A FARM-SCALE INTEGRATED CONSTRUCTED WETLAND TO TREAT FARMYARD DIRTY WATER

END OF PROJECT REPORT

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AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

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TABLE OF CONTENTS

INTRODUCTION

Nutrient loss from agricultural practices both in Ireland and the U.K. has caused point source pollution, which has resulted directly or indirectly to the eutrophication of surface waters (Tunney et al., 1997; Withers et al., 2000). Eutrophication is the major threat to water quality in Ireland and water quality continues to decline (Clenaghan et al., 2001). Point source pollution from agricultural practices can include inappropriately managed agricultural dirty waters such as dairy farmyard dirty water. In Ireland and the U.K., dairy farmyard dirty water is commonly composed of farmyard runoff, parlour washings, silage and farmyard manure effluents along with general farmyard washings (Brewer et al., 1999; Cumby et al., 1999; DAFRD, 2000). Land-spreading is the most widely used practice for managing dairy farmyard dirty water in Ireland; however in some cases this method of management may cause the degradation of surface and ground waters (Healy et al., 2003).

Constructed wetlands, which may be one method of managing such waters, are ecologically engineered systems that are akin to natural wetland systems that are built using quantitative approaches, founded on basic ecological principles (Mitsch and Jørgensen, 1989). Agricultural wastewater management using wetland systems has received interest in countries such as the USA, Norway, Finland, Italy, New Zealand and U.K (Cronk, 1996; Sun et al., 1998; Kern and Idler, 1999; Knight et al., 2000; Newman et al., 2000; Nguyen, 2000, Schaafsma et al., 2000; Koskiaho et al., 2003; Mantovi, et al., 2003; Poach et al., 2003). They are often used as alternatives to, or components of, conventional nutrient management practices to reduce or eliminate contaminant and nutrient loads in agricultural wastewaters (Cronk, 1996; Peterson, 1998; Geary and Moore, 1999; Knight et al., 2000; Borin et al., 2001; Hunt and Poach, 2001; Szögi and Hunt, 2001; Braskerud, 2002). Wetlands used to improve water quality within agriculture typically intercept and retain contaminants and nutrients from incoming waters through a series of vegetated ponds, before waters leave or are reused in farm-scale operations (Knight et al., 2000). Processes involved in contaminant and nutrient retention in wetlands include: sedimentation of particulates (Johnston et al., 1984; Braskerud, 2001; Koskiaho, 2003); nitrification/denitrification (Hammer and Knight, 1994; Phipps and Crumpton, 1994; Poach et al., 2003; Tanner et al., 1999); phosphorus

(P) sorption/desorption, precipitation and burial of P with accreting peat (Walbridge and Struthers, 1993; Richardson et al., 1997; Pant and Reddy, 2003; Reddy et al., 1999; Bridgham et al., 2001) and microbial and vegetation nutrient uptake and release (Smith et al., 1988; Shutes, 2001; Findlay et al., 2003). Most of the processes are regulated by wetland hydrology, which is the single most important factor in wetland function and structure (Kadlec and Knight, 1996, Mitsch and Gosselink, 1993; Werner and Kadlec, 2000).

Percent mass pollutant removal by surface flow constructed wetland treatment of agricultural dirty waters can vary between 48% and 95% of total suspended solids (TSS) (Sievers, 1997; Newman et al., 2000; Reddy et al., 2001); 50% and 99% of nitrogen (N), depending on form; and 30% to 94% of phosphorus inputs, depending on incoming form (Cathcart et al., 1994; Hunt et al., 1994; Humenik et al., 1997; Newman et al., 2000; Reddy et al., 2001). Constructed wetland performance data vary with site, wastewater characteristics, wetland design, application, and water treatment goal; therefore a "systems approach" is often required for successful management of agricultural waters (Payne Engineering and CH2M Hill, 1997; USDA NRCS, 2002). A systems approach recognises site-specific conditions, typically adopting an integrated, multidisciplinary approach to water pollution (Mitsch and Jørgensen, 1989).

In Ireland, the use of constructed wetlands to manage agricultural waters such as farm yard dirty water has been primarily based on an ecosystems approach. Integrated constructed wetlands, which are a design specific approach of conventional surface flow constructed wetlands, were first used in the Anne Valley, Waterford, Ireland (Harrington and Ryder, 2002). At present, 13 farms in the Anne Valley catchment use integrated constructed wetlands to manage farmyard dirty water (Harrington et al., 2004). Fundamental to their design is water quality improvement, landscape fit (designing the wetland into the topography of the landscape) and that the wetland provides an ecological habitat within the agricultural landscape. Typically, integrated constructed wetlands have greater land area requirements than conventional surface flow constructed wetlands in order to provide for these other fundamental ecological services.

Few studies (Ryan, 1990) have addressed the issue of quality and quantity of farmyard dirty generated at farm-scales in Ireland. No studies were readily available documenting the effectiveness of a farm-scale constructed or integrated constructed wetland in Ireland to remove nutrients such as phosphorus (P) from dairy farmyard dirty water on a mass basis. To address such, the main objectives of this research were to (i) determine the quality and quantity of farmyard dirty water generated at a farm-scale (ii) determine the effectiveness of three treatment cells of an integrated constructed wetland to treat farmyard dirty, using the difference between input and output mass loadings, (iii) investigate if there were seasonal effects in the wetland's performance to retain phosphorus, and (iv) assess the impact of the integrated constructed wetland on the receiving environment by monitoring soil-water parameter concentrations up gradient, down gradient and within the wetland system using piezometers at different soil depths.

MATERIAL AND METHODS

Site Description

The integrated constructed wetland was situated at a semi-state research centre (Teagasc Research Centre, Johnstown Castle, Wexford) located in the southeast of Ireland (Irish national grid reference E: 3011524.33 m; N: 116290.22 m). Ireland has a cool temperate west maritime climate. In the southeast, annual rainfall is about 1,000 mm and mean temperature is 10°C (Gardiner and Radford, 1980). The wetland was built in the summer of 2000, on soils that were a complex of imperfectly drained gleys and well to moderate draining brown earths. The wetland system was not lined with compacted clay; rather in situ soils were used. In situ soils had a relatively high silt and medium clay content (33% ± 0.2% and 12% ± 0.9%, respectively).

