# Review of In-stream Nonpoint Source Control Methodologies to Reduce Erosion and Sedimentation and Abate Phosphorus Loadings to the Great Lakes

Great Lakes Commission
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## Introduction

The reemergence of harmful algal blooms (HABs) in the Great Lakes and St. Lawrence River in the last several years is threatening the integrity of the region's water resources. HABs pose a serious risk for human and animal health, and the quality and vitality of aquatic ecosystems. Federal, provincial and state governments have become increasingly concerned about nonpoint source pollution, particularly excessive phosphorus, as it appears to be the major contributor to the recent increase in the frequency and severity of HABs throughout the Great Lakes Basin.

Conservation programs to control soil erosion, reduce sedimentation and manage runoff from rural landscapes have been utilized for many decades. Numerous best management practices (BMPs) have been developed to conserve soil and nutrients, reduce runoff, improve water management and water quality, and increase habitat. As water quality challenges have become more complex and as the nonpoint source pollution contributions to water quality impairments have become better understood, scientists and managers have realized the importance of implementing programs in a more targeted way on a watershed basis. Additionally, in response to limited resources, attempts have been made to focus efforts on those watersheds where increased conservation treatment will likely provide the biggest improvement in water quality. However, the control of agricultural nonpoint source pollution challenges decision makers and land managers both financially and logistically as outcomes of policies are hard to quantify and resources are often limited.

Extensive information is needed to identify new and cost-effective BMPs and successfully implement them at appropriate locations. Several researchers have measured the cost-effectiveness and water quality benefits of a variety of individual BMPs, both upland and in-stream, but fewer studies have extensively compared the advantages, implementation costs and efficiencies of a large array of BMPs options.

One of the focus areas for conservation treatment is in-stream BMPs that are constructed within the streambank boundaries, including the water channel and streambed. These can range from traditional bank armoring to innovative ideas such as in-stream scrubbers. This document presents a comprehensive overview of innovative in-stream BMPs used throughout the United States and Canada to reduce nonpoint source pollution and phosphorus loadings, including constructed wetlands, two-stage ditches, reactive material, riparian buffers and scrubber boxes.

Through a review of the available literature, a series of efficient and innovative NPS control BMPs have been identified that can be implemented within streambank boundaries, including the water channel and streambed, to reduce sediment and abate phosphorus loadings to the Great Lakes. Information is provided on the costs and effectiveness of these innovative technologies as well as examples of successful implementation of these practices.

A series of technical reports, peer-reviewed publications, government publications, books and academic dissertations were reviewed to examine pollutant removal mechanisms, and implementation and maintenance costs of the various BMPs. The last sections outline BMP advantages and disadvantages, comparing their efficiencies along with their implementation and maintenance costs. The document concludes with a short section of findings regarding the suite of BMPs reviewed.

## Constructed wetlands

### Description

Constructed wetlands are used worldwide to treat wastewater from a wide array of sources by removing a variety of water contaminants (e.g., pathogens, nutrients, suspended sediments) (Chen 2011; Scholz 2011). These wetlands can be based on free-water surface flow, horizontal subsurface flow or vertical surface flow, and can provide high nutrient removal capacities (Chen 2011). Constructed wetlands are comprised of four parts: 1) a liner, which is typically a Polyvinyl chloride membrane that isolates wastewater from groundwater sources; 2) a distribution medium, composed of coarse drainfield rocks that enable the distribution of wastewater in the system; 3) plants and microorganisms, typically cattails, reeds, bulrushes or sedges; and 4) an underdrain system that transports the treated effluent out of the system.

### Pollutant removal mechanisms

Plants themselves can be an effective way to remove pollutants from a waterbody. Plants have the ability to uptake dissolved nutrients directly, while their root systems allow for the settling of particles, and provide habitat for good (non-harmful) algae and other microorganisms that break down pollutants (Scholz 2011). Suspended phosphorus can be stored and buried under accumulating peat, chemically precipitated or adsorbed to organic matter in the soil (Chen 2011). Finally, microbes naturally present in the wetland will help diminish nitrogen concentrations of effluents through the process of denitrification (i.e., transformation of nitrates into gaseous nitrogen through molecular respiration).

In the Great Lakes, the performance of constructed wetlands might not be consistent throughout the year (Carleton *et al*. 2001; Werker *et al.* 2002) as changes in climatic conditions – cold temperature in winter for example – and discharge volume – like higher quantity of runoff water in spring during snowmelt – can have an impact on the nutrient and sediment removal capacities (Kostinec 2001; Morrice *et al*. 2004).

### Implementation and maintenance cost and effort

Constructed wetlands are expensive and can require substantial construction costs as the installation requires heavy machinery work, excavation and piping. Costs will vary in function of wetland type (Simeral 2008), field topography, size, and need for pretreatment of influent. There are economies of scale with constructed wetlands as larger wetlands will generally have a lower cost per acre or hectare (Vymazal 2010). Periodic maintenance of constructed wetlands is often required, as pipes need to be frequently checked to prevent blockage, accumulated sediments may need to be removed, and plants have to be harvested or replaced to maintain productivity (Gustafson *et al*. 2002).

Table 1: Examples of Constructed Wetlands from literature

| References | Location | Subject | Findings |
|---|---|---|---|
| De Stefani *et al*. 2011. Performance of a floating treatment wetland for in-stream water amelioration in NE Italy. Wetland Restoration **674**: 157-167. | Italy | In-stream use of floating wetlands to purify water | Successful removal of TP and TN, but higher removal rates with greater initial loadings. |

