Residential subsurface flow treatment wetlands in northern Minnesota

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Abstract Approximately 30% of Minnesotans use on-site systems (~500,000 residences) and >50% are failing or non-compliant with regulations due to restrictive soils and site conditions. Many sites occur near lakes and streams creating health hazards and deteriorating water quality. SSF CWs have been evaluated year-round at two northern sites since 1995. The NERCC CWs simulate single homes and the Grand Lake demonstration CW treats STE from a cluster of 9 lakeshore homes. Systems were generally able to achieve design criteria of 25 mgTSS/L and 30 mgBOD5/L and the NERCC CWs required only 0.3m of unsaturated soil to achieve consistent disinfection to <200 fecals/100 mL year round. Seeding experiments with *Salmonella* indicated removal efficiencies of 99.8% in summer and 95% in winter. High strength (~300 mgBOD/L, 95 mgTN/L) influent at NERCC probably limited system performance, particularly N-removal (mass) which was ~42% in summer and 20% in winter. The data indicate CW's are a viable, year-round treatment option for homeowners in terms of performance, ease of operation, and cost but require additional maintenance related to inconsistent vegetation growth, winter insulation, and meeting concentration-based regulatory standards since they were seasonally and annually variable due to rain events, partial freezing, spring snowmelt, and summer evapotranspiration.

Keywords Alternative technologies; cold-climate; constructed wetlands; pathogens; wastewater

Introduction

Historically, constructed wetlands (CWs) have been used world-wide at numerous locations for over 30 years, in warm and cold climates. In Minnesota, CWs have only recently begun to be used at several locations to treat wastewater from both residential and commercial establishments. In 1995, research sites were set up in northern Minnesota near Duluth at the Northeast Regional Correction Center (NERCC) and at Grand Lake (McCarthy *et al.*, 1997) and in southern Minnesota at Lake Washington, near Mankato (Anderson, 1998; Henneck *et al.*, 2001). The research is in its fifth year of testing alternative on-site treatment technologies.

About 30% of Minnesotans rely upon on-site systems for wastewater treatment (~500,000 residences). 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 health hazard and deteriorating water quality. Constructed wetlands are one option currently being evaluated, as well as sand, peat and textile filters, aerobic treatment units, and drip irrigation (McCarthy *et al.*, 1997, 1998, 1999). The use of alternative on-site technologies for wastewater treatment in Minnesota and other Great Lakes states will be 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.

This paper addresses subsurface flow (SSF) CWs as a viable wastewater treatment

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option in northern Minnesota based on our experiences from 1995–2000 and presents an overview of existing data. These are small flow subsurface flow gravel beds located at the NERCC (Northeast Regional Correction Center) research facility and at the Grand Lake, MN demonstration project. Both sites experience severe winters with extended periods of air temperatures <–20°C and occasionally to <–40°C.

Methods and system designs

The northern Minnesota research site at NERCC, near Duluth, was designed to allow side-by-side comparisons of the performance of both alternative and standard onsite systems using the same wastewater (septic tank effluent [STE]; see McCarthy *et al.*, 1997 for details) at daily flows approximating those used by single family homes in this region ~ 0.95 m^3/day (250 gal/d). One of the two replicated constructed wetlands (CW2) discharges to a standard drainfield trench monitored at three depths by pan lysimeters filled with fine silica beads. All systems were designed to achieve a *secondary* level of treatment of 25 mg TSS/L, 30 mg BOD_5/L, and disinfection to a recreational bathing standard of 200 fecal coliform bacteria per 100 mL. The CWs are two-cell (upper = *Typha*, lower = *Scirpus*), lined, subsurface flow systems. 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. Cell dimensions are 7.0 m L × 5.3 m W × 0.45 m D. Design hydraulic residence time is 13 days with a hydraulic loading rate of 1.3 cm/d (see McCarthy *et al.*, 1997, 1998 for details). For the period through mid-2000, the wastewater strength was higher than anticipated with typical values of BOD_5 >300 mg/L and NH_4-N ~100 mgN/L).

