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THE INTEGRATED CONSTRUCTED WETLANDS (ICW) CONCEPT

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Abstract: The free surface flow Integrated Constructed Wetlands (ICW) concept explicitly combines the objectives of cleansing and managing water flow from farmyards with that of integrating the wetland infrastructure into the landscape and enhancing its biological diversity. This leads to system robustness and sustainability. Hydraulic dissipation, vegetation interception, and evapotranspiration create an additional freeboard at the outlet of each wetland segment and at the point of discharge, thus enhancing hydraulic residence time and cleansing capacity during hydraulic fluxes. The principal design criteria leading to adequate effluent water quality (i.e., molybdate reactive phosphorus less than 1 mg/l) from ICW are that the wetland area needs to be sized by a factor of at least 1.3 times the farmyard area and the aspect ratio for the individual wetland segments (i.e., approximately four cells) needs to be less than 1:2.2 (width to length). Within a year of ICW commissioning, approximately 75% of farmyard runoff was intercepted, leading to improvements in the receiving surface waters of the catchment. Most of the recorded phosphate concentrations after ICW treatment agreed with the Irish Urban Wastewater Treatment Regulation 2001, which can be used as a benchmark to assess ICW treatment performance and which is usually applied unofficially to ICW even if it may appear to be too stringent. A case study of 13 ICWs suggested that phosphorus exported from an ICW system was similar to the typical background concentrations of phosphorus export rates from land to water.

Key Words: aspect ratio, constructed wetlands, design guidelines, farmyard runoff, ground water, Ireland, molybdate reactive phosphorus, principal component analysis, self-organizing map, water quality

INTRODUCTION

Background

The free surface flow Integrated Constructed Wetlands (ICW) concept promoted by the ICW Initiative of the Irish National Parks and Wildlife Service is based upon the use of the land-water interface to enhance environmental and nature conservation management (Harrington and Ryder 2002, Harrington et. al. 2005). The ICW concept was developed from work started in 1990 to improve the management of natural resources for the rural community in the catchment (Figures 1–4) of the Dunhill-Annestown stream in south County Waterford, Ireland (area of 25 km^2). The corresponding water quality status was classified by the Irish Environmental Protection Agency as ''heavily polluted'' during the 1990s (EPA 2002). Dirty runoff from farmyards within the watershed was considered to be a significant contributing factor (Harrington et al. 2005). The ICW working framework deployed to improve the water quality of the watershed is similar to that of the ''small watershed technique'' and associated ecosystem studies developed by Bormann and Likens (1981) at Hubbard Brook, New Hampshire, USA.

As the ICW initiative focuses on an entire catchment, it adheres to and is strongly influenced by methods developed for the United Nations Environment Programme (UNEP) Convention on Biological Diversity (UNEP 2003; see also www.biodiv.org) to which all countries of the European Union and its Commission are signatories. The specific naming of the concept as ICW arose from

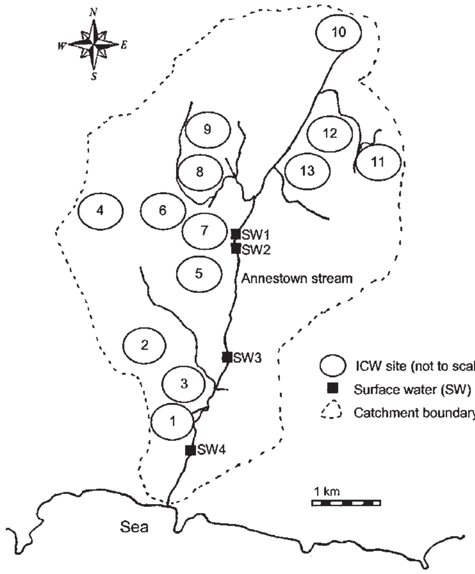

Figure 1. Catchment near Waterford (Ireland) showing 13 Integrated Constructed Wetland sites.

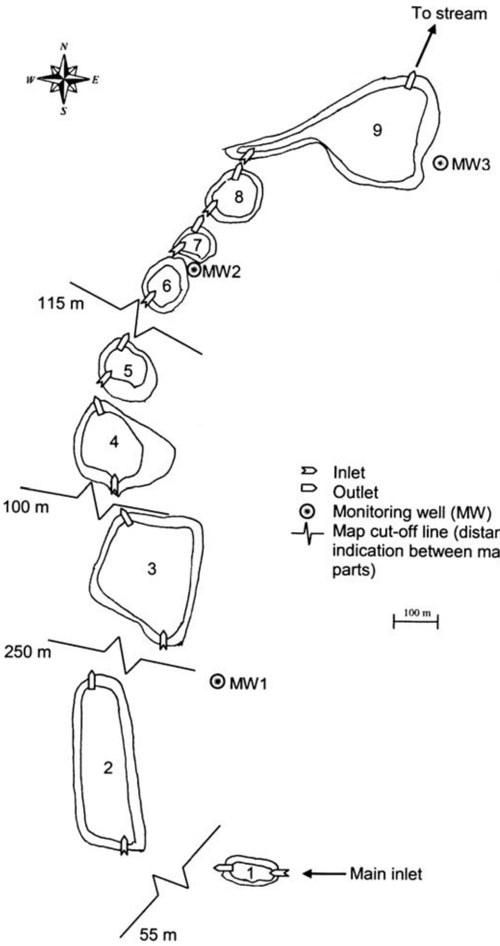

Figure 2. Ground-water monitoring wells for Integrated Constructed Wetland sites 1.

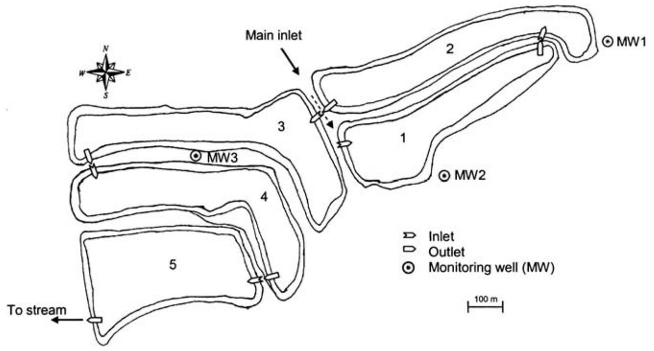

Figure 3. Ground-water monitoring wells for Integrated Constructed Wetland sites 3.

the need to emphasize its integrated approach to the management of natural resources (Harrington and Ryder 2002, Dunne et al. 2005a).

The ICW concept is based on the holistic use of land to control water quality. Because of climate, topography, and soils, wetlands of various types were once ubiquitous throughout Ireland and most of Europe and Northern America. These areas of land-water interfaces once formed an integral part of the environmental and ecological structure of the landscape. They acted as transition zones between dry and inundated land areas and controlled the transfer and storage of water and nutrients (Mitsch and Jorgensen 2003). They also provided habitats for diverse flora and fauna (Mitsch and Gosselink 2000). So great has the loss of this environmental infrastructure been that its environmental and ecological roles are little appreciated. This is reflected in the continuing drainage and infilling of wetlands (Otte 2005). The ICW initiative therefore endeavors to promote the advantages of restoring some of wetlands' key environmental services and their associated lost habitats (Harrington and Ryder 2002).

Wetland landscapes, in particular those dominated by emergent vegetation, with seasonal, shallow water and nutrient-enriched soils, have been espe-

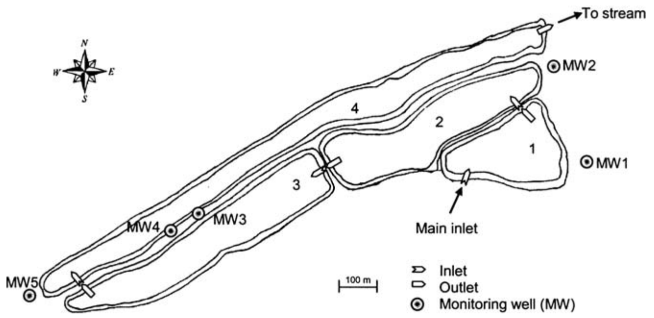

Figure 4. Ground-water monitoring wells for Integrated Constructed Wetland sites 11.

cially vulnerable to drainage and conversion to agricultural land (Mitsch and Gosselink 2000, Scholz 2006). Most ICW mimic to a large extent the structures and processes found in these vulnerable natural wetlands. The ICW initiative's remit is to demonstrate the working capabilities of ICWs and to promote their application, initially through the construction of experimental case study sites and subsequently through the development of guidelines for their use in the management of farmyard waste water.

Objectives of the Integrated Constructed Wetland Concept

The primary objectives of the ICW concept are the explicit integration of a) the containment and treatment of influents within emergent vegetated areas using (wherever possible) local soil material; b) the aesthetic placement of the containing wetland structure into the local landscape with the intention of enhancing the site's ancillary values; and c) enhanced habitat diversity and nature management. This explicit integration of ICW facilitates processing synergies, robustness, and sustainability, which are not generally available in other wetland treatment systems (Scholz 2006). These benefits are primarily due to the greater biological complexity and generally relatively larger land area and associated longer hydraulic residence time of ICW in contrast to traditional constructed treatment wetlands (Kadlec and Knight 1996).

Fundamentally, the concept focuses on the creation of an ecological infrastructure, which is largely self-managing, biologically self-designing, and of social and economic coherence. This robust, sustainable, and multi-benefit yield from ICW systems is assured by appropriate assessment, design, and construction (Harrington et al. 2005, Keohane et al. 2005).

