ONSITE TREATMENT OF SEPTIC TANK EFFLUENT IN MINNESOTA USING SSF CONSTRUCTED WETLANDS: PERFORMANCE, COSTS AND MAINTENANCE

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ABSTRACT

About 30 % of Minnesotans use on-site systems for wastewater treatment (~500,000 residences). Unfortunately, 55-70 % are failing or out of compliance with state standards. Homeowners and small businesses require cost-effective options in locations with restrictive soil and site conditions. In particular, many sites occur near lakes and streams creating a health hazard and deteriorating water quality. Constructed wetlands (CWs) are one option being evaluated and this paper addresses CWs as a viable wastewater treatment option in Minnesota based on experiences at three research sites, encompassing 5 subsurface flow wetlands from 1995-2000. These are small flow ($\leq$1000 gpd) subsurface flow gravel beds located at the Northeast Regional Correction Center (NERCC), Grand Lake, and Lake Washington, MN. Performance monitoring shows that CWs are a viable, year-round onsite treatment option. The systems were generally able to achieve design criteria of 30 mg BOD_5/L, 25 mg TSS/L and 200 fecal cfu/100 mL, although the NERCC CWs required 30 cm. of unsaturated soil to achieve consistent disinfection. High strength (~300 mg BOD/L and 100 mg TN/L) influent at NERCC probably limited system performance, particularly N-removal which was ~40% in summer and ~20% in winter (mass-based). Declining P-removal at the oldest sites suggest substrate saturation. Although CWs remain a viable option for homeowners in terms of performance, ease of operation, and cost, other issues relate to inconsistent vegetation growth (affecting performance and freezing), and meeting concentration-based regulatory standards since they may exhibit substantial variability due to rain events, partial freezing, spring snowmelt, and summer evapotranspiration.

KEYWORDS. Constructed wetlands, wastewater, alternative technologies, cold-climate

BACKGROUND

An estimated half million households in Minnesota are not connected to public sewer systems. Along with seasonal dwellings and lakeshore cabins, these homes have the potential to degrade the state's surface and groundwater resources as they depend primarily on individual sewage treatment systems (ISTSs) for adequate treatment and dispersal of domestic wastewater. Unfortunately, >50% are estimated to be out of compliance with state standards or hydraulically failing and effective treatment options are needed for the thousands of locations with restrictive soil and site conditions. In particular, many sites occur near lakes and streams creating a potential health hazard to swimmers and others using the water for recreation or drinking water, leading to increased algal blooms and aesthetic nuisances, and degraded fish habitat. Constructed wetlands (CWs) are one option currently being evaluated in Minnesota, as well as sand, peat and textile filters, aerobic treatment units, and drip irrigation (McCarthy et al., 1997, 1998, 1999; Anderson and Gustafson, 1998; see also http://www.bae.umn.edu/septic). The use of alternative on-site technologies for wastewater treatment in Minnesota and other Great Lakes states will remain limited until their seasonal performance is proven acceptable. Accurate assessment of the potential risks of these technologies requires quantification of solids, organic matter, nutrients and pathogen removal efficiencies as well as their operation and maintenance requirements and costs during the entire year.

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In 1995, research sites were established in northern Minnesota near Duluth at NERCC and at Grand Lake (McCarthy et al., 1997) and in southern Minnesota at Lake Washington, near Mankato (Anderson and Gustafson, 1998). The research began in 1995 testing alternative treatment technologies for individual homes, including constructed wetlands. Additional background and specific details about the individual sites, overall program objectives, and the performance of other research systems can be found in McCarthy et al. (1997,1998, 1999), Anderson and Gustafson (1998), Crosby et al. (1998), Henneck et al. (1999), Heger Christopherson et al. (2001), Kadlec et al. (2001) and Kadlec (2000 a, b) and Monson Geerts et al. (2001). Pathogen tracer studies performed at the NERCC site are reported in Pundsack (2000), Axler et al. (2000) and Pundsack et al. (In press a, b).

SYSTEM DESIGNS AND METHODS

All systems are subsurface flow (SSF) vegetated CWs with general design specifications listed in Table 1. All systems were initially designed to achieve a *secondary* level of treatment of 25 mgBOD_5/L, 30 mgTSS/L, and disinfection to a recreational bathing standard of 200 fecal coliform bacteria per 100 mL. Design criteria for NERCC represent a hybrid based on criteria reported in Kadlec and Knight (1996), experience gained from operating 6 similarly sized seasonal SSF CWs in northern Minnesota to treat aquaculture wastes (Axler et al., 1996) and consultation with R. Kadlec (Wetland Management Services, Inc., Chelsea, MI, USA). The Grand Lake system was designed by R. Kadlec (as per Kadlec and Knight 1996) using the most current (1995) removal and temperature coefficients but site constraints led to the relatively low L:W ratio (~0.6). The treatment bed was made deeper than NERCC as an additional buffer against freezing. The Lake Washington design was based primarily on the EPA/TVA manual (EPA 1993) with additional size to increase the potential for N-removal via nitrification/denitrification. However, to date, neither design flows nor maximum BOD concentrations have been achieved.

Table 1. Design Parameters for Study CWs.

