Water-Quality Effectiveness of a Detention/Wetland Treatment System and Its Effect on an Urban Lake

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ABSTRACT / A newly installed combined detention/wetland stormwater treatment facility upstream from Lake McCarrons, Roseville, Minnesota, was monitored for 21 months to evaluate its effectiveness and the response of the lake to decreased phosphorus loads. The treatment facility consists of a 1.0-ha detention pond that discharges into a series of six constructed wetland "chambers." Data from snowmelt and rainfall events are presented for several pollutants. Results show good reductions for most pollutants. Discussion on the facets of the system's operation are presented. Data from the lake show very little change in its water quality from three years prior to restoration (1984–1986) to three years following restoration (1987–1989): the lake's phosphorus and chlorophyll has actually increased.

The McCarrons wetland treatment system (MWTS) is a runoff management facility (Figure 1) consisting of a detention pond, followed in-line by six "chambered" wetlands (wet marshes) (Table 1), discharging to Lake McCarrons in Roseville, Minnesota. The system was constructed by the City of Roseville as a Clean Lakes (Section 314) project to improve the quality of surface water draining a fully developed urban watershed. Prior to construction, the area was a long, narrow wetland with a well-entrenched channel that moved surface water rapidly through with little vegetative contact and essentially no detention.

The MWTS was designed to achieve a 75% reduction in the total phosphorus (TP) load from this watershed (Donohue 1983). As a result of this substantial anticipated reduction, we expected that improvements in the lake's water quality would have been observable almost immediately. The measured change in the short-term (two years) phosphorus loading regime through the MWTS and its immediate impacts on the water quality of Lake McCarrons are examined here.

Methods

Surface water quality data collection focused on rainfall and snowmelt runoff events. Flow was continuously monitored from September 1986 through May 1988 and was automatically sampled during 21 rainfall and four snowmelt events at the outflow of the detention pond and at the wetland system outflow (Figure 1). The tributary stations were all sampled manually during events. Event samples were flow-composited and analyzed for total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), total phosphorus (TP), dissolved phosphorus (DP), total Kjeldahl nitrogen (TKN), nitrate nitrogen (NO_3) and total lead (TPb). This report focuses on TSS, TP, and DP; discussion of the other pollutants can be found in the completion report (Oberts and Osgood 1988).

Base flow samples were taken four times during the study; sediment samples were taken within each of the wetland chambers and the pond; and several water samples were taken before project construction was complete. Wet and dry atmospheric input was calculated using data from previous council sampling (Oberts 1982). Pollution loading to the MWTS was determined based on the data collected during 21 of the 57 rainfall events that occurred, four snowmelt events, and base flow. The event mean concentrations at each site for the constituents discussed are listed in Table 2.

Lake McCarrons was sampled from May 1984 through October 1989. The lake was sampled at its deepest spot every two weeks during the open-water seasons and monthly during several winters. Temperature and dissolved oxygen were measured at 0.5- to 1-m intervals (open water), or at larger intervals under the ice, using a Yellow Springs, Inc. model 57 (1984–1987) or model 50 (1988 and 1989) oxygen–temperature meter during open water and by Winkler titrations and a mercury thermometer during the winter. Transparency was measured using a 20-cm black-and-white Secchi disk.

Water was collected from the lake surface (0–2 m) during the open-water seasons using a 2-m-long PVC pipe that held 2 liters of water. Three such grabs were

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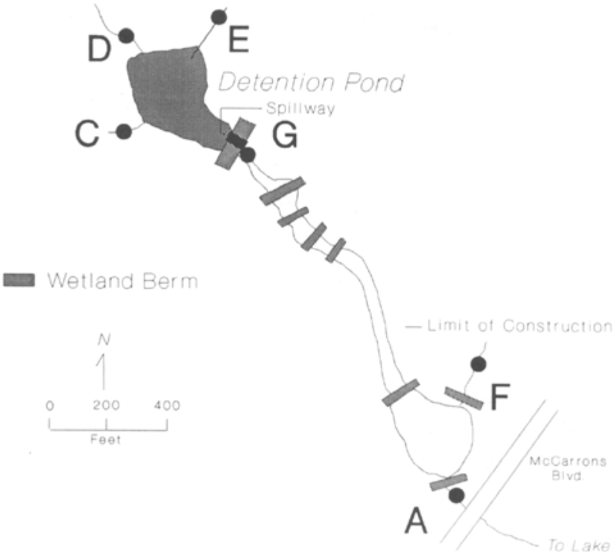

Figure 1. Lake McCarrons wetland treatment system with monitoring sites.

