R&TT

31, St-Paul Street, P.O. Box 580
Alfred (Ontario) K0B 1A0
Telephone: (613) 679-2417 Fax: (613) 679-2420

South Nation River Conservation Authority

Dignard Artificial Wetland

Year 3 of Operation

1997 YEAR-END REPORT

February 1998

EXECUTIVE SUMMARY

This report describes the third year of operation of the Dignard Constructed Wetlands near Embrun in Eastern Ontario. The introduction and the chapter about wetland system design are a synthesis of sections of two previous reports, *Proposed Natural System, Dignard Farm - Embrun, Ontario* (Weil et al., 1994) and *Dignard Artificial Wetland 1995 Year End Report* (Weil et al., 1996). The chapter about system performance contains a synthesis of the results obtained during the first two years of operation (Weil et al., 1997). These chapters have been included as background material for readers not familiar with the three previous reports. Readers are referred to these publications for further details on design, construction and results.

At the Dignard dairy operation, stormwater runoff from a solid manure pile and a 0. 75 ha cattle yard is being treated using a constructed wetlands system to avoid polluting a nearby creek. Prior to construction, the runoff from the feedlot was not collected. The runoff from the solid manure pile was stored in an anaerobic lagoon and periodically spread on cropland. The owner of the 100 cow, 165 heifer herd required a system that would treat all the liquid runoff, otherwise separate systems would have been required for handling liquid and solid manure, increasing equipment and labour costs and wasting precious time in the spring.

In 1994, a wetlands system was designed and constructed, following the guidelines advocated by Donald Hammer of Purdue University (Hammer, 1994) with some site specific improvements, to treat the effluent from the manure lagoon and the cattle yard runoff. Wastewater is stored over the winter months and treated during the summer. The wetlands were planted in the spring of 1995 and the system was put into operation that summer. Settleable solids form a nutrient rich sludge on the wetland floor. Aquatic plants (cattails and bulrushes) supply oxygen to the sludge zone through their roots, promoting the breakdown of the pollutants. The plants also act as physical supports for microorganisms which form a "biofilm" surrounding the plant from the water surface to the wetland floor. As water passes through the thick growth of plants, it is exposed to the living biofilm, which filters pollutants and decomposes them. An overland flow system (filter strip) polishes the effluent.

The wetland system has performed beyond expectations over the first three years of operation. Average reductions in concentrations at the outlet of the second wetland cell (compared to levels in the lagoon) in 1996 were: 98.7% (33.3 mg/l), 97.8% (19.7 mg/l) and 95.3% (4.27 mg/l) for BOD_5, TKN and TP, respectively. Mass reduction of these pollutants at the same stage of treatment was higher than 98.8% during the same year. Based on the concentrations, overall performance of the system in 1997 is similar to 1996 for BOD_5, but somewhat inferior for TKN and TP. Average reductions in concentrations at the outlet of the second wetland cell (compared to levels in the lagoon) were: 97.2% (32.8 mg/l), 93.7% (26.5 mg/l) and 86.4% (9.07 mg/l) for BOD_5, TKN and TP, respectively. It should be mentioned that true comparison of the performance can only be achieved with a mass balance. A mass balance would indicate a higher performance, as water flow diminishes along the system. Due to evaporation, the water flow on the filter strip was so small that it could not even be sampled. Considering this small flow and the level of concentration reduction, the overall performance of the constructed wetland was good.

ACKNOWLEDGEMENTS

The following partners made the construction of the Dignard Constructed Wetland possible:

Agriculture and Agri-Food Canada (Rural Conservation Clubs)
Alfred College of Agriculture and Food Technology
Michel and Hector Dignard - landowners
McNeely Engineering Consultants, Ltd.
Ontario Cattleman’s Association
Ontario Ministry of Agriculture, Food and Rural Affairs
Ontario Ministry of Environment and Energy
Ontario Soil and Crop Improvement Association
Russell Soil and Crop Improvement Association
South Nation River Conservation Authority

The Dignard Constructed Wetland project was managed by a committee composed of the following members:

Gaston Patenaude, Committee Chair
Michel Dignard, Landowner
William Kollaard, Alfred College, University of Guelph
André Lemay,Ontario Ministry of Agriculture, Food and Rural Affairs
Cam McGowan,South Nation River Conservation Authority
Denis Perrault,Ontario Soil and Crop Improvement Association
Gerald Poupart,Russell Soil and Crop Improvement Association
Paul Sabourin,Ontario Ministry of Agriculture, Food and Rural Affairs
Eric Tousignant, McNeely Engineering
Leslie Vanclief,South Nation River Conservation Authority
Claude Weil,Alfred College, University of Guelph
Mary-Ann Wilson,South Nation River Conservation Authority

The 1997 Year End Report was written with the collaboration of the following people:

Pierre-Alain Blais, Alfred College, University of Guelph
Olivier Fankhauser, Alfred College, University of Guelph
William Kollaard, Alfred College, University of Guelph
Leslie Vanclief,South Nation River Conservation Authority
Claude Weil, Alfred College, University of Guelph

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REFERENCES

1. INTRODUCTION

The Dignard dairy farm is located just outside the town of Embrun, within the South Nation River watershed (see figure 1) and also within commuting distance to Ottawa. Because of its location, the farm is subject to the scrutiny of local residents concerned over its impact on the environment. The Dignard herd includes an average of: 100 cows, 60 heifers age 0-4 months, 30 heifers age 4-7 months, and 75 heifers age 8 months and over.

The operation produces wastewater from three sources: runoff from a solid manure pile, stormwater runoff from a 0.75 ha exercise yard (used by 60 heifers) and milkhouse wastewater (the washwater used to clean and sanitize the milk pipeline and bulk storage tank). Solid manure, mixed with milkhouse wastewater, is stacked by an air piston onto a concrete pad. Prior to construction of the wetland system in 1994, runoff from the solid manure pile was stored in an anaerobic lagoon and periodically spread on cropland. The runoff from the feedlot was not collected. The owners required a system that would treat all the liquid runoff without the need for spreading, otherwise separate systems would have been required for handling liquid and solid manure, increasing equipment and labour costs. A constructed wetland was proposed as a suitable solution.

There is much interest in Ontario for using wetlands and associated Best Management Practices (BMP’s) to treat stormwater runoff, liquid manure and milkhouse wastewater. Under the Green Plan, a number of projects have been initiated to evaluate the merit of such BMP's. Wet ponds have been the primary means used to regulate and treat stormwater runoff in urban areas. In rural areas, there is a broader choice of BMP's which can be strategically located throughout a watershed to improve the receiving stream water quality. Considering ease of operation and local climatic conditions, the most practical rural BMP's for Ontario are: facultative ponds, aerobic ponds, constructed wetlands, and slow and rapid rate infiltration systems.

The Dignard Wetland, described in this report, is one of many BMP's undergoing testing in rural Ontario which will soon yield much needed information about their capability to remove pollutants. Removal mechanisms include settling (suspended solids), aerobic or anaerobic digestion (organic matter), soil adsorption (phosphorus), nitrification/denitrification, nutrient uptake by vegetation, and bacterial die-off (pathogens). From the data collected over several seasons, first or second order rates of removal can be established. Estimates of the removal rates for the first two years of operation are included in this report. These removal rates will then be available for optimizing the design of future constructed wetlands.

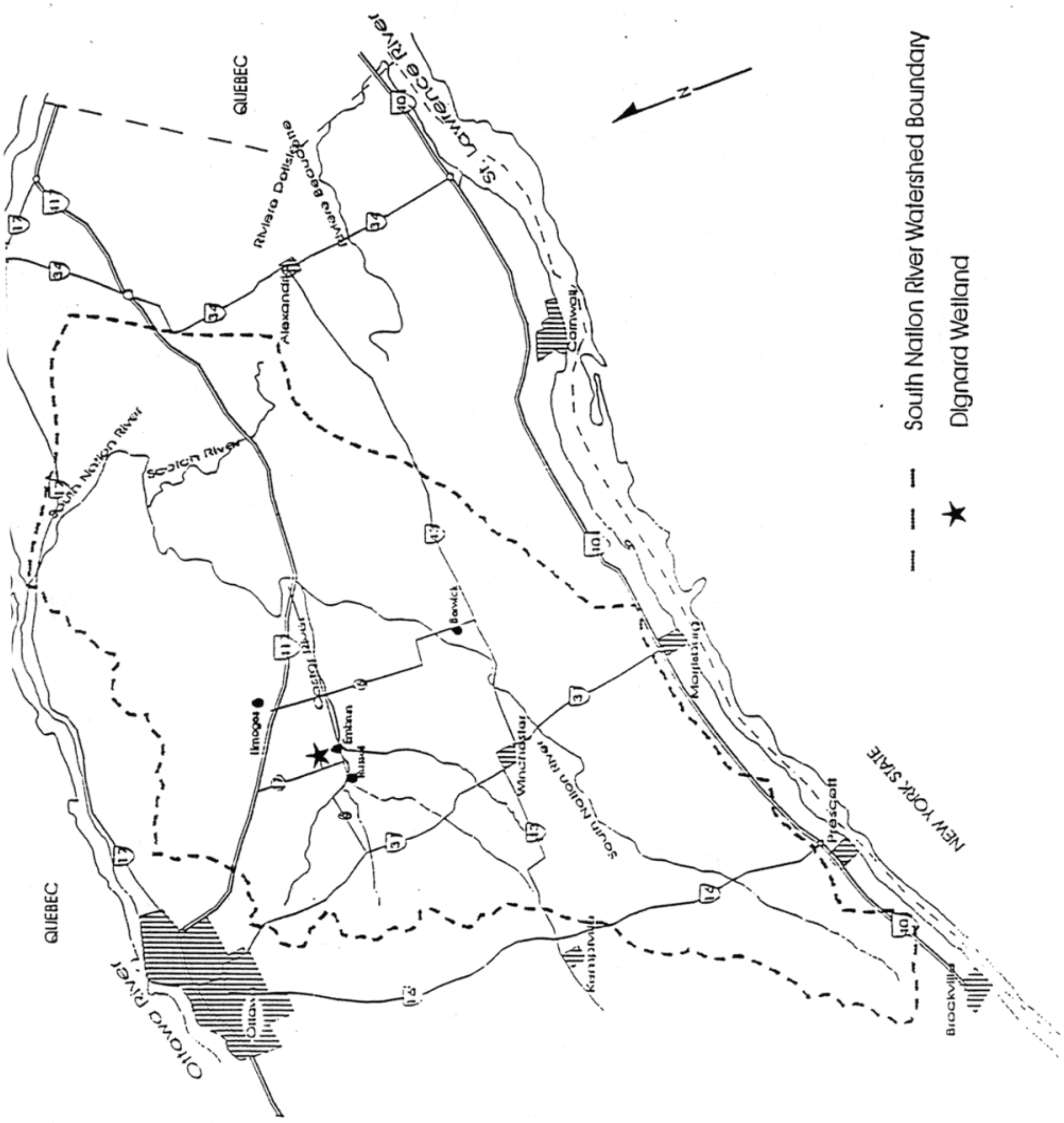


Figure 1.1. Site Location

2. WETLAND SYSTEM DESIGN

The following section is an overview of the design of the Dignard constructed wetland system. A detailed description of the design calculations can be found in the design report (Weil et al., 1994) and further information was included in the 1995 Year End Report (Weil et al., 1996).