The Grand Lake cluster system CW was designed to correct the problems of 10 single family homes along a lakeshore just north of Duluth. The CW receives STE via a small diameter pipe to two cells in series designed for a flow of ~4m^3/day with dimensions of 10 m L × 18 m W × 0.6 m D for cell-1 (*Typha*) and 15 m L × 20 mW × 0.60 m D for the unlined, dispersal cell-2 (details in McCarthy *et al.*, 1997; Crosby *et al.*, 1998; and Axler *et al.*, 1999). Design HRT for the measured flows would be ~15 days (at an HLR = 1.3 cm/d), however, a summer bromide tracer study suggested the actual retention time was ~23 days (Kadlec *et al.*, 2001).

Nutrient analysis methods are described in detail in McCarthy *et al.* (1997, 1998) and follow standard methods (APHA, 1995; Ameel *et al.*, 1998). NERCC removal efficiencies are based on mass-removal (i.e. flow weighted) whereas Grand Lake efficiencies are concentration-based (no outflow monitoring). Salmonella seeding experiments are described in Pundsack *et al.* (2001); somatic coliphages were determined by the double agar method as per APHA (1995) and IOS (1993).

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):

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

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°C, T (°C) is the temperature, and q is the modified Arrhenius temperature factor. A concurrent nonlinear regression was used to optimize the parameters k_{20} and q (R. Kadlec pers. comm.) for each of the water quality constituents.

Results and discussion

NERCC-TSS/BOD5/nutrients

Overall, during the growing season (May/June through September) the NERCC wetlands (2 cell-train) achieved their primary objective of treating septic tank effluent to 2° treatment standards (25 mg TSS/L, 30 mg BOD_5/L), despite higher strength wastewater than anticipated. Annual summer effluent values averaged (mean of annual means) 8 ± 2 mg TSS/L (85% removal) and 23 ± 10 mg BOD_5/L (92% removal) for 1996–1999 (Figure 1). TSS remained low in winter (mean TSS <9 mg/L), effluent BOD values rose for the same 4 years to 51 ± 17 mg BOD_5/L although the mean %-removal remained a relatively high 79%. Although initially designed to reduce growing season effluent-TN to the drinking water standard of 10 mgN/L (assuming all N converts to nitrate-N), the systems have clearly been unable to convert sufficient ammonium to nitrate in order to denitrify a major fraction of the N-load, presumably due to oxygen limitation. Alkalinities have ranged from 300–500 mg$CaCO_3$/L indicating that nitrification was not limited by available inorganic carbon. Influent TN was typically 80–100 mgN/L, >90% as NH_4-N; BOD_5 ranged from ~250 to >300 mg/L, and oxygen was rarely detected in the wetland effluent (although redox values rose steadily along the length of the systems (Axler, unpubl.). The pH has been circumneutral and unchanged across the length of the wetlands, suggesting that ammonia volatilization was a small component of the actual TN loss. The wetlands removed over 50 mgN/L during the summer of their first full year of operation but %-removal has declined annually – from 68% in 1996 to 19% in 1999 (mean of the annual means = 42% for all four years).

Phosphorus removal averaged 51% in summer and dropped to 20% in winter for the four years, again declining throughout the period of record for each season, suggesting saturation (Figure 1). The limestone substrate in the lower cell of each wetland did not enhance phosphate removal relative to the gravel used in the upper cell, as indicated by the gradual decline down the length of the cells (*cf.* Kadlec *et al.*, 2001), presumably due to pH remaining near 7.

