PERFORMANCE AND DESIGN CONSIDERATIONS OF TREATMENT WETLAND SYSTEMS FOR LIVESTOCK WASTEWATER MANAGEMENT IN COLD CLIMATE REGIONS IN SOUTHERN CANADA AND THE NORTHERN UNITED STATES

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ABSTRACT

The livestock industry incorporates the valuable nutrients that manure holds into the soil as part of the sustainable philosophy that farming has always had. However, uncontrolled discharges of nutrients enter the surface water and groundwater. Considerable interest and acceptance has been expressed regarding the use of wetland technology for polishing high-strength livestock wastewater that cannot be economically or practically recycled. Treatment wetland systems are in place or under development in many locations across Canada and the United States. They have been found to reduce contaminant loadings from farming operations to the water environment and have the potential of doing this on a much wider scale.

The Gulf of Mexico Program (GMP) Treatment Wetland Project summarizes available information about the effectiveness of constructed treatment wetlands in managing concentrated livestock wastewater in Canada and the United States. Information was compiled from ongoing evaluations of constructed wetlands for livestock wastewater management. Design and monitoring data from 68 treatment wetland sites were entered into a database. Water quality monitoring data from several of these sites provides valuable information related to the startup and early operation periods of these systems. The data from all of the treatment wetland sites was analyzed to develop treatment wetland design criteria for the differing wastewater streams and the wide range of climatic conditions throughout Canada and the United States.

This paper focuses on the 30 treatment wetland systems located north of the 37th parallel (approximately) since these systems are, for the most part, located in cold climates. Experience has shown that treatment wetland systems can operate in northern climates. In most cases, contaminated washwater and/or stormwater is collected during the winter in holding ponds, which provide primary treatment, and then is discharged to the wetland during the growing season. Many of these systems do not require permitting since the effluent from the treatment wetland does not discharge offsite. The effluent is spray irrigated, allowed to evaporate, or is discharged to a vegetated filter strip for further polishing. Important design considerations in cold climate areas include: requirements for water storage during winter months, inflow and outflow structures that withstand prolonged periods with below freezing temperatures, and extra freeboard for year-round systems.

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INTRODUCTION

Until recently, the agricultural community has not been required to meet the strict surface water discharge regulations imposed on municipalities and industries. This is rapidly changing as water courses and water bodies affected by farming operations continue to receive high levels of nutrients and bacteria that originate from manure storage areas, manure storage tank overflows, feedlot runoff, milkhouse washwater discharges, and aquaculture pond discharges. Throughout Canada and the United States (U.S.), agricultural wastewater streams are increasingly being viewed by regulators and the general public as sources of pollution that will likely require controls in the future since they are contaminating aquatic habitat, drinking water, and recreational waters.

The livestock industry is intent on incorporating the valuable nutrients that manure holds into the soil as part of the sustainable philosophy that farming has always had. Best management practices have been implemented to reduce the wastewater volume and concentration to the lowest possible economic and practical level. Covered manure storage areas, high pressure/low volume hoses and nozzles for washing stalls, routing adjacent stormwater flows around manure storage areas, and water recycling where practical help reduce the discharge of contaminants. Once the best management practices are in place, any flow that might enter surface water or groundwater (for example, direct discharge to a water course, stormwater runoff carrying ponded wastewater, or waste material spread on an open area) must be treated to reduce the potential of water contamination. As effluent limitations become more restrictive, innovative technologies may offer new, affordable methods of compliance.

Constructed treatment wetlands provide one approach to meet these challenges. Treatment wetlands reduce many typical pollutants in agricultural, industrial, and municipal effluents, such as 5-day biochemical oxygen demand (BOD_5), suspended solids, nutrients, and metals. Constructed wetlands rely on the naturally occurring energies of the sun and wind to aid plant growth and provide oxygen for the aerobic processes carried out by microbial populations. Compared with many conventional technologies that rely on inputs of concentrated fossil fuels, the naturally occurring energies in treatment wetlands are diffused over larger land areas.

The agricultural industries in Canada and the U.S. are investigating the use of constructed treatment wetlands to manage effluent quality. Many provincial, state, and federal agriculture departments are holding workshops and training sessions to provide their staff with an understanding of wetland treatment capabilities and design principles and are piloting wetland treatment alternatives. Since about 1990, at least 68 full-scale and pilot-scale constructed wetland treatment systems have been installed in Canada and the U.S. for the treatment of high-strength agricultural runoff at the time that the Gulf of Mexico Program treatment wetlands project was completed.

In the cold climate regions of Canada and the U.S., treatment wetlands have been viewed with some skepticism. It has long been thought that the processes responsible for contaminant reduction within treatment wetlands would be reduced or ceased during cold periods. In fact, the contrary has been found. Data from long-term monitoring of cold climate municipal treatment wetland systems suggest that many of the treatment processes continue unaltered in the water and sediment columns under the cover of ice and snow. This treatment efficiency is supported by early results from some of the cold climate livestock wastewater constructed wetlands. However, the removal rates of some of the treatment processes, like nitrogen transformation that requires oxygen and is temperature dependant, are reduced. Many of the cold climate treatment wetlands are designed to store the high-strength wastewater during the winter months in a holding pond and then discharge the wastewater to the treatment wetland during the growing season.

Gulf of Mexico Program (GMP)

The Gulf of Mexico Program (GMP) was established in 1988 as an inter-agency cooperative program with funding from the U.S. Environmental Protection Agency (EPA) to study factors affecting the ecological and economic viability of the Gulf of Mexico. The Nutrient Enrichment Committee of the GMP is interested in ways to reduce the potential for eutrophication of the near shore waters of the Gulf. Historical impairment and degradation of the rivers and estuaries in the Gulf of Mexico region are partially due to contaminant loadings from agricultural operations, both point source discharges from intensive livestock and aquaculture operations and non-point source agricultural land runoff. The GMP Constructed Wetlands Project was initiated in response to the need to define practical alternatives to reduce contaminant loadings to the Gulf of Mexico.

