Cold climate wetlands: design and 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 $CBOD_5$; cold climate; constructed wetlands; insulation; mulch, nitrogen; oxygen transfer

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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 one source of insulation; however leaf litter is often spotty in distribution, which allows heat to escape. 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 and Watson, 1993) as a means to prevent odors and sunscald in warm climates. Mulch was used as an insulation medium 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 and 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°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 and Knight, 1996; ASCE, 1990). In considering the winter energy balance condition, the situation can be simplified to the following:

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

where:

E_{loss} = energy lost to the atmosphere, MJ/m^2/d
G = conductive transfer from ground, MJ/m2/d
U_i = energy entering with water, MJ/m^2/d
U_o = energy leaving with water, 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.

- 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 MJ/m/d/°C) almost four times greater than liquid water (0.05 MJ/m/d/°C).
- 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 with 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. 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 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°C by December 21, 1998 (Figure 1).

The system was insulated with 15 cm of mulch. A 5 cm air gap was present under the

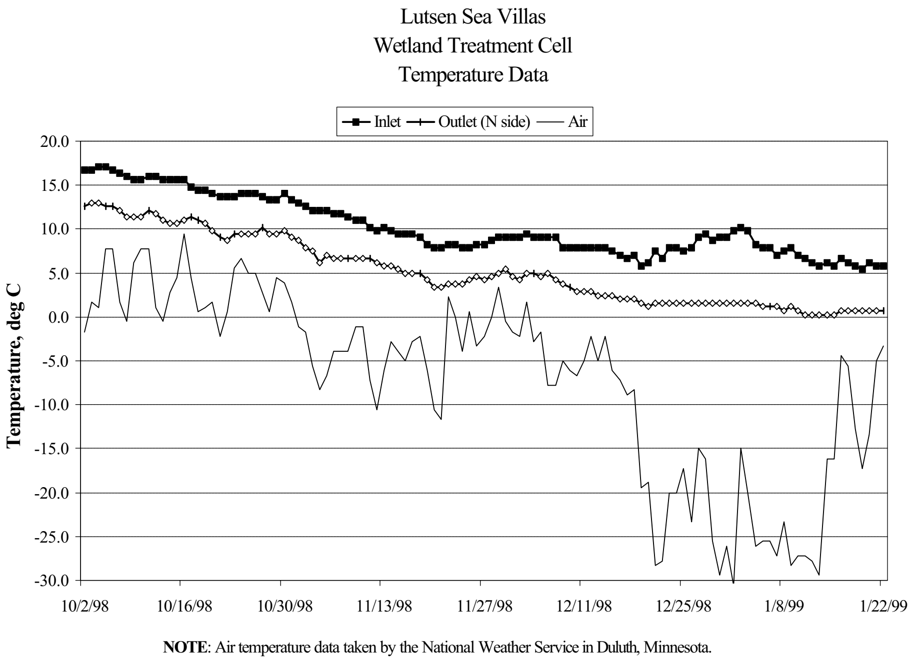

Figure 1 Temperature response of mulch-insulated subsurface flow wetland at Lutsen Sea Villas during extreme freezing event in December 1998 and January 1999

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 MJ/m^2/d. Based on a standard value (Kadlec and Knight, 1996) for the thermal conductivity of the mulch (0.0052 MJ/m/d/°C), the air gap (0.0021 MJ/m/d/°C), and the average thermal gradient (29.5°C), the heat lost to the atmosphere, (E_{loss}) is estimated at 0.56 MJ/m^2/d.

Subtracting ($U_i - U_o$) from E_{loss} results in an estimate of G at 0.32 MJ/m^2/d (Wallace, 2001), which is very close to the transfer value of 0.31 MJ/m^2/d determined for the Houghton Lake wetland system (Kadlec and 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 MJ/m^2/d (almost 4 times greater); an unsustainable heat loss that would result in freezing.

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 and Watson, 1993). After trying a variety of mulch types, preferred materials used by the authors include reed-sedge peat (ASTM, 1969) and high quality yard waste compost. Good mulch material must meet the following characteristics.

- 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 and 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:

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 can place large drought stresses on seedlings without proper water level control. 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, despite climatic limitations. In all cases, the water level should be raised to allow sub-irrigation of the mulch layer for the first growing season.

Treatment 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 and Knight, 1996), which were modified based on prior design experience and temperature-corrected by one of the authors (Wallace). These wetlands all treat domestic wastewater at full design load, and were designed using the same hydraulic and organic loading rates.

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 operating permit. Data collection generally consisted of inlet and outlet concentrations. Although the six systems reviewed had largely similar loading parameters, actual performance varied widely, as shown in Figure 2:

In general, systems with good mulch, featuring substantially decomposed material with a low C^*, achieved a $CBOD_5$ reduction of 75 per cent 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.

