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COLD CLIMATE WETLANDS: DESIGN & PERFORMANCE

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ABSTRACT

Constructed wetlands are gaining widespread use as a simple, low cost means of wastewater treatment. Introduction of constructed wetlands technology into the northern United States has been limited by the ability of conventional wetland systems to operate without freezing during the winter. A design approach using subsurface-flow constructed wetlands covered with an insulating mulch layer has been demonstrated to prevent freezing. However, introduction of a mulch layer will affect oxygen transfer rates, pollutant removal performance, and plant establishment. These factors must be addressed for successful application of constructed wetlands technology in cold climates.

KEYWORDS

Constructed wetlands, Cold-Climates, Insulation, Mulch, $CBOD_5$, Nitrogen, Oxygen transfer

INTRODUCTION

Constructed wetlands have many unique benefits as a wastewater treatment process, including the ability to operate on ambient solar energy, self-organize and increase treatment capacity over time, create wildlife habitat, produce oxygen and consume carbon dioxide, and achieve high levels of treatment with minimal maintenance (Wallace, 1998). The authors primary interest has been in developing simple constructed wetland treatment systems as an alternative to more complex mechanical systems with an emphasis on household and small community wastewater treatment. This is driven in part by the demonstrated need for better wastewater alternatives, even in the United States. On-site septic systems serve approximately 25% of the US population (USEPA 1997), and in 1995 alone, over 2.5 million septic systems malfunctioned (NODP). Contrary to the belief that regional wastewater facilities are solving the nation's problems, more Americans are using septic systems now than in 1990 (NODP).

Initial work on subsurface flow wetlands was developed in Germany (Seidel, 1973). Subsurface flow wetlands have the primary benefit that water is not exposed during the treatment process, minimizing energy losses through evaporation and convection. This makes horizontal subsurface flow (and vertical flow) wetlands more suitable for winter applications.

Adaptation of constructed wetlands technology to sub-freezing environments requires some type of insulation strategy. Leaf litter is often suggested as once source of insulation; however leaf litter is often spotty in distribution, which allows heat to escape. Even small breaches in insulation can result in substantial heat losses in flowing water (Callahan, 2000). To be effective, insulation must be uniform in coverage, which requires that it be designed as an integral part of the wetland system.

Initial use of mulch as a cover in subsurface flow constructed wetlands was suggested by the Tennessee Valley Authority (Steiner & Watson, 1993) as a means to prevent odors and sunscald in warm climates. Mulch was used as an insulation media on the constructed wetland built at the Indian Creek Nature Center in Cedar Rapids, Iowa in 1994 and found to be highly effective in preventing the system from freezing (Wallace & Patterson, 1996). Computer modeling of insulated wetland systems has suggested that adequate insulation would be effective in preventing systems from freezing at temperatures as low as –20 ^{o}C (Jenssen et al, 1996).

INSULATION DESIGN

Designing an effective insulation layer for the constructed wetland requires a knowledge of the basic elements of heat transfer, how the wetland will respond under cold conditions, the effect the mulch material will have on wetland performance, and what plant species are compatible with the mulch layer.

Heat transfer

Factors affecting heat transfer in aquatic and plant systems are discussed at length in several sources (Kadlec & Knight, 1996, Ashton et al, 1986, ASCE, 1990). In considering the winter energy balance condition, the situation can be simplified to the following (Wallace, 2000):

$$E_{loss} = G + (U_i - U_o)$$

Where:

$E_{loss} =$ energy lost to the atmosphere, $\mathrm{MJ/m^2/d}$

$G =$ conductive transfer from ground, $\mathrm{MJ/m^2/d}$

$U_i =$ energy entering with water, $\mathrm{MJ/m^2/d}$

$U_0 =$ energy leaving with water, $\mathrm{MJ/m^2/d}$

Successful design of cold climate wetlands requires that E_{loss} be “throttled down” so that the energy inputs, $G + (U_i - U_o)$ can replace the energy lost. The basic design strategy is to minimize E_{loss}, through the following methods (Wallace, 2000):

- Avoid open water. This minimizes heat loss through evapotranspiration and convection.
- Do not depend entirely on surface ice. Contrary to popular belief, ice is a very poor insulator, and has a thermal conductivity ($0.19\ \mathrm{MJ/m/d/^{o}C}$) almost four times greater than liquid water ($0.05\ \mathrm{MJ/m/d/^{o}C}$). Ice is useful in that it eliminates evaporative losses and it can be used in conjunction with an air gap or snow blanket to increase the thermal resistance. However, without significant snow cover, the insulation value offered by ice is limited.
- Use subsurface flow and vertical flow wetland systems. These systems have a smaller area footprint per unit flow (concentrating the incoming heat, U_i), can be substantially disposed of in the earth (maximizing G), and can be designed to avoid open water.
- Insulate the system. Placing layers with greater thermal resistance on top of the wetland reduces E_{loss}.