SITE	NERCC	Grand Lake	Lake Washington
Notes:	2 lined cells in series (2 replicates)	1 lined + 1 seepage cell (for 10 home cluster)	single lined cell (2 replicates)
L x W x D (m)	7.0x5.3x0.46 (each)	10.3x17.7x0.6 (first cell)	18.3x4.9x0.6
Area (m^2)	75 (both cells)	182m^2 (lined cell)	89
volume (m^3)	13.5 (both cells)	43.7 m^3 (first cell)	21.4
Q (m^3/d)	0.80	2.8	0.63 (median)
q (cm/d)	1.07	1.50	0.70
HRT (days)	16.5-26.6	15.8	34 (median)
BOD load (kg/ha/d)[a]	28.8	27.9	4.6
Plants	bulrush/cattail	cattail/sedge/reed	cattail

a Loading rates are the mean values for the period of record; NERCC 3/96-8/00, Grand Lake 1/96-9/00, and Lake Washington 1/97-4/00.

The NERCC CWs are replicated side by side, two cell in series systems at a research site comparing a variety of alternative systems (McCarthy et al. 1997, 1998, 1999) 16 km north of Duluth MN. Each system receives identical (from a common tank) septic tank effluent (STE) at a correctional facility and inflow (water meters) and outflow (tipping bucket with a data logger) are recorded. The first cell has "pea rock" (0.95-1.9 cm) and was planted with cattail (mixed *Typha latifolia* and *T. angustofolia*) and the second cell has crushed limestone (0.95 cm- 1.9 cm) planted with softstem bulrush (*Scirpus taebormontanii*). Additional treatment goals for the wetlands were to perform advanced wastewater treatment for nitrogen (TN <10 mg/L) during the growing season (May-Oct) and to improve phosphorus removal by using the best P-adsorbing, locally available substrates. For the period through mid-2000, the wastewater strength has been much higher than anticipated with typical values of BOD_5 ~300 mg/L and NH_4-N ~100 mg/L (NH_4-N >95% of the TN).

The Grand Lake cluster system subsurface flow CW was also built in late 1995 and is designed to correct the problems of 10 single family homes along a lakeshore just north of Duluth (Table 1; McCarthy et al.1997, Crosby et al.1998, and Henneck et al. 1999). A small diameter pipe/cluster sewer feeds STE to two cells in series: cell-1 was planted with *Typha sp.* and the unlined /unplanted dispersal cell-2 was insulated with 30 cm of peat. Both cells have 60 cm of 1.3-1.9 cm pea rock. The treatment cell is sampled primarily at its outflow (less frequently at multiple internal sites) and the seepage cell (holds water year-round) is sampled across mid-length composited from two depths at each of three locations across the width.

The Lake Washington CWs are located near Mankato, MN (~300 kms south of Duluth) and are one part of a collection of systems treating the wastewater of 20 lake shore houses (Anderson and Gustafson 1998, Anderson 1998). This region has a median of 32 more days between spring and fall freezes and a mean average temperature ~4 ^{0}C warmer than the Duluth sites. The CWs are replicated single cell subsurface flow systems designed to treat ~1.0 m^3/day, filled with pea rock (0.6 cm - 0.95 cm) and planted with *Typha latifolia* (dimensions and loading rates in Table 1).

Nutrient analysis methods at NERCC and Grand Lake are described in detail in McCarthy et al. (1997, 1998) and follow standard methods (APHA 1995, Ameel et al. 1998). TN for Lake Washington was estimated as TN= TKN + NO_3^-/NO_2^- N (APHA 1995). NERCC removal efficiencies are based on mass removal (i.e. flow weighted) whereas Grand Lake and Lake Washington efficiencies are concentration based (no outflow monitoring). The CWs are sampled at about 3 week intervals (n=72 for NERCC from 1996-2000; n=81 for Grand Lake from 1996-2000; and n=50 for Lake Washington from 1997-2000) throughout the year. None of the wetlands have been harvested or weeded to date.

Pooled data from Years 2-4 for each CW were used to calculate areal removal rate constants assuming the first order plug flow model as derived by Brix (1998) and Cooper and Green (1998):

$$C_{out} = C_{in} \exp [- k/q] \text{ and } k = k_{20}\,^{(T-20)}$$

where C_{out} is the effluent concentration (mg/L), C_{in} is the influent concentration (mg/L), k is the first order areal rate constant (m/yr), q is the hydraulic loading (m/yr), k_{20} is the rate constant at 20^{o}C, T is the temperature (^{o}C), and θ is the modified Arrhenius temperature factor. A concurrent nonlinear regression was used to optimize the parameters k_{20} and θ (R. Kadlec pers. comm.) for each of the water quality constituents. Coefficients are presented only for $r^2 >$ 0.25. Temperature was not monitored routinely at Lake Washington and so θ was not estimated. Direct regressions of specific parameter concentrations versus temperature are reported when statistically significant at $P < 0.05$.

RESULTS AND DISCUSSION

Performance

BOD$_5$- Mass percent removal of BOD at the NERCC wetlands (both wetlands averaged over five years) was 88%, reducing the average influent from 264 mgBOD/L to 37 mgBOD/L. About 52% of the effluent samples were <40 mgBOD/L and all values exceeding 60 mgBOD/L were from winter samples. BOD removal was temperature dependent (although r^2 was only 0.27) and

