DAIRY WASTEWATER REMEDIATION, CONSENT COMPLIANCE AND RESOURCE SAVING OF A 1.25 HECTARE CONSTRUCTED WETLAND.

Forbes E G A.[1] and Mulholland M.V.[2]
[1] Agri-Food and Biosciences Institute, Northern Ireland. [2] Department of Agriculture and Rural Development (DARD) Northern Ireland
Corresponding Author Email: martin.mulholland@dardni.gov.uk

Abstract

Over a ten year period a five-pond constructed wetland (CW) with a 1.25 ha surface area, continuously and successfully treated an agricultural effluent, farmyard dirty water (FDW), composed of milking equipment circulation cleaning water, faeces and urine contaminated dairy parlour washings (average 3m^3/day) and precipitation run-off from grass silage clamps, roofs and yards of the 6,600 m^2 watershed. The CW was designed for a hydraulic retention time of 70 days and average hydraulic loading of FDW including watershed surface area run-off was estimated at ~50m^3/day with ~25m^3/day discharged from the CW. In most years there was no discharge during summertime, due to evapo-transpiration and low rainfall. Average FDW concentrations of biochemical oxygen demand (BOD) were reduced from 1793 to 7.7 mg/L in discharge waters, levels well below the discharge consent limit (40 mg/L) and were relatively unaffected by changes in rainfall volumes. Average phosphorus concentrations were reduced from 57.7 to 6.5 mg/L though reduction efficiency was seen to follow seasonal rainfall patterns and was also seen to reduce in later years. Constructed wetland water remediation negated over-winter storage and traditional, mechanised land-spreading of FDW, considerably reducing dairy operational costs.

Keywords

Agricultural, biochemical, contaminated, constructed, effluent, phosphorus, remediation, wetland

Introduction

Effluents from the agricultural sector have a high pollution potential as they contain both agri-nutrients such as nitrogen (N), phosphorus (P) and highly polluting biochemical oxygen demand (BOD) which, in even relatively low doses, is particularly harmful to aquatic organisms (DARD, 2003). Phosphorus is also known to be the key component in water eutrophication in Northern Ireland (NI) and the primary source is diverse pollution from agricultural sources (Foy *et al,* 2006). Farmyard dirty water (FDW) investigated on 20 farms in England was shown to contain a wide range (N = 0.3 – 0.9 mg/L, P = 0.5 - 90 mg/L, BOD 230 – 6600 mg/L) of these pollutants (Cumby *et al*, 1999) and a review of CW treating FDW on a dairy farms in Ireland, reported concentrations of these contaminants within these ranges (Healy and O'Flynn, 2011). In a previous study of the CW discussed in this paper, the FDW treated between 2006 and 2010 contained similar contaminant concentrations (Forbes *et al*, 2011). Though considered a low level wastewater, FDW still has pollution potential and its storage and disposal is highly regulated in NI (DARD, 2003). The remediation ability of constructed wetland technology has potential application for many areas of water pollution reduction and water cleansing and their use in industrial and commercial situations has been widely documented (Kadlec and Knight,1996; Healy and O'Flynn, 2011). The incorporation of CWs for remediation of agricultural effluents is also increasing in Ireland (Healy and O'Flynn, 2011) and they may offer a particular solution to intensive dairy farms in NI, that can produce large volumes of these wastewaters, in an area where prevention of pollution from farms is highly promoted and regulated (DARD, 2003). Studies of farm effluents treated in CW have shown that they are particularly effective in reducing BOD concentrations to levels well below the set limits for discharge to surface water (NI max = 40 mg/L) and have also been shown to retain agri-nutrients within their confines, reducing these also to much lower concentrations in discharge waters (Harrington and McInnes, 2009; Forbes *et al*, 2011; Healy and O'Flynn, 2011). Considering that on dairy farms in NI a single milking cow may lead to FDW production of up to 45 L/day (DARD, 2003) large volumes can soon accrue, especially if immediate disposal is not feasible. There is considerable potential for constructed wetland technology to prevent or reduce water pollution directly attributable to agricultural sources, though the generally much higher contaminant levels, compared to municipal wastewaters present considerable challenges (Kadlec and Knight,1996; Wetzel, 2001). The normal method for disposal of FDW is land-spreading, usually by tractor drawn tankers with splash plate or trailing shoe applicator which is a labour and machinery intensive operation that adds cost to the farming budget. Also, during winter periods in NI, soils may be saturated for long periods. Current regulations stipulate that when soils are saturated, no land spreading is permitted and therefore farms must in practice have sufficient storage capacity for FDW production (DARD, 2003). This requirement normally requires the building of large concrete structures and steel tanks, often glass lined to prevent potential corrosion, which can add significant capital costs to farms. However, as well as the environmental benefits CW provide by reducing potential water pollution, they may also offer an ecologically acceptable and lower cost construction alternative to such large building and civil engineering works as those normally required to meet the stringent regulations for storage of large volumes of FDW. Combining these aspects of CW efficacy to intensive dairy farming operations in NI could aid considerably in mitigating costs and reducing pollution potential on such farms. Though an earlier study of this CW reported high remediation efficiency during the first five years of operation (Forbes *et al*, 2011), as with any method of FDW treatment, technologies must be seen to operate efficiently and sustainably over a longer term to prove that they are both viable and reliable.

