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INITIAL PERFORMANCE OF A HIGH CAPACITY SURFACE-FLOW TREATMENT WETLAND

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Abstract: The Columbia Wastewater Treatment Wetland ("Columbia Wetland") is a constructed cattail wetland in the Missouri River floodplain outside Columbia, Missouri, USA. The wetland receives mixed primary and secondary effluent ($\approx$60,000 m^3 d^{-1}, BOD_5 $\approx$30 mg L^{-1}, TSS $\approx$13 mg L^{-1}, NH_4-N $\approx$8 mg L^{-1}) from a conventional treatment plant. During its first 6 years of operation (October 1994 through November 2000), the wetland received loadings of BOD_5, COD, and NH_4-N averaging 50, 83, and 12 kg ha^{-1} d^{-1}, respectively, of which averages of 74%, 30%, and 17%, respectively, were removed from the effluent. TSS (mean loading = 21 kg ha^{-1} d^{-1}) frequently increased in the wetland due to erosion and disturbance by waterfowl, but TSS removal efficiency increased with time and the development of macrophyte biomass and averaged 30% by 1998. The wetland typically removed >97% of fecal coliforms and fecal streptococcus, 36% of TN and 4% of TP. In comparison to other large treatment wetlands, BOD removal by the Columbia Wetland has been exceptionally efficient.

Key Words: treatment wetland, wastewater, BOD, nutrients, denitrification, habitat

INTRODUCTION

The Columbia Wastewater Treatment Wetland ("Columbia Wetland") is a surface-flow wetland built to augment treatment of municipal wastewater from Columbia, Missouri, USA (Brunner and Kadlec 1993). The Columbia Wetland is the largest treatment wetland in the region and, in terms of initial design capacity (67,000 m^3 d^{-1}) and hydraulic loading (18 cm d^{-1}), ranks among the largest constructed surface-flow wetlands in the world (Kadlec and Knight 1996). The Columbia Wetland also is notable because effluent from the system is subsequently used for management of constructed habitat wetlands in the Eagle Bluffs Conservation Area ("Eagle Bluffs"), a 1683-ha waterfowl management facility operated by the Missouri Department of Conservation. The Columbia Wetland and Eagle Bluffs are located in the Missouri River floodplain $\approx$10 km southwest of Columbia. The Columbia Wetland began operation in October 1994 for the purpose of removing oxidizable organic matter and suspended solids from combined primary and secondary effluent.

Wastewater treatment using constructed wetlands is increasingly important as an alternative or supplement to conventional waste treatment systems (Kadlec and Knight 1996, Peterson 1998). Most wetland treatment systems have capacities of <4000 m^3 d^{-1} (Knight et al. 1993). In their compilation of North American treatment wetlands, Kadlec and Knight (1996) list only four constructed municipal wastewater surface-flow systems with capacities >20,000 m^3 d^{-1}, and none of these was designed for loading >16 cm d^{-1}. Thus, there are few data available on the performance of high capacity treatment wetlands. The Columbia Wetland system provides an important example for the planning and design of future treatment wetlands.

This paper presents data on the performance of the Columbia Wetland during the first six years of operation prior to an expansion of the facility in November 2000. Included are measurements of BOD_5, COD, suspended solids, total nitrogen, total phosphorus, ammonia, chlorophyll, fecal bacteria, and other water quality variables measured in weekday or monthly samples of the inflow and outflow of the wetland. These data document the Columbia Wetland effectiveness in meeting its design goals (removal of BOD_5 and TSS) and in providing additional water quality improvements beneficial to subsequent uses of the effluent for wildlife management and public recreation on Eagle Bluffs.