Nutrient Control

The changes in concentrations of nutrients across the wetland system are attributable to a number of removal mechanisms such as physical processes, microbial activity, and plant uptake. Some previous studies reported a considerable contribution of various macrophytes to pollutant removal, as reviewed by Lee and Scholz (2007). For example, Karathanasis et al. (2003) reported that the biochemical oxygen demand removal efficiency was lower in unplanted systems (63%) than in planted systems (70%–75%). The removal efficiency of total suspended solids also was significantly lower in unplanted systems (46%) in comparison to planted systems (88%–90%) for subsurface-flow wetlands. Gray et al. (2000) also described that the planted system removed more chemical oxygen demand from sewage than the unplanted system (75% removal compared to 48%) in the surface-flow wetlands.

Phosphorus removal is greatest during the first one to three years of succession when sediment deposition and sorption and/or precipitation of phosphorus are greatest (Craft 1996). Present mass pollutant removal by surface-flow constructed wetland treatment of agricultural dirty water usually varies between 30% and almost 100% of the phosphorus input, depending on its type (e.g., Newman et al. 2000, Reddy et al. 2001, Braskerud 2002). The most relevant work related to the current ICW database has been published by Carroll et al. (2005), Dunne et al. (2005a, b), and Harrington et al. 2005), providing evidence that phosphorus removal correlates positively with an increase in wetland area.

Although the quality and quantity of farmyard dirty water may be similar throughout the year, phosphorus removal varies from 5% in winter to 84% in summer (Dunne et al. 2005a, b). However, these figures refer to relatively under-sized ICW systems. A study in Ireland (Costello in 1989) reported on a dairy farm with a large constructed wetland of 12 ha and found a mean reduction in orthophosphate of up to 91%. In general, the ICW treatment performance improves with an increase in both wetland area and retention time (Harrington and Ryder 2002, Harrington et al. 2005).

However, there are also some other references indicating insufficient phosphorus removal for constructed treatment wetlands. For example, Smith et al. (2006) found that constructed wetlands were not efficient in removing total phosphorus in Nordic countries, especially during high loading periods. Stone et al. (2004) reported a phosphorus removal efficiency of only 8% for a combined marsh, pond, and wetland system but admitted that the researched treatment train of wetlands was too short. Furthermore, Tanner et al. (1999) reported a good initial removal efficiency of total phosphorus, which, however, was less effectively removed after five years of operation.

Various researchers have also tried to enhance nutrient removal efficiencies by incorporating different aggregates into constructed wetlands. For example, Hill et al. (2000) tested fine loam, crushed limestone, fired shale, and calcium metasilicate and found that fired shale had a positive effect on phosphorus removal. In Quebec, 57 materials were

Table 1. Site characteristics of farms and Integrated Constructed Wetland (ICW) systems in the Anne Valley (near Waterford, Ireland).

ICW Number	Farm Enterprise	Farmyard Area (m^2)	ICW Area (m^2)	ICW to Yard Area Ratio	Aspect Ratio of Wetland Cells	Dairy Washings[a] (Number of Cows)	Yard Water	Silage Effluent	Roof Water	Extraneous Surface Water
1	Dairy	4,500	3,906	0.9	1.46	Yes (60)	Yes	No	Yes	Yes
2	Dairy	14,750	22,966	1.6	2.79	Yes (60)	Yes	Yes	Yes	Yes
3	Dairy/beef	5,400	10,288	1.9	6.06	Yes (50)	Yes	Yes	Yes	No
4	Dairy	9,200[b]	10,327	1.1	6.28	Yes (100)	Yes	No	Yes	No
5	Dairy/tillage	4,000	3,940	1.0	7.19	Yes (35)	Yes	Yes	Yes	Yes
6	Dairy	9,800	12,691	1.3	3.29	Yes (80)	Yes	Yes	No	Yes
7	Sewage	n/a	3,075	n/a	4.00	n/a	No	No	No	No
8	Beef	2,300	3,940	2.0	1.84	No	Yes	No	Yes	Yes
9	Mixed	4,800	7,964	1.7	2.46	Yes (55)	Yes	Yes	Yes	No
10	Mixed	2,100	4,375	2.1	3.73	Yes (50)	Yes	Yes	Yes	No
11	Dairy	5,000	7,676	1.5	7.79	Yes (77)	Yes	Yes	Yes	No
12	Mixed	13,600[c]	10,748	0.8	2.42	Yes (85)	Yes	No	Yes	No
13	Sheep/tillage	5,000	5,610	1.1	2.30	No	Yes	No	Yes	Yes

[a] Dairy washings: A "yes" entry indicates discharges to the wetland and a "no" entry indicates that there were none.
[b] 500 m^2 added in 2003.
[c] 2,000 m^2 and 1,100 m^2 added in 2004 and 2005, respectively.

compared for their affinity to adsorb phosphorus, and it was found that electric arc furnace (EAF) steel slag has a high potential for phosphorus removal (Forget et al. 2001). Seo et al. (2005) demonstrated with the help of batch and column experiments that adding oyster shell to the filter medium in the constructed wetland extended the longevity of the constructed wetland by the phosphorus saturation. However, Scholz (2006) demonstrated, with the help of various case studies, that additional filter material including Filtralite (light expanded clay product; Lee et al. 2005) does not remove phosphorus significantly better than mature wetland soil after usually one year of plant operation.

Aim and Objectives

This research paper assessed the philosophy of the ICW concept, putting special emphasis on the specific water treatment potential of example ICW. The objectives were 1) to analyze and assess a unique data set on ICW performance, 2) to assess the contaminant removal capacity of ICW, and 3) to recommend ICW design guidelines for phosphorus removal.

CASE STUDY SITES, MATERIALS, AND METHODOLOGIES

Sites Within the Case Study Catchment

The entire Anneswtown-Dunhill case study catchment (Figure 1) is divided into a number of subcatchments, or nested catchments, serving each farmyard curtilage of the 19 working farms. Effectively, this catchment acts as a field laboratory, which parallels that of the Hubbard Brook catchment (Bormann and Likens 1981).

Integrated constructed wetlands were constructed on various farm enterprises within the watershed (Table 1). In general, ICW sizes ranged between approximately 3,000 m^2 and 22,000 m^2. The runoff typically consisted of yard and dairy washings, rainfall on open yard and farmyard roofed areas, and silage and manure effluents. The mean ICW size was approximately 1.4 times the size of the open farmyard areas. All ICW were in operation for at least six years. The ICW sites 1, 2, 5, 6, 7, 8, and 13 were subject to surface runoff and/or ground-water infiltration, and ICW site 7 was the Dunhill village sewage treatment plant.

Species enrichment through additional planting was necessary for ICW sites where the ammonia concentrations exceeded the tolerance thresholds of the plant species. It follows that at ICW sites 2 and 3, *Glyceria*, *Typha*, and *Scirpus* were planted due to their higher tolerances (Kadlec and Knight 1996).

Site Assessment

Construction site design took into account 1) retaining structures, 2) hydraulic residence time and flow characteristics such as velocity, 3) appropriateness of proposed sites, 4) soil type, geology, hydrogeology, topography, area availability, and coefficients of site uniformity, 5) site values for nature conservation and archaeology/built heritage, 6) nutrient recycling, retention, and retrieval, 7) characteristics of influent (particularly ammonia concentrations) to determine particulate and dissolved components of incoming waters, 8) an appropriate monitoring strategy, including consideration of adjacent wells, watercourses, and ground water, and 9) the assimilative capacity of receiving water courses (Keohane et al. 2005).

The conditions for protection of surface waters were as follows: 1) the discharge into sensitive waters had to be at least neutral and 2) the assimilative capacity of the receiving surface water had to be determined. If a surface water discharge was not possible, then an alternative needed to be examined such as increasing post-treatment ground infiltration.

Sufficient hydraulic resistance to infiltration was created. The following conditions were met: 1) prohibition within 60 m of a well or spring; 2) prohibition within the inner protection zone of a public well, where ground-water vulnerability was extreme; and 3) the ICW was underlain by at least 1.5 m of subsoil, with the upper 0.5 m enhanced where necessary to a hydraulic conductivity of 10^{-8} m/s (Dunne et al. 2005a, b).

The subsoil investigation of a potential ICW site comprised 1) the excavation of trial holes, 2) the description of each trial hole to BS 5930 (BSI 1999), 3) the assessment of the workability of the material to achieve the necessary resistance to infiltration; and 4) the collection of samples for particle size distribution analyses to demonstrate both appropriate resistance to infiltration and the presence of clay content of more than 10% (Dunne et al. 2005a).

Analytical Methods

A water quality monitoring program that was comprised of wetland influent and effluent sampling and receiving watercourse sampling was undertaken for each ICW system. In addition, ground-water samples were available for ICW sites 1, 3, and 11 between January and July 2006 (Figures 2 to 4). Grab samples were carefully taken on an approximately weekly basis for each wetland influent and effluent, and stored, prepared, and analyzed according to standard methods (APHA 1998). Wetland influents were generally taken from the first cell of each ICW, while effluent samples were taken from either the outlet pipe of the last wetland cell or, in the absence of effluent discharge, from the water surface of the last wetland cell of each ICW system.

Since August 2001, approximately monthly grab water samples were taken along the main channel of the Annestown stream and subsequently analyzed according to standard methods (APHA 1998). This stream is the receiving water body for all ICW discharges. Macroinvertebrate surveys of the stream were conducted in 1990, 1991, 1996, 1998, 2001, and 2004 by the Environment Protection Agency (EPA).

A total of 11 piezometric ground-water monitoring wells were placed both upgradient and downgradient at various depths (2–5 m) at ICW sites 1, 3, and 11 (Figures 1–4) in fall 2005. These wells were sampled monthly in 2006. The day before sample extraction (APHA 1998), all wells were purged. Water samples were also taken from the farmers' water supply wells to assess the status of ambient ground-water quality.