The aim of this study was to examine the performance of the CW for continuous agri-nutrient removal and BOD reduction over the ten year period since its inception and also the cost savings accumulated by negating land spreading operations.

Methods and Materials

As an alternative to building standard concrete and steel holding tanks for FDW, during 2004 a gravity fed, surface flow constructed wetland was developed for the dairy unit of the farm at the Greenmount campus (Lat 54. 26 : Long -6. 2) of the College of Agriculture, Farming and Rural Environment (CAFRE) in Northern Ireland. Based on the environmental and sustainable principles of the Integrated Constructed Wetland (ICW) concept (Harrington and Ryder, 2002) the wetland was designed with to incorporate aesthetic values as well as providing a fully functioning treatment system. The average dairy herd cow number was 170 with some calves, milked two times per day, early morning and afternoon, with pipes and milking equipment washed and sterilised immediately after with hot water (minimum 70 °C) and proprietary washing additives. As previously described (Forbes *et al*, 2011) the surface flow CW consisted of five kidney shaped, compacted clay base ponds of differing sizes with a total surface area of 1,25 ha Fig. 1). The ponds were planted in different combinations in each pond with five species of locally sourced emergent macrophytes into 200mm depth of returned soil after construction was completed in August 2004 as detailed in Table 1. The CW was allowed to fill naturally to the required water depth (300mm) by accumulation of precipitation and left to allow root establishment over winter. With a direct pipeline to carry FDW from the dairy unit ~200m distant from the wetland, via a V-notch weir flow measuring unit, to the first receiving pond (Pond 1), ponds were linked by 150mm diameter PVC pipes in successive number order and FDW was introduced during November 2005.