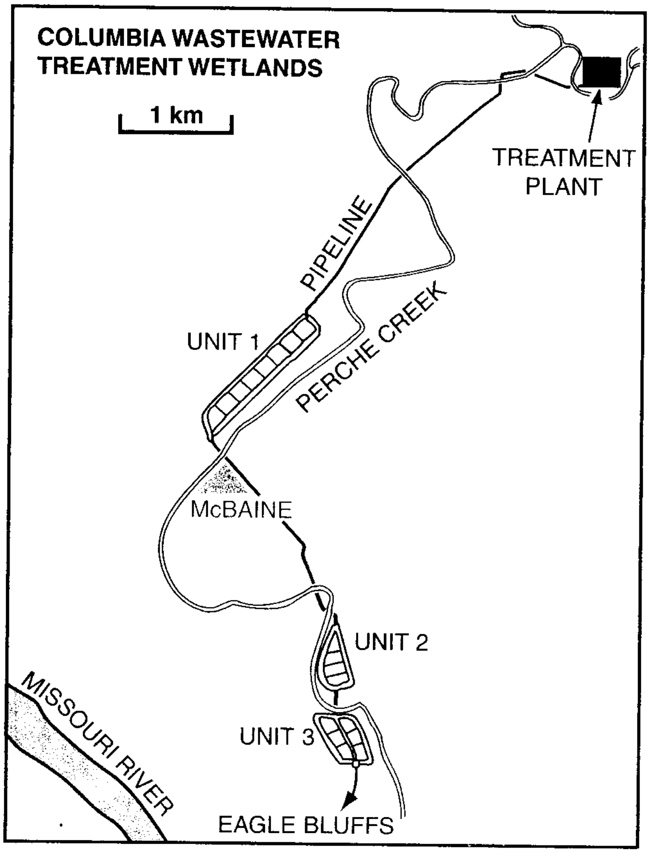

Figure 1. Map of Columbia wastewater treatment facilities near the village of McBaine, Missouri.

STUDY SITE AND OPERATIONAL HISTORY

The Columbia Wetland is located in the Missouri River/Perche Creek floodplain near McBaine, Missouri, USA (Figure 1). The original system comprised three separate "units", each enclosed by flood protection berms and connected in sequence by a 2-m-diameter pipeline extending from the Columbia wastewater treatment plant (Figure 1). Each unit comprises 8.5–19.4 ha of constructed marsh (≈37 ha total) subdivided into 4–8 individual cells (see Chapter 20 in Kadlec and Knight 1996). Units are underlain by a 30-cm clay liner to reduce seepage losses. Cells contain ≈15 cm of topsoil planted with cattails (predominantly *Typha latifolia* L.). Effluent from the pipeline flows into inlet canals bordering each row of cells, then flows through the cells to an outlet canal on the opposite side. Flow through the cells is controlled by gated water-control structures at both ends. Outlet canals in units 1 and 2 empty by gravity into the pipeline. The outlet canal of the third unit drains into a pumping station from which effluent is pumped over an aeration weir and into a 1.2 m pipeline that drains by gravity into the water distribution system of Eagle Bluffs. The water residence time for the whole system is typically ≈2 days.

The Columbia Wetland began operation 7 October 1994. For three weeks during a large Missouri River flood in May–June 1995, pumping of effluent to Eagle Bluffs was curtailed because of an electrical outage and to allow water levels to rise to equalize pressure of flood waters on the surrounding berms. The 1995 flood caused structural damage to the Columbia Wetland, and it was taken out of service for about six weeks in May and June 1996 for repairs. Some or all effluent was diverted to a creek adjacent to the wastewater treatment plant (Figure 1) during repairs and during part of the 1995 flood. Prolonged submergence during the 1995 flood also killed a large portion of the cattails, which were subsequently replanted in 1996. Pumping to Eagle Bluffs has also been suspended for periods of 2–3 days during floods or repairs in 1997, 1998, and 2000. In mid-November 2000, a fourth wetland unit (16 ha) ≈1 km northeast of unit 1 was brought online.