Table 1. Characteristics of the McCarrons wetland treatment system.

	Pond	Wetland
Surface area (ha)	0.97 (1.2 at crest)	2.5
Tributary area (ha)	220[a]	38
Permanent storage volume (m^3)	3415 (design, Sept. 1986)	6685 (design)
	2805 (study end, May 1988)	
Maximum depth perm.stoarge (m)	0.8	Varies by chamber from 0.15 to 0.6
Flood storage volume (m^3)[b]	8905	4940

[a] Area decreases to 143 ha when portion of one tributary retained in upstream pond.

[b] Does not include permanent storage volume.

mixed in an 8-liter plastic jug. Three 2-liter Van Dorn grabs from 0.5-, 1.0-, and 1.5-m depths were mixed to composite the surface sample during the winter. Water from this sample was withdrawn for the following chemical analyses: TP, DP, TKN and chlorophyll *a* (CLA). Subsurface samples were grabbed with a 2-liter Van Dorn bottle to be analyzed for TP.

Results and Discussion

Effectiveness of Treatment System

Pond. Flow into the MWTS begins with three tributary inputs to a detention pond that has a permanent pool surface area of 0.97 ha and a crest surface area of 1.2 ha. This pond serves as a major settling point for solids. The pond had a design crest or overflow volume of 12,320 m^3 (10.1 acre-feet) and a permanent pool volume of 3415 m^3 (2.8 acre-feet). After 21 months of operation under generally low precipitation, the volume at crest overflow decreased by 5% and the permanent storage volume by 18%, while the average depth of the permanent pool decreased by 7.5 cm and the maximum depth decreased by 10 cm.

Any storm greater than 1.27 cm will generate sufficient runoff to displace the entire volume of *design* permanent storage (3415 m^3). If the latest measured permanent storage is considered (2805 m^3), it would take only 1.02 cm of rain to displace the storage. Total displacement of storage, however, does not have to occur for the influence of an inflow to be seen at the outflow. Even though the detention pond is fairly well mixed, its small size means that runoff water will find its way from inflow to outflow in a very short period of time.

Table 3 illustrates the effectiveness of the pond's treatment for rainfall events only and for the snowmelt plus rainfall events. The "event efficiencies" are based on the mass inflows and outflows for each event, summed over the entire period of study. Although these efficiencies were determined on a total mass-through basis, they are essentially equivalent to the "regression efficiencies" that would be determined by plotting the slope of an inflow–outflow regression line, an analytical method proposed by Martin and Smoot (1986). Driscoll (1986) criticizes the use of inflow–outflow mass balances on a single event basis as being unrelated to total annual performance. In a situation such as MWTS, however, this method better describes efficiency. The MWTS is essentially a flow-through system; that is, the permanent storage in the system is very small and inflowing runoff moves quickly to both pond and wetland outflows. Although it is true that a certain portion of the initial outflowing water is leftover, quiescently settled water from the previous event, this volume and mass is a slight portion of the event total. For example, a typical summer event of 1.55 cm on 28 June 1987 resulted in a TP load to the detention pond of 2.67 kg. Outflow load during the period of storm-influenced flow was 0.78 kg, yielding a decrease in event load of about 70%. After each event, this one included, base flow immediately resumes and tributaries contribute little or no flow to the pond. Prior to the next event (5 July), an additional net 0.07 kg of TP left the pond. This mass represents less than 4% of the TP retained in the pond during the 28 June event. The event efficiency of the

