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Nutrient Accumulation in *Typha latifolia* L. and Sediment of a Representative Integrated Constructed Wetland

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Abstract This paper investigates the role of plants and sediment in removing nutrients from wastewater being treated in a representative integrated constructed wetland (ICW). It discusses the role of plants and sediment in removing nutrients from an ICW treating agricultural wastewater for more than 7 years. More nitrogen and phosphorus were stored in wetland soils and sediments than in plants. The first cell had the highest depth of sediment accumulation (45 cm). Over the 7-year operation period, the accretion rate was approximately 6.4 cm/year. With respect to maintenance, desludging of the first wetland cell of the ICW system appears to be necessary in 2011. An average of 10,000 m^3 per year of wastewater entered the ICW. Approximately 74% (780 kg) of the phosphorus and 52% (5,175 kg) of the nitrogen that entered the wetland system was stored in the wetland soils and sediments. Plants stored a small fraction of nutrients compared to soils (<1% for both nitrogen and phosphorus). This study demonstrates that soils within a mature wetland system are an important and sustainable nutrient storage component.

Keywords Nitrogen · Phosphorus · Mature wetland · Accretion · Vegetation · Soil

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1 Introduction

In addition to water quality improvement, wetland plants also have various physical and ecological functions such as transpiration, particulate trapping and flow impedance, while the ecological functions include human use values and wildlife habitat enhancement (Kadlec and Wallace 2009; Scholz 2006). In free water surface constructed wetlands, vegetation influences the treatment mechanisms by reducing water column mixing; hence, it increases sedimentation, and also provides surface area for biofilm attachment (US EPA 2000; Wallace and Knight 2006). Karathanasis et al. (2003) reported higher biochemical oxygen demand and suspended solids removal in planted compared to unplanted systems. Moreover, wetland plants utilise nitrogen and phosphorus for their growth and reproduction. In this way, a portion of nutrients in the water column is transferred to plants, contributing to water quality improvement by reducing nutrient concentrations of the wastewater flowing through the wetland system (Scholz and Hedmark 2010). Moreover, cycling and build-up of plant-derived organic matter provides a sustained supply of organic carbon for microbes, and also sequester organically bound nutrients and act as a barrier to nutrient release (Tanner et al. 1998).

Studies have indicated that improved nutrient removal occurs in planted wetlands compared with unplanted systems (DeBusk et al. 1989; Soto et al. 1999; Tanner et al. 1995; Tanner 2001). However, these studies involved comparatively immature systems where plant uptake and sediment adsorption pools had remaining filling capacity. Borin and Tocchetto (2007) investigated the performance of a constructed surface flow wetland in reducing diffuse nitrogen pollution. They estimated that over a 5-year period, the wetland had a 90% nitrogen-removal efficiency and found that most of the removal was due to plant uptake. Moreover, Gottschall et al. (2007) found that plant uptake was significant ($p<0.05$) for overall nutrient removal in a well-established constructed wetland treating agricultural wastewater since 1996.

Case studies of animal wastewater treatment wetlands have shown varying nutrient removal rates (e.g. 45–98% nitrogen and 35–96% phosphorus) with generally higher nutrient removal in recently established wetlands and those with lower loading rates (Hammer et al. 1993; Hunt and Poach 2000; Newman et al. 2000; Schaafsma et al. 1999). However, most studies were conducted when vegetation was still establishing itself, so there is a lack of information concerning long-term nutrient storage within the vegetation pool in constructed wetlands. There are also concerns about long-term phosphorus removal as the sorptive capacity of wetland soil becomes saturated over time (Wood et al. 2008). Consequently, wetland scientists are sceptical, and have concerns about the long-term performance of these systems, especially in terms of nutrient removal.

As a wetland ages, the creation of new soils and sediments occurs. The incoming solids settle and simultaneously plant litter decomposes. Plant shoots, roots and rhizomes senesce and decay. Some portions of necromass (aboveground and belowground) resist decay and form new accretions that are stable. New sediments comprise the remnants from plant stems, leaf debris, dead roots and rhizomes, and also from undecomposable fractions of dead algae, fungi, invertebrates and bacteria. These new stores of nitrogen and phosphorus are assumed to be decomposition resistant. The least studied aspect of nitrogen and phosphorus transfer in wetlands is these new stores (Kadlec 2005, 2009b).

Ammonia and nitrate are the two most important species of nitrogen that are generally used for assimilation. Ammonia uptake is favoured by wetland plants over nitrate uptake, except for cases in which incoming waters have high concentrations of nitrate. *Typha latifolia* L. (Bulrush, Greater Reedmace or broadleaf cattail) are very able to utilise either nitrate or ammonia (Brix et al. 2002), but there are considerable seasonal variations. For example, Brisson and Chazarenc (2008) reported that in summer *Carex rostrata* Stokes in Withering 1787 (bottle sedge, beaked sedge) removed more ammonium than *T. latifolia*, but the latter removed more total nitrogen in winter. Zhu and Sikora (1995) conducted a short-term study on several surface-flow gravel-based wetland microcosms, and found that between 70% and 80% of the entire nitrate loss was by plant uptake; species wise, 85% of the nitrate was taken up by *Scirpus atrovirens* Willdenow var. *georgianus* (R. M. Harper) Fernald ((Georgian) bulrush), 75% by *T. latifolia*) and 70% by *Phragmites australis* (Cav.) Trin. ex Steud. (Common Reed).