Flow meters were installed at one four-celled farmyard ICW system on site 11. Influent and effluent flows into, between and out of each wetland cell of the ICW were continuously recorded using flow meters and associated data loggers for the period between April 2003 and April 2006. However, flow recordings were frequently very low or flawed due to blockage by vegetation, so flow meter recordings were not reliable. Potentially faulty data were discarded.

Molybdate reactive phosphorus (MRP), which is equivalent to soluble reactive phosphorus, was measured according to APHA (1998). The phosphate budget was calculated by multiplying flow by concentration for the available data. Discharge to the ground below an ICW system was calculated using the mean value of the inlet and outlet concentrations for each cell to account for the concentration gradient along the length of the cell. Surface discharge calculations were based on the outlet concentration.

In March 2005, sediment accumulations were measured at six ICW systems at sites 3, 4, 9, 10, 11, and 12. Sediment samples were taken by manual grab from at least the first three cells of each of the selected ICW. The samples were taken at the inlet, mid and outlet points of cell 1 where heterogeneity was expected to be greatest, and at central points of the second, third and subsequent cells. A total of 35 samples were taken. The sediment depth was measured at each sediment sampling point. The sediment volume in each pond was calculated by multiplying sediment depth by pond area. The mean sediment depth was calculated by dividing the calculated volume by the overall area.

Sediment samples were tested for total phosphorus using the ascorbic acid method following digestion using nitric acid and hydrogen peroxide.

Table 2. Summary data of water quality variables of Integrated Constructed Wetland (ICW) influents (In) and effluents (Ef). Variables include chemical oxygen demand (COD), five-day @ 20°C biochemical oxygen demand (BOD), total suspended solids (SS), and chloride (Cl^-). N = number of entries; Ci = cell number; I = inflow; O = outflow; n/a = not applicable.

	ICW	Influent Source	COD (mg/l)			BOD (mg/l)			SS (mg/l)			Cl^- (mg/l)		
			In 1	In 2	Ef	In 1	In 2	Ef	In 1	In 2	Ef	In 1	In 2	Ef
Mean	1	1) C1, I	8,342.4	n/a	30.4	6,040.8	n/a	11.1	1,013.2	n/a	11.6	446.7	n/a	54.7
N			26	n/a	27	23	n/a	26	24	n/a	24	5	n/a	5
Mean	2	1) C2, I	732.0	n/a	38.6	429.9	n/a	12.9	146.2	n/a	23.3	166.6	n/a	47.6
N			28	n/a	27	21	n/a	26	24	n/a	23	6	n/a	5
Mean	3	1) C2, I	929.5	n/a	88.6	417.1	n/a	19.8	112.6	n/a	18.9	120.4	n/a	57.5
N			35	n/a	42	28	n/a	34	30	n/a	33	25	n/a	32
Mean	4	1) C1, I	1,858.0	n/a	93.2	619.5	n/a	27.6	1,019.0	n/a	43.7	251.4	n/a	74.7
N			51	n/a	42	43	n/a	35	49	n/a	38	39	n/a	27
Mean	5	1) C1, I	1,217.8	n/a	43.8	357.7	n/a	17.3	180.6	n/a	13.2	149.4	n/a	31.5
N			25	n/a	26	24	n/a	25	24	n/a	21	5	n/a	6
Mean	6	1) C1, I	578.4	n/a	50.6	213.2	n/a	16.3	192.3	n/a	19.3	70.2	n/a	30.6
N			25	n/a	27	22	n/a	25	23	n/a	24	4	n/a	5
Mean	7	1) C1, I	514.2	n/a	62.5	337.6	n/a	17.2	286.3	n/a	8.2	71.3	n/a	67.4
N			31	n/a	37	25	n/a	27	26	n/a	27	11	n/a	39
Mean	8	1) C1, I	136.5	n/a	33.7	56.1	n/a	11.9	39.2	n/a	8.2	65.8	n/a	44.5
N			26	n/a	26	22	n/a	22	24	n/a	22	3	n/a	5
Mean	9	1)IC1,I O	960.1	n/a	58.9	520.2	n/a	11.9	408.6	n/a	26.7	200.9	n/a	43.6
N			30	n/a	36	30	n/a	34	29	n/a	32	23	n/a	30
Mean	10	1)IC1a,I O	1,341.0	2930.0	73.0	149.6	208.1	8.8	306.5	207.7	14.0	90.1	80.3	27.67
N			5	36	27	3	30	18	4	31	15	5	35	27
Mean	11	1) C1, I	1,588.7	n/a	78.1	569.7	n/a	20.2	309.4	n/a	21.2	114.1	n/a	40.3
N			60	n/a	59	47	n/a	41	54	n/a	55	75	n/a	75
Mean	12	1) C1.1, I	1,988.3	n/a	67.2	317.3	n/a	18.3	210.0	48.0	19.4	339.0	84.0	45.9
N			6	0	38	6	0	35	4	1	30	11	2	27
Mean	13	1) C1, I	130.6	n/a	36.5	45.8	n/a	15.1	171.3	n/a	17.0	57.1	n/a	40.7
N			20	n/a	21	19	n/a	19	21	n/a	20	4	n/a	5

Density and dry matter measurements were also carried out (APHA 1998).

Water analysis for chemical oxygen demand (COD), BOD, ammonia-nitrogen, nitrate-nitrogen, MRP, total suspended solids (SS), chloride, and *Escherichia coli* bacteria was conducted at the Waterford County Council water laboratory using American Public Health Association standard methods (APHA 1998).

Statistical Analyses

A principal component analysis (PCA) was performed with the Minitab 14 software package (Minitab 2003). The PCA is a multivariate method that detects similarities and patterns among various components of data and attempts to cluster these components on a straightforward two dimensional graph (Townend 2002). In this way, it is possible to find which variables are related to one another based on the measured water quality values.

Furthermore, Self-organizing map (SOM) analysis was performed. This is a very specialized technique belonging to the family of statistical methods known as neural networks. The method is based on an unsupervised data mining algorithm, which, similarly to the PCA, also searches for very subtle relationships among variables and visualizes these on an abstract 'map' in the form of clusters, or indeed lack thereof (Vesanto et al. 2000).

RESULTS AND DISCUSSION

Wetland Water Quality

Water quality data for all wetland influents and effluents for the monitoring period between August 2001 and July 2006 are summarized in Tables 2, 3, and 4. Phosphorus concentration reductions were generally greater than 90%, with the exception of ICW site 7, which, due to the high hydraulic loading rates and its similarity with a sewage treatment tank, exhibited only a 30% phosphorus reduction

Table 3. Summary data of water quality variables of Integrated Constructed Wetland (ICW) influents and effluents. Variables include *Escherichia coli*, ammonia-nitrogen (NH_4^+-N), and nitrate-nitrogen (NO_3^--N). N = number of entries; Ci = cell number; I = inflow; O = outflow; n/a = not applicable.

	ICW	Influent Source	*E. Coli* (CFU/100 ml) In 1	In 2	Ef	NH_4^+-N (mg/l) In 1	In 2	Ef	NO_3^--N (mg/l) In 1	In 2	Ef
Mean	1	1) C1, I	58,493	n/a	37	153.6	n/a	0.3	1.01	n/a	2.78
N			6	n/a	6	26	n/a	27	13	n/a	27
Mean	2	1) C2, I	33,482	n/a	35	64.6	n/a	0.4	1.42	n/a	4.45
N			6	n/a	6	28	n/a	27	13	n/a	27
Mean	3	1) C2, I	225,837	n/a	126	62.9	n/a	1.3	0.20	n/a	1.04
N			7	n/a	7	48	n/a	60	6	n/a	57
Mean	4	1) C1, I	590,583	n/a	395	110.6	n/a	2.5	0.59	n/a	2.09
N			6	n/a	6	69	n/a	55	10	n/a	50
Mean	5	1) C1, I	309,217	n/a	428	71.8	n/a	0.5	0.43	n/a	2.79
N			6	n/a	6	24	n/a	27	9	n/a	25
Mean	6	1) C1, I	23,025	n/a	12	41.2	n/a	0.3	0.61	n/a	0.79
N			6	n/a	6	26	n/a	26	11	n/a	26
Mean	7	1) C1, I	6,887,417	n/a	791	52.2	n/a	22.5	1.01	n/a	1.04
N			6	n/a	10	32	n/a	63	17	n/a	61
Mean	8	1) C1, I	5,567	n/a	264	19.4	n/a	0.2	0.45	n/a	0.21
N			6	n/a	6	25	n/a	26	9	n/a	26
Mean	9	1)IC1, IO	240,283	n/a	52	41.0	n/a	0.6	0.25	n/a	1.39
N			6	n/a	6	51	n/a	57	1	n/a	54
Mean	10	1)IC1a, I O	n/a	65,028	100	26.6	23.2	0.2	1.69	0.88	1.76
N			0	5	1	5	63	40	5	5	37
Mean	11	1) C1, I	728,425	n/a	32	42.2	n/a	0.4	3.75	n/a	1.10
N			6	n/a	6	109	n/a	109	10	n/a	105
Mean	12	1) C1.1, I	n/a	n/a	1,548	129.5	43.9	1.1	n/a	n/a	1.43
N			0	0	6	12	2	51	0	0	50
Mean	13	1) C1, I	n/a	n/a	1,579	10.5	n/a	0.1	2.20	n/a	1.60
N			n/a	n/a	6	22	n/a	24	9	n/a	22

Table 4. Summary data of molybdate reactive phosphorus (PO_4^{3-}-P, mg/l). N = number of entries; n/a = not applicable.