Table 1: Examples of Constructed Wetlands from literature (cont'd)

| References | Location | Subject | Findings |
|---|---|---|---|
| Chen. 2011. Surface-flow constructed treatment wetlands for pollutant removal: applications and perspectives. Wetlands **31**: 805-814. | Worldwide | Literature review on surface flow constructed wetlands | Surface flow constructed wetlands offer high phosphorus, nitrogen and sediments removal efficiency, but are associated with substantial installation and maintenance costs. |
| de Haan, J., van der Schoot, J.R., Verstegen, H. and O. Clevering. 2010. Removal of nitrogen leaching from vegetable crops in constructed wetlands. Acta horticulturae, **852**: 139-144. | Netherlands | Compared cost-efficiency of surface flow, and subsurface flow constructed wetlands. | The surface flow constructed wetland planted with *Phragmites australis* was the most cost-efficient amongst the three systems tested. |
| Wood, J.D., Gordon, R., Madani, A. and G.W.Stratton. 2008. A long term assessment of phosphorus treatment by a constructed wetland receiving dairy wastewater. Wetlands **28**(3):715-723. | Nova Scotia, Canada | Constructed wetland long-term efficiency in treating milk farm wastewaters. | Average removal rates of particulate and total phosphorus were good, but removal capacities fluctuated a lot during the five-year study. |
| Dunne, E.J., Culleton, N., O'Donovan, G., Harrington, R. and A.E. Olsen. 2005. An integrated constructed wetland to treat contaminants and nutrients from dairy farmyard dirty water. Ecological Engineering, **24**(3): 219-232. | Ireland | Season variation in water quality parameters in a dairy farm runoff and phosphorus retention capacities of a constructed wetland. | Water quantity and quality of the agricultural runoff remained constant, but phosphorus retention capacities decreased significantly in winter. |
| Kovacic, D.A., David, M.B., Gentry, L.E., Starks, K.M. and R.A. Cooke. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. Journal of Environmental Quality **29**(4): 1262-1274. | Illinois | Removal of nonpoint nitrogen and phosphorus from agricultural tile drainage waters by constructed wetland | Removal of phosphorus varied within the wetlands depending on flow and retention time, and there was a lower removal rate during winter. |

**De Stefani *et al*. (2011)** tested the use of floating wetlands to purify water in an aquaculture farm and a nature reserve in Italy by monitoring chemical oxygen demand, total phosphorus and nitrogen concentrations for one year after installation. Floating wetlands are defined as floating mats of plant material, including live and dead plant roots, peat and detritus that are used to filter liquids such as stormwater and effluent from pigs and poultry production. Floating wetlands will typically include three components: 1) a structure that provides buoyancy (e.g., inflatable vinyl pillows, polypropylene pipes), 2) an internal structure that serves as a medium for plant growth (e.g. coconut fiber, bamboo reed nets), and 3) plants, preferably native and emergent species. The authors found that floating wetlands achieved a good overall filtration performance in both the aquaculture farm and nature reserve, despite high initial nutrient loadings and a short residence time for water in the system. Total phosphorus removal rates were higher in the aquaculture settings than those observed in the nature reserve experiment, which the authors attributed to higher initial concentrations of phosphorus in the former. Additionally, nitrogen removal rates were generally lower than observed phosphorus removal rates, but still significant. Authors concluded that the use of floating wetlands may represent an efficient way to reduce pollutants in both agricultural and natural conditions, but specified that their efficiency is conditional on the choice of resistant plant species that are well-adapted to local climatic conditions and fluctuations in water levels.

**Chen (2011)** reviewed literature on surface flow constructed wetlands. Free surface flow constructed wetlands have been successfully used to treat wastewater from a variety of sources, including municipal wastewater and agricultural and urban runoff. In several studies, these wetlands showed removal efficiencies above 70 percent for suspended solids, 40-50 percent for nitrates, and 40-90 percent for phosphorus. However, constructed wetlands require periodic maintenance. Plant coverage of 50 percent maintained over time was proven to provide the most efficient intake of nutrients. Notably, Chen reports that two constructed wetlands in Massachusetts and Wisconsin have been successfully operated for over seven years. In addition, constructed wetlands can not only be used for nutrient removal, but may also provide other benefits such as habitat for wildlife and biogas production through fermentation of plant material.

**de Haan *et al*. (2010)** tested the nutrient removal efficiency of three different constructed wetlands in an experimental farm in the Netherlands: 1) a surface flow system with the native *Phragmites australis* (common reed), 2) a horizontal subsurface flow system with *Phragmites*, and 3) a horizontal subsurface flow filled with straw. The horizontal subsurface flow filled with straw and the surface flow system both showed very good nitrogen removal capacities (63% and 58% respectively), while the horizontal subsurface flow planted with *P. autralis*' capacity was significantly lower (25%). However, the horizontal system filled with straw was proven to release phosphorus in the adjacent stream, while the other system had positive but negligible phosphorus abatement rate. The surface flow wetland was the most cost-efficient ($17 per pound of nitrogen removed).

**Wood *et al*. (2008)** monitored the long-term efficiency of phosphorus removal from a constructed wetland in Nova Scotia, Canada. The constructed wetland was fed by surface flows of wastewater from a manure store and milk-house wash system. The wetland covered 100 $m^2$ (0.01 ha) and was composed of shallower portions containing top soil and cattails, as well as deeper portions covered by duckweed. The reduction of phosphorus was generally good throughout the five years of this study (i.e., 53.7% for total phosphorus and 52.7% for soluble reactive phosphorus). However, treatment capacities were highly variable, mainly due to fluctuations in the hydraulic rates of effluents, and negative removal rates were observed during certain high loading periods.

**Dunne *et al.* (2005)** assessed the seasonal variations in water quality parameters in a dairy farmyard effluent and phosphorus retention performances in an adjacent constructed wetland in Ireland. The authors observed little variation in the quality and quantity of dirty water entering the constructed wetland: discharge, nitrate and phosphorus concentration, biological oxygen demand and total suspended sediment loads remained constant throughout the year. The phosphorus retention capacities of this 4200$m^2$ (0.42 ha) constructed wetland were, however, significantly decreased during winter (less than 5% retention rate) but remained constant in spring, summer and fall (phosphorus retention rate of 81-85%). The decrease in phosphorus retention during winter was attributed to increased rainfall and an increased input of phosphorus from decaying plant material.

**Kovacic *et al*. (2000)** tested the effectiveness of constructed treatment wetlands in the removal of nutrients from agricultural tile drainage waters in Champaign County, Illinois. The four studied wetlands received tile drainage from areas of 5, 15, 17, and 25 ha respectively. They were constructed following USDA guidelines on a site that had never been cultivated before by rerouting tile drainage to the ground surfaces above a floodplain. The sampling was conducted over a three year period. The authors discovered that the removal of phosphorus varied within wetlands depending on flow and retention time. The lowest removal rates were during winter and spring. The efficiency of the constructed wetland can be influenced by pulse flows that occur in spring when there is a greater discharge of nutrients.

