; Beauchemin *et al.*, 1998; Vanni *et al*., 2001; Gentry *et al.*, 2007). Considering the characteristics of this potentially treatable water, the investigation of particulate removal, through filtration, in woodchip bioreactors is needed. Because of the plate-like shape and surface roughness of standard 5-cm-diameter woodchips, the potential for a woodchip bioreactor to act as a sediment filter could be substantial. In a previous study of a woodchip filter trenched into a streambed, Chan (2010) observed 70% removal of TSS during a 4-mo period and particularly during high-flow events. Furthermore, the high hydraulic conductivity of woodchip media (1–5 cm/s ; van Driel *et al*., 2006; Chun *et al*., 2009; Cameron and Schipper, 2010) allows robust flow-through rates, and in areas such as southern Ontario, the delivered cost of woodchips ($30 m^3) is generally similar to other potential filter materials such as pea stone. Other practices used to remove P in agricultural settings, such as wetlands and riparian buffers, while providing encouraging results, tend to require large amounts of space (Hey *et al*., 1994; Nairn and Mitsch, 1999; Uusi-Kämppa *et al*., 2000). To avoid impinging on productive arable land, minimizing the area required for treatment is desirable. If woodchip filters can provide P removal for comparable capital and operational expense, with a smaller footprint, this might be viewed as an attractive option for P control in some situations.

In this study, woodchip filter systems were used to treat agriculturally impacted surface waters at five sites in southern Ontario. A filter system installed at Bradford, ON was used to treat root vegetable wash water from a local farm. The wash water had very high TSS levels in the range of 5000 to 10,000 mg/L, with associated TP of 5 to 10 mg/L. Initially, a pilot-scale system was implemented and monitored during May to July 2014. Then, in November 2014, a full-scale system consisting of a 12.3 m^3 concrete sedimentation tank and a slightly larger subsurface woodchip filter (16.1 m^3) was installed and treated wash water discharging at an average rate of 10.8 m^3/d during active vegetable washing. Treatment of total suspended solids and PP was the focus at this site, as it was expected that the treatment system would have limited capacity for removing SRP. This system was monitored intermittently from May 2014 to March 2016.

The second filter was located near Barrie, ON and was installed to treat P in an agricultural drainage ditch. This system was monitored intermittently from December 2014 to March 2016.

The third woodchip filter was installed in May 2014 to treat flow from a drainage tile that discharges from a sod farm located near Keswick, ON. In addition, six multilevel monitoring wells were installed at this site to assess natural nutrient attenuation in the shallow groundwater flow system. This system was monitored intermittently from May 2014 to March 2016.

The final two woodchip filters, were two filters that were installed previously and that have now been in operation for about 10 years or more (van Driel et al., 2006; Robertson and Merkley, 2008; Robertson et al., 2009; Chan, 2010). One is located on Wildwood Lake near St. Marys, ON and treats flow from a drainage tile. The other is located on the headwaters of the Avon River, near Stratford, ON and treats flow in a drainage ditch. Both were initially designed primarily to provide NO3--N removal and consequently, P removal received little attention in previous studies. These systems were monitored intermittently from May 2014 to March 2016.

1.4 Objective

The objective of this study was to test the usefulness of woodchip media filters for control of particulate P export in agricultural drainage. This was achieved by monitoring five relatively large scale field installations that targeted drainage with a broad range of turbidity conditions. The study was carried out over two seasonal cycles to allow monitoring to also include filter performance during high flow, high turbidity events. Although woodchip filters have received considerable attention over the past decade for their ability to remediate NO^{3}- N. The potential for P removal has, so far, been largely ignored. This study was undertaken to address this knowledge gap.

2. Methods

2.1 Sampling

Water samples were collected weekly to bi-monthly, using a 60-cm^3 syringe at all five sites. At the Bradford filter, samples were collected from the inlet of the sedimentation tank and the woodchip filter outlet pipe and also from the outlet of the tank from 15 Dec. 2014 to 28 Mar. 2016. Sampling started for the filters in Big Bay and the other three sites in Dec. 2014, and on May 2014, respectively, and continued until Mar. 2016. The samples for the Big Bay and Avon filters were collected upstream of the filter, downstream from the tile drain pipe (filter influent) and from within the filter effluent pipe. The samples for the Wildwood and Keswick filters were collected at the tile drain pipe (filter influent) and from within the filter effluent pipe. Groundwater samples were collected at the Keswick site on 4 Dec. 2015 and 13 Apr. 2015. Water samples for TSS, TP, SRP, dissolved organic C (DOC), NO_3^-, and NH_4^+ were each collected in separate polyethylene sample bottles. Samples for SRP, DOC, NH_4^+, and NO_3^- were field filtered (0.45 µm), whereas samples for TSS and TP were unfiltered. Samples for SRP were acidified immediately after collection to $pH < 2$ using concentrated HCl. Groundwater samples were also collected for greenhouse gas analysis at the Keswick site on 13 Apr. 2015. These were collected in 10-mL glass vials and preserved using 0.5-mL of $ZnCl_2$. Groundwater samples were not specifically collected for isotope analysis however the extra groundwater samples and tile drain water samples, collected between May 26, 2014 and Jan. 5, 2016, were kept frozen for future isotope analysis. The temperature and dissolved O_2 content of the filter influent and effluent were measured using a field portable meter (Hach Model HQ40d), and flow rates exiting the filter were measured using a calibrated beaker. Field analysis of soluble iron for the influent and effluent flow at the Big Bay site was tested colorimetrically using CHEMets® Visual Kits (Phenanthroline method). At the Bradford filter, the accumulation of sediment in the tank was monitored using a meter stick. All the water samples were returned to the laboratory and kept frozen until analysis, generally within 2 weeks of collection.

2.2 Laboratory Analysis

Samples were analyzed at the Environmental Geochemistry Laboratory, Department of Earth and Environmental Sciences, University of Waterloo, using standard methods (APHA, 1998). Soluble reactive P was analyzed colorimetrically (molybdenum blue technique) using a spectrophotometer (Cary100 UV-Vis, Agilent Technologies), which provided a detection limit of 0.5 µg P/L (Murphy and Riley, 1962; American Public Health Association, 1999). Total P analysis was like SRP, except that samples were digested with H_2SO_4 and $(NH_4)_2S_2O_8$ before analysis. The detection limit for TP analysis was also 0.5 µg P/L. Since the water that will be analyzed is agricultural water, where the main dissolved P component is expected to be orthophosphate, the form that most plants uptake and should be in water leached or drained from fertilized soils, soluble reactive P was considered the major dissolved form of phosphorus. As a result, the particulate P was defined as the difference between SRP and TP. During May to July 2014, some of the TP analyses were completed at the Soil and Nutrient Laboratory, University of Guelph, Guelph, ON, using similar methods. Dissolved organic C was measured using a total C analyzer (Model TOC-L CPH, Shimadzu Corp.). Nitrate was measured by ion chromatography (Model ICS-2100, Dionex Ltd.). Ammonium was measured colorimetrically using a SmartChem 200 WestCo Scientific wet chemistry analyzer (Unity Scientific). Isotope analysis was completed by mass spectrometry, following the methods outlined by Spolstra et al. (2014). The $\delta^{15}N$ and $\delta^{18}O$ values of N_2O were determined on an IsoPrime mass spectrometer, coupled with a Micromass TraceGas Pre-concentrator (GV instruments, Thermo Electron Corp., Manchester, UK). Samples were not collected specifically for iron analysis, however, remaining extra, preserved, filtered water samples from the Wildwood filter were analyzed at the Soil and Nutrient Laboratory, University of Guelph, Guelph, ON and using ICP (Optima 8000 ICP-OES, PerkinElmer Inc.) at the Centre for Cold Regions & Water Science (CCRWS) Analytical Facility, Wilfrid Laurier University, Waterloo, ON. Filtered samples from the Big Bay site for sampling events on 11 Mar. 2015, 30 Jun. 2015 and 2 Nov. 2015 were also submitted for iron analysis at the CCRWS Analytical Facility. The water samples that were submitted for iron analysis at CCRWS Facility were preserved using nitric acid (HNO3) to a pH of 2 or less. Total suspended solids were determined gravimetrically by weighing the sediment retained on 1.6-mm filter paper.

Student’s t-tests were undertaken utilizing Microsoft Excel 2013 to establish if treatment parameters varied significantly between treatment steps. These tests assumed a normal data distribution, although several parameters (TSS, TP, and SRP) had data that was right-skewed, and DOC exhibited a bimodal distribution.

3. Bradford Site

3.1 Site Description

The filter was installed at a farm in a vegetable growing area known as the Holland Marsh, located near the city of Bradford and Lake Simcoe in southern Ontario. The predominant soil type is an organic muck soil throughout the Holland Marsh. In 2013, the farm harvested 14 ha of carrot [*Daucus carota* L. var. *sativus* Hoffm.], 9 ha of beet (*Beta vulgaris* L.), and 3 ha of parsnip (*Pastinaca* L.) during the months of August to October. This produce was stored in wooden pallet boxes at a central location where the washing facility was located and was then sold to a food distribution terminal in Toronto, during the 9-mo period following harvesting, as market conditions dictated. The washing apparatus consisted of a rotating drum and conveyor belt where the vegetables were sprayed with municipally supplied water to remove attached sediment. The wash water then exited the building via a floor drain.

3.2 Filter Description

Initially, a pilot-scale woodchip filter system was installed at the site in May 2014. It consisted of a subsurface trench, 4.0 m long, 1.3 m wide, and 1.0 m deep (5.2 m^3), filled with standard 5-cm-diameter woodchips (red pine, *Pinus resinosa* Aiton) provided by a local supplier. Vegetable wash water exiting the building was routed onto the top of the woodchip trench using a flexible 10-cm-diameter collection hose and a 4-m length of perforated 10-cm-diameter polyvinyl chloride (PVC) pipe. At the inlet of the woodchip trench, a sediment box, 0.4 $m^{.3}$ in volume, was also installed. After exiting the sediment box, the wash water then percolated downward through the woodchips to a collection pipe (10-cm-diameter perforated PVC) installed along the bottom of the trench, from where it then drained into a nearby ditch.

The pilot-scale filter system operated from May to November 2014 and revealed the design parameters required for a full-scale treatment system, which was then installed in November 2014. Rapid accumulation of solids in the sediment box dictated that a much larger sedimentation tank be used (12.3 m^3, dual-compartment, concrete tank). The full-scale woodchip trench was approximately three times larger than in the pilot system, and was 7.0 m long, 2.3 m wide, and 1.0 m deep (16.1 m^3), but general design and flow routing (Figure 3. 1) was similar to the pilot system. One added feature of the full-scale system was that a 20-cm-thick layer of finer wood particle media (sawdust) was installed mid-depth in the trench to act as a hydraulic barrier (Figure 3. 1) to promote more uniform flow through the woodchips. The full-scale filter was installed in a single day and, beginning on November 24, 2014, the entire wash water flow was diverted into the filter. After one full day of vegetable washing (6 h), the sediment tank had accumulated 10.8 m^3 of wash water (7/8 full), and this was used as the representative hydraulic loading rate (10.8 m^3 /d) during periods of active washing.

3.3 Results

Filter Operation and Maintenance

The full-scale filter operated from November 2014 to June 2015 (Stage I), and during this period washing generally occurred on 3 d/week (Monday–Wednesday) at the indicated wash water usage rate of 10.8 m^3/d. During sampling events, spot checks of filter flows during active washing generally ranged from 12 to 32 L/min, consistent with the expected rate considering that washing only occurred during 6 h/d. The water level in the woodchips was maintained 80 cm above the bottom of the trench, thus most of the filter medium was saturated (Figure 3. 1). Operation of the filter system was relatively maintenance free except that by the end of April 2015 the sediment tank was found to be 75% full of solids. The accumulated sediment was then pumped out and applied to an adjacent field as a soil amendment. Four samples of the sediment collected at that time and assayed for solids characteristics indicated a mean particle size distribution, using sieve and hydrometer analysis, of 63% fine sand, 27% silt, and 10% clay, and showed mean organic C content, determined by mass loss on ignition, of 9.7% (w/w). During a 4-wk period in March 2015 (Figure 3. 2), the outlet pipe from the filter froze, necessitating sample collection from an internal riser pipe (Figure 3. 1) that remained unfrozen during this period.

During operation of the woodchip filter at the end of the spring 2015 washing season, increasing water levels were observed within the filter (Appendix A), which resulted in some flow leaking out the top edge of the filter. This reflected a decrease in the permeability of the woodchips because of sludge accumulation and consequently the woodchips were replaced on September 5, 2015. Inspection revealed that sludge accumulation was most intense in the shallow woodchips immediately adjacent to the inlet pipes and was evident to some extent throughout the top layer. The sawdust layer however, although it had black discoloration along its upper boundary, appeared to have little sludge accumulation and its texture remained similar to fresh sawdust. The bottom woodchip layer had distinctly less sludge accumulation than the top layer. Thus, it appears likely that the permeability of the filter would have been restored simply by replacing the top woodchip layer. Although there was little sludge accumulation in the sawdust layer, it was removed during the maintenance operation so that the impact that this finer grained layer had on TSS and P removal could be observed.

Phosphorus and Total Suspended Solids Removal

Figure 3.2 compares influent and effluent TSS, TP, SRP, and PP concentrations throughout the experimental period from May 2014 to March 2016. This includes both the pilot-scale and full-scale filter systems, showing concentrations exiting within the sedimentation tank from the full-scale system, with a sawdust layer, beginning in December 2014 and without a sawdust layer, beginning in September 2015. The raw wash water had variable but generally very high TSS levels in the range of 300 to 20,000 mg/L, whereas TSS levels in the treated effluent were consistently much lower (<500 mg/L, Figure 3.2). Total P levels in the wash water were moderately elevated (2–43 mg/L) but were substantially reduced in the treated effluent (<6 mg/L). Table 3. 1 summarizes the mean concentrations and removal percentages of TSS and the P components during full-scale filter operation from November 24th, 2014 to March 28th, 2016 with and without a sawdust layer, using the detailed geochemistry in Appendix A. When the woodchip filter included a sawdust layer (November 28th, 2015 to September 5th, 2015), the mean TSS value of the tank effluent (411 mg/L) was significantly lower than that of the wash water (5812 mg/L, $p < 0.05$) and the mean TSS of the woodchip effluent (86 mg/L) was further significantly lower than that of the tank effluent ($p < 0.05$). Overall, the first full-scale treatment stage displayed 99% TSS removal, with 93% occurring in the sedimentation tank and the balance of approximately 6% occurring in the woodchip filter (Table 3.1). The woodchips, with a sawdust layer, had significant removal of the TSS within the tank effluent ($p < 0.05$), which accounted for 6% of the overall TSS removal at a high volumetric removal rate of 311 g/m^3/d (Table 3.1). Similar trends were observed after the sawdust layer was removed from the woodchip filter after September 5th, 2015. The woodchip-only stage of treatment displayed an average overall TSS removal of 96%, with 89% occurring in the sedimentation tank and 7% in the woodchip filter. The woodchip filter removed 65% of the TSS that remained in the tank effluent (267 g/L), which is lower than the percentage removed during the treatment period where the filter had the sawdust layer.

During the operation period when there was a sawdust layer in the woodchip filter, the mean TP value of the tank effluent (4.1 mg/L) was significantly lower than that of the wash water (8.8 mg/L, $p < 0.05$), and the mean TP of the woodchip effluent (2.6 mg/L) was further significantly lower compared with that of the tank effluent ($p < 0.05$). Overall, there was 71% TP removal, with 54% occurring in the sedimentation tank and 17% occurring in the woodchip filter. The dominant P component in the wash water was PP, with a mean of 7.3 mg/L (83% of TP), at this treatment stage. The mean PP concentration of the tank effluent (2.1 mg/L) was significantly lower than that of the wash water ($p < 0.05$), and the mean PP concentration of the woodchip effluent (0.63 mg/L) was further significantly lower than that of the tank effluent ($p < 0.05$). Overall, there was 91% PP removal, with 71% occurring in the sedimentation tank and t 21% PP removal occurring in the woodchip filter. The woodchip filter, with the sawdust layer, removed 70% of the PP (1.47 mg/L) that remained in the tank effluent.

For the woodchip only period of the treatment, the mean TP value in the tank effluent (3.9 mg/L) was not significantly lower than that of the wash water (4.9 mg/L, $p > 0.05$). However, the mean TP of the woodchip-only effluent (3.2 mg/L) was significantly lower compared with that of the tank effluent ($p > 0.1$). There was 21% TP removal occurring in the sedimentation tank and 15% occurring within the woodchip-only filter. Overall, PP remained the dominant P component in the wash water, with a mean of 3.9 mg/L (80% of TP). The mean PP concentration of the tank effluent (2.2 mg/L) was significantly lower than that of the wash water ($p < 0.05$), and the mean PP concentration of the woodchip-only effluent (0.9 mg/L) was significantly lower than that of the tank effluent ($p < 0.05$). Overall, there was 77% PP removal, with 45% occurring in the sedimentation tank and the balance of 32% occurring in the woodchip filter.

Table 3.1 shows the rates of TSS and P removal in the woodchip filter and the sedimentation tank. Volume normalized removal in the woodchip filter (with sawdust layer) was 311 g /m^3/day for TSS and 1.47 g/m^3/d for TP. The volume normalized removal in the woodchip only filter was 256 g/m^3/d for TSS and 0.71 g/m^3/d for TP. The hydraulic retention time in the woodchip filter was approximately 1 day, considering the representative wash water loading rate of 10.8 m^3/day and an assumed total pore volume of 11.3 m^3 for the woodchips. The total pore volume (primary plus secondary pore space internal to the wood particles) was estimated by multiplying the woodchip filter volume (16.1 m^3) by an assumed total porosity value of 0.7 determined from previous studies (van Driel *et al*., 2006; Chun et al., 2009).

In contrast to TSS and TP, SRP concentrations were little changed in the treatment system, however, there was a difference in SRP concentrations between the woodchip filter with a sawdust layer and the woodchip-only filter. Table 3.1 shows the mean woodchip effluent SRP concentration (1.9 mg/L), with a sawdust layer, was not significantly different than the wash water SRP concentration (1.5 mg/L, $p > 0.1$). The mean SRP concentration in the tank effluent (2.2 mg/L; Table 3.1) was slightly increased, from the wash water concentrations (1.5 mg/L), during the woodchip and sawdust sampling period which could indicate some leaching of PP retained within the tank, and this increase was significant ($p < 0.5$). There was a slight decrease in the SRP concentration in the woodchip (with sawdust) effluent (1.9 mg/L) from the tank effluent (2.2 mg/L), however, this difference was not significant ($p > 0.5$). Overall, the difference in SRP concentrations from the wash water and the woodchip (with sawdust) effluent was not significant ($p > 0.5$), however, because of its persistence, SRP represented the largest component of TP in the woodchip and sawdust effluent (73%).

During the period without the sawdust layer, the mean tank effluent SRP concentration (1.5 mg/L) was significantly higher than the wash water ($p < 0.5$, 1.1 mg/L), therefore having the same implications about PP leaching as previously mentioned. There was an SRP concentration increase in the woodchip-only effluent (2.3 mg/L) from the tank effluent (1.5 mg/L), however this increase was not significant ($p > 0.5$). Overall, without the sawdust layer, the mean woodchip-only effluent SRP concentration (2.3 mg/L) was significantly different from the wash water SRP concentration (1.1 mg/L, $p < 0.05$). In the woodchip-only effluent, the SRP component of TP was (72%), similar to the woodchip and sawdust sampling period. However, the volume normalized removal of SRP in the woodchip-only filter was lower than the woodchip filter with a sawdust layer, -0.70 g/m^3/d and 0.32 g/m^3/d, respectively. This shows that the treatment period of the woodchip-only filter released more SRP than during the treatment period with a sawdust layer. This SRP release could be contributing to the decrease in TP removal at the woodchip-only treatment stage, considering that the SRP component seems to be a larger part of the TP in the woodchip-only effluent.

Figure 3.3 shows that there was a strong correlation between PP and TP during all three treatment steps (r^2 = 0.51–0.98), whereas SRP was less well correlated to TP (r^2 = 0.47–0.72). Total P and TSS showed only a slight correlation within treatment steps (r^2= 0.03–0.23; Figure 3. 4) but showed a slightly higher correlation when all three treatment steps were considered together (r^2 = 0.35). Likewise, PP and TSS showed only a slight correlation within treatment steps (r^2 = 0.01–0.30; Figure 3. 4) but showed a higher correlation considering all treatment steps together (r^2 = 0.42). There was little correlation between SRP and TSS (r^2 = 0.01–0.09; Figure 3. 4). Overall, the full-scale treatment system, with the sawdust layer, provided 99% TSS removal and 91% PP removal, but a lesser amount of TP removal occurred (71%) because SRP concentrations were little changed. Without the sawdust layer, the full-scale treatment system provided 96% TSS removal and 77% PP removal, but only a 36% TP removal occurred because there was an increase in the SRP concentration in the woodchip-only effluent, particularly during start up, which decreased the overall P removal efficiency.

Nitrogen and Dissolved Organic Carbon

Figure 3.5 shows inorganic N (NO_3^--N and NH_4^+-N) trends, which were relatively low in the wash water during the full-scale treatment, November 24th, 2014 to March 28th, 2016, (means of 0.68 and 0.40 mg N/L, respectively). The overall mean NO_3^-–N concentrations, in the treated effluent (0.13 mg/L) were significantly lower ($p < 0.05$), suggesting that denitrification was most likely active in the woodchip filter. Dissolved O_2 concentrations in the treated effluent were low (<1.5 mg/L, Appendix A), supporting the likelihood of denitrification activity. Concentrations of NH_4^+-N increased significantly to a mean of 1.8 mg/L and 4.2 mg/L in the woodchip effluent, with and without a sawdust layer, ($p < 0.05$). This increasing trend became more pronounced as the trial proceeded (Figure 3. 5). The cause of this apparent NH_4^+ production is uncertain, but it could indicate that mineralization of some of the organic N retained in the filter, was occurring.

During the treatment stage with the sawdust layer, the overall dissolved organic C concentrations in the wash water were high (mean of 117 mg/L; Table 3. 1) but variable (range of 16–386 mg/L; Figure 3.5), and the DOC concentrations in the treated effluent were significantly higher (mean of 169 mg/L, $p < 0.05$; Table 3. 1). During the treatment stage without the sawdust layer, the DOC mean concentration in the wash water remained high (151 mg/L; Table 3. 1) and the DOC concentrations in the woodchip-only effluent was slightly lower, however, the difference was not significant (mean of 147 mg/L, $p > 0.1$). There is some correlation between the DOC and SRP concentrations in the wash water and tank effluent (r^2 = 0.47 and 0.15, respectively; Figure 3.6) however, there is little correlation in the woodchip effluent ($r^2 = 0.06$; Figure 3. 6).

Figures 3.7 and 3.8 are scatter plots that provide a comparison of influent and effluent parameter concentrations (TSS, TP, SRP, PP, DOC, NO_3^--N and NH_4^+) for the tank and woodchip filter separately. This comparison demonstrates the degree of TSS, TP, PP, NO_3^--N and NH_4^+-N removal, and SRP and DOC release within the two filter components.

Sediment Mass Balance

Table 3. 1 shows that most of the TSS removal during stages 1, and 2 at the Bradford system occurred in the sedimentation tank (93%, and 89%, or 5401 mg/L, and 3317 mg/L, respectively), whereas a smaller amount (6%, and 7% or 325 mg/L, and 267 mg/L, respectively) was removed in the woodchip filter. The tank was pumped out at the end of April 2015, after 60 days of washing and had accumulated 9.6 m^3 of sediment at that time. During this period, an estimated 648 m^3 (60 d × 10.8 m^3/d) of wash water was treated, representing 648 m^3 × 5.40 kg/m^3 (5401 mg/L) or 3499 kg of sediment accumulation in the tank. The measured volume of the sediment (9.6 m^3) indicated that this material had a density of 364 kg/m^3 (specific gravity of 0.36). Sediment accumulation in the woodchips during this period was 648 m^3 × 0.324 kg/m^3 = 210 kg. Assuming a similar density of 364 kg/m^3, the volume of this sediment deposited in the woodchips would have been 0.58 m^3. Woodchip medium typically has primary porosity (excluding secondary porosity internal to the wood particles) of approximately 0.5 (Cameron and Schipper, 2010; Robertson, 2010), thus the woodchip trench was expected to have a total primary pore space of 8 m^3 (16.1 m^3 × 0.5), although this was not measured directly. If we

assume that the sediment accumulating in the woodchips had a density similar to that in the tank, about 7% of the available pore space in the woodchip medium would have been in-filled after 60 days of washing.

3.4 Discussion

A substantial fraction of the TSS (91-93%) and TP removal (51-54%) occurred within the sedimentation tank (Table 3.1). In some cases, utilization of a sedimentation tank alone might be adequate for some treatment purposes. Furthermore, during preliminary pilot-scale testing, the sediment box in place at that time was often filled with sediment because of its small size (0.4 m^3) and was largely ineffective. Yet, TSS removal of about 5500 mg/L still occurred in the pilot woodchip trench (Figure 3.2), which was similar to that provided by the full-scale system (5726 mg/L during stage 1 and 3584 mg/L during stage 2; from Table 3.1). This comparison suggests that the initial TSS removal capacity of the woodchip medium alone would be comparable to the full-scale system, although the settling tank provided an invaluable method for extending the filter life. Although much of the TSS and TP removal occurred in the sedimentation tank, substantial removal still occurred in the woodchip filter. The TSS and TP removal during the treatment step with and without the sawdust layer remained significant, however there was a decrease in the removal rate from 311 $g/m^{3/}d$ (with sawdust) to 256 (woodchip-only) $g/m^{3/}d$ for TSS, and from 1.47 $g/m^{3/}d$ (with sawdust) to 0.71 $g/m^{3/}d$ (woodchip-only) for TP. It is noted that even though the TSS and TP were being removed at high rates, the relationship between these two parameters in the wash water, tank effluent and woodchip effluent were low (r^2(In)=0.23, r^2(Out-Tank)=0.03, r^2(Out-Chips)=0.03, Figure 3.4).

The mean removal rates, in the woodchip filter, of 256 to 311 g/m^3/day (or 256 to 311 g/m^2/day considering a filter depth of 1.0 m) for TSS and 0.71 to 1.47 g/m^3/day (or 0.71 to 1.47 g/m^2/day) for TP, with the sawdust layer (Table 3.1) exceed values reported for many constructed wetlands by a large factor. For example, Uusi-Kämppa et al. (2000) reported TP removal ranging from 0.005 to 0.3 g/m^2/day in 11 ponds and constructed wetlands in Scandinavia, and Nairn and Mitsch (1999) reported TP removal of 0.014 g/m^2/d in two constructed wetlands treating river water in Ohio. In a review, Hoffmann et al. (2009) reported TP removal rates of up to 0.035 g/m^2/day in riparian buffers and wetlands. Although the high removal rates reported in the current study largely reflect the very high input rates, these results nonetheless demonstrate the substantial capacity of such a filter system for removal of TSS and TP.

The PP removal within the woodchip biofilter remained significant, with and without the sawdust layer. There was a slight increase from 21% PP removal with the sawdust layer, to 32% PP removal without the sawdust layer. However, there was no drastic change to the TP removal rates (1.43 g/m^3/day with the sawdust layer and 1.21 g/m^3/day without), therefore, the sawdust layer does not seem to have a large effect on the PP removal capability of the woodchip biofilter.

During the period from November 2014 to September 2015, concentrations of SRP in all treatment steps tended to increase from about 1.5 to 1.9 mg/L (Figure 3.2). After the removal of the sawdust layer within the woodchip filter, there was an increase in the amount of SRP that was in the woodchip effluent. The SRP removal rate in the woodchip-only filter decreased from 0.32 g/m^3/day with the sawdust layer, to -0.70 g/m^3/day without the sawdust layer. This further diminished TP removal because SRP remained untreated. There are four possibilities that could have lead to this outcome:

1. The same trend potentially occurred during Fall of 2014 when vegetable washing resumed, however the system was not being monitored during that time.
2. Temperatures were higher during the Fall of 2015 period which possibly promoted leaching of particulate P.
3. Less washing occurred during start-up in September (only 2 days/week instead of 3) compared to the rest of the year. This would mean that the retention time in the woodchips would be longer, thus additional time for SRP leaching.
4. In September 2015, only the top layer of the woodchip filter was switched out, including the sawdust layer, while bottom layer was left in place. This allowed an extended period of leaching of the particulate P remaining in the material that sat stagnant in the summer, within the bottom layer of the woodchips.

The excess SRP leaching is thus likely a start up issue. Revised , TP, SRP and PP concentrations, along with the removal rates, excluding the data from September and October of 2015 is included within Table 3.1. The removal of TP, TP and PP did not drastically change from the values in Table 3.1, however, the overall SRP leaching in the woodchips-only filter decreased from 68% to 33% and decreasing the SRP leaching rate from 0.70 g/m^3/day to 0.32 g/m^3/day (Table 3.1).

Dissolved organic C concentrations increased during the full-scale treatment period (Figure 3.5). During this period, the vegetables being washed experienced an increasingly long period of storage since their harvest the previous fall. One possibility is that there was increasing DOC (and SRP) leaching from the vegetables as they aged.

Dissolved organic C concentrations in the woodchip effluent (mean of 156 mg/L) were not significantly different ($p > 0.1$) than the tank effluent (mean of 145 mg/L; Table 3.1), indicating that possible DOC leaching from the woodchips was not the major source of DOC. However, we note that during the first several months of full-scale operation, most woodchip effluent samples had DOC that was 50 to 100 mg/L higher than the tank effluent (Figure 3.5), indicating that DOC was leaching from the woodchips during the initial operation. This is also reflected in Figure 1.6, which shows no correlation between DOC and SRP for the woodchip effluent ($r^2 = 0.06$), presumably because of the additional DOC that was leached from the woodchips during early operation.

The high TSS content of the wash water required that the sedimentation tank be pumped out after 5 months of washing. The consistency of the sediment was such that it could be easily handled by pumping equipment routinely available for handling slurred manure. A larger tank or excavated pit could be used to extend pump-out periods. The woodchip filter required little maintenance during 16 months of operation, except that the inlet pipe had to be cleared of coarse accumulated organic debris after 6 months of operation and the top most layer of the woodchip filter had to be switched out in September 2015. During the full-scale treatment period, we estimated that only about 7% of the primary pore space in the woodchip medium had been infilled with sediment, suggesting that the filter medium could have potentially remained functional for several years before requiring replacement. Presumably, the spent woodchip medium could also be applied to adjacent farm fields as a soil amendment and in accordance with local regulations.

3.5 Conclusion

Wood particle filter systems, with appropriately sized settling basins for pre-treatment, appear to have a high capacity for removal of suspended solids and associated particulate P from turbid water. In this case, the treatment system had an overall removal of 98% for TSS and 84% for PP but exhibited minimal ability to remove SRP. This was expected because the filter design was chosen to address the relatively larger fraction of PP present in the vegetable wash water. Moreover, the high capacity of the filter presents an opportunity for more efficient treatment, compared with constructed wetlands, for example, because a smaller footprint allows less lost farm space per unit reduction. Removal rates for the woodchip-only filter were 256 $g/m^2/day$ for TSS and 0.71 $g/m^2/day$ for TP, substantially exceeding rates typically reported for constructed wetlands and ponds. Furthermore, because substantial TSS removal occurred in the sedimentation tank (overall 91%), this material was easily accessible, and after 5 months of operation, this sediment was removed and applied to an agricultural field as a soil amendment. The ability to capture and remove a large portion of the TSS was a positive feature of this system because it eliminated the possibility of future remobilization of P entrained within this material, which has been observed with other TSS control technologies. The treatment system was relatively simple to operate and required little maintenance during a period of over one year. These features could make such filters attractive for use in a variety of agricultural operations where turbid waters are generated. Woodchip filters could also have an ability to remove TSS and particulate P from lower turbidity waters and might be useful in other applications, such as in agricultural streams and drainage systems where P export is often dominated by particulate material.

Table 3.1 Bradford (vegetable wash) site: Concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO_3^-–N, NH_4^+–N, and dissolved organic C (DOC) in the wash water, sedimentation tank effluent, and woodchip filter effluent (full scale system only, from November 24th, 2014 to March 28th, 2016), removal percentages with respect to the wash water values, and volumetric removal rates in the sedimentation tank and woodchip filter. Rates consider flow of 10.8 m^3/d, a tank volume of 12.3 m^3, and woodchip pore volume of 11.3 m^3, assuming a porosity of 0.7 (van Driel *et al*., 2006). The mean values within this table do not include dates where samples were collected incorrectly, thus producing values that were not typical of those dates.*

Substance	**Wash Water**	**Tank Effluent**	**Filter Effluent**	**Removal**				
				Total	**Tank**	**Chips**	**Tank**	**Chips**
Woodchip biofilter with a sawdust layer (24 Nov. 2014 to Aug. 2015)								
	---------------------------- mg/L----------------------------			------------ % --------------			------ g/m^{3}/d------	
TSS	5812 ± 2674 (23)[†]	411 ± 223 (17)	86 ± 88 (24)	99	93	6	4743	311
TP	8.8 ± 5.5 (24)	4.1 ± 1.8 (19)	2.6 ± 1.3 (24)	71	54	17	4.16	1.47
SRP	1.5 ± 1.2 (25)	2.2 ± 1.0 (17)	1.9 ± 0.9 (26)	-22	-44	22	-0.59	0.32
PP	7.3 ± 4.6 (24)	2.1 ± 0.9 (17)	0.63 ± 0.76 (24)	91	70	21	4.53	1.43
NO^-_3-N	0.61 ± 0.98 (23)	0.49 ±0.41(16)	0.12 ± 0.17 (21)	80	20	60	0.11	0.35
NH^+_4-N	0.39 ± 0.53 (22)	0.48 ±0.34(13)	1.84 ± 1.79 (23)	-367	-22	-345	-0.08	-1.30
DOC	117 ± 98 (23)	152 ± 81 (17)	169 ± 65 (24)	-44	-30	-15	-30.6	-16.31
Woodchip biofilter with no sawdust layer (Sept. 2015 to 28 Mar. 2016)								
TSS	3725 ± 6296(17)	408±165(14)	141±65(17)	96	89	7	2913	256
TP	4.9 ± 3.1 (17)	3.9 ± 2.5 (16)	3.2 ± 2.3 (17)	36	21	15	0.89	0.71
SRP	1.1 ± 0.36 (15)	1.5 ± 0.83 (14)	2.3 ± 1.5 (17)	-110	-43	-68	-0.40	-0.70
PP	3.9 ± 3.0 (17)	2.2 ± 1.3 (16)	0.9 ± 0.9 (17)	77	45	32	1.53	1.21
NO^-_3-N	0.75 ± 0.53 (17)	0.33 ± 0.24(16)	0.14 ± 0.09 (17)	82	56	25	0.37	0.18
NH^+_4-N	0.49 ± 0.44 (15)	3.45 ± 4.67(13)	4.16 ± 4.01 (15)	-754	-609	-145	-2.60	-0.68
DOC	151 ± 74 (17)	144 ± 52 (16)	147 ± 56 (17)	3	5	-2	6.7	-3.42
Woodchip biofilter with no sawdust layer-Excluding startup events (Oct. 2015 to 28 Mar. 2016)*								
TSS	4846 ± 7269 (12)[†]	426 ± 115 (9)	152 ± 71 (12)	97	91	6	3881	263
TP	5.3 ± 3.3 (12)	2.6 ± 0.6 (11)	1.8 ± 0.5 (12)	65	51	14	2.37	0.73
SRP	1.0 ± 0.38 (10)	1.1 ± 0.3 (10)	1.4 ± 0.5 (12)	-42	-8	-33	-0.07	-0.32
PP	4.4 ± 3.2 (12)	1.5 ± 0.5 (11)	0.4 ± 0.3 (12)	91	65	26	2.50	1.07

[†] Means ± standard deviations; number of replicates in parentheses.