		Integrated Constructed Wetland Site Number												
Flow Type	Statistics	1	2	3	4	5	6	7	8	9	10	11	12	13
Influent 1	Maximum	918.00	28.30	31.70	60.00	99.30	40.00	16.40	5.00	124.71	9.27	50.96	61.11	4.49
	Minimum	0.20	0.20	0.05	1.45	0.01	0.20	0.65	0.05	0.83	2.88	0.35	30.95	0.02
	Mean	75.69	15.46	18.13	22.75	14.33	10.76	7.51	1.46	11.59	5.27	12.02	43.67	0.94
	n	25	28	49	71	25	27	33	26	52	5	112	14	21
Influent 2	Maximum	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	190.60	n/a	10.02	n/a
	Minimum	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.14	n/a	6.33	n/a
	Mean	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10.04	n/a	8.18	n/a
	n	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	62	n/a	2	n/a
Effluent	Maximum	1.30	0.73	11.47	4.70	3.01	0.96	10.35	0.29	1.28	0.36	4.41	3.03	0.32
	Minimum	0.01	0.01	0.02	0.02	0.01	0.01	0.16	0.00	0.03	0.01	0.00	0.01	−0.01
	Mean	0.22	0.27	3.38	1.62	0.24	0.13	5.25	0.04	0.44	0.06	0.96	0.53	0.06
	n	28	28	62	59	28	28	64	27	58	40	114	52	24
% phosphate reduction		99.71	98.22	81.36	92.89	98.34	98.83	30.08	97.21	96.18	99.64	91.98	98.97	93.34

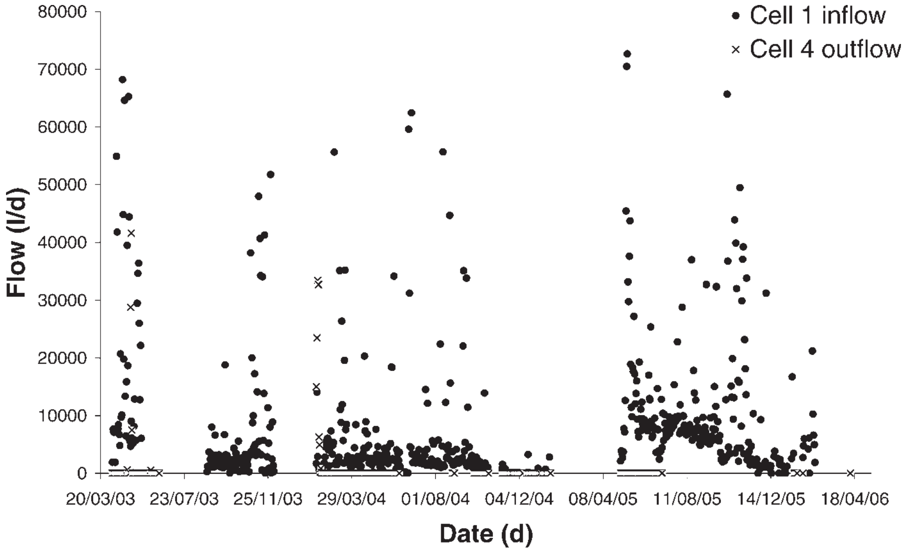

Figure 5. Water flow into and out of the Integrated Constructed Wetland system on site 11.

(Table 4). Concerning the inflow mean water quality values, COD was 1,788 ± 2,248 mg/l, BOD was 791 ± 1587 mg/l, SS was 358 ± 318 mg/l, ammonia-nitrogen was 68.7 ± 48.9 mg/l, MRP was 19.83 ± 20.98 mg/l, and *E. coli* was 833,396 ± 2,022,116 CFU per 100 ml. This indicated a very large variability in terms of water quality for all the tested substances in the farmyard dirty water discharged to the ICW.

The mean effluent water quality that was discharged from the ICW was 58 ± 21 mg/l COD, 16 ± 5 mg/l BOD, 19 ± 9 mg/l SS, 2.4 ± 6.1 mg/l ammonia-nitrogen, 1.02 ± 1.58 mg/l MRP, and 415 ± 556 CFU per 100 ml of *E. coli* during the monitoring period. This suggested that the ICW has a high capacity to remove fecal indicator organisms, as well as all other measured pollutants associated with farmyard dirty water. If the two farm sites (ICW sites 8 and 13; Table 1) without dairy washings were excluded, the BOD concentration of water entering the other ICW systems was approximately 1200 ± 5200 mg/l. This value was consistent with soiled water, such as dairy washings diluted with cleaner water including yard and roof runoff (EPA 2002). No noteworthy similarity was found between inlet and outlet flows (Figure 5).

Findings of Statistical Analyses

Figure 6 shows the principal components for all sites, except those with ground-water infiltration (ICW sites 1, 2, 5, 6, 7, 8, and 13) and ICW site 7 (due to its nature as a sewage treatment tank). Example Kohonen maps (from the SOM analysis) are given in Figures 7 and 8, and show the inflow and outflow for ICW site 9.

Similarity of results from PCA and SOM analyses indicated that there was no strong direct mathematical relationship between the water quality values for the inflow and the outflow for all the ICW, with the exception of ICW site 11. Therefore, it is not possible to replace phosphorus with any other variable as it is fully independent (i.e., no evidence

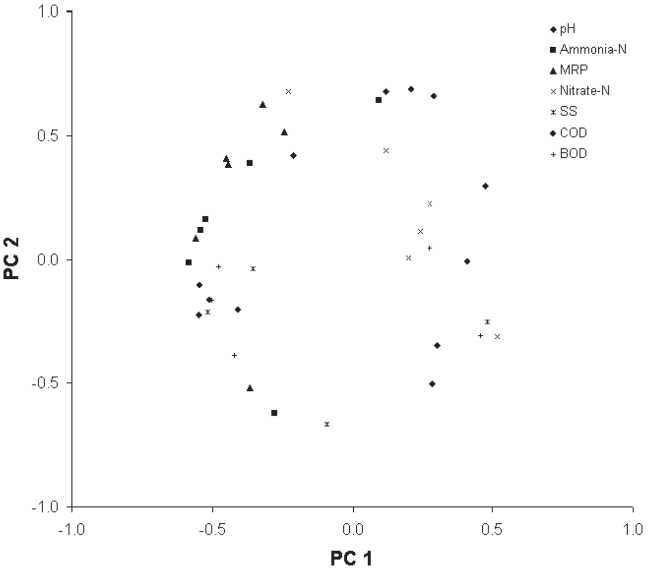

Figure 6. Loading plot of the Principal Component (PC) analysis of ICW sites 3, 4, 9, 10, 11, and 12. N = nitrogen (mg/l); MRP = molybdate reactive phosphorus (mg/l); SS = suspended solids (mg/l); COD = chemical oxygen demand (mg/l); BOD = biochemical oxygen demand (mg/l).

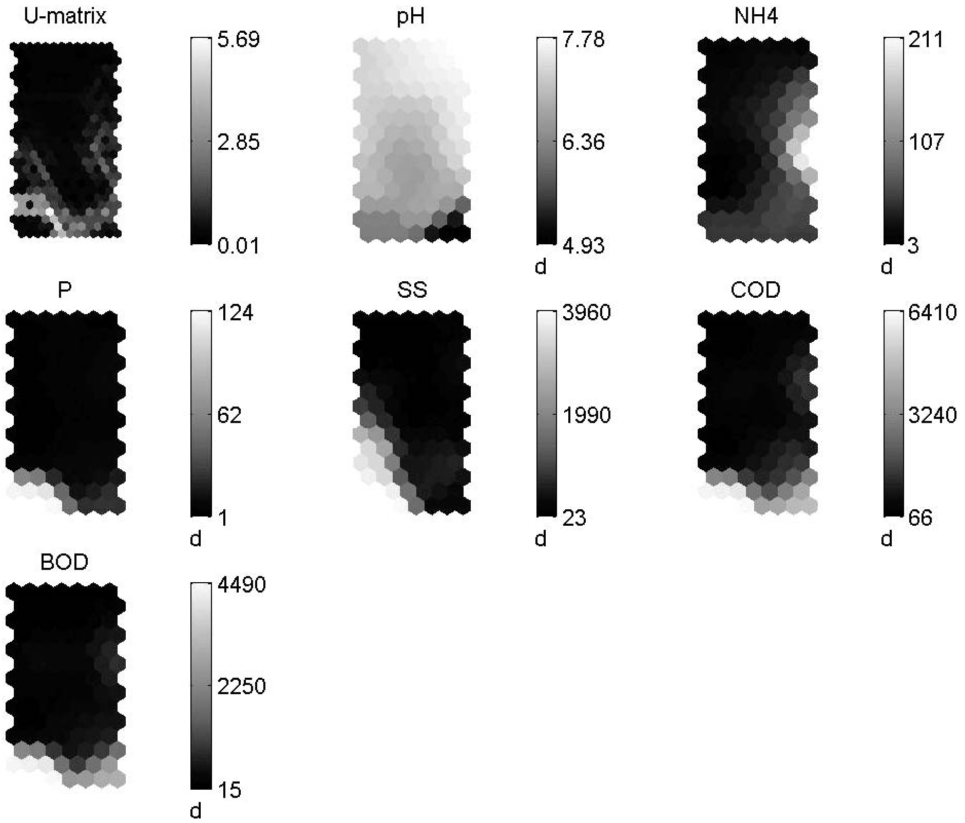

Figure 7. Diagrams of the self-organizing Kohonen map for Integrated Constructed Wetland (ICW) site 9 (inflow). The water quality abbreviations are as follows: NH_4 = ammonia-nitrogen, mg/l; P = phosphate-phosphorus in the form of molybdate reactive phosphorus (mg/l); SS = suspended solids (mg/l); COD = chemical oxygen demand (mg/l); BOD = five-day @ 20°C biochemical oxygen demand (mg/l). The U-matrix is an abstract 'plot' of the clusters in 2D space.

has been found of it having any distinct relationship with any other water quality variable). For the same reason, it is also not possible to accurately predict phosphorus concentrations in the effluent based on influent data; therefore, this variable always must be measured to check for compliance with current best management practice.