During the project definition phase, the team determined that the quantity of useful project data for constructed wetlands treating livestock wastewaters from just the states in the Gulf of Mexico drainage area was limited. For that reason, the literature review and summary of design and operation data were expanded to include all of Canada and the U.S.. The project goals were to (1) compile information on wetlands constructed to treat livestock (cattle, dairy, swine, poultry, fish, and other animals raised in concentrated farming operations) wastewater, (2) present the findings in a widely distributed report and at a technical workshop, and (3) develop a public outreach and education brochure. Details regarding this project can be found in other papers in these proceedings (Knight et al., 1996; Borer et al., 1996; Payne et al., 1996).

Geographic Limits of the Cold Climate Systems

The livestock treatment wetland systems that were reviewed for this paper are in Canada and U.S. EPA Regions 1, 2, 3, 5, 7, and 10. No sites were found in Region 8. Figure 1 shows the EPA regions and the locations of the cold climate treatment wetlands. Table 1 shows the average number of frost free days, average precipitation, and average winter and annual temperatures for each of the sites.

Table 1 shows that most of the cold climate systems are operating under similar average climatic conditions. However, some sites have climatic extremes. For example, high precipitation rates are found in Nova Scotia, whereas Alberta experiences very low precipitation rates. The average winter temperatures in Quebec and Alberta are the lowest for all of the sites. These systems required careful building practices to ensure that the treatment wetland inflow/outflow structures, valves, and piping were able to withstand deep ground frost and extremely cold ambient air. All but one system have below freezing average winter temperatures that result in ground frost penetrating the ground an average of 1 meter and an ice cover on surface water. Although it borders cold climate regions, the Oregon site experiences relatively mild conditions. High rainfall rates such as those experienced in Nova Scotia result in high inflows and the need for larger wetlands to maintain an adequate hydraulic retention time. Under these conditions, it is important to divert uncontaminated stormwater flows, including eaves troughs and field runoff, around the wetland and cover, if possible, the manure storage area to reduce the wetland size requirement.

For most of these sites, the growing season, or number of frost-free days, varies from approximately one third to half of the year. Die off of exposed portions of the vegetation results in an annual buildup of detritus in these wetland systems.

Cold Climate Operation

In the northern U.S. and Canada, the perceived problem associated with wetland technology is operation at cold temperatures. It seems logical that treatment processes will slow or stop at cold temperatures, as they do in conventional treatment plant operations. Wetlands, however, are far more complex than conventional wastewater treatment facilities, and they perform many treatment functions efficiently in winter.

Treatment does not have to rely on slow winter processes. Many northern systems polishing treated municipal wastewater store water during the non-growing season and then discharge to the treatment wetland during the spring, summer, and fall. The advantage of this approach is the availability of warm weather design information; the disadvantage is the cost of the storage lagoons.

Information on winter operation of treatment wetlands is increasing rapidly. Pioneering work on surface flow (SF) wetlands treating municipal wastewater was conducted at Listowel, Ontario, Canada, from 1980 to 1984. Five wetlands were continuously operated throughout the winter by controlling the insulation in a way unique to wetland ecosystems. Water levels were raised at freeze-up, and a layer of ice was allowed to form. The water level was then lowered to create an insulating air gap between the water and ice. The stems of the dense stand of emergent cattails served as supports to keep the ice layer elevated. The standing dead cattails trapped snow and added an insulating snow blanket. Temperature effects were significant for nitrogen reduction, slight for phosphorus, and non-existent for BOD_5 and total suspended solids (TSS). Many northern peatlands exhibit this behavior, with unfrozen water below a snow blanket trapped by the plants (Kadlec, personal communication).

Currently, at least 30 treatment wetland sites in cold climate regions treat high-strength agricultural discharges. The data from these systems will provide design criteria for future installations.

METHODS

A literature review was carried out to review the documentation on constructed wetlands designed to treat high-strength livestock wastewaters. The documents provided design, monitoring, and performance data; operations and maintenance requirements; and opinions and findings that will lead to improved performance of these and other wetland systems. The authors of the documents were contacted by the project team and given the opportunity to participate in the project by providing summarized information for the database.

After reviewing the available literature, a list of authors and co-authors was compiled. An attempt was made to contact each person, introduce the GMP Treatment Wetlands Project, and invite them to participate. The U.S. Department of Agriculture (USDA) staff, known treatment wetland engineers, and wetland organizations in many of the provinces and states were also contacted to determine the extent of their involvement, if any, in livestock wastewater treatment wetland projects. Beginning in fall 1995, more than 100 telephone inquiries were made that led to the identification of more than 30 cold climate systems. Several of these systems are not documented because of a lack of response (despite repeated requests) or because data were delivered after the database had been finalized.

Several general observations were made during the literature review. The constructed wetland technology is a recent alternative for treating concentrated livestock wastes. The papers on cold climate systems were published in 1990 or later, and almost 80 percent were written in 1994 and 1995. The earliest use of a constructed wetland for animal wastewater in the literature was in 1930 on a farm in Iowa (Brenton, 1994). The remaining wetland systems began operating after 1989, with 90 percent of them starting to treat wastewater since 1992. Most systems reviewed do not discharge the wetland effluent offsite, but rather allow the effluent to evaporate, discharge the effluent into sod infiltration areas onsite, or spray irrigate the effluent onto nearby fields. It was reported that, typically, when there is no offsite discharge, no permits are required. In some provinces and states, discharge permits for offsite discharge were not required because agricultural discharges were not regulated.

Many of the farming operations have source controls in the form of a covered manure storage area to reduce the organic loading on the treatment wetland and divert uncontaminated stormwater runoff around the wetland (Hayman and Maaskant, 1994; Neely, 1995).

The control of hydraulic and nutrient loading rates to the treatment wetland systems varied from site to site. Pilot systems such as Oregon State University's systems (Skarda et al., 1994) were treating a small portion of the total waste flow and were able to maintain uninterrupted flow through the site's wetland systems throughout the summer by continuing to pump wastewater from the wastewater lagoon. Full-scale systems in climates with high evapotranspiration rates, low rainfall rates, and/or low wastewater flow rates experienced partially or completely dry periods during the summer, stressing the wetland vegetation (Gerrits, 1994; Holmes et al., 1995; Natzke, 1995; Adams, 1994).

In most cases where wastewater was not pretreated before discharge to the wetland, or where the pre-treatment system was not routinely cleaned and solids overflowed to the wetland, up to the first third of the wetland cell had considerable buildup of solids. Solids accumulation can lead to system failure because they reduce the effectiveness of the treatment wetland by covering the root zone and detritus that house the nutrient reducing bacteria and by reducing the hydraulic retention time. Emergent wetland plants will not survive under extremely anaerobic soil conditions in some highly loaded treatment wetlands.