Farmyard dirty water, which was comprised of rainfall on open farmyard areas (2,031 m^2), farmyard manure and silage effluents, along with dairy and yard washings from a 42-cow organic dairy unit, was collected in a central storage facility. This storage facility was a three-chambered tank where farmyard dirty water underwent some primary treatment (sedimentation). The tank effluent was then discharged to the wetland by a pump-operated system, but there was also a facility to direct tank effluent to a sprinkler system for spreading waters onto grassland areas. The integrated constructed wetland comprised of three surface flow treatment wetland cells with a total area of 4,265 m^2 and one final monitoring pond (490 m^2) (Figure 1). Up gradient and surrounding the wetland system was unfertilised organic grassland pastures. There was also a 30 cm deep surface drain around the up gradient side of the wetland site. Within the first wetland cell there was a deep-water sump (250 m^2 x 2 m deep) to aid sedimentation. Generally, wetland cells were flooded to a water depth of about 30 - 40 cm. Water levels in the final monitoring pond were maintained at about one to two meters. The purpose of the final monitoring pond was to aid further reduction of BOD_5, sedimentation of particulates, but also to aid ease of monitoring by providing a potentially suitable environment for biological indicators of water quality such as freshwater fish. Wetland-treated waters were point discharged (whenever there was outflow) to adjacent riparian woodland, which drained down to a nearby stream.

Piezometers were installed at various soil depths (one to three meters) up gradient, within and down gradient of the wetland site (Figure 1, b) to monitor nutrient concentrations in soil-water.

Several macrophytic species, which were generally sourced locally, were planted at about one square meter spacing in the wetland. Predominant plant species included *Carex riparia* Curtis., *Typha latifolia* L., *Phragmites australis* (Cav.) Trin. ex Steudel, *Sparganium erectum* L., *Glyceria fluitans* (L.) R. Br., *Iris pseudacorus* L., *Phalaris arundinacea* L. and *Alisma plantago-aquatica* L. During the monitoring period of the study, percentage vegetation cover in the three treatment wetland cells was qualitatively assessed to range from 80 to 90% during the growing season; whereas during late autumn and winter periods (October to January) percentage cover was somewhat less about 50%. Monitoring of the integrated constructed wetland was conducted for two and a half years (April 2001 until September 2003).

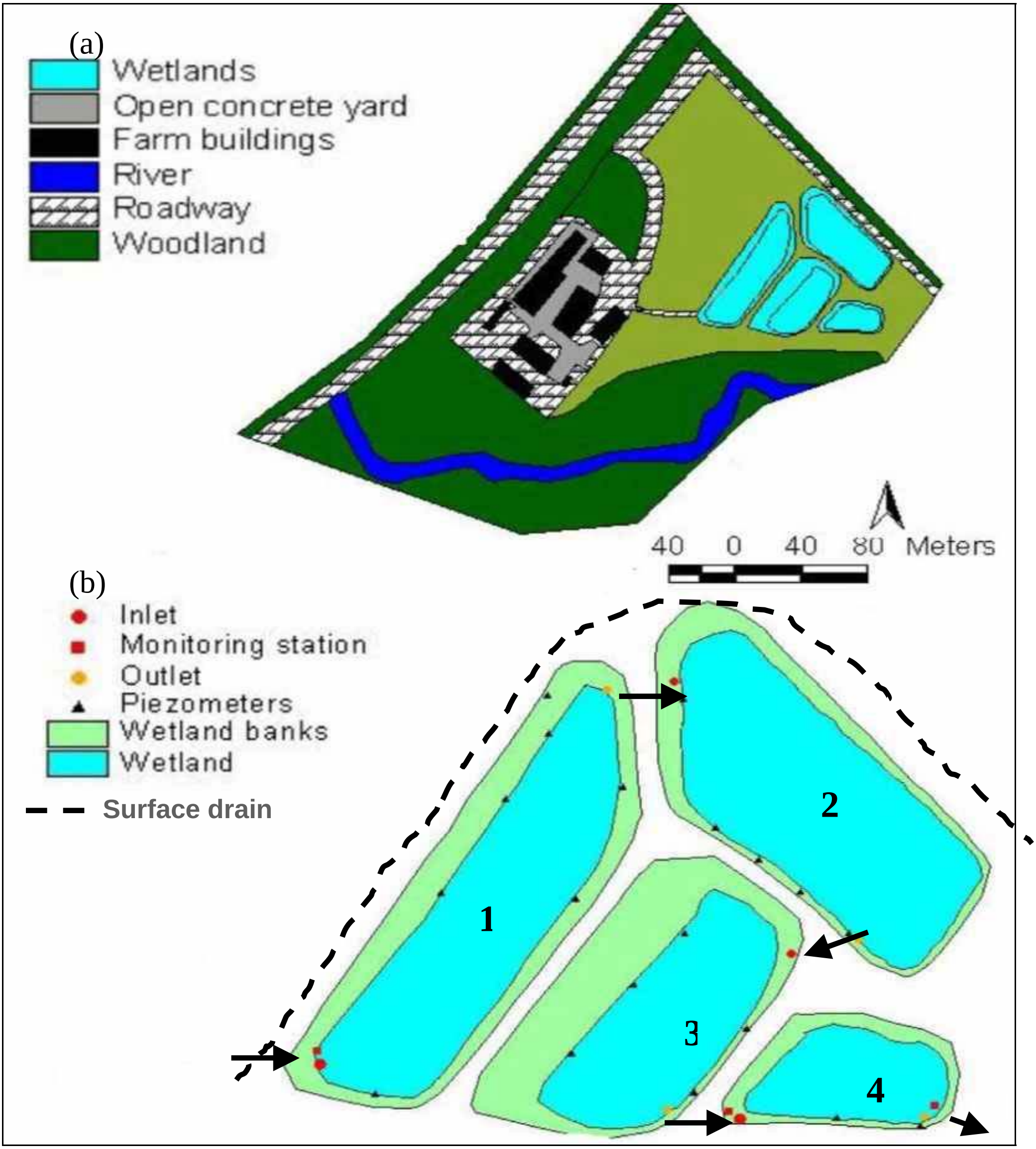

Figure 1: Sketch of (a) farmyard and (b) integrated constructed wetland layout with installed monitoring stations.

Weather Data

Daily rainfall and class A pan evaporation data were recorded at the weather station located at Johnstown Castle Research Centre. Rainfall was measured using a standard rain gauge and evaporation data was measured using a standard evaporation device called a "Class A pan." Both parameters were manually recorded and the weather station was about 750 meters from the actual wetland site. Class A pan evaporation data (mm d^{-1}) was used to determine evapotranspiration (ET) from the wetland system. Kadlec and Knight (1996) suggest that wetland ET is about 70 to 80% of class A pan data as the presence of vegetation retards evaporation. For this particular study, 80% of class A pan data was used to estimate wetland ET.