MATERIALS AND METHODS

Water quality measurements were made on composite samples of effluent flowing into and out of the Columbia Wetland collected five days per week (weekdays) by continuous-flow autosamplers (American Sigma model 800 SL) located in the Columbia wastewater treatment plant (inflow) and at the pump station in the third wetland unit (outflow). Weekday samples were analyzed for total suspended solids, BOD$_5$, COD, and ammonium (NH$_4$-N) (A.P.H.A. 1992) at the treatment plant. Once a month, composite samples were also analyzed for chlorophyll (CHL—Knowlton 1984, Sartory and Grobbelaar 1984), total phosphorus (TP—Prepas and Rigler 1983), total nitrogen (TN—Crumpton et al. 1992), volatile and non-volatile suspended solids (A.P.H.A. 1992), nitrate-nitrite-N (NO$_3$-N—A.P.H.A. 1992), dissolved silica (A.P.H.A. 1992), fecal coliforms (mFC medium), and fecal streptococcus (KF medium) at the University of Missouri Limnology Laboratory. All weekday samples were also analyzed for TP and TN beginning in March 1997. Dissolved oxygen (D.O.) was measured polarigraphically at the wetland pump station and (through June 1996) at the wastewater treatment plant.

RESULTS

Flow to the Columbia Wetland in October 1994 through mid-November 2000 averaged ≈58,000 m^3 d^{-1} (range 31,000–171,000) during periods (n=2158 days) when water was not diverted to the creek. For the same time periods, BOD$_5$, COD, TSS, and NH$_4$-N

Table 1. Mean water quality characteristics of inflow and outflow of the Columbia Wetland, 8 October 1994–14 November 2000. Measurements exclude data collected when effluent was diverted during repairs or floods. Means are in mg L^{-1} except CHL (μg L^{-1}) and fecal bacteria (cells 100 mL^{-1}).

	Inflow		Outflow	
	n	mean	n	mean
BOD_5	1489	31.2	1460	8.2
COD	1506	51.7	1483	36.4
TSS	1506	12.5	1483	16.3
Ammonia-N	1484	7.9	1461	6.5
CHL	78	4.1	85	21.2
VSS	78	11.0	75	4.3
NVSS	78	2.7	75	10.0
TN	949	12.0	945	7.6
TP	949	2.1	945	2.0
Silica	64	20.5	63	18.3
Coliforms	39	237077	34	6414
Streptococcus	35	367200	34	5468

in weekday inflow samples, respectively, averaged approximately 31, 52, 13, and 8 mg L^{-1} (Table 1), and areal loading (concentration × daily flow ÷ surface area) to the wetlands averaged 50, 83, 21, and 12 kg ha^{-1} d^{-1}. Day-to-day variation for influent concentrations was large, with coefficients of variation (CV= 100 × standard deviation ÷ mean) ranging from ±28% for COD to ±54% for TSS. BOD_5, COD, and TSS were positively correlated to flow, and NH_4-N was negatively correlated to flow ($p<0.03$), but in regression analyses, variation of flow explained only 0.1–3.7% of the temporal variation in BOD_5, COD, and NH_4-N, and only 19% of the variation in TSS.

In outflows, BOD_5, COD, TSS, and NH_4-N averaged about 8, 36, 16 and 7 mg L^{-1} (Table 1). Net removal of BOD_5, COD, TSS, and NH_4-N, estimated as the difference between daily inflow and outflow concentrations, averaged 23, 15, −4, and 1 mg L^{-1}, respectively. On an areal basis, these differences indicate removal rates of 37 kg ha^{-1} d^{-1} BOD_5, 25 kg ha^{-1} d^{-1} COD, and 2 kg ha^{-1} d^{-1} NH_4-N. TSS showed a net increase of 5 kg ha^{-1} d^{-1}.

Removal of BOD_5, COD, TSS and NH_4-N by the Columbia Wetland showed large temporal variability (Figure 2) but increased significantly over time (linear regression, $p<0.01$) for BOD_5, COD, and TSS and significantly decreased for NH_4-N (linear regression, $p<0.01$). The increase in BOD_5 removal, which occurred mainly over the first four years of operation, came despite a substantial increase in BOD_5 loading during the period. BOD_5 loading averaged less than 40 kg ha^{-1} d^{-1} in 1995 and 1996 but averaged >55 kg ha^{-1} d^{-1} in 1998–2000. Loading of COD and TSS did not significantly increase over the period (linear regression, $p>0.05$), and loading of NH_4-N significantly decreased.