Annual Water Balance

General Observations for ICW Site 11. Hydraulic influences from extraneous sources were minimal at ICW site 11, thus allowing flow meters to be installed. Typical direct water flow from the sampled farmyard contributed to approximately 25% of the total inflow. The remainder came from rainfall directly falling onto the ICW (approximately 60%) and extraneous water (about 15%) possibly from grassland uphill of the first wetland cell. Approximately 25% of water exited the ICW through evapotranspiration. Roughly 70% of the treated water discharges to the soil below the wetland system. For cell 4 of site 11, most of the treated water discharging to the soil below the wetland system (approximately 45% of total) was lost in the ICW system. Only about 5% of the total water inflow (approximately 10% of the farmyard water) discharged to surface. Influent and effluent flows are presented in Figure 5. The seasonal pattern can be seen, with flow from the ICW only occurring for a short period during spring and winter.

Specific Hydraulic Flows for ICW Site 11. Inflows for cells 1 and 2, and outflows for cell 4 were continuously recorded and the results are show in Figure 5. Mean daily inflows, inflows to cell 2, and outflows from the ICW system during the monitoring period (April 2003 to April 2006) were 8.0 ± 4.54 m^3/d, 10.3 ± 14.69 m^3/d, and 0.6 ± 1.72 m^3/d, respectively. The standard deviations were large, indicating high data variability, which is typical of unstable and dynamic systems (Scholz 2006).

Although there was inflow to the ICW between August 2003 and December 2003, May 2004 and January 2005, and May 2005 and February 2006, there was frequently no outflow from the system during these periods. It follows that there is only

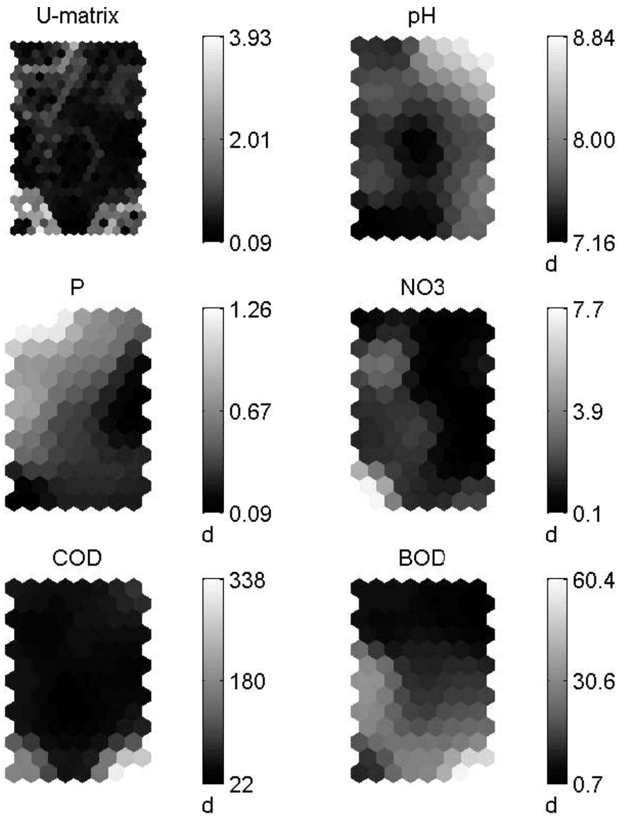

Figure 8. Diagrams of the self-organizing Kohonen map for Integrated Constructed Wetland (ICW) site 9 (outflow). The water quality abbreviations are as follows: NH_4 = ammonia-nitrogen, mg/l; P = phosphate-phosphorus in the form of molybdate reactive phosphorus (mg/l); NO_3 = nitrate-nitrogen (mg/l); SS = suspended solids (mg/l); COD = chemical oxygen demand (mg/l); BOD = five-day @ 20°C biochemical oxygen demand (mg/l). The U-matrix is an abstract 'plot' of the clusters in 2D space.

a short discharge period to surface receiving waters. Discharge was recorded during late winter and early spring. In general, all flows increased between late fall and winter, whereas flows generally decreased during summer (Figure 5). Rainfall on the previous wetland cell was an important contributor to within-system flows. This can be assumed since the effect of other water sources such as surface and subsurface runoff from the surrounding landscape was minimal at this particular site.

During dry weather periods, the loss of water from the ICW due to evapotranspiration and infiltration created an increased water storage capacity within wetland cells. This provided additional buffering capacity of the wetland during wet periods such that waters are stored within the wetland system prior to discharge.

Phosphorus Budget

Overall Observations. Sediment accumulations were measured for six representative ICW sites to obtain information on the nature and rate of sediment buildup in the ICW systems. The amount of sediment accumulation, the rate of buildup, the removal frequency, the composition of the sediment, and the management of removed sediment are the most important items of information for the design engineer.

Over a mean monthly period (sediment data only available for March 2005), an estimated 367.2 kg of phosphorus entered the ICW from the farmyard; 300.5, 21.5, and 45.2 kg were deposited as sediment in the first, second and third cells, respectively. The phosphorus discharged to the soil below the wetland system was expected to bind quickly to the receiving soils of the area (material derived from acidic volcanic rhyolithic and host shale). Finally, the outflow volumes to the receiving watercourses were low (0.5 kg).

Phosphorus Export for Example ICW Site 11. Comparisons were made between the export of phosphorus from the ICW site 11 during the monitoring period and phosphorus export rates reported from other Irish studies that assessed phosphorus losses from agricultural areas to watercourses (e.g., McGarrigle et al. 1993, Tunney et al. 1998, Morgan

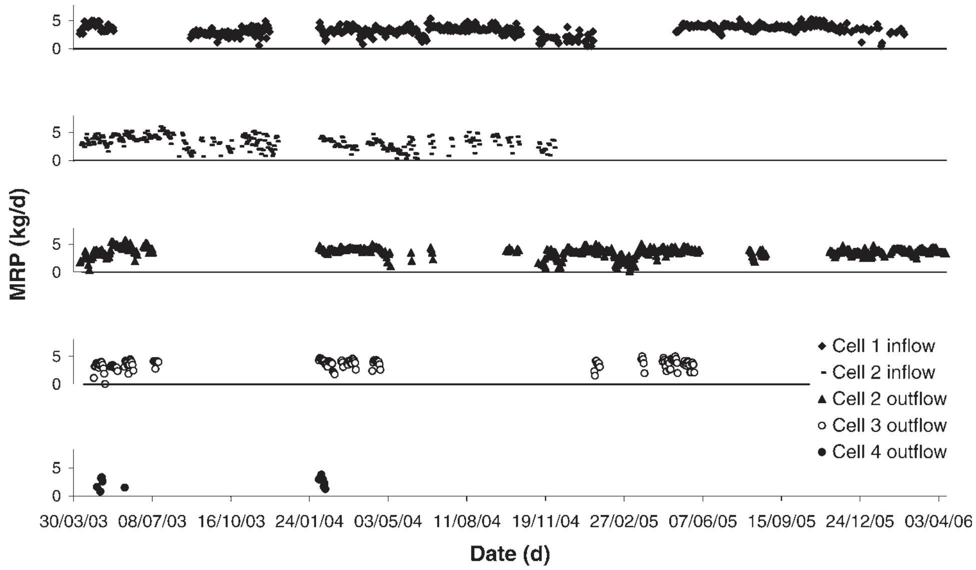

Figure 9. Molybdate reactive phosphorus (MRP) concentrations for the Integrated Constructed Wetland site 11 between April 7, 2003 and April 12, 2006. The total number of observations during this period was 1,729.

et al. 2000). A comparison of the phosphorus budget for various sampling sites in ICW 11 is given in Figure 9. Exports of phosphorus from site 11 were similar to background concentrations of phosphorus export from land to water, and lower than phosphorus loads in runoff from agricultural grassland. For example, Morgan et al. (2000) outlines that where farmyard dirty waters were not managed, leakage of phosphorus from farmyards can be high. Therefore, the appropriate management of these waters is important, and the application of ICW can be an appropriate management option.

Phosphorus Buildup in Sediment

Accumulation Rates and Sediment Composition. Findings related to sediment assessments are summarized in Tables 5 and 6. The mean depth of sediment for the ICW (Table 5) was 13.6 ± 10.12 cm. All ICW systems were in operation for five years and the mean rates of sediment accumulation were approximately 3 cm per annum for the moderately loaded systems. Assuming that each cell is 100 cm deep and allowing a minimum of 20-cm water depth and a further 20-cm freeboard, this leaves a capacity for 60 cm of accumulated sediment before removal is required. Therefore, at a sedimentation rate of 3 cm per annum, removal would be required at intervals of approximately 20 years if the sediment was equally dispersed throughout the entire wetland. This was not the case, however, as the rate of sedimentation varied considerably between individual wetland cells, and the removal frequency required for each cell will therefore vary accordingly.

The rate of deposition in each cell was related to ICW area. This relationship can be most easily explained by taking ICW sites 3, 9, and 11 as examples, as these have linear sequential cell configurations and single influent entry points at cell 1. The other ICW examined have either multiple influent entry points and/or parallel treatment cells, which complicated the interpretation of sediment accumulation rates.

Site 9 has a small (234 m^2) first cell followed by two medium-sized cells. Sediment buildup was low in cell 1 but higher in the second and third cells. At this rate of sedimentation, cells 2 and 3 would require desludging after approximately 13 years, while cell 1 would need desludging after approximately 45 years.

