(WQ) General

CHAPTER 37

Controlling Agricultural Runoff by Use of Constructed Wetlands

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INTRODUCTION

Protection of water resources has, until recently, focused on point source pollution as regulated by the Clean Water Act (CWA) of 1972. Point sources, such as municipal and industrial wastewaters, are easily identifiable and treatable based on their focused source. Non-point source pollution, mainly associated with storm water run-off from urban, agricultural, or mining land uses can be quite diffuse and difficult to treat. Non-point pollution is of sufficient quantity and diverse quality to have serious detrimental effects on regional water resources. The U.S. EPA's Report to Congress[1] stated that non-point source pollution contributed 76% of the pollution to lakes, and that the U.S. Agriculture was responsible for over half of the non-point source pollution.

In a survey of the Long Lake watershed in the St. John Valley of northern Maine, Bouchard et al.[2] found agricultural run-off to be the largest pollutant source to the lake. The survey documented an increased frequency of algal blooms in Long Lake, with agriculture-based activities contributing 64% of the total phosphorus load. As a result, the Soil Conservation Service, St. John Valley Soil and Water Conservation District (SWCD), and the Maine Department of Environmental Protection developed a watershed management plan for Long Lake that targeted the agricultural sources of phosphorus. The plan recommended that conservation techniques be applied by farmers to reduce run-off and pollutants. The St. John Valley SWCD estimated that conservation practices could reduce phosphorus loads to the lake by 10% and sediment loads by 25 to 30%.[3] In addition, the Soil Conservation Service designed treatment systems called Nutrient/Sediment Control Systems (NSCS) to improve run-off quality further. Four systems, consisting of sediment basins, grass filters, and constructed wetland-pond components, have been constructed in the Long Lake watershed.

Most constructed wetlands are designed to treat domestic wastewater and focus on biochemical oxygen demand (BOD) and nutrient removal, whereas systems for mitigating agricultural (cropland) non-point runoff are directed at sediment and nutrients. While many of the basic principles are the same, functional considerations will vary the actual design. The application of constructed wetlands to treat agricultural (cropland) run-off differs from those used to treat wastewater in several significant ways. The hydraulic loading is intermittent and a significant organic load is usually absent. Also, agricultural run-off carries a heavy sediment load and constructed wetlands alone would have a limited capacity to treat agricultural run-off effectively. Agricultural run-off can carry high nutrient and pesticide levels which can create a shock load to any treatment system. Design of a treatment system must consider these problems. When combined with other treatment components, a constructed wetland could be effective in treating the run-off.

SYSTEM DESIGN

The constructed wetland-pond system has, in series, a sedimentation basin, grass filter strip, constructed wetland, and retention pond (Figure 1) which discharges to a final vegetated polishing filter. Run-off collected and diverted from cropland first enters the sediment basin where the water is slowed and detained to allow larger particles to settle and to reduce the hydraulic impact on downstream components.

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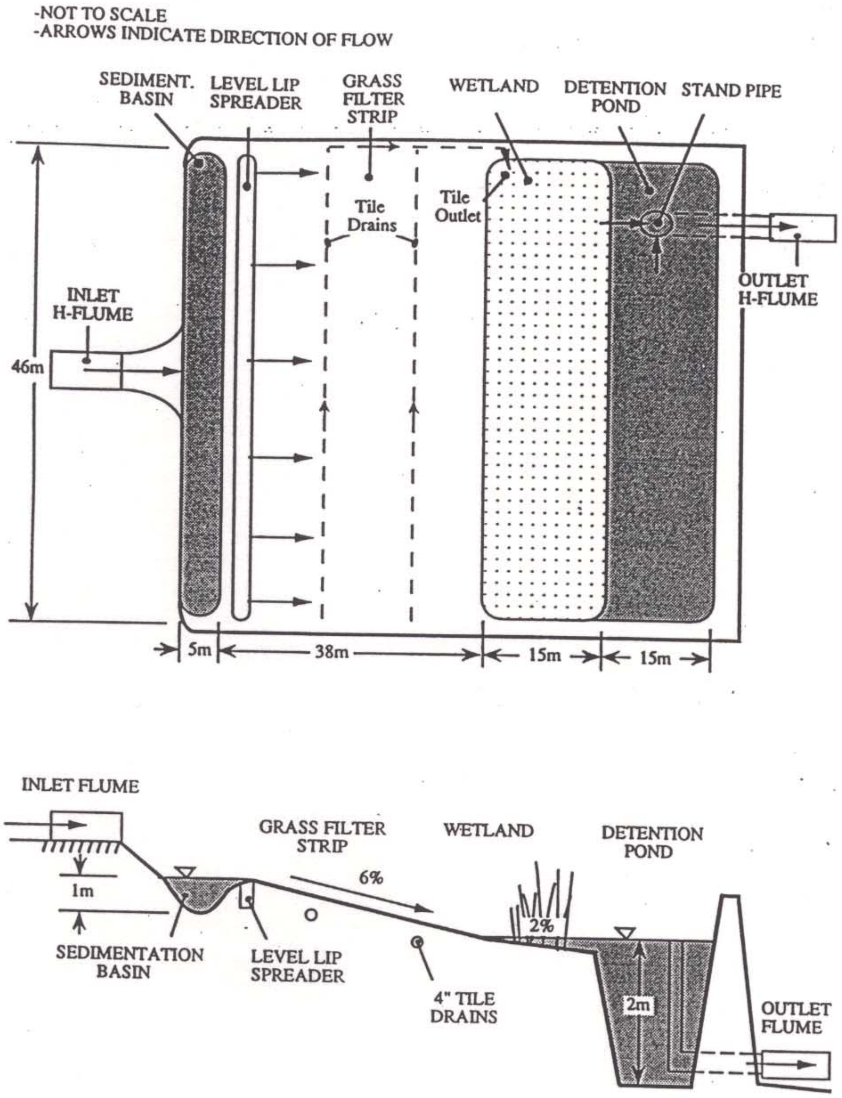