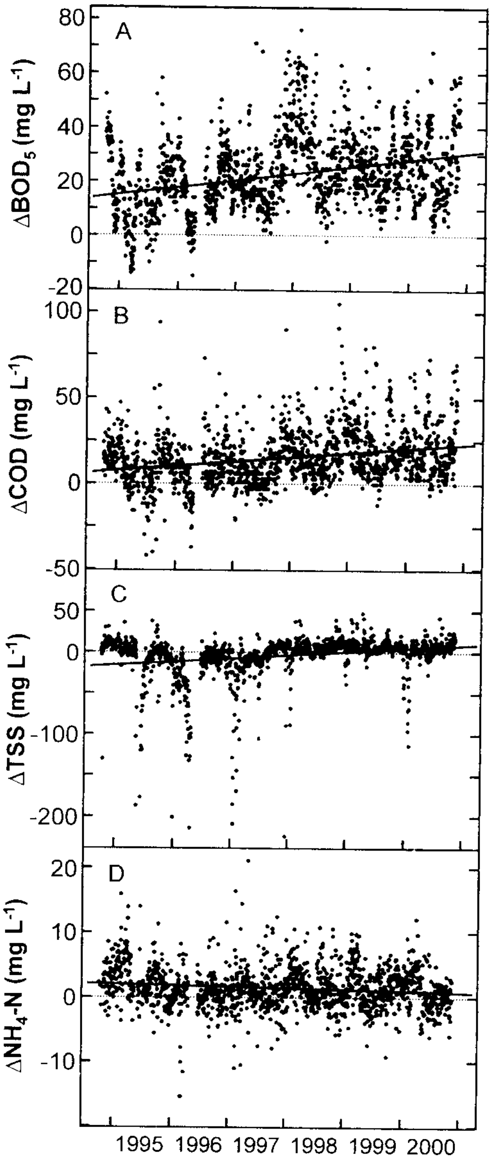

Figure 2. Removal of (a) BOD_5, (b) COD, (c) TSS, and (d) NH_4-N in the Columbia Wetland (1994–2000) estimated as the difference between inflow and outflow concentrations in weekday samples. Solid lines show linear regression models ($p<0.01$) of the change in removal over time.

Improvements in the performance of the Columbia Wetland during the first years of operation are probably the result of increasing biomass of macrophytes and associated periphyton. Cattails present in 1994 had mostly been planted that year and achieved little growth before being drowned in the 1995 flood. Thus, during much of 1994–1996, the wetland cells functioned as facultative ponds with little emergent vegetation. By 1998, however, most of the cells were fully vegetated. This transition from pool to marsh condi-

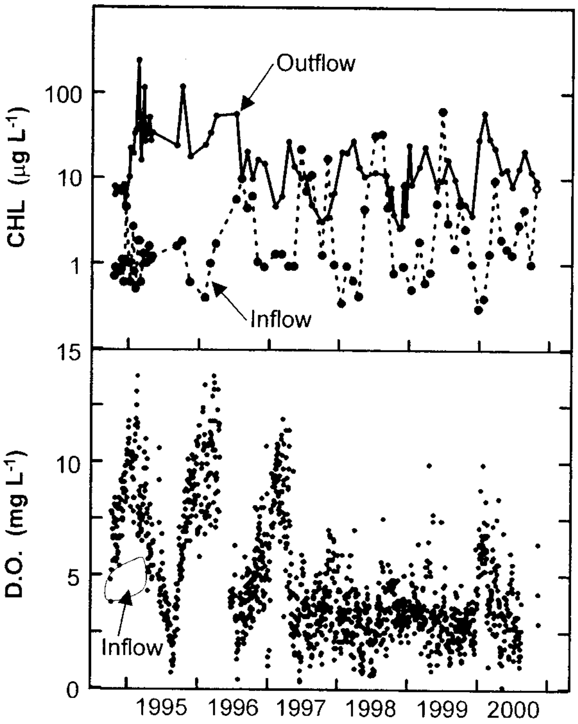

Figure 3. Time series of (a) chlorophyll ($\log_{10}$ transformed) and (b) dissolved oxygen in Columbia Wetland inflow and outflow. The range of inflow D.O. is shown by the shaded area in panel b. Inflow D.O. was not measured after March 1995.