*Dates excluded:
(2015) Mar. 18th, Sept. 2nd, Nov. 4th
(2016) Jan. 13th
(Additional start-up dates excluded in 2015 from last section of table) Sept. 9th, Sept. 16th, Sept. 30th, Oct. 7th, Oct 14th

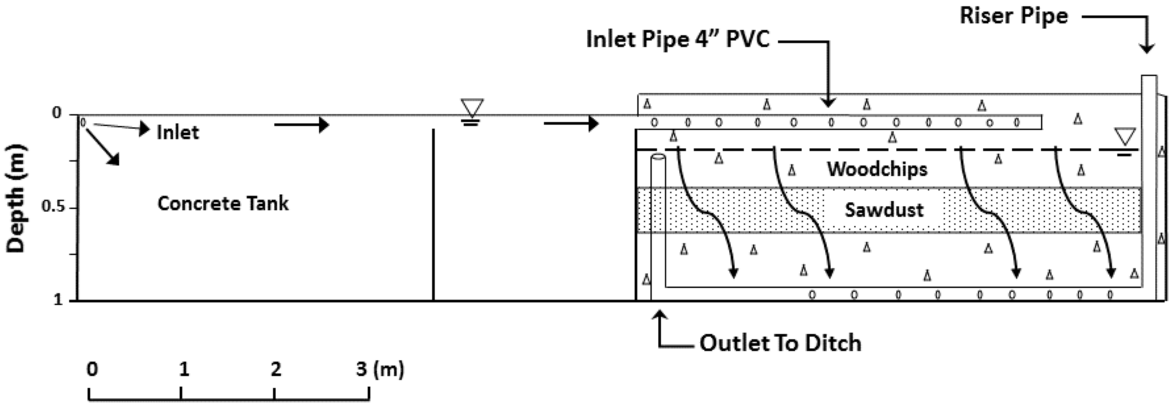

Figure 3.1 Bradford (vegetable wash) site: Design of full-scale vegetable wash water filter system, (Bradford site), showing concrete sedimentation tank (12.3 m^3) and attached wood particle filter (woodchips and sawdust, 16.1 m^3) installed in a subsurface trench. The trench is 2.3 m wide. Arrows indicate the direction of flow.

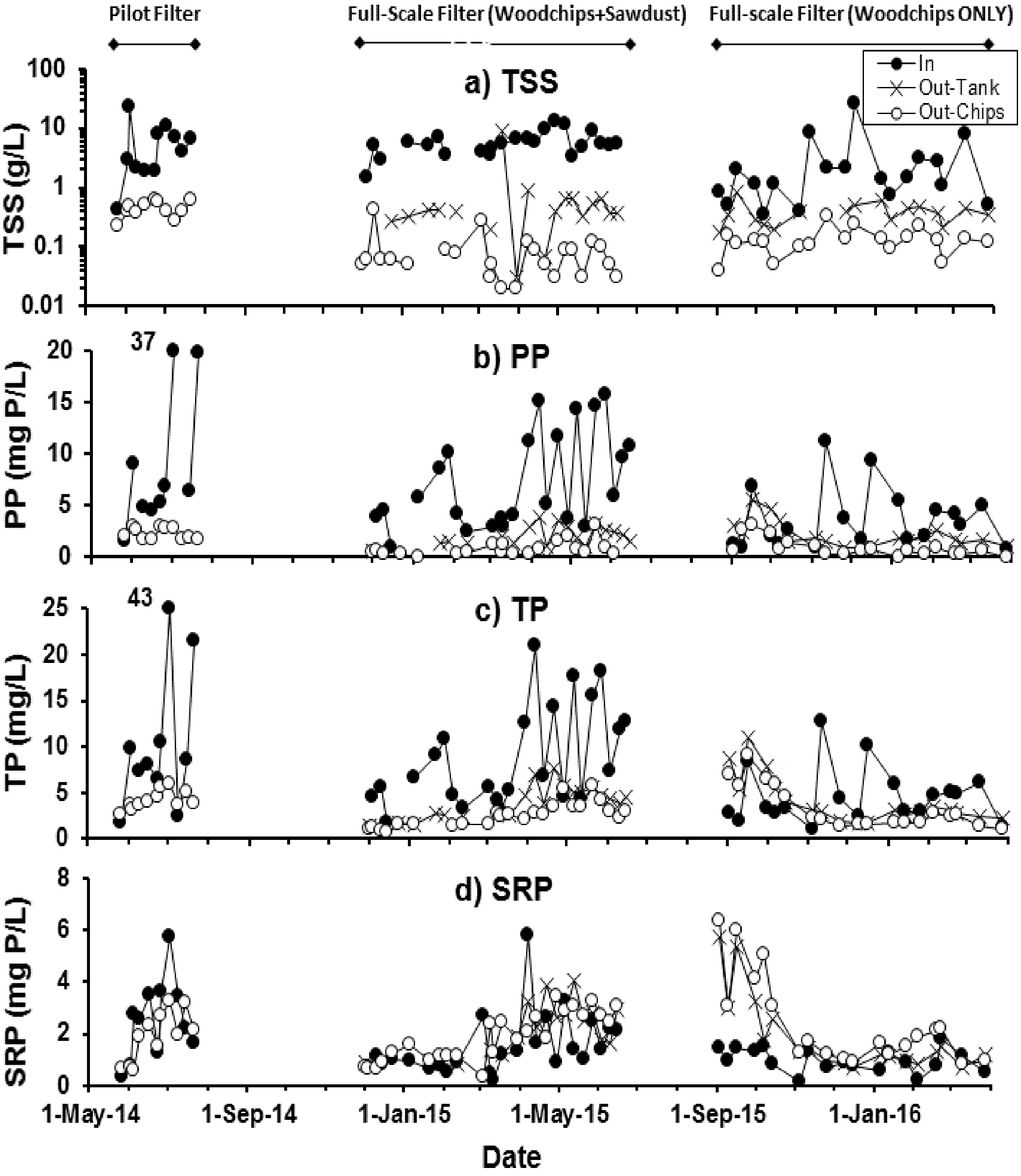

Figure 3.2 Bradford (vegetable wash) site: Trends in (a) total suspended solids (TSS), (b) particulate P (PP), (c) total P (TP), and (d) soluble reactive P (SRP) in the vegetable wash water (In), sedimentation tank effluent (Out-Tank), and woodchip filter effluent (Out-Chips) from May 2014 to March 2016. The pilot-scale filter system operated from May to July 2014 and September to November 2014 (unmonitored). The full-scale filter system operated from November 2014 to September 2015, with sawdust layer, and from September 2015 to March 2016, without the sawdust layer. The dashed line indicates the period when the outlet pipe was frozen during March 2015.

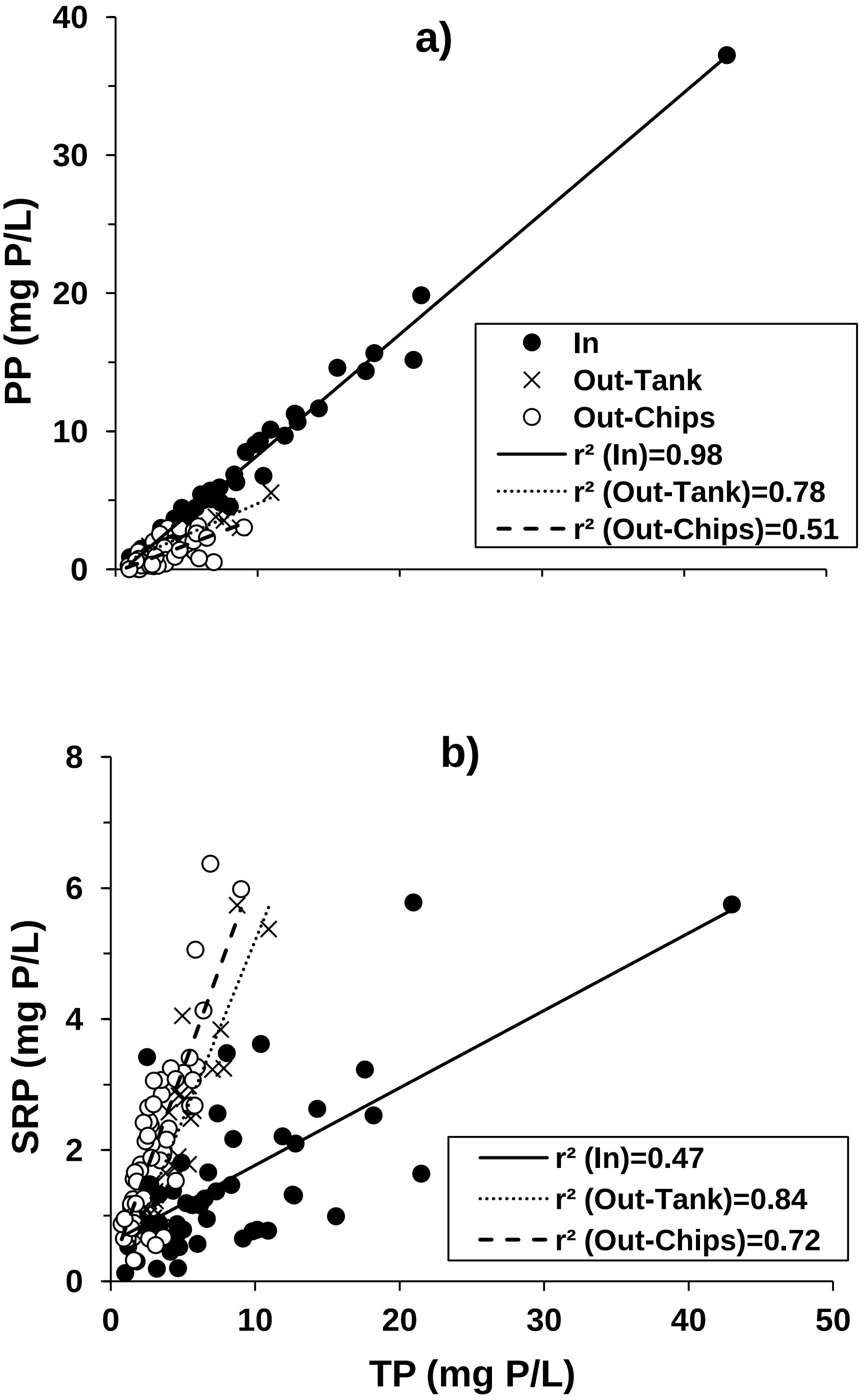

Figure 3.3 Bradford (vegetable wash) site: Correlation of total P (TP) with (a) particulate P (PP) and (b) soluble reactive P (SRP) concentrations in a woodchip filter treating vegetable wash water during a 22-mo period.

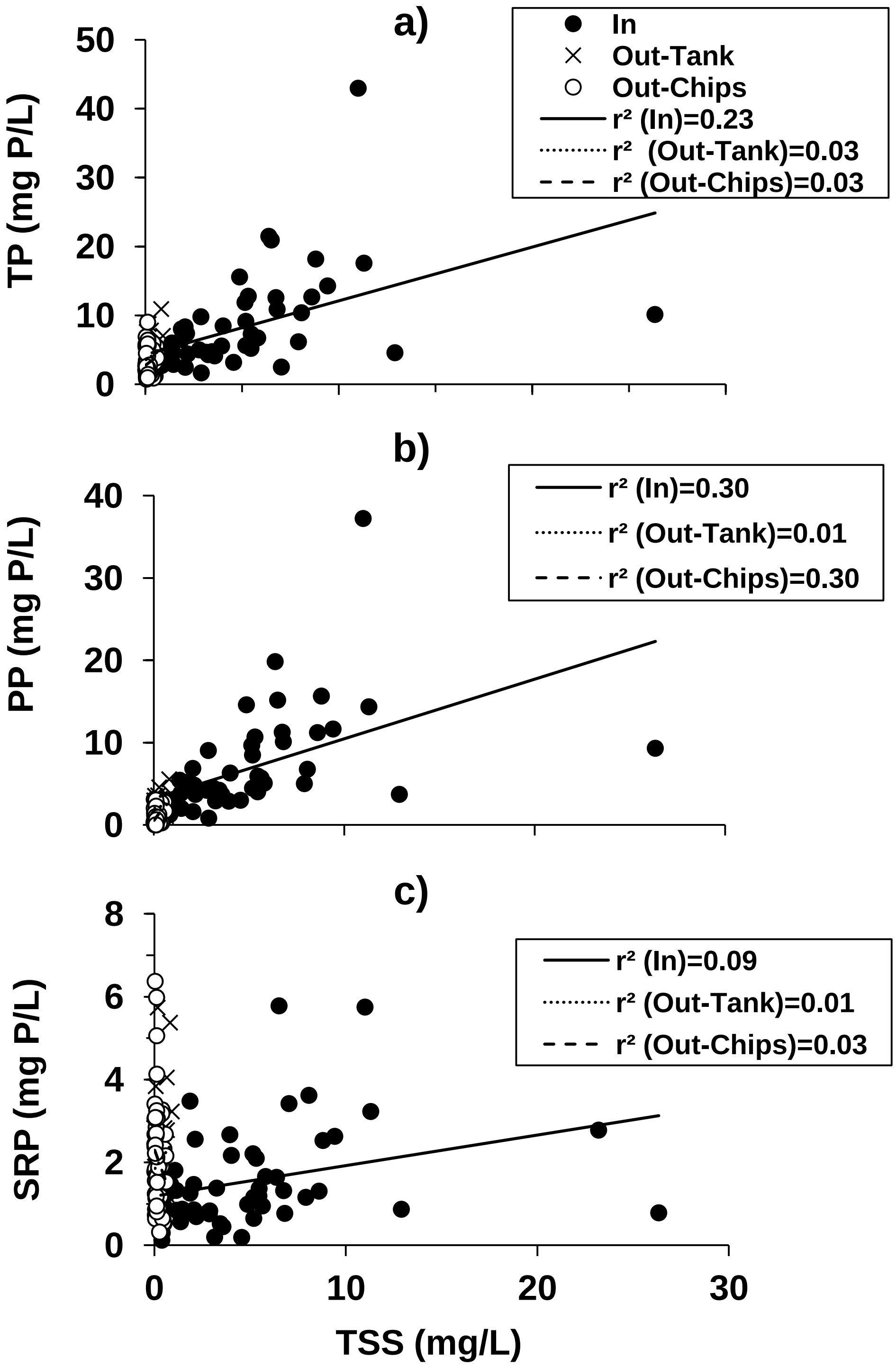

Figure 3.4 Bradford (vegetable wash) site: Correlation of total suspended solids (TSS) with (a) total P (TP), (b) particulate P (PP) and (c) soluble reactive P (SRP) concentrations in woodchip filter system treating vegetable wash water during a 22-mo period.

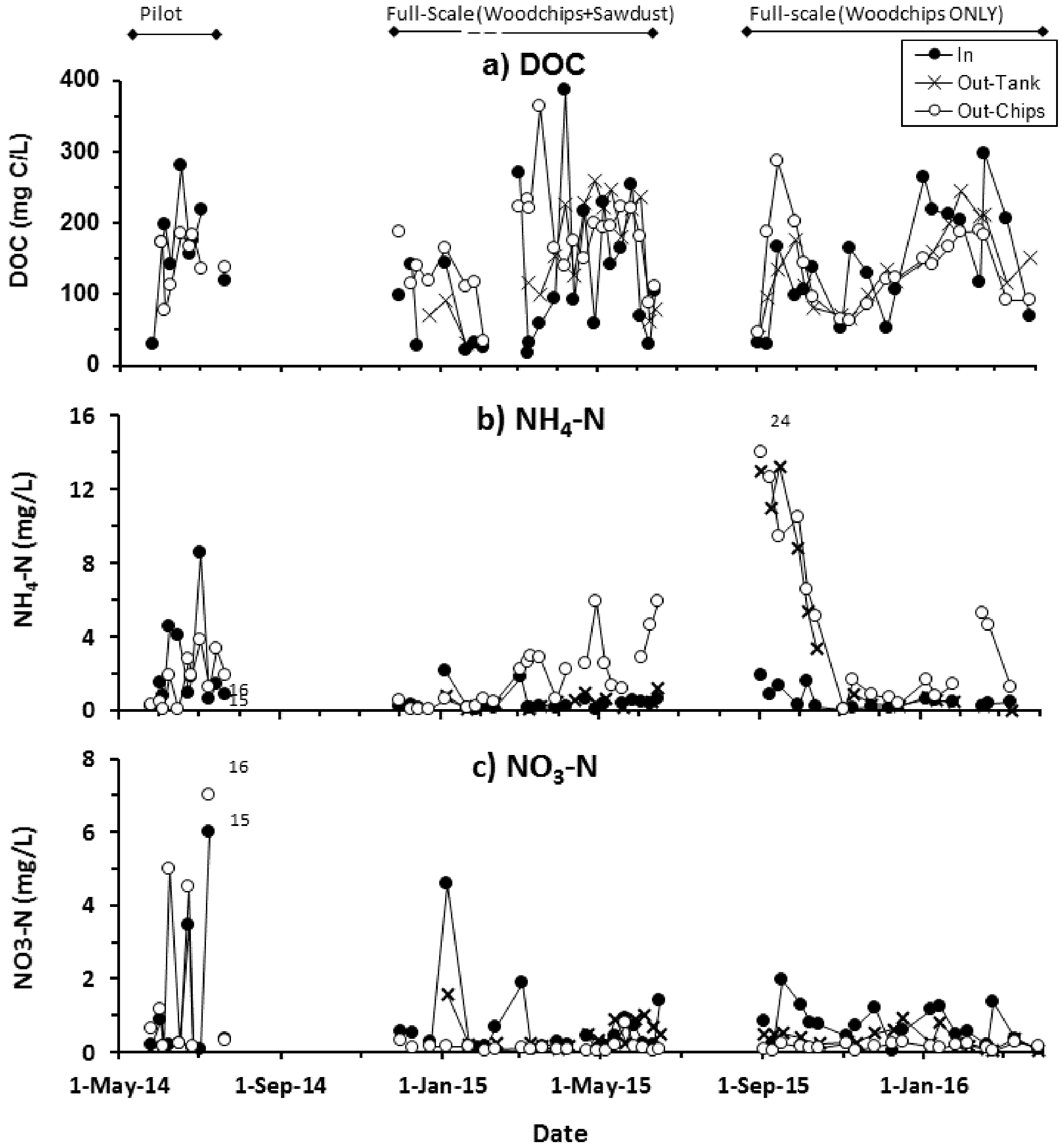

Figure 3.5 Bradford (vegetable wash) site: Trends in (a) dissolved organic C (DOC), (b) NH_4^+–N, and (c) NO_3^-–N in a woodchip filter system from May 2014 to March 2016.

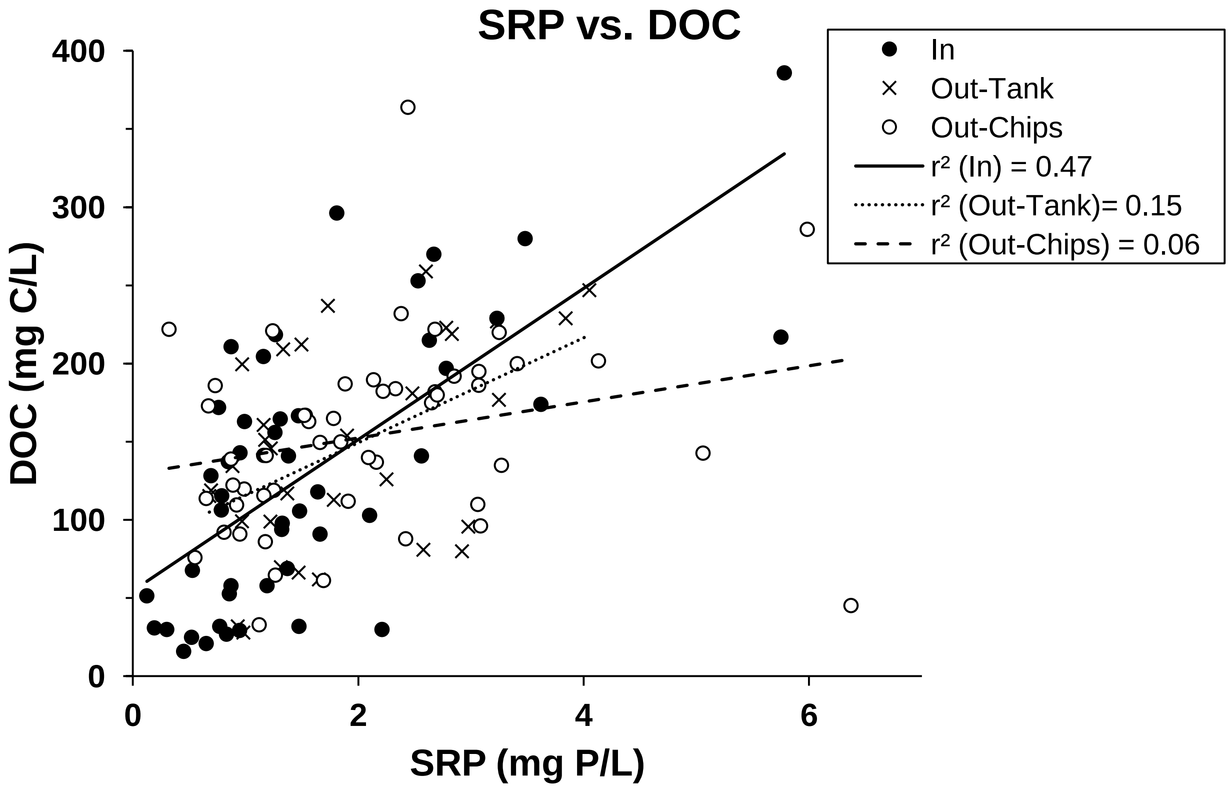

Figure 3.6 Bradford (vegetable wash) site: Correlation of soluble reactive P (SRP) with dissolved organic C (DOC) in woodchip filter system treating vegetable wash water during a 22-mo period.

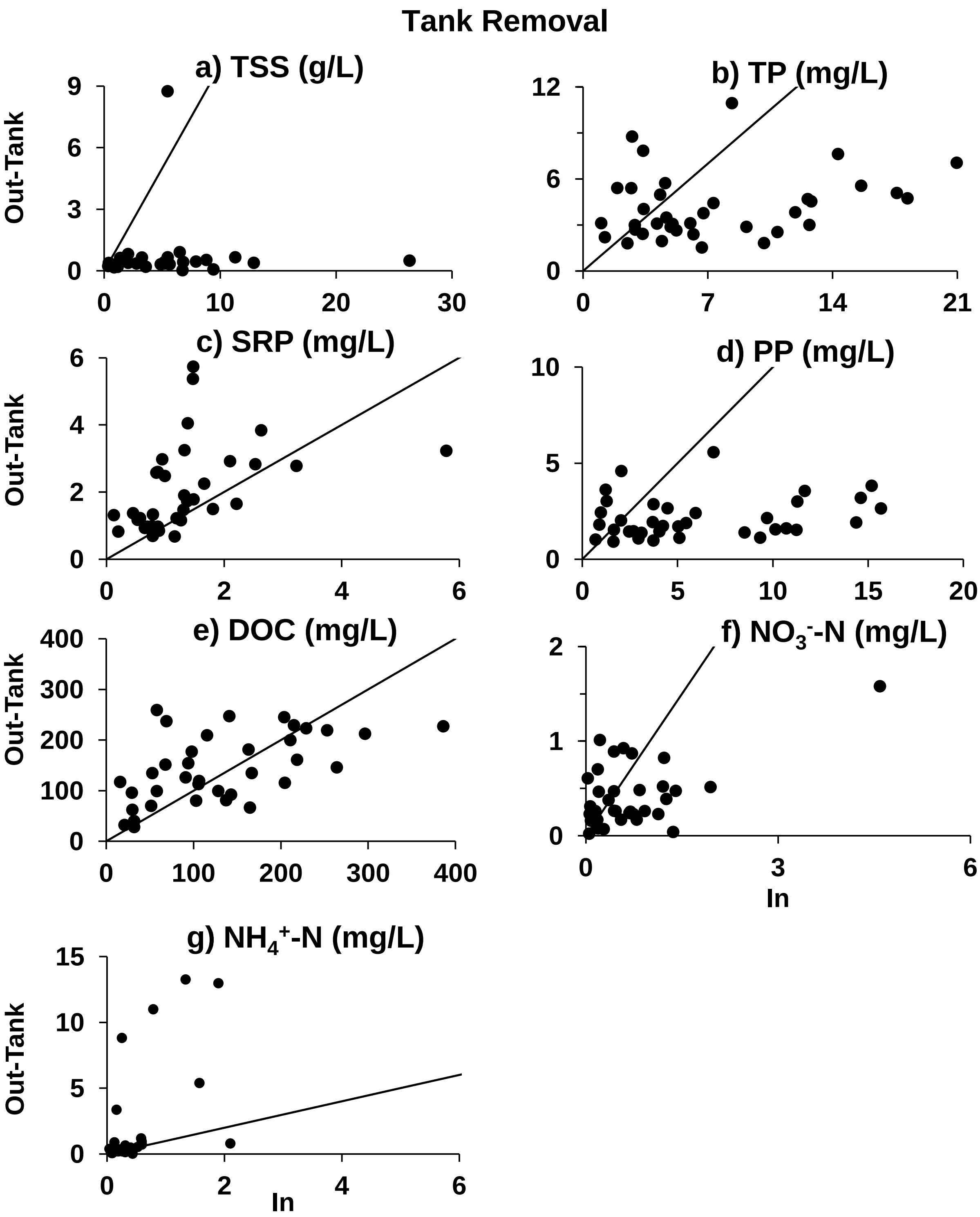

Figure 3.7 Bradford (vegetable wash) site: Comparison of (a) total suspended solids (TSS), (b) total P (TP), (c) soluble reactive P (SRP), (d) particulate P (PP), (e) dissolved organic C (DOC), (f) NO_3^--N and (g) NH_4^+-N from, between wash-water (In) and tank effluent (Out-Tank) (November 2014 to March 2016). Points above the line indicate parameter release in the tank; points below the line indicate parameter retention in the tank.

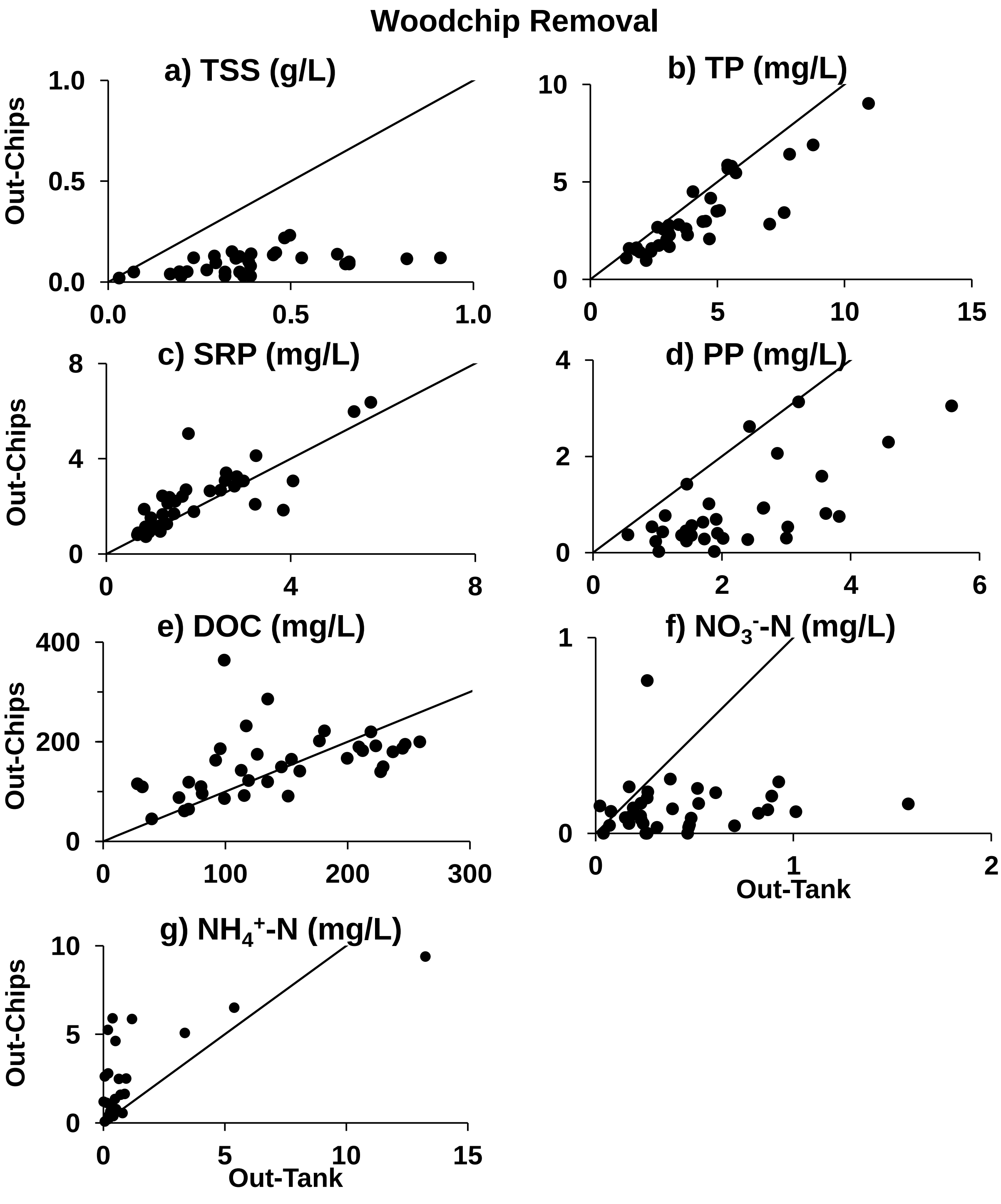

Figure 3.8 Bradford (vegetable wash) site: Changes in (a) total suspended solids (TSS), (b) total P (TP), (c) soluble reactive P (SRP), (d) particulate P (PP), (e) dissolved organic C (DOC), (f) NO_3^--N and (g) NH_4^+-N from November 2014 to March 2016, between the tank effluent (Out-Tank) and woodchip effluent (Out-Chips), where points above the solid line indicate an increase in the woodchip effluent (release), points below the solid line indicate retention within the woodchips (removal).

4. Big Bay (Barrie) Site

4.1 Site Description

The filter was installed in an agricultural drainage ditch located near the city of Barrie in southern Ontario. The ditch is shallow and narrow with widths ranging between 1 and 2 m. The stream bottom sediment is primarily silt. The predominant field crop grown adjacent to the drainage ditch is corn. The drainage ditch starts ~ 50 m upstream from the biofilter location at a point where three field drainage tiles discharge together. Flow in the ditch was seasonably variable from < 2 L/min to greater than 50 L/min (Appendix B), but water was present in the ditch throughout the experimental period.

4.2 Filter Description

The woodchip filter was trenched directly into the streambed of the drainage ditch on Dec.10, 2014 and commissioned on the same day. The trench was filled with 20 m^3 of woodchips (K ~1 cm/s; van Driel *et al*., 2006) and had dimensions of 6.1 m long, 1.9 m wide and 1.1 m deep, with a 0.3 m thick cobble layer placed on top of the woodchips (Figure 4.1). The cobble layer served the purpose of protecting the woodchips as well creating an increase in the steam water level, because of the presence of a cobble berm placed at the downstream end (Figure 4.1). The increase in head then caused the water to percolate downward through the woodchips, before exiting through a collection pipe that discharged downstream of the cobble riffle. The filter design was essentially the same as a stream bed filter installed previously at the Avon site, near Stratford, ON (Robertson and Merkley, 2009; Chapter 7). Previous studies at the Avon site had focused primarily on NO_3^--N removal (Robertson and Merkley, 2009; Elgood *et al*, 2010), whereas the current study is focused on phosphorous, and particularly particulate P, removal. Effluent discharge rates were measured directly at the outlet pipe with a calibrated bucket and stream flow rates were measured using a wood-framed flume that was installed as part of the cobble riffle. (Figure 4.1). The total filter pore volume (14 m^3) was estimated by multiplying the filter volume (20 m^3) by an assumed woodchip media porosity of 0.7 determined from previous studies (van Driel *et al*., 2006; Chun et al., 2009).

4.3 Results

Filter Operation and Maintenance

Filter operation and performance was monitored from December 2014 to March 2016. During sampling events, flow through the filter ranged between nil to greater than 50 L/min, which was determined through effluent flow measurements using a calibrated beaker. The low flow events (discharge of ≤ 2 L/min) occurred during summer dry periods when stream flow was minimal. High flow events (discharge of > 50 L/min) occurred during rainfall events and periods of snowmelt. During high flow events, the outlet pipe was often submerged due to high stream water levels, and as a result the discharge at these times could only be approximated (> 50 L/min).

During operation of the filter, little or no maintenance was required, consistent with the maintenance-free operation of the Avon filter (discussed further in Chapter 7). In January 2015, there was ice cover over the biofilter, yet the filter continued to operate normally (Appendix B).

Phosphorus and Total Suspended Solids Removal

The hydraulic retention time in the filter ranged from less than 0.1 days to greater than 2 days, considering the total filter pore volume of 14 m^3.

Figure 4.2 compares influent and effluent TSS, TP, SRP, and PP concentrations from December 2014 to March 2016. Sampling events when flow rates were less than or equal to 2 L/min or no flow rate data was available were excluded when calculating the mean values given in Table 4.1, as these data were considered unrepresentative of normal operating conditions. The excluded data is included in Appendix B however.

The TSS levels in the stream varied from less than 0.5 to 165 mg/L, with one high TSS value of 504 mg/L on May 6th, 2015. The TSS concentrations varied depending on weather conditions, particularly precipitation events which impacted stream turbidity. The TSS levels in the treated effluent were lower during most sampling events (0.5-22 mg/L, Figure 4.2). Of note, the very high TSS concentration on May 6th, 2015 (504 mg/L) was almost entirely removed in the woodchip filter. Total P levels in the stream water were variable (5-270 µg/L; Figure 4.2), with one very high TP value of 600 µg/L occurring on May 6th, 2015 (Figure 4.2). The high values were generally associated with rainfall and snowmelt events. Table 4.1 summarizes the mean concentrations and removal percentages of TSS and the P components during the monitoring period. Seven low flow events (≤ 2 L/min) and two sampling events with no flow data available are excluded in Table 4.1. The mean TSS value of the filter effluent (14 mg/L) was lower than that of the stream water (24 mg/L, Table 4.1). This represented overall TSS removal of 38%, however this difference was not significant ($p > 0.05$) due to the variability of the data.