Water Sampling

Prior to wetland operation, piezometer water samples were taken fortnightly for three months to establish baseline water quality data on soil-water parameter concentrations. Pre and during wetland monitoring, water quality monitoring stations were installed at the wetland inlet (inlet one) and wetland outlet (outlet of treatment wetland cell three) pipes in April 2001 and December 2001, respectively. Stations were equipped with portable water samplers (Plate 1) (American Sigma, Inc., Loveland Colorado; Model 900 MAX). Pipe flows were measured on a continuous basis using submerged velocity probes that were interfaced with the portable sampler, thus for each sampling period a flow proportional sample was taken. Depending on flow events the portable samplers were programmed to take samples every 1 m^3 or 5 m^3 at the wetland inlet and every 10 m^3 or 20 m^3 at the wetland outlet. At the end of each sampling period, flow proportional samples were composited and a one-litre sub-sample was taken for laboratory analyses. During February 2003 no inflows were measured to the wetland, as the inlet water sampler was removed for maintenance.

Fortnightly, one litre grab samples were taken from wetland inlets two (I2), three (I3), and outlet of final monitoring pond (O4). Also, piezometer water samples were taken about every two months. All water samples (automatic sampler, grab and piezometer) were immediately brought back to laboratory and stored at 4°C until analyses.

Plate 1. Portable water sampler with interfaced velocity probe and intake sampling tube at wetland inlet one monitoring station.

Water Analyses

Water samples were collected, stored at 4°C and analysed for BOD_5 according to APHA method 5210-B (APHA, 1992). The BOD_5 analysis measures oxygen required for biochemical degradation of organic material and the oxygen used to oxidise inorganic material over a five-day incubation period. Total suspended solids were determined by filtering water samples through glass fibre filter paper (Whatman GF/A). The residue retained on the filter was dried to a constant weight at 104°C. Increase in weight of filter paper represented the TSS content of the sample (Method 2540-D; APHA, 1992). To determine soluble reactive P (SRP), samples were filtered to 0.45 µm using membrane disc filters. Filtrate was analysed for SRP using an automated ascorbic acid method (Method 424-G; APHA, 1992). Water samples were also analysed colorimetrically for ammonium (NH_4^+-N) and nitrate (NO_3^--N). Ammonium was measured following Berthelot reduction using the salicylate method (Houba et al., 1987). Nitrate was determined as the difference between nitrite (NO_2^--N) and total oxidisable nitrogen (TON) using the hydrazine reduction method (Method 4500-NO_3^- H; APHA, 1992). All ion concentrations were measured using an automated discrete auto analyser (Konelab Corporation, Espoo, Finland; Model Konelab 30). Many constructed wetland systems that are used to treat agricultural wastewaters have documented total phosphorus and total nitrogen content of wastewaters. This study focused on the more biologically available fractions such as SRP; however large amounts of P may exist in particulate form, as farmyard dirty water has typically high concentrations of BOD_5 and total suspended solids.

Parameter Determination

A site-specific water balance equation was used for this study [Equation 1].

$$\frac{dv}{dt} = Q_{in} + P_w + P_b - ET_w - Q_{out} \qquad [1]$$

where Q_{in} is farmyard dirty water inflow, P_w is the precipitation on the wetland surface area (wetland cells one to three), P_b is inflow from precipitation on the surrounding wetland bank area, ET is the evapotranspiration from the wetland surface area (wetland cells one to three), and Q_{out} is the wetland surface outflow. All units are in cubic meters.

The wetland banks were grass covered, steep sloped and were isolated from surrounding surface hydrologic inflows, as there was a surface drain (30 cm deep) surrounding the up gradient side of the wetland. Soluble reactive P concentrations were not measured in surrounding wetland bank inflows to the wetland; therefore to allocate mass loads to this contributing area, literature values were used instead. Tunney et al. (1997a) found that in a site about one kilometer away from the wetland study site, SRP concentrations in surface runoff from a small, low intensity grassland catchment during a six month period ranged between 0.005 and 0.054 mg l^{-1} SRP. The maximum value (0.054 mg l^{-1}) was used in this study, in conjunction with inflow volumes from the grass covered wetland banks, to estimate the SRP mass load associated with bank inflows to the wetland.

Input and output mass rates (g d^{-1}) were determined for each sampling period. Mass removal or release rate by the wetland was determined as the mass loading rate difference between input and output mass rates [Equation 2].

$$R = M_i - M_o \qquad [2]$$

where R is the mass removal or release rate (g d^{-1}), M_i is mass input rate (g d^{-1}) of all wetland inputs (farm yard dirty water, wetland bank inflow and rainfall), and M_o is mass output rate (g d^{-1}) of the wetland surface outflows. A wetland area based specific mass retention (kg ha yr^{-1}) was also determined. Mean monthly farmyard dirty water wetland inlet one and wetland surface outflow, flow-weighted water quality parameter concentrations were determined using Equation [3].

$$FWC = \sum_{i=1}^{n} M / \sum_{i=1}^{n} Q \qquad [3]$$

where FWC is the mean flow weighted water quality parameter concentration per month (mg l^{-1}), M is the sum of contaminant or nutrient mass per month (g), Q is the sum of flow volume per month (l) and n = total number of sampling time periods per month (i = 1, 2, 3, …n).

Data Analyses

Data distributions were tested for normality. If data was not normally distributed it was log transformed. Statistical analyses were conducted on transformed data, while data presentation uses means of actual measured values. Statistically significant differences were determined at the $P < 0.05$, unless otherwise stated. Comparisons of means were by paired student t-tests and analysis of variance (ANOVA). Within ANOVA, all pairs were compared using Tukey-

Kramer's honest significant difference (HSD). Multivariate linear correlations were determined using the Pearson product-moment correlation. Regression analysis used the standard least squares fit. All statistical analyses were performed using the JMP software programme (SAS Institute Inc., Cary, North Carolina).

RESULTS AND DISCUSSION

Flows

During the monitoring period (April, 2001 until September, 2003) highest monthly rainfall was recorded in July 2001 (5.1 ± 2.9 mm d^{-1}) (mean ± standard error); October 2002 (8.8 ± 2.3 mm d^{-1}); and November 2002 (7.9 ± 1.4 mm d^{-1}). There was no significant seasonal variation in daily rainfall. However, there was large variability in maximum daily rainfall between seasons (Table 1).

Figure 2 shows that farmyard dirty water inflow rate to the wetland varied from month to month. There was a significant positive relationship between measured farmyard dirty water inflow rate to the wetland and rainfall during the monitoring period ($r = 0.55$; $P < 0.01$; $n = 27$). This suggests that rainfall on impervious surfaces such as open yard areas maybe an important component in the generation of farmyard dirty water that is collected, stored and subsequently discharged to the wetland system. However, the low r value implies that there are other interacting factors that need consideration, as there was no simple cause an effect relationship. Cumby et al. (1999) also indicated that volumes of dirty water produced cannot be determined by anyone parameter. For example, they found no simple relationship between dirty water produced and cow numbers in a survey of 20 dairy farms in the U.K. Amount of farmyard dirty water generated in dairy farms can vary with climatic factors such as rainfall (Cronk, 1996; Brewer et al., 1999; Cumby et al., 1999), farm management practices such as volumes of water used to wash down parlour units and milking machines (Ryan, 1990; Cronk, 1996), timing and method of storing farm yard manure and silage in farm yard areas (NRCS, 1991; Cronk, 1996; Brewer et al., 1999; Cumby et al., 1999; DAFRD, 2000).