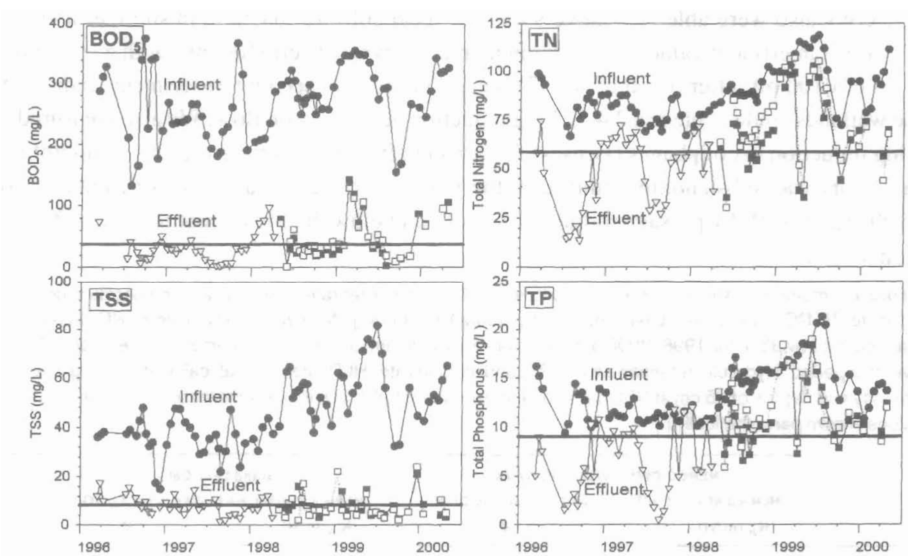

Figure 1 NERCC wetland comon influent (●), and effluent. Effluent values (▽) for 1996–1998 are the means of CW1 and CW2 when inflows were nearly idential. CW2 effluent values for 1998–2000 denoted by open boxes (□) for similar flows; CW1 effluent values for 1998–2000 denoted by closed boxes (■) when flows were reduced by 35%. The solid lines are the mean effluent values (mg/L) for 1996–2000; BOD_5 = 39, TN = 58, TSS = 8 and TP = 9

Vegetative growth and nutrient content (N and P) was monitored from fall 1996 (Year 1) to the present to estimate the plant nutrient uptake during the growing season. Growth was luxuriant from the initial planting in spring 1996 (unlike at Grand Lake, see below) and we estimate that the average N-uptake was ~172 mgN/m^2/day over an average 116 day growing season (shoot emergence to first hard frost). We estimate that plant uptake into aboveground biomass represented ~11–23% of the N-removal during this period and 5–8% of the annual influent-N for years 2 to 4. Although these values are low, they are not unusual in the literature (Kadlec and Knight, 1996; Reed *et al.*, 1995), and in 1999, when summer N-removal was only 19%, plant uptake could potentially have accounted for more than the measured N-removal. Note that these are likely to be conservative estimates because we could not measure root growth. Estimated vegetative P-removal was also low, 11–19% during the growing season and only 4–6% of the annual removal. Note that considerable recycling of these nutrients also must take place since plants were not harvested.

Table 1 summarizes first order plug flow reactor rate constants and temperature coefficients calculated for Years 2–4 for comparison to other published studies since this model is widely used by wetland designers. The limitations of using the first order plug flow model are recognized, in particular the assumption of constant flow. There are strong seasonal and shorter-term variations in hydraulics due to evapotranspiration, snow melt runoff, rainstorms, and freezing effects. The k's also vary with hydraulic loading, mass loading and system age (Kadlec, 2000a; Brix, 1998). Despite these shortcomings, the reaction rate constants provide a basis of comparison to previously published results. The results show that the design values based on the North American Wetland DataBase (USEPA, 1994) greatly overestimated rate constants for all parameters (1–2 orders of magnitude) and also underestimated their temperature dependence-particularly BOD_5. A detailed analysis of seasonal effects for both NERCC and Grand Lake may be found in Kadlec *et al.* (2001). Grand Lake k_{20} and q values were generally similar to those estimated for the NERCC wetlands.

NERCC-Pathogens

The CWs also were able to remove 99.9% of fecal coliform bacteria in summer and the 4-year mean effluent value (mean of annual means) was 491 cfu/100 mL, with a reduction to 58 cfu/100 mL after 0.3 m of soil (Table 2). *Salmonella* seeding experiments indicated the wetlands could achieve a 2.4–5.2 log reduction depending on flow. We also measured a 2 log reduction in coliphages (viruses). Treatment efficiency, as measured by all microbial indicators was substantially reduced in the winter although fecals were still reduced to <100 cfu/100 mL by passage through 0.3 m of soil below the trench that receives effluent from CW2.

