Nutrient release from integrated constructed wetland sediments receiving either farmyard runoff or domestic wastewater

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Abstract There is a risk that contaminants within wetland sediment can either be remobilized or reach the groundwater due to infiltration if the wetland is unlined. This research study assesses laboratory-based integrated constructed wetland (ICW) mesocosms operated in a temperature- and pressure-controlled environment. The wetland columns were filled with contaminated sub-soil collected from the first cell of full-scale ICW systems treating either farmyard runoff or domestic wastewater. The aim was to examine nutrient removal within oxidized and reduced sediment layers throughout the soil profile. The mean removal efficiencies for the farmyard runoff mesocosms were mostly negative for all nutrients such as ammonia-nitrogen (-147.6%), nitrate-nitrogen (87.9%) and ortho-phosphate-phosphorus (-193.9%). Similar values were observed for domestic wastewater treatment mesocosms (system I planted with *Phragmites australis* and system II planted with *Agrostis stolonifera*): ammonia-nitrogen (I: -2.8%; II: -53.4%), nitrate-nitrogen (I: -61.1%; II: -41.7%) and ortho-phosphate-phosphorus (I: -180%; II: -198.3%). Findings indicate that nutrients trapped within sediments leach gradually out into the less contaminated inflow water. The capacity of nutrient retention decreases as the wetlands age. The sediments acted as nutrient sources instead of nutrient sinks. Moreover, the wetland cells planted with *P. australis* achieved better results than cells planted with *A. stolonifera*.
Keywords Integrated constructed wetlands, sediment, soil, nitrogen, phosphorus, COD, groundwater

INTRODUCTION

Background

Integrated Constructed Wetlands (ICW) were originally designed and constructed to treat farmyard runoff and domestic wastewater within the Anne Valley near Waterford in Ireland. This unlined free surface flow wetland treatment system utilizes the same mechanisms that exist in natural wetlands, which include microbial, biological, physical and chemical processes (Scholz et al. 2007).

Purpose

Since wetland aging can be a problem that may contribute to a decrease in contaminant removal rates over time, the authors assessed the nutrient removal efficiency of ICW mesocosms and the nutrient accumulation within oxidized and reduced sediment layers. In addition, the variation of two species of macrophytes (*P. australis* and *A. stolonifera*) on nutrient reduction and the potential risk of ICW application to groundwater contamination were also studied.

MATERIALS AND METHODS

Site description

Integrated constructed wetland systems were constructed on various farm enterprises within the Annestown-Dunhill watershed. All systems have been in operation for at least eight years. The study presented in this paper relates to ICW 7 and ICW 11. The ICW 7 system has a total area of 0.3 ha and was designed to treat local sewage and to contribute to the improvement of the water quality of the Annestown stream. The wastewater inflow was approximately 40 m^3/day. The corresponding outflow was roughly 24 m^3/day.

In comparison, ICW 11 was constructed to treat farmyard runoff and wastewater within the catchments. The effluent entering the system comes from a dairy farm of 0.5 ha with 77 cows. The manure-contaminated wastewater was conveyed to the ICW system by gravity through pipes. Both ICW 7 and ICW 11 had four unlined cells in a row and the subsoil was reworked and used as a natural liner. The primary vegetation types planted were emergent species (helophytes).

Experiment set-up

Five free water surface horizontal-flow constructed wetland mesocosms were set up at The University of Edinburgh to provide nutrient removal and accumulation information. Details of mesocosm design are illustrated in Fig. 1. The laboratory was controlled in terms of temperature, light and humidity, which are key major environmental boundary conditions. The room temperature was maintained at 15ºC. The light was provided by programmable controlled UV lights (model F36W/GRO, Sylvania, Otley Road, Charlestown, Shipley, England, UK) simulating day and night sunshine. The mesocosms were constructed using polyvinyl chloride drainage pipes (height: 83 cm; diameter: 10 cm). Seven plastic taps were evenly placed around the circumference of the pipe for subsequent sample collection. All taps were being penetrated 1.5 cm deep into the rig to reduce preferential flow (‘side effects’) during sampling. Outflow water was collected with vinyl tubing (at the centre of the bottom plate) of 1.2 cm internal diameter.

Of the five mesocosms, two were fed with farmyard runoff (wetlands 1 and 2), which was collected weekly from an outdoor farmyard runoff drain at Gorgie City Farm (Gorgie Road, Edinburgh, Scotland, UK). The raw runoff contains contaminated organic matter such as leaves, cow faeces and urine. Three mesocosms (wetlands 3, 4 and 5) were fed with pre-treated domestic wastewater taken from Edinburgh Seafield Wastewater Treatment Plant (Marine Esplanade, Seafield Road, Edinburgh, Scotland, UK) once per two weeks.