Performance history

One of the authors (Wallace) has designed a number of constructed wetlands since 1997 based on a hydraulic loading rate of 2 cm/day with 15 cm of mulch insulation. Based on data collected during quarterly (or monthly) sampling events and interviews with owners on 28 systems located in Minnesota, none of these systems froze to the extent that hydraulic performance was compromised (local freezing in sampling ports, due to the "chimney effect" or in corners of the bed outside of the primary flow path was observed). However, several wetland systems monitored by the University of Minnesota froze (causing hydraulic failure) during the winters of 1998/1999 and 1999/2000 (McCarthy, 2000 personal communication). These wetland systems had previously performed well during previous winters (McCarthy et al., 1997). The primary difference was that there was ample snow cover during the previous winters but snow cover was lacking during severe cold temperatures in the 1998/1999 and 1999/2000 winters. Clearly, one of the primary benefits of the mulch insulation approach is that it provides a "safety factor" for those winters when it is severely cold without adequate snow cover.

Lutsen Sea Villas Case Study: The benefits of a mulch insulation approach can be clearly illustrated using a real-life example. A subsurface flow constructed wetland was built in 1997 to treat domestic wastewater from 27 town home units located on the north shore of Lake Superior in Lutsen, Minnesota. The fall and early winter were mild, with no snow cover on the ground. On December 19, 1998, temperatures began to drop rapidly, reaching -28 ^{o}C by December 21 (NAWE, 1999):

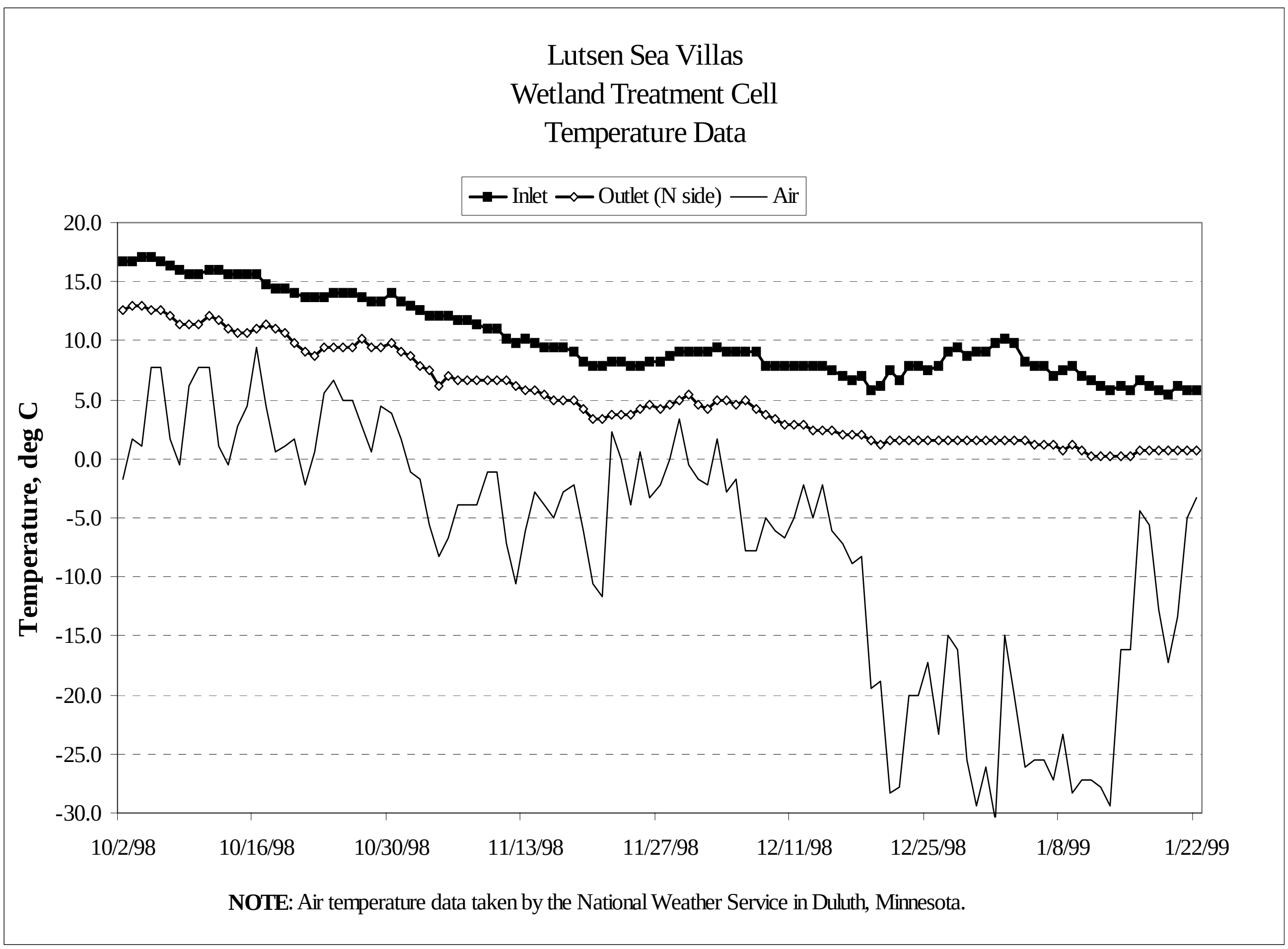

Figure 1. Temperature response of mulch-insulated subsurface flow wetland at Lutsen Sea Villas during extreme freezing event in December 1998 and January 1999.