The mean TP value of the filter effluent (29 ug/L) was significantly lower than that of the stream water (69 µg/L, Table 4.1). This represented, overall TP removal of 58% and this difference was significant ($p<0.05$). There was no correlation between TP mass removal and HRT, as seen in Figure 4.3 ($r^2 = 0.00$). The dominant P component in the drainage ditch was PP, with a mean of approximately 52 µg/L (~75% of TP; Table 4.1). In the filter effluent PP was substantially lower (14 µg/L, Table 4.1) and this difference was significant ($p < 0.05$; Table 4.1). As seen in Figure 4.3, the hydraulic retention time appeared to have no effect on the removal of PP ($r^2 = 0.00$), where most of the mass removal occurred at HRT of less than 1 day.

In contrast to TSS and TP, SRP concentrations were little changed in the treatment system. The relationship been SRP and retention time was minimal ($r^2 = 0.06$, Figure 4.3) with some SRP leaching at higher retention times (> 1 day, > 7000 L/day). The SRP release noted during high HRT events could indicate leaching of some of the PP retained within the filter. Approximately 52% of the effluent TP was SRP (Table 4.1) and some of the SRP release could have contributed to a decreased TP removal when HRT was greater than one day (Figure 4.3). However, when high HRT (flow rates less than 2 L/min) events were excluded, the mean SRP concentration in the stream water (16 µg/L) was not significantly different than in the woodchip effluent (15 µg/L, Table 4.1).

Figure 4.4 shows that there was a strong correlation between PP and TP during the study period ($r^2 = 0.75$-0.98), whereas there was little correlation between SRP and TP ($r^2 = 0.06$–0.45). There was correlation between total P and TSS in the stream water ($r^2 = 0.62$) but not in the filter effluent ($r^2 = 0.01$, Figure 4.5). The PP and TSS correlation showed a similar trend, to that of TP and TSS. There was a correlation in the stream water but little correlation in the filter effluent ($r^2 = 0.65$ and 0.02, respectively; Figure 4.5). There was no correlation between SRP and TSS ($r^2 = 0.00$; Figure 4.5).

Overall, there was 38% TSS removal, and 58% TP removal. The major P component that was removed was PP (74% removal Table 4.1). The dominant P component that remained in the effluent was SRP, (52% of TP, Table 4.1). The modest TP removal rate were due to the fact that there was little change in SRP. The P removal efficiency seemed to not be affected by the HRT values.

Nitrogen and Dissolved Organic Carbon

Figure 4.6 shows inorganic N (NO_3^--N and NH_4^+-N) and DOC trends in the stream water and filter effluent during the sampling period. Table 4.1 compares mean influent and effluent values over this period. During treatment in the filter, mean NO_3^--N concentrations decreased from 3.8 mg/L to 2.9 mg/L, and mean NH_4^+-N increased from 0.02 to 0.04 mg/L. The changes in both NO_3^--N and NH_4^+-N concentrations were significant ($p < 0.05$). There was an increase in DOC from 2.7 to 3.5 mg/L, however this change was not significant ($p > 0.05$). Robust denitrification was generally not expected to occur in the filter because retention times were generally short (mean HRT of 0.4 days, Table 4.1) and the effluent remained aerobic on most occasions (mean effluent DO of 5.8 mg/L; Table 4.1). However, the consistency of the slight NO_3^--N loss observed (Figure 4.6), suggests that some denitrification was likely occurring, possibly within anaerobic microsites present within the filter.

4.4 Discussion

There was some TSS removal in the filter (38%) but this removal was not significant ($p > 0.05$). TP removal (58%) was significant ($p < 0.05$), because PP was the dominant P component in the stream water. There was a correlation between TP and PP to the TSS concentrations in the influent (r^2=0.62 and r^2=0.65, respectively, Figure 4.5) showing that the TP at this site could likely be associated with the influent TSS, which is effectively being removed within the woodchip filter. There was no significant change in SRP concentrations between the drainage ditch and woodchip filter effluent for the duration of the study (7% removal, $p > 0.05$; Table 4.1). There was some SRP leaching occurring within the effluent which could indicate leaching of the particulate P that was accumulating in the filter. One solution for SRP leaching could be to include an additional treatment layer specifically targeting SRP removal. Constituents such as steel shavings and biochar have been shown to provide enhanced SRP removal when added to a woodchip treatment system (Goodwin *et al*., 2015; Bock *et al*., 2015). Several other reactive media types have also been shown to have a high capacity for SRP removal, such as steel foundry slag (Baker *et al.*, 1998), aluminium (Auvray *et al*., 2006) and shrimp chitosan media (Yep *et al*., 2016). These could potentially be added to a woodchip based filter to improve SRP removal.

Although the NO_3^--N removal at the Big Bay filter was low (23%), the removal was significant ($p < 0.05$) and a mean NO_3^--N removal rate of 3.7 g N/m^3/day was observed (Table 4.1). The NO_3^--N trends shown in Figure 4.2 and the significant decrease in DO concentrations ($p < 0.05$) suggests that denitrification was likely active in the woodchip filter. Robertson (2010) concluded that woodchip media can deliver stable NO_3^--N removal rates during long term treatment, and this was observed in this study where NO_3^--N removal remained steady over the 1.5 yr study period (December 2014 to March 2016).

Dissolved organic C concentrations in the treated effluent (mean of 3.5 mg/L) were not significantly different ($p > 0.05$) than the influent (mean of 2.7 mg/L; Table 4.1) indicating that carbon loss from the filter was relatively low. Consequently, the woodchip media exhibited the potential for considerable longevity, consistent with previous field trials (Robertson et al. 2005; Jaynes *et al., 2008;* Robertson et al., 2008a; Robertson et al. 2008b).

4.5 Conclusion

The Big Bay woodchip filter was designed to target PP removal during turbid events and, as a result, higher turbidity conditions associated with rainfall and snowmelt events were targeted. Significant PP removal was observed during this study (74% removal). During this study period, several of the high turbidity events exhibited a very high degree of TSS and PP removal. For example, there was > 99 % removal of TSS of 504 mg/L and 98% removal of PP of

585 μg/L on May 6th, 2015 (effluent flow of 23 L/min; Appendix B) reflecting the filters potential to effectively treat highly turbid flow. There was modest TP removal in the filter but this difference was not significant because some SRP release occurred possibly through the leaching of PP within the filter. In addition to P removal, the Big Bay woodchip filter consistently treated NO_3^--N, although the percentage removal was modest (23% removal; Table 4.1) due to the short retention times. However, since the sampling at this site was taken progressively throughout the study period, the results reported may not reflect the true average conditions. More specifically, more attention should be brought to tolerate high flow events, where most of the TSS loads might be exported over short time periods.

The treatment system was relatively simple to operate and required little maintenance during a period of over one year. These features could make such filters attractive for use in a variety of agricultural operations where turbid waters are generated. This study demonstrated that woodchip filters have an ability to remove TSS and particulate P even in waters with low to moderate turbidity conditions. Continued monitoring is suggested to assess longer-term P and TSS treatment capability. Additional monitoring should particularly focus on high turbidity events where such filters could have the potential to provide the greatest degree of TSS and particulate P removal.

Table 4.1 Big Bay (stream bed) site: Concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO_3^-–N, NH_4^+–N, and dissolved organic C (DOC) in the Big Bay woodchip filter from December 2014 to March 2016, removal percentages with respect to the tile drain values, and volumetric removal rates in the filter. Rates consider the mean flow rate of 41.2 L/min, and pore volume of 14 m^3. The mean values within this table do not include low flow values (≤ 2 L/min) and sampling events for which flow data was unavailable; which excludes a total of nine (9) sampling events*.

Substance	**Tile Drain**	**Effluent**	**Removal**	**Removal Rate**
Mean effluent flow rate (L/min) = 41 ± 27 (35); HRT (days) = 0.4 ± 0.3 (35)†				
			------ % ------	---g/m^3/day--
TSS (mg/L)	24 ± 38 (33)	15 ± 30 (33)	38	38.8
TP (µg/L)	69 ± 113 (33)	29 ± 25 (34)	58	0.17
SRP(µg/L)	16 ± 15 (35)	15± 16 (35)	7	0.005
PP (µg/L)	52 ± 111 (33)	14 ± 19 (34)	74	0.16
NO_3^--N (mg/L)	3.8 ± 1.4 (33)	2.9 ± 1.3 (32)	23	3.7
NH^+_4-N (mg/L)	0.02 ± 0.03 (28)	0.04 ± 0.07 (28)	-179	-0.1
DOC (mg/L)	2.7 ± 2.4 (34)	3.5 ± 3.1 (34)	-33	-3.7
DO (mg/L)	11.7 ± 3.0 (27)	5.8 ± 2.3 (27)	51	25.0

† Means ± standard deviations; number of replicates in parentheses

* Dates excluded:
(2015) Apr. 7th, June 15th, June 30th, July 15th, July 29th, August 11th, Sept. 2nd, Sept. 16th, and Nov. 4th

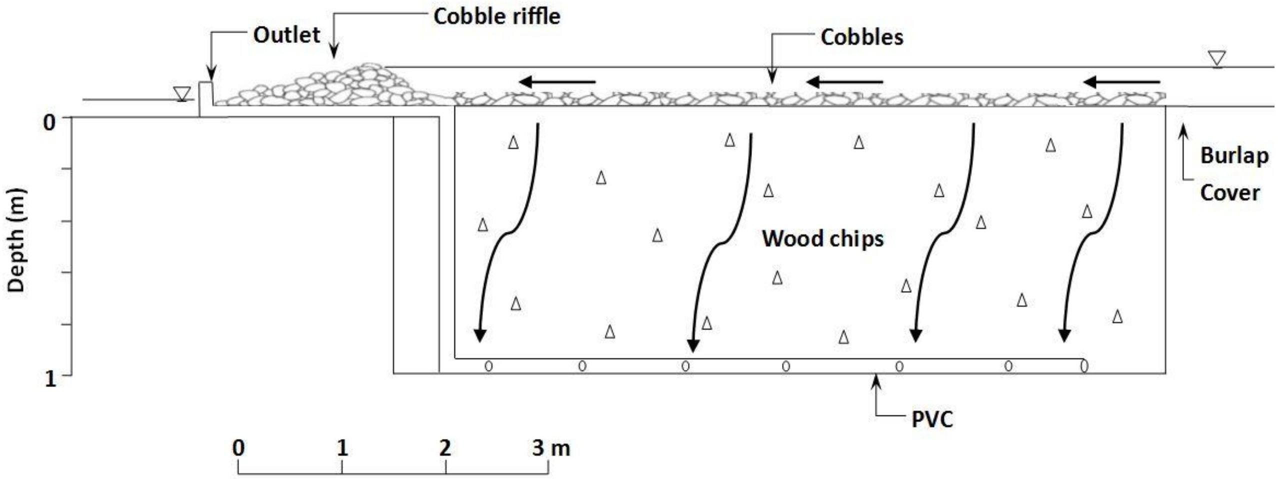

Figure 4.1 Big Bay (stream bed) site: Design sketch of the woodchip filter, installed in an agricultural drainage ditch, December 10, 2014. Filter is 6.1 m long, 1.9 m wide and 1.1 m in depth. Filter volume is 20 m^3 and has total pore volume of approximately 14 m^3, assuming media porosity of 0.7 (van Driel *et al*., 2006). Arrows indicate the direction of flow.

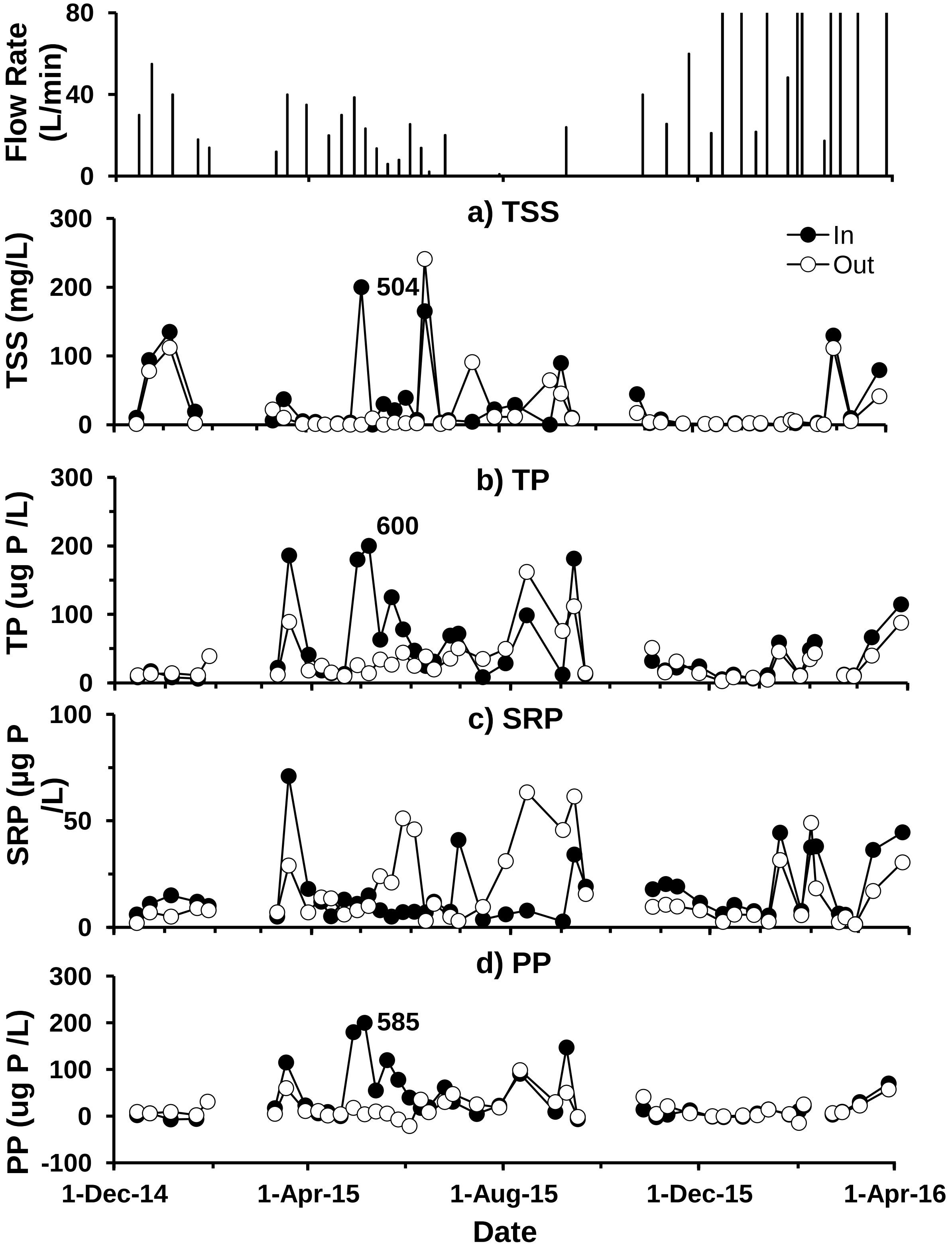

Figure 4.2 Big Bay (stream bed) site: Trends in a) total suspended solids (TSS), b) particulate P (PP), c) total P (TP), and (d) soluble reactive P (SRP) in the stream water (In), and the filter effluent (Out) from December 2014 to March 2016.

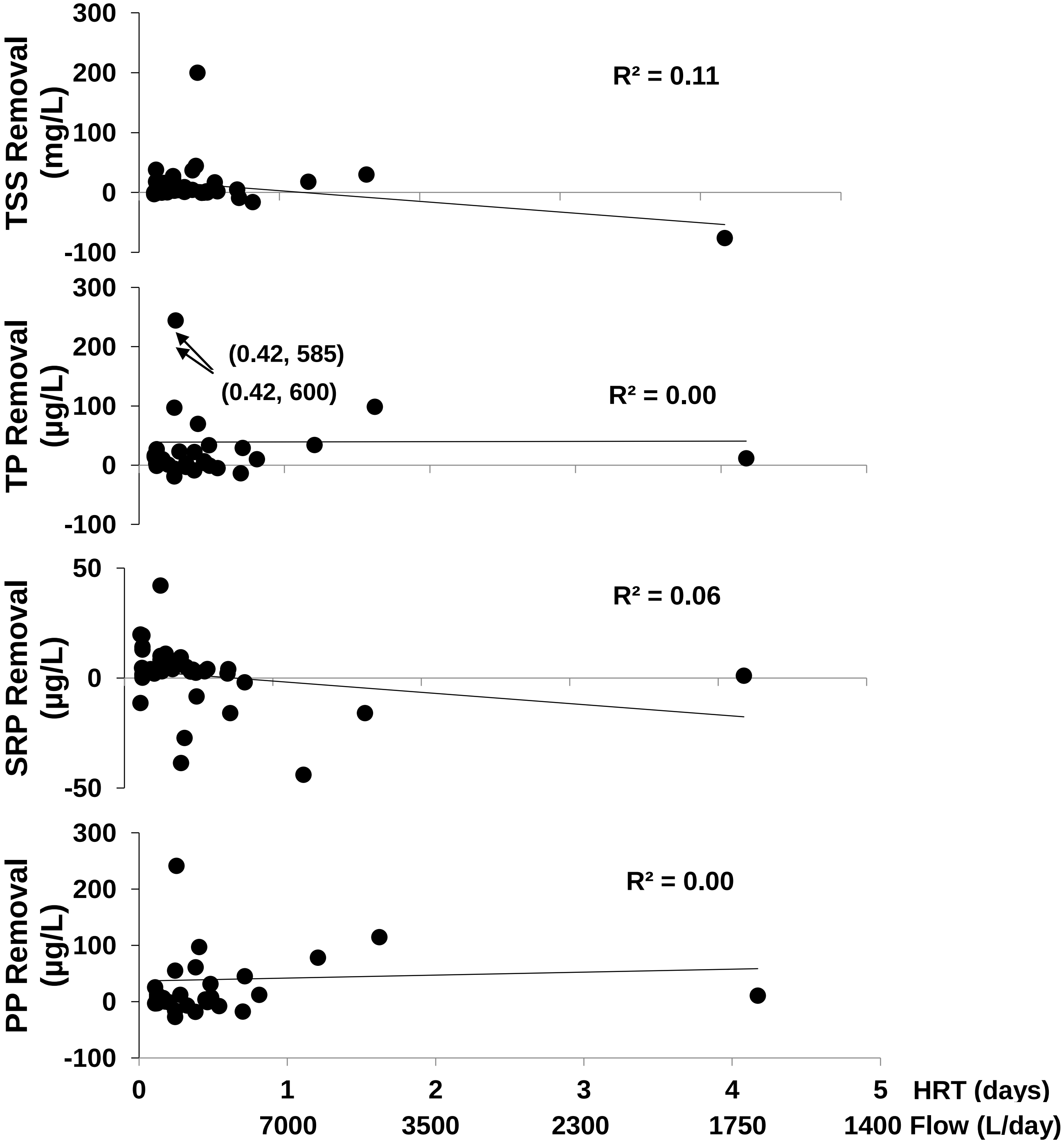

Figure 4.3 Big Bay (stream bed) site: Correlation of hydraulic retention time (HRT) with TSS, TP, SRP, and PP mass removal within the Big Bay filter from December 2014 to March 2016. Low flow values (<2L/min) are not included in this figure.

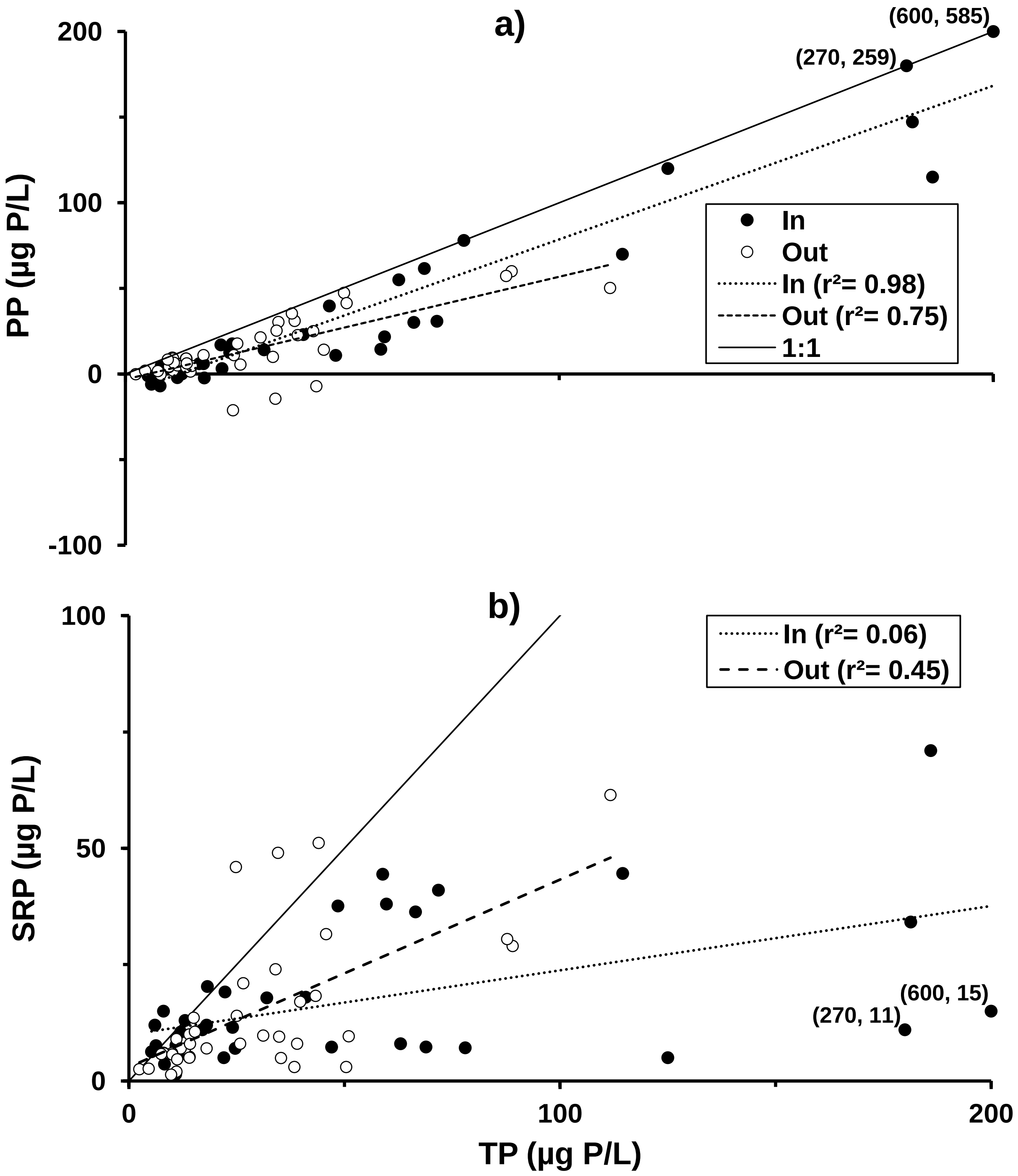

Figure 4.4. Big Bay (stream bed) site: Correlation of TP concentrations with (a) PP and (b) SRP concentrations in the stream water (In) and filter effluent (Out) (December 2014 to March 2016). Points that fell out of range for the respectively graphs are also included within the figure as '(*TP value, the respective P component*)'. Points that fell out of range were included in the regression analysis.

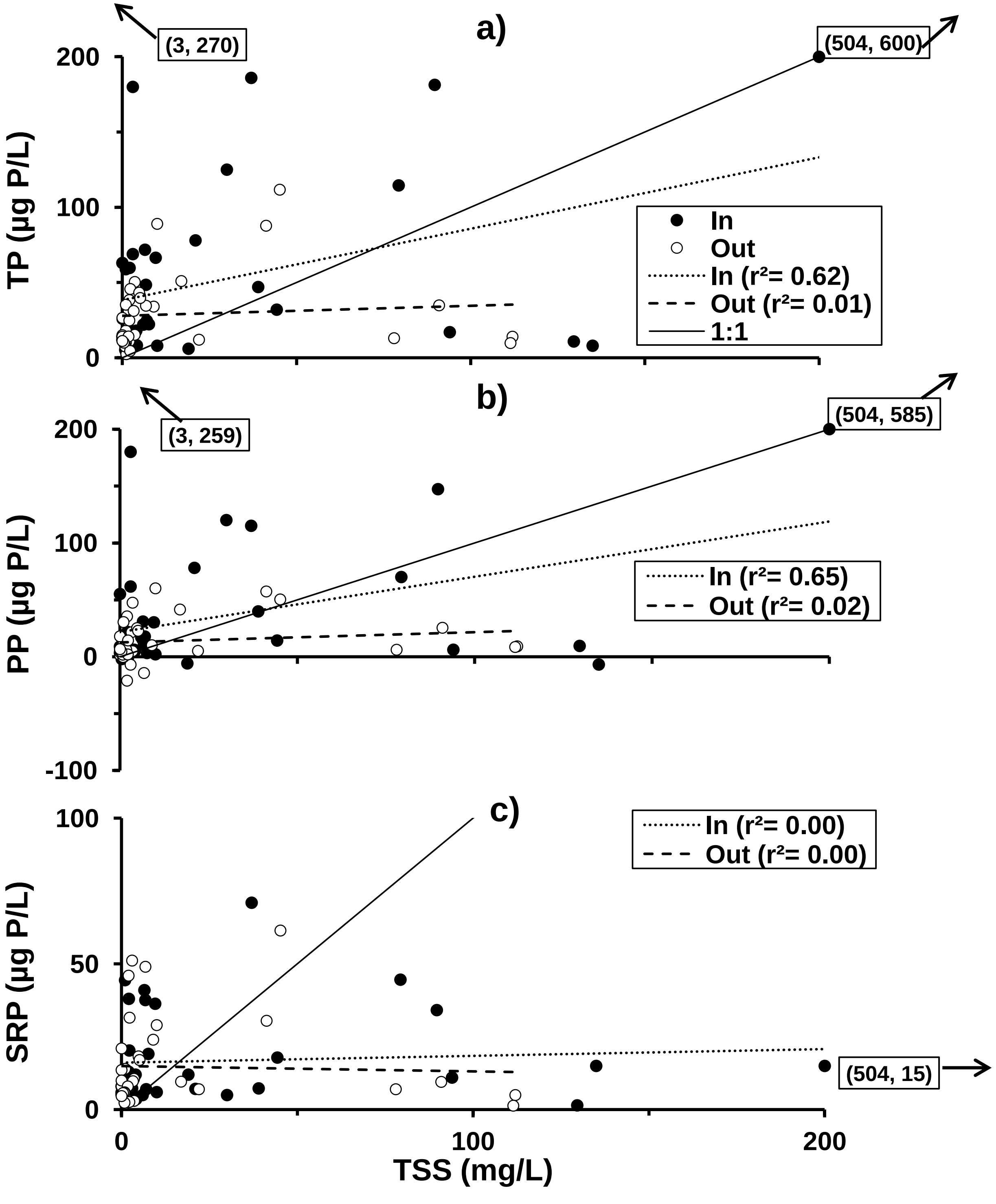

Figure 4.5 Big Bay (stream bed) site: Correlation of total suspended solids (TSS) with (a) total P (TP), (b) particulate P (PP) and (c) soluble reactive P (SRP) concentrations in the stream water and filter effluent (December 2014 to March 2016). Points that fell out of range for the respectively graphs are also included within the figure as '(*TSS value, the respective P component*)'. Points that fell out of range were included in the regression analysis.

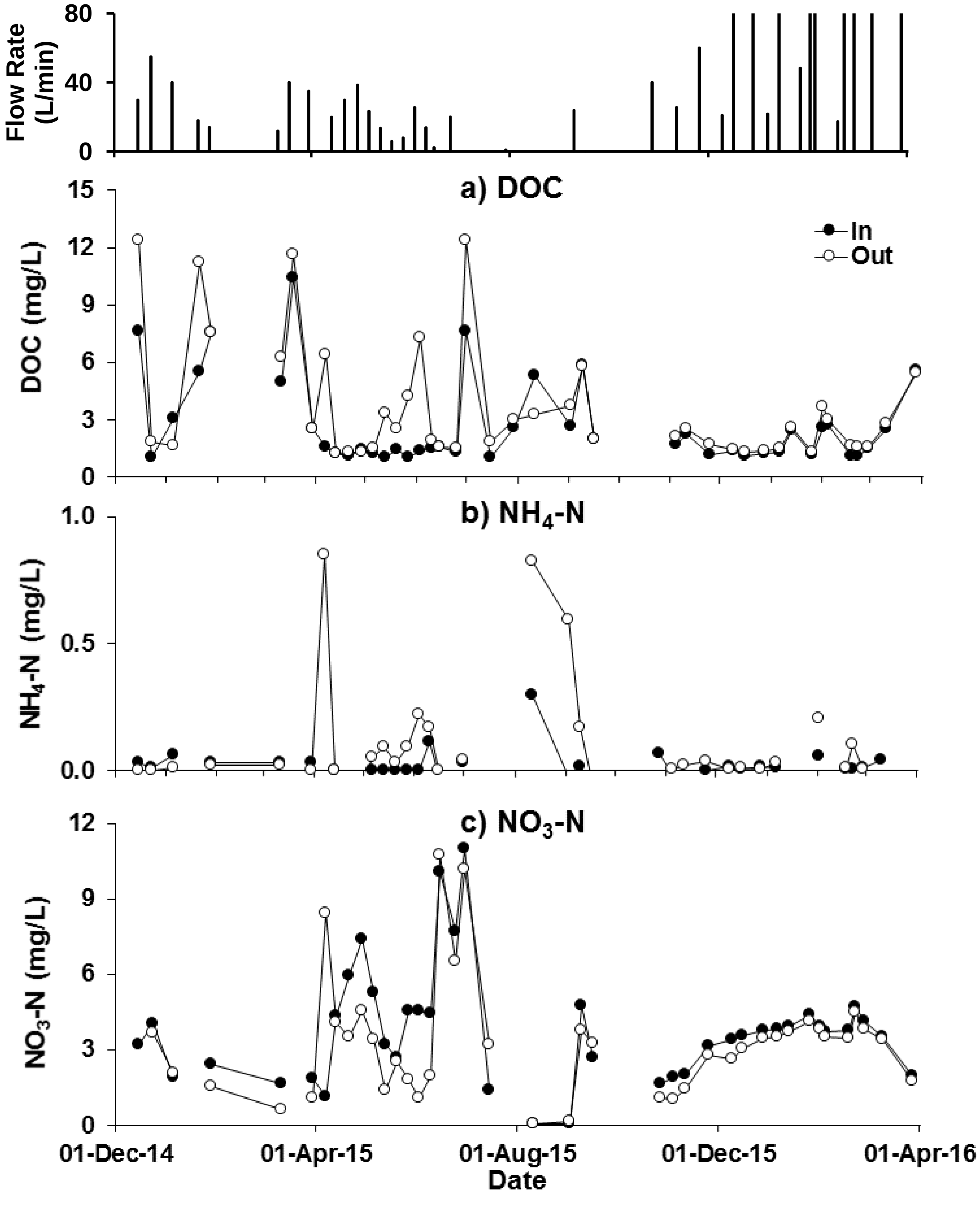

Figure 4.6 Big Bay (stream bed) site: Trends in (a) dissolved organic C (DOC), (b) NH4+–N, and (c) NO3−–N in the stream water (In) and filter effluent (Out) (December 2014 to March 2016.

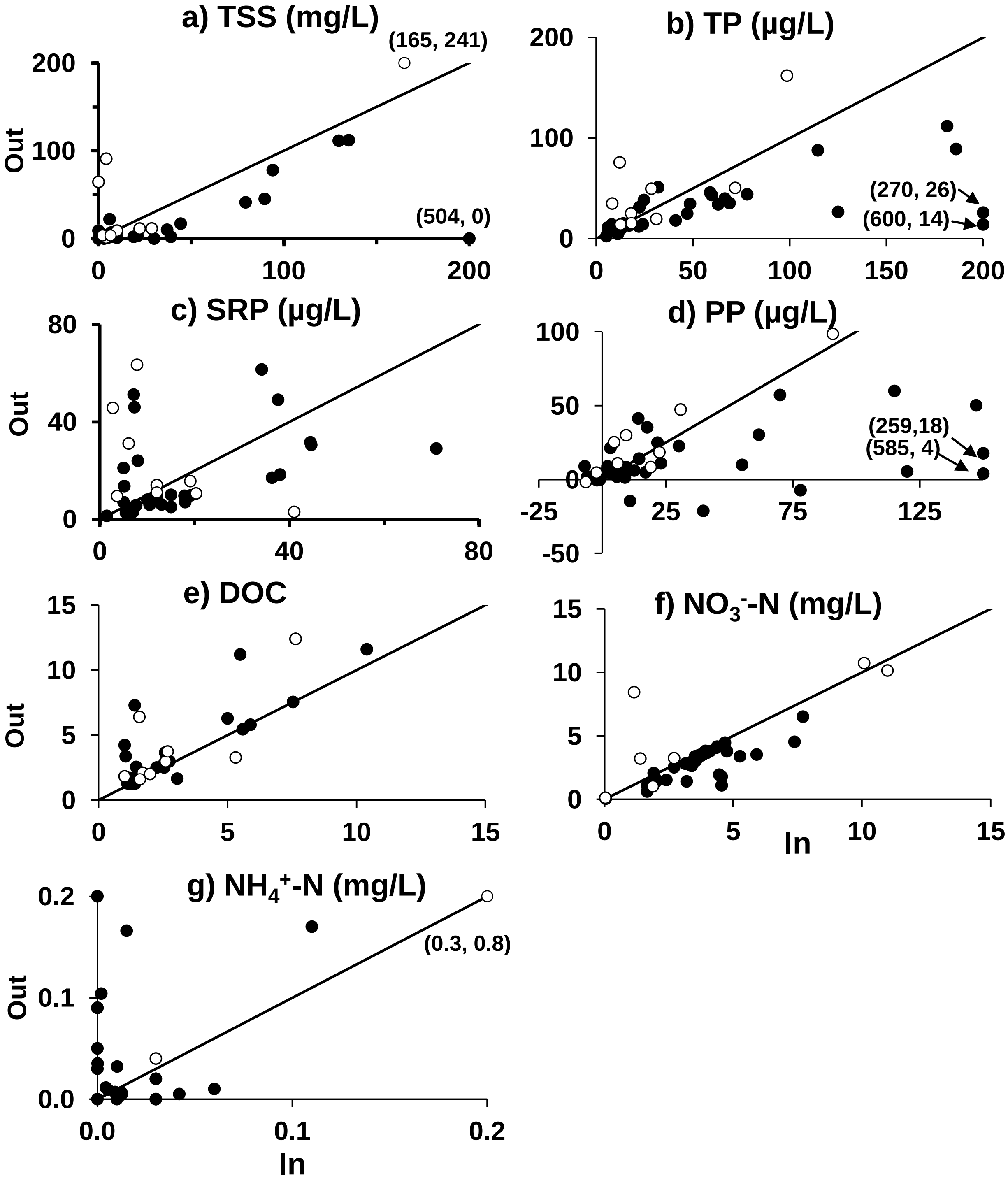

Figure 4.7 Big Bay (stream bed) site: Removal of (a) total suspended solids (TSS), (b) total P (TP), (c) soluble reactive P (SRP), (d) particulate P (PP), (e) dissolved organic C (DOC), (f) NO_3^- and (g) NH_4^+ from December 2014 to March 2016, where points above the solid line indicate an increase in concentration in the effluent (release), points below the solid line indicate retention (removal). White dots indicate low flow conditions (≤ 2 L/min) and values which fell out of the graph are included within the figure as (*In*, *Out*).