Three planted experimental mesocosms (wetlands 2, 3 and 4) were packed with four successive layers (from bottom to top) of aggregates: 50 mm of small gravel (1.2-5 mm), 50 mm of sand (0.6-1.2 mm), 250 mm of sodium bentonite clay (permeability of 10^{-9} m/s) and 350 mm of core sediment (incorporating plants if applicable). These systems were flooded with inflow water at a depth of 100 mm. The core sediment samples of the farmyard runoff treatment mesocosms were directly taken from the surface of ICW 11 (wetland cell 1), which has been used for treating farmyard runoff for more than eight years. The core sediment samples of the domestic wastewater treatment mesocosms were extracted from the surface of ICW 7 (wetland cell 1), which was around seven years old. Two control mesocosms were set up as well. They had the same flow conditions and saturation ratio. The aggregates of the two control mesocosms (from bottom to top) contained 50 mm of small gavel (1.2-5 mm), 50 mm of sand (0.6-1.2 mm) and 600 mm of sodium bentonite clay (permeability of 10^{-9} m/s).

Phragmites australis (Cav) Trin. ex Steud (Common reed) rhizomes were obtained from a mature outdoor wetland rig located at The King’s Buildings, Edinburgh. *Agrostis stolonifera L.* (Creeping Bentgrass) rhizomes were obtained from ICW 7 located in Waterford, Ireland. Wetland 2 was planted with *P. australis* in February 2009. Wetlands 3 and 4 were planted with *P. australis* and *A. stolonifera* rhizomes, respectively, in May 2009. The control mesocosms were left unplanted.

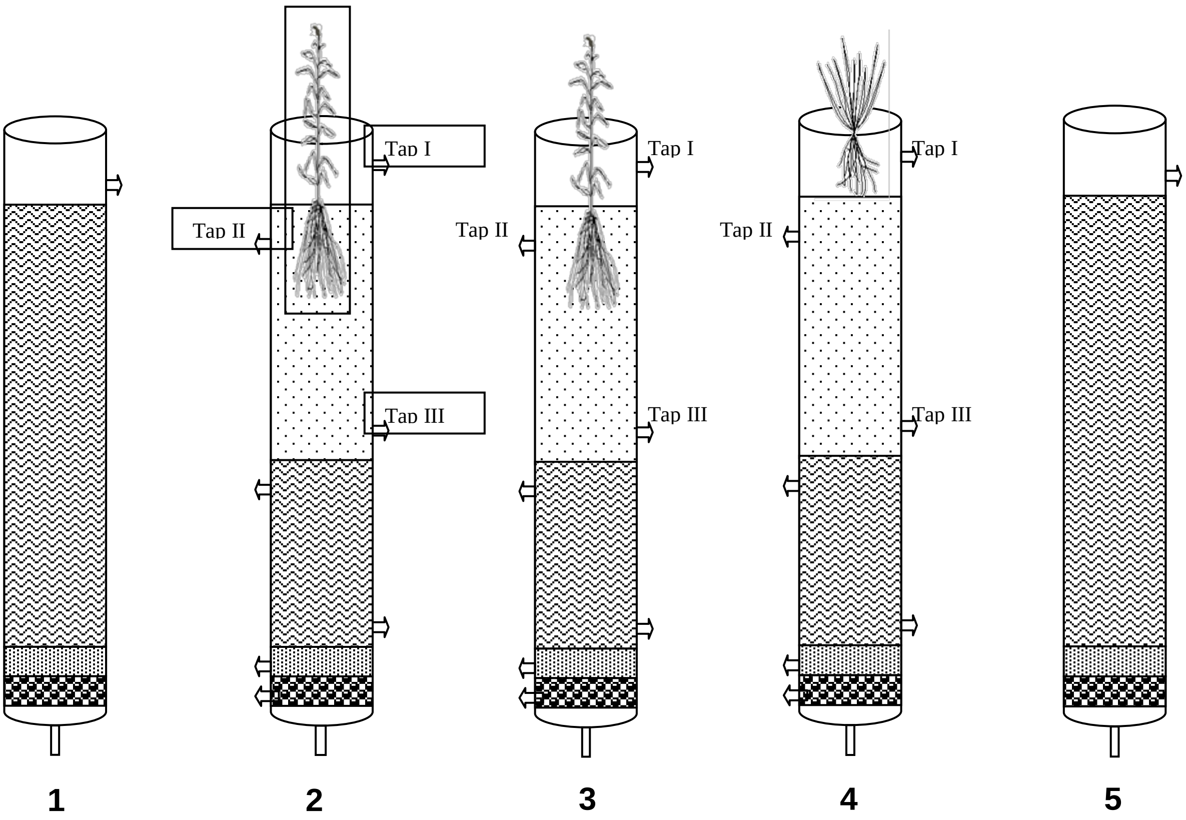

Fig. 1. Layout of integrated constructed wetland mesocosms.