Table 2. Event mean concentrations for monitored events

		Event mean concentration (mg/liter)[a] min max								
Site	Events	TSS	VSS	TP	DP	COD	TKN	NO_3	TN	TPb
A	25	29	10	0.22	0.10	39	1.09	0.28	1.36	0.010
		1	1	0.08	0.04	20	0.60	0.10	0.85	0.001
		205	53	0.52	0.22	152	2.75	0.80	3.55	0.050
C	15	240	73	1.44	0.25	185	3.32	0.66	3.98	0.095
		32	4	0.45	0.08	62	2.25	0.30	1.60	0.018
		1450	406	9.40	0.51	814	9.50	2.10	8.50	0.520
D	20	604	246	0.71	0.14	345	5.00	0.63	5.64	0.137
		20	7	0.10	0.05	33	0.40	0.20	0.60	0.014
		3240	1690	1.80	0.28	2030	18.00	1.50	9.85	0.530
E	16	269	67	0.76	0.29	196	2.59	0.72	3.30	0.087
		36	12	0.16	0.07	29	0.50	0.26	0.80	0.012
		2400	416	3.40	0.45	1060	8.50	1.65	9.05	0.220
F	14	260	67	0.72	0.37	243	2.87	0.69	3.56	0.076
		48	6	0.24	0.16	32	1.00	0.20	1.40	0.007
		1720	416	2.50	0.65	808	7.00	1.65	8.23	0.290
G	25	63	15	0.27	0.10	58	1.41	0.35	1.76	0.024
		3	1	0.05	0.03	20	0.50	0.10	0.60	0.002
		171	48	0.52	0.26	195	3.00	1.10	4.10	0.110

[a] TSS = total suspended solids, VSS – volatile suspended solids, TP - total phosphorus, DP total dissolved phosphorus, COD – chemical oxygen demand, TKN = total Kjeldahl nitrogen, NO_3 – nitrate nitrogen, TN total nitrogen, TPb - total lead.

Table 3. Treatment efficiency (percent removal) of the McCarrons wetland treatment system

Constituent	Pond	Wetland	System[a]
Rainfall events			
TSS	93	84	96
VSS	94	82	96
COD	88	63	89
TP	79	32	77
DP	57	15	48
TKN	78	28	78
NO_3	62	24	64
TN	76	27	76
TPb	88	74	93
Rainfall plus snowmelt events			
TSS	90	83	96
VSS	92	81	95
COD	82	66	89
TP	73	41	78
DP	52	30	56
TKN	70	36	76
NO_3	51	35	63
TN	68	35	74
TPb	78	73	90

[a] Reductions not additive because of tributary and overland inflows into wetland.

pond then is considered 70%, with the additional 4% considered a portion of the base flow contribution, which requires a different approach to management.

Discussion of the effectiveness of the treatment system focuses on solids and nutrients, since these pollutants were the major items of concern in the diagnostic study. Over 90% TSS removal occurred in the pond, indicating that substantial settling occurs. This is the dominant factor in the pond's rapid loss of capacity over the short-term study.

Reductions of over 70% in TP (Table 3) were greater than would be expected by application of prediction methods developed by Walker (1987). The Walker prediction of effectiveness for the McCarrons pond, with a relative volume of 0.8 cm and hydraulic residence time of 0.01 year would be 30%; when the effectiveness is predicted based on the ratio of pond area to impervious watershed area, the Walker predicted value is about 35%. The McCarrons detention pond was designed well below the criteria suggested by Walker for a basin in a watershed of this size, yet a substantial reduction in TP is seen. A similarly unexpected load reduction of 57% occurred for DP.

There are three possible explanations for the very good solids and phosphorus reductions in the pond. First, the three tributaries to the pond are spread equidistantly around the pond (Figure 1), thus dissipating the intense energy of the runoff. Dissipation of this inflow energy helps settling by taking advantage of the full volume of the pond. In spite of this, however, there is direct movement from inflow to outflow, as noted previously.