5. Keswick Site

5.1 Site Description

The filter was installed at a drainage tile from a sod farm located near Keswick in southern Ontario, southeast of Lake Simcoe. A total of 80 acres is drained by the tile line which discharges to a ditch flowing into the Maskinonge River. This river drains into Cook's Bay at the south end of Lake Simcoe. The fertilizer application rate, comprised of N- P_2O_5- K_2O, ranged from 150 to 275 lb/acre at this site, as outlined in Table 5.1, with the main source of nitrogen in the filter being urea ($CO(NH_2)_2$). The main field crop grown adjacent to the ditch is sod, plus five acres of soy in 2015.

5.2 Filter Description

The woodchip filter was installed on March 2014. It consisted of a subsurface ditch, 6 m long, 4 m wide and 1.5 m deep (36 m^3), filled with standard 2-cm-diameter woodchips (red pine, *Pinus resinosa* Aiton). The flow from the tile was routed onto the top of the woodchip filter using a 10-cm-diameter perforated pipe and then percolated downward through the woodchips to the collection pipe (4-inch-diameter perforated PVC pipe) installed along the bottom of the trench. The treated effluent then drained into an adjacent drainage ditch (Figure 5.1).

5.3 Results

Filter Operation and Maintenance

The filter was installed in March 2014 but it was not connected to the tile drain until May 2014, due to difficult snow and frost conditions. Filter operation began in May 2014 and continued until March 2016, however flow from tile ceased in early June in both 2014 and 2015 and did not resume until late fall (November). Thus the filter did not operate during the summer. Also, in January 2015, the intake pipe froze and sampling did not then resume until March 2015.

Six multilevel piezometer bundles were also installed at the site to sample groundwater in the area near the filter (Figure 5.2). These were sampled on three occasions (June 2014, December 2014 and April 2015) for N and P as well as for NO_3-N isotopic composition to test for denitrification activity.

Phosphorus and TSS Removal

The flow rates through the filter ranged from nil (summer months) to greater than 80 L/min (Appendix C). Figure 5.3 compares influent and effluent TSS, TP, SRP, and PP concentrations from March 2014 to March 2016 including low flow (<1 L/min) events. The TSS levels in the tile flow were variable (0–99 mg/L). One sampling event had much higher TSS of 502 mg/L (Jan. 26, 2016; Figure 5.3), which was likely the result of sediment disturbance that occurred while breaking the ice to access the drain pipe. The TSS levels in the treated effluent were generally low for most of the sampling events (0-93 mg/L, Figure 5.3) however much higher TSS was noted on one occasion (276 mg/L Feb. 4, 2016). Total P levels in the tile drainage were variable but generally low (7-159 µg/L). The effluent TP levels were little changed from the tile (11–162 µg/L) except for one much higher value (479 µg/L, 1 Dec. 2014).

Table 5.2 summarizes the mean concentrations and removal percentages of TSS and the P components excluding the low flow events (< 1 L/min, 10 events; Appendix C). The mean TSS value from the tile drain (20 mg/L) was lower than that of the effluent (42 mg/L, Table 5.2), however this increase was not significant ($p > 0.05$).

The mean TP value of the effluent (23 µg/L) was the similar to that of the tile drain (24 µg/L; Table 5.2). The overall TP removal was 2% (Table 5.2) but this difference was not significant ($p > 0.05$). The mean PP value in the effluent (17 µg/L) was lower than that of the tile drain (8 µg/L) resulting in an overall significant PP increase of 119% ($p < 0.05$; Table 5.2),

The mean SRP concentration in the effluent was lower than the mean SRP concentration from the tile drain flow (8 µg/L and 17 µg/L, respectively; Table 5.2), with an overall significant SRP decrease of 52% ($p < 0.05$).

Overall, there was no significant change ($p > 0.05$) in the concentrations of TSS and the P components in the tile drain and effluent flows.

Nitrogen and Dissolved Organic Carbon

Figure 5.4 shows inorganic N (NO_3^--N and NH_4^+-N) trends during the monitoring period. NO_3^--N mean of 3.0 mg/L and NH_4^+-N mean of 0.0 mg/L. The mean NO_3^-–N in the treated effluent (2.4 mg/L, Table 5.2) was not significantly lower than the tile water (3.0 mg/L, $p > 0.05$), which suggests a lack of denitrification activity within the woodchip filter. This was likely because hydraulic retention times within the filter were too short due to the high flow rates (mean of 46 L/min) to fully deplete the DO in the tile water (mean of 10.3 mg/L vs 5.6 mg/L, Table 5.2). The NH_4^+-N in the filter effluent remained relatively unchanged compared to the tile water (approximately 0.00 mg/L, Table 5.2).

The dissolved organic C concentrations in the tile drain flow were low with a mean of 9.4 mg/L (Table 5.2) but variable (range of 2–22 mg/L; Figure 5.3). The DOC increased slightly in the effluent (mean of 14.7 mg/L) but the increase was not significant ($p > 0.05$).

Groundwater Chemistry

Phosphorus

Figure 5.5 shows the trends in the SRP vs depth for groundwater collected in December 4th, 2014 and April 13th, 2015. Groundwater SRP concentrations were generally low, ranging from 12 µg/L to 40 µg/L with one higher value of 242 µg/L (Figure 5.4). There was a moderate trend of increasing SRP concentrations with depth (Figure 5.5)

Nitrate

Figure 5.6 shows the relationship between the NO_3^--N concentrations and $\delta^{15}N$-NO_3^- composition in the groundwater and tile drain samples. Figure 5.7 shows the depth trends of NO_3^--N and $\delta^{15}N$-NO_3^- in the groundwater. Nitrate concentrations in the groundwater were generally low (< 0.1-4 mg/L) with the exception of one higher value (10.4 mg/L) and were similar to the concentrations found in the tile drain samples. A number of groundwater samples had highly enriched $\delta^{15}N$-NO_3^- values of +20 to +30% and these values correlated with low NO_3^--N values (< 2 mg/L; Figure 5.6), indicating that denitrification was likely active. These enriched values occurred at variable depths (Figure 5.7), with little or no apparent depth trend for the $\delta^{15}N$ -NO_3^- values from 2014, however there seems to be a decreasing trend for the 2015 values indicating the possibility of the dilution of the nitrate in groundwater during that year. There is a weak trend of decreasing NO_3^--N with depth, but low values (< 1 mg/L) occurred at all depths.

5.4 Discussion

Most of the concentrations of the geochemical parameters (TSS, TP, NO_3^--N, NH_4^+-N and DOC) were not significantly changed in the Keswick filter. There were only two parameters that displayed a significant change (SRP and PP) with a decrease in SRP concentrations and an increase in PP concentrations. It is important to note however, that most tile drain TP concentrations were less than the Provincial Water Quality Objective of 30 µg/L (PWQO, 1999), to avoid excessive plant growth in rivers and streams and all of the tile drain NO_3^--N concentrations were less than the Ontario Drinking Water Standard of 10 mg N/L (ODWS, 2016). Additionally, TSS levels in the tile water were relatively low (20 mg/L). Thus, the opportunity for the woodchip media to further diminish these already low values (and remove particulate P) was limited here. With the benefit of hindsight gained through the monitoring program, it appears that this site is not well suited for deployment of a biofilter primarily designed for TSS removal.

5.5 Conclusion

The monitoring undertaken at this site provides compelling evidence that the woodchip filter is not well suited for this site. The P and NO_3^--N contents within the tile drain flow fell below some provincial standards as a result of natural attenuation processes and dilution occurring in the groundwater flow system. The observed NO_3^--N and $\delta^{15}N$- NO_3^- relationship in the groundwater supports the likelihood that denitrification occurs naturally in the shallow groundwater at this site. It is suggested that the Keswick biofilter should be decommissioned as there is little use for the treatment system because of robust natural attenuation.

Table 5.1 Keswick (tile drain) site: The 2015 fertilizer application rates with the calculated N, P_2O_5 and K_2O application rates.

Crop	**Area (Acres)**	**Date (in 2015)**	**Fertilizer application rate (lb/acre)**	**Fertilizer composition (N- P_2O_5- K_2O)**	**N (as urea) application rate (lb/acre)**	**P_2O_5 application rate (lb/acre)**	**K_2O application rate (lb/acre)**
Soy	5	May 14	225	7-24-24	16	54	54
Sod	55	May 25	275	25-5-15	69	14	41
Sod	20	May 28	275	25-5-15	69	14	41
Sod	25	June 17	275	25-5-15	69	14	41
Sod	20	July 6	275	25-5-15[1]	69	14	41
Sod	25	July 24	150	46-0-0	69	0	0
Sod	20	August 6	800	8-8-30[2]	64	64	240
Sod	55	August 19	275	25-5-15	69	14	41
Sod	30	October 20	150	46-0-0	69	0	0

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[1] Fertilizer application before harvesting.

[2] Fertilizer application before re-planting.

Table 5. 2 Keswick (tile drain) site: Concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO_3^-–N, NH_4^+–N, and dissolved organic C (DOC) in the tile drain water, and treated effluent (from Mar. 2014 to March 2016), and removal percentages with respect to the tile drain values. The mean values do not include low flow events (< 1 L/min) or sampling events with no flow data available (10 sampling events excluded).

Substance	**Tile Drain**	**Effluent**	**Removal**
Mean effluent flow rate (L/min) = 46 ± 28 (16)†			
			---- % ----
TSS (mg/L)	20 ± 37 (13) †	42 ± 81 (12)	-104
TP (µg/L)	24 ± 16 (14)	23 ± 9 (11)	2
SRP (µg/L)	17 ± 10 (13)	8 ± 4 (12)	52
PP (µg/L)	8 ± 13 (13)	17 ± 10 (10)	-119
NO^-_3-N (mg/L)	3.0 ± 1.2 (14)	2.4 ± 1.4 (14)	17
NH^+_4-N (mg/L)	0.0 ± 0.0 (7)	0.0 ± 0.0 (8)	0
DOC (mg/L)	9.4 ± 7.3 (14)	14.7 ± 20.0 (14)	-57
DO (mg/L)	9.9 ± 1.6 (7)	5.8 ± 2.2 (6)	41

† Means ± standard deviations; number of replicates in parentheses.

* Dates excluded:
(Flow < 1 mg/L)
(2014) Mar. 28th, Apr. 14th, May 26th, Dec. 1st
(2015) Mar. 18th, Apr. 21st, May 6th, May 13th
(2016) Jan. 26th, Feb. 18th
Jan. 5th, 2015 SRP and PP values (Outliers) have been excluded

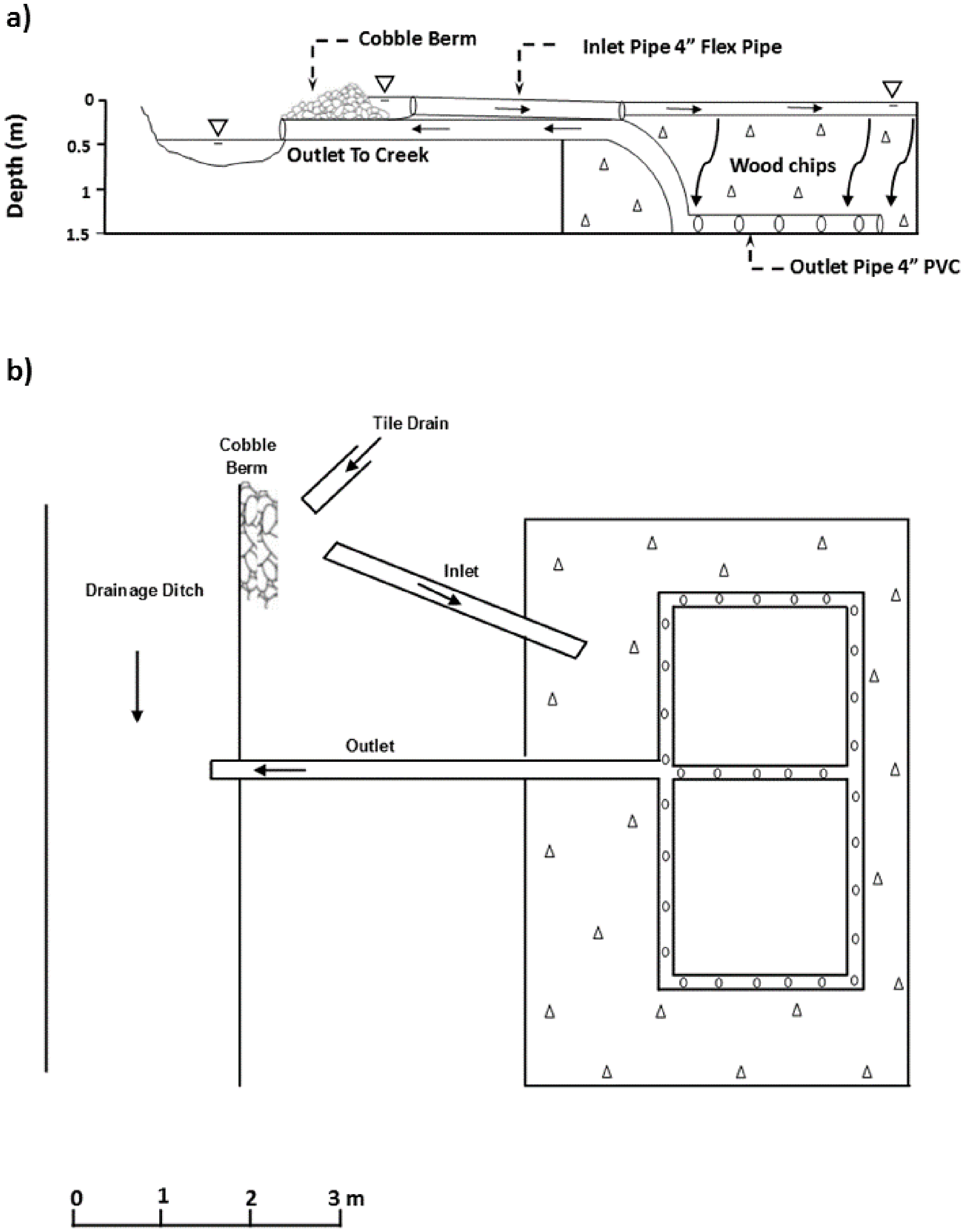


Figure 5.1 Keswick (tile drain) site: Design sketch (not to scale) of the woodchip filter. The bioreactor is 6 m in length, 4 m in width, and 1.5 m deep with 36 m^3 of permeable woodchips placed into the excavated trench as a reactive media. Assuming porosity of 0.7 (van Driel *et al*., 2006), the pore volume is 25 m^3.

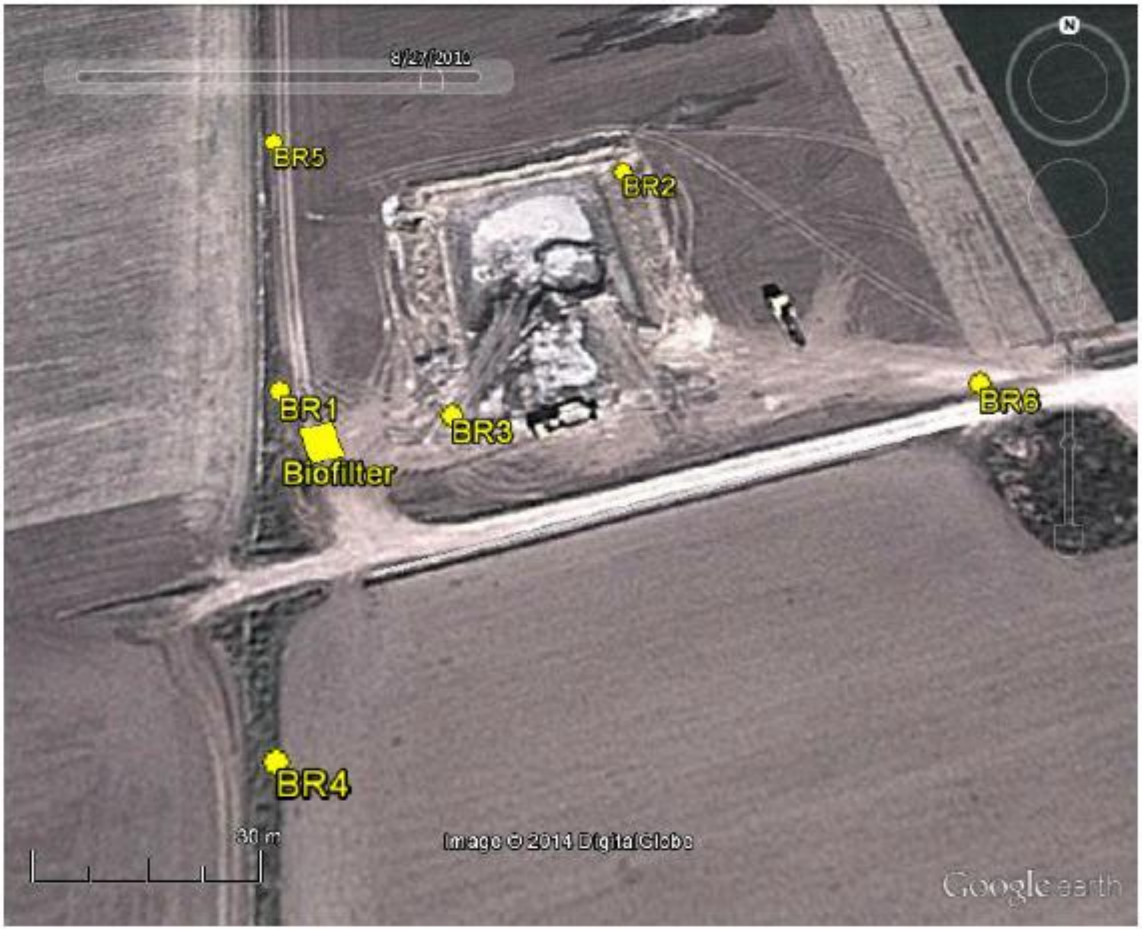


Figure 5.2 Keswick (tile drain) site: Map of the site with the locations of the biofilter and monitoring well bundles BR1 through BR6.

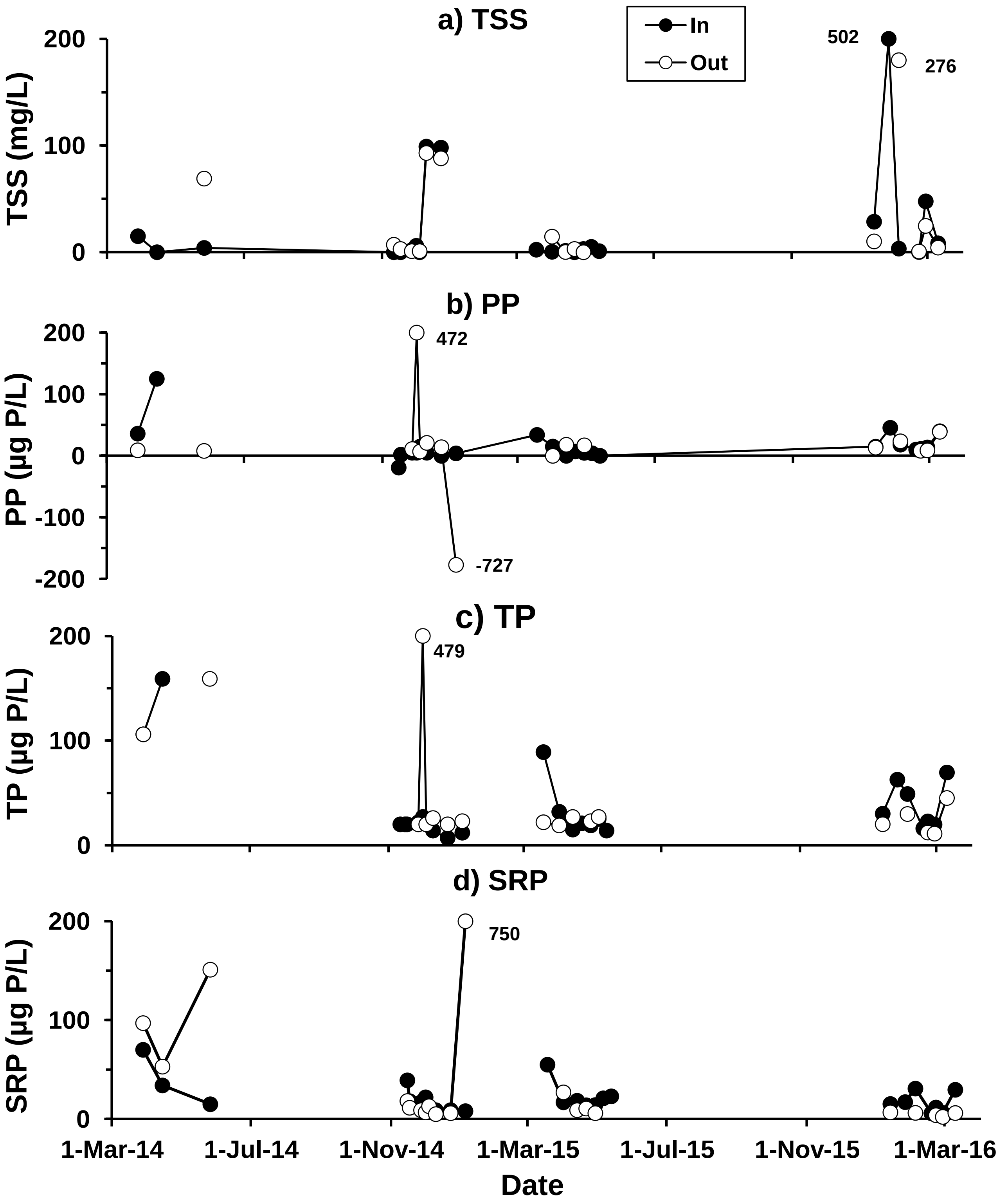


Figure 5. 3 Keswick (tile drain) site: Trends in (a) total suspended solids (TSS), (b) particulate P (PP), (c) total P (TP), and (d) soluable reactive P (SRP) in the tile drain water (In), and treated effluent (Out) from March 2014 to March 2016. The tile drain was dry during the summer and fall (June-November) during both 2014 and 2015.

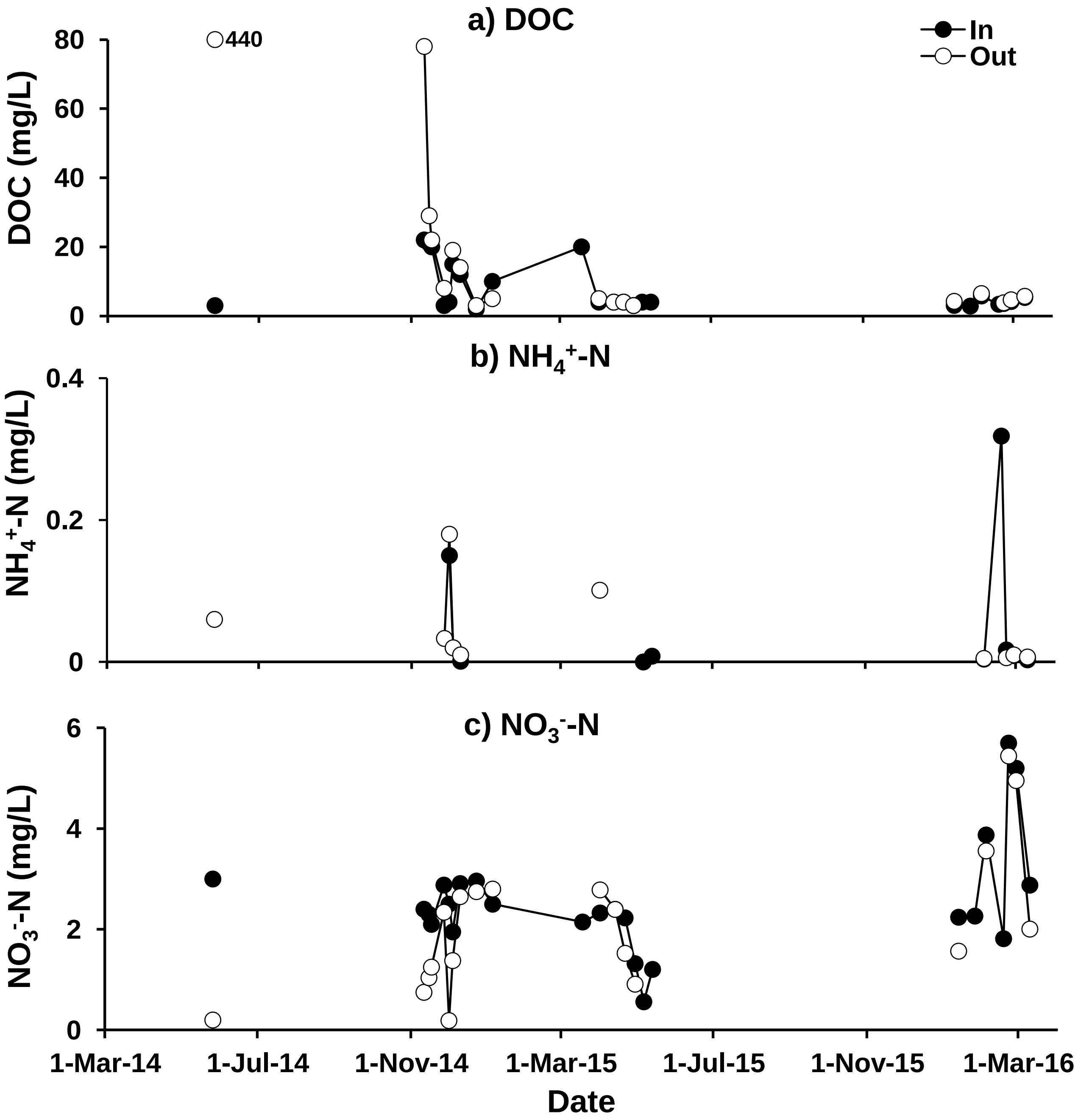


Figure 5.4 Keswick (tile drain) site: Trends in (a) dissolved organic C (DOC), (b) NH_4^+ -N, and (c) NO_3^--N from May 2014 to March 2016.

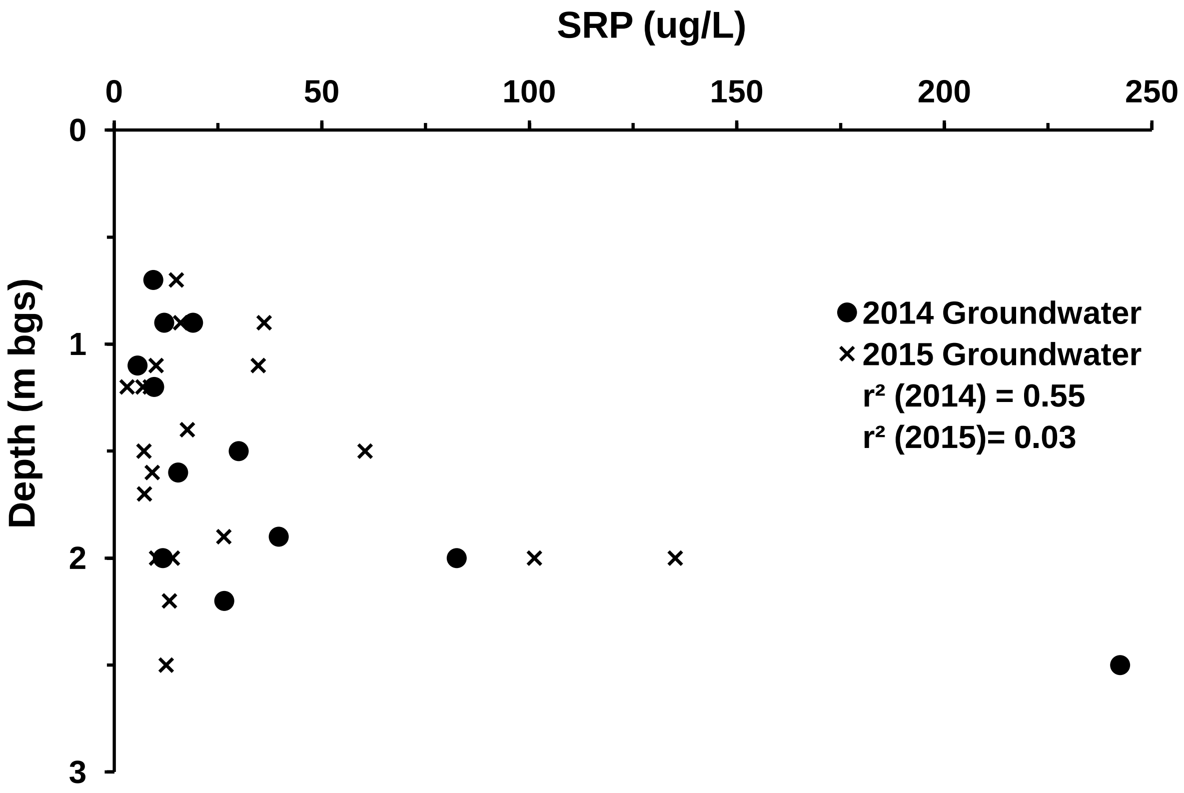


Figure 5.5 Keswick (tile drain) site: SRP trends with depth in groundwater sampled on December 4th, 2014 and April 13th, 2015 from monitoring wells BR-1 through BR-6.

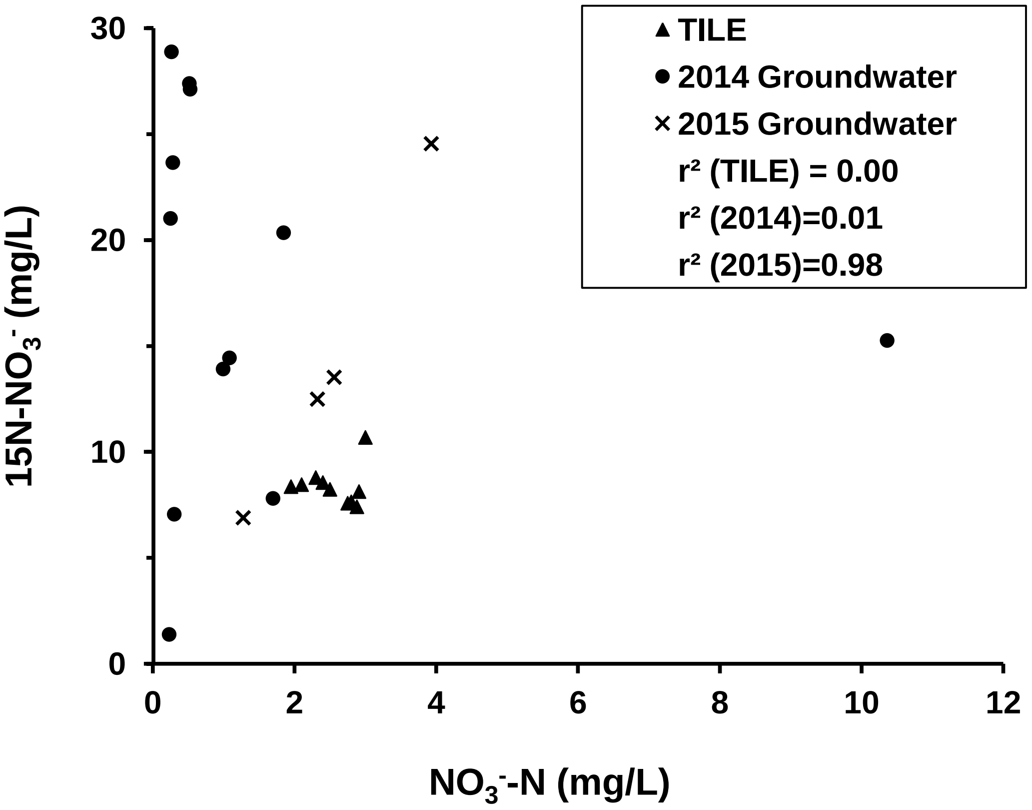
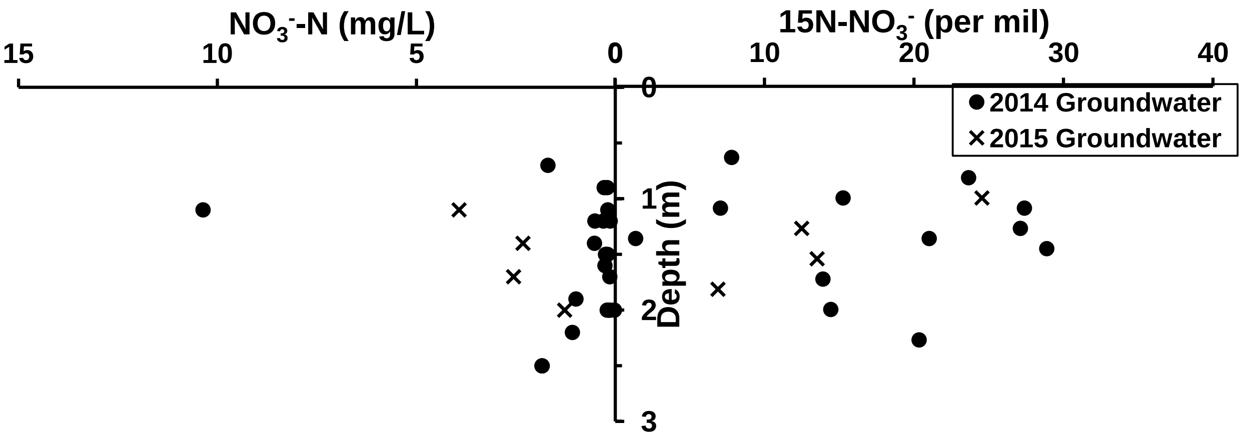


Figure 5.6 Keswick (tile drain) site: Relationship between NO_3^--N and 15N- NO_3^- in groundwater sampled on December 4th, 2014 and April 13th, 2015 from monitoring wells BR-1 through BR-6.

Figure 5.7 Keswick (tile drain) site: NO_3^--N (left) and 15N-NO_3^- with depth in groundwater sampled on December 4th, 2014 and April 13th, 2015 from monitoring wells BR-1 through BR-6.



6. Wildwood Site

6.1 Site Description

The Trout Creek watershed is located within the Upper Thames River watershed (approximately 5% of the Upper Thames River watershed), in southern Ontario ("Upper Thames River Watershed Report Card—Trout Creek", 2012). Approximately 75% of the land in the Trout Creek watershed is used for agriculture ("Upper Thames River Watershed Report Card—Trout Creek", 2012). According to the Trout Creek Watershed Report Card (2012), surface water NO_3^- levels have decreased since 2001, however, P levels have remained relatively steady, with total P levels averaging 88 µg/L and 93 µg/L, between 1996 and 2002, and between 2006 and 2010, respectively. It takes the water in the Trout River watershed just under four weeks to reach Lake Erie.