2.1 Free Water Surface Wetlands

The Dignard Wetland is referred to as a *free water surface wetland*. Free water surface wetlands consist of a series of channels and/or basins which are lined with clay in order to limit infiltration. A layer of soil is provided on top of the clay in which aquatic plants, called macrophytes (such as cattails and bulrushes), are planted. A slow flow rate is applied so that a shallow depth is maintained (Hamilton et al., 1993). Settleable solids are removed by sedimentation. Sedimentation lowers biochemical oxygen demand, and removes particulate forms of phosphorus and nitrogen from the wastewater. A nutrient rich sludge is formed on the wetland floor. The macrophytes supply oxygen to the sludge zone through their roots, thereby promoting aerobic digestion of the pollutants by microorganisms. Macrophytes also act as physical supports for microorganisms which attach themselves to the plants, forming a "biofilm" from the water surface to the wetland floor. As water passes through the thick growth of macrophytes, it is exposed to the living biofilm, which filters pollutants and degrades them.

Dissolved nutrients are also removed in wetlands. The main removal mechanism for dissolved nitrogen is nitrification/denitrification. Nitrification occurs under aerobic conditions: bacteria convert ammonium (NH_4^+) into nitrite (NO_2^-) and nitrite into nitrate (NO_3^-). Denitrification occurs under anaerobic conditions: nitrate is converted into nitrogen gas (N_2) which is released into the atmosphere. Dissolved phosphorus is removed by adsorption, complexation and precipitation with dissolved minerals and by peat accretion (accumulation of organic matter) (Brix, 1994).

2.2 Layout of Dignard Wetland System

The general design principles followed are those advocated by Dr. D. Hammer of Purdue University (Hammer, 1994), although site specific modifications were incorporated into the design, including a facultative pond for pretreatment and a vegetative filter strip for polishing the effluent. The layout of the Dignard Wetland is shown in figure 2.1. The treatment system was designed to operate as follows:

a. The feedlot runoff is intercepted and treated in an overland flow system or grassed swale ("3" in Figure 2.1).

b. The runoff from the manure pile is collected in the existing lagoon ("1" in Figure 2.1).

c. The overland flow system and the lagoon both feed a facultative pond ("4" in figure 2.1).

d. The water then flows through a wetland / aerobic pond / wetland system (“5", “6" and “7" in figure 2.1).

e. An overland flow system (“8" in figure 2.1) completes the treatment.

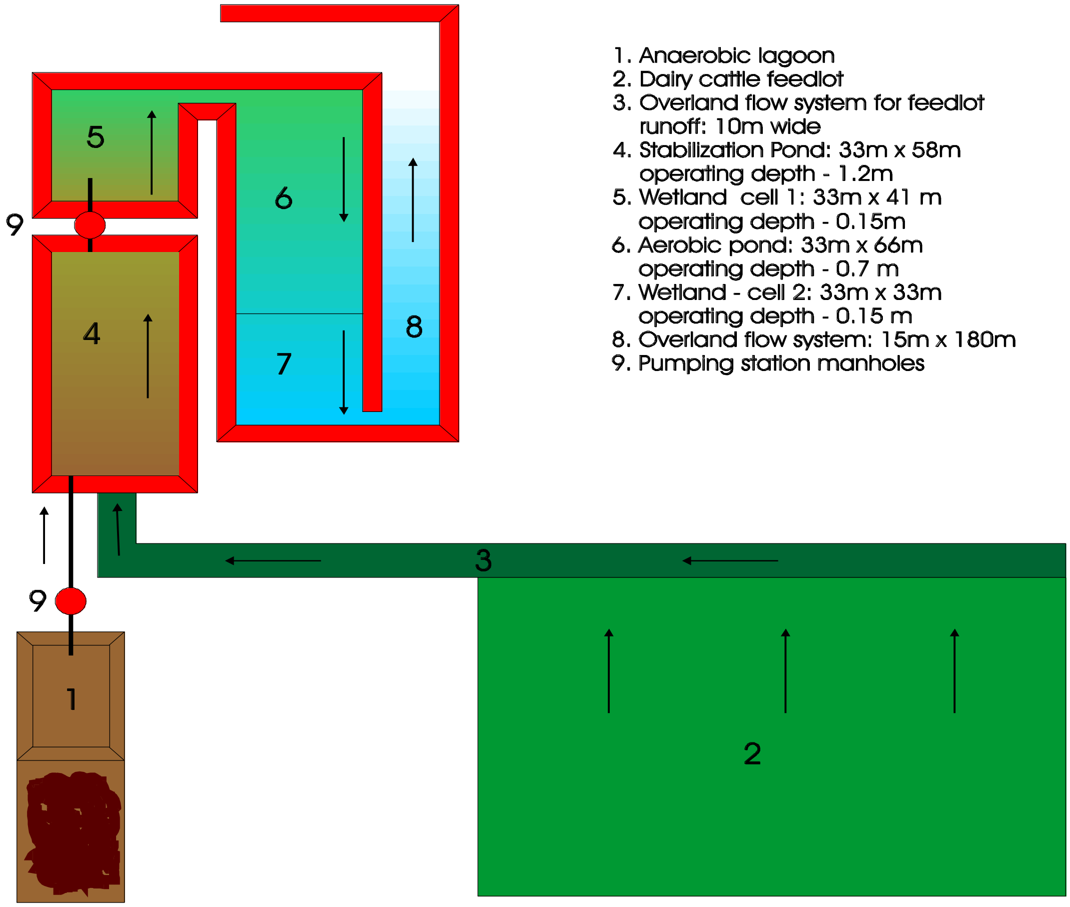


Figure 2.1: General layout of wetland system

2.3 Design Parameters

The design of each component of the Dignard Constructed Wetland system was based on BOD_5 and TKN loading rates found in the literature in addition to several practical considerations concerning local conditions as described below. TKN was the controlling parameter for the wetland cells, TP for the filter strip and BOD_5 governed the design of the stabilisation pond.

2.3.1 Hydrological considerations

- **Design return period: 10 years**

A “wet winter was defined as one for which the excess precipitation (precipitation-evaporation) will probably only be exceeded once in ten years (based on a normal distribution). Using weather data from the weather station at the Ottawa International Airport, the “ten year wet winter” was found to produce an excess precipitation of 523mm.

The wetland was designed to operate from May 1st to September 30th. During the rest of the year, runoff is stored in the lagoon. The lagoon was sized to handle the milkhouse washwater, the runoff from the manure pile and the direct precipitation which would accumulate from September 30th to May 15th during a "wet winter". The total volume of wastewater accumulating in the lagoon during a wet winter was calculated to be 1562 m^3.

Ten year return periods were also used to establish a water budget for each cell of the system, so that appropriate flow depths could be maintained (a wetland can be destroyed by drought) and to determine the quantity of runoff from the cattle exercise yard.

Water budgets were conducted on the basis of the following assumptions:

1. Design return period: 10 years.

2. Infiltration is negligible, due to heavy clay soils and compaction.

3. All cells will always contain water, so actual evapotranspiration = potential evapotranspiration.

2.3.2 Surface Loading Rates

Facultative pond

- **BOD_5 loading rate: 100 kg/ha/day**

The facultative pond was designed using a BOD5 loading rate of 100kg/ha/days as suggested in the literature. The target BOD5 concentration for pond effluent was set at 400 mg/l in order to prevent plant die-off in the first wetland cell.

Wetland/Pond/Wetland

- **BOD_5 loading rate: 75 kg/ha/day**
- **TKN loading rate: 3 kg/ha/day**

BOD: In the Embrun design a loading rate of 75 kg/ha per day was selected based on comparisons with loading rates reported in other wetland studies. Reed et al. (1988) reported that BOD_5 loading rates ranging from 18 to 116 kg/ha per day resulted in up to 93% removal and Hammer (1994) specified an upper loading rate of 100 kg/ha per day for a target effluent quality of 30 mg/l or less.

TKN: Hammer (1994) recommended a stringent overall TKN mass loading rate of 3 kg/ha/day for sizing the wetland/pond/wetland cells as well as the overland flow grassed filter strip. This recommendation was used in the Dignard design.

Overland Flow Grassed Filter Strip

The overland flow system was designed based on the following hydraulic loading rate (Reed et al., 1988):

$$L_w = \frac{qP(100cm/m)}{Z}$$

where L_w = hydraulic loading rate, cm/day
q = application rate per unit width of the slope, m^3/h/m
P = application period, h/day
Z = slope length
m = width of filter

2.4 Summary of Dimensions

Using the parameters described above, the Dignard Constructed Wetland system was designed with the dimensions shown in Table 3.1.

