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9

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AFBI Hillsborough, Large Park, Hillsborough, Co. Down, Northern Ireland BT26 6DR
Tel: +44 28 9268 2484 email: info@afbini.gov.uk

# The performance of a five pond integrated Constructed Wetland for the bioremediation of farm effluents

Preliminary findings on the performance, efficiency and sustainability of the CAFRE constructed wetland system*

Authors: E. G. A. Forbes[1**], R. H. Foy[2] *, M.V. Mulholland[3] and V. B. Woods[1]

[1] Global Research Unit, Agri-Food and Biosciences Institute (AFBI), Hillsborough, BT26 6DR.

[2] Agriculture and Environmental Science Division, AFBI, Newforge Lane, Belfast BT9 5PX and Department of Agriculture and Environmental Science, Queens University Belfast, Belfast BT9 5PX.

[3] College of Agriculture, Food and Rural Environment (CAFRE), Greenmount Campus, Antrim, BT41 4PU.

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** email greg.forbes@afbini.gov.uk

Front Cover photograph; Courtesy of Mr Michael Graham (Farm Manager, CAFRE)

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# 1 Summary

The five-pond integrated constructed wetland (ICW), which received farmyard dirty water (FDW) and dairy washings twice daily from the 140 cow dairy herd and three times daily from the 30 strong dairy-cream herd at the College of Agriculture, food and Rural Enterprise (CAFRE), was intensively monitored from it's inception in November 2005 until February 2008. The principal aim of the study was to observe, sample, analyse and record the efficiency of the ICW for retention/removal of phosphorus (P), nitrogen (N) and reduction of 5 day biochemical oxygen demand ($BOD^5$) from the FDW. The study was conducted for the whole system and for each of the individual five ponds.

Results of water samples taken from the ponds between November 2005 and February 2008 indicated that from the initial FDW influent piped into the system, water discharged from pond 5 after a hydraulic retention time (HRT) of 60-100 days (flow affected), had a significant (*P*=0.001) mean annual reductions in total phosphate (TP) of 94.9 to 97.1%, ammonia nitrogen ($NH_4^-N$) 92.9 to 99% and $BOD^5$ of 99.0%. The largest reduction for $BOD^5$ and TP occurred in pond 1, whereas $NH_4^-N$ levels declined more significantly in pond 2. Soluble reactive phosphorus (SRP) and total soluble phosphorus (TSP) were also significantly reduced during passage through the ponds by 94.5% and 95.9% respectively. Other FDW nutrient contents, total oxidisable nitrogen (TON) and nitrite nitrogen ($NO_2^-N$) were less consistently recorded but reductions were of a similar order. Across the ponds, pH remained relatively constant (mean pH 7.26 ± 0.07), with the largest variation (max pH 9.48, min pH 4.29) recorded in the inlet FDW. Conductivity was continuously reduced across the ponds, with the inlet mean of 760 ± 34 (max 1942) $\mu Scm^{-1}$ reduced to 291 ± 12 $\mu Scm^{-1}$ at the outlet. Faecal coliform (presumptive) and total coliform (presumptive) counts were also significantly lowered (up to log 5 reduction). Although relative percentage reductions in TP concentrations at the ICW outlet remained consistent, actual outflow concentrations increased each year. There was no correlation (*r* = <.1) between TP and $BOD^5$ concentrations measured at the inflow and the outflow from the ICW. The ratio of CW size to watershed area was sufficient to meet the target requirements for FDW nutrient removal and $BOD^5$ reduction.

During summer 2006, a period of low rainfall, dry hot weather and high levels of potential evapotranspiration (PET) effectively caused pond water to fall below the levels of the outfall pipes, resulting in zero flow conditions in all ponds except ponds 1 and 2, which continued to receive FDW. The bioremedial efficacy of these two ponds and the system as a whole was not seen to be damaged or diminished during this period, reflected in the recorded data which showed that although flows between ponds had ceased, $BOD^5$ levels remained below discharge limits and nutrient concentrations (especially P) reduced significantly (*P*=0.001). During 2007, the very wet summer resulted in only intermittent pond water level reductions whereas 2008 saw a prolonged period (from April to September) with zero flow between ponds and no discharges from the CW.