The general trend is that the sediment will preferentially settle in the first large cell of the ICW systems. If the initial cells of a system are relatively small, then a greater proportion of sediment will carry over into subsequent cells. This was observed on site 9, and to a lesser extent on site 3.

Mention should also be made of site 12, which was relatively heavily loaded (mean influent BOD 2,245 mg/l; Table 2) and had a configuration that included a small balancing pond. The annual sedimentation rate in cell 1 was 9 cm, indicating a period of approximately seven years before 60 cm of sediment accumulates in this pond and desludging is required. The remaining cells on site 12 had annual sedimentation rates of between 1 cm and 3 cm, indicating required desludging frequencies of between 20 and 60 years.

Table 5. Mean sediment accumulation and desludging frequencies for six representative Integrated Constructed Wetlands (ICWs).

ICW Site Number	Cell Number	Sediment Depth after 5 Annum of Operation (cm)	Pond Area (m^2)	Volume of Sediment (m^3)	Approximate Sludge Removal Frequency; i.e., Years to 60-cm Depth (a)
3	1	20	629	125.8	15
3	2	17.5	1,668	291.9	17
3	3	8	1,655	132.4	38
3	4	5	2,161	108.1	60
3	Total		6,113	658.2	
4	1	13.5	920	124.2	22
4	2	10	658	65.8	30
4	3	6	1,331	79.9	50
4	4	12	4,186	502.3	25
4	5	10	1,453	145.3	30
4	Total		8,548	917.5	
9	1	6.5	234	15.2	46
9	2	25	910	227.5	12
9	3	20	785	157.0	15
9	4	15	2,872	430.8	20
9	Total		4,801	830.5	
10	1a	20	155	31.0	15
10	1b	1	405	4.1	300
10	2	2	1,939	38.8	150
10	3	2	1,063	21.3	150
10	Total		3,562	95.1	
11	1	35	1,209	423.2	9
11	2	10	1,906	190.1	30
11	3	5	2,126	106.3	60
11	Total		5,241	720.1	
12	1a	10	1,041	104.1	30
12	1b	5	508	25.4	60
12	1c	45	179	80.6	7
12	1d	5	230	11.5	60
12	2	5	724	36.2	60
12	3	15	2,790	418.0	20
12	4	10	2,294	229.4	30
12	Total		7,766	905.2	

Table 6. Accumulation of total phosphorus (TP) in the sediment and likely farm phosphorus annual requirements (%) for selected Integrated Constructed Wetlands.

Site Number	Volume of Wet sediment After 5 Annum of Operation (m^3)	TP within the Sediment After 5 Annum of Operation (kg)	Annual TP Accumulation within the Sediment (kg)	Farm Size (ha)	Annual TP Needs per Farm at 10 kg/ha (%)	Annual TP Needs per Farm at 15 kg/ha (%)
3	658	265	53.0	61	10	6
4	917	438	87.6	121	8	5
9	831	290	58.0	56	12	7
10	95	26	5.2	78	1	0
11	720	367	73.4	130	6	4
12	906	529	105.8	158	7	4

Table 7. Annestown stream water quality monitored at four sites between 2001 and 2006. Summary statistics for five-day @ 20°C biochemical oxygen demand (BOD), ammonia-nitrogen, molybdate reactive phosphorus (MRP), and nitrate-nitrogen.

	Sampling Station (distance from sea)	BOD (mg/l)	Ammonia-Nitrogen (mg/l)	MRP (mg/l)	Nitrate-Nitrogen (mg/l)
Median	Ballyphilip upstream of Dunhill village (4 km)	1.2	0.06	0.03	5.0
Number of Observations		5	67	74	70
Median	Ballyphilip downstream of Dunhill village (3.5 km)	2.2	0.11	0.06	4.9
Number of Observations		16	76	84	77
Median (mean)	Dunhill Castle (2 km)	1.9	0.08	0.09	5.4
Number of Observations		16	79	88	83
Median	Monument (0.5 km)	2.0	0.12	0.05	4.4
Number of Observations		17	76	84	79

Due to variations in rates of sediment accumulation, the desludging frequency will also vary from cell to cell in any ICW system. If a large initial pond is used, then desludging of that pond only appears to be necessary approximately every ten years, as was the case for site 11. A system with smaller cells facilitates a greater spread of sediment (e.g., sites 3 and 9) and hence may need less frequent desludging (approximately each 15 years), but more cells are involved. For a heavily loaded system (e.g., site 12), the inclusion of a balancing pond to act as a sediment trap may extend the operational life of subsequent ponds before desludging is required. Any small balancing pond would require relatively frequent desludging (most likely annually), but could be configured to be as accessible as a standard slurry storage tank (Scholz 2006).

Management of Sediment. The most appropriate way of dealing with removed ICW sediment would appear to be land spreading on the farm in accordance with good farm management practice. The measured phosphorus accumulation for each ICW, expressed as kg per annum, and also as a percentage of likely farm phosphorus annual requirements, are presented in Table 6. For the moderately loaded ICW systems (excluding site 10), the phosphorus content of accumulated sediment would satisfy between 6% and 12% of the farms' annual requirement at a relatively low fertilization rate of 10 kg/ha P. If a fertilization rate of 15 kg/ha P was required, the ICW sediment would satisfy between 4% and 7% of the annual requirement.

A typical desludging schedule would involve one or two cells, containing approximately 60% of total stored sediment, every 10 to 15 years. Thus a typical desludging event could yield 20%–50% of a farm's annual phosphorus requirement. Furthermore, the storage requirements specified in good agricultural practice regulations with respect to farmyard manure should also suffice for ICW sediment to ensure environmental protection (see Stationary Office 2006).

Receiving-Stream Water Quality

Improvement in the Annestown stream water quality coincided with the operation of some ICW systems (Table 7), which treat approximately 75% of all farmyard dirty water generated within the watershed. Seven ICW systems representing more than 80% of farmyard discharge were located upstream of Ballyphilip bridge and Dunhill village (i.e., approximately half way along the stream and midway in the catchment). The water quality of this stream stretch complied with the target phosphorus concentration of a median annual concentration of 0.03 mg MRP/l as required by the Irish Phosphorus Regulations (1998). However, the stream's monitoring sites located downstream of Ballyphilip bridge and Dunhill village did not comply with this regulation. This lower section of the stream is therefore vulnerable to additional sources of nutrients originating from intensive farming of pigs and chickens, horse stabling, and discharges from the Dunhill village sewage works. Furthermore, the farmyard runoff interception by ICW was less than 70% in this lower section of the stream.

Table 8. Integrated Constructed Wetland (ICW) ground-water monitoring results between January and July 2006. N = number of entries.

Statistics	Location	Depth (m)	Ammonia (mg/l)	Nitrate (mg/l)	Molybdate Reactive Phosphorus (mg/l)	*Escherichia Coli* (per 100 ml)
			ICW site 1			
Mean	Farm well	-	0.02	13.4	<0.02	0
Mean	Well down-gradient of ICW cell 3	3	5.8	0.7	<0.03	<50
N			16	14	15	2
Mean	Well down-gradient of ICW cell 5	5	0.96	11.7	<0.02	<50
N			5	5	5	1
			ICW site 3			
Mean	Farm well	-	0.01	10.4	<0.02	0
Mean	Adjacent farmyard well	5	0.29	11	0.05	
N			6	6	6	
Mean	Well up-gradient of ICW cell 2	5	36	<0.03	0.09	100
N			6	6	6	2
Mean	Well beside ICW cell 3	5	11.3	1.6	<0.03	>5,000
N			14	12	14	2
Mean	Well down-gradient of ICW cell 4	3	8.7	1.3	0.17	75
N			5	5	5	0
			ICW site 11			
Mean	Farm well	-	0.01	12.6	<0.02	6
Mean	Well up-gradient of ICW cell 1	5	0.4	0.1	0.02	<50
N			4	4	4	1
Mean	Well down-gradient of ICW cell 3	5	0.77	<0.02	0.01	<50
N			7	7	7	2
Mean	Well down-gradient of ICW cell 3	3	3.8	<0.03	<0.03	<50
N			7	7	7	2
Mean	Well down gradient of ICW cell 4	5	2.9	<0.03	<0.02	<50
N			7	7	7	2
Mean	Well down gradient of ICW cell 5	5	0.3	<0.03	<0.02	<50
N			7	7	7	2

The biological water quality status of the stream has improved from an overall water quality rating of Q2 (seriously polluted) in 1999 to a water quality rating of Q3/4 (slightly polluted) in 2001 (EPA 2002). Further evidence suggests that the water quality rating has since improved to Q4 (unpolluted). Sea trout (*Salmo trutta*) have returned to the stream after many decades of absence. The common newt (*Tritarus vulgaris*) has become abundant in all ICW of the catchment. Although invertebrate monitoring within the catchment (i.e., for individual ICW and along the catchment's streams) is ongoing, preliminary results indicate great ecological habitat enhancement (unpublished; data not shown).

Ground-Water Quality

All ICW were constructed using *in situ* soils. Site subsoil was used and reworked to line wetland bed and bank surfaces, and topsoil was redistributed for plant establishment. This helped to impede infiltration from the bottoms and sides of cells. Inflows of farmyard dirty water were high in BOD and SS concentrations. As this water passes through the ICW, suspended organic material is typically deposited onto wetland soil surfaces, which also helps to impede infiltration from wetland cells (Kadlec and Knight 1996, Scholz 2006).