The woodchip filter is located south of the city of Stratford in southern Ontario, on the Trout Creek watershed. It was installed at a tile drain pipe which drains the adjacent agricultural land into Wildwood Lake (Robertson *et al*., 2009). The tile drain pipe is about 2 m away from the woodchip filter. The flow from the pipe is diverted onto the surface of the filter by a 10-cm-diameter PVC pipe. The field adjacent to the filter is cropped in a corn and soybean rotation and receives regular chemical fertilizer and manure applications (Robertson, 2010).

6.2 Filter Description

The woodchip filter was installed and commissioned in 2002, into a shallow, lined trench beside the tile drain pipe and was originally designed to target nitrate removal. It has dimensions of 13 m long, 1.2 m wide and 1.1 m deep and has a pore volume of 12 m^3 (Figure 6.1). The woodchip filter has a lateral flow design which contains a highly permeable, coarse woodchip core layer (K ~1 cm/s; van Driel *et al*., 2006) situated between underlying and overlying finer layers of sawdust (Figure 6.1.). The upper most layer of the filter is a layer of pea stone, which protects the wood particle media, while the upper sawdust layer acts as a sediment filter. The woodchip, core layer acts as the main flow zone through the filter and flow discharges through an outlet pipe situated at the down gradient end of the filter. Flow rates could be measured directly at the outlet pipe.

Previous studies have monitored the removal efficiencies of NO_3^--N in the Wildwood filter (van Driel *et al*., 2006; Robertson *et al*., 2009). During the first 26 months of operation, NO_3^--N removal rates averaged 2.5 g N/m^2/day, with an average flowrate of 7.7 L/min (van Driel *et al*., 2006). With a carbon consumption of < 2% per year, van Driel *et al*. (2006) speculated about the potential for long term operation of this filter without the need to replace the media. In the sixth and seventh years of operation, Robertson *et al*. (2009) found that the NO_3^--N removal rates remained similar to what was reported by van Driel *et al*. (2006) in the first two years. With increasing filter age, the flooded area overlying the filter, increased in size reflecting decreasing permeability in the upper sawdust layer. However, long term monitoring of the horizontal hydraulic gradient, in the woodchip core layer, showed that horizontal K remained high (0.3 to 5 cm/s) showing little to no deterioration over the seven years of operation (Robertson *et al*., 2009). Although there has been extensive monitoring of media longevity and NO_3^--N removal in the Wildwood filter, very little attention has been paid to phosphorous removal in previous studies.

6.3 Results

Filter Operation and Maintenance

The current study took place from May 2014 to March 2016 (years 12-14 of operation). Since filter installation in 2002, the filter media has not been replaced. During sampling events, the effluent flow ranged between nil and 17.2 L/min. Excluding the low effluent flow events (< 1 L/min), the hydraulic retention times ranged between 0.5 to 5.6 days, considering a total pore volume of 12 m^3 for the filter. The total pore volume was estimated by multiplying the filter volume of 17.2 m^3 by an assumed coarse media porosity of 0.7, which was determined from previous studies (van Driel, 2006; Chun *et al*., 2009). There was an issue with maintaining high enough filter flow rates (> 1 L/min) for much of the study period, particularly during the summer when tile flow dried up. Most sampling was undertaken during the late fall to spring periods when adequate filter flows(> 1L/min) could be maintained (Appendix D, Figure 6.2). There were a few low flow events in the winter which were the result of displacement or freezing of the feed pipe, which connects the filter. The high flow event on February 3, 2016 (17.2 L/min, Figure. 6.2) appeared to be representative of a snowmelt event. During operation of the woodchip filter, there was little to no maintenance required at this site.

Phosphorus and Total Suspended Solids Removal

Figure 6.2 compares influent and effluent TSS, TP, SRP, and PP concentrations from June 2014 to Mar. 2016, which includes data collected during low flow periods (< 1 L/min). The influent TSS levels were variable, 0–150 mg/L. The TSS levels in the treated effluent were low for most of the study (0-38 mg/L, Figure 6.2) with one event where the value was 112 mg/L on 30 Sept. 2014. Total P levels in the tile drain water were low to moderate ranging between 4-169 µg/L (Figure 6.2), however the effluent TP values were generally higher ranging between 5-487 µg/L (Figure 6.2).

Table 6.1 summarizes the mean concentrations and removal percentages of TSS and the P components (TP, SRP and PP) during the sampling period. Sampling events where the flow rate was less than 1 L/min (HRT > 8.3 days) were omitted from the statistical analysis; this excludes 18 sampling events. The mean TSS value in the effluent (11 mg/L) was less than in the tile water (20 mg/L, Table 6.1), but the difference was not significant ($p > 0.05$).

The mean TP value of the filter effluent (83 µg/L) was substantially higher than that of the tile drain (29 µg/L, Table 6.1), but this difference was only marginally significant ($p = 0.053$) because of the variability of the data. Considering the mean values, there was an overall TP increase of 183 %. Particulate P was only a small component of TP for both the tile drain and effluent samples, averaging only 0.4 µg/L and -2.8 µg/L (Table 6.1), respectively. Overall PP removal was not significant ($p > 0.05$). The dominant P component in the tile drain water was SRP, with a mean of 29 µg/L (99% of TP) which was substantially less than that of the filter effluent value (85 µg/L, Table 6.1), but this difference was only marginally significant ($p = 0.062$) because of the high variability of the SRP values. Considering the mean values, there was an overall SRP release of 196%, and this accounted for essentially all of the effluent TP. Figure 6.3 shows that there was good correlation between SRP and TP in the tile drain flow ($r^2 = 0.53$) and a stronger correlation within the filter effluent ($r^2 = 0.86$). There was little correlation between PP and TP ($r^2 = 0.01–0.07$; Figure 6.3). The amount of TP and SRP removed was significantly affected by the HRT within the filter ($p < 0.05$), however the overall correlation between TP and SRP, and HRT is low ($r^2 = 0.05$ and 0.01, respectively; Figure 6.4).

Overall, there was 44% TSS removal, but 183% TP release, where the majority of this was SRP release (112%, Table 6.1).

Nitrogen and Dissolved Organic Carbon

Figure 6. 5 shows inorganic N (NO_3^--N and NH_4^+-N) trends, from May 2014 to Mar. 2016. The tile drain had mean concentrations of 7.2 mg/L and 0.02 mg/L for NO_3^--N and NH_4^+-N, respectively. The overall NO_3^--N concentration in the treated effluent was significantly lower (2.3 mg/L, $p < 0.05$; Table 6.1). The average removal rate in 2014 was 0.86 g N/m^3/day and 2.0 g N/m^3/day for the 2015 and 2016 sampling dates combined, giving an overall removal of 68% and an average removal rate of 1.6 g N/m^3/day. Many of the sampling events during the 2014 period had low flow (< 1 L/min, Appendix D), however, the filter still significantly removed NO_3^--N. The presumed mechanism of NO_3^--N removal is denitrification. There was a significant difference between the dissolved oxygen (DO) concentrations in the tile drain water and the treated effluent, with mean values of 10.7 mg/L and 1.8 mg/L, respectively ($p < 0.05$, Table 6.1).

The mean NH_4^+-N concentration in the tile drain was 0.02 mg/L. There was a slight increase in NH_4^+-N in the filter effluent (Figure 6. 5) with a mean concentration of 0.03 mg/L (Table 6.1), however this increase was not significant ($p > 0.05$).

The dissolved organic C (DOC) concentrations in the influent was low (mean of 2.1 mg/L; Table 6.1) and ranged between 0.4-14 mg/L (Figure 6. 5). The DOC concentrations in the treated effluent was slightly higher, however this difference was not significant (mean of 2.6 mg/L, $p > 0.05$; Table 6.1).

Correlation with Iron

Figure 6.6 shows the relationship between TP, PP, SRP and NO_3^--N with the dissolved iron concentrations. For all three P components, there was little to no correlation with dissolved iron concentrations in the influent, however, there was a statistically significant correlation in the filter effluent. There were significant moderate correlations between TP and SRP concentrations with dissolved iron concentrations in the effluent ($p < 0.05$; $r^2 = 0.52$ and 44, respectively). When considered together (tile water and filter effluent), the relationship of the dissolved iron concentrations with TP and SRP were higher ($r^2 = 0.80$ and 0.55, respectively). The relationship between PP and the dissolved iron concentrations in the effluent was not significant and there was no correlation, between these two parameters, in the effluent.

There was a significant difference between the dissolved iron and NO_3^--N concentrations in the tile drain water and the treated effluent, with mean dissolved iron values of 0.03 mg/L and 0.09 mg/L, respectively ($p < 0.05$, Appendix D). However, the correlations between dissolved iron and NO_3^--N concentrations in the tile drain water and treated effluent were low ($r^2 = 0.30$ and 0.21, respectively; Figure 6.6) but higher when considered together ($r^2 = 0.56$).

Figure 6.7 contains scatter plots that provide a comparison of influent and effluent parameter concentrations (TSS, TP, SRP, PP, DOC, NO_3^--N and NH_4^+) for woodchip filter. This comparison demonstrates the degree of TSS, TP, PP, NO_3^--N and NH_4^+-N removal, and SRP and DOC release within the Wildwood filter.

6.4 Discussion

Overall, there was 44% TSS removal, but 183% TP release, with the majority of it being SRP release (112%, Table 6.1) during years 12-14 of operation (2014-16). It appears likely that the excess dissolved P represents leaching of particulate P associated with the suspended sediment retained the filter. Figure 6.4 shows the relationship between the release of the P components and HRT. There was little correlation between TP concentrations and HRT, however, the relationship between the TP removal and HRT was significant ($r^2 = 0.05$, $p < 0.05$). There is little correlation between SRP concentrations and HRT, however the relationship between SRP release and HRT was significant ($r^2 = 0.01$, $p < 0.05$). There was low correlation between PP and HRT and the relationship was not significant ($r^2 = 0.05$, $p > 0.05$).

The following is an estimate of the time that it would take for the initial intrinsic P content of the woodchip media to be leached out. This calculation helps to provide insight as to whether or not the observed increase in P could be related to P initially present within the fresh woodchip media. The initial carbon mass in the reactor coarse layer (7.8 m^3) was estimated previously at 940 kg (van Driel *et al*., 2006). Assuming a C:P ratio of 9460:1(Moore *et al*., 2005 for Western hemlock *Tsuga heterophylla*) for the woodchips, the initial P content of the coarse layer woodchips would have been 99 g P or 13 g P/m^3. Thus, initially the total volume filter media would have contained 221 g P ((17 m^3 x 13 g P/m^3). At the rate of SRP leaching observed in the current study (-0.019 g P/m^3/day or 0.32 g P/day, Table 6.1), this amount of P would have been leached out after approximately 690 days (~1.9 years) of filter operation. Furthermore, the correlation with P and iron in the effluent indicate that anaerobic conditions within the biofilter could have resulted in a redox reaction where the iron converts to an electron acceptor and thus, releases the associated P. Thus, the continued excess P leaching currently observed during years 12-14 of operation, supports the likelihood that much of this P is derived from slow leaching of particulate P trapped within the filter.

The statistically significant relationship between P and hydraulic retention time indicates that maintaining adequate flow rates through woodchip filters is important for minimizing P leaching. A second option for P control might be to augment the woodchip media with additional media mixtures that have the potential to provide enhanced P removal. Constituents such as steel shavings and biochar have been shown to provide enhanced SRP removal (Goodwin *et al*., 2015; Bock *et al*., 2015) and could be readily added to a woodchip based media mixture at a modest cost.

The mean NO_3^--N removal rate in 2014 (2.87 g N/m^3/day) was slightly higher than the rate in 2015/2016 (1.85 g N/m^3/day,). In the first two years of study, van Driel *et al*. (2006) reported a NO_3^--N removal rates between 2 to 20 g N/m^3/day and Robertson *et al.* (2009) reported a rate of 4.6 g N/m^3/day during the eighth year of operation. The rates for 2014-2016 (years 12-14) fall below this value, indicating a possibly decreasing NO_3^--N removal ability in the Wildwood filter, but over a very extended period and likely affected by the flow rates. Overall, the filter continues to significantly remove NO_3^--N ($p < 0.05$). Low dissolved oxygen and elevated ferrous iron concentrations support the likelihood that NO_3^--N removal has occurred by denitrification. Results of this study support previous studies (Robertson, 2010) indicating that woodchip media can deliver significant NO_3^--N removal rates over decadal time frames.

Dissolved organic C concentration in the treated effluent (mean of 2.6 mg/L) were not significantly different ($p > 0.05$) than the tile drain (mean of 2.1 mg/L; Table 6.1) although a slight increase (21%) was noted. This slight increase was similar to that observed by van Driel *et al.* (2006) in years 5-6 of operation which was indicated to represent only ~ 2% carbon loss per year at that time. These results support the previous indication of substantial media longevity in support of denitrification.

6.5 Conclusions

Monitoring at this site provides compelling evidence that wood particle filters can generate low levels of dissolved phosphorous leaching during long term operation. Since the initial intrinsic P content of the woodchips was much less than the observed amount leached, it is likely that this SRP generation represents leaching of particulate organic P associated with the sediment retained in the filter. This points to a need for the periodic removal and replacement of the wood particle media and associated entrained sediment, if low level phosphorous removal is a principle goal of the filter.

One of the contaminants that the Wildwood filter was designed to treat was NO_3^--N. The filter continued to effectively treat NO_3^{-}N despite the fact that the filter media has not been replaced during the 15 years of operation. The Wildwood filter has continued to operate as a cost effective, low maintenance, method for nitrate removal over a very long period.

Table 6.1 Wildwood (tile drain) site: Concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO_3^-–N, NH_4^+–N, dissolved organic C (DOC) and dissolved oxygen (DO) in the tile drain water, and treated effluent (from May 2014 to March 2016), removal percentages with respect to the tile drain values, and volumetric removal rates in the filter. Rates consider the mean flow rate of 4.0 L/min, and a filter pore volume of 12 m**3,** assuming a porosity of 0.7 (van Driel et al., 2006**)**. The mean values within this table do not include low flow values (< 1 L/min) and sampling events for which flow data was unavailable (18 sampling events*). Detailed geochemical results are presented in Appendix D.

Substance	**Tile Drain**	**Effluent**	**Removal**	**Removal Rate**
Mean effluent flow rate (L/min) = 4.0 ± 4.5 (18); HRT (days) = 2.1 ± 2.4 (18)†				
			------ % ------	---g/m^3/day--
TSS (mg/L)	20 ± 39 (17)	11 ± 29 (16)	44	2.9
TP (ug/L)	29.2 ± 40 (18)	82.5 ± 127 (18)	-183	-0.018
SRP(ug/L)	28.8 ± 43 (18)	85.2 ± 143 (18)	-196	-0.019
PP (ug/L)	0.4 ± 31.0 (18)	-2.77 ± 37.3 (18)	809	0.001
NO_3^--N (mg/L)	7.2 ± 2.7 (17)	2.3 ± 1.9 (15)	68	1.6
NH^+_4-N (mg/L)	0.02 ± 0.05 (14)	0.03 ± 0.06 (14)	-81	-0.16
DOC (mg/L)	2.1 ± 2.8 (18)	2.6 ± 2.5 (18)	-21	-0.004
DO (mg/L)	10.7 ± 1.7 (12)	1.8 ± 1.1 (12)	83	3.0

† Means ± standard deviations; number of replicates in parentheses
*Dates Excluded:
(Flow < 1 mg/L)
(2014) July 17th, July 24th, Aug. 7th, Nov. 15th
(2015) May 7th, May 14th, June 12th, Nov. 13th, Dec. 8th
(2016) Jan. 4th
(Flow not measured)
(2014) May 27th, June 7th, Aug. 19th, Sept. 16th
(2015) Apr. 1st, Apr. 15th, June 15th, Dec. 15th

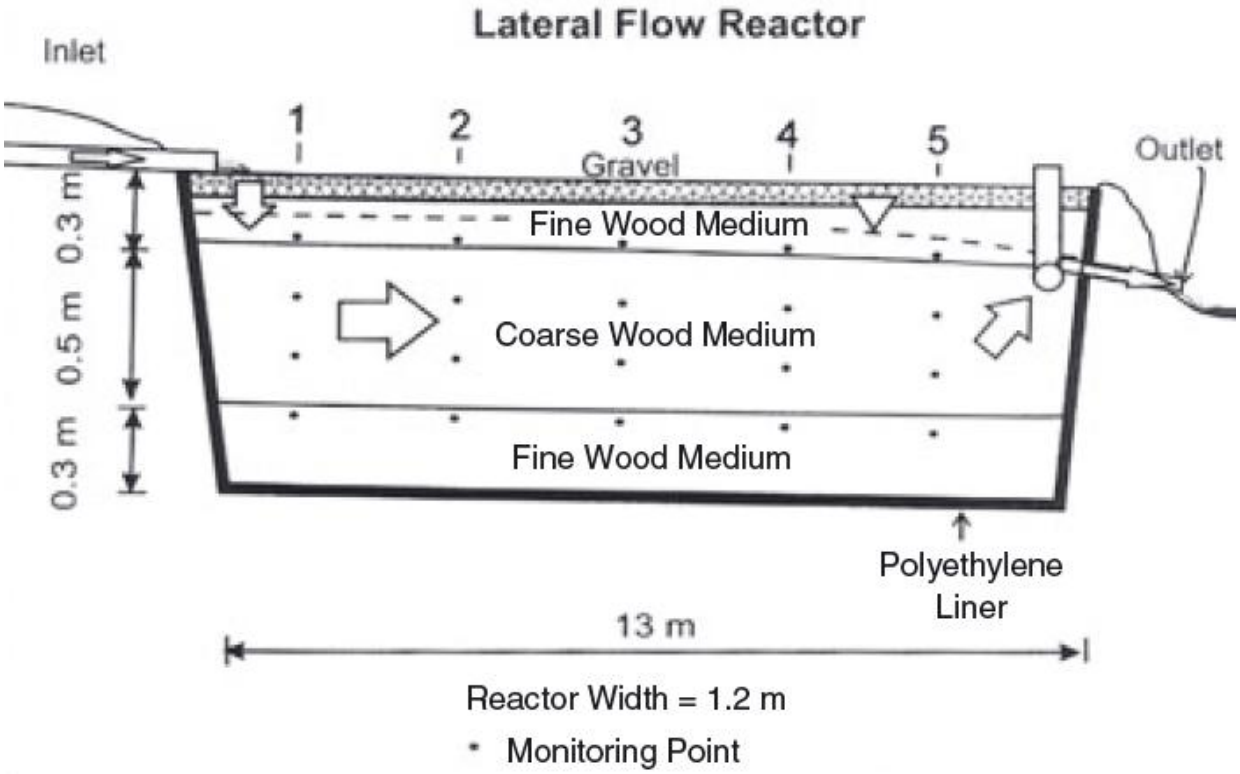


Figure 6.1 Wildwood (tile drain) site: Design sketch of the Wildwood woodchip filter, located south of Stratford, ON, installed 25 Oct. 2001. The bioreactor is 13 m in length, 1.2 m in width, and 1.1 m deep, and has a layer of coarse woodchips ‘sandwiched’ between underlying and overlying fine woodchips. Assuming porosity of 0.7 for the woodchip media (van Driel *et al*., 2006), the filter has a pore volume of 12 m^3. Arrows indicate direction of flow and the dots indicate monitoring well-screen intervals (from van Driel et al., 2006).

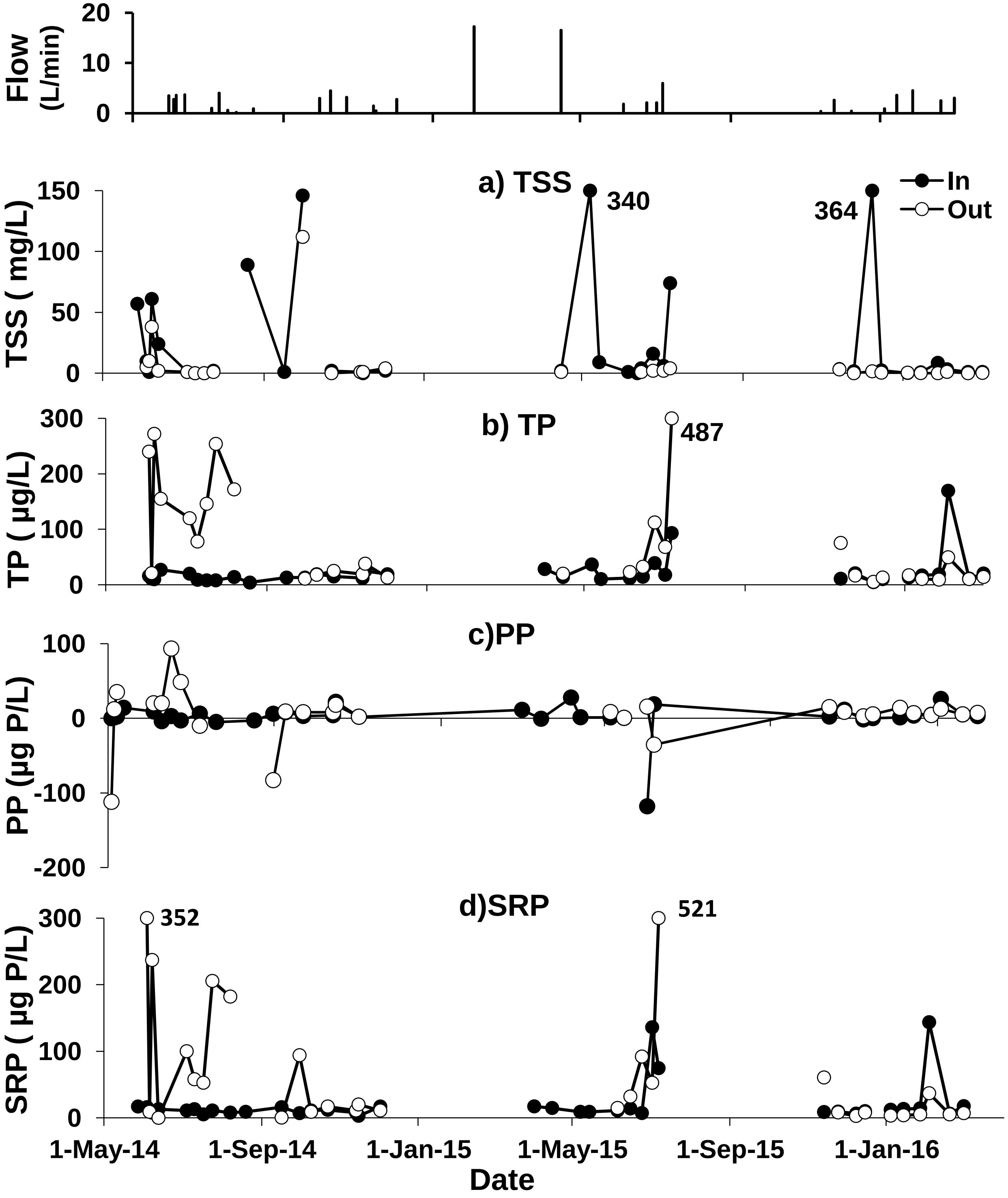


Figure 6.2 Wildwood (tile drain) site: Comparison of influent tile water (In) and filter effluent (Out) for trends in (a) total suspended solids (TSS), (b) particulate P (PP), (c) total P (TP), and (d) soluable reactive P (SRP) in the tile drain water (In), and treated effluent (Out) from May 2014 to March 2016.Top histogram is flow rate through the filter.

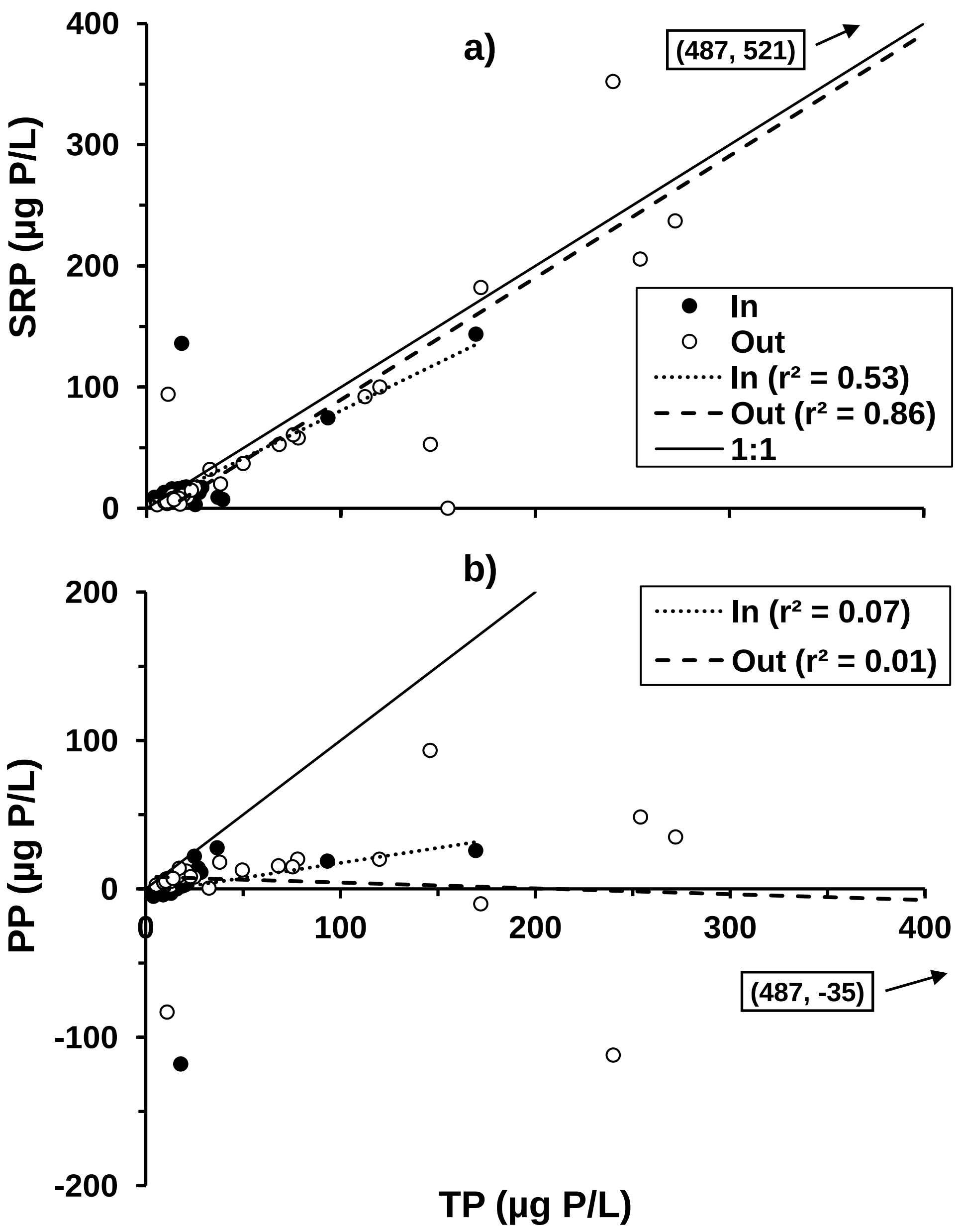


Figure 6.3 Wildwood (tile drain) site; Correlation of total P (TP) with a) soluble reactive P (SRP) and b) particulate P (PP) concentrations in the Wildwood filter (May 2014 to March 2016).

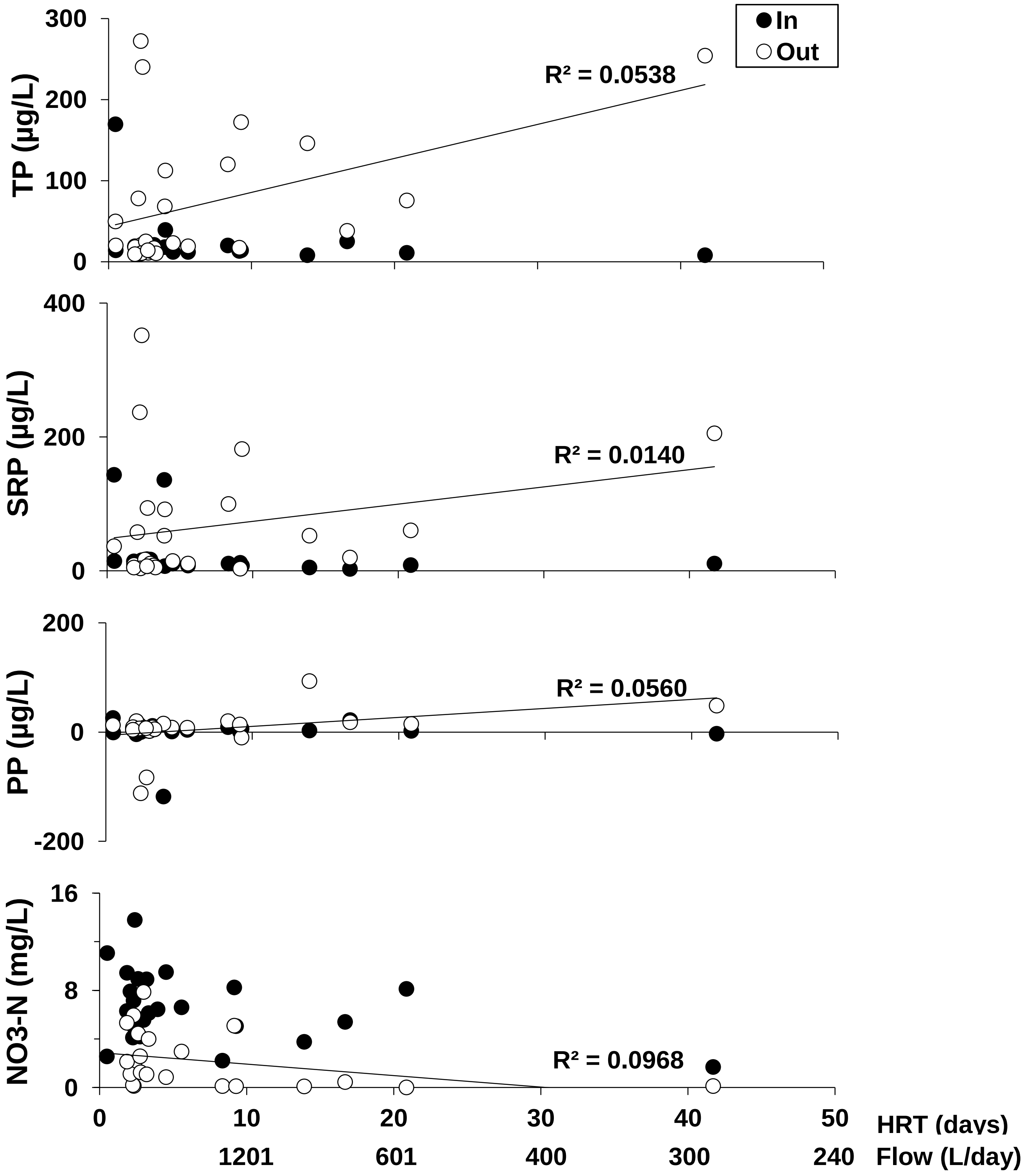


Figure 6.4 Wildwood (tile drain) site: Correlation of total P (TP), soluble reactive P (SRP), particulate P (PP) and nitrate (NO_3^--N) concentrations in the filter effluent with hydraulic retention time (HRT) in the filter (May 2014 to March 2016). Tile water concentrations are also shown.

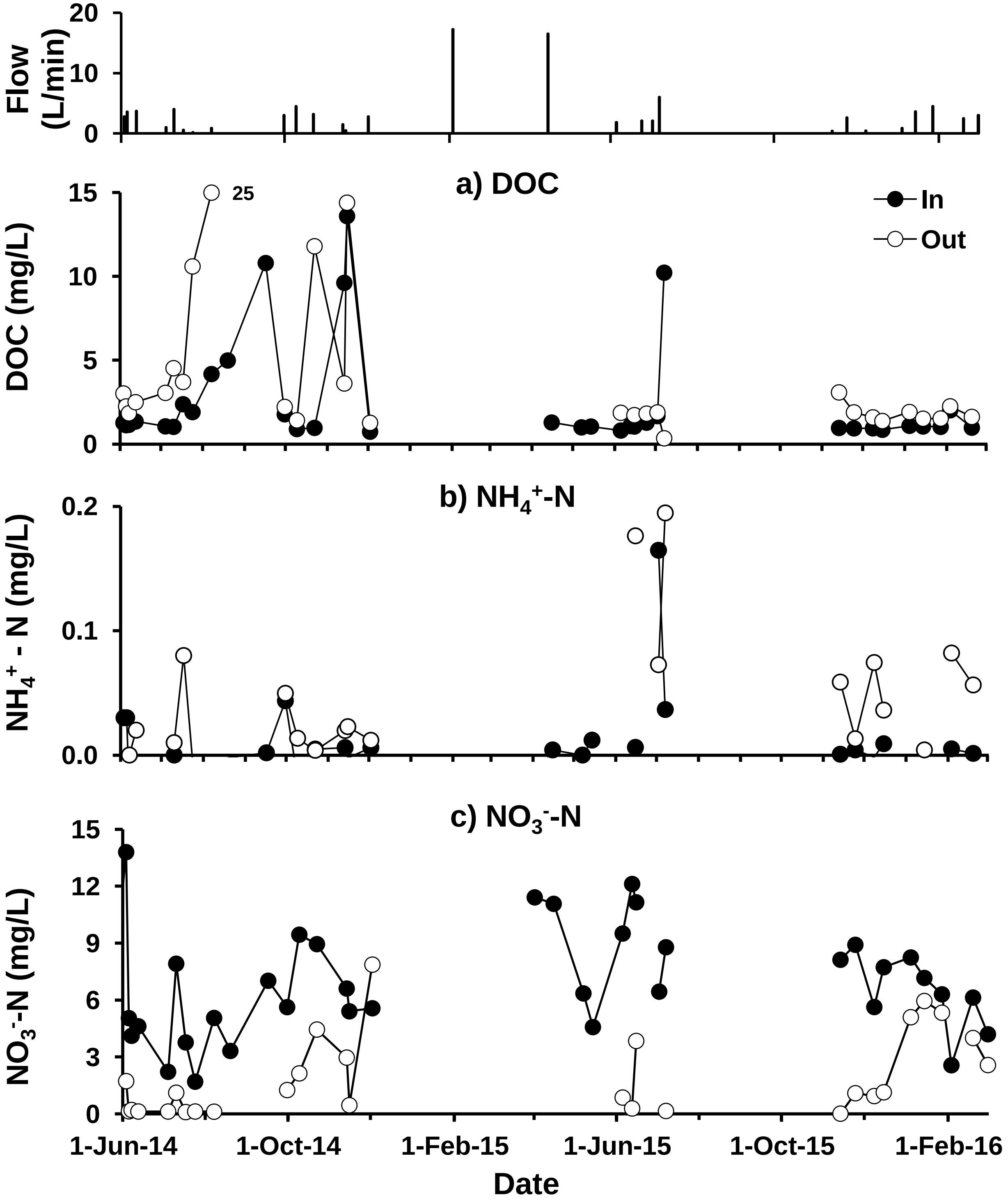


Figure 6.5 Wildwood (tile drain) site: Trends in (a) dissolved organic C (DOC), (b) NH_4^+ -N, and (c) NO_3^--N in the woodchip filter during two seasonal cycles from May 2014 to March 2016.