It was noted that treatment wetland systems must be shown to be reliable so that livestock producers are more receptive to using them. Continued research is necessary to determine treatment efficiencies, optimum loading rates, life expectancy, seasonal treatment variations, and design criteria (Skarda et al., 1994).

REVIEW OF COLD CLIMATE WETLAND SYSTEMS

The following review of cold climate wetland systems includes sites for which operational and monitoring data were available. Included are data from 19 dairy farm and cattle feedlot system sites and two swine system sites.

Dairy Farm and Cattle Feedlot Applications

The database includes 46 sites that are using constructed wetlands to treat high-strength runoff from dairy farm and feedlot operations. Of these 46 sites, 26 are in cold climate regions. The systems are designed to treat wastewaters from herd sizes ranging from 25 dairy cows in Nova Scotia to 7,000 head of cattle at a finishing facility in Indiana. The average herd size was 521 head. All of the dairy and cattle wastewater treatment wetlands in the database are SF systems with the exception of St. Felicien, which is a vertical flow system, and Niagara, which is a subsurface flow (SSF) system. Most systems are rectangular in shape. The exceptions are several of the Ontario systems that are sinuous in shape with high length-to-width ratios (Hayman and Maaskant, 1994).

DePere - David Gerrits Farm (Site Number 523)

Holmes et al. (1992) described the design and construction of a wetland system in a cold climate (Greenbay, Wisconsin) for the treatment of milking center wastewater. The site had four wetland systems, each divided into three cells. Two of the wetland systems were to receive wastewater that had passed through a settling/floatation tank while the other two systems were to receive untreated wastewater. The effect of pre-treatment on treatment efficiencies was evaluated and reported in subsequent papers. Startup problems were encountered when filling the cells. The water level in all cells dropped below the tops of the coffer dams indicating leakage problems with the systems. The leaks were sealed, and the project continued.

Operating descriptions and monitoring data for the Greenbay, Wisconsin, systems were reported in several papers (Holmes, 1994; Holmes et al., 1994; Holmes et al., 1995). During the first winter, difficulties were experienced with delivering the wastewater to the wetland cells. A construction error, excavating and plumbing during the winter, and inadequate winterization caused the system to freeze downstream of the flow distributor during winter

1993. Construction and operation deficiencies were remedied in spring 1993. Because of a very wet spring in 1993, the wetland plants sprouted very well. During much of the summer and fall, the system did not discharge water, and the downstream cells frequently had no standing water. This condition stressed the wetland vegetation. During fall 1993, a weather station was installed with data logging capabilities, wetland plant populations were counted, and wetland cells were repaired and prepared before winter. Operation went well during winter 1994, and wastewater flows were delivered without difficulty.

Data presented in the papers shows a greater concentration reduction efficiency for chemical oxygen demand (COD), BOD_5, total phosphorus (TP), and total Kjeldahl nitrogen (TKN) by the treatment wetland that received non-pretreated wastewater. Although the wetland system that received the pretreated wastewater showed a lower reduction efficiency, the COD and BOD_5 inflow concentrations were more than 40 percent lower, and the TP and TKN concentrations were more than 20 percent lower. Overall, the final effluent water quality in the system receiving pretreated wastewater was better than final effluent from the system receiving non-pretreated wastewater. The authors concluded that the treatment wetlands improved water quality. The reduction in concentration from inlet to third cell discharge for the parameters monitored in 1993 are in Table 2.

It was noted that wetland plants showed no signs of stress in response to the strength of the milkhouse washwater.

Two reports (Gerrits, 1994; Natzke, 1995) presented findings of the adaptability of wetland plants at the Greenbay, Wisconsin, constructed wetland location. A plant count was made of the three dominant species (softstem bulrush [*Scirpus validus*], river bulrush [*Scirpus fluviatilis*], and giant burreed [*Sparganium eurycarpum*], and the survival rate of each was determined from cell to cell and from one year to the next. In her paper, Gerrits reported that the vegetation in the first cell of each system was growing well. However, the plants in the following two cells showed a sharp decline in vegetation growth likely due to the lack of moisture. Natzke noted similar patterns the following year and observed considerable stress in the vegetation after two consecutive years of summer drought conditions.

Softstem bulrush was the dominant plant in all cells in 1995 with a dramatic (74 percent) reduction in the population by the second cells and a further reduction in population in the third cells. River bulrush was the next dominant species in 1995 and showed trends similar to the softstem bulrush, although the population changes were not as dramatic. No giant burreed plants were found in the first cell of any of the systems in 1995 in spite of the scant presence of these plants in previous years. Subsequent cells had small populations of this plant. Population statistics were presented for the years 1990 to 1995. Natzke reported that there was no indication that the wetland plants preferred either the pretreated or the untreated wastewater.

Oregon State University (Site Number 514)

Oregon State University received EPA funding to summarize the results of the design and construction of six wetland demonstration/research systems built south of the university dairy barns (Gamroth and Moore, 1993). The project was designed to determine the effects of hydraulic and nutrient loading rates, vegetation type (cattail [*Typha latifolia*] and hardstem bulrush [*Scirpus acutus*]), and deep zone areas on removal rates. These systems were designed to receive a small percentage of the total wastewater flow generated by the livestock operation. Consequently, the hydraulic and nutrient loading rates were maintained at the design levels, and dilution of the wastewater ensured that maximum rates and concentrations would not be exceeded. Nutria (*Myocastor coypus*), a rodent native to South America, created problems for this wetland site in the early stages of operation by destroying most of the plants and burrowing into the berms. A fence that extended 5 centimeters (cm) into a shallow trench was erected around the site and was reported to be successful in excluding nutria.

Performance data from the Oregon State University wetland systems showed an increase in removal efficiencies from the first year of operation to the second year for the following parameters:

Oregon State University Treatment Wetland Removal Efficiencies
Operating Years 1 and 2

Parameter	Year 1 Percent Removal	Year 2 Percent Removal
Fecal coliform (FC)	80 to 90	89 to 95
BOD_5	40 to 50	59 to 72
TKN	50 to 55	45 to 69
COD	40 to 50	53 to 65
TP	40 to 50	54 to 69
TSS	40 to 50	43 to 56

Improvements in treatment efficiency were not noted for systems with deep center sections, nor for different mixes of plant populations (Skarda et al., 1994; Moore et al., 1995).