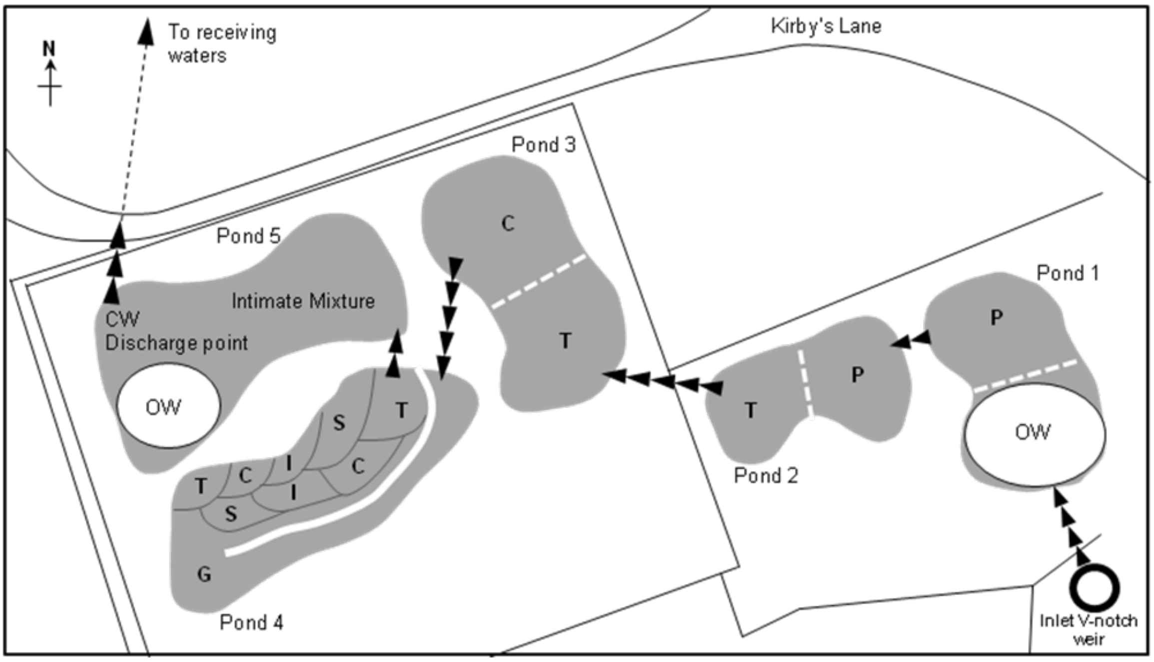

Figure 1. Schematic of the Greenmount CW (not to scale) showing the pond outlines and the basic macrophyte planting patterns. Letters denote species; P = *Phragmites australis*; T = *Typha latifolia*; C = *Carex riparia*; I = *Iris pseudacorus*; S = *Sparganium erectum.* OW = open water. (Reproduced from; Forbes *et al,* 2014, with kind permission of Aqua Enviro).

The CW was designed with a hydraulic retention time (HRT) of approximately 70 days and this was confirmed during the initial sampling and recording carried out during 2005 (Forbes *et al*, 2011). Thereafter, the CW was intensively monitored for the following five years, with weekly grab sampling of FDW influent and at the discharge point of each pond. Samples were analysed of a range of constituents but chiefly N, P, pH and BOD_5 (5 day BOD test) using standard laboratory methods as described by Forbes *et al,* (2011). Since 2010 only a low level monitoring programme was available to allow monthly or infrequent grab sampling of inlet FDW and the CW discharge outlet at pond 5, with sample analysis for ammonium nitrogen (NH_4^+) and phosphate phosphorus (PO_4-P) by photometer (Palintest). Also during the early years (2004 - 2010) of the CW treatment monitoring, weather data was recorded on a weather station located at the Greenmount farm (Forbes *et al*, 2011). However, this facility was not available for the subsequent period (2010 – 2014) and to approximate precipitation during this period, records from a weather station (Aldergrove Meteorological Station: 39170 EGAA) ~4.5 km distant to the CW (Lat 54.65 : Long -6.21), were consulted, though evapotranspriation data was not available. Though located in a temperate zone, the Greenmount CW climatic conditions varied from cool, wet winters with occasional frosts and snow, to dry summers with & high evapotranspiration rates but also with frequent heavy rainfall episodes similar to those found in the earlier study of Forbes *et al*, (2011). No harvesting or replanting was undertaken at the CW though changes in pond plant communities were observed over time (Forbes *et al,* 2014).

Table 1: Number of ponds, pond area and planting density of emergent macrophyte species planted at the Greenmount wetland

Pond	Area (m^2)	Plant Species	Planted Area (m^2)	Density (plants/m^2)
1	2254	*Phragmites australis*	1122	1.3
2	1415	*Phragmites australis*	720	2.7
		Typha latifolia	720	1.4
3	2400	*Typha latifolia*	1200	1.7
		Carex ripraria	1200	1.7
4	3150	*Typha latifolia*	263	1.9
		Carex ripraria	526	1.9
		Sparganium erectum	1052	1.9
		Iris pseudacorus	1052	1.9
5	3300	*Typha latifolia*	526	1.9
		Carex ripraria	526	1.9
		Sparganium erectum	1052	1.9
		Iris pseudacorus	1052	1.9

Results and Discussion

CW hydrology

Milking equipment flushing and parlour washing methods (high pressure lance) within the dairy unit remained unchanged between periods, indicating that the parlour washing contributions to FDW were similar to those reported by Forbes *et al* (2011). Weather records showed that there was little difference (~9.4 %) in overall precipitation volumes between the early (2004 -2010) and subsequent monitoring period (2010 -2014) with annual averages of 943 ± 94 mm and 854 ± 92 mm respectively. Average temperatures were also very similar between years (9.4 ± 0.6 ºC) and though evapotranspiration records were not available, the available data indicated that the overall CW hydrology composed of FDW with precipitation to watershed area and ponds, would have been similar to the average daily flows (49 m^3) reported for the 2005 - 2010 period (Forbes *et al*, 2011). Predictable flow rates are critical to the planning of CW to allow for proper functioning and sustainability of water treatment, avoiding overload and washout of nutrients and other contaminants to local water systems (Kadlec and Knight, 1996: Healy and O'Flynn, 2007, Harrington and McInnes, 2009) and this CW was seen to operate normally even during widely varying conditions.