## Two-stage ditches

### Description

Two-stage ditches are designed to function like a floodplain and a stream channel and, as their name suggests, are composed of two stages: the channel and the bench (which acts as a floodplain). The use of the floodplain stage enhances drainage capacity, which reduces the risk of floods during large storm events as well as increases water residence time within the system, which allows for more time and space for nutrient and sediment removal. In addition, two-stage channels are characterized by lower velocity streamflows, which lead to greater channel stability and decreased erosion. Two-stage ditches also provide habitat, and requirements for maintenance tend to be lower than traditional trapezoidal ditches where significant erosion rates typically result in greater deposition of sediments within the channel.

### Pollutant removal mechanisms

With a two-stage ditch system, coarser sediments are deposited on the stream bench, while finer sediment and nutrients (i.e., particulate phosphorus and nitrogen) can be deposited on benches during high flow events decreasing the quantities of phosphorus and nitrogen being transported downstream. Furthermore, nitrogen deposited on the banks can be broken down by microorganisms through the process of denitrification.

### Implementation and maintenance cost and effort

Two-stage ditches are generally less costly than other BMPs reviewed here, but may require a higher initial investment when compared to traditional trapezoidal ditches. Costs associated with two-stage ditch construction varied between $5-42 per linear foot of stream in the studies reviewed, and covered costs associated with excavation, planting of the flood plain, and installation of erosion control structures (D'Ambrosio *et al.* 2011; Witter *et al.* 2011). The implementation of two-stage ditches may result in a greater loss of cultivable surface, as they typically are three times as wide as traditional ditches (Witter *et al.* 2011). However, two-stage ditches require less maintenance than trapezoidal ditches; and annual, cleanup seems to be sufficient to maintain the ditch vitality (Kramer *et al.* 2011).

Table 2: Examples of Two-stage Ditches from literature

| References | Location | Subject | Findings |
|---|---|---|---|
| Witter, J.D., D'Ambrosio, J.L., Ward, A., Magner J. and B. Wilson. 2011. Considerations for implementing two-stage channels. Great Lakes Regional Water Program. University of Wisconsin-Extension. 4p. | Wisconsin, United States | Main advantages and disadvantages of two-stage ditches. | Two-stage ditches require greater construction costs than traditional ditches, but have higher pollutant removal capacities and demand less maintenance. |

Table 2: Examples of Two-stage Ditches from literature (cont'd)

| References | Location | Subject | Findings |
|---|---|---|---|
| Roley, S.S., Trak, J.L. and R.T. Davis, 2011. The two-stage ditch and its influence on N removal, sediment transport and habitat. Two-Stage Ditch Symposium, The Ohio State University Extension. Available from http://ohiowatersheds.osu.edu/education/stream-systems/two-stage-ditch-symposium/ [cited January 16, 2013] | Indiana, United States | Use of two-stage ditches to reduce N content and sediment loadings in agricultural stream | Significant decrease in nitrogen and sediment loadings. |
| Kramer, G., Wilson, B. and J. Magner. 2011. Two-Stage Ditch Economics. Two-Stage Ditch Symposium. The Ohio State University Extension. Available from http://ohiowatersheds.osu.edu/education/stream-systems/two-stage-ditch-symposium/two-stage-ditch-economics [cited cited January 16, 2013] | Indiana, United States | Cost and economical benefit linked with two-stage ditches implementation | Implementation of two-stage ditches is generally more costly. Subsidies are needed to cover the difference in implementation costs, but can be justified by increased N removal rates. |
| D'Ambrosio, J., Witter, J., Ward, A., Tank, J. and S. Roley. 2012. The Evolution and Water Quality Benefits of Constructed Two-Stage Agricultural Ditches. Proceedings of the 2012 Land Grant/Sea Grant National Water Conference, U.S. Department of Agriculture. Available from http://www.usawaterquality.org/conferences/2012/Concurrent_pdf/D%27Ambrosio_R3.pdf [cited cited January 30, 2013] | Michigan, Ohio and Indiana, United States | Use of two-stage ditches to increase water quality in agricultural stream | Two-stage ditches are characterized by higher sediment trapping, lower total phosphorus, and lower total nitrogen than traditional channels. |

**Witter *et al.* (2011)** reviewed the main advantages and disadvantages of two-stage ditches. Two-stage ditches are characterized by better drainage capacity than traditional trapezoidal ditches. They can also contribute to increased land productivity because they are more effective in reducing erosion, flooding frequency and soil compaction. Two-stage ditches do require a more extensive initial investment, as they demand more earthworks and larger areas, but there fewer maintenance costs with two-stage ditches than with trapezoidal ditches, which need frequent cleaning due to higher rates of erosion and sedimentation. Two-stage ditch implementation may also result in a greater loss of cultivable surface, as they typically require a bench three times as wide as the main channel. Several cost-sharing programs provide financial assistance for the implementation of two-stage ditches as a BMP throughout the United States (e.g., USDA-NRCS Environmental Quality Incentive Program (EQIP) funding and the U.S. Environmental Protection Agency Section 319 Program funding).

**Roley *et al.* (2011)** discussed an experimental two-stage ditch located on a farm in Indiana. The floodplain part of the ditch measured 14 ft. (4.27 m), or three times the main channel width. Results showed that nitrogen removal rates are considerably greater on the bench portion than on the main channel, and lower nutrient loads in the channel were correlated to a high removal efficiency on the bench. Roley and her colleagues also noted that the removal efficiency increases with stream length and floodplain age, as an increase in organic matter over time increases the density of vegetation and sediment deposition. Reductions in phosphorus loadings were not measured in this specific experiment, but the authors hypothesized that the reduced transportation of sediments would trigger a decrease in streams' particulate phosphorus concentrations.

**Kramer *et al.* (2011)** compared the costs associated with the construction and maintenance of two-stage and conventional trapezoidal ditches. The authors estimated construction costs of $32.86 per foot of stream ($107.78 per meter) to cover the excavation, structure, vegetation, and erosion control required for the installation of a two-state ditch. However, maintenance costs for two-stage ditches are minimal, and authors estimated that a yearly cleanup could be sufficient to maintain the ditch vitality. Due to the higher construction costs of two-stage ditches, results of this study also showed that two-stages ditches may be economically preferable to conventional trapezoidal ditches in conditions where construction costs are low or when conventional ditches require a high cleanout frequency. In all other situations, subsidies would help cover the higher implementation costs of a two-stage ditch. In this specific study, subsidies of $10 per foot ($30.28 per meter) were sufficient to cover the difference in construction costs, and could be justified by the significant nitrogen removal capabilities of the more costly two-stage ditch. The cost of nitrogen removal could be as low as $0.18 per kilogram removed ($0.08 per pound) in situations where discount rates are low, few cleanouts are needed, and flooding occurs frequently, but this cost tends to increase with need for increased cleanout frequency or higher construction costs.