In newly constructed wetlands, the development of new vegetation generates a demand for nitrogen that continues only during the growth period (Scholz and Hedmark 2010). For example, Sartoris et al. (1999) conducted a 2-year study of a 9.9 ha free water surface flow constructed wetland at Hemet (California, USA) and reported that as the plant coverage enhanced from near zero (planted clumps at 1.2-m spacing) to about 80%, and vegetation density increased by 67%, there was a decrease in ammonia load from the wetland from 98 to 15 g nitrogen/m^2/a. Subsequently, they found that plant uptake was a primary sink for nitrogen. Nevertheless, the biomass in wetlands has only a finite capacity to retain nutrients. Kadlec (2009b) reported that at the Houghton lake wetland project, removal of nitrogen was controlled by processes involving vegetation and associated biota. Approximately 20% of the added nitrogen was sequestered in the new, larger standing crops.

Phosphorus processing in plants is associated with the important effects of storage and release, and sediment accretion (Kadlec 2005). Plants follow a growth cycle in which phosphorus is stored and released seasonally, and they also assist in the creation of new and stable residuals accreting in wetland systems. Phosphorus is contained in these residuals as part of their structure, and thus accretion is a burial process for phosphorus. The biomass compartment in wetlands has a finite capacity to retain nutrients but accretion is a sustainable process. Kadlec and Bevis (2009) reported that at the Houghton lake wetland project, removal of phosphorus was controlled by processes involving vegetation and associated biota. Approximately 14% of the added phosphorus was sequestered in the new, larger standing crops.

A review of wetland science literature identifies the role of accretion as the main long-term storage for phosphorus, but much of the literature does not address the mechanism of soil-building as a route of nutrient immobilisation. For example, Craft and Richardson (1993) and Reddy et al. (1993) have identified accretion as a principal long-term storage for phosphorus. However, Crites et al. (2006) have ignored accretion as a process for phosphorus storage. A long-term study by Kadlec (2009b) clearly demonstrates that some authors have overlooked the process of soil accretion for phosphorus storage. Nevertheless, US EPA (2000) correctly identifies accretion and burial as a sustainable mechanism. The burial of phosphorus in new accretions of sediments and soils provides a means for sustainable removal (Kadlec 2009b).

Kadlec (2009b) described the development of changes in sediment and soils in a study encompassing three decades of full-scale operation of a lake-like wetland treating wastewater. He found that long-term storage of nutrients in the studied wetland was dominated by the formation and accretion of the new soils, and he concluded that after a period of approximately 5 years, virtually all of the added phosphorus was stored in new soils and sediments.

The aim of this study was to assess the role of plants (particularly *T. latifolia*) and sediment in full-scale ICW treating farmyard runoff. The objectives were to assess the contribution of nutrient uptake by emergent macrophyte, nutrient storage in the accumulated sediments, and new accretions in a mature wetland system.

2 Materials and Methods

2.1 Plant and Sediment Sampling

Plant and sediment samples were collected from the first cell of the ICW 11, where the major contaminant removal is likely to take place (Mustafa et al. 2009). This wetland is located in County Waterford (south-east of Ireland), at a longitude of 07º02′40″ W and a latitude of 52º11′28″ N. The ICW system was constructed in 2000, and commissioned in February 2001 to contribute to the improvement of the water quality of the Annestown Stream. The ICW system has a total area of 0.76 ha. The primary vegetation types used in the ICW are emergent plant species. The first three cells were densely vegetated while the last cell had only sparse vegetation. The cells were not lined with an artificial liner. However, the subsoil was reworked and used as a natural liner. The water flows by gravity through a pipe between each cell. The effluent entering the ICW system comes from a dairy farm of 0.5 ha with 77 cows. The wastewater contained farmyard and roof runoff occasionally contaminated by manure, and was conveyed to the ICW system by gravity through a pipe (Mustafa et al. 2009).

A total of 18 samples of sediment and plants from the first ICW cell were collected and analysed for nutrients. The above ground and below ground biomass of *T. latifolia* in the wetland cell were sampled and analysed for nutrients in summer and winter 2008. Three locations (one near the inflow, one at the middle of the wetland cell and one near the outflow; Fig. 1) were selected, and three quadrants were positioned (0.25 m^2 plots) at each location. Hence, plants were harvested in nine quadrants of the ICW cell during the collection period for a total of 18 quadrants (i.e. nine quadrants per two seasons). For above ground biomass evaluation, the plots were harvested and biomass was separated from the upper zone (leaves and stem), while for the below ground biomass evaluation, it was separated from the lower zone (roots and rhizomes). The samples were sorted and washed in the laboratory, and subsequently dried in an oven at 80°C for a minimum of 48 h. After drying, the samples were weighed and the plant material was ground to less than 1 mm (Planetary Ball Mill PM 100, Retsch, Germany) for nutrient analysis, using standard methods. Plant cover was

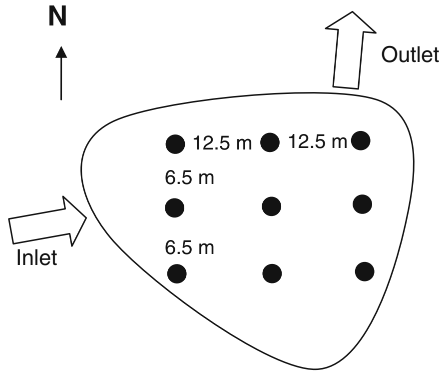


Fig. 1 Plan view sketch of the integrated constructed wetland cell showing sediment and plant sampling locations

assessed by measuring the area occupied by each species in the wetland.