CW water analyses

FDW influent and pond water BOD

Results of analyses showed that BOD_5 concentrations in FDW influent and in pond discharge samples up to 2010 had the largest reduction (84.6%) in pond 1 and 94, 97.3, 98.3 and 99% cumulative reductions in succeeding ponds (Fig 2). These reductions were as those found by Forbes *et al,* (2011) for the CW and were within the ranges commonly reported from other CW studies (Cumby *et al*, 1996; Dunne *et al*, 2005; Healy and O'Flynn, 2011). The large reduction in pond 1 may have been effected as the FDW entered into an unplanted open water area (~50% of total pond area) where a degree of settlement of organic matter occurred, before passage through the vigourous

Phragmites australis planted in half of the pond. Within a few months of operation this unplanted area was colonised by annual meadow grass (*Poa poa*) which availed of the nutrients from the FDW, increasing root mass and thus increasing further the organic matter retention and the filtering capacity within the pond. The BOD reduction capacity was seen to remain highly effective over the whole period of operation from 2006 to 2014, never achieving less than 95% reduction (Figure 3), continuing the high reduction efficiency reported for the early years of operation (Forbes *et al*, 2011). It was found that in all years the BOD concentrations at the discharge point were always well below, and therefore totally compliant, with the regulating authority permitted 40 mg/L.

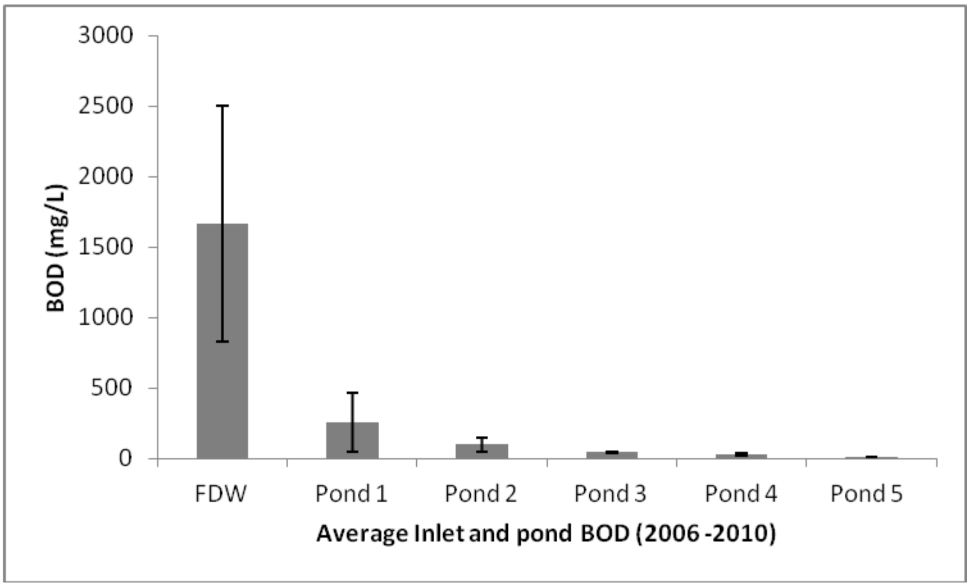

Figure 2. BOD average concentrations found in each pond during the period 2006 to 2010. Error bars show standard deviation (±) in each pond.