**D'Ambrosio *et al.* (2012)** monitored five two-stage ditches in Indiana and Michigan for the year prior to, and post construction. Results of this study show that turbidity is significantly decreased in two-stage ditches when compared to traditional ditches, which can result in decreased suspended sediment content and reduced concentrations in suspended phosphorus within the ditch. Authors also observed that nitrogen removal was significantly higher on benches than within the main ditch. Furthermore, nitrogen removal tended to increase with the age of benches, as older benches were characterized by higher organic matter content, which accelerated the denitrification process. Authors concluded that two stages ditches provide several ecological benefits (e.g. nitrogen, sediment and phosphorus removal; increased habitat; increased bank stability; increased drainage capacity), which could justify the construction cost. For this specific study, average construction costs for a two-stage ditch were $23 per foot, and varied considerably from site to site ($5 to $42 per foot).

## Reactive material

### Description

Reactive materials have been mixed with animal manure and litter to decrease phosphorus solubility, mixed with topsoil rich in phosphorus to minimize the release of phosphorus, integrated into constructed wetlands to enhance their phosphorus removal capacities (Vohla *et al.* 2011), and embedded in barriers and installed directly in ditches to promote adsorbtion of phosphorus in agricultural runoff. Material used can range from natural materials (e.g., shells, plant fibers) to industrial waste and byproducts (e.g., steel slag, gypsum) and other manmade products.

### Pollutant removal mechanisms

Reactive material added to streambeds may either trap phosphorus or aid in its precipitation (i.e., separated out from the waterbody), depending on their chemical content and reactive properties. Material rich in basic cations, such as calcium, gypsum, shells or marine plants fibers, will trigger a precipitation of phosphorus, while substrates and material enriched with iron and aluminum will sequester phosphorus by adsorption. These chemical processes may, however, be influenced by pH (precipitation of phosphorus is more efficient under higher pH conditions) and bacterial activity (which influence the redox potential of soil, and affect its phosphorus sequestration capacities) and may thereby modify the reactive material removal capacities. Redox refers to reduction-oxidation reactions that include all chemical reactions in which atoms have their oxidation state changed—that is, redox reactions involve the transfer of electrons between species.

### Implementation and maintenance cost and effort

The cost of reactive material can be substantial and, in some cases, prohibitive. However, certain studies have successfully used industrial byproducts as reactive agents and by doing so reduced initial implementation costs (e.g., Claveau-Mallet *et al.* 2013). Additionally, the efficiency of reactive material tends to decrease with time and, consequently, materials need to be replaced every three to five years (Shitlon *et al.* 2006; Bryant *et al.* 2012; Pratt *et al.* 2012). McDowell *et al.* (2007) estimated that phosphorus removal costs with this technology were roughly $30 US per kg of phosphorus removed ($13.63 per pound), and concluded that its implementation at a broader scale may prove to be cost prohibitive. However, this BMP has the advantage of being implementable directly on the streambank, thus minimizing the loss of cultivable land.

Table 3: Examples of Reactive Material from literature

| References | Location | Subject | Findings |
|---|---|---|---|
| Bryant R.B., Buda, A.R., Kleinman, P.J.A., Church, C.D., Saporito, L.S., Folmar, G.J., Bose, S. and A.L. Allen. 2012. Using Flue Gas Desulfurization Gypsum to Remove Dissolved Phosphorus from Agricultural Drainage Waters. Journal of Environmental Quality **41**(3):664-671. | Maryland, United States | Use of within ditch filter with gypsum to remove dissolved phosphorus from agricultural ditches | Within stream gypsum-based filter can efficiently trap dissolved phosphorus with low environmental impact, but require considerable maintenance and clean-out fees and effort. |
| McDowell, R.W., Hawke, M. and J.J.McIntosh. 2007. Assessment if a technique to remove phosphorus from stream flow. New Zealand Journal of Agricultural Research **50**(4):503-510. | New Zealand | Use of steel slag filter to remove sorb phosphorus in agricultural catchment | Slag filter could efficiently remove dissolved and total phosphorus at low flow rates, but efficiency was considerably reduced when flow rates were higher than 20L/s. |
| Claveau-Mallet, D., Wallace, S. and Y. Comeau. 2013. Removal of Phosphorus, Fluoride and Metals from a Gypsum Mining Leachate using Steel Slag Filters. Water research **47**: 1512-1520. | Canada | Use of slag filters to remove phosphorus from mining leachate | Filters could remove up to 99% of phosphorus |
| Shilton, A.N., Elmetri, I., Drizo, A., Pratt, S., Haverkamp R.G. and S.C.Bilby. 2006. Phosphorus removal by an 'active' slag-filter-a decade of full scale experience. Water Research **40**: 113-118. | New Zealand | Long term use of steel slag filter to filter waste water | Filter maintained an average phosphorus removal rate of 77% for the first five years, but efficiency was considerably decreased after that. |

### Flue gas desulfurization gypsum

**Bryant *et al*. (2012)** assessed the efficiency of in-stream filters containing flue gas desulfurization gypsum as a reactive ingredient to remove dissolved phosphorus in agricultural ditches. The filters were comprised of six 98 ft-long by 4 in-wide (30 m X 10 cm) tile lines inserted between layers of flue gas desulfurization gypsum and sand. The filters were installed in a ditch at the University of Maryland Eastern Shore Research and Teaching

Farm and monitored for three consecutive years. Performance of the filters was generally very good during storm-induced flow events, with an average total dissolved phosphorus removal rate of 73%. The system also showed good performance during base flow events even when concentrations in dissolved phosphorus were lower than average. The authors noted, however, that efficiency of the system could be reduced during major storm events, as the filter is designed to let excess flow overpass the filter to avoid flooding. The authors were generally satisfied with the overall performance of the system, as 20 kg of dissolved phosphorus (44.9 pounds) were removed during the three year experiment. However, the system's efficiency decreased with time as increased sedimentation and vegetation growth in the ditch diminished the rate of flow through the filters. The authors concluded that the use of gypsum is an efficient way to remove dissolved phosphorus from a stream with low environmental impact. However, the gypsum needs to be periodically replaced, which generates costs that could be prohibitive for farmers.