Sampling and analytical methods

Water samples comprising 100 ml each were subsequently taken from the top (tap I) and the two bottom taps (tap II and tap III). Virtually no water infiltrated into the deeper layers due to the presence of clay. Therefore, water samples at the lower sampling points could not be taken from the corresponding taps. Collected samples were analysed for temperature, pH, conductivity, total dissolved solids, redox potential, dissolved oxygen, suspended solids and COD at The University of Edinburgh. Ammonia-nitrogen, nitrate-nitrogen, total organic nitrogen, chloride and molybdate-reactive phosphorus were tested at the Waterford Country Council water laboratory using American Public Health Association standard methods (APHA 1998) unless mentioned otherwise.

All Statistical analyses were carried out by using the software package Origin 8.0. A parametric analysis of variance was used to determine any significant ($p<0.05$) differences in removal percentages of all water quality variables for both ICW systems.

RESULTS AND DISCUSSION

Water quality

Experiments with the farmyard runoff treatment mesocosms were carried out between February 2009 and June 2010. The systems treating domestic wastewater were operated between May 2009 and June 2010. The first two months were seen as the start-up period characterized by system instability. The results are separated into two parts; namely farmyard runoff treatment and domestic wastewater treatment (Tables 1, 2 and 3).

As shown in Table 1, 2 and 3, organic matter is being released from the sediment into the top water layers for both systems. Kayranli et al (2009) summarized that processes such as biodegradation, photochemical oxidation, sedimentation, volatilization and sorption may affect the overall organic matter composition. It is also believed that the organic matter content and corresponding decomposition are influenced by parameters such as temperature (Barber et al. 2001; Savage and Davidson 2001), organic matter quality (Turcq et al. 2002), residence time (Yu et al. 2002), vegetation pattern, wetland maturity, sedimentation rate, sediment texture and sediment reworking (Shepherd et al. 2007).

Furthermore, the high concentration of ammonia was toxic to wetland plants, and their growth was therefore impaired. more than 90% of the plants were dead after three months. This change in plant cover considerably affects the oxygen transfer rate to the deeper sediment layers. Moreover, aerobic decomposition processes are reduced.

Table 1. Water quality variables for the farmyard runoff mesocosms (April 2009 – June 2010).

Var	n	Farmyard Runoff												
		Influent		Control		Tap I			Tap II			Tap III		
		Mean	SD	Mean	SD	Mean	SD	Rem	Mean	SD	Rem	Mean	SD	Rem
COD	47	74.0	24.6	114.9	22.4	87.8	26.7	-19	99.2	26.9	-34	140.1	48.1	-89
Am-N	42	1.5	1.4	0.1	0.1	3.6	2.5	-148	17.2	4.8	-1067	81.0	13.9	-5411
Ni-N	38	0.6	0.7	19.5	4.7	0.3	0.3	88	0.6	0.6	-11	1.2	1.0	-92
MRP.	42	1.0	0.6	3.8	1.2	2.9	1.1	-194	3.7	1.0	-274	10.7	2.4	-992
Chl	43	19.7	11.5	210.7	40.2	51.8	14.7	-163	46.8	11.7	-137	161.7	69.7	-720
Cond	50	217.8	78.9	1216.1	194.2	444.4	105.3	-	655.3	141.2	-	1943.6	297.5	-
Redox	48	-63	106	-102	111	-154	89	-	-220	130	-	-120	114	-
Wat T	51	18.2	2.7	16.3	1.4	16.7	1.4	-	16.8	1.3	-	16.5	1.1	-
pH	51	6.6	0.3	7.5	0.3	6.4	0.2	-	6.0	0.2	-	6.8	0.4	-

COD, chemical oxygen demand (mg/l); Am-N, ammonia-nitrogen (mg/l); Ni-N, nitrate-nitrogen (mg/l); MRP, molybdate reactive phosphorus (mg/l); Chl, chloride (mg/l Cl); Cond, conductivity (µS/cm); Redox, redox potential (mV); Wat T, water temperature (ºC); Var, variable; n, sample number; SD, standard deviation; Rem, removal efficiency (%).