Figure 1. Plan-profile view of constructed wetland system to treat agricultural run-off.

Once the basin fills, the overflow enters a level lip spreader which is a 0.46-m deep, 0.6-m wide trench filled with crushed rock, The purpose of the level lip spreader is to distribute evenly the sediment basin discharge across the width of the filter strip, thereby reducing channelization and erosion of the grass filter strip. Drainage tiles were placed under the filter strip to promote infiltration of the run-off. Others have reported infiltration improved the efficiency of grass filters.[4,5] The water collected by the drainage tiles is discharged to the wetland in the southeast corner.

After flowing over the grass filter strip, the remaining run-off enters the wetland. The wetland vegetation further impedes flow, settling more particles; nutrients are adsorbed at the soilwater interface and are also taken up by plants and microbes. The floor of the wetland has a 2% slope. Finally, the water enters the retention pond. The pond, permanently flooded, gives greater retention times to settle smaller particles. The pond and wetland act as one integrated component because no barrier exists between the two components. The bottom slope increases to 2:1 at the wetland-pond edge, which defines the end of the wetland and beginning of the pond. The wetland-pond is stocked with small algaevorous fish and freshwater mussels. The diverse biological community creates a well-developed food chain which helps to remove nutrients from the water column. The water level in the wetland-pond is controlled by a standpipe which discharges into a 46-m long vegetated swale that drains to the lake.

The sequence of each component was carefully considered and the selected arrangement was developed specifically to address the unique problems associated with agricultural run-off. Recognizing that storm water run-off can be highly variable in magnitude and frequency, the system was sized to treat and contain many storm events in the first two elements. Since the run-off contains heavy sediment loads, the sediment basin was placed first to protect the downstream components from sediment overload. The grass filter strip was placed ahead of the wetland-pond to serve as an early indicator of the adverse impact of pesticides. In observing farming practices, it was found that the application of pesticides, herbicides, fungicides, and top killer often resulted in the killing of vegetation in run-off channels. A similar occurrence might jeopardize the integrity of the entire wetland/aquatic system. However, by locating the grass filter ahead of the wetland, the grass may be sacrificed to protect the downstream vegetation, depending upon how far through the system the toxic material moves. By placing the grass filter strip ahead of the wetland, an extra margin of safety is obtained. Further, it was reasoned that replacing the grass would be easier than replacing the wetland vegetation and other biota in the aquatic system.

The wetland-pond can also play a role in decreasing the impact of desorbed phosphorus. The soil pH in the potato fields is typically between 5 and 6.[6] At these pH levels, the soils have a greater ability to adsorb phosphorus.[7] When these soils are eroded to surface waters, which typically have a pH greater than 7, the soils' ability to hold phosphorus decreases, and phosphorus is desorbed. Originally, the SCS (Soil Conservation Service) planned to lime the pond and wetland to maintain the pH greater than 7, if necessary. However, the pH has remained greater than 7 without addition of lime. This allows desorption of phosphorus in the wetland-pond, where it can be assimilated by the diverse and abundant biological community.