Crum Farm (Site Number 518)

Data from a 0.1-hectare (ha), two-cell treatment wetland that receives dairy barn waste and stormwater runoff in Frederick County, Maryland, showed overall improvement in water quality (Cronk et al., 1994). However, Cronk et al. reported high wetland influent wastewater concentrations. For example, the average inflow wastewater concentrations in the latter half of 1994 for TSS (4,900 milligrams per liter [mg/L]), BOD_5 (6,450 mg/L), and TP (80 mg/L) likely resulted in the high effluent concentrations of 990 and 4,820 mg/L for TSS, 2,030 and 2,730 mg/L for BOD_5, and 160 and 50 mg/L for TP, from systems 1 and 2 respectively.

Cronk et al. noted that these were not acceptable discharge levels. Establishing good vegetation cover at this site was difficult. All vegetation (cattail [*Typha latifolia*]) in the first cell and two thirds of the vegetation (cattail) in the second cell that had been planted in summer 1993 had died by the fall of the first year of operation. Cell 1 was replanted with softstem bulrush the following year since it was considered to be a hardier plant. In that same year, cell 2 had a 10 percent cover of cattail, 50 percent cover of duckweed (*Lemna* spp.) and a 20 percent cover of barnyard grass (*Eichinochloa crusgalli*).

3M Farm (Site Number 519)

In Kent County, Maryland, a 0.12-ha treatment wetland system was monitored as part of a college program (Adams, 1994). The Adams paper focused on the role of wetlands in the environment and how they can be used to prevent the transport of non-point source pollutants into the Chesapeake Bay. The system was planted with cattail (*Typha latifolia*), pickerel weed (*Pontederia cordata*), and bulrush (*Scirpus* spp.) in the late fall; a few plants survived. Nitrate and ammonia concentrations were reduced by 89 percent and 75 percent, respectively. An exception was in July and August 1994 after a dry spell in June 1994 when most of the vegetation died off and began to decompose, releasing nutrients into the water. The nitrate concentration dropped off through the wetland in the fall but increased again in November and December 1994, likely due to shallow water conditions and the resident duck population. During this period, the ammonia removal efficiency and dissolved oxygen (DO) concentrations also decreased. The pH values through the wetland system remained circumneutral with the exception of the late summer when the pH dropped following the dry spell in June. The wetland was 80 percent dominated by grasses, including barnyard grass (*Eichinochloa crusgalli*) and panic grass (*Panicum dichotomiflorum*), with the remainder of the vegetation being velvet leaf (*Abuttilon theophrasti*), bigseed smartweed (*Polygonum pennsylvanica*), cattail (*Typha latifolia*), and spike rush (*Eleocharis quadrangulata).*

Indiana Projects (Site Number 524, 529)

Reaves (1995) monitored several treatment wetland systems. The dairy in Lagrange County, Indiana, had three wetland cells in parallel covering a total of 0.11 ha (Reaves et al., 1994a; Reaves, 1995). In the first year of operation, the following concentration reductions were reported:

Lagrange County, Indiana Treatment Wetland First Year of Operation Concentration Reduction

Parameter	% Reduction
BOD_5	62 to 81 %
Reactive phosphate	62 to 89 %
TP	49 to 78 %

Lagrange County, Indiana Treatment Wetland First Year of Operation Concentration Reduction	
Ammonia nitrogen (NH_4-N)	50 to 70 %
TKN	36 to 57 %
Dissolved solids	up to 39 %
Nitrites (NO_2-N)	up to 100 %
Nitrates (NO_3-N)	up to 100 %
TSS	65 %

Fecal coliform reductions were greatest during the summer months, but reductions were reported throughout the year. Cattle grazed the wetland vegetation (cattail [*Typha latifolia*]) several times during the year. The vegetation never recovered, leaving the deeper areas free of emergent vegetation. Reed canary grass (*Phalaris arundinacae*) established a monoculture in the shallow zones. Algal blooms developed in the open water areas with increased suspended solids in the effluent. Cattle deposited waste along the entire run of the cells, resulting in a very low residence time for some of this waste. Infrequent cleaning of the solids settling pad resulted in a mean influent TSS of 15,700 mg/L. This affected the inflow concentration to the wetland of all parameters, which were typically at least one order of magnitude higher than those reported elsewhere in the literature. The solids accumulation of up to 10 cm in the front third of the treatment cells occurred during the first year of operation, reducing the system's treatment efficiency and leading to the system's eventual failure.

Reaves monitored a second dairy system was in Kosciusko County, Indiana, that began operating in spring 1994 and was monitored through 1995. The dairy is upgradient from a major lake, causing concern that the operation was adversely impacting the lake's water quality. A manure pit was used for solids reduction upstream of the two-cell constructed wetland. The inflow concentrations of the parameters measured in 1994 were extremely low due to the pumping out and the subsequent slow filling of the manure tank. The next year, the values were more typical. Table 3 shows the 1995 average concentration reductions from cell 1 influent to cell 2 discharge.

During the late summer, the first cell went dry from lack of rainfall. The standing water in the second cell had a hydraulic residence time of approximately 100 days, and most constituents were reduced to near background levels. Poor wetland performance in early spring during cool temperatures and slow microbial metabolism coincided with the highest rainfall and thus highest loading rates. Upstream storage of wastewater flows was recommended to allow for discharge of the wastewater during periods of higher microbial activity and lower precipitation periods. Reaves concluded that farmers must be aware of the limitations of constructed treatment wetland systems if they are to be an effective waste management tool.