Table 4. McCarrons wetland treatment system sediment samples

		Percent of total		Concentration (mg/kg dry weight)			
Site	Date	Total solids	Tot. vol. solids	Total P	Total Fe	Total Al	Total Pb
Pond A	9/4/86	15.7	10.4	185	5025	2898	14.5
Pond B		36.0	11.1	800	8928	4339	34.5
Wetland 4		50.7	9.2	435	19084	11000	69.6
Wetland 3		20.2	11.2	305	5519	5020	24.6
Wetland 2		62.1	5.1	390	14863	8052	117.0
Wetland 1A		47.1	8.7	640	24968	18195	138.0
Wetland 1B		41.2	7.2	555	15136	11867	60.6
Outlet A		32.3	8.1	575	20464	14263	98.1
Outlet B		50.5	7.2	560	23109	13075	134.0
Outlet C		31.2	9.1	550	23529	11147	57.5
Pond A	6/15/88	29.2	7.4	227	4715	2193	45.7
Pond B		39.2	8.8	409	4804	2696	36.8

The second important factor appears to be the DP:TP ratio. Most phosphorus in the surface water flowing into the pond is particulate (DP < 20%) and thus easily subject to settling. Most of this settled phosphorus appears to stay in the pond. The DP:TP ratio at the pond outflow increases by about 15%.

The third reason suspected for the high removal of phosphorus in the pond relates to complexing of phosphorus with organic and mineral soils flowing into the pond and to the composition of the soils from which the pond was scoured. Solids flowing into the pond are a mix of mineral and organic soils, which tend to readily adsorb available phosphorus and settle it. The pond bottom was scoured from sapric (highly decomposed) peat. Soils were characterized to a depth of 76 cm over the entire wetland treatment system at the beginning of the study, and ten samples were collected for physical–chemical analysis. Research conducted on wetland soils by Richardson (1985) shows that phosphorus retention can be greatly influenced through geochemical adsorption by extractable aluminum (Al) and iron (Fe) minerals. Table 4 shows that the two pond sites are relatively low in Al and Fe compared to the downstream wetland sites; however, the peaty soils at the pond, where still exposed, likely have more sorption capacity available than soils downstream that have been exposed for longer periods. The data show differing phosphorus content in the pond, possibly indicating that the sorptive capacity of these newly exposed soils has not been reached. As noted by Richardson, however, at high loading rates, saturation occurs within several years and phosphorus uptake is greatly reduced. This, coupled with the fact that the peat is being buried by inflowing sediment, points to a reduction of this mechanism as an important factor in phosphorus reduction as time goes on.

An analysis of the pond was done to see if there were any dominant hydrologic factors associated with rainfall events that seemed to be controlling water quality in the pond. The load reduction percentages for each constituent by season (spring, summer, or fall) for each event were run in a stepwise regression as dependent variables against a suite of independent hydrologic variables consisting of rainfall depth, duration, and intensity; pond inflow volume and hydraulic detention time; and time since last rainfall more than 2.5 mm. The dominant hydrologic variables leading to increased efficiency in the pond for the fall season were rainfall intensity and hydraulic detention time. These variables are also important in increasing efficiency in the summer, along with the time since the last rainfall greater than 2.5 mm. Spring effectiveness, however, is almost totally dominated by the total amount of precipitation in the event and by rainfall over 2.5 mm. The fact that increased intensity shows up so significantly in the summer and fall is most likely related to the previous discussion of settling. During high-intensity storms, a large amount of debris is picked up from urban surfaces and moved along with stormwater until quiescent waters of the detention pond are reached. It is easier to show good reductions from highly concentrated inflows than it is from relatively clean inflows. The hydraulic detention time variable reflects the importance of increased detention time in the reduction of both settleable and soluble pollutants. The spring responds to different hydrologic variables, but with some similarities. The nearly total dominance of precipitation depth indicates again the phenomenon of greater pollutant reductions occurring from larger, more intense storms with higher pollutant concentrations.