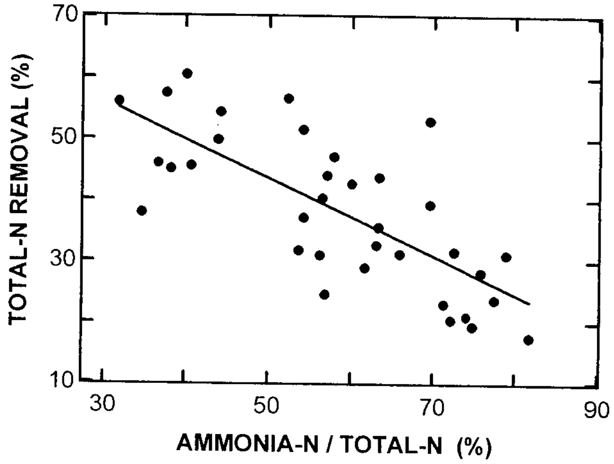

Figure 4. Effect of varying ammonium content on the percent removal of TN in the Columbia Wetland. Data are monthly averages for 1998–2000. The regression model is: % Removal $= -0.595 \times$ % NH_4-N $+ 0.713$, $r^2 = 0.50$, $n=35$, MSE=0.0075.

tions is reflected in concentrations of suspended CHL and D.O. in the system. During the first two years of operation, the effluent showed large net gains of CHL (Figure 3a) as the result of intense algal blooms (CHL > 40 μg L^{-1}) in the largely unvegetated pools (Figure 3). In 1997–1998, CHL never exceeded 30 μg L^{-1}, and peaks of CHL in outflows were mostly confined to winter when macrophyte foliage was minimal. Likewise, D.O. in the outflow (Figure 3b) initially decreased with the transition from open water to vegetated marsh conditions in the wetland cells.

Vegetation development also reduced the addition of suspended solids to the effluent by the wetland. From mid-1995 through late 1997, TSS usually showed net increases in the Columbia Wetland (Figure 2c). This effect was due to erosion or resuspension of bottom and bank soils and was most acute during periods of heavy use by waterfowl, which often aggregate in the system, especially when nearby wetlands and ponds are ice-covered. The eroded material is mostly mineral, and thus, suspended solids in outflows typically contain about three times the proportion of non-volatile material (NVSS) measured in inflows (Table 1). With maturation of the macrophyte communities in the Columbia Wetland, the addition of sediment to the effluent decreased even during winter periods characterized by minimal vegetation and maximum waterfowl use (Figure 2c). In 1999, there were 15 instances in which outflow TSS exceeded inflow TSS, compared to 161 such instances in 1996 (Figure 2c). Erosional inputs were also reduced by surfacing some exposed pool banks with crushed rock.

In addition to removing organic materials, the Columbia Wetland also has affected concentrations of fecal bacteria, nitrogen, and to a small extent, phosphorus reaching the Eagle Bluffs system. Counts of fecal coliforms and streptococcus in wetland outflows have averaged <3% of inflow counts (Table 1). Total nitrogen in outflows averaged ≈4.4 mg L^{-1} less (≈37% less) than inflows (Table 1). Removal of TP, however, has been slight. Outflow TP has averaged only 4%, or about 0.1 mg L^{-1}, less than inflows (Table 1). Outflows have also contained an average of 2.2 mg L^{-1} less dissolved silica than inflows (Table 1), indicating substantial growth of diatoms in the wetland.

Nitrogen removal as a percent of inflow TN varied on a monthly average basis from 17 to 59% during 1998–2000. In regression analyses, about half this variation can be accounted for by variation in proportion of NH_4-N in influent TN (Figure 4). Nitrogen removal decreased as the ammonia content of TN increased, probably because increasing ammonia meant there was less NO_3-N in the effluent to serve as substrate for denitrification. Jointly, NH_4-N and NO_3-N account for most of TN in effluent ($x=81\%$, range 61–99%), and thus, NO_3-N shows a very strong inverse relation to NH_4-N ($r=-0.93$, $p<0.0001$, $n=82$) when both are expressed as a percent of TN. Other variables in the data set seem to have little influence on the removal of TN. In multiple regressions, neither water temperature, oxygen concentration, BOD$_5$ concentration, nor TN loading rate added significantly to the variation explained by the ratio of NH$_4$-N to TN (Figure 4).