University of Connecticut - Kellogg Dairy Research Facility (Site Number 521)

A treatment wetland system was constructed at the University of Connecticut (Neafsey and Clausen, 1994) with a pre-treatment settling/floatables area, three parallel cells with three subcells totaling 0.037 ha, and a 27-day residence time. This system required a high-density polyethylene (HDPE) liner. The cells were planted with cattail (*Typha* spp.), common reed (*Phragmites*), and three square bulrush (*Scirpus americanus*). Contaminant mass reduction varied greatly between seasons, as the data below demonstrate:

Parameter	% Mass Retention Before Senescence	% Mass Retention After Senescence
TKN	99.6	55.3
NH_4-N	97.2	-253
NO_3+NO_2-N	93.1	83.6
TP	99.3	44.9
TSS	97.8	55.3
FC	99.9	99.9
BOD_5	99.1	56.6

Piscataquis River (Site Number 528)

A 0.04-ha, four-cell wetland was constructed at a 330-head Holstein cow farm in north-central Maine to determine the effectiveness of wetlands in cold climates (Doll et al., 1994; Holmes et al., 1995). The system was designed for a loading rate of 73 kilograms per hectare per day (kg/ha-day) and a 20-day detention time. Construction was completed in fall 1993. Design methodology and calculations for the wetland were presented, but performance data were not reported.

Brenton Cattle (Site Number 525)

In Iowa, a constructed wetland was used to reduce contaminant loadings from cattle feedlot stormwater runoff to surface water. A 47-ha, two-cell treatment wetland was constructed at a 7,000-head cattle finishing facility. The first cell was built in the 1930s on a pasture and hay field. The second cell was constructed in the late 1960s downgradient from the first cell on similar land. The wetland system received stormwater runoff from more than 800 ha of crop and pasture lands. Sampling data from the treatment wetland system show the following concentration reductions:

Parameter	Inflow Concentration	Outflow Concentration
FC (cfu/100 mL)	143	25.5
TP (mg/L)	0.61	0.12
BOD (mg/L)	278.6	20.1
TKN (mg/L)	50.8	16.5
NH_4-N (mg/L)	9	3.3
NO_3-N (mg/L)	39.2	10.8
TSS (mg/L)	521.6	50.8
Turbidity (mg/L)	336.8	42.3

With the exception of phosphorus, all data reported for the wetland system effluent showed better water quality than the receiving stream (Brenton, 1994).

Nowicki Farm (Site Number 526)

A 0.05-ha, two-cell treatment wetland was recently constructed in Alberta, Canada, to treat feedlot runoff. After operation begins, the wastewater flow will be pre-treated in a manure settlement area, an anaerobic pond, and a storage and facultative pond. Discharge from the facultative pond to the parallel wetland cells will be regulated. Excess flow will be routed via swales around the wetland and discharge into the creek. The wetland will be filled batchwise using a manual valve. Treated water will be discharged to a holding pond that will allow for recycling of water in the case of high nutrient loads or summer drought conditions. A complete sampling and operating program has been established for the system. Planting of the wetland vegetation is scheduled for 1996 (Amell, 1995).

Ontario, Canada (Site Number 501 through 509)

Several treatment wetland systems in Ontario, Canada, treat dairy or cattle barnyard runoff as part of a province-wide research project to determine the practicality and treatment effectiveness of these systems for livestock wastewater treatment. Designs have incorporated runoff holding ponds, vegetated marsh treatment cells that are sinuous in shape, and water quality polishing cells. Several systems have similar designs to allow for comparison under Ontario’s range of soil and climatic conditions. The monitoring program includes bacterial and chemical parameters in the groundwater, surface water, and bottom sediments; surface water levels; relative humidity; water temperature; rainfall; vegetation; macroinvertibrates; and wildlife. These systems will allow for an assessment of treatment efficiencies, management requirements, and economic benefits to Ontario farmers, and will further the development of low cost alternatives to protect water quality for the farming community. Data from the first treatment system shows good reductions in bacteria (approximately three orders of magnitude) and nutrients (TP in 1994 decreased from approximately 25 mg/L to less than 4 mg/L) through the summer (Maaskant, 1995).

Swine

Several successful swine treatment wetlands are operating in cold climate regions. In spite of high inflow ammonia concentrations compared to dairy operations, concentration reduction efficiencies for all parameters have been similar to other cold climate livestock wastewater systems.

Delmarva Farms (Site Number 520)

A treatment wetland system was built at a 900-swine operation in Worchester County, Maryland, in late summer 1994 (Baldwin and Davenport, 1994). It was installed in response to an agreement by the State of Maryland and the other states in the Chesapeake Bay watershed to reduce nutrient loadings to the Bay. The 0.73-ha system has a 13-day residence time. The wastewater is pre-treated in an anaerobic lagoon and a sand filter, and a portion of the flow is discharged to the wetland. The wetland effluent is recycled through the swine operation and used for flush water. The remainder of the lagoon effluent is spray irrigated. A compacted clay liner in the wetland controls seepage. Although the paper does not discuss water quality improvements, it does provide a comprehensive operation and maintenance plan that includes a vegetation establishment plan, a water quality monitoring list, sampling procedures, and a wetland management plan (Baldwin and Davenport, 1994).

Purdue University (Site Number 530)

An experimental constructed wetland project for swine waste treatment is underway at the Purdue University Animal Science Research Center in Indiana. The system, which has 16 parallel unlined cells, is designed to treat process wastewater from a swine waste lagoon. The system design, experimental plan, and the monitoring plan of cell influent, effluent, and groundwater quality are outlined in a report (Reaves et al., 1994b).

The cells were tested at three hydraulic loading rates and two operating depths. Treatment efficiencies and vegetation performance were compared to determine the optimum system operating parameters for a treatment wetland in northern Indiana. Data collected during the first year of operation indicate that a depth of 15 cm and a 14-day hydraulic retention time provide better water treatment for the climate. At this operating scenario, influent concentrations and percent reductions were as follows:

Parameter	Influent	Percent Reduction
BOD_5	116 mg/L	58.6
Total fecal coliforms	78 cfu/100 mL	97.4
TP	14.5 mg/L	26.1
Total nitrogen (TN)	497.4 mg/L	29.8
TSS	122.6 mg/L	60

During the first year of operation, greater reductions of TN and TP were noted in the unvegetated cell when compared to the vegetated cells with the same hydraulic loading rate and depth. The reduction in the TN concentration may have been due, in part, to the higher DO concentration in the unvegetated cell that allowed higher nitrification rates. The open cell appeared to exhibit greater rates of chemical precipitation, thus reducing the TP concentration in the cell. In the late summer, water was removed for spray irrigation from the storage lagoon that was used as the wastewater source. At that time, the ammonia concentration rose from about 200 mg/L to more than 1,000 mg/L. Several plant species died off following this increase. Only the broad leaf cattail (*Typha latifolia*) and the softstem bulrush (*Scirpus validus*) survived the change in concentration. Percent vegetation cover and plant vigor were better in shallow treatment systems for most of the growing season. Plants growing in shallow water within a cell were better able to tolerate increased ammonia loading in late summer. However, plants survived mild freezes better at greater water depths (Reaves et al., 1995).