Reduction efficiencies are noticeably lowered during the snowmelt (Table 3) when detention ponds are covered by ice, wetlands are biologically nonfunctional, and infiltration surfaces are frozen to some degree. The performance of detention ponds and wetlands during the winter in northern climates can be improved by drawing down water levels before freeze-up to avoid pressurized under-ice flow and over-ice flow with no settling depth, diverting meltwater around wetlands that could be sources of nutrient inputs, and, providing maximum depth at the outlet structure to minimize scour as pressurized meltwater emerges from under the ice.

Wetland. The postdetention wetland system was intended to "polish" the water released from the detention pond before it reached Lake McCarrons. Throughout this discussion, it is important to remember that most of the water entering the wetland system comes from the pond and has, therefore, been pretreated; however, overland flow and tributary site F also flow into the wetland system downstream from the pond. Table 3 shows that smaller load reductions are seen in the wetland for every monitored constituent. The reductions for the solids-related constituents are generally similar to values seen in the pond, but the reductions for nutrients are less.

Apparently the reduced nutrient efficiencies are due to their return through biological processes as part of the physical–chemical–biological treatment system. Biological contact in the wetland system is greatly increased because the shallow storage depths and widespread nature of the chambers allows water to spread out and come into contact with dense vegetation. This supplements the physical settling and filtration and the chemical interaction between water and soil. Although often promoted as efficient sinks for nutrients, Howard-Williams (1985), Richardson (1985), and Hemond and Benoit (1988) point out that wetlands can also periodically release previously removed nutrients. In four small events, there was a net increase in TP as stormwater passed through the wetland. The four contributing events occurred during senescence in late summer–early fall, when decaying vegetation released nutrients.

Richardson (1985) stresses the importance of extractable Fe and Al in retaining phosphorus in wetlands. The McCarrons wetland system has a high Fe and Al content in its relatively undisturbed interbedded peat–mineral soils (Table 4). These soils may be fairly well saturated with phosphorus at the sediment–water interface, however, as indicated by the nearly uniform sediment TP content of the wetland soil samples. Sediment phosphorus retention capacities were not analyzed as part of this study.

The DP fraction in runoff is reduced by vegetative and biotic uptake and by various chemical reactions with soil. Seven events contributed DP and an additional three were relatively even; these events do not appear to be seasonally distributed. In fact, some of the best reductions occurred in the fall during senescence, while contributions occurred in the spring and summer when uptake of DP by vegetation would be expected.

The wetland outlet was completely frozen during the winter of 1987–1988, allowing base flow and the early portion of melt to build up behind the outlet berm. Data on performance of the wetland during the snowmelt must be viewed with caution. Sediment and debris accumulated on and in the ice during the winter and into the melt period. Even though the outlet culvert eventually opened to free flow, a substantial amount of runoff debris and associated pollutants were left behind in the outlet wetland. Loading for the first postmelt rainfall event (24 March 1988) shows that treatment levels in the wetland were the lowest observed; a maximum reduction of any pollutant was only 34%. The outlet wetland was, in fact, flushing itself of accumulated winter debris. The next event, 2–3 April 1988, showed a marked improvement in treatment, but reduction levels were still below those seen in any other nonmelt event. Unfortunately, no subsequent events were sampled, so we are not sure how long the wetland took to rid itself of accumulated debris. It can be stated, however, that deceptively high pollutant reductions can be undone by subsequent events that flush accumulated material.

System. Data collected for the wetland treatment system show that the best overall reductions are for pollutants associated with solids and with the particulate portion of the nutrient load. Soluble nutrients are not as easily removed because of their tendency to move quickly through the system.