Table 1: Within season mean daily rainfall and mean class A pan evaporation ± one standard error along with within season maximum daily rainfall for the monitoring period (April 2001 - September 2003).

Season	Month	Mean daily rainfall		Class A pan evaporation		Maximum daily rainfall
		mm d^{-1}				mm
Spring	1st Feb. - 31st Apr.	3.14	± 0.33	2.25	± 0.34	28
Summer	1st May - 31st Jul.	2.88	± 0.43	1.74	± 0.22	85
Autumn	1st Aug. - 31st Oct.	2.97	± 0.44	3.47	± 0.26	52
Winter	1st Nov. - 31st Jan.	3.53	± 0.36	0.71	± 0.19	27

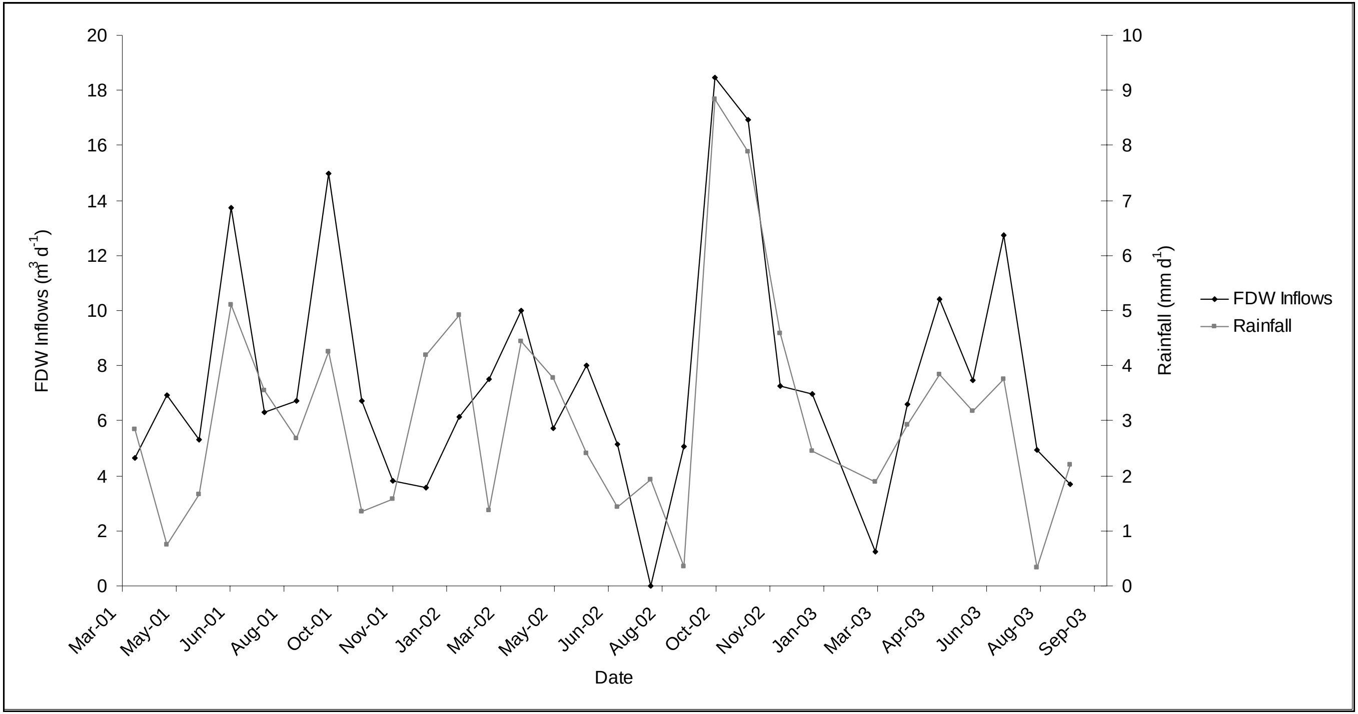

Figure 2: Farmyard dirty water wetland inflow rate measured at wetland inlet one and rainfall per month during monitoring period (April 2001 - September 2003).

When there was inflow to the integrated constructed wetland, monthly farmyard dirty water inflow rate varied from 3.6 - 18.5 $m^3 d^{-1}$. This was similar to Geary and Moore (1999) who observed dairy wastewater inflow rates of 4.5 - 10.6 $m^3 d^{-1}$ to a surface flow constructed wetland that treated dairy wastewaters from a 110-cow dairy herd in Australia. The Livestock Wastewater Treatment Wetland Database, USA reports that inflow rates of agricultural wastewaters to treatment wetlands are typically less than 10 $m^3 d^{-1}$ (Knight et al., 2000) suggesting that most wetland applications to retain contaminants and nutrients from livestock wastewater are relatively small-scale. Farmyard dirty water inflow to the wetland at inlet one was greatest during autumn and smallest in spring, while wetland outflow was greatest in winter and lowest in spring (Table 2). During autumn and winter periods, there was a large range in farmyard dirty water inflow rates, while there was a large range in surface outflow rates during winter periods. This is probably due to high rainfall in October and November 2002, which in turn resulted in high farmyard dirty water inflow rates to the wetland and subsequently high wetland outflow rates in November and December 2002. During November and December 2002, there was a significant relationship between rainfall and wetland surface outflow rates ($R^2 = 0.70$; $P < 0.01$; $n = 8$). Newman et al. (2000) suggested that at their particular study site (a surface flow constructed wetland used to treat milkhouse wastewater in Connecticut, USA) seasonal variation was controlled by evapotranspiration, rather than hydrologic inputs such as rainfall.

Table 2. Seasonal farmyard dirty water hydraulic load rate inflow rates measured at wetland inlet one and wetland surface outflow rates measured at the wetland outlet during the monitoring period (April 2001 - September 2003).

		Inflow				Outflow			
Season†	***n***	**Mean**	**Standard error**	**Min.**	**Max.**	**Mean**	**Standard error**	**Min.**	**Max.**
		$m^3\ d^{-1}$							
Spring	5	5.92	1.23	1.23	13.94	13.94	4.02	7.11	32.3
Summer	9	8.39	1.07	5.15	20.99	20.99	6.79	3.33	39.7
Autumn	8	8.62	2.16	3.87	37.46	37.46	13.43	14.41	60.9
Winter	6	7.54	1.99	3.56	51.85	51.85	21.37	15.10	133.0

† Spring is 1st of February until 31st of April, Summer is 1st of May until 31st of July, Autumn is 1st of August until 31st of October, and Winter is 1st of November until 31st of January.