The groundwater impacts from the Purdue wetland system were evaluated. The unlined cells were constructed in mesic soil. Before system startup, lithium tracer was used to determine the level of leakage before system startup and revealed potential for groundwater contamination from some of the cells. Preliminary results from a detailed groundwater monitoring system indicate that unlined constructed wetland cells in native soils are not contaminating groundwater. Compaction of suitable mesic soils should enable more cost-effective construction. Reaves notes that further testing is warranted to supplement these preliminary results.

DESIGN SUMMARY

Capital, Operation, and Maintenance Costs

Wetland construction costs are determined by the cumulative cost of land, earthwork, planting, design, monitoring, and maintenance. Capital costs for SF constructed wetlands for treating high-strength agricultural runoff in cold climate regions in North America were reported to be between $4,000 and $50,000 for wetlands ranging in size from 0.01 ha to 1 ha. The range in costs reflects variables such as liner installation, removal and replacement of topsoil, and specialized monitoring equipment.

The high cost of gravel fill can raise the price per hectare of SSF wetlands to as much as four times the cost of a SF wetland. However, SSF wetlands can handle somewhat higher contaminant loading rates than SF wetlands and, therefore, require less land. The system in Quebec, Canada, is a 0.7-ha vertical flow (VF) system that was constructed at a cost of $500,000. This VF system is much more complex than SF systems and receives visitor washroom septic tank effluent as well as surface water runoff from the animal exhibits at the zoo. Higher costs are also associated with the pumps, valves, and control hardware.

The primary economic disadvantages of wetland treatment is the cost of land and the possibility of taking farmland out of production. However, for a farm operation that has land available for this treatment technology, particularly land that is poor quality or that is already wetland, land costs become less of an issue. Operating costs are generally very low and depend on the extent of monitoring data collection, exotic plant control, burrowing animal activity, and water management.

The available data show that the area occupied by wetlands treating high-strength agricultural wastewater ranges from 0.01 to 0.64 ha per 100 animal units (1 animal unit = 1,000 kg live weight), for an average of 0.13 ha/100 animal units. Approximate construction costs ranged from $26/animal unit (for 340 animal units) to $540/animal unit (for 100 animal units). In general, the construction cost was approximately $194/animal unit for farm operations with fewer than 100 animal units and approximately $77/animal unit for 100 to 400 animal units. The average capital cost was $129/animal unit. These costs represent a variety of wetland designs and, in many cases, unknown contaminant loadings. They do not necessarily reflect optimum treatment efficiencies.

Permitting Requirements

Municipalities, provinces, and states generally regulate treatment and disposal of wastewater to surface waters. In Canada, each provincial environment ministry sets treatment and discharge policies, and most ministries directly affect the permitting and implementation of wetland wastewater treatment systems. A provincial Certificate of Approval is required for almost all point discharges of water and wastewater into waters of Canada. Other potentially significant regulations include the Canada Environmental Protection Act, Environmental Assessment Act, and Fisheries Act.

More than half of the agricultural treatment wetlands reviewed do not require permitting because, in most cases, the wetland effluent is collected in a holding pond and then allowed to evaporate, is spray irrigated onto surrounding crop lands, or is discharged onto adjacent fields as overland flow without discharging to surface water. Typically, when there is no offsite discharge, no approvals that require compliance with discharge water quality objectives are necessary. In some provinces and states, discharge permits for offsite discharge are not required for agricultural discharges.

Design Considerations for Future Systems

It is important to learn from the work of others and provide guidance for future treatment systems so that these systems will meet or exceed expectations. The following summarizes several recommendations and considerations based on the observations of engineers and operators of livestock wastewater treatment wetlands.

Pre-treatment

As with any treatment wetland system, the pre-treatment of the wastewater flow is critical for successful operation. Experience at several sites has shown that the absence of pre-treatment facilities or poorly managed pre-treatment facilities results in a buildup of solids within the wetland. This buildup impairs the nutrient removal efficiency by covering the microorganisms that are responsible for providing treatment, thereby increasing the nutrient loading to the system, and reducing the hydraulic residence time within the wetland cells. Bacterial action is a time dependent process; reducing the time available for the microorganisms to treat the wastewater reduces removal efficiencies.

A primary treatment lagoon or settling pond is recommended upstream of the treatment wetland. A lagoon or pond allows initial removal of settleable contaminants, particularly suspended solids that typically are high in phosphorus and BOD_5, and provides an area where the contaminated stormwater can accumulate and be discharged at a controlled rate to the wetland for maximum removal efficiency.

Aeration

The conversion of ammonia to nitrate (nitrification) is an aerobic process that requires oxygen. If the property exhibits topographic relief, cascading flow from one wetland cell to the next provides some of the oxygenation required for the nitrification process.

Dilution

In some cases, wastewater may need to be diluted before discharge to the constructed wetland. Wastewater can be diluted by mixing with other stormwater runoff on the property or by pumping the polished wetland effluent back to the point of inflow to the wetland at a ratio that provides the wetland with nutrient concentrations and loadings that it can reasonably handle. The requirement for dilution must be considered at the predesign stage of the project, since the size of the wetland is in part determined by the hydraulic loading rate or wastewater flow rate.

Climate

The climate must be considered when determining the feasibility of a livestock wastewater treatment wetland. For example, if precipitation exceeds evapotranspiration, the system can be designed to provide the required treatment without relying on evaporation to reduce the discharge volume. Consideration must be given to collecting the discharge for spray irrigation, or a surface discharge permit or Certificate of Approval may have to be secured to discharge to surface water. In regions where the precipitation rate is considerably lower than the evapotranspiration rate, consideration must be given to providing enough water to ensure plant survival throughout the year. Alternatives for providing year-round water include circulating water from one wetland cell to the next by pumping (electric or wind driven), discharging gray water from the residence into the wetland, and storing water within the wetland by increasing the operating water depth in anticipation of dry summer conditions.