### Slag filter

**McDowell *et al.* (2010)** tested the use of a steel slag mixture to remove phosphorus from an agricultural catchment in New Zealand. One hundred ninety 1-meter long by 9-cm diameter (3.2 ft. by 3.5 in) P-socks were constructed with heavyweight steel slag placed in a geotextile cloth with a 2 mm mesh and installed in a 200 meter (656.2 ft) stream bed. Water samples were collected the day prior to the installation, and for up to five months after installation. During low flow episodes, the P-sock showed a good overall efficiency, with an average total phosphorus removal rate of 21 percent, and an average dissolved reactive phosphorus removal rate of 35 percent. Phosphorus uptake decreased drastically when flow rates were faster than 20 L per second. Estimated phosphorus removal costs with this technology were roughly $30 USD per kg of phosphorus removed ($13.63 per pound). Thus, successful implementation of slag filters at a broader scale may prove to be cost prohibitive.

**Claveau-Mallet *et al.* (2013)** used steel slag filters to treat reconstituted mining leachates. The slag that was used originated from two different electric arc furnaces (Forth Smith and Blytheville, Arkansas) and differed slightly in chemical composition. Results showed that these filters could remove a considerable proportion of phosphorus (99% removal rate), as well as fluoride, manganese and zinc, but that removal rates were affected by decreases in pH. Toxicity analyses were conducted and proved that these filters have low environmental impacts as the concentration of metal assessed was either low or below the detection limit of measuring tools. The authors concluded that this technology provides an economical alternative for treatment of mining leachates.

**Shilton *et al.* (2006)** provided a long-term study of the efficiency of slag filters in a wastewater treatment plant in New Zealand over a 10-year period. Ten 310 $ft^2$ (28 $m^2$) filter beds filled with steel slag produced in a nearby steel mill were added to a pond used to treat wastewater. The filters treated an average daily flow of 7,063 $ft^3$ (200 $m^3$) per day and were characterized by a mean hydraulic retention time of three days. The filters provided an average phosphorus removal rate of 77 percent during the first five years, but removal capacity decreased considerably after this initial period.

## Riparian buffers

### Description

Riparian buffers, also known as buffer strips and vegetative filter strips, are strips of vegetation installed between a waterbody and cropland or grazing land. Riparian buffers are particularly efficient at trapping sediments, but may also contribute to the abatement of phosphorus, nitrogen and pesticides. These also enhance drainage and filtration capacities of cropland, thus reducing the velocity and volume of runoff (Green *et* *al.* 2006). In addition, buffers provide wildlife habitat and may increase the aesthetic value of agricultural landscapes. Vegetation from the buffers needs to be periodically harvested.

### Pollutant removal mechanisms

The presence of plants in the buffer strip offers a resistance to the water flow, contributing to a decrease in velocity and speed of runoff. It can also contribute to the deposition of suspended sediments, thus keeping sediment out of the receiving nearby waterbody. The dense root system of resident plant species will also increase the permeability of soil, increase infiltration and, consequently, reduce the amount of runoff. Similar to constructed wetlands, vegetation in a buffer will use some of the dissolved phosphorus in the runoff for their own growth needs.

### Implementation and maintenance cost and effort

Riparian buffers may require substantial up-front costs for installation costs and continual maintenance is required throughout the life of the buffer. Initial up-front costs for implementation will include development of a plan for installation and maintenance, preparation of the soil, and planting of grasses or trees to achieve maximum benefit, as well as calculating the necessary width of the buffer. Forested buffers may require a greater initial investment, but they may also generate additional revenues for farmers (i.e., sale of wood) (UPA Mauricie 2009). Periodic maintenance will also be required to maintain the buffer's removal capacities, as plants may need to be mowed or removed at the end of the growing season. Plants also need to be protected against parasites and regular channel maintenance will be required (Dunn *et al.* 2011). Finally, buffer strips may result in significant loss of land available for row crop production or other agricultural commodities, as they typically occupy 10-30 meters (32.8-98.4 ft) on each side of the stream.

Table 4: Examples of Riparian Buffers from literature

| **References** | **Location** | **Subject** | **Findings** |
|---|---|---|---|
| Duchemin, M. and R. Hogue. 2009. Reduction in agricultural non-point source pollution in the first year following establishment of an integrated grass/tree filter strip system in southern Quebec (Canada). Agriculture, Ecosystems and Environment. **131**: 85-97. | Quebec, Canada | Use of integrated grass/tree filter strips | Use of trees increases the phosphorus removal efficiency of buffer strips. |
| Dunn A.M., Julien G., Ernst, W.R., Cook, A., Doe, K.G. and P.M. Jackman. 2011. Evaluation of buffer zone effectiveness in mitigating the risks associated with agricultural runoff in Prince Edward Island. Science of the Total Environment **409**: 868-882. | Prince Edward Island, Canada | Effectiveness of Prince Edward Island buffer zone legislation | Buffer strips are mostly successful at trapping suspended particles, but are less efficient for dissolved contaminants. |

Table 4: Examples of Riparian Buffers from literature (cont'd)

| References | Location | Subject | Findings |
|---|---|---|---|
| Mayer, P.M., S.K. Reynolds, M.D. McCutchen, and T.J. Canfield. 2006. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: A review of current science and regulations. EPA/600/R-05/118. Cincinnati, Ohio, U.S. Environmental Protection Agency. | United States and Canada | Review of study addressing the nitrogen removal efficiency of vegetated buffers | Nitrogen removal efficiency varied greatly in between studies, but the overall performance was good. Buffer width, buffer type, and hydrology influence performances. |
| Giri, S., Pouyan Nejadhashemi, A. and S.A. Woznicki. 2012. Evaluation of targeting methods for implementation of best management practices in the Saginaw River Watershed. Journal of Environmental Management **103**: 24-40. | Michigan, United States. | Modeled nutrient removal efficiencies of different BMPs in a watershed of Michigan. | Riparian buffers achieved the greatest nutrient removal rates. |
| Dorioz, J.M., Wang D., Poulenard, J. and D. Trévisan. 2006. The effect of grass buffer strips on phosphorus dynamics- A critical review and synthesis as a basis for application in agricultural landscape in France. Agriculture, Ecosystems and Environment. **117**: 4-21. | France | Review of literature on constructed wetlands' nutrient removal efficiency. | Observed nutrient removal efficiencies varied greatly among study, particularly for phosphorus. |

**Duchemin and Hogue (2009)** assessed the use of fast growing trees to increase the phosphorus removal efficiency of buffer strips. Grass-only buffer strips were compared to buffers with a combination of grass and tree species and a control plot with no buffers. Concentrations of dissolved phosphorus, total phosphorus and suspended sediments were significantly lower in the grass and tree buffers than the grass-only buffer 30 days after the buffer implementation. However, both buffer designs proved to significantly reduce runoff velocity and increase infiltration capacities. These results suggest that the use of trees in buffer strips could compensate for the low efficiency typically observed in the first years of buffer strips. These trees could also represent an additional source of revenues and, hence, reduce the costs associated with the implementation of buffer strips.