During the monitoring period, there was no significant seasonal difference in farmyard dirty water wetland inflow and wetland surface outflow rates. Thus, the average farmyard dirty water inflow and wetland surface outflow rates were 7.5 ± 0.8 and 30.9 ± 7.6 m^3 d^{-1}, respectively, for the time period December 2001 to September 2003. The discrepancy between flows suggests that there were other hydrologic inputs to the wetland other than farmyard dirty water. Regression analysis between the total cumulative wetland inputs and total cumulative wetland outputs at this site suggest that most inflows and outflows to and from the system were accounted for (Figure 3) using the site specific water balance equation [Equation 1]; therefore groundwater inflows and outflows to and from the wetland were not an important consideration at this particular constructed wetland site. The wetland bank areas surrounding the wetland were about 52% of the total wetland surface area. In terms of hydraulic loading during the monitoring period, precipitation onto wetland surface areas accounted for 45% of the hydrological inputs, while precipitation on wetland bank areas and inputs of farm yard dirty water accounted for 28 and 27%, respectively. The net effect of these contributing waters is a reduction in hydraulic residence time (HRT) of wastewaters within a treatment wetland system, which ultimately results in degraded wetland outflow water quality (Kadlec and Knight, 1996).

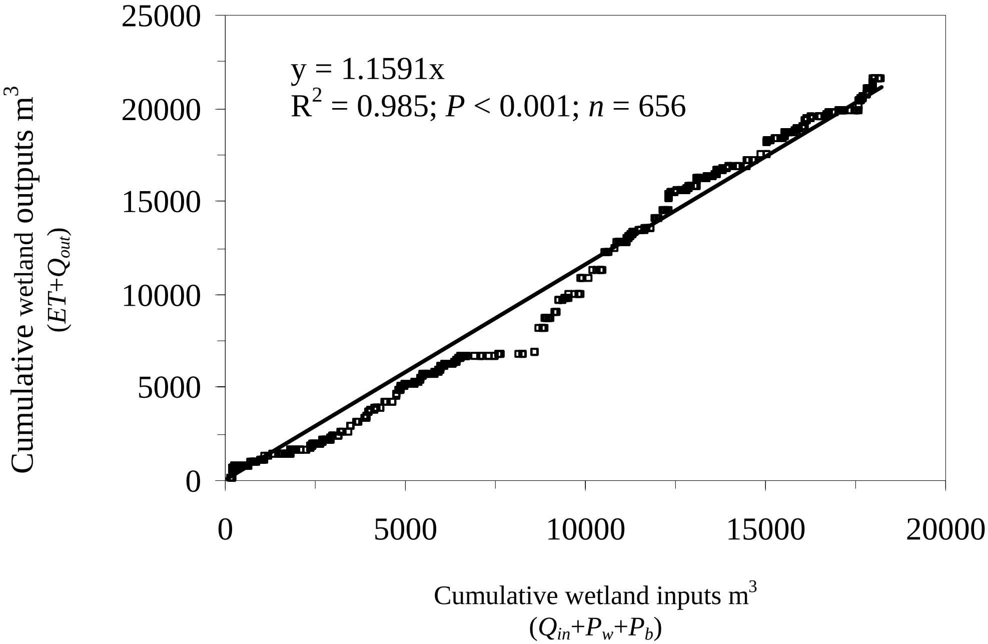

Figure 3: Relationship between cumulative wetlands inputs (farmyard dirty water in (Q_{in}), precipitation on wetland surface area (P_w), and inflow from precipitation on surrounding wetland banks (P_b)) and cumulative wetland outputs (evapotranspiration from the wetland surface area (ET), and wetland surface outflows (Q_{out})).

Water Quality Parameter Concentrations

Five-day biological oxygen demand and TSS concentrations of farmyard dirty water at wetland inlet one were highest during winter, while SRP and NH_4^+ concentrations were highest in spring and autumn, respectively (Table 3). However, one would expect low parameter concentrations in winter due to dilution effects of rainfall and higher concentrations in summer due to lack of it. Although water quality parameter concentrations of farmyard dirty water varied, there was no significant seasonal difference, which is contrary to Brewer et al. (1999) in their study of 20 days farms in the U.K. where they found that contaminant and nutrient concentrations were likely to vary between seasons. Average concentrations of water quality parameters that were discharged to the integrated constructed wetland during the monitoring period were 2806 ± 120 mg l^{-1} BOD_5, 905 ± 43 mg l^{-1} TSS, 44.98 ± 2.29 mg l^{-1} NH_4^+, and 18.86 ± 0.87 mg l^{-1} SRP. These concentrations were within ranges reported by other studies (442 to 6,600 mg l^{-1} BOD_5, 111-1645 mg l^{-1} TSS, 8-500 mg l^{-1} NH_4^+, 25-100 mg l^{-1} TP, and up to 415 mg l^{-1} SRP) where concentrations varied depending on management practices, site characteristics, and climate (Hammer, 1989; Cronk, 1996; Cumby et al., 1999; Knight et al., 2000; Newman et al., 2000; Schaafsma et al., 2000).

Water quality parameter concentrations decreased between wetland inlet and outlet of final monitoring pond during the monitoring period (Figures 4 and 5). Concentrations of SRP and NH_4^+ were significantly reduced between wetland inlet one and two ($P < 0.05$); however there was no significant difference in parameter concentration reduction between inlet three and inlet to monitoring pond, which was probably the result of a short HRT in the third treatment wetland cell (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996). Significant reductions of BOD_5 and TSS were observed between all of the wetland inlets ($P < 0.05$). Five-day biological oxygen demand and TSS concentrations of wastewaters typically decrease steeply once wastewaters are discharged to wetlands (Kadlec and Knight, 1996).

Table 3. Farmyard dirty water at wetland inlet one parameter concentrations for monitoring period (April 2001 - September 2003).

Season		*n*	**Farmyard dirty water parameter concentrations†**							
			SRP		**NH_4^+**		**BOD_5**		**TSS**	
			----------------mg l^{-1}----------------							
Spring	1st Feb. - 31st Apr.	7	21	± 2	53	± 8	2703	± 457	941	± 154
Summer	1st May - 31st Jul.	10	19	± 3	36	± 6	2682	± 482	978	± 190
Autumn	1st Aug. - 31st Oct.	5	19	± 3	61	± 10	2303	± 351	921	± 55
Winter	1st Nov. - 31st Jan.	6	15	± 3	42	± 7	2828	± 412	1078	± 161

† SRP, soluble reactive phosphorus; BOD_5, five day biological oxygen demand; and TSS, total suspended solids.