The system was insulated with 15 cm of mulch. A 5 cm air gap was present under the mulch insulation. Based on elapsed time meter readings on the pumps, the system was operating at 0.88 cm/day. Based on the inlet and outlet water temperatures, the heat input associated with the water $(U_i - U_o)$ is calculated as $0.24\ \mathrm{MJ/m^2/d}$. Based on a standard value (Kadlec & Knight, 1996) for the thermal conductivity of the mulch ($0.0052\ \mathrm{MJ/m/d/^{o}C}$), the air gap ($0.0021\ \mathrm{MJ/m/d/^{o}C}$), and the average thermal gradient ($29.5\,^{o}\mathrm{C}$), the heat lost to the atmosphere, (E_{loss}) is estimated at $0.56\ \mathrm{MJ/m^2/d}$.

Subtracting $(U_i - U_o)$ from E_{loss} results in an estimate of G at $0.32\ \mathrm{MJ/m^2/d}$ (Wallace, 2000), which is very close to the transfer value of $0.31\ \mathrm{MJ/m^2/d}$ determined for the Houghton Lake wetland system (Kadlec & Knight, 1996). If a 5 cm ice cap and 5 cm air gap had been used instead of the mulch insulation, the resulting heat loss would have been $1.22\ \mathrm{MJ/m^2/d}$, almost 4 times greater.

Other Temperature Results: It can be seen that mulch insulation is necessary when a constructed wetland must face extreme winter temperatures. Temperature response of five constructed wetlands in the Minneapolis/St. Paul area are summarized in Figure 2 (NAWE, 1998). All use the mulch insulation method just described.

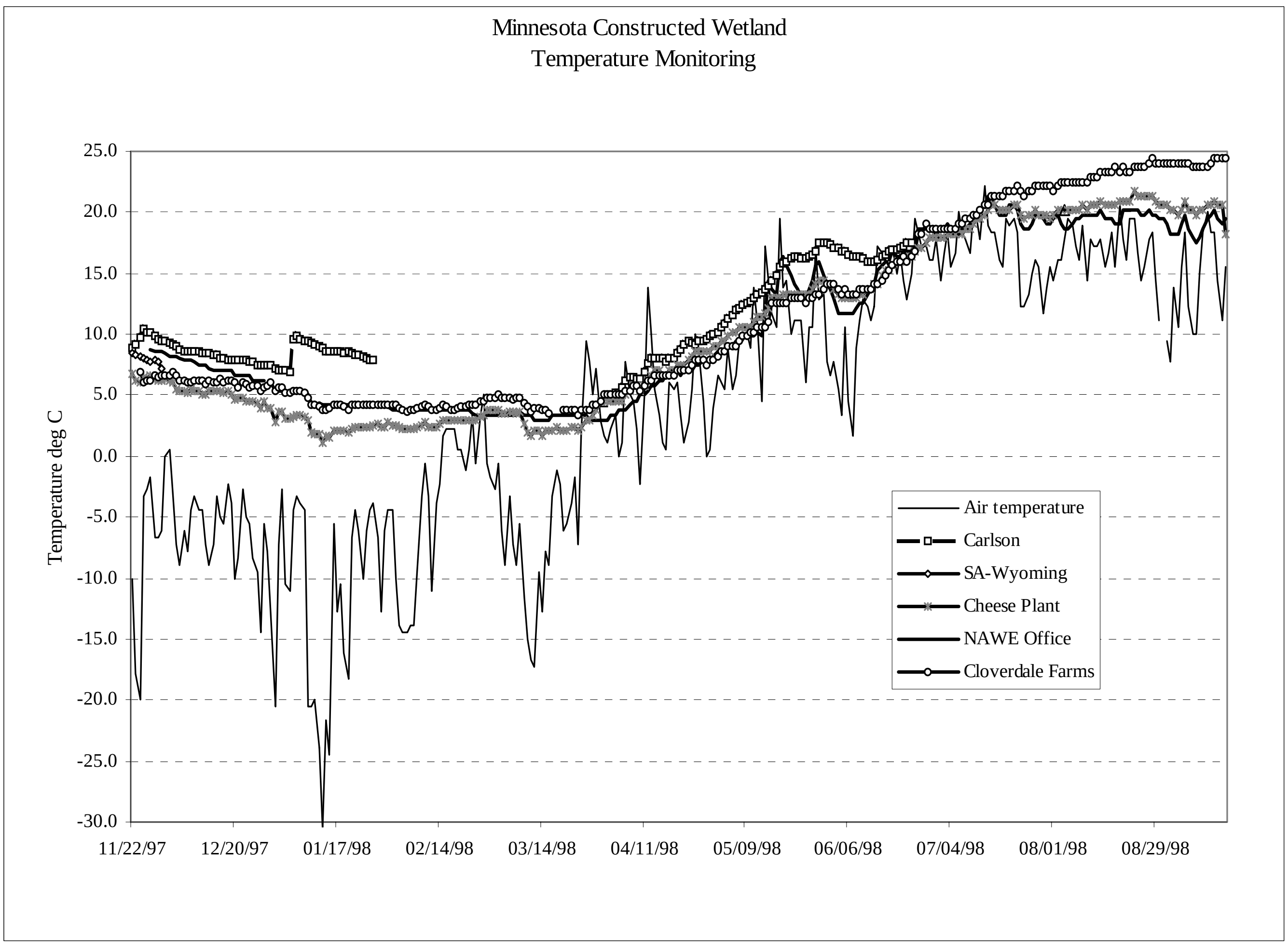

Figure 2: Effluent temperatures for five mulch-insulated subsurface flow wetlands located near Minneapolis, Minnesota. In one of the systems (Carlson) the hot tub was dumped to the septic tank, resulting in the temperature spike seen on the left hand side of the graph.