Table 2. Influent and Effluent Concentrations for The Three Wetland Systems.						
WETLAND/	SITE	BOD[a] (MG/L)	TSS[a] (MG/L	Fecal Coliforms[b] (cfu/100ml)	TN[a] (mg/L)	TP[a] (mg/L)
EFFLUENT	TARGET	<-30	<-25	<-200	<-10*	-
NERCC	Influent	266 +- 60	46+- 14	$4.2x10^5$ ($1.1-15.7x10^5$)	85+-15	13+- 2.8
CW - 1	cell-1	48+- 30	10+- 6	$6.7x10^3$ ($1.0-42.7x10^3$)	66+-17	10+- 3.2
(Q ~0.6 m^3 /d)	cell-1&2	38+- 34	9+- 6	$1.6x10^3$ ($0.2-19.0x10^3$)	56+- 21	11+- 4.1
CW - 2	cell -1	53+- 42	8+- 4	$8.1x10^3$ ($1.3-51.0x10^3$)	68+-18	8.6+- 3.4
(Q ~0.9 m^3 /d)	cell-1&2	38+- 28	8+- 5	$1.9x10^3$ ($0.2-25.7x10^3$)	60+- 23	9.0+- 4.2
Grand Lake	Influent	184+- 43	27+- 8	$2.6x10^5$ ($0.4-14.7x10^5$)	59+-12	7.9+- 1.4
"	cell-1	70+- 44	6+- 4	$0.29x10^3$ ($0.03-2.64x10^3$)	37+-16	5.1+- 2.8
"	cell-1&2	44+- 37	8 +- 15	$0.35x10^2$ ($0.05-2.3x10^2$)	29+-17	3.9+- 2.6
Lake Washington	Influent	63+- 31	64+- 62	$1.4x10^5$ ($0.1-12.8x10^5$)	33+-11	5.4+- 1.5
CW - 1	Effluent	11+- 7	15+- 12	$0.38x10^2$ ($0.02-6.7x10^2$)	17+- 7	0.4+-0.7

performance decreased 14% on average from summer to winter (Table 2). The estimated BOD K_{20} for the five years was 18.2 m/yr, with $\theta = 1.064$. The mass percent removed was similar to the concentration percent removed as the water budget over the five years showed a net loss of only ~5% of the inflow, although the inflow was entirely evapotranspired on occasion during warm summer days. The annual average performance (as both % BOD removed and effluent concentration) has decreased about 10 %, although this effect may be more associated with a gradual increase in influent strength over the past five years.

Several attempts have been made to reduce the organic load to the NERCC CWs to determine if performance could be improved. The flow into CW-1 was reduced by 33% from May 1998-May 2000. However, performance was not significantly improved by reducing the hydraulic and organic loading rates, with CW-1 summer values being 27 ± 14 mgBOD/L as compared to 32 ±16 mgBOD/L for CW-2 during the same period. During winter (Nov-Mar) since 1998, CW-1 averaged 66 ±52 mgBOD/L relative to 58 ±36 mgBOD/L for the higher flow CW-2. Interpreting these results is especially difficult since the summer influentincreased by 50 mgBOD/L and the winter by 45 mgBOD/L over this period as well. To help resolve these performance versus loading questions, we modified the distribution system in summer 2000 to dilute the STE by about 50% using well water, while maintaining the two different flow regimes but there is presently insufficient data to speculate about the effects of the reduced organic loading rate. The second cell of the two-cell wetland train contributed 5-8% (relative to total system removal) of BOD removal in both summer and winter. Overall, performance declined from an average of 81% in summer to 69% in winter for the upper cell and from 92% to 78% for the 2-cell system (Table 3).

Table 3. Seasonal %-removal.

	NERCC [a] (cell 1&2)		Grand Lake [b] (cell 1&2)		L. Washington [b] (single cell)	
	Summer [c]	Winter [d]	Summer [c]	Winter [d]	Summer [c]	Winter [d]
BOD	92	78	82	70	83	75
TSS	87	81	86	70	81[e]	61[e]
Fecal	99.6	94.2	99.9	99.3	99.9	99.5
TN	41	21	51	51	54	50
TP	50	16	59	45	97	89

a mass-based

b concentration based

c summer May-Sep

d winter Oct-Apr

e Lake Washington TSS is reported as the median

Averaged over all seasons and years, the Grand Lake (GL) CW removed 60% ± 27% of the BOD from an influent of 184 ± 43 mgBOD/L to 70 ± 44 mgBOD/L after the lined first cell and 44 ± 37 mgBOD/L at the middle of the seepage cell (Table 2). Total system removal averaged 76 ± 20%. We have no flow data out of the GL wetland so these are concentration based percent removal efficiencies. The site is only 10 km from the NERCC wetlands and of similar age and so evapotranspiration rates should be similar on an areal per unit biomass basis. Although vegetation growth has been problematic at GL since its construction relative to NERCC, there was only about a 5% annual loss of inflow at NERCC over the period of record and so we would expect GL mass-% removal to be similar to the concentration based estimates- at least on an annual basis. Effluent from the first cell had <40 mgBOD/L 34% of the time while the second cell had <40 mgBOD/L 60% of the time. Effluent BOD was significantly correlated with temperature ($r^2 = 0.54$) indicating a moderate temperature dependence reflected in the 12% decrease in winter performance (Table 3). The K_{20} for the first cell was 19.5 m/yr with $\theta = 1.133$. The overall performance over time for the system has decreased 32% but the majority of this change is due to the decreasing summer performance despite relatively consistent influent BOD since 1996 (CV= 26 %).

The Lake Washington (LW) constructed wetlands removed an average of 79 ± 26% of the influent BOD over the period of Jan 1997-Apr 2000. The influent concentration averaged 63 ± 31 mgBOD/L (Table 2) and the effluent for the average of the two wetlands was 9.1 ± 4.9 mgBOD/L. The effluent concentration was less than 30 mgBOD/L 93% of the time with the exceedances divided evenly among the seasons. No temperature data was recorded for these wetlands. The estimated K was 22.7 m/yr. Summer removal was 8% greater than the winter (Table 3) and the effluent concentration over time has remained essentially unchanged.