Table 1 Empirically estimated (Kadlec and Knight, 1996) first order rate constants and temperature coefficients for NERCC and Grand Lake wetlands from July 1996 through May 2000. Flow from NERCC-CW1 was reduced by 35% for 1998–2000 but there was no significant difference in parameter values from CW2 over this period. Hydraulic retention time (HRT) and loading rate (HLR) are nominal, calculated using a 40% porosity and depths of 45 cm at NERCC and 60 cm at Grand Lake. L is the organic loading rate. Design values shown parenthetically [ ]

	NERCC-CW1, CW2 (2 cell-trains) HLR = 0.86 m^3/d, HRT = 16–26 d, L = 2.8 g BOD/m^2		Grand Lake Cell-1 HLR = 2.31m^3/d, HRT = 24 d, L = 2.3 g BOD/m^2	
	K_{20} (m/yr)	θ	K_{20} (m/yr)	θ
TSS	5.0, 8.1 [3000]	0.983, 1.001 [1.000]	13.2 [3000]	1.037 [1.000]
BOD	19.4, 15.0 [180]	1.071, 1.043 [1.000]	19.5 [180]	1.133 [1.000]
Fecals	27, 28 [95]	1.053, 1.049 [1.000]	45 [95]	1.028 [1.000]
TN	1.3, 1.5 [27]	1.019, 1.021 [1.050]	3.0 [27]	1.037 [1.050]
TP	1.7, 1.9 [12]	1.049, 1.035 [1.000]	3.6 [12]	1.064 [1.000]

NERCC-ice and vegetation

Substantial performance declines for all parameters in the last two winters are presumed to be a result of partial freezing in 1998/99 (reducing HRT by ~15–65%), and ultimately complete freezing in Feb 2000. These were warmer (still extremely cold), but much drier than usual winters, and even applying about 0.5 m of straw to the existing plant cover was insufficient insulation without normal snow accumulations to prevent freezing. A similar problem occurred at Grand Lake in late winter 2000 and has forced us to add a 15 cm insulating layer of reed-sedge peat for winter 2001. Performance improvements noted for CW1 in summer 1998 when the flow was reduced by 35% (to decrease the organic loading rate) were not evident in 1999 and we attribute this, at least in part, to poor plant growth this year and invasion by terrestrial weeds. Bulrush declines in cell-2 were particularly apparent and may have been associated with freezing damage the previous winter. We actively removed invasive species in summer 2000 and this, along with the addition of insulation will be important recommendations to homeowners and contractors in the future.

Grand Lake – TSS/BOD$_5$/nutrients/pathogens

Performance data are reported in Table 2 and Figure 2 for Years 2–4. This CW-seepage cell system has successfully solved a lakeshore problem although performance of the CW has again been poorer than expected. As for NERCC, wastewater BOD$_5$ and TN have been higher than design criteria, and the calculated first order rate constants (Table 2) were far below those used for the design. Concentration based performance (no outflow sensing) for the system has been generally acceptable with average (mean of annual means) summer effluent quality of 5 mg TSS/L (82% removal), 45 mg BOD$_5$/L (76% removal), and 443 cfu/100 mL (99.7% fecal removal). Nutrient treatment was relatively poor, with summer values of 48 mgTN/L (only 20% removal) 5.9 mgP/L (30% removal). Winter performance was reasonably good for TSS (6 mg/L;73%) and fecal coliforms (1265 cfu/100 mL; 98.9%) but was again greatly reduced for BOD$_5$ (86 mg BOD$_5$/L;49% removal) and poor for N (45 mgTN/L; only 21% removal) and P (6.6 mgP/L; only 15% removal). Despite somewhat lower strength STE, the Grand Lake CW has had generally poorer performance than at NERCC for several reasons including: (1) Poorer vegetative growth – cattails have not grown well since initial planting in fall 1995 and the CW has been replanted annually, including a variety of species, with only moderate success. Initial construction delays necessitated filling the cell with local bogwater that clearly led to nutrient deficiency for the cattails and then later problems as the denser wastewater stratified within the bed