Sediment samples were also collected from the same locations as the macrophyte samples to assess the sediment depth and quality. The sampling was conducted along transects across each wetland cell; three points along the primary axis from the main inlet to the outlet of each pond, and also perpendicular to this. The water depth was measured, and sediment cores were collected in a plastic liner (diameter, 48 mm) within a stainless steel aquatic sediment sampler (Wildco hand corer; length, 0.51 m), equipped with a Lexan nosepiece and a rubber flutter valve to provide suction. The corer was attached to a steel extension rod and driven into the sediment by hand for sample collection. The sampling points were marked with permanent markers and ropes to ensure that the sediment samples were collected from the same locations during both seasons. This procedure allows for a comparison of results between seasons. Samples were divided into five subsections: top sediment, middle sediment, bottom sediment, top clay and bottom clay. The samples were transferred to sample bags and retained for subsequent laboratory analysis.

2.2 Nutrient and Carbon Analysis

For the determination of total nitrogen and total phosphorus in the plant and sediment, the samples were milled and subsequently oven-dried. Kjeldahl digests were prepared. For laboratory quality control purposes, all analyses were performed with certified reference material. Total nitrogen and total phosphorus concentrations were subsequently determined by automated colorimetry (Auto analyser, Bran+Luebbe, Model AA3, Norderstedt, Germany).

Carbon was determined in the soil and litter samples using a Carlo Erba NA2500 Elemental Analyser. The method is based on the complete and instantaneous oxidation of the sample by flash combustion, which converts all organic and inorganic substances into combustion products. The resulting gases pass through a reduction furnace and are swept into the chromatographic column by helium used as a carrier gas. The gases are separated in the column and detected by the thermal conductivity detector, which gives an output signal proportional to the concentration of the individual components of the mixture.

2.3 Statistical Analyses

All statistical analyses were performed using the analytical and graphical software tool Origin 7.5. The seasonal effects on water quality improvement were tested by analysis of variance (ANOVA) at $p < 0.05$. The effects of sampling date and sampling location on plant tissue nutrients (above ground and below ground nutrient content) were tested by analysis of variance (two-way ANOVA). To determine the influence of wastewater nutrient concentrations on the plant uptake, regression analyses were conducted.

2.4 Limitations and Estimations

The ICW system studied is semi-natural and open. Inflow and outflow loading rates, and losses to groundwater or athmosphere cannot be accurately determined. Nevertheless, the total mass removal of nutrients in the ICW cell was estimated using mean inflow and outflow nutrient concentrations, as well as flow rate data calculated from the annual water budget of the wetland system, which was determined previously by Mustafa et al. (2009).

3 Results and Discussion

3.1 Nutrient Uptake by Vegetation

The nutrient content of the above ground and below ground *T. latifolia* biomass varied noticeably. In summer, at most locations the above ground tissues had a higher nutrient content than the below ground plant matter (Fig. 2). Conversely, in winter, the below ground biomass had a higher nutrient content than the above ground tissues. Two-way ANOVA (Table 1) were conducted to test the significance of differences over the two seasons and between various sampling locations. With regard to the locations of sampling points, there were no significant differences observed for both total nitrogen (p=0.413) and total phosphorus (p=0.530). This can be explained by the fact that

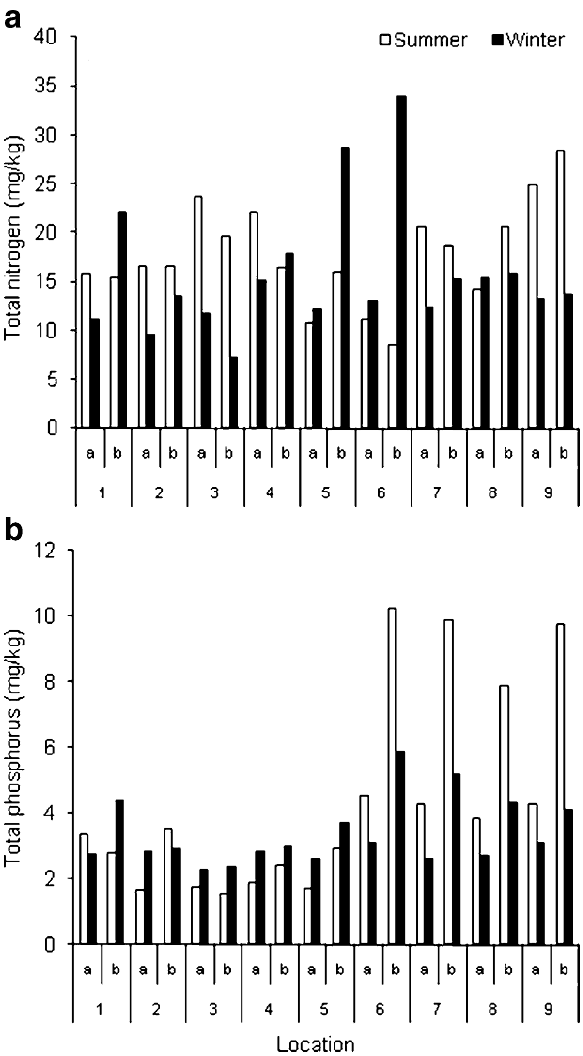


Fig. 2 Mean concentration of **a** total nitrogen and **b** total phosphorus in the aboveground and belowground plant tissues of the studied integrated constructed wetland system during summer 2008 and winter 2008. *a*, stem and leaves; *b*, roots and rhizomes; *1–9*, sampling quadrants