Design Criteria

When designing a treatment wetland system, an experienced wetland engineer with knowledge of current technology should be retained. Design criteria have changed considerably over the past 20 years because of the large number of research and full-scale projects and because of the increasingly stringent discharge criteria.

SUMMARY OF OPERATIONAL PERFORMANCE

Contaminant Concentration Reduction

In general, the livestock wastewater treatment wetlands in the database reduced contaminant concentrations more than 90 percent of the time when comparing inflow and outflow concentrations for all parameters reported. Reduction efficiencies varied from parameter to parameter and from site to site. Due to the lack of flow data, loading data were not calculated for most sites (see Knight et al., 1996). Although many of the systems showed reasonable to good concentration reduction efficiencies, the final effluent concentrations, in most cases, were much higher than the discharge criteria requirements typical for most municipalities or industries. Thus, many of the treatment wetlands were undersized and could not adequately reduce the contaminant loadings, or the pre-treatment system was undersized and could not provide adequate TSS reduction. The consequence was that high concentrations of contaminants that tend to be tied up with the TSS continued through the treatment wetland system. It must be emphasized that the data reported is from treatment wetland systems that are relatively new and that these are early operational data.

The data reviewed for this effort indicate that the background concentrations (C*) for most parameters appear to be higher than the C* value for municipal treatment wetlands (Knight et al., 1996). This potential point of contention may need to be reviewed with the regulatory agencies while monitoring these systems and seeking ways to optimize them for improved contaminant reduction.

TSS

As described earlier, the influent TSS concentration to some treatment wetland systems was very high and affected the overall average data. At most sites with high influent TSS concentrations, the pre-treatment system was overloaded, not properly maintained, or nonexistent. In spite of the high loadings, reasonable to good concentration reduction efficiencies of 47 to 81 percent were realized, as is reflected in Figure 2. The data points in Figure 3 show that 94 percent of the samples analyzed showed a reduction in TSS concentration. The average and median concentration reductions, maximum and minimum concentrations, count, and standard deviation for TSS for cattle, dairy, and swine wastewater are in Table 4. Inflow concentrations for sites treating wastewater from cattle operations had few high data points. The maximum inflow concentration of 29,845 mg/L was from a dairy operation in Indiana that failed after 1 year. Figure 4 shows the gradual increase in inflow TSS concentration and the delayed but expected response of the treatment wetland to the increasingly higher loadings. The trend of a system with good pre-treatment facilities is reflected in the same figure. Figure 5 shows the effect of pre-treatment on average TSS inflows and outflows. The swine systems had adequate pre-treatment facilities and reported much lower average inflow concentrations than those reported for other livestock wastewaters.

BOD_5

The high BOD_5 concentrations reported by many of the authors reflected the high TSS loadings. The one exception is shown in Figure 6 where, despite reasonable inflow TSS concentrations, BOD_5 inflow concentrations were high at Site 521, likely due to high concentrations of dissolved BOD_5 in the milkhouse washwater. The concentration reduction efficiency was 59 to 83 percent (Figure 2). Average BOD_5inflow and outflow concentrations were highest at the dairy sites with the cattle and swine systems showing similar relatively low values (Table 4). Figure 6 shows the effects of pre-treatment on inflow BOD_5concentrations. Figure 7 shows the gradual increase in inflow BOD_5concentrations and the delayed but expected response of the treatment wetland to the increasingly higher loadings. The trend of a system with good pre-treatment facilities is reflected in the same figure. The data points in Figure 8 show that 96 percent of the samples that were analyzed showed a reduction in BOD_5concentration. The average and median concentration reductions, maximum and minimum concentrations, count, and standard deviation for $BOD_5$for cattle, dairy, and swine wastewater are in Table 4.

Nitrogen

The NH_4-N and TN concentrations reported for the swine sites reflect the higher nitrogen content of swine manure (Table 4). The high nitrogen concentrations reported from the dairy sites reflect the limited pre-treatment at several sites. The concentration reduction efficiency was 38 to 64 percent (Figure 2). Average inflow and outflow concentrations were the highest at the dairy and swine sites with the cattle systems showing relatively low values (Table 4). Figure 9 shows the effects of pre-treatment on the inflow NH_4-N concentration. The data points in Figure 10 show that 93 percent of the samples analyzed showed a reduction in NH_4-N concentration.

Total Phosphorous (TP)

The high average TP concentration reported for dairy sites reflects the high average influent TSS concentrations. The concentration reduction efficiency for all cold climate sites ranged from 25 to 77 percent (Figure 2). Average inflow and outflow TP concentrations at the swine systems were the next highest concentration and likely reflect the generally higher TP concentrations of swine waste. The relatively low inflow TP concentration in the cattle systems reflect the pre-treatment provided to the wastewater. The average and median concentration reductions, maximum and minimum concentrations, count, and standard deviation for TP for cattle, dairy, and swine wastewater are in Table 4. Figure 11 shows the effects of pre-treatment on the inflow TP concentration. The data points in Figure 12 show that 93 percent of the samples analyzed showed a reduction in TP concentration.

Applicability to the Agricultural Industry

The benefits of using constructed wetlands to treat livestock wastewaters in cold climate regions varies from site to site. In areas where precipitation exceeds evapotranspiration, treatment wetlands are a simple and relatively low-cost way to reduce the potential for pollution of surface water and groundwater. Response to this technology in the midwest was one of skepticism; because the soils are nutrient poor in this region of the country, it is considered that nutrients available from the manure are best applied to crop production rather than treated in a constructed wetland with little benefit to the landowner/farmer. For that reason, wetland systems are recommended as a treatment alternative for discharges of wastewater that will not or cannot be reused and that therefore might negatively affect surface water or groundwater.

The agricultural industries in Canada and the U.S. are investigating the use of constructed treatment wetlands to meet effluent management responsibilities. Many provincial, federal, and state agriculture departments are piloting the wetland treatment alternative and are holding workshops and training sessions to provide their staffs with an understanding of treatment wetland capabilities and design principles. Since about 1990, at least 68 full- and pilot-scale constructed treatment wetland systems have been installed in Canada and the U.S. for the management of high-strength livestock wastewaters.