The prototype system, denoted by the landowner's name (Tardiff), was built in 1988 and treats a 7-ha watershed cultivated mostly in potatoes. The land area covered by the system is 0.61 ha. The watershed has a 6% average slope, with moderately well-draining plaisted Howland soils, and is considered in good hydrologic condition according to an SCS field study.[8] Crop rotations usually contain 60% potatoes, with the remainder planted in small grains such as oats or millet. Diversions placed in the watershed direct flow to a culvert which flows underneath a road and into the system.

The sizing of the system was based in part on run-off calculations for the 7-ha watershed using the hydrologic method developed by the Soil Conservation Service[9] and on the capacity of a road culvert that carries water to the system. This culvert has a capacity of 0.9 m^3/s. If more flow results, it will continue past the culvert and bypass the system. The 0.9-m^3/s flow is approximately equivalent to the 10-year storm event for the watershed. The sizing of components is also partly based on similar constructed wetland-ponds used for municipal wastewater treatment. The USDA/SCS[10] currently has interim minimum sizing criteria based on watershed area. The cost of construction was about $14,000 for the entire system.

Vegetation in the grass filter strip was well established by spring 1989, having been seeded the previous fall, while the wetland was not planted until June 1989. Monitoring of the Tardiff system began June 17, 1989.[8] H-flumes were installed at the inlet of the sediment basin and the outlet of the retention pond (see Figure 1). The flumes were equipped with flowmeters and automated samplers which collect flow-proportioned composite samples during run-off events. The composite samples were analyzed for total phosphorus (TP), total suspended solids (TSS), and volatile suspended solids (VSS). In addition to the composite samples, grab samples were taken throughout several storm events to determine changes in pollutant concentration as a function of run-off. These grab samples were analyzed for TP, TSS, VSS, and dissolved phosphorus (DP).

RESULTS AND DISCUSSION

The constructed wetland-pond system combines the attributes of retention ponds, filter strips, and wetlands. The system approach incorporates design ideas based on the ecology of natural wetlands, in addition to design parameters already reported in the literature on the individual performance of ponds, filter strips, and wetlands. Although the design concepts for individual pond-wetland system components are available, the application and validity of these design parameters have not been studied as a system. Reed[11] makes this point for all constructed wetland systems, stating that there is "... no generally accepted consensus regarding design ... also (there is) no consensus on system configuration, and other details such as aspect ratio, depth of water to media, type of media, slope of bed, inlet and outlet structures." Thus, the monitoring program focused on assessing the overall efficiency of the system in terms of nutrients, hydraulics, and sediment retention capacity.

While monitoring began with the 1989 season, the data are not discussed in detail because only summer and fall seasons were monitored. The 1989 performance of the system was also limited by the fact that the wetland did not become fully established until late summer. For the period monitored (June 17 to November 20, 1989), removals were 92% for TP, 95% for TSS, and 94% for VSS.[8] Monitoring for the 1990 season began May 1 and in 1991 began April 26. Monitoring for both years ended in mid-November when the system froze over. The 1990 and 1991 data showed annual removal efficiencies of 82 to 91% for TP, 96 to 97% for TSS, and 92 to 94% for VSS.

Although the annual removals were good, seasonal removals varied considerably, with spring (April to May) flows actually exporting more phosphorus and sediment from the system than was imported (Table 1). As can be seen from Table 1, spring outflow was greater than inflow due to the high groundwater table which puts the system in a discharge area. During this time, groundwater surfaced in the system beyond the inlet monitoring station, but it was measured at the outlet monitoring station. Thus, more flow was measured exiting than entering the system. This groundwater flow was mostly intercepted by the under-drain tiles. The under-drain flow was grab sampled in spring 1991 to determine the phosphorus and suspended solids concentrations in the groundwater. These samples were only collected when no influent surface run-off was entering the system because the under-drains also collected water which infiltrated from the grass filter strip during run-off events. Discharge from the under-drain continued through the spring. The average concentrations were 0.010 mg/L TP, 0.008 mg/L DP, 0.6 mg/L TSS, and 0.42 mg/L VSS. These concentrations remained relatively constant during the periods of no inflow.