The temperatures presented in Figure 2 are effluent temperatures. In reality, the heat associated with the influent flow is dissipated quickly due to the increased thermal gradient, often within the first 25% of the bed length (Kadlec et al., 2000). Consequently, the majority of the wetland is at a "balance point" temperature. If only the tail end of the wetland is considered, the energy balance can be further simplified to $E_{loss} \leq G$. Simply put, if E_{loss} cannot be minimized to a rate where G can keep up, the system will freeze. Unfortunately, G has only been measured directly for a handful of wetland systems. Without knowledge of the maximum sustainable rate of G for a given site, insulation requirements cannot be directly calculated.

Mulch effects

Early references to potential mulch use in constructed wetlands suggested that a wide variety of materials such as bark, pine straw, wood chips, etc. would be suitable (Steiner & Watson, 1993). After trying a variety of mulch types, preferred materials used by the authors include reed-sedge peat (ASTM 1969, Malterer et al. 1991) and high quality yard waste compost. Good mulch material must meet the following characteristics (Wallace, 1999):

- Be substantially decomposed, and not exert a secondary organic loading on the system.
- Have a balanced nutrient composition and a circumneutral pH.
- Have a fluffy structure with high fiber content to provide good thermal insulation and not wash down into the gravel bed.
- Be fine enough so that there is good contact between the seed coat and the mulch for germination (if seeding is used as part of plant establishment).
- Have good moisture holding capacity so that seedlings are not subjected to drought stress.

Bad mulch will adversely affect plant establishment. Mulch materials such as wood chips that have a high carbon: nitrogen ratio will cause nitrogen deficiency problems during plant establishment. Material that is chipped (rather than ground) packs tightly, making plant root penetration very difficult.

Bad mulch will also degrade treatment performance as it decomposes. One way to assess the effect of a bad mulch material is to consider how the secondary organic loading elevates the background $CBOD_5$ concentration of the effluent, C* (Kadlec & Knight, 1996). As the mulch decomposes, C* will improve as the secondary organic load decreases over time. However, it may take several years to see substantial improvements. Estimated C* parameters for different mulch materials are listed in Table 1:

Table 1: Estimated $CBOD_5$ C* Parameters for Various As-Constructed Mulch Materials

Material	Year 1	Year 2
Wood Chips	40 mg/L	20 mg/L
Poplar Bark ("hog fuel")	60 mg/L	20 mg/L
Wood Chips buried under Sand	120 mg/L	80 mg/L
Reed-Sedge Peat	5 mg/L	3 mg/L
High Quality Yard Waste Compost	5 mg/L	5 mg/L

Plant Selection

Introduction of a mulch layer on top of the wetland cell creates an unsaturated zone for plants to root in. This tends to shift the competitive advantage away from obligate wetland plants towards facultative wetland species (US Army Corps of Engineers, 1987), many of which are unfamiliar in the treatment wetland literature. In addition, moving away from a strictly obligate wetland environment opens up opportunities for invasion by exotic species such as Reed Canary Grass (*Phalaris arundinacea)* and feral hops (*Humulus spp*.).

In some cases, constructed wetlands become preferred wintering areas for deer, and when this occurs, grazing pressure can be severe. In a system planted by one of the authors (Wallace), deer successfully harvested 239 out of 240 Cardinal Flower (*Lobelia cardinalis*) plants during the winter of 1998/1999. In pioneering a new environment, plant seedlings may be subjected in unusual stresses. In this same system, over 75% of the Swamp Milkweed (*Asclepias incarnata*) seedlings planted were consumed by Monarch Butterfly (*Danaus plexippus*) caterpillars in the spring of 1999. Successful plant species must propagate well, spread rapidly, and be resistant to grazing pressure.

The authors have experimented with a number of facultative wetland and obligate wetland plant species native to the Upper Midwest (Wallace, 1999). Recommended plant species are listed in Table 2:

Table 2: Recommended Wetland Plant Species

Common Name	Scientific Name
Duck Potato	*Sagittaria latifolia*
Green Bulrush	*Scirpus atrovirens*
Blue Flag Iris	*Iris versicolor*
Cup Plant	*Silphium perfoliatum*
Stiff Goldenrod	*Solidago rigida*
Swamp Milkweed	*Asclepias incarnata*
Sandbar Willow	*Salix exigua*

The rate of plant establishment is strongly influenced by the mulch material used. Systems that have a mulch layer with poor moisture holding capacity (or no mulch layer) have extremely poor seed germination and place large drought stresses on seedlings. In these systems, plants can only become established though rhizome spread from mature plants. In a northern climate like Minnesota this will take a minimum of three growing seasons. Better mulch design results in surface conditions much more hospitable to plant seedlings and also allows for seed germination. Under these circumstances, plant establishment can occur in as little as one growing season (Wallace, 1999). In all cases, the water level should be raised to allow sub-irrigation of the mulch layer for the first growing season.