Table 2 Pathogen removal by NERCC constructed wetlands for septic tank effluent (STE). Fecal coliform and coliphage data compiled from routine monitoring (Winter = Nov–Apr; Summer = May–Oct). Salmonella experiments based on seeding experiments where removal efficiency is based on the total seeded cells recovered following ~7 d of dosing (Pundsack et al., 2001). %-removal (R) was converted to Log factors by Log Removal = – log [1-(%R/100)]. Standard deviations are for seasonal variation (for FC's), for duplicate wetlands (Salmonella experiment), or for trench lysimeters (FC and coliphage). n = number of measurements. [ ][a] = geometric mean of effluent concentrations for both CW's, in cfu/100 mL

	NERCC CW Pathogen Removal (log reductions relative to STE influent)					
	SUMMER (May–Oct: 15.7°C)			WINTER (Nov–Apr: 2.6°C)		
Site	Fecal coliforms (1996–00)	Salmonella choleraesuis (seeded 1998)	somatic coliphage (1998–00)	Fecal coliforms (1996–00)	Salmonella choleraesuis (seeded 1998)	somatic coliphage (1998–00)
CW1 & CW2	2.8 ± 0.6	5.2 @ HRT 14d	1.7 ± 0.2	1.9 ± 0.2	1.4@ HRT 22d	1.2 ± 1.0
(14d & 9d)	(n = 64) [491][a]	2.4 @ HRT 9d	(n = 20)	(n = 88) [6211][a]	1.3@ HRT 17d	(n = 19)
Trench – CW2 0.3 m deep	3.8 [58][a]	5.4 ± 0.4	2.0	3.7 [79][a]	3.3 ± 0.7	1.2
0.6 m deep	3.9 [43][a]	5.8 ± 0.4	2.3	3.8 [26][a]	4.0 ± 10	1.2
0.9 m deep	4.4 [13][a]	6.0 ± 0.1	2.6	4.3 [16][a]	5.9 ± 0.1	1.8

and flowed beneath the root zone (note – these problems were corrected after Years 1 and 3, respectively. The low aspect ratio of the cell (0.6) necessitated by the site likely exacerbated this short-circuiting. (2) Partial (1998/99) and complete (March 2000) winter freezing also reduced the HRT and perhaps affected subsequent plant growth and net oxygen translocation to the bed; and lastly, (3) the bed depth was 0.60 m, relative to NERCC's 0.45 m. The bed was deeper in order to minimize potential for freezing, but the trade-off is that less water is exposed to the root-zone. Our experiences at these and other Minnesota SSF CWs has been that typical rooting depths have only been ~0.25–0.40 m (Axler *et al.*, 1999, unpubl.).

The entire system, CW + seepage cell, has however, consistently met design criteria for TSS, BOD and fecals in summer, and for TSS and fecals in winter (Axler *et al.*, 1999; Henneck *et al.* 2001; Kadlec *et al.*, 2001). Summer averages for the seepage cell for 1997–1999 were 4 mg TSS/L (system removal 88%), 29 mg BOD/L (84% removal) and 30 cfu/100 mL (99.98% removal) and winter averages were 8 mg TSS/L (69%), 63 mg BOD (4%) and 62 cfu/100 mL (99.94% removal), respectively. TN and TP means for summer were 41 mgN/L (32%) and 3.9 mgP/L (50%) and for winter were 34 mgN/L (43%) and 5.1 mgP/L (35%).