Alterations to the wetland FDW catchment area drainage occurred during spring 2008, changing the flow of rainfall and dilution of the FDW. This in turn, increased concentrations of contaminants (see 2008 - 2009 Update: page 59). To avoid inclusion of data resulting from changed parameters, the main body and findings of the report are confined to the period ending March 2008.

## 2 Introduction

The Code of Good Agricultural Practice issued by Department of Agriculture and Rural Development (DARD 2003) defines dirty water as “a low dry matter waste made up of water contaminated by manure, urine, waste milk and cleaning materials”. The regulations governing the operation of the Nitrates Directive in Northern Ireland further define dirty water for land spreading during the closed period in terms of Biochemical Oxygen Demand (BOD) concentrations of ≤2,000 mg/litre, total nitrogen of ≤300 mg N/l and with a dry matter content of <10,000 mg/l. These concentrations are considerably lower than would be expected from animal manures and silage effluent for which BOD typically exceeds 30,000 mg/l, total nitrogen >3,000 mg N/l and dry matter >60,000 mg/l.

However, when compared to many other pollutants and the standards required for maintaining rivers and lakes in a good water quality state, dirty water is highly polluting. The BOD of raw sewage, for example, would be expected to be between 200 and 300 mg/l, while $BOD^5$ recorded in the Greenmount FDW averaged ~1180 mg/l. For lakes and rivers, concentrations of phosphorus (P) should be kept <0.05 mg P/l to lower the risk of eutrophication but the total P concentration of dirty water reported in this report exceeded 50 mg P/l. The Code of Good Agricultural Practice states that dirty water “should be collected and disposed of carefully and must never be allowed to enter a drain or waterway.”

Because it is generally produced in large volumes with minimal value as a source of fertiliser, management of dirty water poses considerable difficulties for Northern Ireland farmers, and in particular for dairy farmers, who not only often have areas of yard that are contaminated due to the movement of cattle but who also generate significant volumes of wash water from milking parlours. Constructed wetlands have been mooted as a possible treatment option for FDW. They are widely used in municipal and industrial wastewater remediation schemes (especially in Europe and the USA) where they are claimed to offer a simple technology with a low environmental impact, based on the pollution mitigation ability of natural wetland systems (Environment protection Agency CEPA 1998). A review of the potential of ICW for treating dirty water on Northern Ireland farms was commissioned by DARD (Forbes *et al*., 2004). This report entitled “Constructed Wetlands and their use to provide bioremediation of farm effluents in Northern Ireland” reviewed the scientific and industry literature on their performance, efficiency and experience. It was noted that CW had a proven capacity to treat and retain inputs of BOD and nitrogen compounds, but their capacity to retain P was more uncertain. Within Northern Ireland, the ability to control P discharges is of key importance in water quality management given the role of this nutrient in promoting freshwater eutrophication in lakes such as Lough Neagh and Lough Erne (Foy *et al*.,2002).

However, a type of CW described as an integrated CW (ICW), with the descriptor “integrated” referring to the integration into the landscape, was promoted for treating dirty water and farm wastes in general in South East Ireland (Harrington *et al*., 2005). Such wetlands are passive structures in which water moves through under gravity as surface flow. They have a minimal requirement for maintenance but their most striking characteristic is their large area as they are designed to have a surface area of approximately 1.5 to 2 times the contributing area of yards and roof waters.

During 2002, staff from DARD visited the following dirty water treatment facilities: 1). An intensive aeration treatment system with a reed-bed designed and installed at Scottish Agricultural College in Ayr, 2). The ADAS/Silsoe University DW-STOP experimental program on a dairy farm in Sussex which was testing down-flow reed beds, percolating soil plots, overland flow plots and settlement plus intensive aeration and, 3). A selection of ICW in the Anne Valley, Co. Waterford. Effluent data from aeration treatment systems suggested a low capacity to retain P which was considered a key criterion for defining the successful treatment of dirty water, while the DW-STOP was still at a developmental stage.