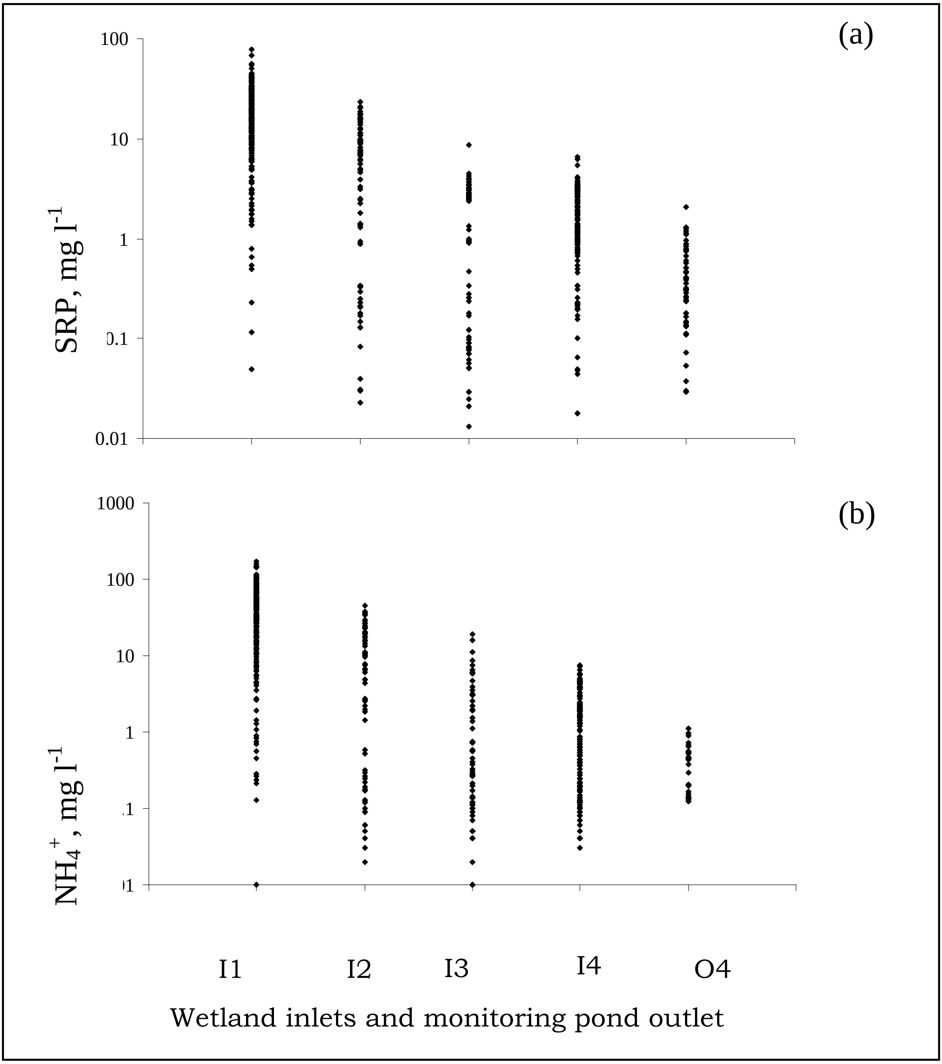

Figure 4: Log reduction of (a) soluble reactive phosphorus (SRP) and (b) ammonium (NH_4^+) in mg l^{-1} between wetland inlets (I1-I3) and inlet and outlet of final monitoring pond, respectively (I4-O4) during the monitoring period (April 2001 - September 2003).

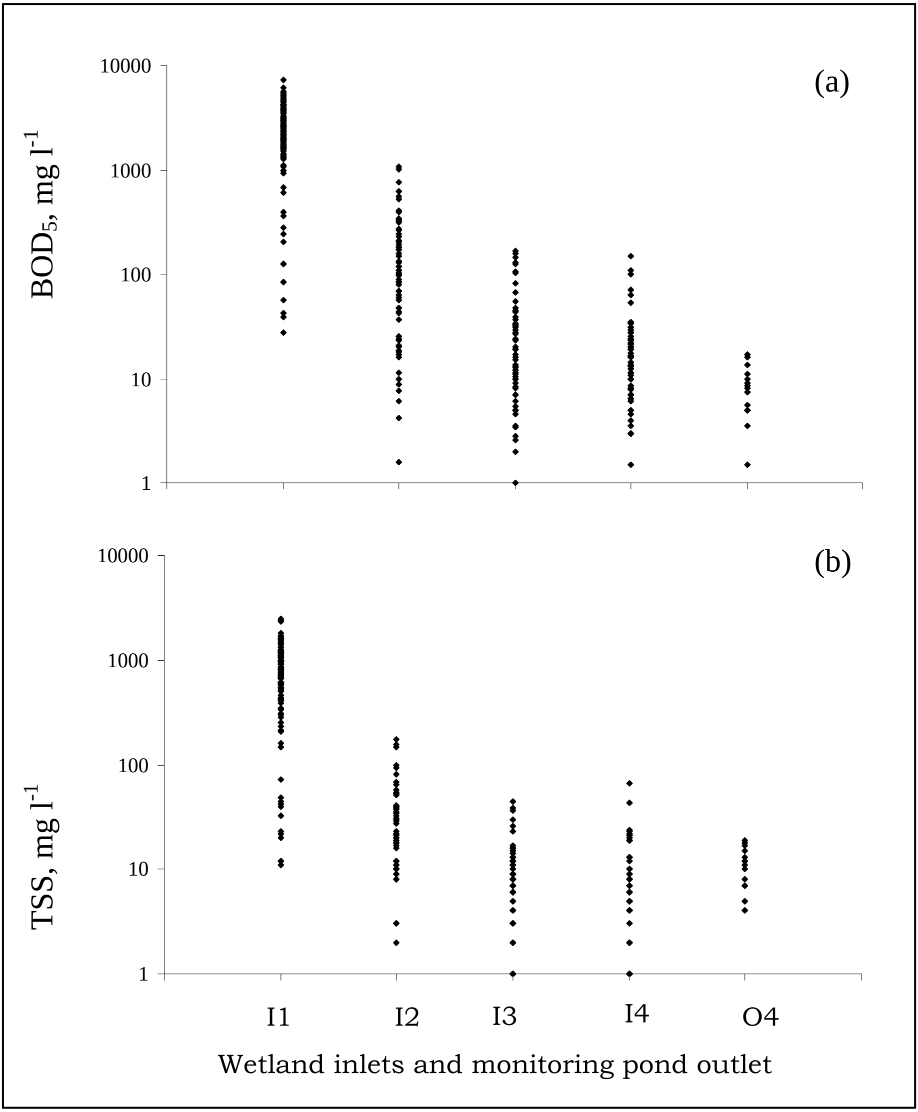

Figure 5: Log reduction of (a) five day biological demand (BOD_5) and (b) total suspended solids (TSS) between wetland inlets (I1-I3) and inlet and outlet of final monitoring pond, respectively (I4-O4) during the monitoring (April 2001 – September 2003).