TREATMENT PERFORMANCE

Early design equations for constructed wetlands were predicated on the assumption of first-order kinetics and plug flow (USEPA 1988, Reed et al 1988, WPCF 1990). However, it has been demonstrated that flow within constructed wetlands is not plug flow (Kadlec 1994, Werner & Kadlec, 2000), and that first-order models do not accurately predict wetland performance (Kadlec, 2000). At the present time there does not exist a good set of design equations that are firmly grounded in theory and can be used to predict wetland performance.

A subset of six Minnesota constructed wetlands built in 1997 and 1998 were selected for data comparison purposes. Initial design was based on generic wetland parameters (Kadlec & Knight, 1996), which were modified based on prior design experience and temperature-corrected by one of the authors (Wallace). These wetlands have the following design parameters in common:

- All are subsurface flow constructed wetlands with a horizontal flow path. No recirculation, vertical flow, or aeration was used.
- All were designed at a hydraulic loading rate of 2 cm/day.
- All have length: width ratios greater than 1:1 and do not suffer from surfacing of flow or obvious hydraulic short-circuiting (dispersion within the bed is assumed).
- All have the same gravel bed media, consisting of 25 to 6 mm river-run gravel. Local gravel pits were personally inspected to ensure that the proposed material had the proper packing factor.
- All systems were insulated with 15 cm of mulch, although the material used varied.
- All systems were full-size operating systems, treating settled sewage of domestic strength or greater.
- All systems received full loading immediately after start-up.

Carbonaceous Biochemical Oxygen Demand

All six systems were monitored under County or State operating permits. Monitoring requirements were generally quarterly or monthly, depending on the permit (NAWE 1998, NAWE 1999, MPCA 1997). Data collection generally consisted of inlet and outlet concentrations. Although the six systems reviewed had largely similar design parameters, actual performance varied widely, as shown in Figure 3:

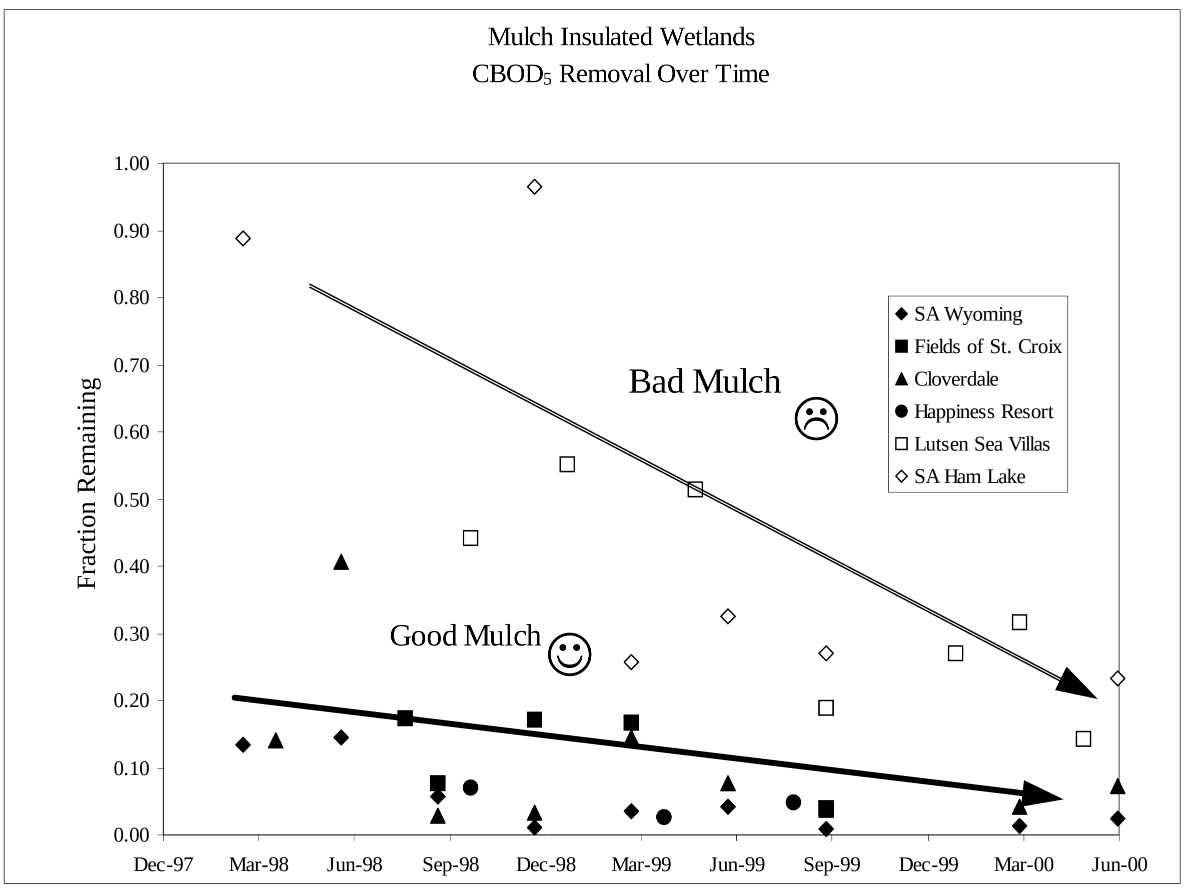

Figure 3: Summary of long-term trends in CBOD5 removal for six mulch-insulated subsurface flow wetland systems located in Minnesota. Systems represented by black data points were constructed with good mulch. Systems represented by white data points were constructed with bad mulch.