Given the positive claims made for ICW, in terms of their effluent characteristics and low direct operational costs, plus the widespread interest in them by the agricultural sector, a decision was taken in 2004 to establish an ICW at the Greenmount Campus of the College of Agriculture, Food and Rural Enterprise (CAFRE) in Co. Antrim, to provide a site to test the efficiency of the ICW system under controlled conditions. The Greenmount ICW design followed the ICW specification with respect to vegetation planting and size appropriate to treat the dirty water from the dairy unit at Greenmount Campus.

The ICW consisted of five ponds which were constructed in the summer of 2004 and planted in autumn of 2004. To allow the wetland plants to become established the ICW was not used to treat dirty water until November 2005. This report summarises the surface and ground water quality monitoring data from the ICW from November 2005 until February 2008. It is important to emphasise that the report presents a preliminary assessment of the appropriateness of ICW for treating FDW.

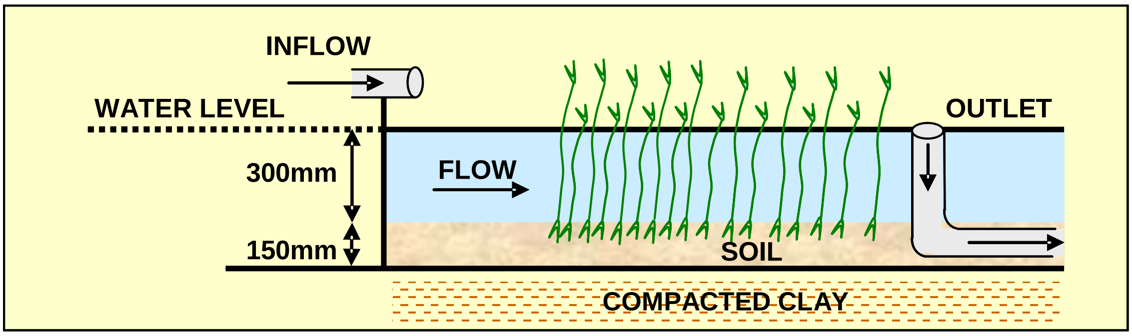
Sampling and analyses were jointly undertaken by staff from Agri-Food and Biosciences Institute (AFBI), (CAFRE) Greenmount Campus, and the Queens University of Belfast. The report also contains bacteriological pathogen data from monitoring performed by staff from the Water Management Unit of the Northern Ireland Environment Agency (NIEA).

# 3 Integrated Constructed Wetland description, planning and construction

## 3.1 Constructed Wetland description

The Greenmount ICW was a horizontal surface flow (HSF) wetland (Figure 1), designed whereby the influent waters ingressed from a connecting 150 mm Ø pipework into the ponds sequentially, which allowed water levels to remain constant throughout the year.

**Figure 1** Schematic of a simple Horizontal surface flow wetland (HSF)



The ICW was designed by the professional consulting firm, Consulting Engineers, and was constructed in a meadow that had previously been used for extensive grazing. It consisted of five ponds of different shape and size (Figure 2) each containing one or more of five different types of vascular macrophyte (aquatic) plants that were planted in mono-plots or as intimate mixtures. The combined area of the ponds was 1.25 ha and the total contributing area from the dairy unit was estimated at 0.66 ha. The passage of water through the ICW was designed to have a hydraulic retention time (HRT) of 60 to 100 days. Three groundwater monitoring boreholes were established adjacent to the ponds (GW 1, GW 2, GW 3, as shown in Figure 2).