It is apparent that most of the treatment in the MWTS occurs in the detention pond. In order to see if there was a statistical difference between inflow to the pond and outflow from the pond, and between inflow to the wetland and outflow, a series of statistical tests were run on the concentrations of the respective events. Results using the nonparametric Mann-Whitney T statistic show that the event mean concentrations of the inflows to the pond are significantly higher than the outflows ($P < 0.05$) for all constituents. The event mean concentrations for the inflows to the wetland are significantly higher than the outflows for TSS, TP and NO_3, but not for DP, TKN, or TN. Long-term removal of DP, TKN, or TN does not, therefore, appear to occur as a result of the wetland

Table 5. Annual water and phosphorus budgets.

Year	Water income (10^3 m^3)	Phosphorus income (kg)
1984	858	522
1985	683	387
1986	754	446
1987	399	195

polishing the water from the pond and intermediate inflows to the lake.

It is expected that the treatment role of the wetland system would become increasingly stressed as the pond fills and loses some of its ability to treat inflow, thus emphasizing the need to regularly remove the sediment from the pond. Unfortunately, the system has not been well maintained and has become visually degraded during the summer of 1989. We measured a loss of 18% in the permanent storage pool during the course of the study and observed several incidents of berm failure, which to date have not been repaired. We expect that this lack of maintenance has resulted in the decreased treatment efficiency of the MWTS.

Response of Lake McCarrons

The annual water and phosphorus budgets for Lake McCarrons are summarized in Table 5 (Oberts and Osgood 1988), where the water income includes direct precipitation and surface runoff and the phosphorus income (to the surface of the lake) includes inputs from the atmosphere, inputs from macrophyte transport (estimated from literature values), and inputs from surface runoff. The incomes for 1988 and 1989 were not measured in this study; however, 1988 was very dry and the water and phosphorus inputs to the lake were probably much lower than in 1987; and the water and phosphorus loadings in 1989 were probably intermediate between 1987 and 1988.

Lake McCarrons had greater phosphorus concentrations in the years following the wetland treatment (Table 6) despite the lower inputs of phosphorus. Other trophic state indicators, nitrogen, chlorophyll *a*, and Secchi disk transparency have also not improved (Table 6). Nitrogen and chlorophyll appear to have increased and the Secchi disk transparency has decreased since 1984 (Table 6). In addition, no quantitative or qualitative changes in the phytoplankton community have occurred throughout the study (Oberts and Osgood 1988).

Table 6. Trophic state indicators, Lake McCarrons: May–September surface averages

	1984	1985	1986	1987	1988	1989
Total phosphorus (mg/m^3)	38	34	28	46	61	34
Total dissolved P (mg/m^3)	—	17	—	19	27	—
Total Kjedahl N (g/m^3)	1.08	0.97	0.82	1.11	1.38	1.01
Chlorophyll *a* (mg/m^3)	20	16	14	26	30	17
Secchi disk (m)	2.3	2.1	2.8	1.8	1.3	1.8

A more complete analysis of the response of Lake McCarrons appears elsewhere (Osgood 1989). Briefly, Lake McCarrons appears to be insensitive to the external inputs of DP to its summertime epilimnion. Since the lake is so strongly thermallly stratified, inputs of internal phosphorus to the epilimnion do not occur during the summer. Also, the three postrestoration years were abnormally dry, which affects the water loading to the lake. We estimate that the MWTS under normal hydrologic conditions would reduce the lake's summertime epilimnetic TP concentrations by 8% (Osgood 1989). However, due to the rapid degradation of the MWTS that we have observed, this may overestimate the long-term benefit to the lake.

The temperature of the inflow to the lake may have increased as a result of the project. Since we have no data, this is a hypothetical analysis; however, we believe it should be considered. Prior to the project, the flow through the project area occurred very quickly through a channel. Following the construction of the outlet berm, there were standing pools of water along the stream. We assume that the temperatures of these pools increased relative to the runoff during nonrunoff periods. During a runoff event then, the runoff water would mix with the pooled water and the overall temperature would increase. Normally this effect may not be important; however, Lake McCarrons is very stably stratified during the summer. If the temperature of the runoff was even slightly cooler before the project, it may have plunged and may have become entrained at the level of the thermocline, and therefore may not have been available to the epilimnion. Following the construction of the MWTS, the warmer interflow would more readily mix with the surface waters. This may explain inverse response of the lake to reduced phosphorus inputs.