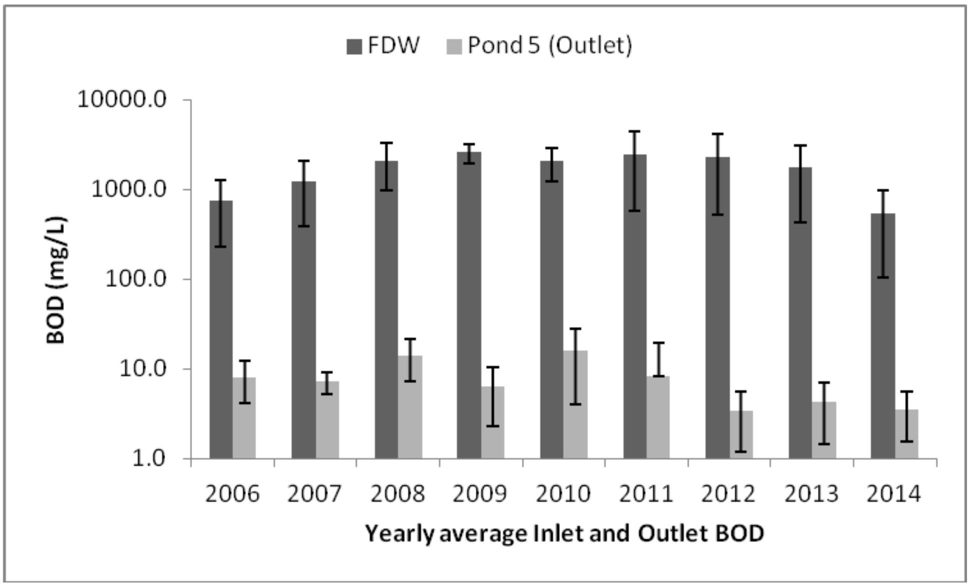

Figure 3. Yearly average BOD concentration at Inlet and Outlet during the period 2006 to 2014. Error bars show standard deviation (±) within each year. *(Values for 2014 are for four months only (January – April).*.

FDW influent and pond water phosphorus

Total phosphorus (TP) concentrations were seen to display a similar trend of reduction through ponds with an average 76, 80.3, 86.1, 95.8 and 95.5% cumulative reduction from ponds 1 to pond 5 during the period 2006 -2010 (Figure 4). This resulted in an average concentration reduction of 95.5% from inlet (56.9 ± 19.1 mg/l) to discharge outlet (2.0 ± 0.9 mg/L). Concentration reductions between inlet and outlet were found to average 56.6 ± 16.6 mg/L at inlet which was very consistent with the 2005 – 2010 period. However, distinct changes in reductions were found after 2011 (Figure 5) with average outlet phosphorus concentrations (7.0 ± 6.6 mg/L) representing an 8.0% drop in reduction efficiency to 87.5%. The concentrations of phosphorus were similar in range to those reported in reports from other CW within the UK and Ireland ((Cumby *et al*, 1996; Dunne *et al*, 2005; Healy and O'Flynn, 2011). There were also similarities between the P removal efficiencies found in this study compared to the values reported previously for other CW studies (Dunne *et al*, 2005; Harrington and McInnes, 2009; Healy and O'Flynn, 2011).

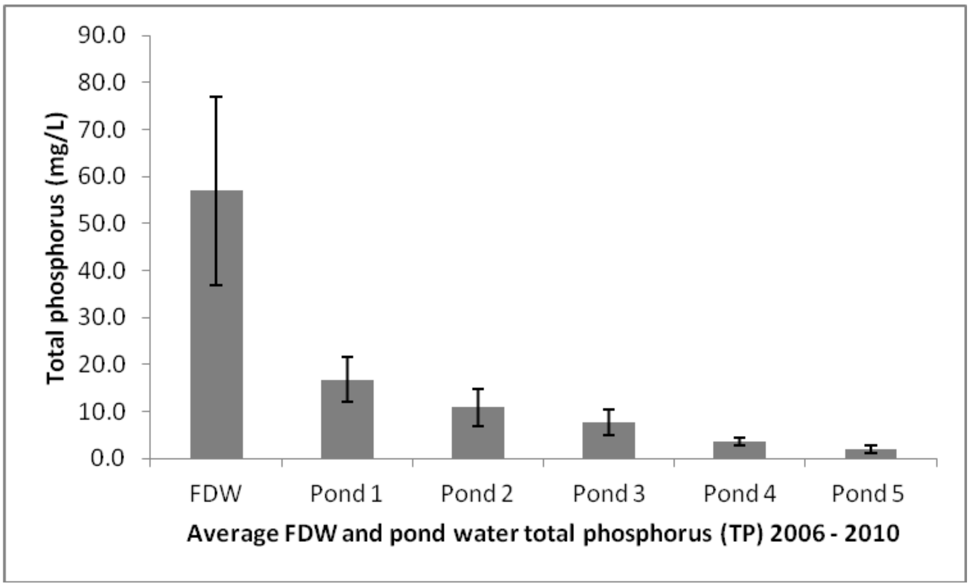

Figure 4. Average concentrations of TP in each pond during the period 2006 to 2010. Error bars show standard deviation (±) within each year.