<u>TSS</u> - Total suspended solids (TSS) at NERCC were reduced 84 ± 12% as the five year average for both sets of 2-cell wetlands. Effluent values were <25 mgTSS/L 96 % of the time and values were typically <10 mg/L. Winter performance was not significantly lower than in summer. The first cell accounted for 97% of the TSS -removal. Performance changed little over time (<2%) and reducing the flow by 33% in CW-1 has not lowered its effluent TSS.

TSS removal at Grand Lake for cell-1 alone averaged about 82 ± 9% (6 ± 4 mg/L). The second cell did not further improve effluent TSS quality. Regressions of TSS vs temperature were not statistically significant although average summer values (4 ± 3 mgTSS/L) were substantially lower than in winter (12 ± 19 mg/L). Wetland performance over time has remained nearly unchanged.

The TSS influent at Lake Washington has been highly variable with an average of 64 ± 62 mgTSS/L (median = 47) since 1997. CW-1 and CW-2 have removed an average of 57 ± 47% (median = 76%) of the influent TSS. Summer %-removal was substantially better than in winter (Table 3) but the data was too noisy to be conclusive with high variability in the influent and effluent (summer influent was 85 ± 72 mg/L, median 52, and winter influent was 48 ± 48 mg/L, median 45). The data suggests that there have not been substantial changes in performance since 1997.

<u>Fecal coliform bacteria</u> - The NERCC CWs removed an average of 96.8% (median = 99.4%) of the fecals since 1996. Effluent values <200 cfu/100ml accounted for 16% of the samples and the geometric mean summer value was 491 and winter was 6211. Fecal coliform K_{20} for the five years was 37.5 m/yr with $\theta = 1.063$. Average annual performance (as % fecal coliforms removed and concentration in the effluent) over time has remained essentially unchanged. The reduced flow to CW-1 had no effect on the number of exceedances of the target 200 cfu/100mL- both wetlands met this target 15% of the time. Lower flow CW-1 achieved the <1000 cfu/100mL level more frequently than CW-2, 33% and 23%, respectively, with most of the reduced flow benefits occurring in winter.

Fecal coliform removal at GL averaged over five years was 98.6 ±3.6% from the lined first cell and 99.6 ±2.6% from the whole system. The first cell had <200 fecal coliform cfu/100ml 40% of the time and the second cell reached this level 83% of the time. A lower but often cited criterion of 1000 cfu/100mL was achieved 70% of the time for cell-1 and 95% of the time for the total system. No significant relationship was found between effluent values and temperature with little difference between winter and summer percent removal (Table 3). The cell-1 effluent averaged 189 cfu/100ml (C.I. 21-1690) in the summer and 401 cfu/100ml (CI 44-3628) in the winter. Treatment by the seepage cell improved performance throughout the year - removing an additional 170 cfu/100ml in summer and 360 cfu/100ml in winter. Cell-1 performance was temperature dependent ($r^2 = 0.57$) and the estimated K_{20} was 19.5 m/yr with $\theta = 1.133$.

The cell-1 overall average performance has changed little with time (Table 3) although there appears to be a steady increase in effluent concentration in summer - from 24 cfu/100ml (CI 6-94) in Year-1 to 2219 (CI 601-8189) cfu/100ml in year-5 despite relatively stable influent values.

The Lake Washington constructed wetlands removed 99.6 ± 0.7% of the influent fecal coliform from Jan 1997-APR 2000. The effluent average for the two wetlands was 60 (CI 5-741) cfu/100ml and there was little difference between summer and winter values. The effluent concentration was < 200 cfu/100ml 65% of the time with the exceedances divided evenly among seasons and no apparent trends over time.

TN - Ammonium nitrogen (NH_4^+-N) comprised >95% of the total-N at all points in the NERCC wetlands at nearly all times of the year. Nitrate/nitrite-N concentrations rarely exceeded 0.1 mg/L, although fall 1997 had concentrations as high as 3.0 mg/L and concentrations >1 mg/L for nearly 3 months. A regression of effluent concentration versus temperature was not statistically significant indicating little direct temperature dependence. Performance, in terms of either %-removal or effluent concentration has varied considerably over time from a low of 9% in the winter of 1996/1997 to a high of 63% in summer 1997. For the entire data set, summer %-N-removal performance was nearly double that in winter (41% versus 21%, Table 3). Mean summer effluent concentration during the first two summers was 30 ± 13 mgTN/L compared to the winter average for these same two years of 59 ± 12 mgTN/L. Coincident with an increase in influent nitrogen from 78 ± 6 mgTN/L (Years 1 and 2) to 95 ± 12 mgTN/L for Years 3 and 4, the effluent values increased to 74 ± 20 mgTN/L and 69 ± 20 mgTN/L for summer and winter, respectively. Reducing the flow (and therefore BOD and N-loading) to CW-1 resulted in a decrease of ~6mgTN/L in its effluent. The first cell of the 2-cell wetlands accounted for 77% of the TN that was removed regardless of the season.