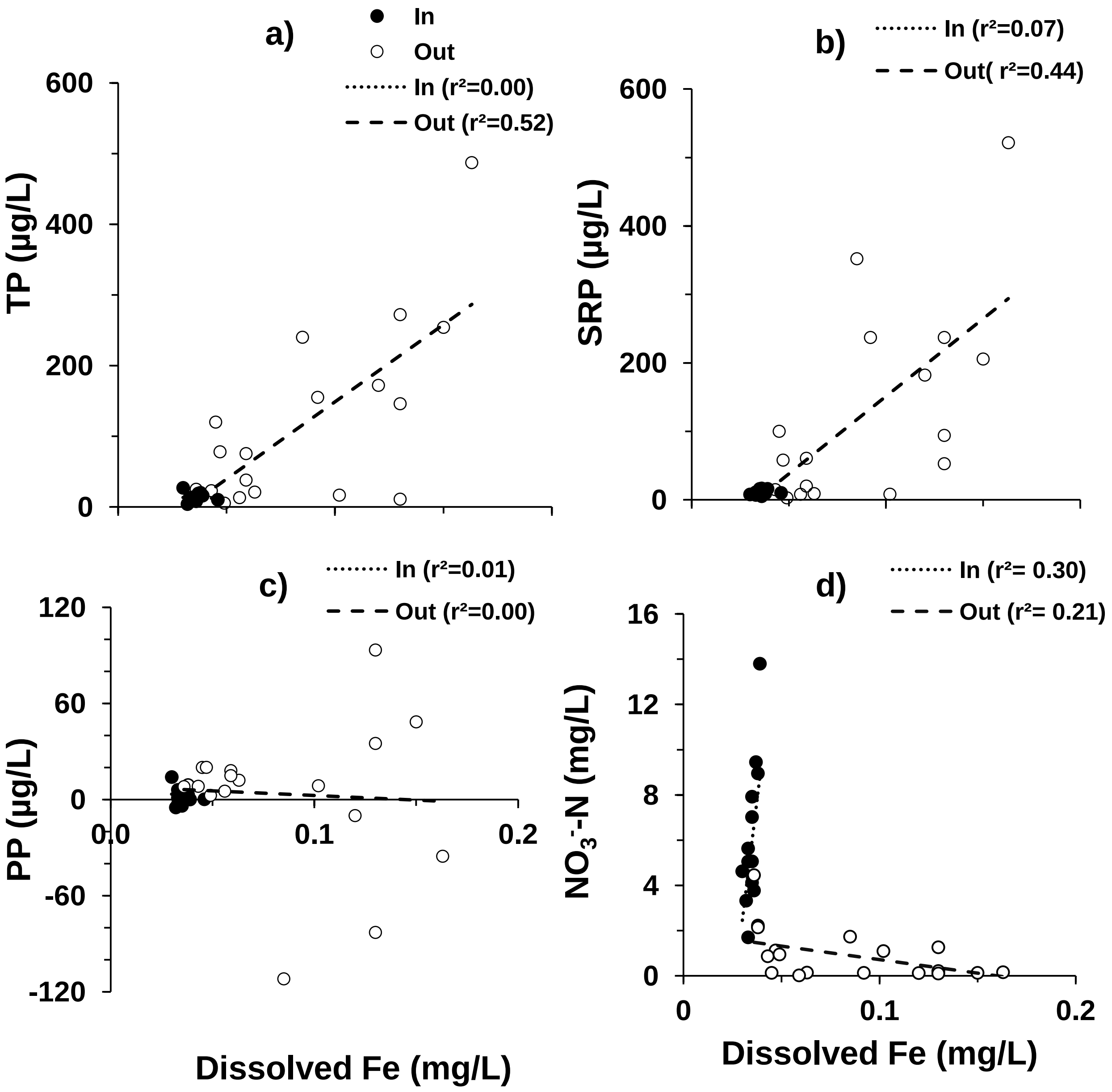


Figure 6.6 Wildwood (tile drain) site: Correlation of dissolved Fe with a) TP, b) SRP, c) PP and d) NO_3^--N in the woodchip filter effluent (May 2014 to March 2016).

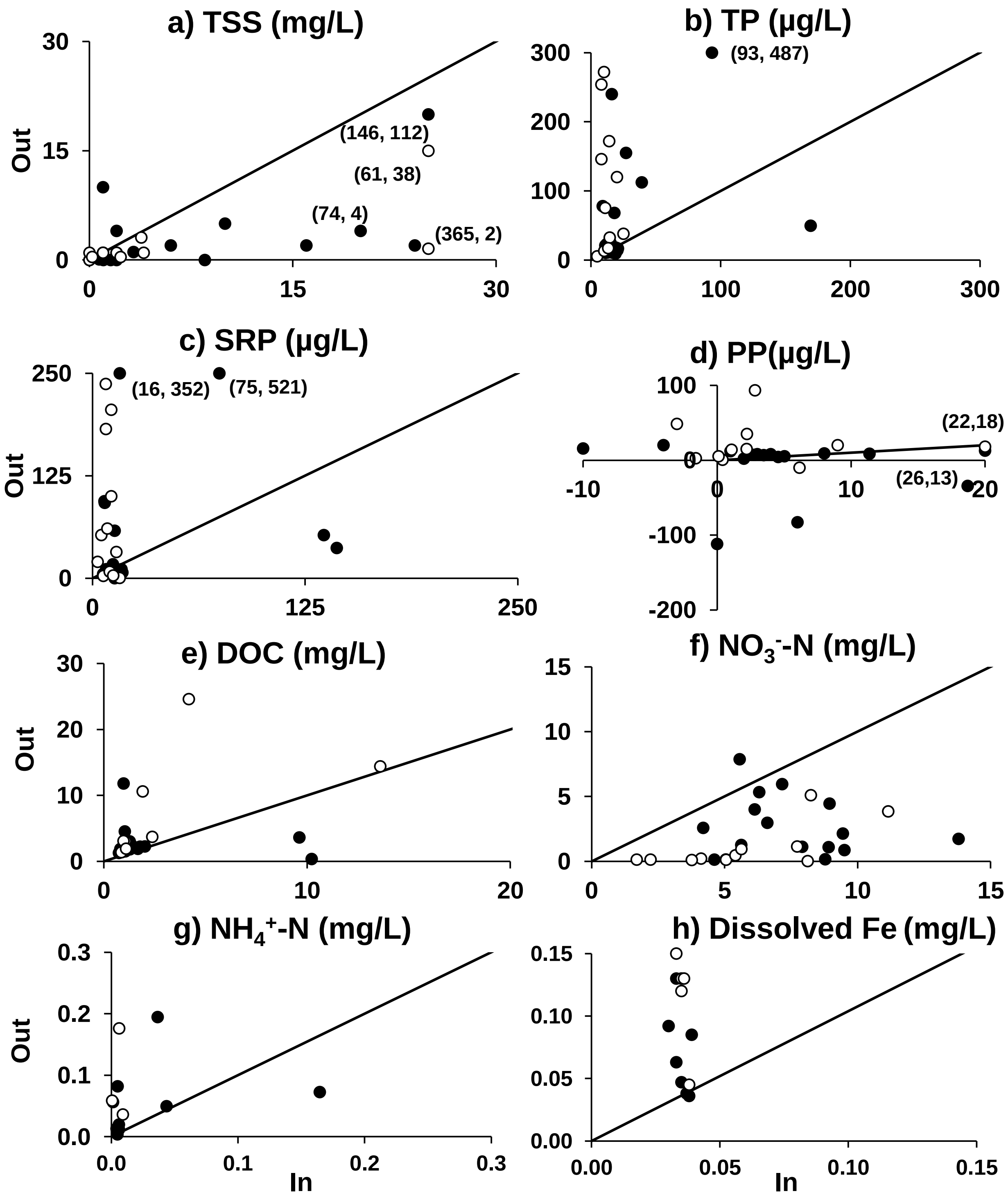


Figure 6.7 Wildwood (tile drain) site: Comparison of (a) total suspended solids (TSS), (b) total P (TP), (c) soluble reactive P (SRP), (d) particulate P (PP), (e) dissolved organic C (DOC), (f) NO_3—N, (g) NH4+-N and (h) dissolved Fe between tile flow and filter effluent (May 2014 to March 2016). White dots are for events when flow is less than 1 L/min and for when there was no flow data. Points above the 1:1 line shown, indicate parameter release in the filter; points below the line indicate parameter retention in the filter.

7. Avon Filter

7.1 Site Description

The Avon River watershed is located within the Upper Thames River watershed (approximately 5% of the Upper Thames River watershed), in southern Ontario with 75% of the land being used for agriculture ("Watershed Report Card: Avon River", 2012). According to the Avon River Watershed Report Card (2012), surface water NO_3^- and P levels have decreased since 2001 and the 1970s, respectively. The P levels have steadily decreased, with total P levels averaging 162 µg/L between 1996 and 2000, 128 µg/L between 2001 and 2005, and 91 µg/L between 2006 and 2010. It takes the water in the Avon River an average of just under four weeks to reach Lake Erie.

The woodchip filter is located east of the city of Stratford, located on the Avon River watershed. It was installed in a drainage ditch that receives inflow from a number of drainage tiles that underlie the adjacent agricultural land. This stream flows into the Avon River and is about 2-3 m wide and is ditched to a depth of 1 to 2 m (Robertson and Merkley, 2009; Robertson, 2010). The stream has a low hydraulic gradient (-0.001) and often freezes over during the winter months (Robertson and Merkley, 2009). The stream extends about 1 km upstream from the woodchip filter and has about four tile outlets that discharge upstream of the filter (Robertson and Merkley, 2009; Robertson, 2010). The main field crops grown adjacent to the installation are corn and soybeans and these receive applications of both chemical fertilizers and manure (Robertson and Merkley, 2009).

7.2 Filter Description

The woodchip filter was installed and commissioned on November 1st, 2006. A mechanical excavator trenched below the bottom of the streambed where the woodchip filter was installed to a depth of 1 m below the streambed over a length of 20 m and width of 2.5 m (Robertson and Merkley, 2009). The trench was filled with 40 m^3 of woodchips. The upstream half of the filter was then covered with 1-2 cm diameter gravel, with a thickness of approximately 20 cm and the downstream half had a low permeability silt layer placed on top (Figure 7.1) (Robertson and Merkley, 2009). The filter effluent drains out of a 10 cm diameter PVC pipe that lies at the bottom of the filter and discharges downstream of a cobble riffle installed at the downstream end of the filter. The flow rate through the filter can be manipulated by adjusting the height of the discharge pipe outlet..

The filter was initially installed to target NO_3^--N removal (Robertson and Merkley, 2009) but subsequent studies also investigated TSS removal (Chan, 2010), greenhouse gas production Elgood *et al*, 2010) and methyl mercury production (Shih *et al*., 2011). It was established that NO_3^--N removal was more complete during warmer temperatures. These studies also concluded that control of the flow rate was of considerable value in avoiding undesirable side effects such as the production of H_2S, methane (a powerful greenhouse gas), and methyl mercury which occurred when retention times became too long, due to low flow rates.

Although the Avon filter was designed for NO_3^--N removal, Chan (2010) also examined P and TSS treatment in the filter. Substantial TSS removal was observed, however it was found that under reducing conditions, SRP concentrations in the filter effluent increased and consequently TP removal efficiency decreased. However, this study had a limited dataset, collected over only a three-month period and P was analyzed at a higher analytical detection limit (~50 µg/L) that was inadequate for many of the samples. Additional monitoring, at a much lower TP detection limit (0.5 µg/L), was undertaken during the current study. The filter was 8-9 years old at the time of the current study.

7.3 Results and Discussion

Filter Operation and Maintenance

For the current study period (May 2014 to November 2015), there was an issue with achieving adequate flow rates through the filter. Flows generally remained < 4 L/min (Figure 7.2). Table 7.1 summarizes the mean concentrations and removal percentages of TSS, the P components, NO_3^--N, NH_4^+-N, DOC and Cl^- during the sampling period. The detailed data is given in Appendix E. Sampling events when flow rates were less than 1 L/min (18 events) were excluded when calculating the mean values given in Table 7.1. Figure 7.2 compares stream water and filter effluent TSS, TP, SRP, and PP concentrations from May 2014 to Nov. 2016, (including low flow events, < 1 L/min). Differences in the influent and effluent TSS, TP, SRP and PP concentrations were not significant ($p > 0.05$) because of the high variability of the data. However, there was a relatively consistent trend of increased SRP concentrations in the filter effluent (mean of 108 µg/L) compared to the stream water (mean of 63 µg/L).

Figure 7.3 compares the influent and effluent NO_3^-–N and Cl^- concentrations. The filter effluent NO_3^-–N concentrations (mean of 0.6 mg/L; Table 7.1) were significantly lower than the stream water (mean of 3.4 mg/L, $p < 0.05$; Table 7.1). However, the mean Cl^- concentration in the treated effluent (23 mg/L) was much higher than in the stream water (9 mg/L, Table 7.1) and this difference was significant ($p<0.05$). This indicated that the steam water was not effectively flowing through the filter. The woodchips had not been replaced since their installation in 2006, creating the possibility of that the filter had become clogged with sediment. In June 2015, in an effort to unclog the filter, hydraulic fracking was attempted by pumping water into the outlet pipe at a high rate. However, this was unsuccessful in increasing the flow rate and Cl^- values did not substantially change.

Sampling of this system was terminated in November 2015 as a result of the dissimilar influent and effluent Cl^- values. This suggested that the outlet pipe was likely intercepting primarily groundwater, rather than filtered stream water. Replacement of the woodchip media would presumably be necessary in allow effective operation of the filter to resume.

Despite the apparent flow problems, the observation of increased SRP concentrations in the filter effluent is of interest. The mean effluent SRP concentration of 108 ug/L is unusually high for groundwater and likely indicates that some portion of the flow did migrate through the woodchip media. If this is the case, the observed increase in SRP values could reflect leaching of particulate P associated with the entrained sediment. If so, this behaviour is similar to what was observed at the other older filter site (Wildwood site) and has important implications for the long term management strategies of such filters.

Table 7. 1 Avon (stream bed) woodchip filter: Concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO_3^-–N, NH_4^+–N, dissolved organic C (DOC) and chloride (Cl^-) in the stream water, and treated effluent (from May 2014 to November 2015), removal percentages with respect to the stream values, and volumetric removal rates in the filter. Rates consider the mean flow rate of 2.9 L/min, and filter pore volume of 28 m^3, assuming a porosity of 0.7 (van Driel *et al*., 2006). The mean values exclude low flow values (< 1 L/min) and sampling events for which flow data was unavailable (18 sampling events, Appendix E)*.

Substance	Stream	Effluent	Removal	Removal Rate
Mean effluent flow rate (L/min) = 2.9 ± 1.6 (20)[†]				
			------ % ------	---g/m3/day--
TSS (mg/L)	33 ± 41 (18)	26 ± 54 (18)	22	1.1
TP (µg/L)	116 ± 128 (17)	159 ± 161 (18)	-38	-0.01
SRP(µg/L)	63 ± 104 (19)	108 ± 89 (18)	-73	-0.007
PP (µg/L)	55 ± 44 (17)	62 ± 177 (18)	-13	-0.001
NO_3^--N (mg/L)	3.4 ± 2.8 (18)	0.6 ± 0.5 (18)	83	0.41
NH_4^+-N (mg/L)	0.08 ± 0.25 (18)	0.12 ± 0.14 (17)	-46	-0.01
DOC (mg/L)	7.5 ± 2.2 (19)	8.3 ± 5.9 (19)	-11	-0.12
Cl^- (mg/L)	9 ± 2 (19)	23 ± 6 (19)	-164	-2.1

[†] Means ± standard deviations; number of replicates in parentheses.

* Dates excluded:
(2014) May 23rd, May 30th, July 24th, Sept. 16th and Dec. 19th
(2015) Jan. 6th, Apr. 1st, Apr. 22nd, Apr. 24th, May 21st, June 2nd, June 12th, June 15th, June 24th, July 2nd, July 16th, Aug. 11th, and Nov. 13th

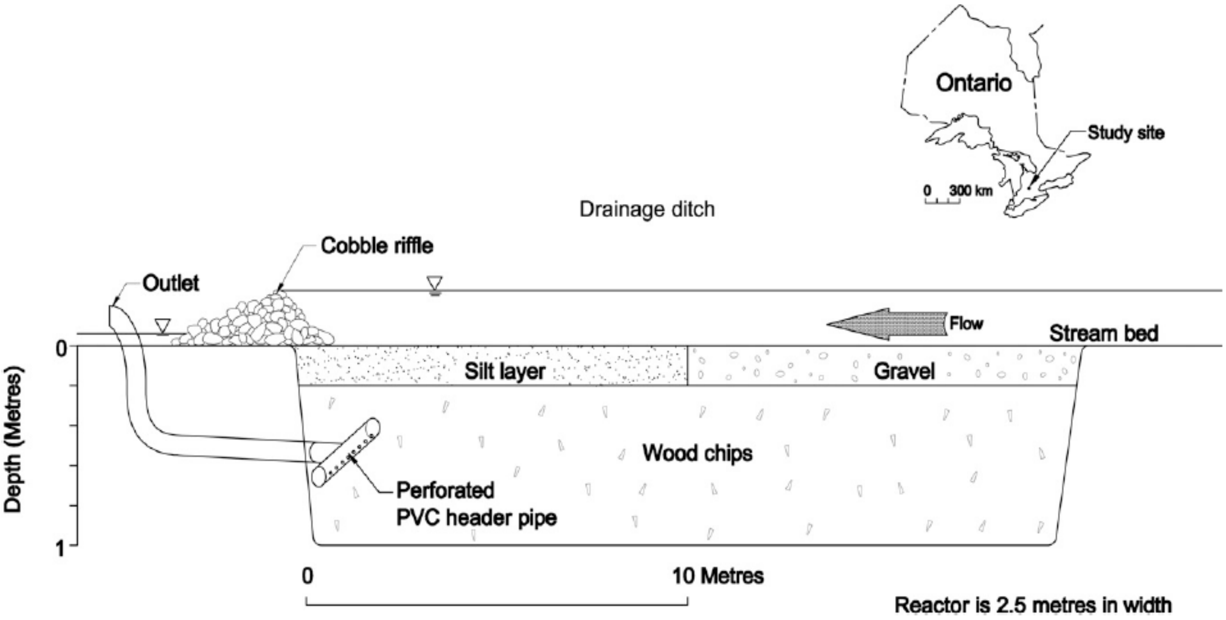


Figure 7.3 Design sketch of Avon woodchip filter (from Robertson and Merkley, 2009). The bioreactor is 20 m in length, 2.5 m in width, and 1 m deep below the streambed. Approximately 40 m^3 of permeable woodchips were placed into the excavated trench. Assuming porosity of 0.7 for the woodchip media (van Driel *et al*., 2006), the filter has a pore volume of 28 m^3.

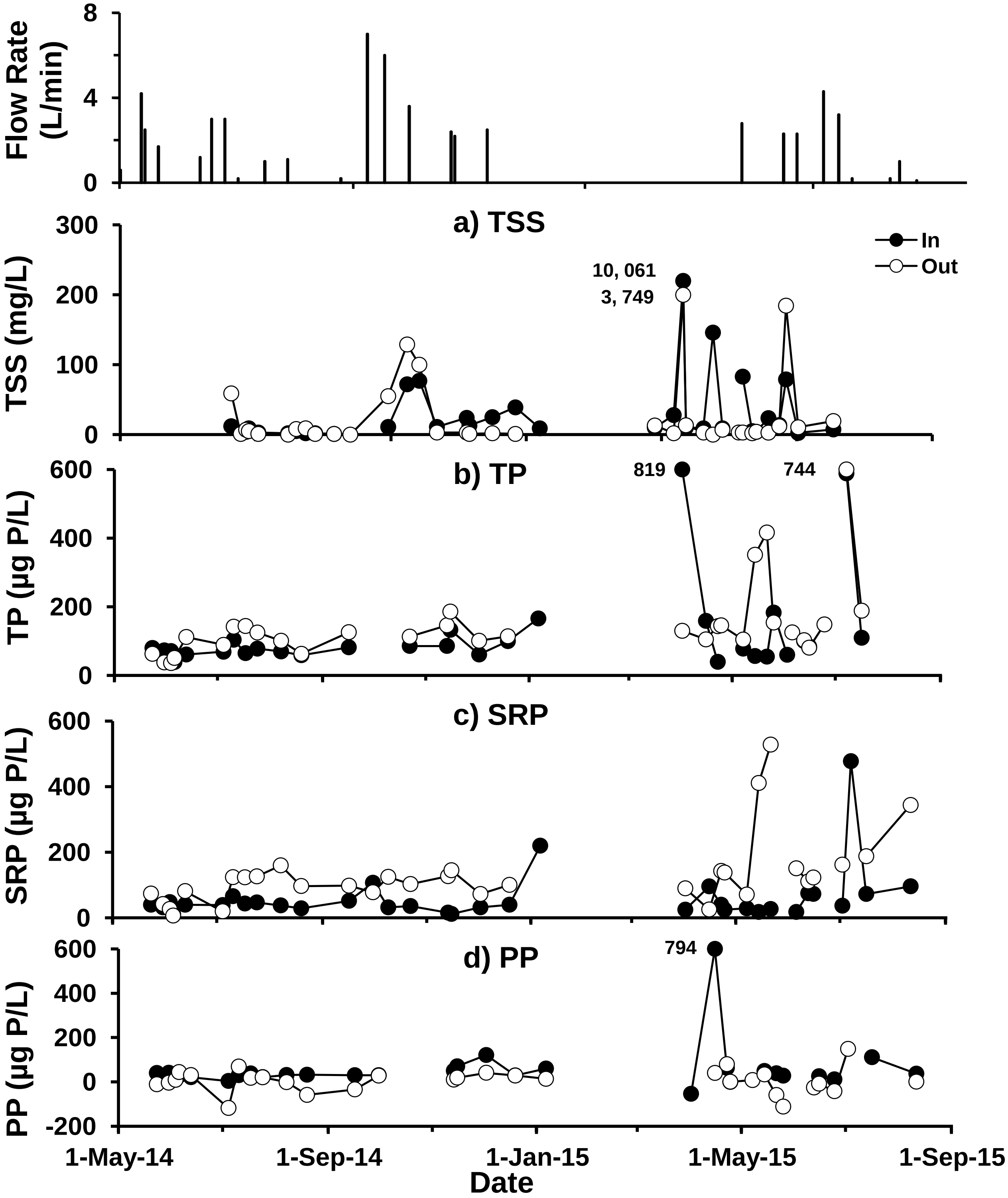


Figure 7. 4. Avon (stream bed) filter: Trends in (a) total suspended solids (TSS), (b) total P (TP), (c) soluble reactive P (SRP), and (d) particulate P (PP) in the stream water (In), and treated effluent (Out) from May 2014 to Nov. 2015.

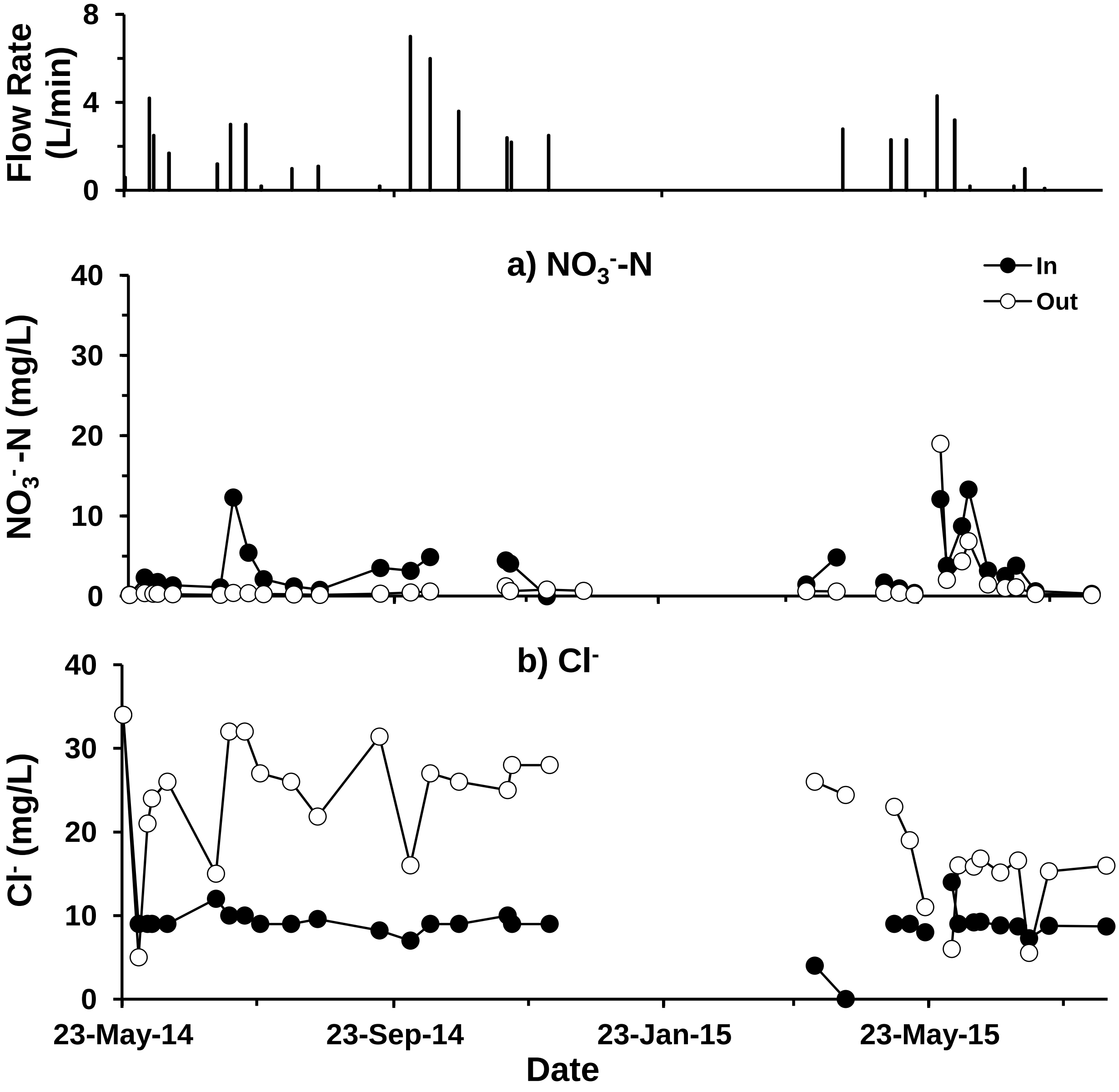


Figure 7. 3 Avon (stream bed) site: Trends in (a) NO_3^--N, and (b) Cl^- in the Avon filter system, from May 2014 to November 2015.

8. Conclusion and Recommendations

This study showed that wood particle filter systems have a substantial capacity for the removal of particulate P and total suspended solids from turbid agricultural waters. The technology was low cost, was simple to operate and maintain and required a relatively small footprint. These features could make woodchip filters potentially attractive for implementation in a wide range of situations where phosphorus export in urban and agriculturally impacted water courses is dominated by particulate material. Tables 8.1-8.4 compare the differences in treatment of TSS, TP, PP and SRP between the five sites monitored in this study and these differences are discussed below.

Total Suspended Solids

A summary of the TSS removal at all five woodchip filters are outlined in Table 8.1. Of the five woodchip filters, the Bradford treatment system displayed significant TSS removal capability with an overall average of 97% to 99% removal within the treatment system, where the mass removal rate within the woodchip component was an average of 263 to 311 g/m^3/d. There was poor TSS removal observed at the Big Bay, Keswick and Wildwood sites however there were many sampling events where TSS values were low (< 10 mg/L; Appendix B, C and D, respectively) thus giving the woodchip media little opportunity to provide additional filtration of TSS when the initial TSS concentration was already low. The TSS concentrations that were observed at the Avon site provided no input into the TSS removal capability of the woodchip filter since the influent water was different from the effluent water, which was determined from the difference in chloride concentrations (conservative tracer).

Based on these observations an initial TSS concentration greater than approximately 40 mg/L is required for the woodchip filters to be beneficial.

Total Phosphorus

A summary of the TP removal at all five woodchip filters are outlined in Table 8.2. Significant TP removal was observed at the Bradford and Big Bay woodchip filters with normalized mass removal rates of 0.73 to 1.47 g/m^3/d and 0.17 g/m^3/d (Table 8.2), respectively. Of these two, the highest removal was observed at the Bradford filter due to the increased P loading from the wash water, thus giving more opportunity for the woodchip media to remove the P. The TP at the Wildwood site was leaching from the woodchip filter at an average normalized rate of 0.018 g/m^3/d. This phenomenon was likely a result of P leaching from the particulate P that had accumulated over the 15 years that the woodchip filter had been in operation. At the Keswick filter, there was little TP removal observed at this site as a result of the combination of low TP concentrations (< 100 mg/L) in the tile drain and dry conditions, thus providing little opportunity for the woodchip media to filtrate the TP. The TP concentrations that were observed at the Avon site provided no input into the TP removal capability of the woodchip filter since the influent water was different from the effluent water, which was determined from the difference in chloride concentrations (conservative tracer). Based on these observations an initial TP concentration greater than approximately 40 mg/L is required for the woodchip filters to be beneficial.

The correlation between TP and TSS were also observed in this study and it was found that there was a weak correlation between these two parameters (r^2=0.23) in the vegetable wash water and low correlations in the tank and woodchip effluent (r^2= 0.03) at the Bradford site. However, at the Big Bay site, there was a higher correlation between TP and TSS in the influent (r^2 = 0.62) than what is observed at Bradford. The clear difference between these two sites is that the influent are the different sources of water and that the Bradford site has approximately 10^6 times more TP and 200 times more TSS than what is in the Big Bay influent. These larger TP and TSS concentrations at Bradford could be a reason for why the correlation observed at Bradford was weak and possibly have implications for sample collection and analysis at the Bradford site.

Particulate Phosphorus

A summary of the PP removal at all five woodchip filters are outlined in Table 8.3. The PP removal was significant at two out of the five woodchip filters – the Bradford site and at the Big Bay site. The average overall PP removal at the Bradford and Big Bay site were 91% and 74%, respectively, with average removal rates, at the Bradford site, of.07 to 1.43 g/m^3/day (within the woodchip filter), and, at the Big Bay site, 0.16 g/m^3/day. For the Big Bay woodchip filter, although there was a high removal percentage (74%), for most of the sampling events, the influent PP concentrations were low (< 100 µg/L; Appendix B) which reduced the PP removal opportunities by the woodchips. The PP removal at Wildwood is likely exaggerated due to the fact that there was little PP in the influent to begin with. There seemed to be an overall release of PP at the Keswick woodchip filters of 119% (Table 8.3), however, there were many sampling events where the filter was dry and could not be sampled or where PP values were low (< 100 µg/L; Appendix C) thus giving the woodchip media little opportunity to provide additional filtration of PP. The PP concentrations that were observed at the Avon site provided no input into the PP removal capability of the woodchip filter since the influent water was different from the effluent water, which was determined from the difference in chloride concentrations (conservative tracer).

Based on the observations for the PP trends, an initial PP concentration greater than approximately 100 µg/L is required for the woodchip filters to be potentially beneficial for PP removal.

Soluble Reactive Phosphorus

A summary of the SRP removal at all five woodchip filters are outlined in Table 8.4. The woodchip filter showed minimal ability to remove SRP in this study thus decreasing the overall TP removal. At the Bradford site, there was some SRP leaching within the end of the sedimentation tank, most likely due to the relatively stagnant water at the second compartment of the tank, which can lead to a lack of oxygen mixing into the water, thus releasing the P under anaerobic conditions. There was further SRP leaching from the woodchip component of the treatment system, also likely from the anaerobic conditions within the woodchip filter. At the Big Bay site, the average SRP concentrations in Table 8.4 show that there was little change in the concentrations and the changes that occurred were statistically insignificant. However, during periods of low effluent flow events, the SRP concentrations in the effluent were higher than the concentrations in the stream water going into the filter. The P leaching was likely due to the anaerobic conditions within the filter caused by the increased retention time which reduced oxygen mixing within the system. At the Wildwood site, the SRP was the dominant component in the total P. There was significant SRP leaching from the filter, however, the woodchips were likely not the source of this P due to calculations that determined that it would take approximately 1.9 years, from when the filter began operation, for the P in the woodchips to be depleted. Furthermore, the correlation with dissolved iron and the SRP in the effluent showed that anaerobic conditions (average dissolved oxygen of 1.8 mg/L) was likely the cause of P leaching from the particulate P that had been accumulating within the biofilter since it was installed in 2001.

The SRP concentrations that were observed at the Avon site provided no input into the SRP removal capability of the woodchip filter since the influent water was different from the effluent water, which was determined from the difference in chloride concentrations (conservative tracer).

Nitrate

Although not the main focus of this study, the woodchip filter showed effective nitrate removal capabilities. At the Bradford, Big Bay and Wildwood sites, the nitrate was significantly removed at a total average of up to 80%, 23% and 68%, respectively. The Wildwood filter was installed in 2001, and has since never had the media switched out. This displays the potential treatment longevity of the woodchip media for nitrate removal where the nitrate was still being significantly removed after over 15 years of operation.

8.1 Operationing Conditions and Maintenance

The treatment systems were relatively simple to operate and required little maintenance during the two year duration of the study. The only site (excluding Avon) that required active maintenance was the Bradford site because it had TSS levels (mean of 4846 to 5812 mg/L in the washwater and 86 to 152mg/L in the woodchip effluent) that were over 100 times higher TSS levels at the other sites. At the Bradford site, the maintenance that was required was regular monitoring of the sedimentation tank and emptying it out when it was full (twice during the study). Also, once during the study, the top layer of the woodchip filter (including the sawdust layer) was removed and replaced with new woodchips (September 2015). This showed the effectiveness of the sedimentation tank in reducing the frequency of woodchip replacement. At the Keswick site, the tile drain was mostly dry however, the few samples that were collected from the tile drain water had low nitrate concentrations (mostly <10 mg/L) and TP concentrations (mostly < 100 mg/L) which showed that there may not be a need for a woodchip filter at this site.

At the Avon site, there seemed to be a clogging issue since the stream water going into the filter was not the same water that was coming out of the outlet pipe. A hydraulic fracking attempt in June 2015 did not seem to fix this issue, hence, sampling ceased in November 2015. However, this provided a benchmark for the longevity and maintenance implications of the woodchip media at this site. The woodchip media at this site has not been switched out since its installation in 2006, which means that the woodchip filter required little to no maintenance for approximately nine years until sample termination in 2015. The Big Bay and Wildwood filters required little to no maintenance.