Wetland treatment can be implemented with ease on farms in cold climates. These low-technology, solar-driven systems are passive and user-friendly. Farmers do not need to acquire the skills of wastewater treatment plant operators since the operation of a wetland system ties in to current farming practices. Just like any crop the farmer may plant, the wetland system requires sunlight, nutrients, and water. The treatment wetland plants can tolerate relatively high concentrations of nutrients and must be established in an environment where the soil will be saturated with water for most or, preferably, all of the time. Extremely high concentrations of nitrogen damage the wetland plants in the same way that high nutrient levels affect a planted crop.

By viewing a watershed or a subwatershed as a single system and dealing with the point and nonpoint source polluters as a whole, a more cost-effective approach for wastewater treatment may be realized. Many municipal and industrial point source polluters in Canada and the U.S. have already reduced contaminant loadings from their sites to the environment. To require further reductions may be very costly and may force businesses to relocate or close. However, the overall loading of the stream may be reduced by focusing on the agricultural practices within the watershed area. Farmers can be provided with incentives that allow them to reduce their non-point source pollution. Municipalities and industries can offer upstream farmers assistance for implementing non-point source controls. These controls might include fencing to restrict the access of livestock to streams, rivers, and lakes to reduce the potential for direct manure contamination or construction of vegetated filter strips and treatment wetlands to reduce contaminant loadings to surface water or groundwater. Reducing loadings within the watershed may allow industries and/or municipalities to expand, which may not be otherwise possible.

CONCLUSIONS

The agricultural industry has expressed considerable interest and acceptance of wetland technology for the polishing of high- and low-strength agricultural wastewater and stormwater. Treatment wetland systems are in operation or under development in many locations across Canada and the U.S. They have been found to reduce contaminant loadings to the water environment and have the potential for operation on a much wider scale.

Other natural treatment technologies, including vegetated filter strips and poplar trees, can be incorporated into the wetland technology and may provide economic benefit to the farmer in the form of fodder and/or pulp wood.

Most environmental concerns or risks related to wetland treatment systems can be eliminated through sound project design and use of current and evolving technology. The data collected to date provide preliminary information for furthering the technology. Continued data collection is required to provide the long-term data that track systems after reaching equilibrium. Continued improvements in technology and research will enhance the understanding of the wastewater and stormwater constructed treatment wetland technology.

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TABLE 1
Climatic Data for the Northern Systems in the Livestock Wastewater Treatment Wetland Database

Site	Site Name	State or Province	Closest Community with Climatic Data	Frost Free Days	Annual Average Precipitation (cm)	Average Winter Temperature (^oC)*	Average Annual Temperature (^oC)
500	Saint-Felicien	QUE	Roberval	124	90.8	-14.1	2.2
501	Essex County	ONT	Windsor	177	90.1	-3.6	9.1
502	Perth County	ONT	Stratford	140	105.0	-6.1	6.6
503	Simco County #1	ONT	Barrie	112	94.9	-7.5	5.8
504	Region of Niagara	ONT	Grimsby	167	88.0	-3.2	8.9
505	Hamilton-Wentworth	ONT	Brantford	151	85.5	-4.6	7.9
506	Region of Ottawa-Carlton	ONT	Ottawa	147	91.1	-9.2	5.8
507	Russel County	ONT	Cornwall	152	96.2	-7.5	6.8
508	Region of Peel	ONT	Toronto	153	78.0	-5.4	7.2
509	Simco County #2	ONT	Midland	161	106.4	-6.4	7
510	Lucky Rose	IN	Indianapolis		101.8	-1.1	11.4
511	Wayne White	N_S	Truro	111	117.6	-5.8	5.5
512	David Thompson	N_S	Collegeville	93	138.0	-5.6	5.6
513	Ken Hunter	N_S	Port Hastings	145	144.9	-3.8	6.3
514	Oregon State University	OR	Portland	180	99.1	4.9	16.8
515	Hickok Veal	PA	Scranton		93.6	-2.2	9.72
516	Cobb	PA	Scranton		93.6	-2.2	9.72
517	Moyer	PA	Baltimore		104.7	-3.2	12.8
518	Crum	MD	Baltimore		104.7	-3.2	12.8
519	3M	MD	Baltimore		104.7	-3.2	12.8
520	Delmarva Farms	MD	Baltimore		104.7	-3.2	12.8
521	U of Connecticut	CT	Hartford	156	111.8	-2.1	8.9
522	Dunstaffnage	PEI	Charlottetown	128	110.0	-5.3	6.6
523	De Pere	WI	Milwaukee		78.5	-4.9	8.1
524	Norwood Farms	IN	South Bend		92.3	-3.2	9.7
525	Brenton Cattle	IA	Des Moines		81.0	-4.6	10
526	Nowicki Farm	ALB	Edmonton	105	46.6	-12.4	2.1
528	Piscataquis River	ME	Caribou		92.8	-10.6	3.8
529	Tom Brothers	IN	South Bend	150	92.3	-3.2	9.7
530	Purdue University	IN	Indianapolis	150	101.8	-1.1	11.4
Average				142	98.0	-4.8	8.5

*December, January, February

TABLE 2
Concentration Reductions for Milking Center Wastewater, DePere-David Gerrits Farm, 1993

Parameter	Reduction in Concentration without Pre-treatment			Reduction in Concentration with Pre-treatment		
	Inflow (mg/L)	3rd Cell Outflow (mg/L)	% Reduction	Inflow (mg/L)	3rd Cell Outflow (mg/L)	% Reduction
COD	488	114	77	275	86	69
BOD_5	168	17	90	97	15	84
TP	16.9	2.8	83	13.5	2.4	82
TKN	19.8	5.2	74	14.7	4.4	70

TABLE 3
Average Concentration Reductions for Kosciusko County, Indiana

Parameter	Cell 1 Influent		Cell 2 Discharge
	Septic Manure Pit	Yard Runoff	
BOD_5 (mg/L)	910.3	94.0	67
Reactive phosphate (mg/L)	47.3	23.6	10
TP (mg/L)	25.3	9.7	4.2
NH_4-N (mg/L)	242.1	148.7	26.2
TKN (mg/L)	215.3	139.9	30.4
TN (mg/L)	215.3	141.6	30.7
NO_2-N (mg/L)	0.0	0.0	0.6
NO_3-N (mg/L)	0.0	7.9	0.6
TSS (mg/L)	483.4	106.4	66.4
FC (cfu/100 mL)	236	58	11

cfu = Colony forming units
mL = Milliliter