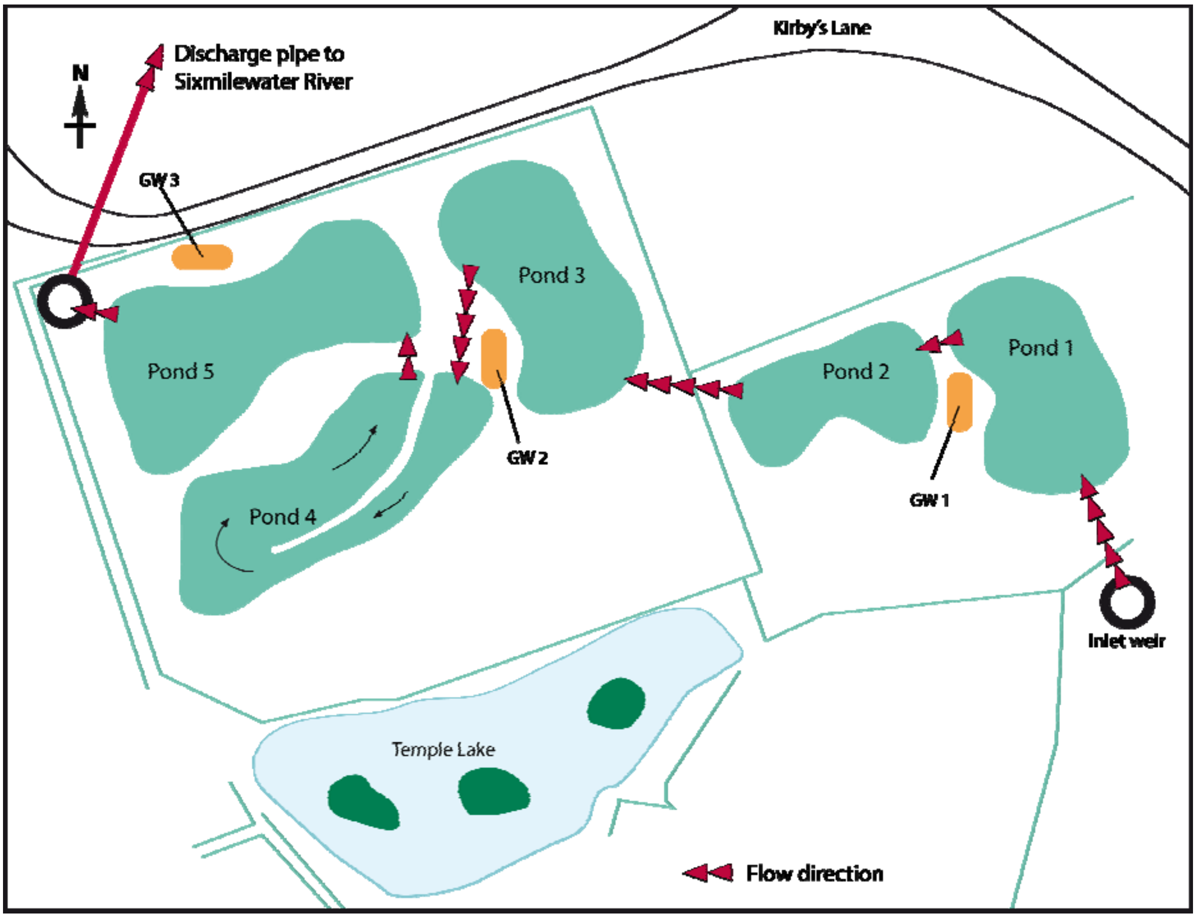
## 3.2 Dirty water sources

Influent from the Greenmount dairy unit consisted of:

- Parlour and bulk tank washings from two milking parlours where 170 cows were milked two or three times per day.
- Runoff from five unroofed silo pits covering an area of 1000 m$^2$. Runoff from these pits was only diverted into the ICW during the winter feeding period as at other times, silage effluent was diverted to an effluent store.
- Runoff from yards traversed by dairy cows both outside the parlours and the lane to grazing paddocks. With respect to the guidance document issued by DARD to farmers for the Nitrates Directive and Phosphorus Regulations Directive, these areas would be considered to be lightly contaminated and the yard area where the cows stand before milking was cleaned / brushed twice daily.

The effluent from these areas was augmented by runoff from other yard areas and some roof runoff. All runoff and effluent were combined in a mixing chamber before being piped through a V-notch weir, which was installed for monitoring flows and water sampling. These waters were piped directly by gravity flow through a 150 mm Ø pipeline to pond 1, where the line diverged to five inlet points at one end of the pond. Waters flow from the pond via 5 surface-level outflow pipes at the opposite end and this pattern was repeated in each of the ponds 2, 3, 4 and 5.