Table 2.1: Summary of Wetland System Dimensions

Cell	Length (m)	Width (m)	Operating Depth (m)	Volume at Operating Depth (m^3)	Average Detention Time (d)
Facultative stabilization pond:	58	33	1.2	2430	177
1st wetland:	41	33	0.1	203	12
Aerobic pond:	66	33	0.7	1570	102
2nd wetland	33	33	0.1	163	12
			lateral slope:	**longitudinal slope:**	
Overland flow system	180	15		0.3 %	
Overland flow system for feedlot		10	2 %	0.2 %	

2.5 Schedule of Operation

In order to ensure that there is enough water at all times to support the plant life in the wetlands, the water depth is maintained between 90 and 120 cm in the facultative stabilisation pond. This is done by adjusting the outflow pumping rate at the beginning of each month to compensate for high or low precipitation during the previous month. This strategy will also ensure adequate storage throughout the following winter. Table 2.2 shows the suggested operation schedule for the Dignard Wetland.

Table 2.2: Operation Schedule

Start Date	Lagoon Pump			Facultative Pond Pump		
	Flow m^3/d	Start Time	Stop Time	Flow m^3/d	Start Time	Stop Time
May 1	0.0	OFF	OFF	202.5	19:00	18 00
May 12 -18	11.0	07:00	08:17	15.2	19:00	20:46
June 1	11.0	07:00	08:17	22.3	19:00	21:36
July 1	11.0	07:00	08:17	24.0	19:00	21:48
August 1	11.0	07:00	08:17	19.8	19:00	21:18
September 1	11.0	07:00	08:17	13.0	19:00	20:31
October	0.0	OFF	OFF	0.0	OFF	OFF

3. MONITORING

3.1 Surface Water Monitoring

The 1997 surface water monitoring program was conducted from June 5 to August 27. Samples were collected weekly by the staff of South Nation River Conservation Authorities and analyzed by the MOE for *Escherichia coli, faecal streptococcus, Pseudomonas aeruginosa,* ammonia, nitrite, nitrate, total Kjeldahl nitrogen, phosphate, total phosphorus, biochemical oxygen demand, dissolved organic and inorganic carbon, suspended solids, reactive silicate, pH and conductivity.

There were six sample locations within the wetland during the 1997 monitoring season (fig. 3.1). The locations are the following:

(S1) anaerobic lagoon (sampled from the outflow pipe of the manhole into which it discharges);
(S2) stabilization pond effluent (dip samples collected near its outlet);
(S3) marsh # I (sampled at the outlet weir);
(S4) aerobic pond effluent (dip samples collected near its outlet);
(S5) effluent of marsh # 2 (sampled at the outlet weir); and,
(S9) edge of the cattle feedlot (composite samples collected from three cups buried in the ground at the edge of the cattle feedlot).

Three sample locations used in 1995 and 1996 were not monitored in 1997 due to a lack of water:

(S6) mid-point of the finishing filter strip (composite samples taken from three tubes inserted 30cm into the topsoil);
(S7) end of the finishing filter strip (composite samples taken from three tubes inserted 30cm into the topsoil); and,
(S8) outlet of the filter strip pretreating the cattle feedlot runoff (three sampling tubes were inserted, but no water accumulated).

3.2 Ground Water Monitoring

Ground water was monitored to assess if the wetland impacted shallow ground water quality. Shallow groundwater piezometers were installed by Alfred College staff in the spring of 1994. Most of these tubes had to be replaced in the spring of 1995 due to damage by machinery during construction. In 1996, tubes were repositioned to avoid contamination by surface water. Groundwater collection tubes were monitored at the SE comer (S10), the E end (S11), the NE comer(S12), the S side (S14) and at the edge of the creek down-grade from the system (S13), as indicated in Figure 3.1. Samples were to be collected whenever enough water had accumulated in the tubes to collect an adequate sample. However, during the 1997 season, water levels in the collection tubes were rarely above the level required for sampling. As a result, only location S11 could be sampled successfully and just for one sample.

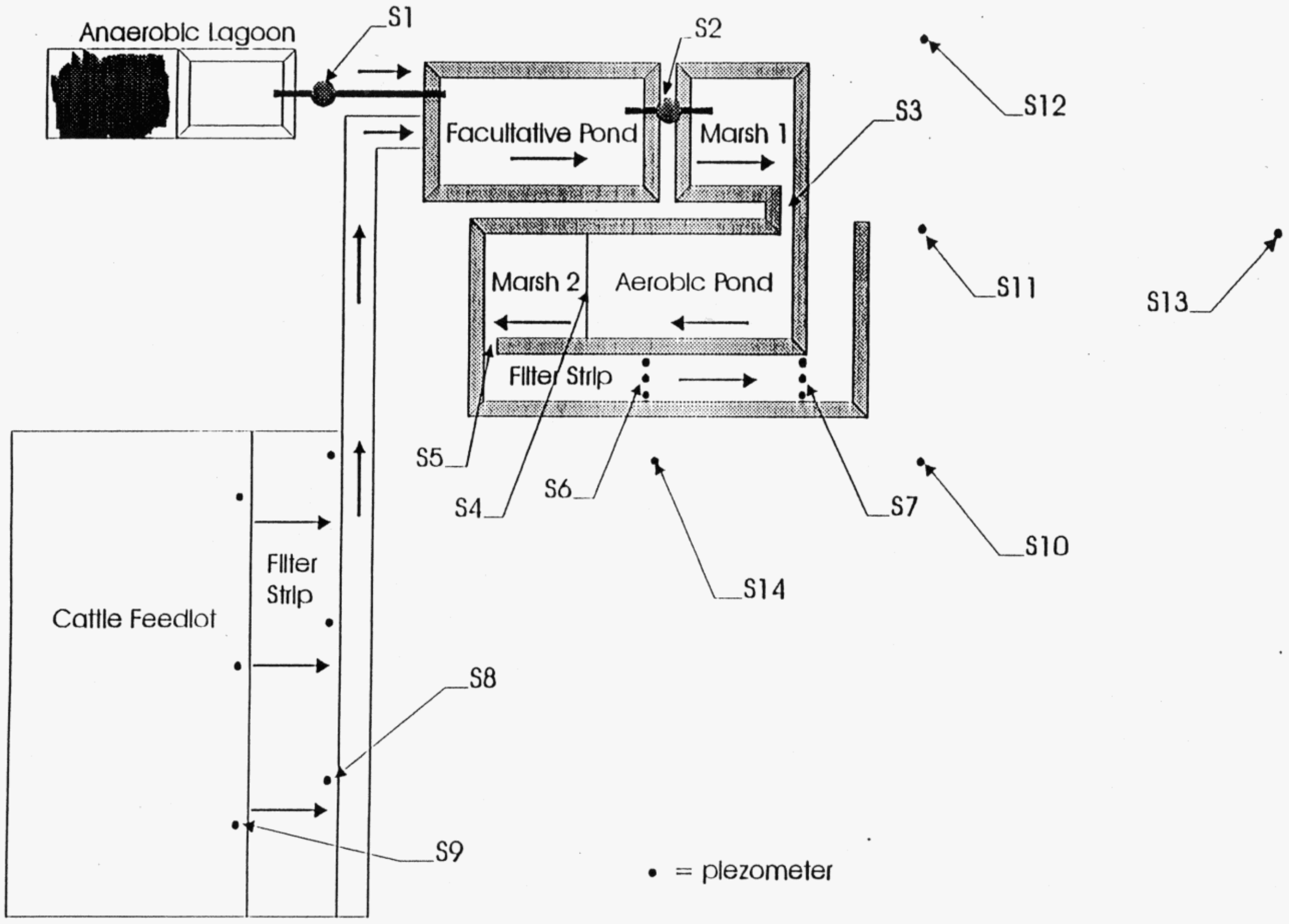
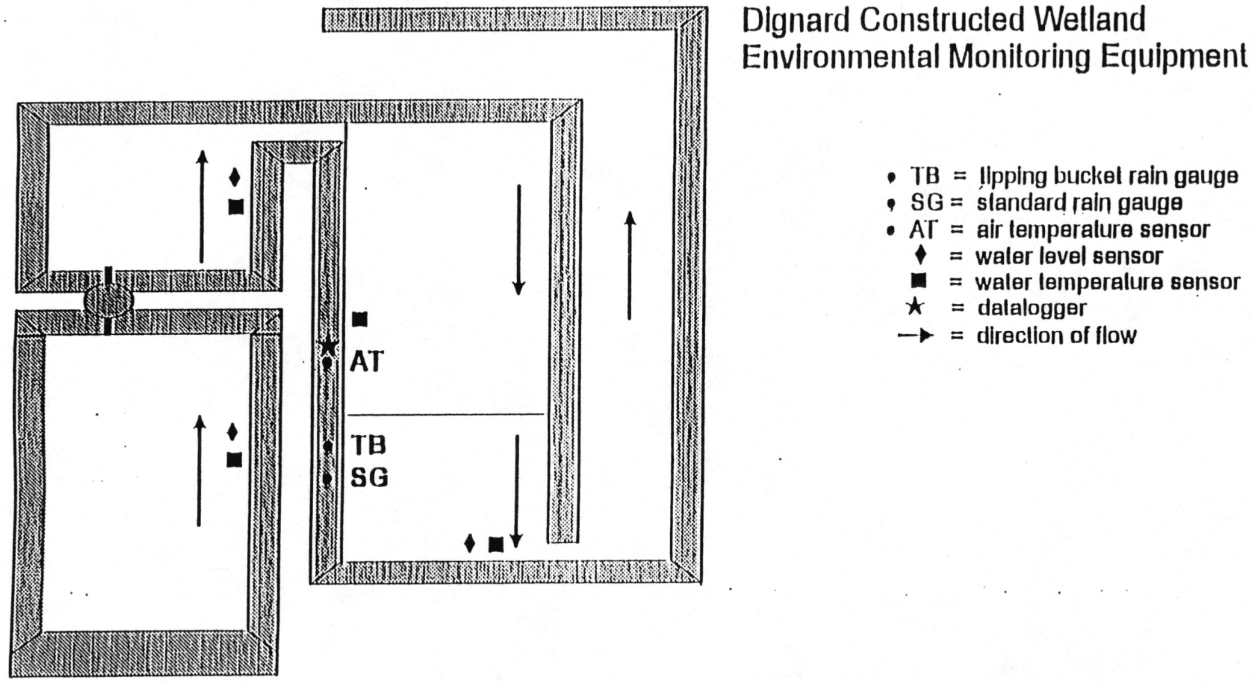


Figure 3.1. Sampling Locations at the Dignard Constructed Wetlands Site

3.3 Temperature and Water Levels

The monitoring equipment installed in 1995 was put back into operation in the early spring of 1997. The objective of this monitoring was to provide information on environmental factors to assist with calculating the water budget for the wetland system and assessing wetland performance. Figure 3.2 indicates the location of the sensors installed at the Wetland site. Information collected during the 1997 season consisted of air temperature, rainfall (tipping bucket rain gauge and standard rain gauge), water temperature, and water elevation. Staff from the South Nation River Conservation Authority collected monthly data reports from the data logger and maintained the equipment in the field.