Conclusions

The overall goal of reducing TP load to Lake McCarrons by 75% from the wetland watershed was achieved through the installation of the MWTS. Although the 21-month period of study had unusual precipitation conditions, a representative series of snowmelt and rainfall runoff events was collected.

Even though the pond seemed to be underdesigned, it worked better than expected and was responsible for most of the treatment that occurred within the system. Enhanced performance of the detention pond appears to be due to diffuse inflow from tributaries, a high percentage of easily settleable particulates, and newly exposed peat soils that appear to readily adsorb TP. The pond lost 18% of the permanent storage and 5% of the total storage to sedimentation, which could have been avoided by presettling of coarse-grained particulates. The treatment system is likely performing as well as can ever be expected because of its recent construction and its observed rate of disrepair. Maintenance of the system is required if treatment ability is to be kept high.

The dominant hydrologic factors increasing pollutant removal efficiencies of the pond in the fall are rainfall intensity and hydraulic detention time. These same variables, as well as time since last rainfall greater than 2.5 mm, dominate in the summer. Spring effectiveness is almost totally dominated by the amount of precipitation in the event and by the time since last rainfall greater than 2.5 mm. These variables relate to the buildup of pollutants on urban surfaces and the energy with which these surfaces are washed off; that is, intense storms easily mobilize pollutants that have accumulated between events. Treatment facilities then show good pollutant removal percentage because the inflowing runoff is so highly concentrated.

Treatment efficiencies are lower for the wetland part of the MWTS because of pretreatment by the detention pond. Solids-related pollutants are removed efficiently by the wetland chambers, whereas nutrients, particularly soluble components, are less effectively removed. Vegetative decay and associated nutrient release is evident during senescence. Treatment might be enhanced by alternating chamber outflow, replacing culverts with riprapped swales, providing drawdown and diversion capability, harvesting vegetation, or providing more permanent pool volume in the chambers. We also have observed that the efficiency of the system has decreased rapidly as a result of lack of proper maintenance.

Ice and snow hamper the ability of detention facilities, as runoff is forced into pressurized sub-ice flow and unsettleable over-ice flow. In wetlands, the winter conditions mean that a minimum amount of biological activity will occur. Snowmelt and spring rainfall runoff events following melt can "flush" debris settled above the ice and incorporated into various layers of ice during the winter. Runoff treatment systems can be designed to minimize the effects of winter.

The MWTS did reduce the phosphorus load to Lake McCarrons, but the water quality of the lake is unchanged. The TP concentration of the lake surface waters, other trophic state indicators, the rate and extent of oxygen depletion, and the lake's plankton community structure are all essentially unchanged. Considering TP loading alone, there should have been substantial improvements in the lake's quality with the reductions that have occurred. However, the lake is more responsive to summer loads of dissolved phosphorus, which were reduced to a lesser extent by the MWTS. It is possible that the increased temperature of the outflow from the MWTS prevents the runoff from becoming entrained below the lake's thermocline, thus allowing more of the inflow to become available to the lake's surface waters; however, this hypothesis was untested. We expect that under normal hydrologic conditions, the summertime surface TP concentration would be reduced by 8% as long as the MWTS continues to perform as effectively as it did during this study.

Finally, we believe that the disproportionately low response of Lake McCarrons to a measurable reduction in phosphorus load is a general occurrence (Oberts and others 1989; Osgood 1989). We have found other watershed treatment systems (wetlands, ponds) to be similarly effective, but most other lakes in our region to be less responsive. The reduced responsiveness of the lakes is due largely to the more general occurrence of internal phosphorus loading affecting the lakes' summertime epilimnetic phosphorus concentration (Osgood 1988). We are *not* recommending that the use of watershed treatment systems be discontinued; rather, we believe that their limitations relative to immediate lake water quality improvement be acknowledged and that the use of in-lake management techniques be considered as part of a comprehensive lake management plan.

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