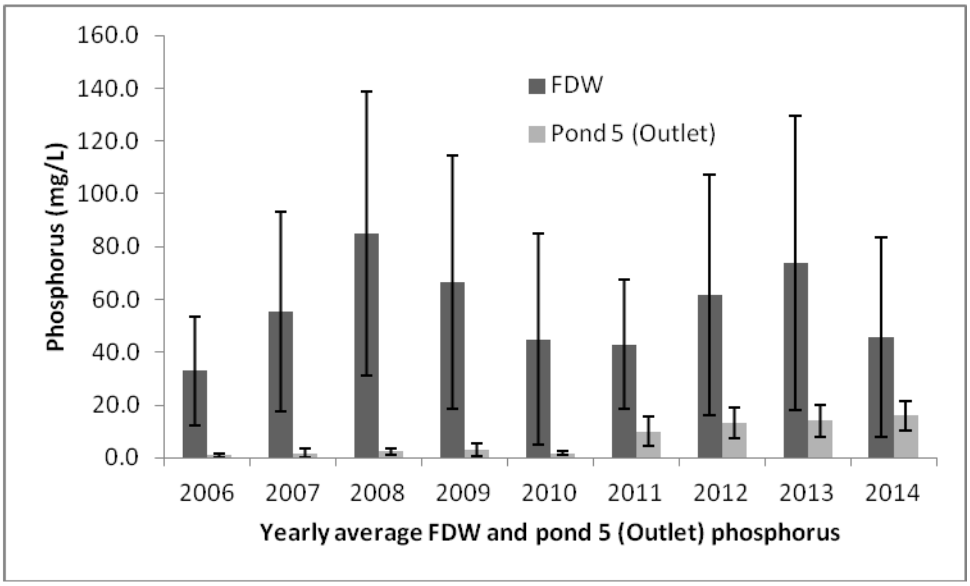

Figure 5. Average total phosphorus (2006 -2010) and phosphate phosphorus (2011 - 2014) concentrations found in CW inlet FDW and outlet (pond 5) waters at discharge point. Error bars show standard deviation (±) within each year. *(Values for 2014 are for four months only (January – April).*

FDW influent and pond water nitrogen

Compared to BOD and TP, nitrogen (as ammonium nitrogen) reduction was much less efficient in the first two ponds of the CW and overall during 2006 to 2010 (Figure 6). FDW at inlet averaged 6.2 ± 1.3 mg/L and 0.3 ± 0.2 mg/L at outlet, representing an average reduction from to 95.0% at outlet. Reductions in pond 1 averaged 14.2%, rising to 55.7 and 61.2% cumulatively in ponds 2 and 3 respectively, with higher levels of reduction in ponds 4 and 5 (92.4 and 95% respectively). However, over the longer term (2006 to 2014) a decline in nitrogen reduction efficiency was clearly seen (Figure 7) with outlet concentrations averaging 2.5 ± 0.9mg/L between 2011 and 2014, representing an average reduction efficiency of 64 ± 9.8%. The concentrations of ammonium-N were much lower than ranges reported by Harrington and McInnes (2009) and Healy and O'Flynn (2011) but removal was within the range (67 – 99.9%) reported by the latter.

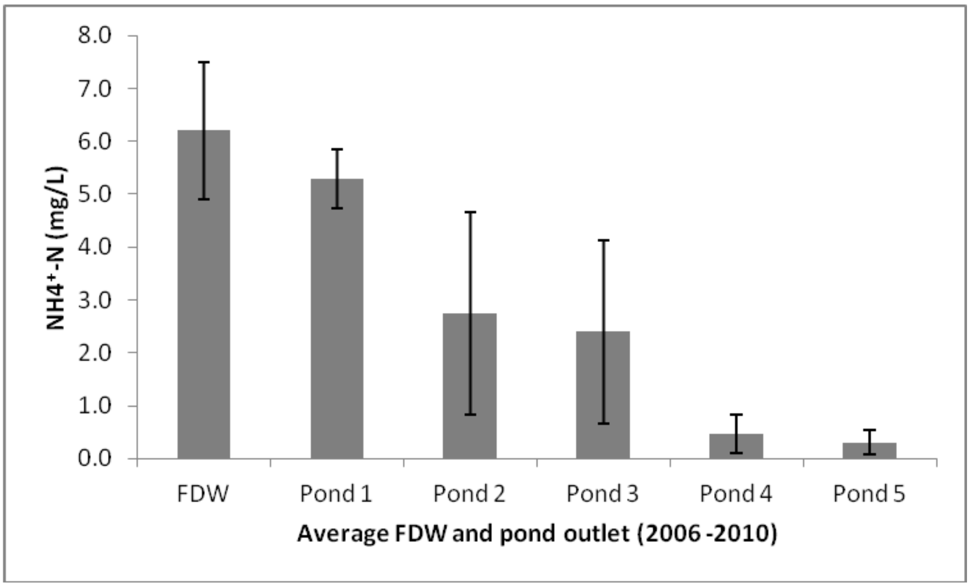

Figure 6. Ammonium nitrogen average concentrations in each pond during the period 2006 to 2010. Error bars are standard deviation (±) within each year.