Conclusions

Overall, despite poorer performance and more operation and maintenance problems than originally anticipated, SSF constructed wetlands offer significant potential for effectively treating small-flow, domestic residential wastewater at sites with poor and/or shallow soils, or limited drainfield areas in the cold climate of northern Minnesota. Previous analyses have shown them also to be viable financially (McCarthy *et al.*, 1997) and they also offer the potential for significant nitrogen reduction, unlike many other alternative technologies. The data to date suggest that literature summaries of first order plug flow reaction rate constants and Arrhenius temperature coefficients are too high for our systems although the reasons may relate to the relatively high strength septic tank effluent in our systems. Although

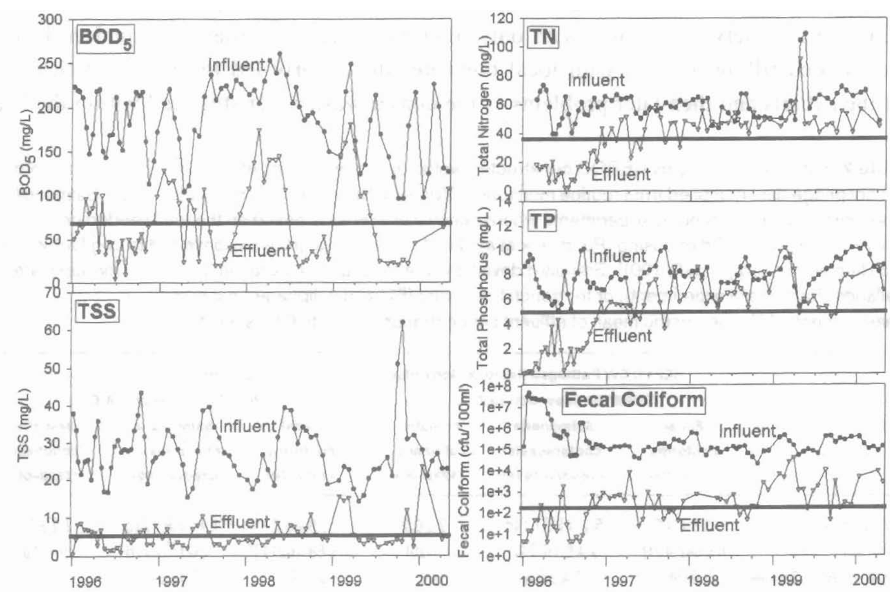

Figure 2 Grand Lake wetland influent and effluent values for 1996–2000. The solid lines are the mean effluent values (mg/L unless noted); BOD_5 = 69, TSS = 5, TN = 37, TP = 5, and fecal coliform = 323 cfu/100 ml

higher STE values than reported in the literature (e.g. Reed *et al.*, 1995; Kadlec and Knight, 1996; Crites and Tchobanoglous, 1998) one would expect higher values in areas constrained by site conditions due to voluntary water conservation.

Winter in northern Minnesota presents special challenges, particularly in light of the fact that our recent warm winters were much more of a problem than the first two cold winters because of the lack of snow cover (cf Kadlec, 2001). Maehlum and Jenssen (1998) offer some cold weather design considerations based on their experiences in Norway, but at odds are the need to provide longer retention times to meet performance expectations due to the colder temperatures and the potential for freezing due to the longer retention time and the potential for water to pass below the root zone if the beds are deepened. The shorter growing season also allows the plants less time to fill in densely in a climate where insulative growth is critical. After determining the flow characteristics (both rate and wastewater strength) and the performance level required, the wetland size must be balanced between being large enough for adequate treatment but not so large as to allow freezing problems to occur. Local building codes require that uninsulated water pipes be buried five feet (1.5 m) below the surface to prevent freezing so special care must be taken since pipes will hold water just below the surface of the wetland. The outlet structure is an area of special concern as the wastewater is most exposed to the environment and at its coldest temperature. We have now added an insulating layer (15 cm) of reed-sedge peat to be left in place throughout the year as per Wallace *et al.* (2001). Other construction techniques to minimize freezing include foam around and on top of the septic tank to help maintain the wastewater heat, grass over the piping to provide additional insulation, and limiting traffic over the pipes to minimize compaction of the earth and lessen frost depth. Plant growth is critical by providing insulating mulch and trapping snow. A layer of foam around the perimeter of the wetland beds may also be prudent.

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