Table 1 Two-way analysis of variance results for nutrient content of *Typha latifolia* L. at the integrated constructed wetland in 2008

Factor	*df*	*F* static	*p* value
Total nitrogen (main effects)			
Location	8	0.687	0.413
Date	1	85.99	0.000
Interaction			
Location × date	8	0.687	0.413
Total phosphorus (main effects)			
Location	8	0.401	0.530
Date	1	2.172	0.150
Interaction			
Location × date	8	0.401	0.530

The effects of location and date were tested

df degrees of freedom

dense vegetation and a relatively low flow velocity do not lead to preferential flow paths within the wetland.

Differences by sampling dates were found to be highly significant for total nitrogen only (p<0.001). With change in seasons, there is translocation of nutrients within the plants. Prior to senescence in autumn, the important ions are translocated from the shoots to the roots and rhizomes. The stored nutrients are then utilised in early spring growth (Garver et al. 1988).

To find the relationship between surface water quality and plant nutrient (particularly total nitrogen and total phosphorus) uptake, regression analyses were conducted. However, the regression analyses revealed no significant relationships between surface water nutrients and the concentrations of nutrients in plants (Table 2). Significant relationships between ammonia concentrations in the wastewater and total nitrogen concentrations in plant tissues were observed; corresponding R^2 values ranged between 0.38 and 0.89.

A previous study of the seasonal variations in ICW performance for nutrient removal indicated high ammonia-nitrogen efficiencies during spring and summer (Mustafa et al. 2009). The sampling for this study was carried out in mid-summer, a period when the plants had fully grown and utilised the nutrients in rebuilding their tissues. Gottschall et al. (2007) found significant relationships between ammonia concen-

Table 2 Regression analyses for plant and water quality data at the studied integrated constructed wetland (2008)

Season	Dependent variable	Predictor	Significant difference	R^2	p value
Summer	Total nitrogen in a and b	Ammonia-nitrogen	Above	0.89	0.01
			Below	0.65	0.01
	Total nitrogen in a and b	Nitrate-nitrogen	Above	−0.09	0.52
			Below	0.48	0.35
	Total phosphorus in a and b	Molybdate reactive phosphorus	Above	−0.47	0.65
			Below	−0.25	0.58
Winter	Total nitrogen in a and b	Ammonia-nitrogen	Above	0.88	0.01
			Below	0.38	0.03
	Total nitrogen in a and b	Nitrate-nitrogen	Above	−0.44	0.64
			Below	−0.57	0.69
	Total phosphorus in a and b	Molybdate reactive phosphorus	Above	−0.47	0.65
			Below	−0.89	0.82

a above plant matter, *b* below plant matter

trations within wastewater and corresponding total nitrogen values in plants.

The ICW system studied here was dominated by ammonia-nitrogen. The first cell of this wetland system had the highest ammonia-nitrogen concentrations, and it is likely that during the growing season (i.e. in spring when the plants rejuvenate), plant uptake was driven by the ammonia concentrations within the wastewater. A study by Gottschall et al. (2007) also confirms this. Moreover, Brix et al. (2002) found higher nutrient uptake and growth rates for *T. latifolia* when supplied with ammonia rather than nitrate as the exclusive nitrogen source.

Figure 3 represents nutrient content changes in tissues of *T. latifolia*. There was a marked difference among above ground and below ground tissues during the two sampling periods. More nutrients (nitrogen and phosphorus) were stored in the below ground tissues in summer as compared to winter for the obvious reason that there is a translocation of nutrients (Meuleman et al. 2002). Gottschall et al. (2007) also found nutrient content changes in plant tissues with respect to seasons. Differences by sampling date were found to be significant only for total nitrogen but not for total phosphorus (Table 2). The results corroborate with those by Gottschall et al. (2007)

3.2 Nutrients in Litter

Mean total nitrogen and total phosphorus concentrations in litter were 17.3 g/kg and 1,550 mg/kg, respectively. Debusk and Reddy (2005) conducted a study of litter decomposition and nutrient dynamics in the Everglades marsh, and found mean total nitrogen and total phosphorus concentrations in *T. latifolia* and *Cladium* (fen-sedge, sawgrass or twig-sedge) litter were 22,000 and 1,153 mg/kg, respectively. Some nitrogen is utilised by plants and remaining nitrogen uptake is either leached from biomass or necromass (weight of dead organisms) into water in a soluble form or remains in dead plants (Kadlec 2005). The poorer fall performance of ICW in ammonia removal (Mustafa et al. 2009) is most likely due to the return of soluble nitrogen to the water column. However, partially decomposed litter of *T. latifolia* is characterised by low nitrogen and phosphorus content, primarily due to leaching. When this partially decomposed litter is added to the wetland soil surface, it acts as a strong nutrient sink because of its relatively high carbon content as compared to the carbon content of the soil layer below. Debusk and Reddy (2005) reported that the high sink strength of litter in the Everglades marsh was due to the combination of an extremely low nutrient content and relatively high carbon quality.