Nitrate concentrations were elevated (>10 mg/l) in most of the participating farmers' water supply wells (Table 8), which were monitored to assess background nitrate concentrations in ground water. These high concentrations suggested that the farmer's drinking water supply was impaired during the time of sampling. Nitrate concentrations of ground water in wells located uphill, downhill, or adjacent to ICW cells were generally lower (<0.6 mg/l) than those associated with farm wells. However, the mean concentration of 11.7 mg/l for site 1 was an exception. Ammonia concentrations for all wells uphill, downhill, or adjacent to ICW cells other than those present at site 3 were 2.4 ± 2.12 mg NH_4^+/l. At site 3, concentrations were much higher than at all other wells. Mean ammonia concentrations of well waters at this ICW site were 18.7 ± 15.07 mg/l. A possible explanation for these high concentrations is that these wells are within the floodplain of the Annestown stream, which has naturally high ammonia concentrations due to predominantly waterlogged organic-rich soil. The MRP concentrations and *E. coli* counts of well waters generally were low (Table 8). One borehole at site 3 had elevated *E. coli* counts. However, this borehole was occasionally surrounded by flood water from the adjacent Annestown stream.

A major objective of ICW design and operation is to eliminate the need for conventional land spreading of dirty water. Several studies in Ireland (e.g., Rodgers et al. 2003) have reported that land spreading of dirty water can lead to (either directly or indirectly) high nitrate concentrations in soil pore water and ground water. Given this evidence and the findings of the ICW Initiative, it seems that ICW cells could provide an appropriate alternative management option for the treatment of dirty water. The organic matter accumulating in the ICW greatly enhances the rate of impedance of water to the soil.

It is clear from these four ICW sites alone that the shallow ground water around the wetland cells is minimally affected by pollutant exfiltration, and the phosphorus means are consistently well below 0.1 mg/l (Table 8). This conclusion holds strong even for ICW site 7, a sewage treatment tank (Table 1), which is subjected to very high pollutant loads, and hence allows one to conclude that ICW do not pollute the underlying aquifers.

Finally, the ammonia-nitrogen concentrations observed in pyrometer samples close to ICW (apart from ICW site 3) were less than international drinking water nitrate-nitrogen thresholds (Scholz 2006), and as such would not cause ground-water contamination problems upon oxidation to nitrate.

Variables Influencing Wetland Performance

The mean and maximum MRP concentrations in the ICW effluents were used as the key indicator of water treatment performance. Effluent MRP concentration is considered an appropriate indicator, as phosphorus is recognized as one of the most difficult nutrients to remove from water and it is the limiting nutrient in most European and American freshwater systems (Scholz 2006).

For the purpose of analyzing the influence of ICW size on performance, the intercepted area from which water was observed to flow to the wetland system was measured. There was a significant correlation ($r = -0.81$; $p < 0.05$) between these ratios and wetland effluent MRP concentrations (Table 4). These findings suggest that interception areas such as farmyard open areas were important for adequate sizing of ICW to attain wetland effluent MRP concentrations of sufficient quality.

There was no obvious mathematical relationship between mean wetland influent and effluent MRP concentrations, nor was there a relationship between cow numbers and wetland effluent MRP concentrations. This may suggest that the amount of dairy wash water generated per cow has little effect on the overall performance of the ICW. Furthermore, there was no significant difference in effluent MRP concentrations between ICW systems receiving silage effluent and those that did not.

The MRP effluent concentrations for all ICW are shown in Table 4. All ICW were operated for a minimum of six years. Effluent MRP concentrations were variable (ranging between 0.04 and 5.25 mg/l) between and within sites during the monitoring period. Sites 3 and 4 had relatively high and variable effluent MRP concentrations with means of 3.38 and 1.62 mg/l, respectively. The remaining sites (with the exception of ICW site 7 which has an effluent MRP concentration of 5.25 mg/l) displayed less variability and relatively low (below 1 mg/l) mean effluent MRP concentrations (mean of 1.02 mg/l; standard deviation of 1.577 mg/l) in comparison to influent concentrations. The effluent quality did not worsen over the monitoring period.

Design Considerations

The cleansing effectiveness of surface flow wetland systems is typically based on having appropriate hydraulic residence times. In shallow, emergent, and/or vegetated wetlands, such as ICW, this depends on having sufficient functional wetland area with an appropriate length to width ratio and an emergent vegetation density. Surface hydraulic effectiveness of the ICW depends on 1) segmentation of the wetland into a number of wetland cells of appropriate configuration (see following), 2) avoidance of preferential flow (i.e., direct and linear flow path between inlet and outlet), 3) vegetation stand density, and d) managing the water depth to ensure optimal functioning.

Infiltration of wetland waters from wetland bed and bank surfaces, along with evapotranspiration, creates increased storage capacity (freeboard), thereby increasing hydraulic residence times. Such water

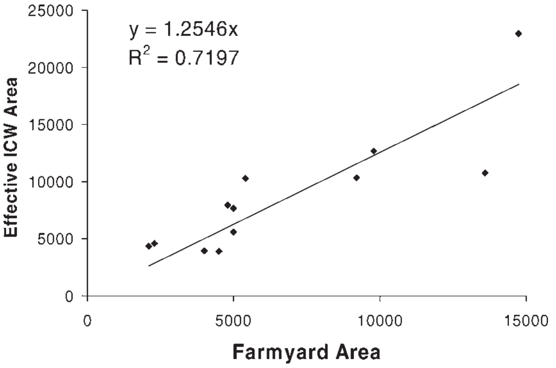

Figure 10. Linear regression plot of the farmyard area (m^2) versus the effective Integrated Constructed Wetland (ICW) area (m^2).

loss buffers the impact of precipitation-generated fluxes through the ICW system.

The required effective ICW area can be related to the farmyard area by a simple linear regression equation as shown in Figure 10, with a coefficient of determination (r^2) of 0.72. Consequently, the ICW area should be at least 1.3 times the farmyard area, and ideally closer to twice the interception area for some ICW systems to allow for topographical and other site conditions. From an exponential best-fit plot of the cell position versus the phosphorus concentration in the outflow from the cell (Figure 11, $r^2 = 0.34$), it is evident that the desired threshold of less than 1 mg/l is obtained when the ICW has four cells or more.

The aspect ratio is defined as the mean length of the wetland system divided by the mean width. In this study, aspect ratios ranged from 1.46–7.79 (Table 1). A linear regression analysis between the aspect ratio and the effluent phosphorus concentrations had a coefficient of determination of 0.55 (Figure 12). To obtain an outlet phosphorus concentration of 1 mg/l or less (see Irish Urban Waste Water Treatment Regulations 2001), the ICW aspect ratio should be less than 2.2. In fact, the closer the aspect ratio is to 1 (i.e., the more the ICW shape is square), the better the treatment properties of the wetlands.

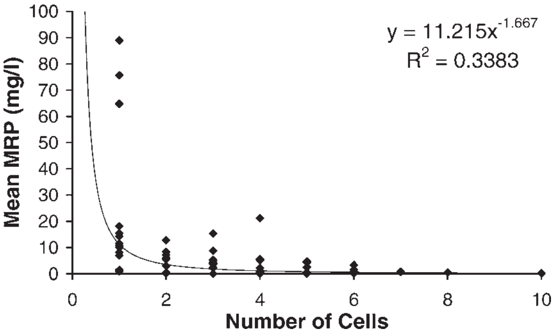

Figure 11. Exponential regression plot of the cell number and position *versus* the mean molybdate reactive phosphorus (MRP) (mg/l) concentrations at those cells for all ICW.

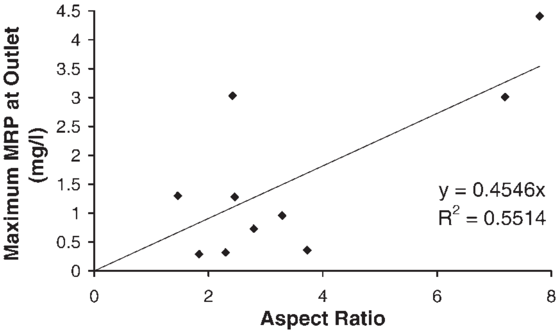

Figure 12. Linear regression plot of the Integrated Constructed Wetland (ICW) aspect ratio *versus* the maximum molybdate reactive phosphorus (MRP) (mg/l) concentration at the outlet of each ICW.

Contrary to the popular concepts behind traditional sewage treatment works (Kadlec and Knight 1996, Scholz 2006), the water must stay as long as possible in the ICW (and have as low a flow velocity as possible) to allow the respective plant ecosystems to develop, thrive, and be able to remove the pollutants. This is achieved by a square (or even better by a round cell, which is, however, not economic if land costs are high) cell geometry and low gradients, hence allowing the pollutant plume to spread as slowly as possible throughout each ICW cell.

Using the above guidelines, it is very simple to design the geometry of an ICW. For example, a dairy farm with an effective yard runoff area of 10,000 m^2 requires an ICW size of 12,546 m^2. If the ICW system should comprise (at least) four cells, all of them square, then each cell requires an area of 3,137 m^2 with dimensions of 56 m by 56 m (Figures 10 to 12). However, curvilinear ICW would be preferable in practice (see preceding). Increasing the cell count decreases the required size of any single cell. This, combined with remaining design guidelines (i.e., lining if ground water requires protection and appropriate freeboard) is sufficient to adequately design ICW. Further variables such as the number of milking cows, do not contribute to the accuracy of what is already a very simple design process and only introduce unnecessary complexity.

The summary water quality values in Table 2 illustrate that even ICWs following design guidelines inferior to those given previously (i.e., the aspect ratios are significantly above 2.2 for the majority of ICW in the Anne Valley, Table 1) are more than capable in treating dairy farm runoff effectively (with the obvious exceptions of ICW 3, 4 and 7, due to excessive gradients, too high aspect ratios, and/or overloading).