Flow Rates

Patterns between HRT and PP removal can be observed at the Bradford and Big Bay filters. At the Bradford filter, the HRT was 1 day (flow rate of 10.8 m^3/day which is equal to 7.5 L/min) and showed consistent PP removal trends. It is noted that the water from the tank, going into the woodchip filter component of the treatment system, has high PP concentrations (approximately > 1 mg/L; Appendix A) thus increasing the opportunity for the woodchip media to remove PP. At the Big Bay filter, although the PP removal was statistically significant, the removal trend was not consistent throughout the study. This is likely due to the very low HRT of 0.4 days (effluent flow rate of 41 L/min) which varied greatly throughout the study period (± 0.3 days, ± 27 L/min, Table 8.1; Appendix B). The implications for P removal, based off of these observations, is that maximum PP removal can be achieved when the HRT is approximately 1 day, where some significant PP removal can occur at HRTs as small as 0.4 days. The Keswick and Wildwood filters showed little to no PP removal of the woodchips, due to low influent PP concentrations, and the Avon filter did not reflect the removal ability of the woodchip filter due to maintenance and operations issues (as previously discussed) therefore a comparison between flow rates at these three sites were not possible.

In comparison to the relationship between HRTs and PP removal, the relationship between HRTs and nitrate removal can be observed at the Bradford, Big Bay, and Wildwood filters, where there was significant nitrate removal. Hydraulic retention times ranged from 0.4 to 2.1 days (flow rates ranging from 4 to 41 L/min), where the lower end of the range (highest average flow rate) was the Big Bay filter, which also exhibited the lowest overall nitrate removal out of these three sites. The higher end of the HRTs was at the Wildwood filter, where nitrate removal was consistently observed during the study period, including dates where the flow rates fell below 8.3 days (<1 L/min, Appendix D). The implications for nitrate removal, based off of these observations, is that nitrate removal can be maximized at HRTs that range between approximately 1 to 8 days, with significant nitrate removal still occurring at low HRTs, as small as 0.4 days and possibly shorter.

Negative side effects that have been observed in previous denitrifying reactors with higher retention times (low flow rates), such as oxygen depletion, methane and H_2S generation and methyl mercury generation (Christianson, 2011; Christianson *et al.*, 2013), would then be avoided for P filters if HRTs are maintained at about 1 day. This HRT would also allow nitrate removal, as observed at the Bradford filter. Cost and reduced chances of undesirable reactions are features that could make such filters attractive for use in a variety of agricultural operations where turbid waters are generated. Woodchip filters could also have an ability to remove TSS and particulate P from lower turbidity waters and might be useful in other applications, such as in agricultural streams and drainage systems where P export is often dominated by particulate material.

8.2 Recommendations

Based on the results in this study, the following actions are recommended:

- Long-term monitoring and sampling of the influent and treated effluent samples at all sites;
- Decommissioning of the woodchip filter the Keswick site;
- Replacing the woodchips at the Wildwood and Avon woodchip filters; and.
- Augment woodchip media with additional media mixtures to enhance SRP removal.

Decommissioning at the Keswick site

The tile drain water at this site had low TSS concentrations (mean of 20 mg/L), nitrate concentrations that were mostly below the ODWS (2016) limit of 10 mg/L and TP concentrations which mostly fell below the PWQO (1999) total phosphorus limit for maintaining the health of aquatic life of 30 µg/L. This means that there is no need for a woodchip filter at this site and should therefore be decommissioned.

There are different decommissioning strategies that can be applied here including dismantling, entombment or simply take no action. Dismantling would include phases of decommissioning, thus may take some time to fully decommission and is likely the more expensive method. Taking no action is not a good path, for decommissioning, at this site because this would mean that the tile drain flow would continue to be diverted to the filter, because of the cobble berm and, if left alone, the woodchip filter has the potential to produce unwanted contaminants (e.g. H_2S and methyl mercury) if retention times become excessively long with low flow rates. The easiest, relatively safest and cheap option is entombment, which would mean that either the outlet pipe is plugged, thus stopping flow, or removing the cobble berm so that the tile drain water can go directly into the nearby creek instead of being directed to the woodchip filter. Since woodchips are biodegradable, it is expected that the woodchips would degrade over time if entombment is the decommissioning strategy that is selected.

Woodchip replacement

The woodchips require replacement at the Wildwood and Avon sites for two separate reasons. At the Wildwood site, as discussed previously, the solid phase P (sorbed or particulate material) that has accumulated in the filter over 15 years of operation, is now leaching out. Although the filter continues to effectively remove nitrate, there is a need for a change in the woodchip media to also optimize P. Switching the woodchip media should be followed by regular, long-term monitoring and sampling. The media at the Wildwood filter should continue to be switched when significant excess P leaching is observed during filter monitoring and sampling.

At the Avon site, the clogging indicates that the woodchips require replacement after approximately 10 years of being in operation.. This should be followed by regular, long-term monitoring for effective P and nitrate removal, and to monitor for any P leaching phenomena similar to that observed at the Wildwood filter. Significant P leaching would be an indication that the media needs to be replaced if P treatment is the primary goal of the filter.

Additional Media Mixtures

During this study, most of the SRP trends indicated that SRP was either being not treated or was being leached out in excess. The addition of a secondary treatment media could potentially provide better SRP treatment. Studies have shown that other materials such as biochar, steel foundry slag, aluminium, chitosan media, etc can be quite effective in removing SRP from contaminated water (Goodwin *et al*.2015; Baker *et al*., 1998; Auvray *et al*., 2006; Yep *et al*. 2016, respectively). Several of these media types are relatively low cost and could be readily added to a woodchip mixture without fundamentally changing the low cost, ease of operation characteristics of woodchip filters. Future studies should include these additional mixtures to assess the potential for improved SRP treatment.

Long-term monitoring and sampling

Regular long-term monitoring and sampling is recommended at all five sites, subject to the media replenishment suggestions provided. Although some experience with media longevity was gained through the current study (e.g. Avon and Wildwood sites), this information remains incomplete and longevity will likely vary considerably between sites depending on TSS conditions. Continued long term monitoring will help to address this information gap.

In the current study, monitoring was undertaken under all seasonal conditions and at the Big Bay site for example, sampling did attempt to target some of the higher turbidity conditions associated with rainfall and snowmelt events. However, this sampling was undertaken in a piecemeal fashion such that it remains uncertain whether or not results reported herein reflect true average conditions. Future monitoring programs should be more rigorously designed to reflect true average conditions. In particular, more attention should be brought to bear on high flow events, where relatively large fractions of annual TSS loads may be exported over short time periods. Some of the sampling at the Big Bay site did indicate that woodchip filters can perform quite well under more turbid conditions, providing greater percentage TSS removal during those episodes. Thus, there is the potential that a sampling program that more accurately reflects high flow conditions, could demonstrate even better TSS and TP removal than was observed in this study.

Table 8.1 Summary of the concentrations of total suspended solids (TSS) from the influent and effluent at all five sites from May 2014 to March 2016—Bradford, Big Bay, Keswick, Wildwood and Avon sites. The removal percentages with respect to the wash water values, and volumetric removal rates in the woodchip filter are also shown. Flow rates that were considered to calculate the respective normalized mass removal rates are also indicated in the table. Further details for flow rate calculations and samples that have been omitted from the summary table for each site are in their respective chapters.

Site	**Mean Flow Rate (L/min)**	**Mean HRT (days)**	**Average TSS (mg/L)**		**% Removal**	**Normalized Mass removal ($g/m^3/d$)**
			In	**Out**		
Bradford	10.8	1.0	4846 ± 7269 to 5812 ± 2674	86 ± 88 to 152 ± 71	97 to 99	263 to 311[1]
Big Bay	41 ± 27	0.4 ± 0.3	24 ± 38	15 ± 30	38	38.8
Wildwood	4.0 ± 4.5	2.1 ± 2.4	20 ± 39	11 ± 29	44	2.9
Keswick	46 ± 28	-	20 ± 37	42 ± 81	-104	-
Avon	2.9 ± 1.6	-	33 ± 41	26 ± 54	22	1.1

[1] Removal rate within the woodchip filter component of treatment system.

Table 8.2 Summary of the concentrations of total phosphorus (TP) from the influent and effluent at all five sites from May 2014 to March 2016—Bradford, Big Bay, Keswick, Wildwood and Avon sites. The removal percentages with respect to the wash water values, and volumetric removal rates in the woodchip filter are also shown. Flow rates that were considered to calculate the respective normalized mass removal rates are also indicated in the table. Further details for flow rate calculations and samples that have been omitted from the summary table for each site are in their respective chapters.

Site	**Mean Flow Rate (L/min)**	**Mean HRT (days)**	**Average TP (µg/L)**		**% Removal**	**Normalized Mass removal ($g/m^3/d$)**
			In	**Out**		
Bradford	10.8	1.0	$4.9*10^6 \pm 7.3*10^6$ to $5.8*10^6 \pm 2.7*10^6$	$0.09*10^6 \pm 0.09*10^6$ to $0.15*10^6 \pm 0.07*10^6$	65 to 71	0.73 to 1.47[1]
Big Bay	41 ± 27	0.4 ± 0.3	69 ± 113	29 ± 25	58	0.17
Wildwood	4.0 ± 4.5	2.1 ± 2.4	29.2 ± 40	82.5 ± 127	-183	-0.018
Keswick	46 ± 28	-	24 ± 16	23 ± 9	2	-
Avon	2.9 ± 1.6	-	116 ± 128	159 ± 161	-38	-0.01

[1] Removal rate within the woodchip filter component of treatment system.

Table 8.3 Summary of the concentrations of particulate phosphorus (PP) from the influent and effluent at all five sites from May 2014 to March 2016—Bradford, Big Bay, Keswick, Wildwood and Avon sites. The removal percentages with respect to the wash water values, and volumetric removal rates in the woodchip filter are also shown. Flow rates that were considered to calculate the respective normalized mass removal rates are also indicated in the table. Further details for flow rate calculations and samples that have been omitted from the summary table for each site are in their respective chapters.

Site	Mean Flow Rate (L/min)	Mean HRT (days)	Average PP (µg/L)		% Removal	Normalized Mass removal (g/m^3/d)
			In	Out		
Bradford	10.8	1.0	4400 ± 3200 to 7300 ± 4600	400 ± 300 to 630 ± 760	91	1.07 to 1.43[1]
Big Bay	41 ± 27	0.4 ± 0.3	52 ± 111	14 ± 19	74	0.16
Wildwood	4.0 ± 4.5	2.1 ± 2.4	0.4 ± 31.0	-2.77 ± 37.3	809	0.001
Keswick	46 ± 28	-	8 ± 13	17 ± 10	-119	-
Avon	2.9 ± 1.6	-	55 ± 44	62 ± 177	-13	-0.001

[1] Removal rate within the woodchip filter component of treatment system.

Table 8.4 Summary of the concentrations of soluble reactive phosphorus (SRP) from the influent and effluent at all five sites from May 2014 to March 2016—Bradford, Big Bay, Keswick, Wildwood and Avon sites. The removal percentages with respect to the wash water values, and volumetric removal rates in the woodchip filter are also shown. Flow rates that were considered to calculate the respective normalized mass removal rates are also indicated in the table. Further details for flow rate calculations and samples that have been omitted from the summary table for each site are in their respective chapters.

Site	**Mean Flow Rate (L/min)**	**Mean HRT (days)**	**Average SRP (µg/L)**		**% Removal**	**Normalized Mass removal ($g/m^3/d$)**
			In	**Out**		
Bradford	10.8	1.0	1000 ± 380 to 1500 ± 1200	1400 ± 500 to 1900 ± 900	-22 to -42	-0.32 to 0.32[1]
Big Bay	41 ± 27	0.4 ± 0.3	16 ± 15	15± 16	7	0.005
Wildwood	4.0 ± 4.5	2.1 ± 2.4	28.8 ± 43	85.2 ± 143	-196	-0.019
Keswick	46 ± 28	-	17 ± 10	8 ± 4	52	-
Avon	2.9 ± 1.6	-	63 ± 104	108 ± 89	-73	-0.007

[1] Removal rate within the woodchip filter component of treatment system.

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Appendix A
Bradford Biofilter Geochemical and Field Data

Appendix A. 1. Bradford (vegetable wash) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), $NO3^-$–N, $NH4^+$–N, and dissolved organic C (DOC) in the wash water, sedimentation tank effluent, and woodchip filter effluent from 26 May 2014 to 28 Mar. 2016, which includes data during the pilot scale treatment period (Appendix A.1a) and full scale treatment periods

Date	**TSS (g/L)**			**TP (mg/L) (Unfiltered)**			**SRP (mg/L)**			**PP (mg/L)**			**DOC (mg/L)**			**NO_3-N (mg/L)**			**SO_4-S (mg/L)**			**Cl^- (mg/L)**			**NH_4-N (mg/L)**		
	In	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**
Appendix A.1a. Philips vegetable washing pilot-scale biofilter treatment system; Geochemistry May 26-September 2, 2014; In the vegetable washing water (influent) and the treated water (effluent) discharging into a nearby creek.																											
26-May-14	0.41		0.22	1.80		2.66	0.30		0.65	1.50		2.0	30			0.19		0.61	2.1		3.8	27		32	0.2		0.3
2-Jun-14	2.87		0.40	9.82		3.67	0.76		0.67	9.06		3.0	172		173	0.87		1.13	5.5		3.6	32		36	1.5		0.5
4-Jun-14	23.2		0.48			3.12	2.78		0.55			2.6	197		76	0.13		0.15	3.1		2.0	36		32	0.7		
9-Jun-14	2.13		0.38	7.40		3.62	2.56		1.91	4.84		1.7	141		112	0.19		5	0.9		2.4	33		33	4.5		1.9
16-Jun-14	1.86		0.50	8.04		4.02	3.48		2.33	4.56		1.7	280		184	0.23		0.21	3.4		2.4	37		35	4.0		
23-Jun-14	1.86		0.61	6.51		4.51	1.26		1.53	5.25		3.0	156		167	3.46		4.49	41.4		26.9	47		48	0.9		2.8
26-Jun-14	8.07		0.57	10.4		5.50	3.62		2.68	6.78		2.8	174		182	0.09		0.14	7.3		3.1	39		40	1.8		1.9
2-Jul-14	11.0		0.40	25.0		5.98	5.75		3.27	20.0		2.7	217		135	0.07			4.0		1.9	44		41	8.5		3.8
9-Jul-14	7.03		0.27	2.52		3.65	3.42		1.96	-0.9		1.7				4		5	23.9		23.8	22		22	0.6		1.2
15-Jul-14	4.02		0.39	8.49		5.04	2.17		3.18	6.32		1.9							6.0		5.2	35		38	1.4		3.3
21-Jul-14	6.38		0.60	21.5		3.87	1.64		2.16	19.9		1.7	118		137	0.33		0.29	2.6		2.6	42		37	0.8		1.9
Appendix A.1b. Philips vegetable washing, full-scale biofilter treatment system; Geochemistry December 1 2014-September 2, 2015; In the vegetable washing water (influent), the end of the sedimentation tank and the treated water (effluent) discharging into a nearby creek; wood-chip and sawdust fill.																											
1-Dec-14			0.05		1.41	1.10		0.86	0.73		0.54	0.4	98		186	0.56		0.32	4.6		6.9	33		29	0.2		0.5
4-Dec-14	1.43		0.06	4.57		1.18	0.70		0.64	3.87		0.5															
10-Dec-14	5.19		0.42	5.64		0.92	1.16		0.65	4.48		0.3	141		114	0.51		0.1	5.0		6.1	38		35	0.3		0.0
15-Dec-14	2.89		0.06	1.67		0.76	0.83		0.87	0.84		-0.1	27		139										0.1		0.0
23-Dec-14		0.27	0.06		1.82	1.55	0.99		1.25			0.3		70	119	0.27		0.15	7.9		4.6	36		34			0.0
5-Jan-15	5.64	0.32	0.05	6.66	1.52	1.59	0.95		1.56	5.71		0.0	143	92	163	4.59	1.58	0.15	32.3	12.6	37.5	51	39	24	2.1	0.8	0.6
21-Jan-15	5.19	0.43		9.16	2.87		0.65	0.93		8.51	1.39		21	32	110	0.12	0.19	0.13	3.3	6.4	1.4	32	45	38	0.1	0.1	0.1
28-Jan-15	6.81	0.43		10.9	2.53		0.77	0.98		10.1	1.55		32	28	116	0.08	0.16		3.9	6.1		36	38		0.1	0.2	0.2
3-Feb-15	3.44		0.09	4.75		1.42	0.52		1.12	4.23		0.3	25		33	0.14		0.03	3.1		2.0	30		37	0.2		0.6
11-Feb-15		0.39	0.08	3.34	2.41	1.59	0.89	0.85	1.14	2.45	1.44	0.5				0.68	0.24	0.05	3.1	4.6	1.9	34	35	39	0.1	0.4	0.4
3-Mar-15	3.94		0.27	5.57		1.61	2.67		0.32	2.90		1.3	270		222	1.89		0.08	6.7		2.2	39		38	1.8		2.2
9-Mar-15	3.58	0.20	0.03	4.14	3.08	2.78	0.45	1.37	2.38	3.69	1.93	0.4	16	117	232	0.06	0.23	0.07	3.9	8.6	2.1	31	39	39	0.1	0.1	2.6
11-Mar-15	4.56		0.05	3.20		2.40	0.19		1.24	3.01		1.2	31		221	0.04			2.0			27			0.1		2.9
18-Mar-15	5.46	8.75	0.02	5.23	2.64	2.68	1.19	1.22	2.44	4.04	1.45	0.2	58	99	364	0.14	0.15	0.08	4.3	5.1	2.0	38	35	40	0.2	0.2	2.8
30-Mar-15	6.75	0.03	0.02	12.6	4.68	2.08	1.32	1.90	1.78	11.3	3.00	0.3	94	154	165	0.28	0.07	0.04	6.1	7.1	1.8	43	45	42	0.1	0.4	0.6
7-Apr-15	6.51	0.91	0.12	20.7	7.05	2.84	5.78	3.23	2.09	15.2	3.82	0.8	386	227	140	0.18	0.17	0.05	4.2	5.9	2.6	35	46	39	0.2		2.2
13-Apr-15	5.81		0.09	6.75	3.76	2.60	1.66	2.25	2.65	5.09	1.11	0.0	91	126	175											0.5	
21-Apr-15	9.42	0.07	0.05	14.3	7.62	3.43	2.63	3.84	1.84	11.7	3.55	1.6	215	229	150	0.44	0.47	0.03	7.0	7.5	2.4	63	53	38	0.6	0.9	2.5
29-Apr-15	12.9	0.39	0.03	4.60	5.72	5.47	0.87	2.60	3.41	3.73	2.86	2.1	58	259	200	0.07	0.31	0.03	2.4	9.3	1.7	29	45	41	0.0	0.4	5.9
6-May-15	11.3	0.66	0.09	17.6	5.08	3.54	3.23	2.78	2.85	14.4	1.91	0.7	229	223	192	0.15	0.26	0.00	2.7	6.0	2.5	22	45	46	0.3	0.6	2.5
12-May-15	3.25	0.65	0.09	4.32	4.97	3.50	1.38	4.05	3.07	2.94	1.08	0.4	141	247	195	0.44	0.89	0.19	5.8	8.0	4.5	24	60	49			1.3
20-May-15	4.87	0.32	0.03	15.6	5.55	5.81	0.99	2.48	2.68	14.6	3.19	3.1	163	181	222	0.92	0.26	0.78	5.7	6.8	6.2	38	46	40	0.3	0.1	1.1
27-May-15	8.81	0.53	0.12	18.2	4.73	4.17	2.53	2.83	3.25	15.7	2.64	0.9	253	219	220	0.72	0.87	0.12	4.6	9.1	2.0	36	40	33	0.5		

Appendix A. 1. Bradford (vegetable wash) site: Detailed concentrations oftotalsuspendedsolids(TSS),totalP(TP),solublereactiveP(SRP),particulateP (PP),NO3−–N, NH4+–N, and dissolved organic C (DOC) in the wash water, sedimentation tank effluent, and woodchip filter effluent from 26 May 2014 to 28 Mar. 2016, which includes data during the pilot scale treatment period (Appendix A.1a) and full scale treatment periods (Appendix A.1b

Date	**TSS (g/L)**			**TP (mg/L) (Unfiltered)**			**SRP (mg/L)**			**PP (mg/L)**			**DOC (mg/L)**			**NO_3-N (mg/L)**			**SO_4-S (mg/L)**			**Cl^- (mg/L)**			**NH_4-N (mg/L)**		
Appendix A.1c. Philips vegetable washing, full-scale biofilter treatment system; Geochemistry September 2, 2015-March 28, 2016; In the vegetable washing water (influent), the end of the sedimentation tank and the treated water (effluent) discharging into a nearby creek; wood-chip only fill.																														
	In	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**	**In**	**Mid**	**Out**
3-Jun-15	5.47	0.66	0.10	7.31	4.42	2.97	1.37	1.73	2.70	5.94	2.40	0.3	69	237	180	0.22	1.01	0.11	5.2	7.7	2.4	40	38	38	0.4		2.8
10-Jun-15	5.15	0.36	0.05	11.9	3.82	2.28	2.21	1.65	2.42	9.69	2.14	-0.1	30	62	88	0.19	0.70	0.04	4.3	5.4	1.1	52	38	35	0.3	0.5	4.6
15-Jun-15	5.32	0.37	0.03	12.8	4.53	2.99	2.10	2.92	3.06	10.7	1.60	-0.1	103	80	110	1.40	0.47	0.04	6.1	4.4	0.8	39	39	20	0.6	1.2	5.9
2-Sep-15	0.85	0.17	0.04	2.75	8.76	6.90	1.47	5.74	6.37	1.27	3.02	0.5	32	40	45	0.84	0.48	0.08	3.3	2.7	2.3	35	35	22	1.9	13.0	23.8
9-Sep-15	0.5	0.34	0.15	1.91	5.40	5.69	0.95	2.98	3.07	0.97	2.43	2.6	29	96	186	0.20	0.47	0.00	6.0	2.8	2.7	32	35	33	0.8	11.0	12.7
16-Sep-15	2.05	0.82	0.12	8.35	11.0	9.03	1.47	5.37	5.98	6.88	5.56	3.0	167	135	286	1.95	0.51	0.23	5.5	2.8	1.8	42	38	31	1.3	13.3	9.4
30-Sep-15	1.14	0.29	0.13	3.37	7.83	6.43	1.32	3.25	4.13	2.04	4.58	2.3	98	177	202	1.26	0.39	0.12	11.7	6.93	2.14	141	163	129	0.3	8.8	10.4
7-Oct-15	0.34	0.23	0.12	2.70	5.40	5.87	1.48	1.78	5.06	1.22	3.61	0.8	106	113	143	0.79	0.17	0.08	3.6	2.5	2.7	49	44	45	1.6	5.4	6.5
14-Oct-15	1.15	0.19	0.05	3.39	4.03	4.50	0.85	2.58	3.08	2.68	1.45	1.4	137	81	96	0.74	0.23	0.09	4.6	3.5	1.7	61	35	35	0.2	3.4	5.1
4-Nov-15	0.39	0.38	0.10	1.01	3.11	2.28	0.12	1.31	1.26	0.89	1.80	1.0	52	70	65	0.44	0.26	0.21	2.3	2.5	0.9	25	31	19	0.0		0.0
11-Nov-15	8.60		0.11	12.7	3.00	2.05	1.46	1.47	1.69	11.2	1.53	0.4	165	66	61	0.70	0.25	0.00	5.9	3.2	2.3	42	32	31	0.1	0.9	1.6
25-Nov-15	2.19		0.32	4.42	1.94	1.41	0.69	0.97	1.17	3.72	0.97	0.2	128	99	86	1.20	0.52	0.15	3.5	2.9	2.1	34	34	34	0.2	0.3	0.8
9-Dec-15	2.06	0.39	0.14	2.48	1.80	1.52	0.86	0.88	0.99	1.63	0.91	0.5	53	135	120	0.03	0.61	0.21	1.7	4.7	3.1	19	36	36	0.1	0.3	0.6
16-Dec-15	26.3	0.50	0.23	10.2	1.81	1.62	0.82	0.69	0.86	9.33	1.12	0.8	106	119	122	0.59	0.93	0.26	3.1	4.4	1.0	34	36	35	0.3	0.2	0.4
06-Jan-16	1.37	0.63	0.14	6.01	3.10	1.68	1.38	1.22	1.66	4.63	1.88	0.0	264	146	150	1.13	0.23	0.15	5.7	4.6	2.4	57	57	56	0.6	0.7	1.6
13-Jan-16	0.72	0.29	0.10	2.92	2.69	1.74	1.26	1.16	1.18	1.65	1.53	0.6	219	161	141	1.22	0.82	0.10	4.8	3.9	0.9	36	47	43	0.5	0.5	0.8
26-Jan-16	1.45	0.46	0.15	2.90	2.99	1.81	0.87	0.97	1.52	2.02	2.02	0.3	211	200	167	0.47	0.26	0.18	5.3	5.5	3.3	46	44	38	0.4	0.5	1.4
04-Feb-16	3.15	0.48	0.22	4.67	3.47	2.81	0.20	0.82	1.88	4.47	2.65	0.9	204	245	187	0.55	0.17	0.24	5.6	11.2	4.1	56	59	41			
18-Feb-16	2.78	0.36	0.13	5.01	3.06	2.42	0.79	1.33	2.13	4.23	1.73	0.3	115	209	190	0.19	0.08	0.11	3.4	7.6	2.2	38	44	42	0.2	0.2	5.3
22-Feb-16	1.07	0.22	0.05	4.91	2.87	2.58	1.81	1.50	2.22	3.10	1.37	0.4	296	212	182	1.36	0.04	0.0	6.0	6.4	2.3	52	43	40	0.3		4.6
10-Mar-16	7.91	0.45	0.13	2.31	2.38	1.44	0.89	0.57	0.79	1.42	1.81	0.65	205	115	92	0.36	0.38	0.28	6.0	7.1	2.4	45	35	30	0.4	0.0	1.2
28-Mar-16	0.51	0.35	0.12	1.22	2.19	0.97	0.53	1.17	0.95	0.69	1.02	0.02	68	151	91	0.19	0.08	0.11	3.4	7.6	2.2	38	44	42			

Appendix A.2 Bradford (vegetable wash) site: Field notes of operating conditions, vegetable being washed, sludge depth the beginning of the sedimentation tank (In) and at the end of in the sedimentation tank, woodchip effluent flow, and dissolved oxygen (DO), electrical conductivity (EC) and temperature (in C) in the wash water, sedimentation tank effluent, and woodchip filter effluent from 26 May 2014 to 28 Mar. 2016, which includes data during the pilot scale treatment period (Appendix A.2a) and full scale treatment periods (Appendix A.2b and Appendix A.2c).

Date	Operation	Vegetable	Sludge Depth (mbs)		Flow (L/min)	DO (mg/L)			EC (µs)			Temperature (^{o}C)		
			In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips
Appendix A.2a. Bradford vegetable washing pilot-scale biofilter treatment system; Field notes May 26-September 2, 2014; In the vegetable washing water (influent) and the treated water (effluent) discharging into a nearby creek.														
26-May-14	Normal	Carrots							399		511	12.3		15.7
02-Jun-14	Normal				12				545		562	10.7		12.1
04-Jun-14	Normal	Carrots			24				542		547	1.5		12.5
09-Jun-14	Normal				30				593		575	11.2		14.1
16-Jun-14	Normal				24				664		646	10.8		13.9
23-Jun-14	Normal				30				571		628	10.7		12.6
26-Jun-14	Normal				22				636		733	10.4		14.9
02-Jul-14	Normal				27				688		702	13		15.4
09-Jul-14	Normal				15				627		667	12.7		16.2
15-Jul-14	Normal				32				551		693	12.1		14.8
21-Jul-14	Normal		0.2	0.26	10				515		644	16.6		18.7
02-Sep-14	Not Washing													
Appendix A.2b. Philips vegetable washing, full-scale biofilter treatment system; Field notes December 1 2014-September 2, 2015; In the vegetable washing water (influent), the end of the sedimentation tank and the treated water (effluent) discharging into a nearby creek; wood-chip and sawdust fill.														
01-Dec-14	Normal				15	3.4		0.8	446		527	6.1		3.3
04-Dec-14	Normal		0.88	0.89		5.8		0.4						
10-Dec-14	Normal		0.80	0.89	17	5.8		0.4	563		629	6.8		6.8
15-Dec-14	Normal			0.9	30				530			5.5		5.4
23-Dec-14	Outlet pipe frozen			0.06	8				534		734	5.8		5.7
05-Jan-15				0.06					544	550	750	4.6	4.2	5.2
21-Jan-15	Outlet pipe frozen		0.4	0		7.9		1.3		596		6.9	5.5	
28-Jan-15	Outlet pipe frozen		0.7	0.9		8		2	471	517		5.9	5	
03-Feb-15	Outlet pipe frozen													
11-Feb-15	Outlet pipe frozen, snow on filter		0.6	0.9		9.3	4.7	0.4	450	509	586	6.1	5.6	5.4
03-Mar-15	Outlet pipe frozen								530		920	4.4		3.8
09-Mar-15	Outlet pipe frozen		0.01	0.86		9.6	1.3	0.7	436	530	706	6.9	4.7	3.4
11-Mar-15	Normal								423		860	7.4		2
18-Mar-15	Normal			0.87			3.8	0.8	416	470	738		5.9	4.4
30-Mar-15	Normal	Beets												
07-Apr-15	Normal	Beets												

Appendix A.2 Bradford (vegetable wash) site: Field notes of operating conditions, vegetable being washed, sludge depth the beginning of the sedimentation tank (In) and at the end of in the sedimentation tank, woodchip effluent flow, and dissolved oxygen (DO), electrical conductivity (EC) and temperature (in C) in the wash water, sedimentation tank effluent, and woodchip filter effluent from 26 May 2014 to 28 Mar. 2016, which includes data during the pilot scale treatment period (Appendix A.2a) and full scale treatment periods (Appendix A.2b and Appendix A.2c).

Date	**Operation**	**Vegetable**	**Sludge Depth (m)**		**Flow (L/min)**	**DO (mg/L)**			**EC (µs)**			**Temperature (°C)**		
			In	**Out-Tank**	**Out-Chips**	**In**	**Out-Tank**	**Out-Chips**	**In**	**Out-Tank**	**Out-Chips**	**In**	**Out-Tank**	**Out-Chips**
13-Apr-15	Normal	Beets		0.7		9.3	5.2	0.2	430	566	660	8.3	7.9	7
21-Apr-15	Normal	Carrots												
29-Apr-15	Normal	Carrots	0.35	0.86										
06-May-15	Normal	Carrots	0.25	0.8										
12-May-15	Biofilters being pumped out	Carrots		0.65										
20-May-15	Woodchips clogged	Carrots	0.65	0.9	2	4.2	0.2	0.4	597	708	913	8.9	10.1	11.5
27-May-15	Normal					3.8	0.3	0.1	465	636	801	12.1	11.9	12.4
03-Jun-15	Water leaking from end of woodchips	Beets	0.93	0.95		5.6	1.7	0.2	532	612	757	11.8	10.6	11.3
10-Jun-15	Normal	Beets			14	8	0.4	0.1	571	593	726	12.6	11.3	12.4
15-Jun-15	Normal	Carrots	0.1	0.87	13	7.2	1.1	0.1	664	682	667	10.7	12.6	13.6
02-Sep-15	Normal	Carrots	0.35	0.88	3	3	1.2	0.1	1034	1192	1144	19.4	19.8	19.7
Appendix A.2c. Philips vegetable washing, full-scale biofilter treatment system; Field notes September 2, 2015-March 28, 2016; In the vegetable washing water (influent), the end of the sedimentation tank and the treated water (effluent) discharging into a nearby creek; wood-chip only fill.														
09-Sep-15	Normal- top part of woodchips just switched out, new sump pump tank at the end of the filter	Carrots	0.33	0.87	9	0.16	0.91	0.61	771	1002	558	20.9	21.3	19.4
16-Sep-15	Normal; soil v. dry at this time of year so less soil bound to the carrots	Carrots	0.35	0.88	14.2	0.17	1.15	0.61	808	1192	1119	18.4	16.9	18.3
30-Sep-15	Normal	Carrots	0.32	0.88	9.09	3.61	0.25	0.54	855	1146	1095	14.1	16	16.4
07-Oct-15	Normal	Carrots	0.32	0.87	2.3	0.22	0.39	0.55	770	916	974	14.6	12.7	13.5
14-Oct-15	Normal	Carrots	0.32	0.87	8	0.21	0.41	0.52	625	716	778	14.1	12.4	13
4-Nov-15	Outlet pipe submerged	Carrots	0.35	0.9	2.86	0.24	3.47	0.59	544	594	619	11.8	10.9	10.2
11-Nov-15	Outlet pipe submerged	Carrots	0.35	0.9		7.75	4.37	1.57	556	579	640	9.4	9.7	9.7
25-Nov-15	Outlet pipe submerged	Carrots	0.29	0.9		9.3	5.72	0.74	543	597	642	8.8	6.6	6.9
09-Dec-15	Outlet pipe submerged; feeder pipes on top of woodchips was clogged	Carrots	0.28	0.9		6.77	4.3	0.48	509	565	662	7.6	6.1	6.6
16-Dec-15	Outlet pipe submerged; feeder pipes on top of woodchips working fine	Carrots	0.28	0.89		8.83	3.71	0.38	534	568	638	8	8.1	7.9
28-Dec-15	Outlet pipe frozen and submerged; not washing due to mechanical issues													
6-Jan-16	Outlet pipe submerged and there is snow everywhere; feeder pipes working fine	Carrots				9.73	4.59	0.52	622	688	755	5.3	4.6	4.9

Appendix A.2 Bradford (vegetable wash) site: Field notes of operating conditions, vegetable being washed, sludge depth the beginning of the sedimentation tank (In) and at the end of in the sedimentation tank, woodchip effluent flow, and dissolved oxygen (DO), electrical conductivity (EC) and temperature (in C) in the wash water, sedimentation tank effluent, and woodchip filter effluent from 26 May 2014 to 28 Mar. 2016, which includes data during the pilot scale treatment period (Appendix A.2a) and full scale treatment periods (Appendix A.2b and Appendix A.2c).

Date	Operation	Vegetable	Sludge Depth (m)		Flow (L/min)	DO (mg/L)			EC (µs)			Temperature (^{O}C)		
			In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips	In	Out-Tank	Out-Chips
13-Jan-16	Prefilter installed on the 11th thus less flow+sediment coming from IN pipe; Outlet pipe submerged and there is snow everywhere; feeder pipes working fine	Carrots	0.15	0.88		9.55	3.3	0.64	551	679	663	6.2	5.4	4.8
26-Jan-16	Outlet pipe submerged and there is snow everywhere; one feeder pipe clogged with ice	Carrots	0.38	0.88		9.62	5.71	0.58	516	592	681	7.5	7.1	4.5
4-Feb-16	Sunny, cold, feeder pipes are flowing well	Carrots	0.93	0.95		9.82	1.02	0.45	535	736	763	6	5.5	4.7
18-Feb-16	Sunny, very cold, feeder pipes are flowing well	Carrots	0.9	0.93		10.1	0.78	0.53	685	746	816	5.7	4	3.9
22-Feb-16	Sunny, cold, two out of four feeder pipes not flowing	Carrots	0.87	0.9		9.48	0.54	0.57	594	731	794	6.2	3.8	3.7
10-Mar-16	Rain, warm, feeder pipes working	Carrots	0.75	0.88		9.69	0.47	0.29	482	571	570	8.4	6.5	4.8
28-Mar-16	Heavy rain, breezy, feeder pipes flowing well	Radish and beets	0.68	0.87				<1	409	596	536	4.7	5.5	4.9

Appendix B
Big Bay Biofilter Geochemical and Field Data

Appendix B. 1. Big Bay (stream bed) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), $NO3^{-}$–N, $NH4^{+}$–N, and dissolved organic C (DOC) from December 15, 2014 to March 28, 2016.