3.3 Sediment Accumulation

The amount of sediment accumulation, rate of build-up, removal frequency, sediment composition and management of removed sediment are the most important items of information required by the design

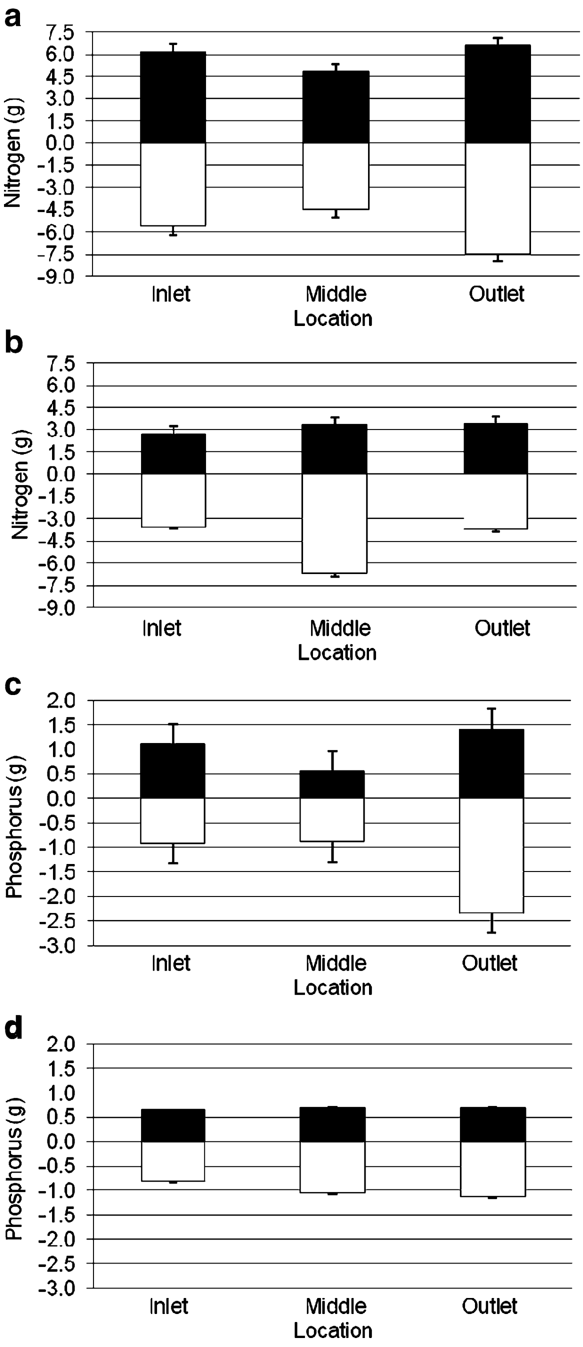


Fig. 3 Changes in **a** total nitrogen in summer, **b** total nitrogen in winter, **c** total phosphorus in summer, and **d** total phosphorus in winter within the *Typha latifolia* L. plant tissues in cell 1 for the integrated constructed wetland 11 in 2008. Aboveground tissues are shown as positive values while belowground tissues are shown as negative values. The nutrient content is expressed in g/0.25 m^2, representing the mean of sample quadrants (n=3); standard error estimates are included

engineer (Scholz et al. 2007). Surveys to determine sediment accumulation were conducted on two occasions. The first survey was performed in 2006, 5 years after the commissioning of ICW 11. Sediment accumulations were measured for the ICW 11 to obtain information on the nature and rate of sediment build-up in the ICW systems. The second survey was conducted in 2008, at the time of core sampling. The mean depth of sediment for the ICW 11 was 13.6± 10.12 cm.

The first wetland cell of ICW 11, which is approximately 100 cm deep, allows for a minimum water depth of 20 cm and a freeboard of 20 cm. The remaining 60 cm of depth can be used for sediment accumulation. 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. However, this was not the case. As the rate of sedimentation varies considerably within and between individual wetland cells and ICW systems, the removal frequency required for each cell will therefore vary accordingly. Due to variations in rates of sediment accumulation, the desludging frequency will also vary from cell to cell in any ICW system. The first cell has the highest rate of sediment accumulation. The sediment depth in the first cell after 5 and 7 years of operation was 35 and 45 cm, respectively. This shows that desludging of the first pond appears to be necessary approximately every 10 years.

The surveys conducted to determine sediment accumulation rate showed increases in depth of the wetland soil. The soil investigation results at the time of construction indicated the presence of clay in the substratum of the ICW. Since the start of its operation, there was an average increase in depth of 45 cm of new material in the first cell of the studied wetland system. Over this 7-year operation period, the accretion rate was approximately 6.4 cm/a.

3.4 Nutrient Accumulation in Soils and Sediment

Soil cores from ICW 11 collected in summer 2008 and winter 2008 were divided into sections by depth, and analysed for nutrients. Nitrogen and phosphorus were stored in the wetland soil. After 7 years of operation, the concentrations of nitrogen and phosphorus in wetland soils were found to be 21,900± 5,010 and 3,410±850 mg/kg, respectively (Table 3).