DISCUSSION

The Columbia Wetland was designed with the goal of reducing monthly mean BOD$_5$ and TSS to <30 mg L^{-1} in effluent already partially treated by conventional primary and secondary methods (Brunner and Kadlec 1993). In 1998–2000, outflow from the wetland was always well within the goal for BOD$_5$; daily values never exceeded 23 mg L^{-1}. Monthly mean TSS exceeded 30 mg L^{-1} once during the period (January 2000) and was >30 mg L^{-1} in daily samples on 24 of 726 sampling days, all but one of which was in winter. The low average concentrations of VSS and high mineral content of seston in outflow, compared to inflow (Table 1), suggest that high TSS resulted from internal processes such as bank erosion or waterfowl disturbance, rather than failure to remove incoming wastewater solids.

For one of its design functions, BOD removal, the Columbia Wetland seems to be unusually effective. In a recent assessment of treatment wetlands, the U.S.E.P.A. (1999) presented a comparison of 38 surface-flow treatment wetlands (the Technology Assessment Data Base, or TADB, wetlands), including data for the Columbia Wetland during its first two years of operation. Most TADB wetlands are systems of relatively low capacity. Other than the Columbia Wetland, only three TADB wetlands had average inflows $>17{,}000$ m^3 d^{-1}, and these systems each had average hydraulic loading rates <4 cm d^{-1} compared to >14 cm d^{-1} for the Columbia Wetland. In 1998–2000, the BOD$_5$ concentration in the outflow from the Columbia Wetland averaged 7.3 mg L^{-1} despite average BOD$_5$ loading >57 kg ha^{-1} d^{-1} (Figure 5a). Only six TADB wetlands had BOD loading >50 kg ha^{-1} d^{-1}, and of the six, none produced average effluent BOD concentrations <24 mg L^{-1}. The average ratio of effluent BOD$_5$ to BOD$_5$ loading of the Columbia Wetland (0.13 mg L^{-1} per kg ha^{-1} d^{-1}) was only about half that of the best performing TADB wetland (Figure 5a).

The Columbia Wetland also seems relatively effective in the removal of nitrogen. In comparison with the 18 TADB wetlands with TN data (Figure 5b), the Columbia Wetland has a higher average TN loading and higher effluent TN than the majority of wetlands. However, the Columbia Wetland has yielded lower ratios of effluent TN to TN loading than all but one of the TADB systems. Nitrogen removal is not a design function of the Columbia Wetland, and it is not managed for that purpose, but the system has considerable potential in that direction. Denitrification in the Columbia Wetland seems to be largely a function of nitrate supply (Figure 4), which is substantially under the control of the Columbia Treatment Plant managers. Nitrate concentrations in the effluent can be manipulated by varying aeration rates during secondary treatment. Thus, the tendency in many wetlands for the nitrification process or nitrate inputs to limit denitrification rates (Verhoeven and Meuleman 1999, Smith et al. 2000, Spieles and Mitsch 2000) can be easily overcome in systems that combined treatment wetlands with conventional treatment plants.