**Dunn *et al.* (2011)** evaluated the effectiveness of Prince Edward Island's buffer zone regulations. Since 2000, all agricultural fields bordering watercourses are required to maintain a 10-meter (32.81 ft.) vegetated buffer zone for moderate slope areas (i.e., less than 5%), and a 20-meter zone (65.61 ft.) for steeper slopes. Sample collectors were placed at 44 locations at the end of the agricultural field (0 m) and down-slope in the buffers at a 10-meter (32.81 ft.) distance from the field edge. Additional sample collectors were placed in certain farms at distances up to 30 meters (98.4 ft.) from the field edge. Water samples were collected after major rainfall events and analyzed for pesticides and water quality metrics (e.g., phosphorus, nitrogen, suspended solids, pH). Water samples collected in the buffer, within a 10-meter distance from the field edge, showed significantly lower (52 to 88%) concentrations in aqueous and particulate pesticides (endosulfan, chlorothalonil, carbofuran, linuron, metribuzin, metalaxyl, mancozeb), as well as an average decrease of 34 percent in phosphorus concentrations and a 38 percent decrease in nitrate-nitrogen concentrations when compared to samples collected on field edges. Buffer zones were most efficient at trapping suspended solids (a 64% decrease). The authors noted, however, that the increased capacity of buffer zones to trap sediments implied a need for more frequent cleaning of the strips.

**Mayer *et al.* (2006)** reviewed 44 peer-reviewed studies that addressed the effectiveness of vegetation buffers in decreasing nutrient loadings in streams. A percentage of nitrogen removal effectiveness was calculated for each study, and the authors assessed the incidence of buffer width, buffer type and hydrology on this metric. The nitrogen removal effectiveness varied greatly between studies, but the overall performance was generally good (average nitrogen removal effectiveness of 74.2%). Buffer width, buffer type and hydrology all had a significant impact on the effectiveness level. Buffers were generally better at removing nitrogen in subsurface flow (average effectiveness of 89.6%) than surface flow (average effectiveness of 33.3%). In addition, forested buffers were generally better at filtering nitrogen than grassland buffers. Buffer width had little or no impact on the removal capacities of wetlands and forested buffers, but the efficiency of grasslands increased with buffer width. Buffers were generally effective when their widths were between 10 and 50 meters (32.8 and 164.4 ft), and higher efficiencies were achieved with 30-meter buffers. However, the authors could find very few studies that addressed the effectiveness of small buffers (less than 10 m). Finally, the authors provided a short review of regulations and recommendations developed across Canada and the United States. Canadian standards were slightly higher, as a width of 13.8 to 43.8 m were recommended (45.3 to 143.7 ft). U.S. state guidelines varied between 15.5 and 24.2 m (50.8 and 79.4 ft). Policies and regulations typically varied with slope, presence/absence of fish, and waterbody size.

**Giri *et al.* (2012)** modeled the potential impact of 10 BMPs on total phosphorus, total nitrogen and sediment loadings in the Saginaw River watershed in Michigan. The authors used the Soil and Water Assessment Tool (SWAT) to identify the major sources of sediment, phosphorus and nitrogen based on a set of physical and anthropogenic variables (e.g., weather, hydrology, pesticide use, land management practices) and established priority areas for the installation of BMPs. Results showed that the installation of native vegetation on the stream shore could achieve greater reduction in total phosphorus loadings than the other BMPs measured, including contour farming, terraces, conservation tillage and residue management.

**Dorioz *et al.* (2006)** reviewed scientific literature on riparian buffers' nutrients removal efficiency rate, and observed an important heterogeneity among nutrient removal and sediment trapping capacities measured in the different studies. Notably, the authors report that total phosphorus retention capacities varied from 8 percent to 97 percent between the different studies assessed. Important variation in dissolved phosphorus retention performance was pointed out as the main culprit for this important variation, as reported particulate phosphorus retention capacities were more homogenous. Total suspended sediment abatement varied from 53 percent to 93 percent, while nitrogen removal capacities were within 47 percent to 100 percent. In the light of their reading, authors noted that there seems to be an optimal width for buffer strips, over which not much gain is achieved. Buffer width does not influence sediment trapping capacities much (under average soil/climate condition, most of sediment are deposited within the first few meters) but has a greater incidence on dissolved phosphorus abatement and the deposition of particulate phosphorus bounded to fine particles.

## Scrubber boxes

### Description and pollutant removal mechanisms

Algae scrubber boxes have been successfully used to filter agricultural runoff, domestic sewage and industrial wastewater (Pizarro *et al*. 2006). They are composed of a combination of algae and microorganisms attached to a screen through which wastewater flows. Algae will uptake the inorganic components of wastewater (i.e., phosphorus and nitrogen) and transform it into organic compounds (mainly biomass) through respiration. Algae turf scrubbers have been used on large-scale projects in Florida and Texas, and are currently being trialed in Chesapeake Bay (Mulbury *et al.* 2010). Further, algae produced from this process could potentially be used as a byproduct for fertilization or animal feed and could, thus, represent an additional source of revenue for farmers.

### Construction and maintenance cost and effort

The cost-efficiency of scrubber boxes has received little attention. Pizarro *et al.* (2006) noted that implementation costs might be prohibitive on dairy farms where a pre-treatment of wastewater would be required, but no other studies were found that estimated construction and maintenance costs in other type of farms. Nevertheless, scrubber boxes present the great asset of being implementable directly on the stream bed, which minimizes loss of land available for agricultural production.