Grand Lake influent TN to the lined first cell was also comprised almost entirely of ammonium-N. The five year average removal efficiency was 36 ± 29%, reducing the influent from 59 ± 12 to 37 ± 16 mgTN/L. The seepage cell further reduced TN to 29 ± 17 mgTN/L (Table 2). Cell-1 effluent values were not correlated with temperature and the winter and summer performance were similar (Table 3). The K_{20} for the first cell was 3.0 m/yr (r^2 = 0.51) with θ = 1.037. Cell-1 average winter performance decreased during the first four years but has rebounded somewhat during the 1999/2000 winter. Summer performance decreased to a low of 16% removal in Year-3 but has since returned to 36% removal in summer 2000. Nitrate/nitrite-N was <0.1 mg/L in the cell-1 effluent >95% of the time. The cell-2 effluent had nitrate/nitrite spikes of 3-7 mg/L every fall that lasted for ~2 months (not shown).

Lake Washington NH_4^+-N was >90% of the TN most of the time, although NO_3^-/NO_2^- N was present in both the influent and effluent in concentrations as high as 16 mg/L. TN-removal averaged 52% ± 20% over the three years of monitoring. The mean influent concentration was much lower than at the northern systems averaging 33 ± 11 mgTN/L and the effluent mean for the two wetlands was 15 ± 6.2 mgTN/L (Table 2). Summer removal was only slightly greater than for winter (Table 3) and the wetland removal efficiency has increased 27% over time.

TP - TP removal at NERCC averaged 30 ± 41%, reducing the influent from 13.5 ± 2.8 mgTP/L to 8.8 ± 4.1 mgTP/L in the effluent. Regressing effluent concentration versus temperature yielded no significant temperature dependence, but there was a 34% decrease in removal efficiency between winter and summer performance (Table 3). Average summer effluent concentration was 7.5 ± 4.7 mgTP/L and winter was 9.8 ± 3.3 mgTP/L. Occasional TP transport out of the wetland has been noted due to high flow out (rain events or snow melt) which results in the relatively large standard deviations.

The flow reduction in NERCC CW-1 reduced the effluent TP by nearly 1 mgTP/L during the winter but has had little effect during the summer. The removal of TP was greatest during the first two summers and has fluctuated between 3% and 60% removal since then. Inflow concentration has increased from ~11mgTP/L during the first two years to ~15 mgTP/L after that but TP after cell-1 was consistently ~3 mg/L less than the influent regardless of the season or age of the wetland. During the first two summers the system removed an average of 5 mgTP/L and 2 mgTP/L during the winter. During the last two years the system removed only 1.6 mgTP/L in the summer and 0.4 mgTP/L during the winter.

The GL wetland, averaged over five years, behaved similarly to those at NERCC with a TP removal of 34% in the first (lined) cell and 51% for the whole system. There was no indication of temperature dependence when the entire data set was analyzed. During the first two years winter and summer performance were nearly identical with 53%-56% removal by the first cell. During the next 3 years the first cell's effluent concentration increased and removal efficiency declined to an average of 25% in the summer and only 9% in the winter. For the entire period of record, winter removal was less than the summer (Table 3) and over time has decreased 62% (Axler et al. submitted). The empirical best fit for plug flow, first order reaction kinetics yielded a K_{20} for the first cell of 3.6 m/yr (r^2 = 0.57) with _ = 1.064. Further analysis of seasonal patterns of the first four years of NERCC and Grand Lake N and P performance data is in Kadlec et al. (2001).

The Lake Washington constructed wetlands have removed an average of 93 ± 8.6% of the influent TP, reducing the mean effluents for both wetlands to only about 0.5 mgTP/L, and many values were below detection. Summer % removal was 8% higher than the winter (Table 3) and there has been no clear indication of deterioration in performance over time although the limited data suggest that performance has declined over the past two years, particularly in fall and winter (not shown).

Maintenance and Costs

Wetlands require that some maintenance (i.e. periodic inspection of water levels, plumbing and plants, pumping septic tank) occur on a regular basis, which after the first few years should be no more than that required of a "standard system". A major concern in the extremely cold climate of northern MN (although only 46^0 50' N latitude, Duluth has winter average temperatures ~ 4^0C colder than Anchorage, AK at 61^0 10') is the freezing potential. Our experience is showing that snow cover is the single most critical factor in preventing freezing. Even in some of the coldest years on record (the first 2 years at NERCC and Grand Lake), when snowfall was far above average, the wetlands experienced virtually no freezing problems. However, in relatively warm winters with below average snowfall (1998/99 and 1999/00) some significant freezing problems have occurred. The NERCC wetlands were insulated with straw the first two years which was removed the following spring, a labor intensive process lacking appeal to the average homeowner. In subsequent years we relied on the *natural* vegetative cover and snow for thermal insulation but encountered freezing problems the past two winters. After consultation with staff from N. American Wetlands Engineering (Forest Lake, MN), a group which over the past few years has independently evaluated a variety of insulating materials for their CWs in central Minnesota, we have now added an insulating layer (~15 -20 cm) of reed-sedge peat to be left in place throughout the year at Grand Lake and NERCC (Wallace et al. 2000). The seepage cell at Grand Lake was covered with 60 cm. of straw and peat during construction (wetland plant growth was not an issue for this cell's design) and we have seen no evidence of freezing despite significant water accumulation in this bed. Additional valuable cold weather suggestions are offered by Maehlum and Jenssen (1998) based on their experiences in Norway.