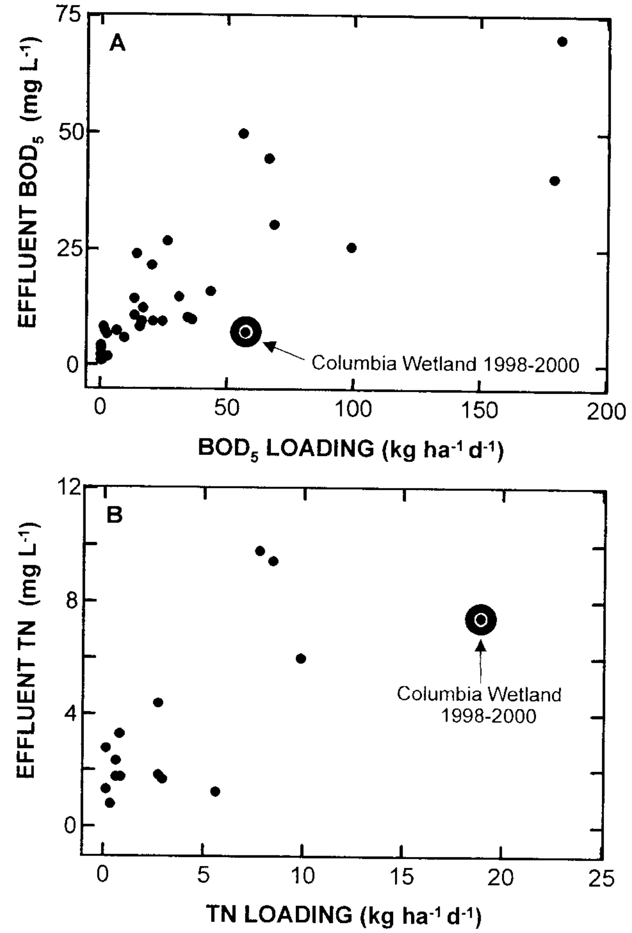

Figure 5. (a) Mean BOD$_5$ concentrations and areal loading rates of 38 surface-flow treatment wetlands from the U.S.E.P.A. Technology Assessment Data Base (U.S.E.P.A. 1999) and the Columbia Wetland (1998–2000). (b) Mean total nitrogen concentrations and areal loading rates of 18 surface-flow treatment wetlands from the U.S.E.P.A. Technology Assessment Data Base (U.S.E.P.A. 1999) and the Columbia Wetland (1998–2000).

In addition to providing secondary treatment of wastewater, the Columbia Wetland provides some ancillary benefits. As in most treatment wetlands, the Columbia system greatly reduces fecal bacteria (Hiley 1995, Kadlec and Knight 1996), making the effluent more suitable for use on the Eagle Bluffs Area, a popular site for hunting, fishing, bird-watching, and other public recreation. The Columbia Wetlands also provide some recreational benefits, as the system is located adjacent to two popular hiking/biking trails, the City of Columbia's "MKT" trail and the Katy Trail State Park, which provide easy access for bird-watchers and site-seers. As its heavy use by waterfowl suggests, the Columbia Wetland also provides valuable wildlife habitat, especially during cold weather when other open water resources are unavailable. Treatment wetlands, especially those in areas with few natural wetland habitats, may assume great importance to wildlife (Knight 1992, Knight 1997, Worrall et al. 1997).

The wildlife benefits provided by the Columbia Wetland are counterbalanced by the problem of sediment disturbance attributable to waterfowl and, more seriously, by damage caused by an overabundance of muskrats (*Onadara zibethica* L.). Muskrats have heavily invaded the wetland units, where their feeding and house building have caused moderate to severe damage to cattail stands and created open water pools that further attract waterfowl, thus exacerbating the problem of sediment disturbance. Burrowing by muskrats has also damaged berms in the wetland cells and could compromise the clay liner that protects local ground water from wastewater infiltration. The City of Columbia, with help from the U.S. Department of Agriculture, has removed over 1300 muskrats in the past 2.5 years, mostly by trapping. Removal efforts have recently increased— 733 animals were trapped in 2000 and 286 in the first three months of 2001, but the muskrat population is still thriving. A long-term solution to the problem has not been discovered.

In conclusion, the Columbia Wetlands have proved to be very effective in providing the secondary wastewater treatment for which they were designed and also provide substantial tertiary treatment. These wetlands also constitute a habitat more highly prized by wildlife than may be consistent with their optimal performance as waste-treatment facilities. Thus, the Columbia Wetlands serve as an illuminating example of the potential of high capacity treatment wetlands and also illustrate the need to consider potential wildlife problems in their design and construction.

ACKNOWLEDGMENTS

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