Figure 3.2. Physical factors sample locations



4. SYSTEM PERFORMANCE

Chapters 4.1 and 4.2 concern the 1996 monitoring season and chapter 4.3 concerns 1997.

4.1 Reduction in pollutant concentrations during the 1996 operating season

The wetland treatment system performed beyond expectation over the first two years of operation. During the 1996 season, the average BOD_5, TKN and TP concentrations at the system outlet were 3.1 mg/l, 2.83 mg/l and 0.07 mg/l respectively (table 4.1). This represents a reduction in concentrations greater than 99.7% (table 4.2).

Table 4.1: Average pollutant concentrations at the outlet of the wetland components in 1996.

	BOD_5		TKN		$N\text{-}NO_3$		$N\text{-}NO_2$		TP	
	mg/l	n	mg/l	n	mg/l	n	mg/l	n	mg/l	n
Lagoon	2567.3	14	883.5	14	0.27	11	0.51	11	90.4	14
Feedlot runoff	97.4	4	167.7	3	0.04	3	0.17	3	47.7	3
Facultative pond	215.5	15	101.8	15	0.11	14	0.14	15	17.0	15
Marsh#1	168.1	15	91.3	15	0.08	13	0.10	13	13.8	15
Aerobic pond	44.2	15	38.7	15	0.50	14	0.37	14	7.16	15
Marsh#2	33.3	15	19.7	15	0.09	14	0.16	14	4.27	15
Mid-Point Filter-strip	4.40	2	2.23	2	0.11	1	0.05	1	0.04	2
End of Filter-strip	3.10	2	2.83	2	1.38	1	0.13	1	0.07	2

Note: n = number of samples (little water accumulated in the sampling tubes in the filter strip).

Table 4.2: Average reduction in pollutant concentrations during the 1996 operating season.

		BOD_5		TKN		TP	
		Reduction within cell %	Overall reduction %	Reduction within cell %	Overall reduction %	Reduction within cell %	Overall reduction %
Facultative pond	S2	91.6	91.6	88.5	88.5	81.2	81.2
Marsh#1	S3	22.0	93.5	10.3	89.7	18.6	84.7
Aerobic pond	S4	73.7	98.3	57.6	95.6	48.3	92.1
Marsh#2	S5	24.6	98.7	49.2	97.8	40.4	95.3
Mid-Point Filter-strip	S6	86.8	99.8	88.7	99.7	99.0	100.0
End of Filter-strip	S7	29.5	99.9	-27.0	99.7	-53.5	99.9

Prior to construction, the BOD_5 concentration in the manure lagoon was measured to be 1700 mg/L, and this value was used for design purposes. Over the 1996 monitoring season, during which 15 samples were collected, the average BOD_5, concentration in the lagoon was 2619.5 mg/l. Despite its higher than predicted influent BOD_5 concentration, the facultative pond produced an effluent of greater quality than predicted: a conservative estimate of 400 mg BOD_5. The effect of the generally decreasing concentrations in the lagoon as the season progressed was dampened before discharge into the filter strip. Concentrations recorded for the effluent of the second wetland cell would seem to show no general seasonally related trend.

Nitrogen was found to exist mostly as organic nitrogen and ammonium (measured as Total Kjeldahl Nitrogen, TKN) in all cells of the system, other than the filter strip. Nitrate and nitrite levels were always at least one order of magnitude lower than corresponding TKN values, except in the filter strip. Therefore, TKN data can be used to approximate Total Nitrogen (TN) throughout the system except in the filter strip. In the manure runoff lagoon, the average TKN was found to be 883.5 mg/L, much higher than the 219 mg/L recorded prior to construction of the wetlands. TKN levels in the lagoon were more stable than BOD_5 concentrations. There was no dramatic decrease in TKN in the lagoon in August, as was observed for BOD5.

Since nitrates and nitrites were expected to be generated by nitrification of ammonium, they were not predicted to gradually drop from cell to cell within the wetland system. The purpose of the alternating pond/wetland design was to promote the nitrification and subsequent denitrification of ammonia-nitrogen. The limiting step was most likely nitrification in the "aerobic" pond (which requires sufficient oxygen). The data collected in 1996 showed an increase in nitrate as the wastewater passed through the aerobic pond (0.082 mg/L to 0.495 mg/L). This concentration is still very low compared to the average TKN concentration at the outlet of the pond (38.7 mg/L). This may suggest the presence of aerobic and anaerobic conditions present in the pond, causing the denitrification cycle to occur in conjunction with the nitrification cycle (ie. nitrate produced in aerobic zones is broken down into nitrogen gas in anaerobic zones) within the pond. Alternately, nitrogen may have been lost to the atmosphere in other gaseous forms or adsorbed onto precipitating solids.

It should be noted that simply measuring influent and effluent concentrations to evaluate the efficiency of the treatment system does not account for changes in volume due to precipitation or evaporation. The average flow discharged from the wetland was far lower than the controlled flow rate entering the system. Water losses were attributed to evaporation rather than infiltration for the following reasons: the wetland system was constructed over heavy clay which was compacted during construction; no water ponded in low areas surrounding the system; and ground water samples collected did not show elevated pollutant concentrations. Evaporation would have a concentrating effect on pollutant concentrations in the wetlands. Therefore, the actual total mass removal of pollutants was almost certainly higher than the reduction in concentrations shown in Table 4.2.

Finally, overall reduction in phosphorus concentration reached 99.9% across the system in 1996. However, desorption of phosphorus from the wetland cells have not been specifically assessed. Continuing monitoring is necessary to assess the long term pollutant removal efficiencies. Additional information can be found in the *1996 Year-End Report* (Weil et al., 1997).

4.2 Mass balance of pollutants for the second year of operation

Based on concentrations, the wetland system has performed beyond expectations over the first two years of operation. A better method of evaluating the true performance of the wetland treatment system is to perform a mass balance of pollutants. This involves keeping track of the total mass (in kilograms) of each pollutant passing through the system per day. A mass balance approach not only allows for a better assessment of the system's performance, it also facilitates comparison among systems and may be used to determine parameters for future designs.

4.2.1 Methodology

The data collected included weekly BOD_5, TKN and TP concentrations at the outlet of each lagoon, pond and wetland cell.. For the purpose of the daily mass balance calculations, the concentrations of these parameters were assumed to vary linearly between sample times. Concentration values for days when samples were not taken were estimated (eg. the TKN concentration on May 16 was measured as 63 mg/L and on May 23 was measured as 70 mg/L; the concentration was assumed to increase by 1 mg/L each day).

Pollutant concentrations were also measured after rain events for runoff from the cattle exercise yard and at the outlet of the filter strip. Since there was limited data for these locations, averages were used for the purpose of the mass balance calculations. Using a Campbell Scientific data logger equipped with several gauges, hourly data was tabulated for precipitation, air temperature, water temperature and depth of each treatment cell.

In order to perform a mass balance on the facultative pond, all the inputs and outputs had to be quantified. Inputs included pumped flow from the anaerobic lagoon, runoff from the exercise yard and precipitation. Outputs included evaporation, infiltration and pumped outflow to Marsh # 1. Due to reworked clays with extremely low permeability, infiltration was assumed to be zero for all ponds. The runoff from the feedlot was estimated using the SWWM4 runoff module, which utilizes the Horton model to estimate infiltration (Huber & Dickinson, 1988).

The following site information, measured prior to construction in 1993, was used for the SWMM4 simulation: hourly precipitation; feedlot area (0.75 ha); saturated hydraulic conductivity (0.23 mm/hr); asymptotic infiltration rate (10 mm/hr); infiltration decay rate (0.00115 sec^{-1}); average depression storage (6.8 mm); Manning’s roughness coefficient (0.02); and average feedlot slope (0.01). Once the SWMM calculation was conducted and hourly exercise yard runoff volumes were estimated, evaporation was the only remaining unknown and was calculated hourly by:

$$E = P + Q_{P1} - Q_{P2} + R - (S_n - S_{n-1}) \qquad (1)$$

where:

E = evaporation (m^3);
P = direct precipitation (m^3);
Q_{P1} = Pumped flow from anaerobic lagoon (m^3);
Q_{P2} = Pumped flow into marsh # 1 (m^3);
R = Runoff from cattle exercise yard (m^3);
S_n = Storage volume in pond at end of hour (m^3); and
S_{n-1} = Storage volume in pond at end of previous hour (m^3).

This value of E was then converted into mm/hr and used for all other treatment cells. For marsh 1, the volume at each time step was calculated in the following manner:

$$V_1 = V_0 + P + Q_{P2} - E - Q_{OUT} \qquad (2)$$

where: V_1 = the volume at the end of the time step;
V_0 = the volume at the beginning of the time step;
Q_{OUT} = cell outflow, calculated using a V-notch weir equation: $Q_{OUT} = 4968H^{5/2}$; and
H = height above weir (m)

The inputs and outputs from the aerobic pond and the second marsh were calculated in a similar fashion. After the flows and volumes of each cell were estimated, the mass balance was performed for each cell as follows:

$$IN - OUT = REMOVAL + STORAGE \qquad (3)$$

where: IN = the mass of pollutant input to the pond;
OUT = the mass of pollutant output from the pond;
REMOVAL = the mass of pollutant removed; and
STORAGE = the mass of pollutant temporarily stored in the pond.