In order to calculate the pollutant mass balance for the spring season, the data from the inflow monitoring station was supplemented by the groundwater data. Measurement of the flow from the under-drain during 1991 showed that the under-drain flow was equivalent to the difference between inflow and outflow. For example, on May 10, 1991, the flow measured at the under-drain was 0.0012 m^3/s; the flow measured at the outlet in May 10 was 0.0013 m^3/s. This followed a 4-day period of no inlet flow so that the under-drain discharge represented groundwater flow. Therefore, the groundwater volume was approximately the difference between system inflow and outflow (direct precipitation on the system was considered offset by the evapotranspiration from the system). Using the measured concentrations and the estimated groundwater volume as outflow minus inflow, the spring mass inputs due to groundwater were determined and added to the spring influent mass. System performance was still negative after the groundwater input was added to the inlet measured values, thereby suggesting an internal source of phosphorus and solids. One possible source is leached phosphorus from dead and decaying plants and biota in the wetland and pond.[12] Another possible source could be the anaerobic release of phosphorus from bottom sediment in the pond since no dissolved oxygen was measured at the sediment-water interface during ice cover. Also, the spring overturn in the retention pond, coupled with wind mixing, could resuspend bottom sediments and phosphorus, which could then be washed from the pond by spring run-off. The large influx of groundwater could exacerbate the loss from the system. By May 28, 1991, outflow from the system had ceased; and on June 5, 1991, flow from the under-drain also stopped.

During the summer (June to August) of 1990, storage and evapotranspiration in the system held all incoming flow without discharge, thus 100% retention of phosphorus and sediment was recorded. During the summer of 1991, two storm events created outflow, but excellent removals were still achieved for the summer (99% for TP, TSS, and VSS).

Removals declined during both fall seasons (September to November) as outflow increased. During fall 1990, removals were 73% TP, 96% TSS, and 94% VSS. For the fall of 1991, removals were 83% TP, 95% TSS, and 88% VSS. High groundwater levels developed during the fall of both years, and similar to spring, more flow was measured exiting the system than entering; however, unlike spring, positive removals were maintained.

Grab samples from three 1990 storm events were analyzed for TSS, VSS, TP, and DP. Six storms were also grab sampled during 1991, along with one snowmelt event. Results from only one event will be discussed, since similar patterns were observed for all the events sampled. The run-off and subsequent outflow during August 19–20, 1991 (Figure 2) was the result of a 2-in. rainfall. As can be seen from Figures 3 and 4, influent TSS and TP concentrations followed the pattern of the hydrograph. Despite the variance for the influent concentrations, outflow concentrations remained relatively constant. Approximately 1102 kg TSS entered the system and 32 exited, a 97% reduction in TSS mass. Similarly, 4.55 kg TP entered, while 0.07 kg exited, a 98% reduction in TP mass. Although not shown in the figures, dissolved phosphorus concentrations remained

Table 1. Results of 1990-1991 Composite Sampling Programs

Season 1990	Flow in (m^3)	Flow out (m^3)	TP in (kg)	TP out (kg)	Percent removal	TSS in (kg)	TSS out (kg)	Percent removal	VSS in (kg)	VSS out (kg)	Percent removal
Spring	648	1767	0.06	0.13	—	7.3	8.1	—	3.4	7	—
Summer	292	0	3.06	0.00	100	1144	0	100	113	0	100
Fall	7296	12,295	4.63	1.26	73	3884	144	96	546	35	94
Total	8236	14,062	7.76	1.38	82	5036	152	97	663	42	94
Season 1991											
Spring	1387	7685	0.30	0.76	—	54	107	—	7	26	—
Summer	2023	743	12.4	0.11	99	3505	10.8	99	393	4	99
Fall	1526	3102	3.9	0.70	82	644	33.8	95	84	10	88
Total	4936	11,530	16.6	1.57	91	4203	152	96	484	40	92

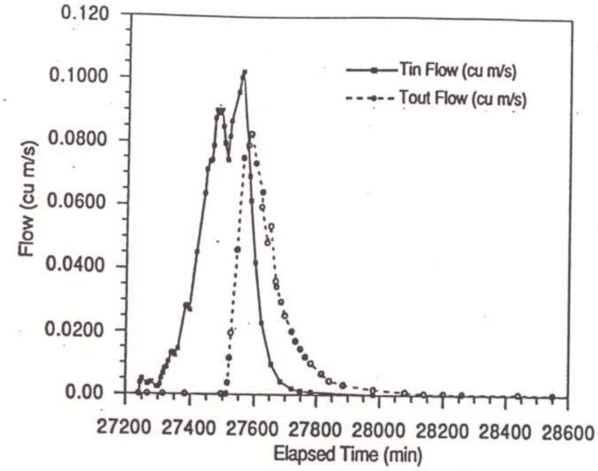

Figure 2. Inflow and outflow hydrographs for the storm of August 20–21, 1991.