In general, the ammonia-nitrogen concentrations for all systems were relatively high, in particular for sampling point III. This is probably because a large amount of ammonia-nitrogen accumulated at the bottom of the sediment, and was subsequently released during the study period. In constructed wetland systems, adsorbed ammonia is bound loosely to the substrate such as sediment, and can be released easily when the water chemistry and other environmental factors change.

Once the ammonia concentration in the water column has been reduced as a result of nitrification, some ammonia will be absorbed to regain an equilibrium with the new concentration (Lee et al. 2009). In addition, kinetic ammonification (mineralization) of organic nitrogen proceeds more rapidly than nitrification, thus creating the potential for an increase in ammonium concentration in the outlet.

The mean nitrate-nitrogen concentrations of farmyard runoff and domestic wastewater systems are shown in Tables 1 to 3. The low nitrification rate could have been caused by a number of factors, including oxygen shortage, low pH and low temperature values. The nitrification process is largely oxygen demanding. During the study period, most plants were dead where high concentrations of ammonia were present. This resulted in a low transferring of oxygen to the sediment.

Table 2. Water quality variables for the domestic wastewater mesocosm I (June 2009 – June 2010).

Var	n	Domestic wastewater												
		Influent		Control		Tap I			Tap II			Tap III		
		Mean	SD	Mean	SD	Mean	SD	Rem	Mean	SD	Rem	Mean	SD	Rem
COD	44	78.5	49.7	97.0	38.2	91.6	38.3	-17	131.6	52.1	-68	154.2	63.2	-96
Am-N	36	10.0	4.7	0.3	0.4	10.3	8.7	-3	47.4	23.0	-375	53.0	31.6	-432
Ni-N	20	0.4	0.1	2.2	2.2	0.6	0.3	-61	0.9	0.6	-150	1.2	0.7	-225
MRP	38	1.2	0.6	3.5	1.0	3.2	1.9	-180	3.7	1.7	-221	2.8	1.0	-146
Chl	39	106.8	39.7	491.5	84.6	233.5	44.4	-119	218.8	45.8	-105	333.8	152.7	-213
Cond	43	599.1	136.0	2327.1	221.8	1112.7	171.7	-	1415.9	121.2	-	2040.8	445.2	-
Redox	41	-82	103	-120	101	-200	74	-	-247	117	-	-201	111	-
Wat T	44	16.4	2.5	16.2	1.4	16.4	1.4	-	16.3	1.2	-	16.6	1.2	-
pH	44	6.7	0.3	7.5	0.2	6.6	0.2	-	6.5	0.2	-	7.4	0.7	-

COD, chemical oxygen demand (mg/l); Am-N, ammonia-nitrogen (mg/l); Ni-N, nitrate-nitrogen (mg/l); MRP, molybdate reactive phosphorus (mg/l); Chl, chloride (mg/l Cl); Cond, conductivity (µS/cm); Redox, redox potential (mV); Wat T, water temperature (ºC); Var, variable; n, sample number; SD, standard deviation; Rem, removal efficiency (%).

Table 3. Water quality variables for the domestic wastewater mesocosm II (June 2009 – June 2010).

Var	n	Domestic wastewater II												
		Influent		Control		Tap I			Tap II			Tap III		
		Mean	SD	Mean	SD	Mean	SD	Rem	Mean	SD	Rem	Mean	SD	Rem
COD	44	78.5	49.7	97.0	38.2	92.7	31.4	-18	118.8	49.9	-51	129.1	48.1	-64
Am-N	36	10.0	4.7	0.3	0.4	15.3	11.8	-53	40.1	21.8	-302	45.4	15.1	-355
Ni-N	20	0.4	0.1	2.2	2.2	0.5	0.3	-42	0.9	0.6	-147	1.5	0.7	-308
MRP	38	1.2	0.6	3.5	1.0	3.4	1.7	-198	4.4	2.2	-278	4.3	1.9	-271
Chl	39	106.8	39.4	491.4	84.1	161.0	28.6	-51	165.7	26.3	-55	220.8	67.8	-107
Cond	43	599.1	136.0	2327.1	221.8	883.1	129.2	-	1110.5	144.2	-	1423.6	217.6	-
Redox	41	-82	103	-120	101	-286	110	-	-265	113	-	-272	102	-
Wat T	44	16.4	2.1	16.4	1.4	16.6	0.2	-	16.8	1.6	-	16.5	1.3	-
pH	44	6.7	0.3	7.5	0.2	6.2	0.2	-	6.1	0.1	-	6.5	0.2	-

COD, chemical oxygen demand (mg/l); Am-N, ammonia-nitrogen (mg/l); Ni-N, nitrate-nitrogen (mg/l); MRP, molybdate reactive phosphorus (mg/l); Chl, chloride (mg/l Cl); Cond, conductivity (µS/cm); Redox, redox potential (mV); Wat T, water temperature (ºC); Var, variable; n, sample number; SD, standard deviation; Rem, removal efficiency (%).