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

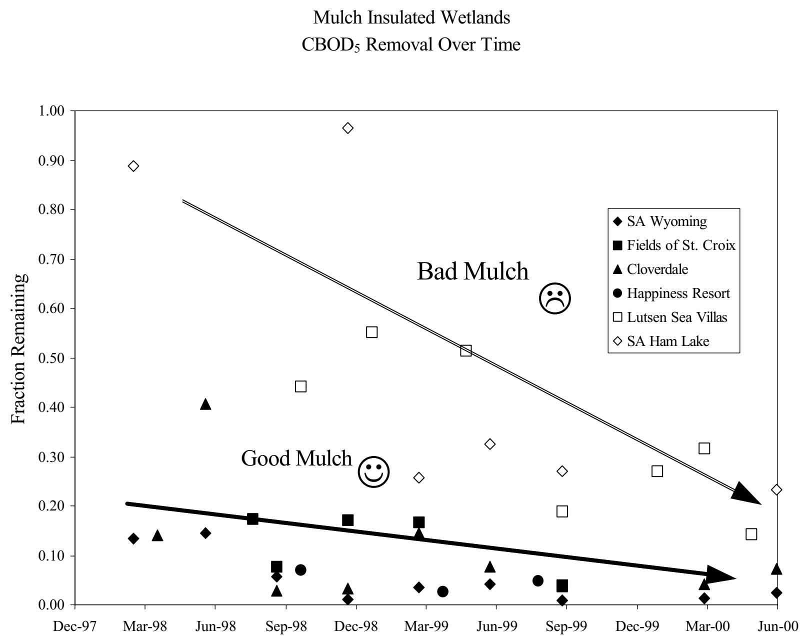

Figure 2 Summary of long-term trends in $CBOD_5$ removal for six mulch-insulated subsurface flow wetland systems located in Minnesota. Systems represented by black data points were constructed with good mulch. Systems represented by white data points were constructed with bad mulch

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 3:

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 *et al.*, 2000).

Methods to improve treatment performance

While effective in CBOD reduction, cold-climate subsurface flow wetlands have demonstrated limited Total Nitrogen removal. This could be attributed to either cold temperatures (that inhibit bacterial action) or limited oxygen transfer (not enough oxygen is available for ammonia oxidation).

A pilot-scale wetland (97 square metres) 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 insulated for cold-climate operation, with an aeration system (Wallace, 2001) to eliminate any oxygen transfer limitations. 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

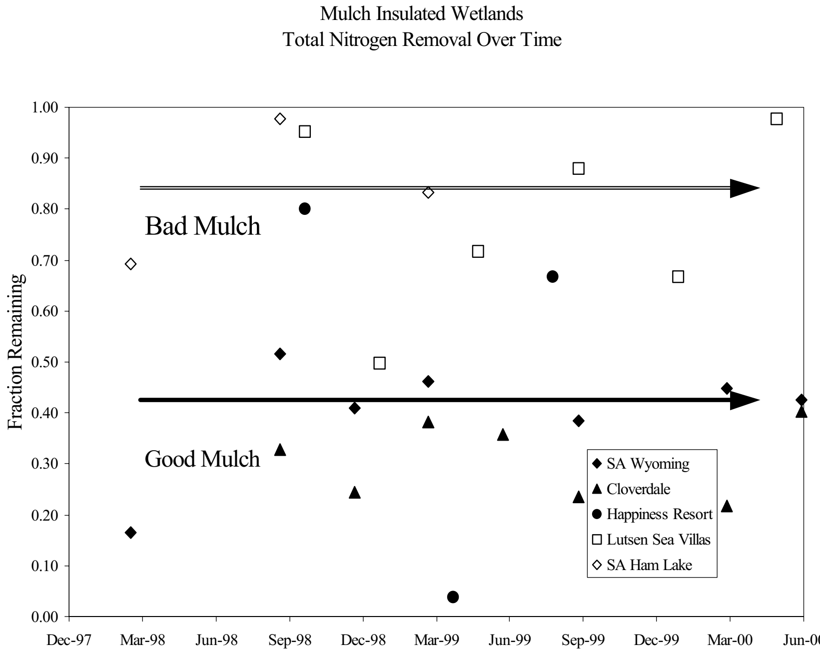

Figure 3 Summary of long-term trends in Total Nitrogen removal for five mulch-insulated subsurface flow wetland systems located in Minnesota. Systems represented by black data points were constructed with good mulch. Systems represented by white data points were constructed with bad mulch. None of the systems were aerated

is ongoing and data interpretation is still preliminary at this time. However, the system has consistently achieved very high ammonia removal rates (approximately 90%), despite the very high ammonia influent concentration (500 mg/L), with concurrent production of nitrate (approximately 100 mg/L), under winter operating temperatures very close to 0°C (Parkin and Cross, 2000).

This low-temperature nitrification is consistent with other wetland reactor designs that provide a high degree of oxygen transfer (Lemon *et al*., 1996).

Conclusions

Use of constructed wetlands in sub-freezing winter environments imposes a number of unique design requirements. 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.
- 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 demands. Alternative reactor configurations that have higher levels of oxygen transfer are necessary for nitrogen removal. For

cold-climate wetlands, temperatures below 4°C are not a barrier to nitrification, provided the wetland is designed to prevent freezing.

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