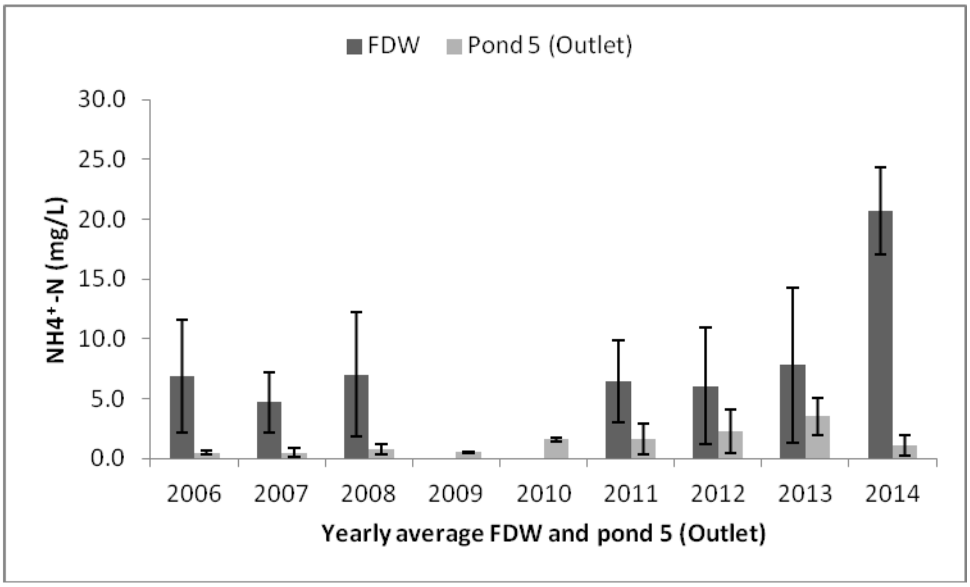

Figure 7. Average FDW and pond 5 (outlet) ammonium nitrogen concentrations between 2006 and 2014. Error bars show standard deviation (±) within each year. *(Values for 2014 are for four months only (January – April).*

FDW and pond water pH

pH was found to be relatively stable (pH 7.1 ± 0.2) across the CW during the period 2006 to 2010 with very small differences seen between ponds (Figure 8). Inlet FDW pH was consistently lower than the average pH in succeeding ponds (pH 6.8 ± 0.8 and 7.0 ± 0.9 respectively). However, over the latter half of the longer term (2006 to 2014) from 2010 onwards a consistent change in inlet and pond pH was seen (Figure 8) with inlet profiles showing pH increase to an average pH 7.9 ± 0.2 compared to an average pH 6.6 ± 0.8 during 2006 to 2009. Outlet pH were very similar (average pH 7.2 ± 0.3) over all years (Figure 8) appearing to be unaffected by inlet pH changes.

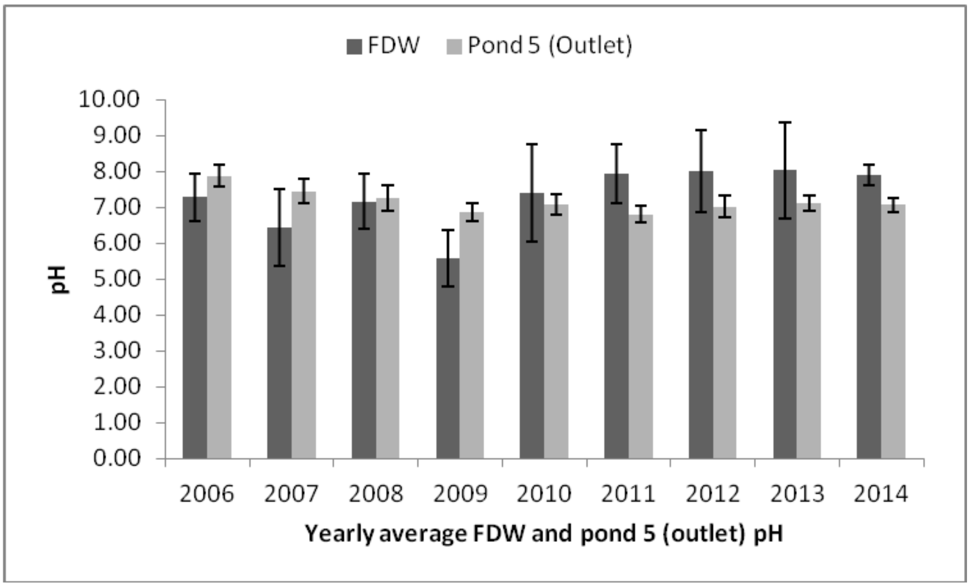

Figure 8. Average yearly pH concentrations of inlet FDW and outlet (pond 5) waters. Error bars show standard deviation (±) within each year. *Values for 2014 are for four months only (January – April).*