The concentration of molybdate reactive phosphorus (MRP) found in the mesocosm treating farmyard runoff and domestic wastewater increased steadily from sample tap I to III through the study. These findings indicate that the sediments were saturated with MRP, acting therefore as the source of MRP. The alteration of environmental conditions such as the contact with less polluted incoming water triggered the phosphorus releasing process, resulting in a decrease of the removal efficiency (Carucci et al. 1997; Panswad and Anan 1999; Wang et al. 2007).

Annelies et al. (2009) discovered that some surface flow and subsurface flow constructed wetlands initially remove phosphorus and later on release it again from the substrate. In addition, the carbon concentration may also influence the phosphorus removal efficiency either by blocking the adsorption sites or competing with phosphates for them (Sakadevan and Bavor 1998; Vohla et al. 2007). A study by Mann and Bavor (1993) monitored the performance of a full scale subsurface flow gravel wetland over two years and demonstrated that non-reactive sorbents can remove significant amounts of phosphorus, but that sorption sites for removal quickly become saturated.

Vegetation types

Concerning the two mesocosms treating domestic wastewater, COD, ammonia-nitrogen and MRP concentrations were lower for wetland 3 compared to wetland 4. It is a possibility that the presence of *P. australis* within the wetland systems has limited the diffusion of oxygen to the lower sediment layers. Relatively low oxygen concentrations can be identified as the main contributor to the inadequate removal of COD and ammonia-nitrogen.

Groundwater contamination

The ICW was constructed using in situ soils. As the contaminated effluent passes through the system, the suspended matter settles on the soil surface and subsequently slows the infiltration of contaminants through the wetland cells (Scholz 2006). An outlet tube was located on the base plate of each experimental mesocosm to gauge the possibility of groundwater contamination by infiltration of the polluted water. However, throughout the study period, no groundwater contamination was recorded.

The decrease of infiltration rate was probably because the compact bentonite clay layer acted as an excellent barrier to prevent nutrient transfer to potential aquifers. Furthermore, there are many biogeochemical processes that play important roles in clogging of the soil matrix; for example, biomass accumulation and/or insoluble biogas (i.e. methane) formation through soil microbes (Kellner et al. 2004; Tokida et al. 2005).

Sediment management

Sediment serves as the reservoir of contaminants within a wetland system, and was identified as the source for contaminants during long-term operation. In March 2005, sediment accumulations were measured at six ICW sites in Waterford. The mean rates of sediment accumulation were approximately 3 cm per annum for the moderately loaded systems, but in fact the rate of sedimentation varied between individual wetlands, and the removal frequency required for each cell was therefore different.

Previous research (Scholz 2007) results indicate that the approximate sludge removal frequency of cell 1 within ICW 11 would be nine years taking the overall pond capacity into account. However, from the nutrient removal perspective, a higher desludging frequency of five or six years appears to be necessary.

CONCLUSIONS

The concentrations of most water quality parameters such as COD, ammonia-nitrogen, nitrate-nitrogen and MRP increased with soil depth for all ICW mesocosms. The nutrient removal performances of the sediments were relative poor and the systems acted as nutrient sources rather than nutrient sinks.

Due to several years of full-scale operation and high nutrient loadings entering the full-scale ICW systems, high amounts of nutrients were trapped and accumulated at the bottom of the sediment. Most plants died during the course of the study due to elevated ammonia-nitrogen and/or salinity within the wastewaters. The restricted oxygen transfer through vegetation adversely affected the removal efficiency of COD and ammonia nitrogen.

Wetland designers and operators should take sediment accumulation rates into consideration. For similar operations, sediments should be removed from the first cell of an ICW system after approximately five to six years of operation to maintain high removal efficiencies.

The compact bentonite clay layer was an excellent barrier to prevent nutrient transfer to potential aquifers. The frequent absence of an artificial liner such as bentonite clay makes ICW technology affordable. However, appropriate sediment management is paramount to protect groundwater and receiving watercourses during storm events.

There is still limited understanding of the key biotic and abiotic variables, their interactions at temporal and spatial scales, and their effects on nutrient removal or accumulation within sediments. Further research should also investigate the sediment nutrient removal capacity both in pilot-scale and full-scale ICW under natural environmental conditions.

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