Table 3 Concentration of nutrients at various depth ranges in the soils and sediment of the studied integrated constructed wetland (ICW) system ICW 11

Season/sampling point	Distance from inflow (m)	Nitrogen (g/kg)				Phosphorus (g/kg)			
		0–15 cm	15–30 cm	30–45 cm	0–45 cm	0–15 cm	15–30 cm	30–45 cm	0–45 cm
Summer[a, c]									
1	8.5	15.8	5.74	3.90	25.4	2.99	1.15	0.88	5.02
2	6.0	14.1	11.9	4.31	30.3	2.14	1.89	0.78	4.81
3	8.5	16.0	11.8	1.83	29.6	2.19	1.64	0.25	4.08
4	20	8.17	9.83	1.67	19.6	0.82	1.05	0.68	2.55
5	18	18.5	16.1	4.26	38.8	2.17	1.86	0.84	4.87
6	20	9.23	4.32	2.14	15.6	2.31	1.56	0.99	4.86
7	35	8.50	6.12	4.96	19.6	0.98	0.91	0.74	2.63
8	33	6.27	5.12	4.04	15.4	0.90	0.88	0.65	2.43
9	35	9.74	7.22	3.92	20.8	2.00	1.75	1.11	4.86
Winter[b, c]									
1	8.5	9.09	7.16	4.50	20.7	1.82	1.48	0.71	4.01
2	6.0	9.75	6.27	3.57	19.6	1.80	1.14	0.55	3.49
3	8.5	8.24	7.41	3.96	19.6	1.80	1.22	0.56	3.58
4	20	10.6	5.32	4.25	20.2	1.39	0.85	0.68	2.92
5	18	15.7	8.32	2.32	26.3	2.02	1.09	0.18	3.29
6	20	14.07	4.11	0.99	19.2	1.31	0.53	0.16	2.00
7	35	8.24	5.16	3.81	17.2	1.12	0.77	0.47	2.36
8	33	9.23	7.25	1.99	18.4	0.94	0.44	0.15	1.53
9	35	8.63	5.31	3.42	17.4	1.02	0.62	0.41	2.05

[a] Mean±standard deviation: nitrogen (g/kg), 23.9±7.79; phosphorus (g/kg), 4.01±1.14

[b] Mean±standard deviation: nitrogen (g/kg), 19.8±2.71; phosphorus (g/kg), 2.80±0.85

[c] Mean of summer and winter: nitrogen (g/kg), 21.9±5.01; phosphorus (g/kg), 3.41±0.85

These high concentrations can predominantly be explained by long-term deposition of suspended solids within the wastewater and accumulation of detritus from dead plants. In comparison, the mean ammonia-nitrogen and total phosphorus concentration in the influent were 39 and 14 mg/l, respectively.

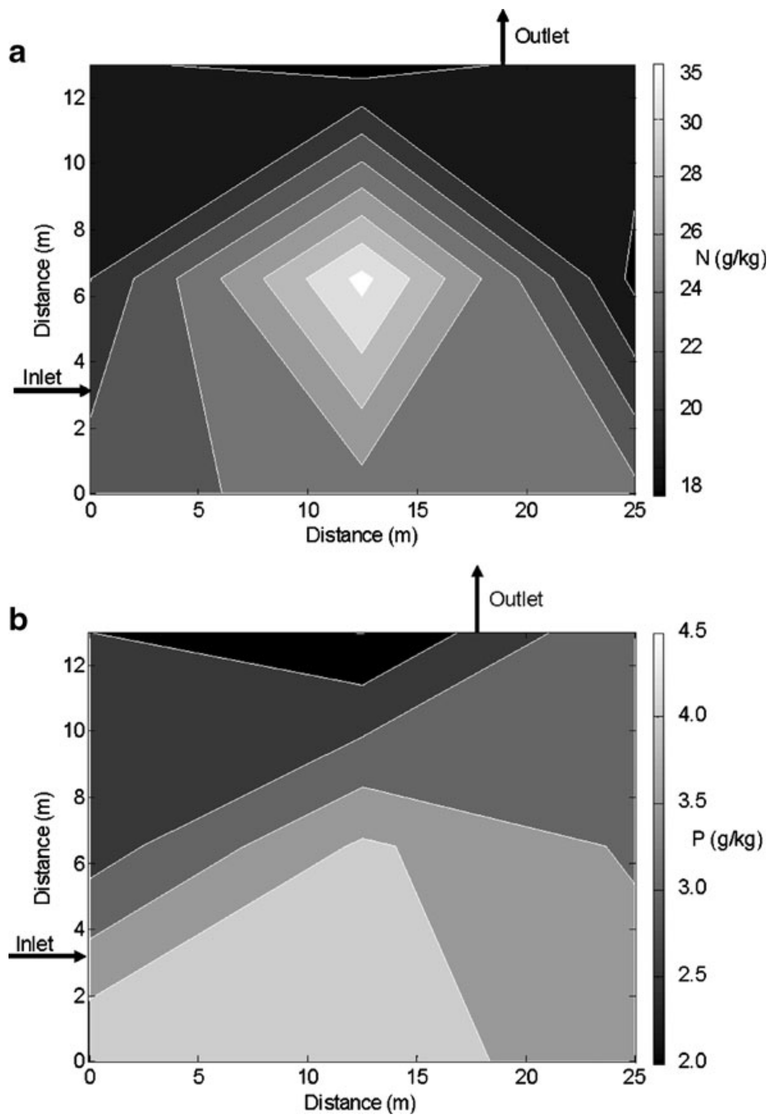
The concentrations of both nitrogen and phosphorus varied with depth. The top sediments had relatively high concentrations of nutrients, while the corresponding concentrations decreased progressively with depth for most samples. Differences were observed with respect to seasons. Higher nutrient concentrations were noted in summer than in winter (Table 3). This may be because of the change in hydrological regime during the two seasons. There was much reduced or no outflow during summer and much higher flows in winter compared to summer.