The mass coming "IN"-to as well as that going "OUT" of the facultative pond were calculated by multiplying the measured concentration by the flow rate (giving kg of pollutant per m^3 per day). The "STORAGE" was defined as the amount of pollutant temporarily in the pond at any given time. The mass in STORAGE was calculated assuming a completely mixed flow regime (i.e. the concentration was the same at all points throughout the pond, including its outlet). The STORAGE was calculated as the change in mass over time, using the effluent concentration as the concentration in the pond:

$$STORAGE = \frac{\Delta M}{\Delta t} = \frac{C_{1,1}V_1 - C_{1,2}V_2}{t_1 - t_2} \qquad (4)$$

where: Δ M = change in mass in storage;
V_1 = volume of pond at time t_1;
V_2 = volume of pond at time t_2;
$C_{1,1}$= concentration in effluent at time t_1 (= concentration in pond at time t_1);
$C_{1,2}$= concentration in effluent at time t_2 (= concentration in pond at time t_2); and
Δt = change in time.

Once the mass of pollutant loaded INto and discharging OUT of the pond as well as that in STORAGE were calculated, the REMOVAL was determined using Equ. 3. However, more useful information was obtained from the mass balance by substituting a removal algorithm into the equation. Many biological pollutant removal processes have been found to correspond well to the relationship:

$$REMOVAL = kM \qquad (5)$$

where k is a constant (in units 1/d) and M represents the mass in the pond. This is referred to as a "first order decay" model. Substituting equations for IN, OUT, STORAGE and REMOVAL into the general mass balance formulation gives:

$$Q_0 C_0 - Q_1 C_1 = k C_1 V + \frac{C_{1,1} V_1 - C_{1,2} V_2}{t_1 - t_2} \qquad (6)$$

This can be rearranged to give:

$$k = \frac{Q_0 C_0 - Q_1 C_1 - \left(\frac{C_{1,1} V_1 - C_{1,2} V_2}{t_1 - t_2}\right)}{C_1 V} \qquad (7)$$

The constant k, used in such models, can be related to temperature as follows:

$$k_T = k_{20} \theta^{(T-20)} \qquad (8)$$

where: k_T = constant at temperature T;
k_{20} = constant at 20^0C;
θ = temperature activity coefficient = 1.04 (Metcalf & Eddy (1991) recommend 1.04 for activated sludge processes and 1.035 for trickling filters); and
T = temperature in ^{0}C.

4.2.2 Results

A mass balance calculation was performed for each cell. Initially, flow rates between the first wetland cell and the aerobic pond, and also between the second wetland cell and the grass filter were to be measured with weirs in place. In 1995, it was found that debris collecting across the V notch could alter the readings. Table 2 includes, for the period from May 23rd to August 27th, 1996, the following information for each cell: mean daily inflow and outflow rate, and mean daily temperature. Load reductions for BOD_5, TKN and TP are also reported with their associated mean kinetic rate constant adjusted to a temperature of 20 ^{0}C.

Table 4.3: Summary of BOD, TKN and TP mass balance (May 23 to August 27, 1996).

	Facultative Pond	**Marsh # 1**	**Aerobic Pond**	**Marsh #2**	**Vegetated Filter**
Flows					
Mean daily inflow rate (m^3/day)	15.50	21.49	15.83	4.45	0.09
Mean daily outflow rate (m^3/day)	21.49	15.83	4.45	0.09	0.37
Temperature					
Mean daily water temperature (^{0}C)	14.90	15.68	16.78	16.67	N/A
BOD_5					
Mean daily influent loading (kg/day)	28.98	4.57	2.56	0.187	0.0024
Mean daily effluent loading (kg/day)	4.57	2.56	0.19	0.002	0.0011
Mean daily removal (kg/day)	39.65	2.24	2.34	0.160	0.0013
Mean kinetic rate constant, k_{20} (1/day)	0.066	0.091	0.053	0.19	N/A
Standard error of mean k_{20} (1/day)	0.027	0.027	0.018	0.10	N/A
Load reduction within cell (%)	84.23	43.95	92.71	98.69	53.01
Cumulative load reduction (%)	84.23	91.16	99.36	99.99	100.00
TKN					
Mean daily influent loading (kg/day)	10.54	2.20	1.47	0.163	0.0021
Mean daily effluent loading (kg/day)	2.20	1.47	0.16	0.002	0.0010
Mean daily removal (kg/day)	10.69	0.50	1.08	0.133	0.0011
Mean kinetic rate constant, k_{20} (1/day)	0.031	0.041	0.029	0.19	N/A
Standard error of mean k_{20} (1/day)	0.008	0.022	0.022	0.07	N/A
Load reduction within cell (%)	79.15	33.18	88.92	98.71	50.62
Cumulative load reduction (%)	79.15	86.07	98.46	99.98	99.99
TP					
Mean daily influent loading (kg/day)	1.22	0.38	0.232	0.029	0.0006
Mean daily effluent loading (kg/day)	0.38	0.23	0.029	0.002	0.0000
Mean daily removal (kg/day)	0.59	0.10	0.112	0.018	0.0006
Mean kinetic rate constant, k_{20} (1/day)	0.008	0.048	0.013	0.19	N/A
Standard error of mean k_{20} (1/day)	0.012	0.017	0.018	0.08	N/A
Load reduction within cell (%)	69.19	38.43	87.53	92.73	93.98
Cumulative load reduction (%)	69.19	81.03	97.64	99.83	100.00

4.2.3 Discussion

The treatment performance of the Dignard constructed wetland was high during the second year of operation. The average BOD_5, TKN, and TP at the system outlet were 3.1 mg/l, 2.83 mg/l and 0.07 mg/l, respectively, well below the target levels set at 20 mg/l, 20 mg/l, and 1mg/l. This represents overall concentration reductions of more than 99.7% for these pollutants across the treatment system. The removal rates achieved by the facultative pond alone were 91.6%, 88.5%, and 81.2% respectively for BOD_5, TKN, and TP. However, it is the marsh-aerobic pond-marsh-grassed filter that allowed the target levels to be met.

Load reduction for BOD_5, TKN, and TP was greater than 99.9%. However, desorption of phosphorus from the wetland cells that are not harvested have not been specifically assessed. The grass filter/slow rate infiltration system at the outlet of the second wetland cell is harvested at least twice a season. It leads to a meadow, which is also harvested. This systematic removal of vegetation may or may not be sufficient to avoid long term desorption of phosphorus, which future research will have to assess.

The kinetic rate constants for the removal of BOD_5, TKN and TP have been established for each cell. Each rate constant has a large variation as can be seen in standard error of the mean. This can be partially explained by the seasonal variations of many factors that were not taken into account in the calculations. For example, the variation of the duration of daylight affects photosynthesis, as well as the overall development of the plants. Seasonal characteristics will also have an effect on dissolved oxygen, which was not measured, but has a great influence on the fate of contaminants.

Experimental errors such as sampling variances, the assumption that concentrations vary linearly between sample times, and errors introduced by estimating unmeasured information (feedlot runoff and evaporation) might explain the large standard deviation of the kinetic removal rate. Finally, there are uncertainties about the value of the temperature coefficient (?) for the different pollutants for treatment wetlands. As an example, Kadlec & Knight (1996) mention that “in light of the data presently available, it appears that temperature effects for BOD_5 reduction are negligible for surface flow wetlands”. This might have introduced variability when the kinetic rate constants were corrected for the temperature.

The development of kinetic rate constants for the removal of BOD_5, TKN and TP under Eastern Ontario conditions will allow to better understand the mechanisms involved in constructed wetlands. This will lead to improved systems for the region and will allow greater flexibility when designing constructed wetlands. Continuing monitoring of the system is necessary to assess the overall performance in pollutant reduction over the long term.

4.3 Results for the 1997 operating season

During the 1997 monitoring season, little water accumulated on the filter strip and in the ground water tubes. For this reason, only a ground water tube was sampled once and no sample was taken on the filter strip. Overall performance of the system is similar to 1996 for BOD_5, but somewhat inferior for TKN and TP (Tables 4.4 & 4.5, Figure 4.1). It should be mentioned that true comparison of the performance can only be achieved with a mass balance and that a lower concentration reduction does not necessarily mean a smaller removal of pollutants. For this reason, a mass balance will have to be performed for the 1997 monitoring season.

Table 4.4: Average pollutant concentrations at the outlet of the wetland components in 1997.