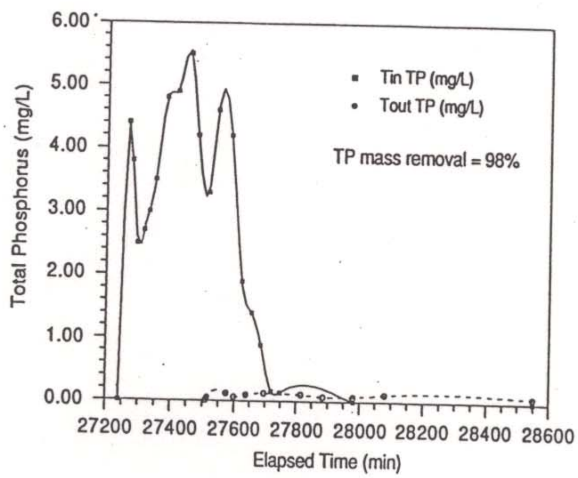

Figure 3. Inflow and outflow total phosphorus concentrations for the storm of August 20–21, 1991.

relatively constant in the influent and effluent. Mass reduction of dissolved phosphorus was 82%, and the flow weighted mean concentrations were 0.172 mg/L for the inflow and 0.047 mg/L for the outflow. The influent DP/TP ratio was 0.04, while the effluent ratio was 0.50. Similarly, the average influent VSS/TSS ratio was 0.11 and, at the outlet, the ratio was 0.16. Thus, a transformation of phosphorus and suspended solids species occurred within the system. Mitsch and Gosselink[12] described the function of wetlands to act as transformers.

Sediment accumulation was monitored annually in the sediment basin by measuring the depth of sediment overlaying the parent material placed during construction. Since the system began receiving flow (June 1989), 6.2 cm of sediment has accumulated in the sediment basin. The SCS[10] recommends sediment removal when accumulation reaches 30 cm to prevent overflow of solids into downstream components. To facilitate sediment removal by heavy machinery, an access ramp was constructed at the north end of the basin with a 10:1 slope. At the current accumulation rate, the basin will need to be dredged about every 10 years.

The accumulation of 6.2 cm sediment is calculated to represent 9500 kg sediment. The total mass of TSS measured entering the system since June 1989 was 17,000 kg. Therefore, the sediment basin retained about 56% TSS. The average TP concentration of the sediment was measured at 2300 mg/kg. Thus, the retained mass of sediment in the sedimentation basin is estimated to contain about 22 kg phosphorus. The total inflow of phosphorus to the system since June 1989 was 46 kg; thus the basin retained about 48% total phosphorus.

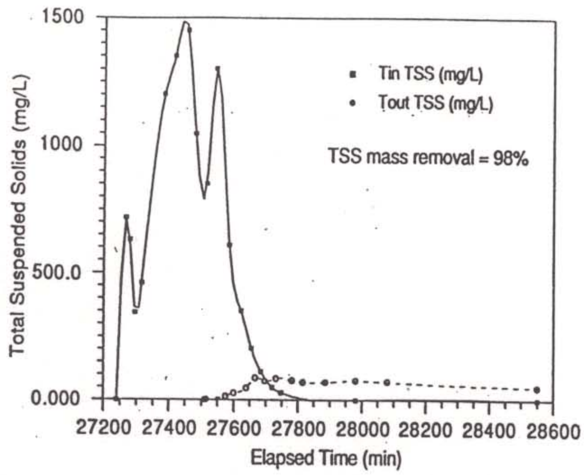

Figure 4. Inflow and outflow of total suspended solids for the storm of August 19–20, 1991.

Direct assessment of the grass filter strip efficiency was not performed because physical constraints did not allow for monitoring. However, observance of the filter revealed that channelization of flow occurred during large run-off events. This was due to the placement of the inlet relative to the sediment basin and grass filter. The inlet is perpendicular to the basin and once the basin is full, the flow has a minimal distance to travel before reaching the level lip spreader and grass filter (see Figure 1). Minimal reduction of the flow energy occurred in this distance, and the level lip spreader could not effectively distribute the flow across the width of the grass filter. The flow then channelized through the grass filter, directly across from the inlet. Aerial photographs of the system showed a noticeable enhancement of wetland growth along the flow path of this channel. Obviously, channelization reduces the effectiveness of the grass filter. Dillaha et al.[13] reported sheet flow was critical for adequate performance of a grass filter. Restructuring the flow path from the inlet would reduce channelization. The inlet could be placed at one end of the sediment basin. The flow path would then be parallel to the length of the basin instead of perpendicular, thereby increasing the travel distance of the flow and decreasing its energy.