The costs of these systems is variable and dependent on a number of factors with the gravel media typically the greatest expense, including the cost of trucking and placement within the wetland (McCarthy et al. 1997; Anderson and Gustafson 1998). The wetlands at the NERCC site were estimated at $6650 / 400 ft^2 (37 m^2) cell (increasing to 600 ft^2 increased the cost to $8000) which does not include the cost of final effluent dispersal (also variable and dependent on location, soil conditions and availability of materials). The Grand Lake CW cost was estimated at $10,500 per home, which included the design and construction of the collection and wetland systems, formation of the Triple Lakes Sewer Corporation, individual septic tanks, land costs, and final dispersal cell. The Lake Washington wetlands were estimated at $8325, which also does not include the cost of final effluent dispersal. These costs are estimates due to the donation of some labor (private sector and research team), equipment and supplies but should approximate the costs a homeowner would incur. A typical mound system in MN would cost ~$8700, with costs rising towards $15,000 for difficult soils, high water table or remote sites.

DISCUSSION

Influent (STE) strength varied greatly between the three sets of CWs - NERCC being higher than typical, Lake Washington lower, and Grand Lake intermediate (Tables 1 and 2; Crites and Tchobanoglous 1996). The wetlands also differed in terms of growing season duration, winter severity, configuration, depth of media, and hydraulic and mass loading rate. Overall, despite poorer performance and more operation and maintenance problems than originally anticipated, all of these SSF constructed wetlands offered significant potential for improving the year-round treatment of small-flow, domestic residential wastewater at sites with poor and/or shallow soils, or limited drainfield areas in the cold climate of Minnesota.

The NERCC and Grand Lake wetlands performed similarly in terms of both percent removed and final effluent concentrations; the Lake Washington effluent concentration was considerably lower than the northern wetlands, probably due to the low influent concentration, although the %-removal was similar. The BOD mass loading rates at NERCC and Grand Lake (29 and 28 kg/ha/d) were typical of the BOD loading rates in the North American Wetland Database (see Kadlec and Knight 1996), however, the influent concentration was an order of magnitude greater at NERCC and ~7 times greater at Grand Lake. BOD removal at both sites was somewhat better in the summer than winter, as both % removed and concentration, but only a weak direct correlation to effluent temperature was noted. The reaction rate constants (K_{20}s)are included to provide a comparison to historical data conceding the limitations of the first order model as detailed by Kadlec (2000 a), Brix (1998), Crites and Tchobanoglous (1996) and others. The majority of the BOD at NERCC and Grand Lake was removed in the first cell (at NERCC much is removed in the upper half of the first cell; see also Kadlec et al. 2001), however the second cell did not consistently reduce the concentration to <30 mg/L. The relatively "*lightly*" loaded Lake Washington CW did consistently reduce the effluent BOD to <30mg/L. Performance has declined somewhat in the past two years for NERCC and Grand Lake CWs but at NERCC we assume this is due primarily to increasing STE strength and to a lesser extent from less vigorous plant growth the past two summers. The freezing problems the past two winters (frozen beds in mid-winter 2000) also likely contributed to this decline, in part because of reduced bed volume and restricted flow through the root zone. Such interannual differences highlight the need for long-term monitoring. The Lake Washington effluent BOD has been more consistent over time, although the data record is shorter, but this apparent consistency may be largely a result of their much lower organic loading rate.

The CWs have been effective at consistently removing TSS to levels below 25 mgTSS/L and typically 8-15 mgTSS/L. Most of the TSS at NERCC and Grand Lake was removed by the first cell as expected. The TSS at Lake Washington has shown occasional effluent *spikes* above 25 mgTSS/L but these were associated with high (>100-200 mgTSS/L) influent values of unknown origin and may be due to sampling error.

Fecal coliform percent removal has been good in all of the CWs with 94%-99.6% removal, although the target criterion of 200 cfu/100mL year-round was not always attained, particularly at NERCC. Summer performance was clearly better than winter especially at the NERCC CWs. As for BOD, most of the removal occurred in the first cell of the two cell systems with the second cell contributing substantially less treatment. The second cell (strictly a gravel bed for seepage with minimal vegetation) at Grand Lake reduced the influent to <200 cfu/100ml consistently. The second cell (lined and vegetated) at NERCC did not consistently reduce effluent fecals to <200 cfu/100ml although water collected after CW dispersal in soil (sandy loam) to a depth of 30 cm (1 foot) below a standard trench system have averaged <100 cfu/100mL and shown a consistent order of magnitude reduction for fecals and a 2-3 order of magnitude reduction for a tracer spike of *Salmonella choleraesuis* (Axler et al. 2000, Pundsack 2000, Pundsack In press a,b). The Lake Washington wetland has consistently reduced effluent fecal coliforms to <200 cfu/100ml to date. It is likely that this is in part a consequence of its relatively long hydraulic retention time (nominally 34 days).

Nitrogen removal at both NERCC and Grand Lakes was not as good as expected. The NERCC CWs were initially designed to reduce growing season effluent-TN to the drinking water standard of 10mgN/L (assuming all N converts to nitrate-N). However, the higher than expected influent strength, in terms of both BOD and NH_4^+, has apparently limited the potential for nitrification to occur and the effluents have remained anoxic although redox values rise steadily along the length of the systems. TN levels in the influent were typically 80-100 mgN/L, >95 % as NH_4-N, and BOD_5 ranged from ~250 to >300mg/L. The relatively high alkalinity of the effluent, >300 $mgCaCO_3$/L, suggests that nitrification was not limited by available inorganic carbon. Nevertheless the NERCC CWs removed over 50 mgN/L during the summer of their first full year of operation and continue to remove about 25 mgN/L during summer 2000. The %-removal has however declined over time from 68 % in summer 1996 to 17-32% in 1999 and 2000 (mean of 40% for all five summers). Estimates of vegetative uptake by plants for 1997-1999 suggest that about 10-20% of the growing season N-removal was assimilated by plants. Since pH was circumneutral and too low for significant ammonia volatilization, it appears that most of the N-removal was due to immobilization in the bed or via coupled nitrification/denitrification. Poorer performance the past two years when plant growth was less vigorous are consistent with N-removal being closely related to root-zone mechanisms. In midsummer 2000 we modified our influent system to dilute the STE ~1:1 with low nutrient well water in order to determine if N-removal can be substantially increased when organic and ammonium loads are reduced. Previous attempts to accomplish this by reducing flow in one of the NERCC CWs presented sampling problems in midsummer when daytime outflows were reduced to a trickle by evapotranspiration.