Table 5: Examples of Scrubber Boxes from literature

| References | Location | Subject | Findings |
|---|---|---|---|
| Mulbury, W., Kangas, P. and S. Kondrad. 2010. Toward scrubbing the bay: Nutrient removal using small algal turf scrubbers on Chesapeake Bay tributaries. Ecological Engineering **36**: 536-541. | Chesapeake Bay, United States | Use of small-scale algal turf scrubber to remove non-point source nutrients | Nutrient removal performance was relatively low compared to other studies. |
| Pizarro C., Mulbury W., Blersch, D. and P. Kangas. 2006. An economic assessment of algal turf scrubber technology for treatment of dairy manure effluent. Ecological engineering **26**: 321-327. | Maryland, United States | Economics of algae turf scrubbers | Operation of algae turf scrubber is costly when compared to profits generated by cow. The use of algae as byproducts could, however, represent a good avenue to decrease costs. |

**Mulbury *et al*. (2010)** conducted a trial of small-scale algal turf scrubbers for removing nonpoint source nutrients in three tributaries of the Chesapeake Bay. The $1m^2$ ($10.8\ ft^2$) algal turf scrubbers were put on docks to avoid tree shade, and monitored for 5 to 10 months. Results varied between tributaries. In the best case scenario, annual nutrient removal was equivalent to 380 kg of nitrates (66 pounds) and 70 kg of phosphorus (154 pounds) per hectare. Nutrient removal capacities were smaller than what was observed in other studies, which authors attributed to a smaller initial loading. Mean algal fatty acid production rate was relatively slow (23 to 54 mgFa $m^{-2}day^{-1}$), and thus unlikely to successfully compete with other forms of feedstock. The authors nevertheless concluded that the algae biomass produced could represent an interesting source of biofuel.

**Pizarro *et al*. (2006)** evaluated the potential costs associated with the implementation of algal turf scrubber treatment technology in a model medium-size (i.e., 100 cows) dairy farm. With their study, the authors were pursuing the following treatment goals: 1) concentrate and stabilize nutrients to facilitate their recycling or off-farm exportation, 2) operate algal turf scrubbers year-round, 3) filter water from a variety of effluents and variable concentrations in solid and nutrients, and 4) surpass a reduction of 80 percent in phosphorus and nitrogen at an overall cost of less than $5 per pound of nutrients ($11 per kg). Based on previous studies, the authors estimated that each hectare of algal turf scrubbers could filter the volume of manure produced by 92 cows, for an average algal production of 270 days a year. An anaerobic pre-treatment of manure could reduce the operational costs by 36 percent. The authors estimated that operational costs were of $454 per cow, $6.20 per kg of nitrogen removed, and $31.10 per kilogram of phosphorus removed. Operational costs are high when compared with the potential long-term annual profits generated by each cow ($500 per cow according to a study in Maryland). However, harvesting algae and biomass as byproducts could generate considerable profits that could cover or decrease the operational costs of implementing this technology.

## Bed load interception technology

### Description

Bed load is the heavier, larger-grain-sized sediment that bounces along the bottom of a stream. This material causes damage when it settles out in harbors or other critical areas and has to be removed at considerable expense. However, bed load material can be captured before it reaches these critical areas by creating a depression – also called a sediment trap – upstream of the critical areas, where it is trapped. Bed load interception is minimally disruptive to aquatic habitat and stream ecology. The efficiency of sediment traps has been questioned (Zorn 2012), but recent on-the-ground work has shown promising results (White 2014).

The University of Akron, with the financial support of the Cleveland Port Authority, recently tested the use of bed load sediment collectors in the Cuyahoga River at river miles 11.5 and 21 as a way to evaluate this technology to help reduce dredging costs. The collected bed load material was retrieved daily, and characterized for grain size distribution and toxicity. Results showed that the collectors could trap a good quantity of sediment, with a wide variety of grain size (White 2014). Bed load interception is significantly less costly than dredging and placement in confined disposal facilities (CDFs). Furthermore, toxicity level of the collected sediment was generally low (i.e., low content in arsenic, mercury and other contaminants), which would allow for a commercial use or reutilization of the collected sediments.

### Pollutant removal mechanisms

Bed load can be collected passively, relying on the natural energy of the river with minimal disruption to stream ecology, by deepening an area where the current is lessened naturally, such as a river bend, and the load is captured in the stream bed basin. The accumulated materials are periodically removed to maintain the efficiency of the structure.

### Implementation and maintenance cost and effort

In reviewing the limited studies available, bed load interception appears to be significantly less costly than dredging (and placing dredged materials in CDFs) as a way to remove sediments from streams, channels and harbors. In the Cuyahoga River bed load study, dredging was estimated to cost $13 per cu/yd, and placing the material in a CDF was approximately $16 per cu/yd. Bed load harvesting of sediment was estimated to cost $6-$8 per cu/yd.

Table 6: Examples of Sediment Traps from literature

| References | Location | Subject | Findings |
|---|---|---|---|
| U.S. Army Corps of Engineers. 2012. Sediment Trap Assessment – Saginaw river, Michigan. U.S. Army Corps of Engineers, Detroit District, Technical Report, 12p. | Saginaw River, Michigan | Sediment traps efficiency | Sediment traps are efficient for sand removal, but not for other type of material, and the traps have to be dredged annually in order to preserve optimal performance. |
| U.S. Army Corps of Engineers. 2001. Sediment Trap Assessment – Saginaw river, Michigan. Baird and Associates Technical Report, 18p. | Saginaw River, Michigan | Sediment traps efficiency | Length and depth of sediment traps can have an impact on silt and sand removal, but the traps are ineffective for clay. |

**U.S. Army Corps of Engineers (2012)** performed model analyses to assess the efficiency of sediment traps from three different sites on the Saginaw River in Michigan using data from 1989 to 1999. For all sites, sand was efficiently removed, but other types of material – clay and silt – were not. On the most optimal site for sand, the efficiency was around 60 percent for the first two years; however this efficiency declined with time. It was also determined that annual dredging would be required to preserve the optimal removal performance of the traps. Finally, because the model analyses were performed with historical data, changes in the hydrological conditions along the river might have an impact on the traps and should be taken into consideration for future analyses. The models should also be updated with more data to reduce the long-term variation of the hydrological conditions.

**U.S. Army Corps of Engineers (2001)** conducted an assessment of the efficiency of sediment traps of various sizes in the Saginaw River in Michigan, with widths of 490, 620, 690 and 787 ft, depths of 5, 10 or 15 ft, and lengths of 300, 600 and 1200 ft. They performed theoretical and numeric modeling of the traps and came to similar conclusions with both types of analyses. For sand, the efficiency of the traps varies from 12 percent to 62 percent for theoretical analysis and from 9 percent to 88 percent for numeric analysis. And the depth of the trap was found to have an impact on the efficiency of sand removal, but not the length. For silt, the efficiency varies from 5 percent to 22 percent for theoretical analysis and 4 percent to 12 percent for numeric analysis. Here, both the depth and length of the trap have an impact on the trap's efficiency for silt removal. For both analyses, the results show no removal of clay from the traps.