There was some seasonal variation in water quality parameter concentrations at each inlet. At wetland inlet one, concentrations varied but not significantly so (Table 3). At wetland inlet two, the highest seasonal SRP concentration was in spring (13.40 ± 1.88 mg l^{-1}), which was significantly higher than autumn concentrations (P < 0.05). At wetland inlet three, concentrations of NH_4^+ were highest and TSS concentrations lowest during winter (4.47 ± 1.14 mg l^{-1} and 8 ± 3 mg l^{-1}, respectively) relative to summer and autumn (P < 0.05). Finally, at the inlet to the monitoring pond, concentrations of SRP (2.2 ± 0.21 mg l^{-1}) and NH_4^+ (3.41 ± 0.46 mg l^{-1}) were highest during winter (P < 0 .05). It is hypothesised that SRP and NH_4^+ concentrations were highest during winter because of increased surface outflow rates (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996; Koskiaho et al., 2003).

There were significant correlations between flow weighted mean monthly farmyard dirty water parameter concentrations at wetland inlet one with wetland surface outflow parameter concentrations (Table 4). The most significant relationship was between BOD_5 and TSS concentrations in farmyard dirty water. This suggests that most of the organic material in dirty water is in a suspended form or vice versa. Cumby et al., (1999) observed that there was a good correlation (87%) of BOD_5 concentrations with total solid (TS) concentrations in dairy farm wastewaters. There were also significant relationships between farmyard dirty water concentrations of SRP and NH_4^+ (P < 0.05) prior discharge to the integrated constructed wetland. Simple relationships such as those established allow prediction between parameters (Cumby et al., 1999) and between inlet and outlet concentrations of the same parameter (Kadlec and Knight, 1996), which can help to generate empirical relationships that are useful for wetland design.

Table 4. Correlation matrix of mean monthly farmyard dirty water and wetland surface outflow, flow-weighted concentrations for period April 2001 - September 2003 (*n* = 16).

	Water quality parameter concentrations														
	SRP_{in}		**$NH_4^+{}_{in}$**		**BOD_{5in}**		**TSS_{in}**		**SRP_{out}**		**$NH_4^+{}_{out}$**		**BOD_{5out}**		**TSS_{out}**
SRP_{in}	1														
$NH_4^+{}_{in}$	0.5606	*	1												
BOD_{5in}	0.0325	NS‡	0.1129	NS	1										
TSS_{in}	0.156	NS	0.1725	NS	0.9083	***	1								
SRP_{out}	0.6104	**	0.1819	NS	-0.3514	NS	-0.2339	NS	1						
$NH_4^+{}_{out}$	0.1385	NS	0.1839	NS	-0.26	NS	-0.3042	NS	0.3707	NS	1				
BOD_{5out}	0.0438	NS	0.1023	NS	0.5875	*	0.4521	NS	-0.0799	NS	0.3273	NS	1		
TSS_{out}	-0.0297	NS	-0.2374	NS	0.7136	**	0.656	*	-0.4037	NS	-0.1782	NS	0.4939	*	1

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability levels, respectively
† SRP, soluble reactive P; BOD5, five-day biological oxygen demand; and TSS, total suspended solids
‡ Not significant.

Farmyard Dirty Water Loading Rates

Mass input rates of SRP, NH_4^+, BOD_5, and TSS in farmyard dirty water to the wetland, did not vary with season (Table 5) as there was no significant seasonal difference in hydraulic inflows (Table 2) or water quality parameter concentrations (Table 3). Thus, during the monitoring period, mass-loading rate of BOD_5 to the integrated constructed wetland averaged 3.57 ± 0.49 g m^{-2} d^{-1}. This was about five fold less than that indicated by Newman et al. (2000). Other studies reporting the effectiveness of constructed wetlands to treat dairy wastewaters have determined mass loading rates of up to 9 g of BOD_5 m^{-2} d^{-1} (Reaves et al., 1994; Skarda et al., 1994; Geary and Moore, 1999). The Natural Resource Conservation Service (NRCS), USA as cited from Cronk (1996) and Newman et al. (2000) recommend a maximum BOD_5 mass loading rate of 7.3 g m^{-2} d^{-1}. The mass loading rate of TSS to the integrated constructed wetland was 1.04 ± 0.15 g m^{-2} d^{-1}, whereas TSS mass loading rates reported from other constructed wetlands used to treat dairy wastewaters were slightly higher (2-8 g m^{-2} d^{-1}) (Reaves et al., 1994; Skarda et al., 1994; Newman et al., 2000).

Table 5: Mass input rates from farmyard dirty water at wetland inlet one during monitoring period (April 2001 - September 2003).

		Farmyard dirty water mass input rate†							
Season‡	***n***	**SRP**		**NH_4^+**		**BOD_5**		**TSS**	
		g d^{-1}				**kg d^{-1}**			
Spring	5	126	± 17	307	± 54	15.0	± 2.6	4.1	± 1.0
Summer	8	140	± 39	513	± 184	17.5	± 6.3	4.4	± 1.5
Autumn	9	149	± 33	321	± 87	15.7	± 3.3	5.0	± 1.3
Winter	6	101	± 24	259	± 59	11.9	± 3.5	3.7	± 1.3

† SRP, soluble reactive P; BOD5, five day biological oxygen demand; and TSS, total suspended solids.
‡ Seasons are spring (1st Feb. - 31st Apr.), summer (1st May - 31st Jul.), autumn (1st Aug. - 31st Oct.) and winter (1st Nov. - 31st Jan.).

Ammonium loading rates (83 ± 13.64 mg m^{-2} d^{-1}) to the integrated constructed wetland were lower than those reported by Reaves et al. (1994) and Skarda et al. (1994). Geary and Moore (1999) recorded a loading rate of 3,200 mg m^{-2} d^{-1}. Total P loading rates to surface flow constructed wetlands receiving dairy farm wastewaters are often variable (30 mg m^{-2} d^{-1} to 1.5 g m^{-2} d^{-1}) (Reaves et al., 1994; Skarda et al., 1994; Geary and Moore, 1999; Newman et al., 2000; Jamieson et al., 2001). Soluble reactive P was loaded at rate of 30.89 ± 3.67 mg m^{-1} d^{-1} to the wetland. In general, farmyard dirty water loading rates to the integrated constructed wetland were lower than those documented for other similar studies.