The wetland was planted in the summer of 1989 with *Typha latifolia* at a density of 9 stems per square meter. In August of 1991, the mean density had increased to 31.6 stems per square meter. *Sparganium* sp. was also planted at the same time, but in 1 year had been mostly eliminated due to the vigorous growth of *Typha*. A stratified random sample of square meter quadrats (n = 15) revealed the mean tissue P density to be 805.5 mg/m^2 in the 980-m^2 wetland. Thus, the above-ground shoots and stems of the *Typha* in the wetland contained 0.8 kg phosphorus. This is only 5 to 10% of annual influent phosphorus mass measured during the study. Thus, recommendations for harvesting of wetland plants once a year during the fall or winter[10] would remove little TP from the system, especially during the recommended winter harvesting; by then, much of the phosphorus would likely have been translocated to the roots or leached from the plants.

The ability of constructed wetlands to remove phosphorus over long term appears to be limited, according to the literature.[11] Due to recycling of phosphorus from plants and other biota, long-term removal of phosphorus in constructed wetlands is limited to burial in sediments or accumulation in woody tissue. At best, constructed wetlands are typically able to remove 30 to 40% of incoming phosphorus.[11] The removal efficiency is important, though, when coupled with the removal of 48% TP by the sediment basin. The plants provide resistance to flow which will further reduce velocity and enhance sedimentation of smaller particles which have passed through the sediment basin. Settling of the smaller soil particles is important because they typically carry larger amounts of adsorbed material due to their larger surface area.[14] In addition, smaller particle size is indicative of cohesive soils such as clays and fine organic matter. Cohesive and organic soils have a much higher adsorption potential than noncohesive soils such as sand and gravel.[15,16]

Sediment collection cups placed on the bottom of the retention pond were annually monitored for sediment depth and TP concentrations. The sediment was typically fine, black, highly organic material with an anaerobic odor. Small leaf sections of *Typha* were found in the cups. An average of approximately 1.4 cm sediment was deposited per year in the pond. From the bottom area of the pond and sediment density, an estimated 6300 kg sediment was deposited on the pond bottom. However, a portion of this sediment was

Table 2. Cost Effectiveness of TP Reduction from Current Options

Treatment option	Cost/acre	Cost/kg TP removed
Conservation Reserve Program	$1250	
NSC System	$190	$500
St. Agatha POTW Diversion		$4350

biomass created within the wetland and pond, and does not represent only incoming sediment. Kadlec[17] reported that the generation of fine detritus litter occurs faster in wetlands receiving wastewater than in natural wetlands due to increased productivity and microflora and microfauna which die and accumulate in the bottom sediments.

The average phosphorus concentration of the sediment in the Tardiff pond was 913 mg/kg, which indicates the pond bottom contained about 5.7 kg phosphorus. This was 12% of the influent TP recorded entering the system during the 3 years of study. Unlike the sediment, phosphorus is not created within the system, although some was introduced by planting the ***Typha***, but it is likely negligible. Some phosphorus was also present in the material placed during construction; but since only the material that had been deposited in the collection cups was sampled, it is representative of the influent material.

Bouchard et al.[2] compared two other alternatives of phosphorus reduction to Long Lake: a $3 million sewage treatment plant diversion and the Conservation Reserve Program (CRP). The CRP pays farmers to convert highly erodible cropland to grassland for 10-year periods. Bouchard et al.[2] estimated CRP land gave equivalent reductions of phosphorus as the NSCS. Between the three alternatives being used in the Long Lake watershed, the constructed wetland-pond system is the most cost effective in removing phosphorus, as shown in Table 2.

SUMMARY

It should be stressed that constructed wetland-pond systems are supplemental to conservation practices to be used on the cropland. These practices are important in reducing pollutants at their source and also protecting the resources of the farmer. The constructed wetland-pond system functioned well during the monitoring period, with minimal maintenance. The sedimentation basin provides about half the total removal. Most summer storms are contained within the sedimentation basin alone, and it is during these summer storms that high sediment and phosphorus loads occur. Thus, for the amount of land required and construction cost, the sediment basin appears most effective since the majority of phosphorus was associated with solids. Typically, outflow during the summer is minimal. As a result, removals are highest during the summer. Reducing the input of phosphorus to Long Lake during the summer will likely diminish the risk of algal blooms.

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