CONCLUSIONS

Findings suggest that ICW systems are capable of treating farmyard dirty water and that they provide a sustainable management option to effectively reduce nutrient and contaminant loss from farmyards to water resources. They also provide additional benefits such as habitat enhancement. Significant concentration reductions in suspended organic material, nutrients, and fecal bacteria between ICW influents and effluents were observed. Surface discharges from the ICW sites had seasonal patterns. The export of phosphorus from the intensively monitored ICW site 11 and most other ICWs to surface waters was similar to background phosphorus export rates.

Sediment accumulation in ICW occurs at a mean rate of approximately 3 cm per annum. The rate varies among ponds in individual systems and depends on the size of the wetland cells, the configuration of the system, and the nature of the influent. Based on quantified examples, it is likely that removal of sediment will be required approximately every 10 years from the first cell, and between 20 and 60 years from subsequent cells. The ICW sediment can be used as fertilizer and provide between 4% and 12% of a farm's annual phosphorus requirement.

Pyrometer well water quality data suggest that ICW had negligible effects on receiving ground water. This is important as present land spreading practices of farmyard dirty water can lead to the degradation of ground-water quality.

In terms of ICW design for the southeast of Ireland, it is proposed that the effective ICW area can be determined from the farmyard area by applying a multiplying factor of at least 1.3 to the latter. The optimal ICW cell aspect ratio (to achieve an effluent MRP concentration below 1 mg/l) is approximately 2.2, but performance improves greatly the closer this ratio is to unity (i.e., the ICW becomes square or, preferably, round but maintaining the same surface area). The recommended minimum number of cells within each ICW is four. However, constructing a greater number of curvilinear cells with greater surface areas is highly advised, as both the treatment performance and the aesthetical appeal of the ICW system increases substantially with increasing total wetland area.

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LITERATURE CITED

American Public Health Association (APHA). 1998. Standard Methods for the Examination of Water and Wastewater, twentieth edition. American Public Health Association (APHA), American Water Works Association and Water and Environmental Federation, Washington, DC, USA.

Bormann, F. H. and G. E. Likens. 1981. Pattern and Process in a Forested Ecosystem. Springer, New York, NY, USA.

Braskerud, B. C. 2002. Factors affecting phosphorus retention in small constructed wetlands treating agricultural non-point source pollution. Ecological Engineering 1:41–61.

British Standards Institute (BSI). 1999. Code of Practice for Site Investigation. BSI, London, UK. BS 5930.

Carroll, P., R. Harrington, J. Keohane, and C. Ryder. 2005. Water treatment performance and environmental impact of integrated constructed wetlands in the Anne Valley watershed, Ireland. p. 207–17. *In* E. J. Dunne, K. R. Reddy, and O. T. Carton (eds.) Nutrient Management in Agricultural Watersheds: A Wetlands Solution. Wageningen Academic Publishers, Wageningen, the Netherlands.

Dunne, E. J., N. Culleton, G. O'Donovan, R. Harrington, and K. Daly. 2005a. Phosphorus retention and sorption by constructed wetland soils in Southeast Ireland. Water Research 39:4355–62.

Dunne, E. J., N. Culleton, G. O'Donovan, R. Harrington, and A. E. Olsen. 2005b. An integrated constructed wetland to treat contaminants and nutrients from diary farmyard dirty water. Ecological Engineering 24:221–34.

Environmental Protection Agency (EPA). 2002. Interim report: the biological survey of river quality 2001. EPA, Johnston Castle, Wexford, Ireland.

Forget, C., A. Drizo, Y. Comeau, and R. P. Chapuis. 2001. Elimination du phosphore d'effluents de pisciculture par marais artificiel a substrat absorbant. Presented at Americana 2001, Reseau Environnement, Montreal, March 28–30 (in French).

Gray, S., J. Kinross, P. Read, and A. Marland. 2000. The nutrient assimilative capacity of maerl as a substrate in constructed wetland system for waste treatment. Water Research 34: 2183–90.

Harrington, R., E. J. Dunne, P. Carroll, J. Keohane, and C. Ryder. 2005. The concept, design and performance of integrated constructed wetlands for the treatment of farmyard dirty water. p. 179–88. *In* E. J. Dunne, K. R. Reddy, and O. T. Carton (eds.) Nutrient Management in Agricultural Watersheds: A Wetlands Solution. Wageningen Academic Publishers, Wageningen, the Netherlands.

Harrington, R. and C. Ryder. 2002. The use of integrated constructed wetlands in the management of farmyard runoff and waste water. *In* Proceeding of the National Hydrology Seminar on Water Resources Management Sustainable Supply and Demand. The Irish National Committees of the IHP (International Hydrological Programme) and ICID (International Commission on Irrigation and Drainage), Tullamore, Ireland.

Hill, C. M., J. Duxbury, L. Geohring, and T. Peck. 2000. Designing constructed wetlands to remove phosphorus from barnyard runoff: a comparison of four alternative substrates. Journal of Environmental Science and Health Part A – Toxic and Hazardous Substances and Environmental Engineering 35:1357–75.

Irish Phosphorus Regulations. 1998. Water Quality Standards for Phosphorus. Local Government (Water Pollution) Act 1977. Irish Government, Dublin, Ireland. S.I. No. 258 1998.

Irish Urban Waste Water Treatment Regulations. 2001. Urban Waste Water Treatment Regulations. Irish Government, Dublin, Ireland. S.I. No. 252 2001.

Kadlec, R. L. and R. H. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL, USA.

Karathanasis, A. D., C. L. Potter, and M. S. Coyne. 2003. Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. Ecological Engineering 20:157–69.

Keohane, J., P. Carroll, R. Harrington, and C. Ryder. 2005. Integrated constructed Wetlands for farmyard dirty water treatment: a site suitability assessment. p. 196–206. *In* E. J. Dunne, Ks. R. Reddy, and O. T. Carton (eds.) Nutrient Management in Agricultural Watersheds: A Wetlands Solution. Wageningen Academic Publishers, Wageningen, the Netherlands.

Lee, B. H. and M. Scholz. 2007. What is the role of *Phragmites australis* in experimental constructed wetland filters treating urban runoff? Ecological Engineering 29:87–95.

Lee, B. H., M. Scholz, and A. Horn. 2005. Constructed wetlands for the treatment of concentrated stormwater runoff (Part A). Environmental Engineering Science 23:191–202.

McGarrigle, M., T. Champ, R. Norton, P. Larkin, and M. Moore. 1993. The trophic status of Lough Conn, County Mayo, Ireland. Mayo County Council, Castlebar, Ireland.

Minitab Inc. 2003. Minitab Statistical Software, Release 14 for Windows. State College, PA, USA.

Mitsch, W. J. and J. G. Gosselink. 2000. Wetlands, third edition. John Wiley & Sons, Inc., New York, NY, USA.

Mitsch, W. J. and S. E. Jorgensen. 2003. Ecological Engineering and Ecological Restoration. John Wiley & Sons, Inc., New York, NY, USA.

Morgan, G., Q. Xie, and M. Devins. 2000. Phosphorus export from farm in Dripsey catchment, County Cork, Ireland. Environmental Protection Agency, Dublin, Ireland. Research and Development Report, Series No. 6.

Newman, J. M., J. C. Clausen, and J. A. Neafsey. 2000. Seasonal performance of a wetland constructed to process dairy milkhouse wastewater in Connecticut. Ecological Engineering 14:181–98.

Otte, M. L. 2005. Wetlands of Ireland – An overview: diversity, ecosystem services and utilization. p. 39–44. *In* E. J. Dunne, K. R. Reddy, and O. T. Carton (eds.) Nutrient Management in Agricultural Watersheds: A Wetlands Solution. Wageningen Academic Publishers, Wageningen, the Netherlands.

Reddy, G. B., P. G. Hunt, R. Phillips, K. Stone, and A. Grubbs. 2001. Treatment of swine wastewater in marsh-pond-marsh constructed wetlands. Water Science and Technology 44:545–50.

Rodgers, M., P. Gibbons, and J. Mulqueen. 2003. Nitrate leaching on a sandy loam soil under different dairy wastewater applications. *In* Proceedings of the International Water Association's 7th International Specialized Conference on Diffuse Pollution and Basin Management, University College Dublin, Dublin, Ireland.

Scholz, M. 2006. Wetland Systems to Control Urban Runoff. Elsevier, Amsterdam, the Netherlands.

Seo, D. C., J. S. Cho, H. J. Lee, and J. S. Heo. 2005. Phosphorus retention capacity of filter media for estimating the longevity of constructed wetland. Water Research 39:2445–57.

Smith, E., R. Gordon, A. Madani, and G. Stratton. 2006. Year-round treatment of diary wastewater by constructed wetlands in Atlantic Canada. Wetlands 26:349–57.

Stationary Office. 2006. European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006. Government Publications Office, Dublin, Ireland. S.I. No. 378 of 2006.

Tanner, C. C., J. P. S. Sukias, and M. P. Upsdell. 1999. Substratum phosphorus accumulation during maturation of gravel-bed constructed wetlands. Water Science and Technology 40:147–54.

Townend, J. 2002. Practical Statistics for Environmental and Biological Scientists. John Wiley & Sons, Inc., New York, NY, USA.

Tunney, H., O. Carton, T. O'Donnell, and A. Fanning. 1998. Phosphorus loss from soil to water. Teagasc, Ireland. End of Project Report ARMIS 4022.

United Nations Environment Programme (UNEP). 2003. Convention on Biological Diversity. 9th Meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (November 10–14, 2003), Montreal, Canada (UNEP)/CBD/SBSTTA/9/INF/4.

Vesanto, J., J. Himberg, E. Alhoniemi, and J. Parhankangas. 2000. SOM Toolbox for Matlab 5 Documentation. Helsinki University of Technology, Helsinki, Finland.

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