Date	TSS (mg/L)		TP (µg/L) (Unfiltered)		SRP (µg/L)		PP (µg/L)		DOC (mg/L)		NO3-N (mg/L)		SO_4 (mg/L)		Cl^- (mg/L)		NH_4^+ (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
15-Dec-14	10.0	1.0	8	11	6	2	2	9	7.6	12.4	3.2		7		178		0.0	0.0
23-Dec-14	94.0	78.0	17	13	11	7	6	6	1.0	1.8	4.0	3.7	12	12	65	69	0.0	0.0
05-Jan-15	135.0	112.0	8	14	15	5	-7	9	3.1	1.7	1.9	2.1	39	15	60	100	0.1	0.0
21-Jan-15	19.0	2.0	6	11	12	9	-6	2	5.5	11.2								
28-Jan-15				39	10	8		31	7.5	7.6	2.4	1.5	7	7	84	113	0.0	0.0
11-Mar-15	6.0	22.0	22	12	5	7	17	5	5.0	6.3	1.7	0.6	55	23	2876	1254	0.0	0.0
18-Mar-15	37.0	10.0	186	89	71	29	115	60	10.4	11.6								
30-Mar-15	5.0	1.0	41	18	18	7	23	11	2.5	2.5	1.8	1.1	8	5	93	70	0.0	0.0
07-Apr-15	4.0	1.0	18	25	12	14	6	11	1.6	6.4	1.1	8.4	5	6	66	88		0.8
13-Apr-15	0.0	0.0	14	15	5	14	9	1	1.2	1.2	4.3	4.1	12	12	69	79	0.0	0.0
21-Apr-15	2.0	1.0	13	10	13	6	0	4	1.1	1.3	5.9	3.5	12	9	61	45	0.0	0.0
29-Apr-15	3.0	0.0	270	26	11	8	259	18	1.4	1.3	7.4	4.5	17	13	118	90	-0.1	-0.1
06-May-15	504.0	0.0	600	14	15	10	585	4	1.2	1.5	5.3	3.4	14	14	119	126	0.0	0.1
13-May-15	0.0	9.0	63	34	8	24	55	10	1.1	3.4	3.2	1.4	11	31	104	374	0.0	0.1
20-May-15	30.0	0.0	125	27	5	21	120	6	1.5	2.6	2.7	2.5	7	8	66	120	0.0	0.0
27-May-15	21.0	3.0	78	44	7	51	78	-7	1.0	4.2	4.6	1.8	12	9	82	86	0.0	0.1
03-Jun-15	39.0	2.0	47	25	7	46	40	-21	1.4	7.3	4.6	1.1	15	7	71	75	0.0	0.2
10-Jun-15	7.0	2.0	25	38	7	3	18	35	1.5	1.9	4.5	1.9	11	10	53	56	0.1	0.2
15-Jun-15	165	241	31	19	12	11	19	8	1.6	1.6	10.1	10.7	19	20	29	38	0.0	0.0
25-Jun-15	3.0	1.0	69	35	7	5	62	30	1.3	1.5	7.7	6.5	22	22	41	40		
30-Jun-15	6.5	3.6	72	50	41	3	31	47	7.6	12.4	11.0	10.1	27	27	26	28	0.0	0.0
15-Jul-15	4.2	90.9	8	35	4	10	5	25	1.0	1.8	1.4	3.2	9	22	22	96		
29-Jul-15	22.2	11.4	28	50	6	31	22	18	2.6	3.0								
11-Aug-15	28.7	11.4	99	162	8	63	91	99	5.3	3.3	0.0	0.0	33	61	57	37	0.3	0.8
02-Sep-15	0.0	64.6	12	76	3	46	9	30	2.7	3.7	0.0	0.1	91	71	25	39	0.0	0.6
09-Sep-15	89.7	45.2	181	112	34	61	147	50	5.9	5.8	4.8	3.8	38	43	28	31	0.0	0.2
16-Sep-15	10.0	8.9	13	14	19	16	-7	-2	2.0	2.0	2.7	3.2	16	18	41	44	-0.1	0.0
27-Oct-15	44.3	16.9	32	51	18	10	14	41			1.7	1.1	27	31	124	114	0.1	0.0
04-Nov-15	2.2	3.6	18	15	20	11	-2	5	1.7	2.1	1.9	1.0	16	18	195	196	0.0	0.0
11-Nov-15	7.6	3.2	22	31	19	10	3	21	2.2	2.5	2.0	1.4	21	22	172	199	0.0	0.0
25-Nov-15	1.5	1.8	24	14	12	8	13	6	1.2	1.7	3.1	2.8	17	17	96	104	0.0	0.0
09-Dec-15	0.8	1.1	5	2	6	3	-1	0	1.4	1.4	3.4	2.6	15	14	106	102	0.0	0.0
16-Dec-15	0.5	0.9	12	8	10	6	-2	0	1.1	1.3	3.5	3.0	16	15	68	72	0.0	0.0
28-Dec-15	2.2	0.8	6	7	8	6	-1	2	1.2	1.3	3.8	3.5	12	11	56	62	0.0	0.0

Appendix B. 1. Big Bay (stream bed) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO3^{-}–N, NH4^{+}–N, and dissolved organic C (DOC) from December 15, 2014 to March 28, 2016.

Date	TSS (mg/L)		TP (µg/L) (Unfiltered)		SRP (µg/L)		PP (µg/L)		DOC (mg/L)		NO3-N (mg/L)		SO$_4$ (mg/L)		Cl$^-$ (mg/L)		NH$_4^+$ (mg/L)	
	In	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
06-Jan-16	1.7	2.2	11	5	5	3	6	2	1.3	1.5	3.8	3.5	16	16	116	126	0.0	0.0
13-Jan-16	1.0	2.3	59	46	44	32	14	14	2.5	2.6	3.9	3.7	15	10	40	46		
26-Jan-16	0.7	0.4	11	10	8	6	3	4	1.2	1.3	4.4	4.1	13	13	73	78		
01-Feb-16	6.8	6.8	48	35	38	49	11	-14	2.6	3.7	3.9	3.8	15	14			0.1	0.2
04-Feb-16	2.1	4.8	60	43	38	18	22	25	2.7	3.0	3.7	3.5	15	15	34	43		
18-Feb-16	2.9	0.8			6	2			1.1	1.6	3.8	3.4	13	14	122	129	0.0	0.0
22-Feb-16	0.0	0.0	12	11	6	5	3	7	1.1	1.6	4.7	4.5	15	15	45	51	0.0	0.1
28-Feb-16	130	111	11	10	1	1	9	8	1.5	1.6	4.1	3.8	14	14	93	104	0.0	0.0
10-Mar-16	9.6	5.1	66	40	36	17	30	23	2.5	2.8	3.5	3.4	13	13	30	36	0.0	0.0
28-Mar-16	79.3	41.3	115	88	45	30	70	57	5.6	5.4	1.9	1.8	9	8	27	35		

Appendix B. 2 Big Bay (stream bed): Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), electrical conductivity (EC) and CHEMET iron concentrations of the Barrie woodchip filter from Dec. 2014 to Mar. 2016.

Date	Operating Conditions	Temperature (°C)		Influent Flow (L/min)	Effluent Flow (L/min)	DO (mg/L)		EC (µs/cm)	
		In	Out			In	Out	In	Out
15-Dec-14		5.3	5.3		30			1069	1085
23-Dec-14		4.8	4.7		55			794	812
05-Jan-15		2.8	3.2	59.34	40			850	876
21-Jan-15	Iced over	1.8	3		18	14.6	5.2		1106
28-Jan-15	Iced over	1.2	2.6		14	12.1	4.0	8.75	828
11-Mar-15		0.7	0.7		12			8500	5400
18-Mar-15		1.4	1.1		40	11.3	8.8	230	313
30-Mar-15		2.6	3.6		35	11.7	6.6	602	597
07-Apr-15									
13-Apr-15					20				
21-Apr-15		3.6	5.2		30	7.9	7.5	920	585
29-Apr-15		7.4	6.5		38.57	13.0	6.5	592	591
06-May-15		11.4	7.9		23.33	14.2	4.9	696	773
13-May-15		10.3	9.7		13.64	17.4	4.3	957	979
20-May-15	Sunny, warm, breezy, white bacteria near outlet, sulfur smell in effluent	14.1	8.7	13.85	6	16.3	4.7	393	961
27-May-15		16.4	14.1		8.06	6.8	2.5	833	880
03-Jun-15	Sunny, warm (~22C), presence of algae in influent waters, sulfer smell in effluent	15.2	12	41.32	25.5	14.4	1.5		805
10-Jun-15	Cloudy, warm (~17C), sampled after rain event	15	13.3		13.9	10.1	1.8	709	755
15-Jun-15	Cloudy, little bit of rain	14.8	15.9	548.31	2.33	7.9	4.2	682	701
25-Jun-15	Cloudy, warm(25C)	16.6	16.1	306.12	20.2	8.7	3.5	663	676
30-Jun-15	Raining, warm	17.6	17.7	3944.63		7.0	2.8	573	580
15-Jul-15		5.3	5.3						
29-Jul-15	Sunny, hot (30C), mild sulfur smell in outlet	20	17.7		1	13.0	2.3	667	771
10-Aug-15		17.9	17.1		0	3.2	0.2	650	590
02-Sep-15	Sunny, hot(30C), bugs inside outlet pipe (snails?)	19.4	20.4		0	10.9	0.1	613	682
09-Sep-15	Cloudy, warm, rained the day before	19.4	19.5		24	7.2	2.1	558	558
16-Sep-15	Sunny, hot	20.9	17.3		0.18	6.6	5.8	812	865
27-Oct-15	Turbid	9.9	10.9	98.9	40			872	835
4-Nov-15									
11-Nov-15		11.1	10.7		25.6	9.4	3.7	1199	1081
25-Nov-15	Sunny, no snow	8.9	8.9	223.46	60	10.3	6.3	865	897

Appendix B. 2 Big Bay (stream bed): Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), electrical conductivity (EC) and CHEMET iron concentrations of the Barrie woodchip filter from Dec. 2014 to Mar. 2016.

Date	Operating Conditions	Temperature (°C)		Influent Flow (L/min)	Effluent Flow (L/min)	DO (mg/L)		EC (µs/cm)	
09-Dec-15	Sunny, no snow	8.1	7.6	76.57	21.1	13.3	6.3	910	946
16-Dec-15	Turbid, cloudy, rained two days earlier, no sulfur smell	8.2	7.5	276.92	82	10.4	7.7	784	817
28-Dec-15	Turbid, sunny, below freezing temperature, no sulfur smell			494.5	80	9.0	7.0		
06-Jan-16	Turbid, sunny, below freezing temperature, no sulfur smell, snow surrounding area	5	5.7	53.95	21.74	12.3	6.6	996	499
13-Jan-16	Turbid, outlet pipe submerged, windy, below freezing, no sulfur smell, snow on surrounding area but no snow/ice on filter, flow rate estimated	3.9	4.2	666.74	80	12.3	8.5	665	663
26-Jan-16	Turbid, windy, below freezing, no sulfur smell, snow on surrounding area but no snow/ice on filter	4.6	5.6	120.76	48.33	12.6	8.3	804	814
01-Feb-16	Turbid, flooding, flume is flooded-unable to measure in flow, rained the day before	4.4	4		90	7.0	7.0	580	613
04-Feb-16	Sunny, below freezing, turbid, flooding, rained the day before, outlet pipe submerged, no sulfur smell	3.4	3.3		90	10.7	7.9	552	588
18-Feb-16	Sunny, below freezing, brown type of algae or vegetation over biofilter but not present around tile drain pipe	3.1	2.7	47.95	17.39	17.5	6.0	949	950
22-Feb-16	Sunny, cold, less snow surrounding biofilter due to warming from previous days, outlet pipe submerged	3.9	4.8	641.7	80	14.6	9.7	673	633
28-Feb-16	Sunny, ~10 degrees weather, Outlet pipe submerged, snow on corn field			8.28	60				
10-Mar-16	Raining, warm (~10), outlet submerged	3.8	3.4	659.33	Submerged	9.9	6.7	510	537
28-Mar-16	Heavy rain, breezy, flume and outlet pipe completely submerged	4	4					372	422

Appendix C
Keswick Biofilter Geochemical and Field Data

Appendix C. 1. Keswick (tile drain) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO3^{-}–N, NH4^{+}–N, and dissolved organic C (DOC) from March 28, 2014 to March 10, 2016.

Date	**TSS (mg/L)**		**TP (µg /L) (Unfiltered)**		**SRP (µg/L)**		**PP (ug/L)**		**DOC (mg/L)**		**NO_3-N (mg/L)**		**SO_4 (mg/L)**		**Cl^- (mg/L)**		**NH_4^+ (mg/L)**	
	In	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
28-Mar-14	15		106	106	70	97	36	9										
14-Apr-14	0		159		34	53	125											
26-May-14	4	69		159	15	151		8	3	80	3.0	0.2	24	10	305	222	0.0	0.1
11-Nov-14	0	7	20						22	78	2.4	0.8	51	24	462	241		
15-Nov-14	2		20		39	18	-19		21	29	2.3	1.0	49	50	516	523		
17-Nov-14	0	3	20		18	11	2		20	22	2.1	1.3	48	13	508	503		
27-Nov-14	2	1	22	20	17	9	5	11	3	8	2.9	2.3	53	48	313	265		0.0
1-Dec-14	6		27	200	22	7	5	200	4		2.5	0.2	50	8	BLS	43	0.2	0.2
4-Dec-14	0	1	23	20	8	13	15	7	15	19	2.0	1.4	48	51	BLS	BLS	0.0	0.0
10-Dec-14	99	93	14	26	9	5	5	21	12	14	2.9	2.7	44	41	384	385	0.0	0.0
23-Dec-14	98	88	7	20	9	6	0	14	2	3	3.0	2.8	60	60	264	262		
5-Jan-15			12	23	8	200	4	-177	10	5	2.5	2.8	59	98	237	216		
18-Mar-15	2		89	22	55		34		20		2.1		12		155			
1-Apr-15	0	15	32	19	17	27	15	0	4	5	2.3	2.8	20	24	308	0		0.1
13-Apr-15	1	0	15	27	19	9	0	18	4	4	2.4	2.4	26	30	156	0		
21-Apr-15	0	3	21		14	11	7		4	4	2.2	1.5	39	30	176	113		
29-Apr-15	3	0	19	23	14	6	5	17	3	3	1.3	0.9	43	50	207	257	-0.1	-0.1
6-May-15	5		25	27	21		4		4		0.6		16		153		0.0	
13-May-15	1		14		23		0		4		1.2		24		253		0.0	
13-Jan-16	29	10	30	20	15	7	15	13	3	4	2.2	1.6	56	49	293	266		
26-Jan-16	502		63		17		46		3		2.3		45		376			
4-Feb-16	3	276	49	30	31	6	18	24	6	6	3.9	3.6	39	38	269	264	0.0	0.0
18-Feb-16			16		6		10		3		2		43		363		0.3	
22-Feb-16	0	1	23	12	12	4	11	8	4	4	6	5	39	38	333	326	0.0	0.0
28-Feb-16	48	25	20	11	6	2	14	9	4	5	5	5	32	31	319	322	0.0	0.0
10-Mar-16	8	4	70	45	30	6	40	39	5	6	3	2	31	27	213	193	0.0	0.0

Appendix C. 2 Keswick (tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from March 2014 to March 2016.

Date	Operating Conditions	Temperature (°C)		Effluent Flow (L/min)	DO (mg/L)		EC (µs/cm)	
		In	Out		In	Out	In	Out
28-Mar-14	Normal							
14-Apr-14	Normal							
26-May-14	Normal	10.7	16.8				680	782
11-Nov-14	Normal	10	9.1	30			1987	1563
15-Nov-14	Normal	8	7.4	8			2300	2250
17-Nov-14	Normal	8.1	7.1	30			2240	2250
27-Nov-14	Normal	6.8	6.4	70			1524	1508
01-Dec-14	Normal	6.8					1168	
04-Dec-14	Normal	5.7	4.4	40			1832	1794
10-Dec-14	Normal	6.8	5.1	24.8			1180	1211
23-Dec-14	Normal	4.1	4.8	60			1471	1470
05-Jan-15	Normal	3.6	2.9	60			1379	1375
18-Mar-15	Normal	1.4			9.7			
01-Apr-15	Normal	3	1.3	1.08	9.2	7.8	1280	1265
13-Apr-15	Normal	4.7	7.9	20	8.2	4.5	1165	1015
21-Apr-15	Normal	3.6	4.6		7.9	4.2	920	850
29-Apr-15	Normal	4.4	7.6	20.08	10.2	2	783	820
06-May-15	Outlet Dry	7.4			10.9		722	
13-May-15	Outlet Dry	9.3			9.7		2080	
09-Dec-15	No flow							
16-Dec-15	No flow							
28-Dec-15	No flow, v. Small, frozen puddle near tile drain							
14-Jan-16	Ice and snow over tile and outlet pipe(but removed), below freezing, windy, ice over biofilter, outlet pipe submerged	4.6	3.9	80	7.9	6.26	1550	1503

Appendix C. 2 Keswick (tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from March 2014 to March 2016.

Date	Operating Conditions	Temperature (°C)		Effluent Flow (L/min)	DO (mg/L)		EC (µs/cm)	
		In	Out		In	Out	In	Out
26-Jan-16	Ice and snow over tile and outlet pipe(but removed), below freezing, windy, ice over biofilter, no outlet flow	4.1			12.4		1770	
04-Feb-16	Sunny, cold, outlet pipe submerged	2.4	2.5	60	10.77	6.67	1335	1306
18-Feb-16	Outlet pipe covered in ice	3			13.7		1668	
22-Feb-16	No snow on sod field, sunny, cold	2.8	2.7	56	12.45	7.85	1621	1476
28-Feb-16	Sunny, ~10 degrees weather							
10-Mar-16	Raining, warm (~10), filter is flooded							

Appendix D
Wildwood Biofilter Detailed Geochemical and Field Data

Appendix D. 1. Wildwood (tile drain) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO3^{-}–N, NH4^{+}–N, dissolved organic C (DOC) and iron from May 27, 2014 to March 1, 2016.

Date	TSS (mg/L)		TP (µg/L) (Unfiltered)		SRP (µg/L)		PP (ug/L)		DOC (mg/L)		NO_3-N (mg/L)		SO_4 (mg/L)		Cl^- (mg/L)		NH_4-N (mg/L)		Iron (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out			In	Out
27-May-14	57				17				1		8.5		11		5		0.3			
3-Jun-14	10	5	16	240	16	352	0	-112	1	3	13.8	1.7	24	4	16	10	0.0	0.0	0.04	0.09
5-Jun-14	1	10	11	21	10	9	1	12	1	2	5.1	0.1	29	16	15	9	0.0	0.0	0.03	0.06
7-Jun-14	61	38	10	272	8	237	2	35	1	2	4.1	0.2	16	13	9	8	0.0	0.0	0.04	0.13
12-Jun-14	24	2	27	155	13		14		1	3	4.6	0.1	19	12	9	8	0.0	0.0	0.03	0.09
4-Jul-14	1	1	20	120	11	100	9	20	1	3	2.2	0.1	17	2	9	9			0.04	0.05
10-Jul-14	0	0	9	78	13	58	-4	20	1	5	7.9	1.1	18	17	8	7	0.0	0.0	0.04	0.05
17-Jul-14	0	0	8	146	5	53	3	93	2	4	3.8	0.1	20	6	11	10	0.0	0.1	0.04	0.13
24-Jul-14	2	1	8	254	11	206	-3	48	2	11	1.7	0.1	18	4	11	11	0.0	0.0	0.03	0.15
7-Aug-14			14	172	8	182	6	-10	4	25	5.1	0.1	19	2	12	9			0.04	0.12
19-Aug-14	89		4		9		-5		5		3.32		13		15		0.0		0.03	
16-Sep-14	1		13		16	0	-3		11		7.0		10		9		0.0		0.04	
30-Sep-14	146	112	13	11	7	94	6	-83	2	2	5.6	1.3	10	8	9	10	0.0	0.0	0.03	0.13
9-Oct-14			19	18	11	9	8	9	1	1	9.5	2.1	8	6	5	3	0.0	0.0	0.04	0.04
22-Oct-14	2	0	15	25	12	17	3	8	1	12	9.0	4.5	11	10	7	6	0.0	0.0	0.04	0.04
13-Nov-14	1	1	12	19	8	11	4	8	10	4	6.6	3.0	18	14	13	9	0.0	0.0	0.09	0.06
15-Nov-14	0	1	25	38	3	20	22	18	14	14	5.4	0.5	17	16	15	11	0.0	0.0	0.14	0.05
2-Dec-14	2	4	19	13	17	11	2	2	1	1	5.6	7.9	13	11	6	5	0.0	0.0	0.04	0.05
23-Jan-15																				
1-Apr-15			28		17		11				11.4		6		3		0.0			
7-May-15	150		37		9		28		1		6.4		16		6		0.0			
14-May-15	9		10		9		1		1		4.6		14		8		0.0			
5-Jun-15	1		12	23	11	15	1	8	1	2	9.5	0.9	14	9	4	3			0.047	0.08
12-Jun-15	0								1		12.1	0.3	9	9	3	5				
15-Jun-15	4	1	14	33	14	32	0	1	1	2	11.2	3.8	11	7	5	3	0.0	0.2		
24-Jun-15	16	2	39	112	7	92			1	2										
2-Jul-15	6	2	18	68	136	53	-118	16	2	2	6.4		12		6		0.2	0.1		
7-Jul-15	74	4	93	487	75	522	19	-35	10	0	8.8	0.2	7	1	2	6	0.0	0.2		
13-Nov-15	4	3	11	75	9	61	2	15	1	3	8.1	0.0	15	1	9	7	0.0	0.1		
24-Nov-15	2	0	21	17	9	8	11	9	1	2	8.9	1.1	15	14	7	8	0.0	0.0	0.10	0.11

Appendix D. 1. Wildwood (tile drain) site: Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), NO3$^-$–N, NH4$^+$–N, dissolved organic C (DOC) and iron from May 27, 2014 to March 1, 2016.

Date	TSS (mg/L)		TP (µg/L) (Unfiltered)		SRP (µg/L)		PP (ug/L)		DOC (mg/L)		NO_3-N (mg/L)		SO_4 (mg/L)		Cl^- (mg/L)		NH_4-N (mg/L)		Iron (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out			In	Out
8-Dec-15	150	2	5	5	6	3	-2	3	1	2	5.6	0.9	9	8	5	5	0.0	0.1	0.11	0.03
15-Dec-15		2	8	10	0	10	13	0	5	1	1	7.7	7	14	0.0	6	1.1	0.0	12	0.07
4-Jan-16	0.9	0.20	3	13	0.42	12	17	1	14	1	2	8.2	4	11		4	5.1		8	
14-Jan-16	3.6	0.72	4	17	0.09	13	11	3	7	1	2	7.2	4	9	0.0	3	6.0	0.0	8	0.08
27-Jan-16	4.5	8.51	5	19	0.00	14	9	5	4	1	2	6.3	3	9		3	5.3		8	
3-Feb-16	17.2	3.25	37	169	1.10	144	50	26	13	2	2	2.57		4	0.1	1		0.0		
19-Feb-16	2.5	1.023	5	11	0	6	10	5	5	1	2	6.13	4	11	0.1	4	4.00	0.0	10	
1-Mar-16	3.0	1.04	7	20	0.251	18	14	3	7	1	2	4.20	2	7		3	2.58		7	

Appendix D. 2. Wildwood (tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from May 2014 to March 2016.

Date	Operating Conditions	Temperature (^{o}C)		Effluent Flow (L/min)		DO (mg/L)		EC (µs/cm)	
		In	Out	In	Out	In	Out	In	Out
27-May-14	Cloudy, windy	10.9			0			550	
30-May-14	Sunny, warm	12.7	13.3		3.5			648	609
3-Jun-14		14	14.4		2.8				650
5-Jun-14		13.1	13.5		3.6			700	659
12-Jun-14		14.2	14.8		3.7			675	674
4-Jul-14	Sunny, warm	15.9	17		1			727	720
10-Jul-14	Sunny, warm	16.5	17.1		4			722	664
17-Jul-14	Sunny, warm	16.2	17.8		0.6			789	771
24-Jul-14	Sunny, warm	15.7	17.1		0.2			758	757
7-Aug-14	Sunny, warm	15.3	16.1		0.9			522	468
19-Aug-14	Sunny, warm, flow was too low-unable to obtain sample	15			0			671	
16-Sep-14	Sunny-cloudy, warm, white algae like substance around effluent ditch	15			0			463	
30-Sep-14	Sunny, warm	14	14		3				
9-Oct-14		13	13		4.5			604	589
22-Oct-14	Sunny, cold	12.6	11.5		3.2	9.2	1.9	455	460
13-Nov-14	Snowing	7.1	8.1		1.5	10.8	2.4	345	545
15-Nov-14	Snow on biofilter and adjacent field	7.4	6.4		0.5	11.2	2.7	569	581
2-Dec-14	Flow on biofilter and adjacent field	4.7	4.5		2.8	12.1	2.7	484	512
6-Jan-15	No flow								
23-Jan-15	No flow								
7-May-15		11.4			0	11.6		292	
14-May-15	Sunny, warm	11.2			0	10.2		543	
5-Jun-15	Sunny, warm	14.1	15		1.85	9.4	2.1	640	569
12-Jun-15	Cloudy, warm, light rain	14.1			0	8.8		579	
15-Jun-15	Sunny, warm	16.4	16.1		n/a	8.8	1.9	632	578
24-Jun-15		16.7	18.8		2.1	9.4	1.4	650	603
2-Jul-15	Sunny, warm	15.7	16.7		2.12	8.7	1.3	684	671
7-Jul-15	Warm, Light rain during time of sampling	17.3	17.1		6	8.4	0.8	554	651
13-Nov-15	Light rain	11.1	-		0.4	9.5		667	
24-Nov-15	Snow on the adjacent field	8.4	7.6		2.62	10.6	2.1	660	641
08-Dec-15	Cloudy, no snow, sulfur smell but no white algae	7.2	7.9		0.4437	11.0	2.2	649	614

Appendix D. 2. Wildwood (tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from May 2014 to March 2016.

Date	**Operating Conditions**	**Temperature (^oC)**		**Effluent Flow (L/min)**		**DO (mg/L)**		**EC (µs/cm)**	
		In	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
15-Dec-15					n/a				
04-Jan-16	Sunny, snow on adjacent field	5.3	4		0.912	11.6	1.8	558	558
14-Jan-16	Cloudy, snow over biofilter	4.2	2.6		3.63	11.4	1.6	567	552
27-Jan-16		3.6	3.3		4.52	13.4	1.3	536	530
03-Feb-15	Rained in the morning; about 13 degrees	3.8	4.4		17.22	12.0	4.8	347	377
19-Feb-16	Sunny, windy, snow on biofilter and adjacent field	3.6	3.1		2.51	12.7	1.4	574	560
01-Mar-16	Snow on adjacent field	3.3	8.2		3.04	12.6	1.2	523	490

Appendix E
Avon Biofilter Detailed Geochemical and Field Data

Appendix E. 1. Avon(tile drain) site; Detailed concentrations of total suspended solids (TSS), total P (TP), soluble reactive P (SRP), particulate P (PP), $NO3^{-}$–N, $NH4^{+}$–N, dissolved organic C (DOC) and iron from May 27, 2014 to March 1, 2016.

Date	TSS (mg/L)		SRP (µg/L)		TP (µg/L)		DOC mg/L		NO3-N (mg/L)		NH4-N (mg/L)		N02- (mg/L)		Cl- (mg/L)		SO4 (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
23-May-14	12	59	40	74	80	63	11	3	0.19	0.15	0.13		0.08		34	34	3	2
30-May-14	3	1	32	42	73	38	10	3	2.33	0.39	0.00	0.04	0.03	0.03	9	5	17	10
03-Jun-14	4	7	48	27	71	36	9	9	1.66	0.31	0.08	0.44	0.05	0	9	21	18	11
05-Jun-14	9	5	11	7	39	51	8	6	1.77	0.31	0.04	0.16	0.01	0.01	9	24	18	11
12-Jun-14	3	1	40	82	61	112	7	7	1.36	0.25	0.03	0.24	0.06	0	9	26	17	8
04-Jul-14	2	0	39	20	69	89	5	4	1.10	0.18	1.06	0.13	0.01	0	12	15	20	2
10-Jul-14	5	8	66	124	104	142	7	4	12.30	0.41	0.03	0.01	0	-0.01	10	32	25	16
17-Jul-14	2	9	44	124	65	144	7	10	5.42	0.38	0.01	0.05	0.06	0.01	10	32	24	9
24-Jul-14	2	1	47	126	78	125	6	5	2.12	0.26	0.10	-0.02	0.03	-0.01	9	27	19	6
07-Aug-14	1	1	38	160	70	101	5	13	1.23	0.22					9	26	17	6
19-Aug-14			29	97	59	63	3	3	0.80	0.17	0.00	0.01	0.00	0.01	10	22	16	3
16-Sep-14	11	55	52	98	82	126	11	15	3.52	0.32	0.04	0.01	0.05	0.01	8	31	21	9
30-Sep-14	72	129	107	78			14	6	3.16	0.47	0.00	0.00	0.07	-0.03	7	16	17	5
09-Oct-14	77	100	32	125			10	9	4.88	0.59	0.01	0.02	0.02	-0.01	9	27	22	10
22-Oct-14	11	3	36	103	86	113	9	12			0.04	0.03	0.05	0.06	9	26	25	12
13-Nov-14	24	3	16	127	86	146	7	25	4.46	1.24	0.08	0.06	0.11	0.11	10	25	26	13
15-Nov-14	13	1	12	145	133	186	7	21	4.07	0.64	0.09	0.02	0.13	0.04	9	28	25	9
2-Dec-14	25	2	32	73	61	101	8	4	5.6 *	0.83	0.07	0.04	0.04	0.04	9	28	27	15
19-Dec-14	39	1	40	101	100	114	8	20		0.67		0.04		0.00				9
6-Jan-15	9		220		166						0.09		0.01					
1-Apr-15	10	13	25	90	819	130	9	28	1.47	0.62	0.72	0.21	0.04	0.00	4	26	12	11
15-Apr-15	28	2	96	26	159	105	9	3	4.83	0.59	0.04		0.01		0	24	17	9
22-Apr-15	10061	3749	40	143	40	143	10	4			0.00	0.27	0.01	0.01				
24-Apr-15	10	13	25	138		146	8	4										
07-May-15	9	3	29	71	78	105	8	6	1.72	0.45	-0.11	0.29	0.02	0.02	9	23	18	8
14-May-15	146	0	18	411	57	351	7	6	0.98	0.43	0.01	0.40	0.04	0.00	9	19	18	6
21-May-15	9	7	27	528	55	416	6	6	0.41	0.21	0.02	0.44	0.02	0.00	8	11	16	4
25-May-15				187	183	154	5	6		0.17	0.02	0.13	0.00	0.00		11.79		10.38
02-Jun-15		3		76	60		9	6	12.10	19.00	0.02		0.07		14	6	27	27
05-Jun-15	83	3	18	151		125	7	5	3.79	2.04	0.01	0.04	0.11	0.07	9	16	18	18
12-Jun-15	5	2	75	111	100	103	9	6	8.72	4.35					9	16	20	16
15-Jun-15	4	4	73	123	84	81	9	6	13.29	6.86	1.01	0.02	0.14	0.03	9	17	20	16
24-Jun-15	24	3		152		149	10	7	3.19	1.46					9	15	17	13
02-Jul-15	14	12	37	162			8	6	2.53	1.04	0.02	0.01	0.10	0.00	9	17	15	12
07-Jul-15	79	185	477		589	744			3.81	1.12					7	6	10	4
16-Jul-15	2	10	73	188	110	189	9	6	0.62	0.28					9	15	12	10
11-Aug-15	7	19	96	344			4	4	0.29	0.15	0.08	0.07	0.10	0.04	9	16	11	4
13-Nov-15			76	220	112		6	3	3.23	0.09					11	24	39	8

Appendix E. 2. Avon(tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from May 2014 to March 2016.

Date	Temperature (°C)		Effluent Flow (L/min)	Stream Velocity (m/min)	DO (mg/L)		EC (µs/cm)	
	In	Out	Out		In	Out	In	Out
23-May-14	23.4	10	0.6				322	856
30-May-14	23	12.8		27			517	761
03-Jun-14	22	17	4.2				518	669
05-Jun-14	17	14.5	2.5					717
12-Jun-14	18.4	15.1	1.7	10			466	649
04-Jul-14	17	16.8	1.2				468	677
10-Jul-14	15.9	14.7	3				634	766
17-Jul-14	16.2	15.2	3	12.8				
24-Jul-14	17.7	16.7	0.2	6			514	126
07-Aug-14	15.7	14.7	1	4.3			406	480
19-Aug-14		14.9	1.1					581
16-Sep-14	13.3	13.6	0.2	14			445	502
30-Sep-14	15	15	7				554	623
09-Oct-14	12	13	6				626	703
22-Oct-14	9.4	11	3.6	10	6.2	0.4	500	505
13-Nov-14	3.7	7.3	2.4	7.1	8.9	1.6		
15-Nov-14	3.3	7.6	2.2	16	9.9	0.4	540	568
2-Dec-14	0.7	5.9	2.5	13	8.7	0.4		
19-Dec-14					9.3	0.3		
6-Jan-15					7.5			
1-Apr-15					6.6	0.3		
15-Apr-15	12.5	6.9	2.8		11.4	0.3	429	556
22-Apr-15								
07-May-15	21.6	11.1	2.3	8.4	11.2	0.4	412	541
14-May-15	12.2	11.1	2.3	8.8	11.7	0.2	485	693
21-May-15	15.5	12.8		6.2	12	0.3	501	715

Appendix E. 2. Avon (tile drain) site: Field notes of operating conditions, temperature (in C), influent flow, effluent flow, and dissolved oxygen (DO), and electrical conductivity (EC) of the Barrie woodchip filter from May 2014 to March 2016.

Date	Temperature (°C)		Effluent Flow (L/min)	Stream Velocity (m/min)	DO (mg/L)		EC (µs/cm)	
	In	Out			In	Out	In	Out
28-May-15	24	18.6	4.3		5.7	0.2	482	562
02-Jun-15	17.3	13.2		0.1	7.62	0.91	637	691
05-Jun-15	18.8	15	3.2	6.1	6.7	0.5	577	645
12-Jun-15	16.5	14.6	0.2	0.04	4.5	0.3	556	651
15-Jun-15	22.3	17.7		12.1	6	0.4	605	688
24-Jun-15	18.5	17.6			4.4	0.3	470	573
02-Jul-15	15.4	15	0.2	0.1	3	0.2	530	662
07-Jul-15	18.5	16.4	1	3.1	4.4	0.2	405	523
16-Jul-15	16.1	16.2	0.1	6.9	0.3	1.2		
11-Aug-15	17.8	16.4			1.36	0.3	425	641
13-Nov-15								