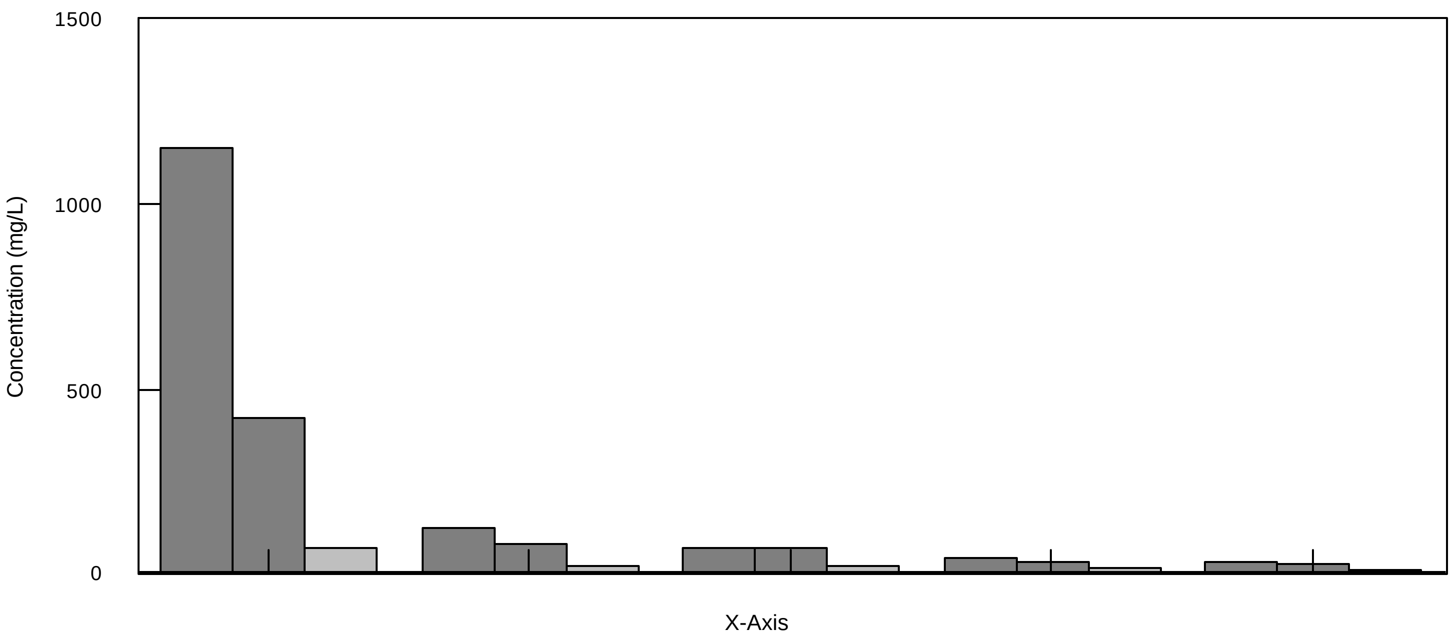
	BOD_5		**TKN**		**$N\text{-}NO_3$**		**$N\text{-}NO_2$**		**TP**	
	mg/l	n	mg/l	n	mg/l	n	mg/l	n	mg/l	n
Lagoon	1153	11	421.3	10	0.07	11	0.4	11	66.6	10
Feedlot runoff	24.9	3	14.3	3	0.16	3	0.09	3	8.7	3
Facultative pond	122.6	13	79.1	13	0.12	13	0.08	13	19.6	12
Marsh#1	71.3	13	66.8	13	0.11	13	0.11	13	20	12
Aerobic pond	42.9	13	32.6	13	0.11	13	0.08	13	12.41	15
Marsh#2	32.8	9	26.5	9	0.1	9	0.21	9	9.07	9

Note: n = number of samples (little water accumulated in the sampling tubes in the filter strip).

Table 4.5: Average reduction in pollutant concentrations during the 1997 operating season.

		BOD_5		TKN		TP	
		Reduction within cell %	Overall reduction %	Reduction within cell %	Overall reduction %	Reduction within cell %	Overall reduction %
Facultative pond	S2	89.4	89.4	81.2	81.2	70.6	70.6
Marsh#1	S3	41.8	93.8	15.5	84.1	-2.2	70
Aerobic pond	S4	39.8	96.3	51.2	92.3	37.9	81.4
Marsh#2	S5	23.5	97.2	18.7	93.7	26.9	86.4

Figure 4.1. Average pollutant concentrations at the outlet of each cell during 1997 operating season



■ BOD5	1,152.5	122.6	71.3	42.9	32.8
■ TKN	421.3	79.1	66.8	32.6	26.5
□ TP	66.6	19.6	20.0	12.4	9.1

4.3.1 BOD$_5$

Over the 1997 monitoring season, during which 11 samples were collected, the average BOD$_5$ concentration in the lagoon was 1152.5 mg/l (Table 4.6). This concentration was lower than the one encountered in 1996 (2567 mg/l) and the one measured prior to the construction of the wetland (1700 mg/l). The concentration in the lagoon reached a climax in the middle of June (2610 mg/l) and decreased steadily until the middle of July when it reached values around 200-250 mg/l. This decrease in BOD$_5$ during the monitoring season was also noticed in 1996 and was attributed to increased microorganic activity caused by the warmer weather as well as the age of the manure.

Performance of the wetland in 1997 was similar to the one encountered in 1996. As shown in Table 4.5, the BOD$_5$ was considerably reduced at each stage of the system. The facultative pond takes out most of the load, but the wetland cells are necessary to polish the effluent. As in 1996, the facultative pond produced an effluent of greater quality (123 mg/l) than predicted: a conservative estimate of 400 mg BOD$_5$. There was no apparent seasonally related trend for the BOD$_5$ of the facultative pond.

Average effluent concentrations in the wetland-pond-wetland cells were found to be 71.3 mg/l, 42.9 mg /l and 32.8 mg/l respectively. The average BOD$_5$ at the outlet of the second wetland cell was 97.2% lower than the concentration in the lagoon. The average reduction in pollutant concentration is a little bit smaller than the 98.7% encountered in 1996. However, the concentration is similar to the 33.3 mg/l measured the previous year. The slight reduction in performance is probably due to the fact that the incoming BOD$_5$ had a lower concentration in 1997. Concentrations recorded for the effluent of the second wetland cell shows no general seasonally related trend.

Concentration at the outlet is unknown, as no samples were taken in the filter strip due to a flow that was too small (a lot of evaporation takes place on the filter strip). However, the filter strip most likely removed 90% of the pollutants that were present in the second marsh effluent, as measured in 1996.

Table 4.6: Concentrations of BOD5 at each monitoring location during the 1997 operating season

	S1 Lagoon	S2 Facultative Pond	S3 Marsh # 1	S4 Aerobic Pond	S5 Marsh # 2	S9 Feedlot Runoff	S11 GW Tube E
June 5	466	118	151	63	17.8		
June 11	2580	125	175	36	24.4		
June 19	2610	69.8	23.6	11.4	14	13.2	
June 26	2360	125	43.8	20.6	73.6		
July 3	2110	66.4	49.2	24.8	35.4	41.2	15.4
July 8	1420	103	49.6	29.2	14.8	20.2	
July 17	263	86.6	54.2	49.8	38.2		
July 24	234	210	49.2	24.8			
July 30	198	133	47.4	44.6			
August 6	236	223	74.4	71			
August 12	200	63.2	81.4	40			
August 20		48.8	60.2	70.8	28		
August 27		222	67.8	71.6	49		
Mean	1152.5	122.6	71.3	42.9	32.8	24.9	15.4

4.3.2 Nitrogen

Total nitrogen (TN) is made up of organic nitrogen, ammonia, nitrite and nitrate. Bacteria convert organic nitrogen into ammonia (ammonification/mineralization); ammonia into nitrite and nitrate (nitrification); and nitrate into nitrogen gas (denitrification). In 1996, nitrogen was found to exist mostly as organic nitrogen and ammonium (measured as Total Kjeldahl Nitrogen, TKN) in all cells of the system, other than the filter strip. During the 1997 monitoring season, nitrate and nitrite levels were always at least two orders of magnitude lower than corresponding TKN values, which confirms this observation (Tables 4.7, 4.8 and 4.9). As no samples were taken from the filter strip, TKN data can be used to approximate Total Nitrogen (TN) throughout the system.

In the manure lagoon, the average TKN was found to be 421.3 mg/L, higher than the 219 mg/L recorded prior to construction of the wetlands, but lower than the average 883.5 mg/l recorded during the 1996 monitoring season. TKN levels in the lagoon were more stable than BOD_5 concentrations (around 500 mg/l), with the exception of the first and last samples collected (150 and 276 mg/l). There was no dramatic decrease in TKN in the lagoon in August, as was observed for BOD_5. The analysis of the July 17 sample collected from the lagoon was considered to be erroneous and have been excluded from the calculation of average concentrations.

Average Total Kjedahl Nitrogen concentrations (Table 4.7) decreased progressively from cell to cell. Average TKN was reduced to 79.1 mg/l (1996: 101.8 mg/l) in the facultative pond then gradually to 26.5 mg/l (1996: 19.7 mg/l) by the outlet of the second wetland cell. The average TKN concentration in the effluent of this cell was 93.7% lower than the average concentration in the lagoon (Table 4.5). The reduction in concentration is lower than the 97.8% observed in 1996. Compared to 1996, most of the components were as efficient to reduce the concentration, except the second marsh which reduced TKN concentration by only 18.7% (1996: 49.2%). Further analysis of the results will show if this reduction of performance is due to internal (i.e. decomposition of previous year plants returning nitrogen back to water) or external factors (i.e. higher evaporation). True comparison of the performance between the years can only be achieved with a mass balance.

Nitrate and nitrite concentrations are reported in Table 4.6 and 4.7. Since nitrates and nitrites were expected to be generated by nitrification of ammonium, they were not predicted to gradually drop from cell to cell within the wetland system. The purpose of the alternating pond/wetland design was to promote the nitrification and subsequent denitrification of ammonia-nitrogen. The limiting step was most likely nitrification in the "aerobic" pond (which requires sufficient oxygen). The data collected in 1997 showed a small increase in nitrate as the wastewater passed through the facultative and the aerobic ponds and a small decrease after the two wetlands. However, these differences are too small to be really significant. Furthermore, the nitrate concentration (approx. 0.1 mg/l) is very low compared to the average TKN concentration (27-421 mg/l) in all the components of the system. This may suggest that denitrification occurs in conjunction with the nitrification cycle (ie. nitrate produced in aerobic zones is broken down into nitrogen gas in anaerobic zones) within all components of the system. Alternatively, nitrogen may have been lost to the atmosphere in other gaseous forms (although no particularly foul odours were observed), consumed by plants or adsorbed onto precipitating solids.