In general, systems with good mulch, featuring substantially decomposed material with a low C*, achieved a $CBOD_5$ reduction of 75 percent in the first year, with treatment performance generally exceeding 90% in the second year. The four good mulch systems shown in Figure 3 (SA Wyoming, Fields of St. Croix, Cloverdale, and Happiness Resort) had a high proportion of reed-sedge peat in the mulch layer, although two of the systems (Fields of St. Croix and Cloverdale) initially had wood chips that were replaced in late summer 1998 with reed-sedge peat.

Improvements in $CBOD_5$ removal over time is attributed to development of a mature, stable microbial population and plant establishment, with the most dramatic improvements occurring after the conclusion of the first growing season. Systems subjected to a late fall "cold start" at full design load will generally perform poorly over the first winter, and may not improve until the end of the first growing season, almost a full year after initial start up.

Total Nitrogen

Five of the six systems were also monitored for nitrogen. Reductions in total nitrogen varied widely, with no discernable improvement over time, as shown in Figure 4:

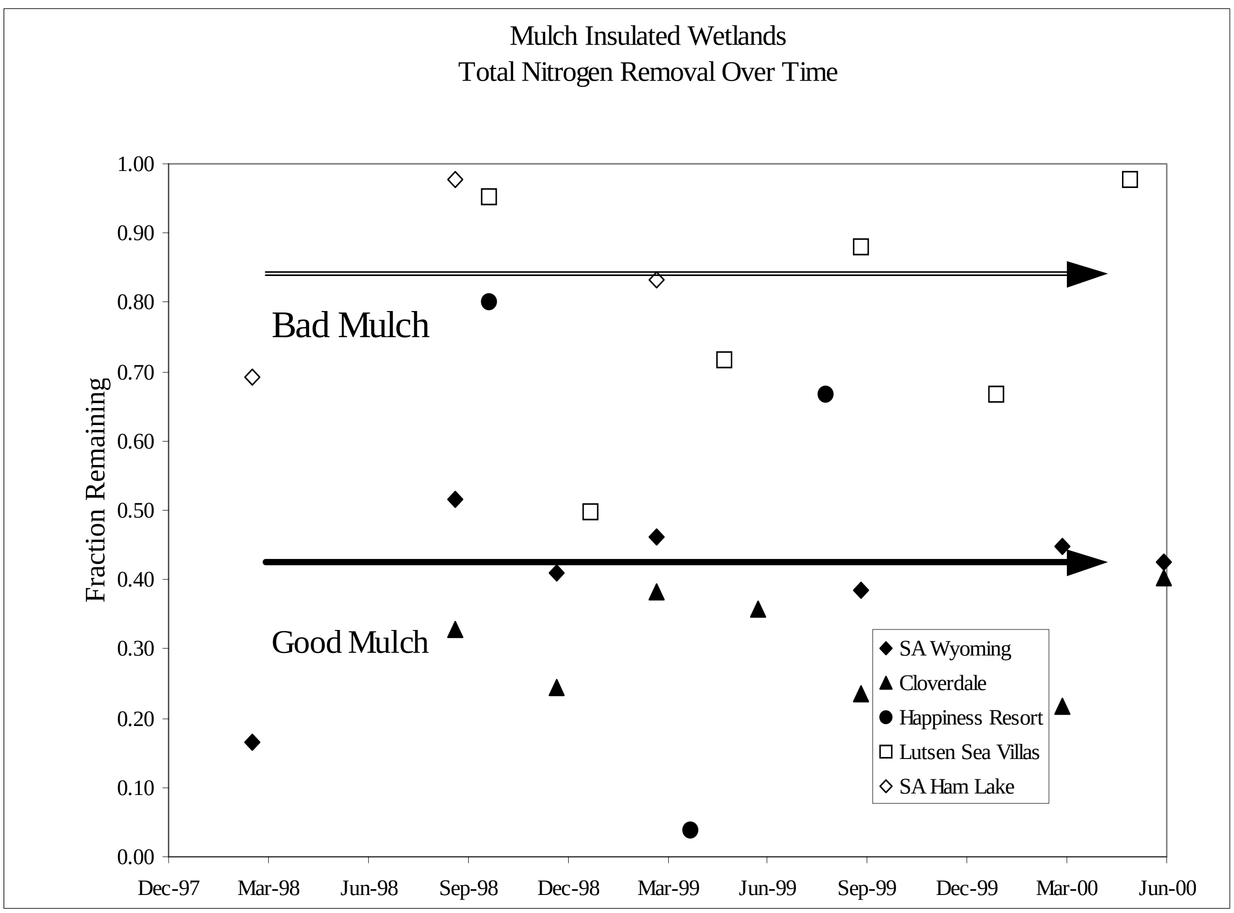

Figure 4: Summary of long-term trends in Total Nitrogen removal for five mulch-insulated subsurface flow wetland systems located in Minnesota. Systems represented by black data points were constructed with good mulch. Systems represented by white data points were constructed with bad mulch. None of the systems were aerated.