Finally, in terms of yearly mass loads and independent of season, farmyard dirty water was discharged to the integrated constructed wetland at a rate of 47 ± 10 kg SRP yr^{-1}, 128 ± 35 kg NH_4^+ yr^{-1}, 5484 ± 1433 kg BOD_5 yr^{-1}, and 1570 ± 465 kg TSS yr^{-1}. These loadings rates during the monitoring period resulted in average outflow concentrations (from the three treatment wetland cells to the final monitoring pond) of 1.7 ± 0.14 mg l^{-1} SRP, 1.9 ± 0.4 mg l^{-1} $NH_4^{+,}$ 20 ± 3 mg l^{-1} BOD_5 and 11 ± 1 mg l^{-1} TSS.

Phosphorus Inputs and Retention Rates

Total mass SRP input rates to the wetland were determined as the sum of SRP loading rates from farmyard dirty water, rainfall and wetland bank surface inflows. There was no significant seasonal variation in total mass SRP inputs between December, 2001 and September, 2003 (Table 6) as most of the SRP load was from farmyard dirty water, which was relatively stable. However, there was some seasonal variation in wetland SRP mass output rates. The wetland generally discharged output loads at highest levels during winter periods (P < 0.05). The higher SRP output rates in winter may reflect the high rainfall months of October and November, 2002 as wetland surface outflows typically increased during these periods.

Table 6. Seasonal total mass soluble reactive phosphorus (SRP) input, output and rate to and from the wetland ± one standard error for period between December 2001 and September 2003.

Season†	***n***	**Total Inputs‡**		**Total Outputs§**		**Retention**	
		-----------------**kg yr^{-1}**		----------------		**kg ha yr^{-1}**	**%**
Spring	7	40	± 8	7	± 3	79	84
Summer	9	54	± 12	10	± 4	104	81
Autumn	8	45	± 14	8	± 7	86	81
Winter	6	37	± 9	35	± 18	4	5

† Seasons are spring (1st February until 31st of April), summer (1st May until 31st of July), autumn (1st August until 31st of October) and winter (1st November until 31st of January).
‡ Total inputs include SRP mass load from farmyard dirty water, precipitation on wetland surface areas and wetland bank inflow.
§ Total outputs are the SRP mass load in wetland surface outflow.

Table 6 shows that SRP percent mass retention by the wetland was seasonally variable. During spring, summer and autumn retention rates were similar, whereas during winter, the wetland retained least amounts of P and in some instances released P, also a probable result of decreases in HRT. Wetlands used to treat dairy farm wastewaters have retained between 27 to 68% of incoming P loads (Reaves et al., 1994; Skarda et al., 1994; Geary and Moore, 1999; Newman et al., 2000). Specific SRP mass retention by the integrated constructed wetland varied from 4 to 104 kg SRP ha yr^{-1} depending on season. These values are within the ranges reported for other surface flow constructed wetlands that are used to treat dairy wastewaters (Cronk, 1996).

Mechanisms involved in P removal by a wetland ecosystem include: sedimentation, precipitation, plant uptake, peat accretion, sorption reactions (Craft and Richardson, 1993; Mitsch and Gosselink, 1993; Reddy et al., 1999; Kadlec and Knight, 1996; Braskerud, 2002; Koskiaho et al., 2003).

Generally, the variability in treating dairy wastewaters by surface flow constructed wetlands has been attributed to differences in wastewater management practices, site specific characteristics, wetland design and layout, hydrologic inputs, scale of operation and climate (Cronk, 1996; Peterson, 1998; Knight et al., 2000 Schaafsma et al., 2000). This makes direct comparisons between wetland studies somewhat difficult.

Environmental Impact

Water quality parameter concentrations in piezometers that were installed at various depths (one to three meters) up gradient, within and down gradient of the integrated constructed wetland indicate that there was very little difference between concentrations of SRP, NH_4^+ and NO_3^- in soil-water before and during wetland operation (Table 7). This suggests that waters infiltrating from the wetland are having little impact on soil-water nutrient concentrations.

CONCLUSIONS

Contaminant and nutrient loss from agriculture can cause point source pollution. Constructed wetlands are often used as alternates to or components of conventional nutrient management practices to reduce or eliminate contaminant and nutrient loads in agricultural wastewaters around the world.

In this study, there was little variation in seasonal inflow rates and seasonal water quality parameter concentrations of farm yard dirty water. Mass loads of SRP, NH_4^+, BOD_5, and TSS on a yearly basis suggest that farm yard dirty water contains considerable amounts of nutrients and contaminants, thus management of those resources are important at farm-scales.

There was a positive relationship between farmyard dirty water inflow rate to the wetland and rainfall, indicating that rainfall on impervious surfaces such as open yard areas may be an important factor in the generation of dirty water at this farm-scale. Precipitation on wetland surface areas and inflows from surrounding wetland bank areas were the main controlling hydrological factors, whereas mass loads in farm yard dirty water were the main loading factor.

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Table 7. Nutrient concentrations (soluble reactive phosphorus, SRP; ammonium, NH_4^+; and nitrate, NO_3^-) in sampled piezometersbefore and after farmyard dirty water discharge to the wetland ± one standard error. Data refers to March 2001 - September 2003.

Piezometer location	Piezometer number	SRP					NH_4^+					NO_3-				
		Before		After			Before		After			Before		After		
Up†	1	0.013	± 0.006	0.026	± 0.005	NS§	0.42	± 0.14	0.28	± 0.09	NS	0.19	± 0.093	0.09	± 0.015	NS
Wetland cell 1	2-7	0.023	± 0.007	0.043	± 0.015	NS	0.55	± 0.08	0.43	± 0.1	NS	0.28	± 0.085	0.23	± 0.059	NS
Wetland cell 2	8-13	0.016	± 0.003	0.030	± 0.01	NS	0.44	± 0.10	0.18	± 0.03	*	0.24	± 0.074	0.17	± 0.048	NS
Wetland cell 3	14-18	0.058	± 0.024	0.033	± 0.008	NS	0.44	± 0.09	0.19	± 0.04	*	0.10	± 0.002	0.15	± 0.056	NS
Wetland cell 4	19-20	0.023	± 0.004	0.033	± 0.007	NS	0.37	± 0.15	0.57	± 0.15	NS	0.27	± 0.098	0.93	ND	ND
Down‡	21-23	0.030	± 0.015	0.007	± 0.005	NS	0.74	± 0.30	0.24	± 0.02	NS	0.35	± 0.253	0.17	± 0.020	

* Significant at the 0.05 probability level
† Piezometers located up gradient of wetland
‡ Piezometers located down gradient of wetland
§ Not significant
¶ Not determined

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