The first cell from which core samples were collected received the highest concentration of nutrients (nitrogen and phosphorus), which has resulted in higher biomass. Compared to other cells, the first cell had an obviously higher biomass resulting in higher necromass and more accretion. Nitrogen and phosphorus concentrations were higher near the inflow and varied with distance (Table 3). An average of 70,000 m^3 of wastewater entered the ICW during 7 years of operation. The influent contained 15 mg/l of total phosphorus, 10.5 mg/l of molybdate reactive phosphorus, 140 mg/l of total nitrogen, 41.9 mg/l of dissolved inorganic nitrogen; 38.6 mg/l of ammonia-nitrogen, 2.5 mg/l of nitrate-nitrogen and 0.76 mg/l of nitrite-nitrogen. Nitrogen and phosphorus were successfully stored in the wetland soils and sediment. Over the 7-year period, approximately 1,046 kg of phosphorus entered the wetland system. A total of 63 kg were exported, thus resulting in a mass removal of 94%. Approximately 780 kg of phosphorus was stored in the first cell. Thus, the soils and sediments in the first cell stored 74% of the incoming phosphorus load.

Accumulation of nutrients in the soil of the first cell of the ICW 11 is depicted in Fig. 4. The maximum nitrogen accumulation is in the centre, while overall the figure shows an almost symmetrical distribution pattern. For phosphorus, the distribution is asymmetrical with maximum concentrations dispersed in a triangular shape from the inlet. The different spatial patterns of nutrient accumulation in sediments show that variations may have been influenced by the wetland hydraulics. For nitrogen, low values (18,000–22,000 mg/kg) are found at points close to the inlet and outlet, while for phosphorus medium values (3,500 mg/kg) are found near the inlet with comparatively low values near the outlet (2,500 mg/kg). Generally, nutrient accumulation depends on factors such as hydrology, hydraulics and vegetation.

Dolan et al. (1981) found in a pilot-scale treatment wetland that soil was the most significant compartment for phosphorus storage, followed by plant roots

Fig. 4 Contour map showing accumulation of **a** total nitrogen and **b** total phosphorus in sediments of cell 1 for the integrated constructed wetland 11



and rhizomes, and plant litter. Most of the phosphorus stored in wetland surface soils is part of the organic matter fraction (Graham et al. 2005; Reddy et al. 1998). Dunne et al. (2007) found that storage of phosphorus in surface soils (depth: 0–10 cm) was greatest (>87%) relative to the sum of all other ecosystem compartments. Debusk and Reddy (2005) studied nutrient dynamics in the Everglades marsh and reported mean total nitrogen concentrations in soil of 28,000 and 29,000 mg/kg for the depth intervals 0–10 cm and 10–30 cm, while phosphorus concentrations were 1,150 and 640 mg/kg, respectively. The results reported here show that soil is an important wetland component for long-term storage of phosphorus.

Tanner et al. (1998) reported that under suitable conditions in surface-flow constructed wetlands, high rates of plant-derived organic matter accretion may provide substantial long-term immobilisation and storage of nutrients, and a sustained carbon supply for microbial denitrification. In general, the upper soil of the wetland (0–15 cm) had higher phosphorus concentrations than the bottom layers (Table 3). In these systems the wetland plants were not harvested, resulting in the accumulation of organic matter. Some of the detritus decomposes but recalcitrant portions have most likely resulted in accretion of new sediments (Kadlec 2005). The accretion of new sediments assists in the long-term sequestration of phosphorus (Wallace and Knight 2006). Approximately 50% of the nitrogen in this study was also stored in the soils and sediment of the first ICW cell. Borin and Tocchetto (2007) evaluated the performance of a constructed surface flow wetland treating diffuse nitrogen pollution from croplands and estimated the five year water and nitrogen balances. They found that the wetland soil accumulated more than one quarter of the incoming nitrogen load.

Moreover, the ICW subsequently changes from an initially mineral based system to an organic based system with a higher phosphorus removal capacity. In acid soils, inorganic phosphorus can be adsorbed onto iron and aluminium oxides (Faulkner and Richardson 1989; Rhue and Harris 1999). In organic soils, such as those present in wetland ecosystems, inorganic phosphorus can react with aluminium and iron, which are associated with organic matter (Rhue and Harris 1999). Organic matter accumulation and subsequent accretion are important for long-term phosphorus retention (Craft and Richardson 1993; Pant and Reddy 2001). Five upper soil layer samples from ICW 11 were randomly selected and the iron content was determined. The iron content in the samples showed a strong relationship with phosphorus (R^2= 0.74). Dunne et al. (2005) also reported that phosphorus sorption was significantly related to the iron content of soils.

3.5 Carbon in Litter and Sediments

Carbon accumulation expressed in mg/kg was measured for six samples in the direction of flow. Carbon concentrations decreased from the inlet towards the outlet. Mean carbon accumulation in the upper 6 cm of the soils and sediments was 181,300±27,500 mg/kg. This is high when compared to values reported in literature. Vohla et al. (2007) measured carbon concentrations in soil samples collected from a horizontal subsurface flow constructed wetland ranging between 2,200 and 5,700 mg/kg. The reason for lower concentrations of carbon accumulation in a horizontal subsurface flow constructed wetland may be due to factors such as the characteristics of the soil (coarse sand rich in calcium, magnesium and iron) and the type of wastewater (septic tank effluent). Conversely, ICW 11 has soil rich in organic matter and receives nutrient-rich wastewater from a farmyard. The litter on top of the sediments had a high carbon content of 362,200± 75,500 mg/kg.