The Grand Lake system has achieved an average of ~ 50% N-removal over its five year life (Table 3; Axler et al. submitted). However, the system has also *underachieved* relative to design estimations (see also Kadlec et al. 2001). Although influent BOD and ammonium are lower for this system (Table 2), they are still relatively high. Further, the gravel bed is deeper than NERCC (Table 1) and despite many attempts at revegetation, plant cover has never been as complete as at NERCC, for unknown reasons, which likely limits its N-performance. Lake Washington's CWs also removed ~50% of influent nitrogen, decreasing it from ~33 to16 mgN/L averaged over the period of record. As for Grand Lake, cattail growth at LW has not reached its full potential, but the lower loading rates for water, BOD and NH_4-N may explain the substantial N-removal. All systems have also shown improved summer Vs winter performance (see also Kadlec et al. 2001 and Axler et al. submitted) although N-removal has not correlated well with water temperature, presumably due to lags between effluent and ambient temperatures, gradients along the wetlands, seasonal changes in plant assimilation and O_2 translocation, differences in microbial consortia temperature sensitivity as well as spring snowmelt and fall rainstorms.

Phosphorus removal from the Minnesota wetlands may reasonably be assumed to be consistent with the large body of published literature- that is, removal is primarily due to chemical adsorption to the bed substrate. Tables 2 and 3 shows that overall P-removal at NERCC has been about 33% and that summer removal (mass) has been much greater than in winter. As for nitrogen, enhanced removal correlated with summer evapotranspiration and the period of lowest removal was during late winter/spring snowmelt runoff. Time plots (Axler et al. submitted) show that effluent P-concentrations have increased dramatically since 1998 relative to the first two years of operation suggesting that vegetative uptake has stabilized and active adsorption sites are nearing saturation. Although the gravel in the lower cells of each CW are comprised of crushed dolomite (carbonate rock) the circumneutral pH is probably too low for substantial P-precipitation to occur. P-removal at Grand Lake, based on concentration data (no outflow data) has been somewhat higher than at NERCC (Table 2) although time plots of the full data set suggest a similar trend of steadily increasing effluent concentrations during the period of record, presumably due to the saturation of active sites. It is also noteworthy that effluent values at both Grand Lake and NERCC were lowest during the first year of operation, even when plant densities and root depth were low, again suggesting that adsorption is the more important sink for phosphorus.

Phosphorus removal (concentration based) at Lake Washington has been outstanding to date, with effluent levels of only about 0.5 mgTP/L and removal efficiencies exceeding 90% most of the year. As for the northern sites the lowest effluent concentrations occurred in the first year or two after operation began and data since 1999 have begun to show a qualitatively increasing trend (not shown). The LW wetlands are much more lightly loaded with wastewater than the northern CWs and the gravel substrate is a significantly finer material and so the initially low phosphorus concentrations are not surprising.

Freeze prevention strategies are at odds with the need to provide longer retention times to meet performance expectations due to colder temperatures and the potential for freezing and for water passing below the root zone (i.e. reduced treatment) if the beds are deepened. The short northern growing season also prolongs the time needed for plants to fill in densely, thereby reducing thermal insulation as well as treatment potential. After determining the STE strength, flow requirement and effluent criteria, the wetland size must be balanced between being large enough to provide effective treatment but not so large as to cause freezing problems.

In summary, the data indicate that subsurface flow constructed wetlands are a viable, year-round treatment option for homeowners in terms of performance, ease of operation, and cost They will clearly require additional maintenance and management relative to standard drainfields due to variations in vegetative growth, winter insulation, and in meeting concentration based regulations. Regulatory criteria will need to consider the short-term, seasonal and interannual variability due to rain events, partial freezing, snowmelt runoff, summer evapotranspiration, and plant variability.

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REFERENCES

1. Ameel, J., E.Ruzycki and R.P.Axler. 1998 Analytical chemistry and quality assurance procedures for natural water samples. 6th edition., NRRI Tech. Rep. NRRI/TR-98/03, Natural Resources Research Institute, University of Minnesota, Duluth, MN.

2. Anderson, J. and D. Gustafson.1998. Development of alternative on-site treatment systems for wastewater: A demonstration project for southern Minnesota. Fin. Rep. to Minnesota Pollution Control Agency/Legislative Comm. on Minnesota Resources, St. Paul, MN

3. Amer. Publ. Health Assoc.,Amer.Water Works Assoc.,Wat. Environ Fed, APHA 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed, Washington, D.C.

4. Axler, R., J.Henneck and B. McCarthy. Submitted for publication. Residential subsurface flow treatment wetlands in northern Minnesota. Water Science and Technology.