The changes found in inlet FDW pH marked the largest changes seen in FDW pond water chemistry during the operation of the CW. The reasons for the changes are uncertain but the very low pH levels recorded during 2007 and 2009 (Figure 8) would have influenced the early period (2002 -2010) averages. However, the change could reflect an unrecorded change in dairy parlour washing practices, different washing detergent or concentrations or possibly other general practices within the CW watershed areas. Pond water pH is an important factor in regulating nitrogen, especially ammonia-N in wetlands (Kadlec and Knight, 1996) and the pH levels found here indicate that relatively stable conditions pertained within the CW.

Generally, the CW has been shown to be effective in removing and retaining most of the contaminants monitored and maintaining pH at consistent concentrations during the full term of its operation. Also, the strong growth performance of the CW flora previously reported (Forbes *et al*, 2014) has been observed to continue to the present time, suggesting that the wetland might continue to function effectively for a further number of years. However, CWs are known to be somewhat ephemeral and show considerable variation in performance both over time and seasonally (Kadlec and Knight, 1996; Wetzel, 2001; Healy and O'Flynn, 2011) which has also been shown previously to occur within this CW (Forbes *et al*, 2011) and were also observed in the latter period (2010 -2014). For phosphorus especially, caution must be taken when considering retention performance as this is generally considered short term, as retained P can be released over the longer term of a CW (Kadlec and Knight, 1996; Wetzel, 2001; Healy and O'Flynn, 2011).

CW effected cost reductions in farm operations

Constructed wetlands are a relatively low cost technology that offers potential cost savings and environmental benefits compared to standard concrete and steel works normally employed to contain dirty water prior to land spreading. To minimise the size and construction cost of a farm wetland, clean and dirty water should be separated where feasible. As a rule-of-thumb, to allow sufficient dirty water residence time for effective treatment, the size of a wetland should be twice the area of dirty yards and unroofed silos from which dirty water will be treated.

Assumptions:

- 3000 m^2 dirty yard area
- Average rainfall 4mm per day
- Dairy washings 5m^3 per day
- Dirty water storage cost £40 per m^3
- Land spreading cost £30 per hour
- Wetland construction cost £30,000

Constructing a 6,000 m^2 wetland on a farm with dirty yard and un-roofed silo areas of 3,000 m^2 may cost between £20,000 and £30,000. Savings in land spreading and storage costs should ensure a 4 to 6 year payback on the investment (Table 2). On farms with heavy land, where more than 6 weeks dirty water storage is required, the payback period for a constructed wetland will be significantly reduced.

Table 2: Cost benefit analysis (annual basis) of dirty water constructed wetland treatment versus land spreading of FDW.

Constructed Wetland		**Land Spreading**	
Extra costs		Costs saved	
Construction depreciation Maintenance Replacement land rental	£3,000 £500 £222	Tank depreciation Dirty water spreading	£2,856 £6,807
Total	£3,722	Total	£9,663
		Extra costs	**£5,941**

Conclusions

1. Overall the pond water chemistry of the tested parameters has shown that the CW has retained a high level of functionality,

2. The level of BOD reduction achieved by the CW has remained extremely effective since the first years of operation and has operated consistently at >95% and always below the set discharge limit.

3. Phosphorus retention and nitrogen (as ammonium nitrogen) reductions within the wetland appear to have declined slightly since 2010 though reductions between inlet and outlet are still relatively effective when compared with other CW results.

3. Changes in pH of the FDW influent did not affect pond water and discharge water pH concentrations.

4. Cost and resource saving resulting from avoiding land-spreading FDW and construction depreciation were positive and resulted in a 5 to 6 year payback on CW development costs.

5. These findings show that an agricultural constructed wetland, appropriately designed for the expected hydraulic loading and with defined contaminant parameters, can function efficiently, reliably and sustainably over a term of at least ten years.

Acknowledgements

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