A look at the distribution of the different forms of nitrogen across the system might partially explain this behaviour (Fig. 4.2). At the entrance of the system, most of the nitrogen is ammonia, with significant levels of organic nitrogen as well. This is consistent with the fact that “ammonia is one of the principal forms of nitrogen found in many wastewaters" (Kadlec & Knight, 1996). Ammonia is majorly reduced in the facultative and the aerobic ponds. Ammonia is the preferred nitrogen source for most wetland plant species and autotrophic bacteria species. However, just a few plants are located in the pond and consumption of nitrogen by algae and bacteria should increase levels of organic nitrogen in the system. It is uncertain if this would result in increases in the organic nitrogen content of water, as bacteria and algae might settle and not reach the effluent. Thus, reduction in ammonia could be partially due to assimilation by microorganisms and plants. On the long term, this pathway is unlikely to have an effect because the assimilation-mineralization cycle of nitrogen will reach a steady state.

Other possibilities include the adsorption of ammonia onto precipitating solids, volatilization and nitrification-denitrification. Adsorption of ammonia onto precipitating solids could be a major sink in the facultative pond, as concentration of suspended solids is majorly reduced. However, it is not the case for the aerobic pond. Ionized ammonia (or ammonium ion: NH_4^+) is predominant in most wetland systems. However, when the pH (pH>7) and the temperature (ET>25EC) increase, ionized ammonia is progressively transformed into un-ionized ammonia (NH_3). As indicated by Kadlec & Knight (1996), "the volatility of un-ionized ammonia results in ammonia losses from lagoons and from wetlands under high pH and temperature conditions". The average pH in the ponds is of approximately 7.8. At such a pH and even at a temperature of 40EC, less than 10% of ammonia would be un-ionized. Thus, a part of ammonia is likely to have volatilized, but it should not be a major pathway.

The most likely pathway for ammonia reduction is through nitrification-denitrification. According to Kadlec & Knight (1996), the optimum pH range for ammonification, nitrification and denitrification are 6.5-8.5, 6.5-7.5 and above 7.2, respectively. The pH across the system ranges from 7.5-7.8. Thus, the conditions for the ammonification-nitrification-denitrification cycle are ideal. Further analysis of the data will be necessary to evaluate more precisely the pathway of nitrogen reduction in the constructed wetland. However, it seems that nitrification-denitrification occurs directly in each components and not sequentially as expected. This could be due to the detention times which are quite long in each component and to the fact that each component of the system has aerobic (i.e. surface of the ponds) and anaerobic (i.e. sediments in the ponds) zones.

Table 4.7: Concentrations of TKN at each monitoring location during the 1997 operating season

	S1 Lagoon	S2 Facultativ Pond	S3 Marsh #	S4 Aerobic Pond	S5 Marsh #	S9 Feedlot Runoff	S11 GW Tube E
June 5	150	87.8	89.5	36.7	17		
June 11	531	87.3	101	26	29.5		
June 19	537	90.9	29.9	42.9	16.5	12.1	
June 26	528	71.9	39.5	25.6	20.5		
July 3	534	56.3	44.4	29.9	29.4	17.4	5
July 8	514	61	66.4	24.3	21.2	13.4	
July 17	2690**	67.5	71.3	23.4	24.5		
July 24	535	91.5	65.7	25			
July 30	495	65.5	59.5	28			
August 6	534	136	61	24.4			
August 12	276	71	84	27.5			
August 20		57.9	88.8	58	34.5		
August 27		83.5	68	52.1	45.3		
Mean:	421.3	79.1	66.8	32.6	26.5	14.3	5

** Concentration of TKN in the lagoon on July 17 was ignored due to its inconsistency with the rest of the data.

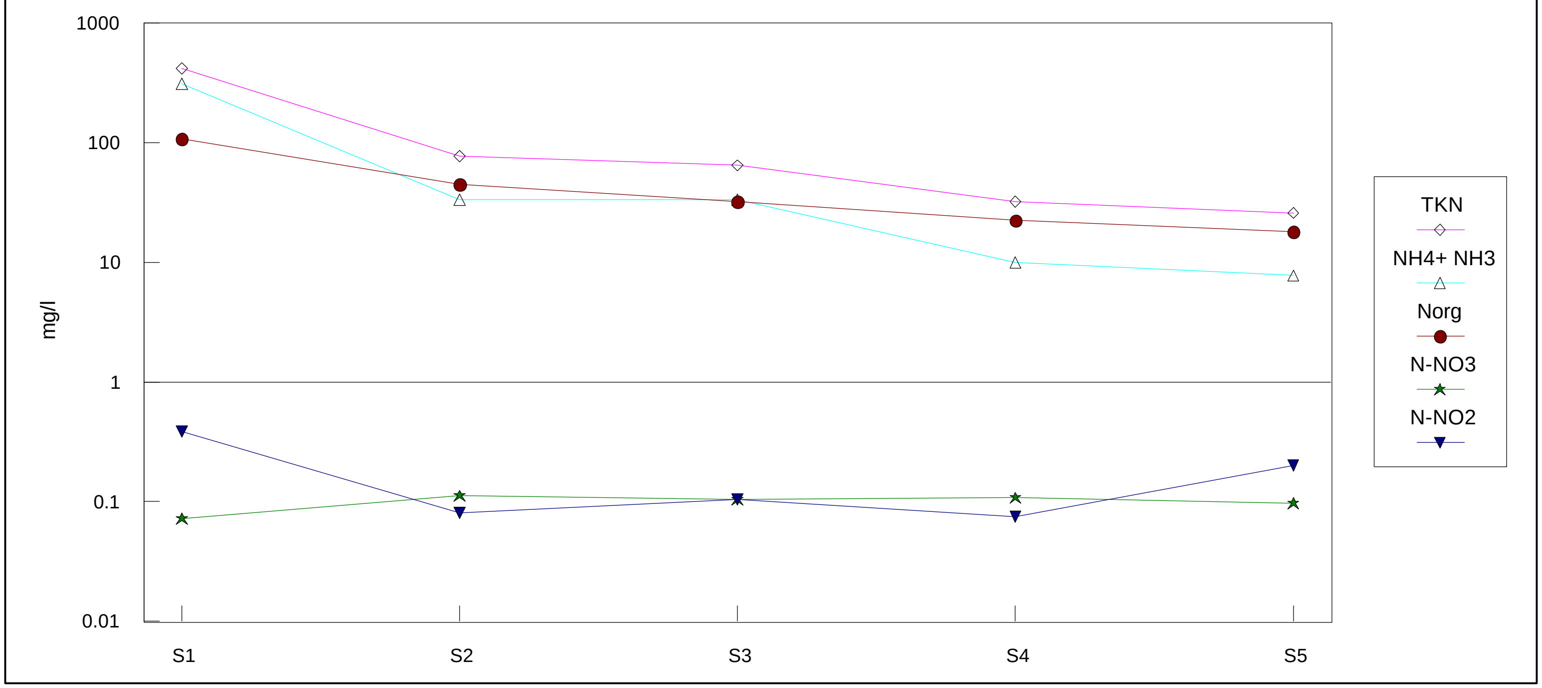
Table 4.8: Concentrations of N-NO$_3$ at each monitoring location during the 1997 operating season

	S1 Lagoon	S2 Facultative Pond	S3 Marsh # 1	S4 Aerobic Pond	S5 Marsh # 2	S9 Feedlot Runoff	S11 GW Tube E
June 5	0.105	0.09	0.045	0.015	0.025		
June 11	0.155	0.11	0.12	0.09	0.07		
June 19	0.05	0.09	0.125	0.105	0.115	0.145	
June 26	0.11	0.08	0.125	0.105	0.145		
July 3	0.19	0.15	0.165	0.16	0.15	0.15	1.48
July 8	0.145	0.21	0.18	0.18	0.195	0.185	
July 17	0	0.09	0.085	0.065	0		
July 24	0	0	0	0.01			
July 30	0.06	0.175	0.175	0.155			
August 6	0	0.085	0.035	0.19			
August	0	0.015	0	0.11			
August		0.29	0.215	0.14	0.01		
August		0.115	0.1	0.12	0.17		
Mean:	0.07	0.115	0.105	0.111	0.098	0.16	1.48

Table 4.9: Concentrations of N-NO_2 at each monitoring location during the 1997 operating season

	S1 Lagoon	S2 Facultative Pond	S3 Marsh # 1	S4 Aerobic Pond	S5 Marsh # 2	S9 Feedlot Runoff	S11 GW Tube E
June 5	0.1	0.06	0.055	0.035	0.025		
June 11	0.345	0.09	0.08	0.06	0.08		
June 19	0.35	0.11	0.275	0.045	0.035	0.06	
June 26	0.39	0.12	0.075	0.045	0.055		
July 3	0.41	0.1	0.085	0.04	0.05	0.15	0.27
July 8	0.405	0.09	0.17	0.12	0.055	0.07	
July 17	0.485	0.06	0.065	0.085	1.24		
July 24	0.47	0.07	0.065	0.04			
July 30	0.445	0.075	0.075	0.095			
August 6	0.48	0.065	0.065	0.06			
August	0.475	0.085	0.135	0.09			
August		0.06	0.085	0.21	0.09		
August		0.085	0.15	0.08	0.23		

Figure 4.2: Concentrations of forms of nitrogen in the wetland



4.3.3 Phosphorus

Phosphorus concentration reduction was lower in 1997 than in 1996 (Tables 4.5 & 4.10). This is principally due to the first marsh, which did not reduce the concentration of phosphorus. Other components were also less efficient to remove phosphorus. As a result, the concentration of phosphorus in the effluent of the second marsh was 86.4% lower than in the lagoon (1996: 95.3%). Even though the concentration in the lagoon was lower in 1997 (66.6mg/l vs. 90.4mg/l), the effluent of the second marsh had a higher concentration (9.07mg/l vs. 4.27mg/l). However, these numbers are based on concentrations and not on a mass balance. As the volume of water diminishes across the system, the actual performance would be higher. For example, based on the volumes of water computed for the 1996 monitoring season, the 2.2% increase in concentration after the first marsh would actually represent a reduction in the load of phosphorus. A mass balance is needed to confirm this hypothesis.