In general, good mulch systems performed better than bad mulch systems. In all of the five systems, nitrogen removal was limited due to a failure to convert ammonia to nitrate. Limited nitrogen removal in other Minnesota subsurface flow wetlands (that do not have mulch insulation) has also been observed (Kadlec at al, 2000). Similar results have been documented at other subsurface flow constructed wetlands (Johns et al. 1998).

METHODS TO IMPROVE TREATMENT PERFORMANCE

It is apparent that cold climate subsurface flow constructed wetlands are effective in CBOD removal based on the operational history of full-sized systems in Minnesota. However, these same systems have not reduced Total Nitrogen in a consistent or logical way, even when sized at hydraulic loading rates that should have allowed nitrification to occur.

Nitrogen removal is believed to be temperature dependent in constructed wetlands (Kadlec & Knight 1996), with some authors suggesting that nitrification essentially stops at $4^{\circ}C$ (USEPA, 1993). However, data has shown that lightly loaded subsurface flow constructed wetlands can oxidize ammonia at temperatures of 2.8 to $4.4^{\circ}C$ (Wallace & Patterson, 1996). Wetland reactor configurations that allow greater air movement within the bed also have good nitrogen removal. A vertical flow wetland in Canada achieved nitrification at temperatures of 2 to $5^{\circ}C$ (Lemon et al, 1996), and a reciprocating bed design patented by Tennessee Valley Authority has demonstrated total nitrogen removal rates in excess of 85% (Behrends, 1999).

A patent-pending wetland aeration process (Forced Bed Aeration™) has been developed by one of the authors (Wallace) and applied to a number of waste streams, including domestic wastewater, dairy waste, restaurants, landfill leachate, and petroleum contact water, in both horizontal subsurface flow and vertical flow configurations (Wallace 1999, MPCA 1998, SDDENR, 1998).

A pilot wetland (97 square meters) was installed at the Jones County, Iowa landfill to demonstrate the use of constructed wetlands as a low-cost treatment alternative for leachate generated at small rural landfills. The basic reactor is a horizontal subsurface flow wetland with mulch insulation, and Forced Bed Aeration™. Instrumentation installed at the site includes influent and effluent flow meters, sampling ports at six locations and three depths down the flow path, precipitation, and influent, effluent, and air temperatures. The system was placed into operation in August 1999. Due to the waste strength (influent CBOD of approximately 200 mg/L, influent ammonia of approximately 500 mg/L), the initial loading was set at 4 mm/day. Monitoring is ongoing and data interpretation is still preliminary at this time. However, the system is achieving CBOD removals in excess of 93% and ammonia reductions in excess of 90%, even at very low temperatures (Parkin & Cross, 2000). A typical nitrogen transformation transect is shown in Figure 5:

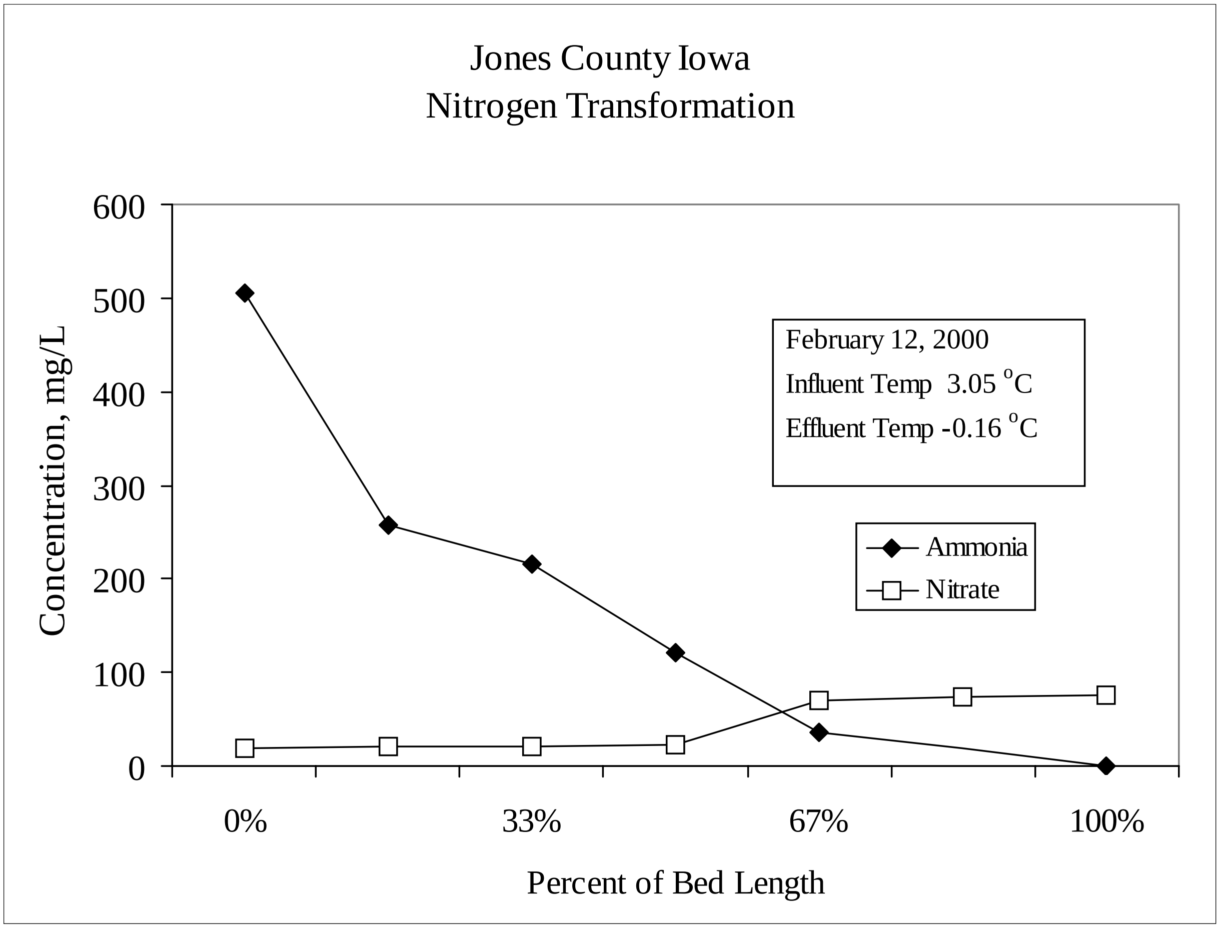

Figure 5: Ammonia and nitrate concentrations along the main flow path of the mulch-insulated subsurface flow wetland at the Jones County Landfill on February 12, 2000. This system was aerated to remove oxygen limitations to nitrification. Due to the high levels of total dissolved solids in the landfill leachate, the effluent temperature was depressed below 0 °C.

As seen in Figure 5, it does not appear that temperatures below 4 °C are a barrier to nitrification in constructed wetlands, provided the system is protected from freezing and adequate oxygen is available. During February 2000, the Jones County system operated at an influent temperature of approximately 3 °C and an effluent temperature of –0.16 °C (depression of the freezing point was observed due to the high total dissolved solids in the leachate). This low-temperature nitrification is consistent with earlier results in horizontal subsurface flow wetlands (Wallace & Patterson, 1996 and vertical flow wetlands (Lemon et al. 1996). In another system, a vertical flow wetland reactor with Forced Bed Aeration™ treating domestic wastewater at a single family home (Bornholdt residence in Blaine, Minnesota) was studied during February 2000 and found to nitrify and denitrify under winter conditions, achieving Total Nitrogen reductions of 89% or greater (NAWE 2000).

The Jones County system is typical of other Forced Bed Aeration™ wetlands, in that first-year lags in treatment efficiency are minimized. Part of this is attributed to the creation of a more favorable environment for slow-growing bacteria of the order *Nitrobacteria* (Margulis & Schwartz, 1988). It has also been demonstrated that the root morphology of wetland vegetation is positively influenced by aeration and resultant changes in redox potential (Behrends et al. 1996, Lockhart 1999). Consequently reactor configurations such as Forced Bed Aeration™, reciprocating beds, and vertical flow wetlands can result in greater root biomass with more rapid plant establishment than conventional horizontal subsurface flow wetlands. The primary benefit of the Forced Bed Aeration™ reactor configuration is that it was developed specifically for use in cold climate insulated wetlands.

CONCLUSIONS

Use of constructed wetlands in sub-freezing winter environments imposes a number of unique design requirements not commonly encountered elsewhere in the wetland literature. Lessons learned from early wetland designs could be applied to other cold-climate wetlands in the future. Based on the performance history of constructed wetlands in Minnesota and Iowa, the following conclusions can be drawn:

- Properly designed insulation of the wetland bed is effective in preventing freezing and resulting hydraulic failure. Relying on snow and ice cover does not provide reliable insulation during cold periods with limited snow pack.
- The type of mulch insulation used can strongly affect the performance of the system. Only well decomposed organic materials can be used without degrading treatment efficiency.
- Presence of a mulch layer will affect the type of vegetation used in the system. Plant species used in the wetland should tolerate the presence of an unsaturated root zone in the mulch layer.
- Properly designed cold climate insulated wetlands can achieve high levels of CBOD removal. Treatment performance will improve after the first growing season.
- In order to achieve high levels of nitrogen removal, adequate oxygen must be available. Standard horizontal subsurface flow wetlands do not transfer enough oxygen to satisfy both the carbonaceous and nitrogenous oxygen demand in cold climates. Alternative reactor configurations that have higher levels of oxygen transfer are necessary for nitrogen removal. Temperatures below $4\,^{o}C$ are not a barrier to nitrification, provided the wetland is designed to prevent freezing.

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