The litter from decaying macrophytes provides considerable surface area for the attachment of biofilms, and plays an important role in supporting microbial processes in wetlands (Brix 1994). Also wetland sediments have been shown to be important habitats for microorganisms supporting denitrification (Bastviken et al. 2003). Hence, sediment and associated litter are components that support microbial-mediated processes. A study on the microbial ecology conducted for this ICW system reports that the litter component supports a more diverse microbial community compared to the sediments (Atif Mustafa, unpublished). During cell synthesis, microbes assimilate carbon and nitrogen. For aerobic decomposition of plant detritus a carbon to nitrogen ratio of 25 is required (Reddy and DeLaune 2008), and the litter in this study had a corresponding ratio of >40 for most of the collected samples.

According to Reddy and DeLaune (2008), if the carbon to nitrogen ratio of litter is >25, then net immobilisation of inorganic nitrogen will occur as a result of assimilation of nitrogen by microbes during decomposition. In this case, immobilisation will be greater than ammonification. It is more likely that organic substrates with a higher carbon to nitrogen ratio near the ICW inlet encourage nitrogen immobilization in comparison to other locations far away from the inlet where the carbon content is low, which may encourage ammonification.

3.6 Nutrient Storage in Vegetation and Soils

The total nutrient storage in ICW 11 was calculated (Table 4). There was a decrease in plant nutrient storage from summer (July) to winter (December). For total nitrogen, the reduction was about 31% from 50.9 kg in summer to 35.2 kg in winter. For total phosphorus, the reduction was around 45% from 13.7 kg in summer to 7.6 kg in winter. Overall total nitrogen and total phosphorus storage in plants decreased from summer to winter. Nutrient uptake studies have been conducted at various geographical locations including Australia, Spain and the USA. Greenway and Woolley (2001) conducted a study on a constructed wetland treating municipal wastewater in Australia, and found that between 24% and 47% of total nitrogen and between 47% and 56% of dissolved phosphorus removal was due to plant uptake. Newman et al. (2000) studied the seasonal performance of a dairy wastewater system constructed on the University of Connecticut's Storrs campus (Connecticut, USA), and found that uptake by *T. latifolia* and *P. australis* accounted for approximately 3% of nitrogen removal. All these case studies were conducted on wetland systems, which were under 5 years old and in which vegetation is still establishing itself.

A similar evaluation of plant nutrient uptake has been reported by Gottschall et al. (2007). They elucidated the role of plants in the removal of nutrients at a well-established constructed wetland treating agricultural wastewater since 1996. The overall plant uptake accounted for 0.7% of total nitrogen removal. When considered separately, 9% of total nitrogen and 5% of total phosphorus removal were due to an increase in plant storage in cell 2 of the wetland system. In this study, plant uptake in the first cell accounted for 0.4% of the total nitrogen removal and 0.8% of the total phosphorus removal. The lower nutrient storage capacity by plants in cell 1 could be as the result of Brix's (1997) argument that plant uptake is only significant under low nutrient loading conditions. It is clear that the first cell receives the most contaminated influent and highest load, as the untreated wastewater enters the system and the plants in this part of the wetland system are most likely to store small amounts of nutrient species, as compared to other cells.

The analysis revealed that total nitrogen in the soil samples of ICW 11 was higher than total phosphorus. The storage of nitrogen in new soils and sediments was approximately six times more than phosphorus. Kadlec (2009a) found that nitrogen accretion in new soils and sediment at Houghton lake wetland was ten times more than phosphorus. The new soil layers were formed in the studied ICW system through the accumulation of incoming solids entering the system along with the nutrient-enriched wastewater, macroscopic accretions (macrophyte detritus) and microscopic accretions (algal, bacterial and microbial detritus). Consequently, new residuals from various

Table 4 Nutrient storage estimates in vegetation and soil/sediments in the studied integrated constructed wetlands

Nutrient component	Summer (kg)	Winter (kg)	Difference: summer–winter (kg)
Total nitrogen			
Plant	50.9	35.2	15.7
Soil and sediment	6,057	4,201	1,856
Total	6,107.9	4,236.2	1,871.7
Total phosphorus			
Plant	13.7	7.6	6.1
Soil and sediment	899	662	237
Total	912.7	669.6	243.1

sources were deposited on the wetland soil surface (Kadlec 2005).

Since 2001, the wastewater discharge added approximately 9,760 kg of nitrogen to the ICW 11. A total of 223 kg were exported, so mass removal was approximately 98%. About 5,175 kg of nitrogen was stored in the soils and sediments of the first cell. This figure represents 52% of the incoming nitrogen load.

4 Conclusions

This paper described the role of plants and sediment in removing nutrients from an ICW treating agricultural wastewater for more than 7 years. The study demonstrates the importance of wetland soils and sediment in accumulation of nutrients. The studied wetland system trapped approximately 0.8 t of phosphorus and 5.2 t of nitrogen over just less than 7 years of operational period. Overall, the system removed 74% of phosphorus and 52% of nitrogen within an area of just under 1 ha. Moreover, the paper discusses the seasonal variation in storage capacities of the plant and soil matrices in constructed wetlands. The plants when compared to sediment stored only a very small proportion of nutrients. It shows that the soil component of a mature wetland system is an important and sustainable storage component that acts as a sink for nutrients.

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