A decrease in phosphorus removal performance in a constructed wetland over the first years is normal. According to Kadlec & Knight (1996), the startup period for a wetland can extend over varying periods of time, ranging from 1 to 5 years for phosphorus removal. During this period, performance for phosphorus removal is supposed to decrease until it reaches a steady state. To explain this phenomena, a closer look at phosphorus reactions must be taken.

The sinks affecting phosphorus present in water are caused by chemical, biological or physical processes. Phosphorus can react and coprecipitate with aluminium, iron, calcium and magnesium compounds. According to recent studies, it seems that a gaseous form of phosphorus, phosphine (PH_3) has been identified as a potential compound of significance in wetland environments. Measured emissions from a constructed wetland in Hungary reached 1.7g/m^2/yr of phosphorus (Kadlec & Knight, 1996). Phosphorus is also incorporated in the tissues of all living organisms and is therefore present in all wetland biota and the corresponding detritus. Most of this phosphorus is returned to the system when the organic matter is mineralized. However, according to Kadlec & Knight (1996), small amounts are sustainably stored in accretions of biomass residuals and minerals. Finally, phosphorus can adsorb on particles that settle or directly be adsorbed to the wetland soil.

During the first years, two phenomenas increase the phosphorus removal efficiency: adsorption and plant assimilation. The soil has a limited number of sites onto which phosphorus can adsorb. After a few years and when steady state conditions are established, all these sites are full and the adsorption capacity of the soil is reached. Also, mineralization of the plant tissues is much slower than phosphorus assimilation by live plants and organisms. For this reason, during the first years, there is a delay between the amount that is consumed by the plant and the amount that is returned. After 4-5 years, such a cycle reaches a steady state as well. It would thus be normal that the performance of the wetland would diminish during the first years of operation. Finally, scientists have noticed that the phosphorus removal capacity of wetlands demonstrates a high variability from year to year and presents a stochastic/chaotic behaviour.

As a conclusion, it is necessary to continue monitoring to assess constructed wetlands performance to remove phosphorus on the long term and to perform mass balance analysis.

Table 4.10: Concentrations of TP at each monitoring location during the 1997 operating season

	S1 Lagoon	S2 Facultative Pond	S3 Marsh # 1	S4 Aerobic Pond	S5 Marsh # 2	S9 Feedlot Runoff	S11 GW Tube E
June 5	31.6	18.3	20.1	11.1	6.1		
June 11	114	19.3	26.6	8	8.2		
June 19	105	21.6	13.3	19.1	6.4	9	
June 26	98.8	21.9	16.9	10.4	6.1		
July 3	90	18.2	14.7	10.8	8.64	7.1	0.8
July 8	75	17.6		10.7	7.96	10	
July 17	**548	18.2	22.4	9.44	10.5		
July 24	55.5	20.6	19.7	10.2			
July 30	52.1	17.6	21.5	13.7			
August 6	61.5	25.9	20	10.3			
August 12	48.8	18.6	24.2	12.7			
August 20		16.8	22.2	19	13		
August 27		19.7	18.4	15.9	14.7		
Mean:	66.6	19.6	20	12.41	9.07	8.7	0.84

** Concentration of TP in the lagoon on July 17 was ignored due to its inconstitency with the rest of the data.

4.3.4 Dilution and Concentrating Effects

Simply measuring influent and effluent concentrations to evaluate the efficiency of the treatment system does not account for changes in volume due to precipitation or evaporation. The average flow discharged from the wetland was far lower than the controlled flow rate entering the system. For the majority of the operating season, there is no outflow at all. Water losses were attributed to evaporation rather than infiltration for the following reasons: the wetland system was constructed over very heavy clay which was compacted during construction; no water ponded in low areas surrounding the wetland system; and ground water samples collected adjacent to the wetlands did not show elevated pollutant concentrations. Evaporation would have had a concentrating effect on pollutant concentrations in the wetlands. Therefore, the actual total mass removal of pollutants was almost certainly higher than the reduction in concentrations shown in Table 4.5. This phenomena could also explain the lower percentage reduction of the pollutant concentrations in 1997 compared to 1996. Effectively, 1997 was a warmer and dryer year than 1996, thus resulting in higher evaporation and concentrations in the wetland cells this year.

In table 4.5, the manure runoff lagoon was used as a basis for evaluating the treatment effectiveness of the wetland system. This approach did not account for the potential dilution effect of the runoff from the cattle feedlot, which drained into the facultative pond and had far lower pollutant concentrations than lagoon effluent. Runoff from the feedlot only occurred following storm events and its contribution to the total volume accumulating in the facultative pond was estimated to be approximately 30% for the 1996 monitoring season. Based on the mass balance computed for the second year of operation, this would have meant that approximately 1% of the BOD_5, 8% of the TKN and 18% of TP came from the feedlot runoff. To allow for comparison with the 1996 year end report and as the mass balance for 1997 has not been completed yet, it was decided to continue using this table.

5. COST ANALYSIS

On-farm constructed wetlands are currently being developed as environmentally-sound solutions to decontaminate runoff water emanating from manure storage and feedlot yards. Although the efficiency of the water treatment technology is important, it is also important to evaluate the cost of implementing the technology. This chapter presents an analysis of the costs and benefits associated with the choice of the wetland technology compared to using the alternative of spreading the runoff onto cropland. This study is based the Dignard wetland. More information can be found in the report entitled “Cost-benefit analysis for a constructed wetland in Eastern Ontario, Canada” (Blais & Weil, 1998).

Table 5.1: Cost-analysis of wetland versus runoff land application.

<table>
<tr><td colspan="2">PARTIAL BUDGET
Add an artificial wetland instead of custom spreading (on an annual basis)</td></tr>
<tr><td>Additional costs: Wetland
a. Depreciated construction costs: $2015
b. Interests on investment: $1961
c. Operation and maintenance costs: $737
Total: $4713</td><td>Additional returns:</td></tr>
<tr><td>Reduced returns:
e. Land area unusable for crops: $507</td><td>Reduced costs: No more custom spreading
a. Spreading by tankers $6817
b. Construction of lagoons $330
c. Interests on investment: $359
Total: $7506</td></tr>
<tr><td>(A) Total annual additional costs and reduced returns:
$4713 + $507 = $5220</td><td>(B) Total annual additional returns and reduced costs:
$7506</td></tr>
<tr><td colspan="2">Net change in income (B minus A): $2286</td></tr>
<tr><td colspan="2">Notes: There is an improvement in income from the adoption of the wetland technology that is to replace the custom spreading of large volumes of runoff waters.</td></tr>
</table>

All the costs of financing, operating and maintaining the wetland including depreciation have been taken into account to estimate the annual cost, which is adjusted to 1997 Canadian dollars. The total annual cost of this structure is estimated at $5,220, while the alternative of spreading the same runoff volume on land would cost $2,286 more per year. Annual depreciation on the investment represents $2,015, the interest service is $1,961, the operation and maintenance $737 and the loss of crop land is evaluated at $507. A realistic economic lifespan of 30 years has been attributed to the wetland based on comparable structures. Other components have been attributed appropriate economic lifespans. In terms of payback period, the initial investment of $54,090 for the wetland would be paid in slightly more than 7 years. It appears that the wetland technology may be one of the best low-cost solutions in Ontario to treat contaminated farm runoff water before it is allowed to re-enter the natural system.

The costs of the wetland can be expressed as a function of chosen parameters such as the size of the wetland, the size of the herd, or the volume of runoff water to be annually treated.

On a per-hectare basis: Total wetland investment ÷ area of wetland (ha)
= $54,090 ÷ 1.125 ha = $48,100 per hectare ($Cdn - 1997)

On a per-acre basis: Total wetland investment ÷ area of wetland (ac)
= $54,090 ÷ 2.78 ac = $19,500 per acre ($Cdn - 1997)

The existence of the wetland also bring benefits that are difficult to establish in financial terms, but are nonetheless important human aspects. Indeed, the owners enjoy an aquatic setting amidst their farmstead that draws many species of wildflowers and animals, including waterfowls. It also is being used as a relaxation place, where one can forget for a privileged moment the stressful necessities of managing a modern farm operation. One also does not have to coordinate the custom work operations into his crop management.

In conclusion, the choice of the wetland technology has been the best economical choice, because it allows the farmer to save a substantial amount of money over the alternative of spreading. And this is evident without considering other factors such as the quality of life brought by the aesthetic value of the wetland and the reduced stress of having to negotiate with manure haulers for timing of their operations and pricing.

6. CONCLUSIONS

1) The strong performance of the Dignard wetland during the 1996 monitoring season was confirmed by computation of the mass balance of pollutants in the system. Average reductions in concentrations at the outlet of the second wetland cell (compared to levels in the lagoon) were: 98.7% (33.3 mg/l), 97.8% (19.7 mg/l) and 95.3% (4.27 mg/l) for BOD_5, TKN and TP, respectively. Mass reduction of these pollutants at the same stage of treatment was higher than 98.8%. Based on a limited number of samples, it seems that the filter strip reduced concentrations to the following levels: BOD_5=3.10 mg/l, TKN=2.83 mg/l and TP=0.07 mg/l.

2) Based on the concentrations, overall performance of the system in 1997 was similar to 1996 for BOD_5, but somewhat inferior for TKN and TP. Average reductions in concentrations at the outlet of the second wetland cell (compared to levels in the lagoon) were: 97.2% (32.8 mg/l), 93.7% (26.5 mg/l) and 86.4% (9.07 mg/l) for BOD_5, TKN and TP, respectively. It should be mentioned that true comparison of the performance can only be achieved with a mass balance. A mass balance would indicate a higher performance, as water flow diminishes along the system. Due to evaporation, the water flow on the filter strip was so small that it could not even be sampled. Considering this small flow and the level of concentration reduction, the overall performance of the constructed wetland was excellent.

3) A cost analysis demonstrated that constructed wetlands to treat solid manure and feedlot runoff is a viable alternative to land spreading. In the case of the Dignard wetland, the initial investment would be paid back in slightly more than 7 years. The cost per hectare is approximately $48,000. The existence of the wetland also brings benefits that are difficult to quantify in financial terms, but are important human and environmental aspects.

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