## Comparison of reviewed BMPs

In the following section, a comparison of the summarized BMPs is presented including the perceived advantages and disadvantages of each, the associated implementation and maintenance costs, and other important issues such as the complexity of installation and use, anticipated lifespan and land requirements.

Table 7: Relative advantages and disadvantages of reviewed BMPs

| BMP | Advantages | Disadvantages and limitations |
|---|---|---|
| **Constructed treatments wetlands** | 1. Reduces contents of heavy metals<br>2. Provides wildlife habitat<br>3. Aesthetic advantages.(i.e., visually attractive)<br>4. Reduces incidence of flooding downstream<br>5. Provides good control of channel erosion<br>6. Reduces odor of wastewater | 1. Plants need to be periodically harvested to maintain productivity<br>2. P retention capacities are reduced during periods of heavy rainfall and flooding<br>3. Less effective or nonoperational in winter months in northern states/provinces<br>4. Water level need to be maintained which implies a need for additional sources of water in arid areas or during drought<br>5. May require electricity to pump water |
| **Steel slag filters** | 1. Can be implemented directly in the streambed or other waterbody | 1. Filtration media needs to be in direct contact with water to work efficiently<br>2. May not be as effective or may be completely unsuitable for big streams with high runoff volumes |
| **Two stage ditches** | 1. Increases ditch stability which slows runoff and reduces erosion<br>2. Reduces flooding frequency<br>3. Reduces soil compaction creating better plant growing conditions<br>4. Lower maintenance costs than traditional trapezoidal ditch<br>5. Provides habitat for wildlife | 1. Higher construction costs than typical drainage ditches<br>2. Requires more space than typical trapezoidal ditches thus creating a greater loss of cultivable land |
| **Riparian buffer** | 1. Good pesticide removal capability<br>2. Provides streambank stabilization<br>3. Provides habitat for wildlife<br>4. Aesthetic advantages (i.e., visual enhancement of fields)<br>5. Potential source of additional revenues (e.g. wood, berries, feedstock for ethanol production) | 1. Greater potential release of phosphorus in late autumn-winter when plants are dormant.<br>2. Space requirements contribute to Loss in cultivable land |
| **Scrubber boxes** | 1. Implementable directly in the streambed<br>2. Potential secondary uses of harvested algae (e.g. biofuels, fertilizer) | 1. Algae need to be periodically harvested to maintain productivity<br>2. May not work as well during high flow periods or on larger streams |
| **Bed load interception** | 1. Low impact on environment<br>2. Collects sediment passively<br>3. Efficient for large-sized materials like sand | 1. Need to remove the accumulated material periodically<br>2. Not efficient for some materials like clay |

Table 8 shows a relative comparison of the construction and maintenance cost and effort, lifespan and land surface requirements of various in-stream BMPs.

Table 8: Comparison of construction and maintenance costs and implementation requirements of reviewed BMPs

| | Construction cost and effort | Maintenance Cost and effort | Lifespan | Land surface requirement |
|---|---|---|---|---|
| **Constructed wetland** | High | High | 25-50 years | Large |
| **Two-stage ditch** | High | Low | Over 30 years | Medium |
| **Reactive material** | Medium | Medium | Unknown | None |
| **Riparian buffer** | High | Medium | 30 years | Medium to High |
| **Scrubber-box** | High | High | Unknown | None |
| **Bed load interception** | Medium | Low | Unknown | Medium to High |

Table 9 depicts the removal capacities for nutrients, sediments and other water quality parameters for in-stream BMPs evaluated through this literature review.

Table 9: Relative efficiencies of reviewed BMPs

| | High Efficiency | Good Efficiency | Poor Efficiency |
|---|---|---|---|
| **Constructed wetland** | Total phosphorus<br>Dissolved phosphorus<br>Suspended sediment<br>Chemical oxygen demand<br>Biochemical oxygen demand<br>Pathogens | Nitrogen<br>Heavy metal | |
| **Two-stage ditch** | Total nitrogen<br>Suspended sediment | Particulate phosphorus | Dissolved phosphorus |
| **Reactive material** | Total phosphorus | Dissolved phosphorus<br>Heavy metals | |
| **Riparian buffer** | Suspended sediment<br>Particulate phosphorus<br>Pesticides | Total phosphorus<br>Total nitrogen | Dissolved phosphorus |
| **Scrubber-box** | Total nitrogen | Total phosphorus<br>Dissolved phosphorus | |
| **Bed load interception** | Suspended sediments* | Suspended sediments* | Suspended sediments* |

*Efficiency varies according to type of material and hydrologic conditions

## Summary Findings

The review of in-stream control methodologies for nonpoint source pollution to control erosion, reduce sediment and abate phosphorus runoff and the comparison of the various BMPs identified in the literature yielded a small number of findings that are valuable to decisionmakers and agency officials as they consider nonpoint source pollution and prevention and control options. These findings are presented below:

1. Construction and maintenance costs and complexity vary greatly among NPS control technologies and need to be considered along with other factors when selecting an appropriate BMP to address a specific problem.

2. Few NPS control technologies, except constructed wetlands, showed good to high efficiencies for both nitrogen, phosphorus and sediment removal. NPS control technologies should be selected as a function of runoff or wastewater type and the type and/or amount of the pollutant of interest.

3. The efficiency of BMPs is often scale-dependent. Certain BMPs, such as scrubber boxes or reactive materials, are best implemented in small streams or agricultural ditches. Constructed wetlands and riparian buffers have been showed to successfully treat greater runoff volumes, but require more land area in order to do so.

4. Constructed NPS control technologies that showed the highest efficiencies were generally more costly and required more land surface. The use of floating constructed wetlands (study by De Stefani and colleagues, 2011), could represent a good alternative to traditional constructed wetlands.

5. All BMPs generally achieved lower nutrient removal rates under high flow conditions, with the exception of two-stage ditches, which are specifically designed to trap a maximum of nutrients under floods. High-flow conditions are often associated with higher inputs in particulate phosphorus. This suggests that in-stream BMPs should be paired with BMPs that reduce phosphorus emission at the source.

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