5. Axler, R.P., J. Henneck, S. Bridgham, C. Tikkanen, D. Nordman, A. Bamford, and M.E. McDonald. 1996. Constructed wetlands in northern Minnesota for treatment of aquaculture wastes. In Proc. Constructed Wetlands in Cold Climates, The Friends of Fort George, Niagara on the Lake, Ontario, Canada.

6. Axler, R.P., J. Henneck, B. McCarthy. 2000. Residential subsurface flow treatment wetlands in northern Minnesota. 7th International conference on Wetlands for water pollution control,IWA, London, UK.

7. Brix, H.1998. Denmark. In: Constructed wetlands for wastewater treatment in Europe, J.Vymazal, H.Brix, P.F.Cooper, M.B.Green and R.Haberl (eds.), Backhuys Publ., Leiden, Netherlands, pp.123-152.

8. Cooper, P.F. and M.B.Green.1998, UK. In: Constructed wetlands for wastewater treatment in Europe, J.Vymazal, H.Brix, P.F.Cooper, M.B.Green and R.Haberl (eds.), Backhuys Publ., Leiden, Netherlands, pp.315-335.

9. Crites, R. and G. Tchobanoglous.1998. Small and Decentralized Wastewater Management Systems. McGraw-Hill, Companies, Inc., pp.1084

10. Crosby, J., B. McCarthy, C. Gilbertson and R. Axler. 1998. A regulatory perspective on impediments and solutions to the use of performance standards for on-site wastewater treatment., In: Onsite Wastewater treatment, Proc. 8th Internat. Symp. on Individual and Small Community Sewage Systems, Amer. Soc. of Agricultural Engineers, St. Joseph, MI. 49085-9659 USA. pp. 259-267

11. EPA. 1993. Subsurface flow constructed wetlands for wastewater treatment: A technology assessment. EPA 832-R-93-001. Environmental Protection Agency, Washington, D.C.

12. Heger, S., J. Anderson and B. McCarthy. 2001. Evaluation of recirculating sand filters in a northern climate. 9th National Symposium on Individual and Small Community Sewage Systems, ASAE, St. Joseph, MI 49085-9659 USA.

13. Henneck, J., R. Axler, D. Nordman, B. McCarthy and S. Monson Geerts.1999. Operation and maintenance

experiences with constructed wetlands in Minnesota. *In* Proc. National On-Site Wastewater Recycling Assoc, NOWRA, Laurel MD. pp. 219-223

14. Kadlec, R. and R. Knight.1996. Treatment Wetlands. Lewis Publ., Boca Raton, FL.

15. Kadlec, R. 2000 a. The inadequacy of first-order treatment wetland models. Ecol. Eng. 15(2000):105-119.

17. Kadlec, R.H. 2000 b. Thermal considerations of constructed wetlands in cold climates. 7th

International conference on Wetlands for water pollution control, IWA, London, UK.

16. Kadlec, R.H., R. Axler, B. McCarthy and J. Henneck. 2001. Subsurface treatment wetlands in the cold climate of Minnesota. *In* Advances in Ecological Sciences, U. Mander, Editor, Constructed Wetlands for Wastewater Treatment in Cold Climates.

18. Maehlum, T. and P. Jenssen. (1998). Norway. In: Constructed wetlands for wastewater treatment in Europe, J.Vymazal, H.Brix, P.F.Cooper, M.B.Green and R.Haberl (eds.), Backhuys Publ., Leiden, Netherlands, pp. 206-217.

19. McCarthy, B., R. Axler, S. Monson Geerts, J. Henneck, D. Nordman, J. Crosby, P. Weidman, 1998. Performance of alternative treatment systems in Northern Minnesota. , *In*: Onsite Wastewater treatment, Proc. 8th Internat. Symp. on Individual and Small Community Sewage Systems, ASAE, St. Joseph, Missouri. pp 446-457

20. McCarthy, B., R. Axler, S. Monson Geerts, J.Henneck, J. Crosby, D.Nordman, P.Weidman and T. Hagen. 1997. Development of alternative on-site treatment systems for wastewater treatment: A demonstration project for Northern Minnesota. Tech.Rep. NRRI/TR-97/10, U. of Minnesota, Duluth, MN.

21. Monson Geerts, S., B. McCarthy, R. Axler, J.Henneck, S. Heger, J.Crosby and M.Guite. 2001. Performance of peat filters in the treatment of domestic wastewater in Minnesota. 9th National Symposium on Individual and Small Community Sewage Systems, ASAE, St. Joseph, MI.

22. Pundsack, J.P. 2000. Pathogen removal by alternative on-site systems for treatment of single home wastewater flows. M.S. thesis, U. of Minnesota, Duluth, MN.

23. Pundsack, J., R. AXLER, R. Hicks, J. Henneck, D. Nordman and B. McCarthy. In Press a. Seasonal Pathogen Removal by Alternative On-site Wastewater Treatment Systems. Water Environ. Research.

24. Pundsack, J.W., R.E. Hicks and R.P. Axler. In Press b. Effect of alternative on-site wastewater treatment on the viability and culturability of *Salmonella choleraesuis*. Appl. Environ. Microbiol.

25. Reed, S., R. Crites and E. Middlebrook. 1995. Natural Systems for Waste Management and Treatment. McGraw-Hill Companies, Inc.

26. Wallace, S., G. Parkin, C. Cross, 2000. Constructed wetlands in cold climates: Thermalconsiderations. North American Wetlands Engineering manuscript. 7th Internationalconference on Wetlands for water pollution control, IWA, London, UK.