**Figure 2** Basic CAFRE ICW scheme and pond outlay design



(Image adapted from original (Courtesy of *ie*Consulting : permission, Mr M. Mulholland, CAFRE)
(GW 1, 2, 3 = Groundwater monitoring points)

## 3.3 Wetland construction

Based on the natural site topography, the ponds were designed to allow water to flow through the system by gravity. The level of each pond was constructed to provide a fall of at least 300 mm between each pond. The first pond was designed to include a sedimentation area to allow deposits to accumulate. The final pond also included a deep pool into which fish could be introduced. The outlet of the final pond discharged to the Sixmilewater River.

Key stages in the pond construction completed by Belfry Construction Ltd, included:

- Stripping the topsoil (Figure 3)
- Stripping the subsoil
- Bank formation from subsoil (Figure 4)
- Puddling/compaction of the subsoil base
- Installation of pipe-work to convey FDW to and between ponds
- Replacement of 150 mm of topsoil in the pond base and planting of ponds (Figure 7)

Mechanical excavators removed and stacked topsoil, excavated each pond to a set level and formed the banks and pathways between them. Tests of the underlying clays indicated excellent impermeability (after compaction), negating the requirement for lining. Ponds were linked sequentially by a series of 150 mm Ø PVC pipes. Soil was replaced in the base of each pond to a depth of 150 mm and the planting of selected species for each pond was completed during September 2004. Water levels were increased solely by precipitation until summer 2005 when FDW was piped into the ICW on a few occasions to prevent extreme drying conditions. The full FDW hydraulic load from yard/roof area and parlours were channelled into the ICW continuously from November 2005 and thereafter.

**Figure 3** Stage 1: Topsoil was stripped

**Figure 4** Stage 2: Pond excavation

A key stage of the construction process was subsoil puddling to minimise the permeability of the pond base. The permeability of the base of each pond was assessed by means of double-ring infiltrometers and through core samples analysed through the Geotechnical Testing Laboratory at the Queens University of Belfast. Permeability results averaged in the $1 \times 10^{-8}$ m/sec range. Figures 5 and 6 showed *in-situ* permeability tests on the base of pond 5.

**Figure 5** Pond 5 before flooding

**Figure 6** Pond 5 after flooding

**Figure 7** *Phragmites australis* (Common reed) planted in Pond 1. The excavators in the background were completing bank formation and levelling topsoil

# 4 Pond plants

The ICW ponds were planted by hand with a range of aquatic plants including: *Phragmites australis* (common reed), *Typha latifolia* (bullrush), *Carex ripraria* (common sedge), *Iris pseudacorus* (yellow flag Iris) and *Sparganium erectum* (burr reed) species in September 2004. The plants were grown under a tender arrangement using seed of as local a provenance as commercially available. Pond 1 (area 2,245 m$^2$) had an area of open water (~50%) and the remaining was planted in a mono-block of 1500 *Phragmites australis* (common reed). Figure 8 shows pond 1 with the open water - *Phragmites* interface now edged by invasive grasses.

**Figure 8** Pond 1. Open water area and *Phragmites* planted area

Pond 2 (area 1,415 m$^2$ ) contained 2000 *Phragmites australis* and 1000 *Typha latifolia* (bulrush) planted in two distinct blocks with the former at the inlet half of the pond and the latter in the outlet half. The interface between the plant species is clearly visible in Figure 9.

**Figure 9** Pond 2. *Phragmites* (foreground) and *Typha* interface with invasive grasses intergrown

Pond 3 (2,400 m$^2$) had separate blocks of 2000 *Typha latifolia* (inlet area) and 2000 *Carex riparia* (common sedge) and small areas of open water invaded by grasses (Figure 10).

**Figure 10** Pond 3. Typha (foreground) with *Carex ripraria* (common sedge) and reeds in background. Invasive grasses have turned brown due to lack of water during dry weather

Pond 4 (Figure 11) contained randomly planted blocks of *Typha* (500), *Carex* (1000), *Iris pseudacorus* (2000) and 2000 *Sparganium erectum* (bur-reed), with small open water areas invaded by grasses. This pond (area ~3,150 m$^2$) also had a long narrow inlet channel formed within its area to allow inlet waters to be channelled in furthest from the outlet points.

**Figure 11** Pond 4. *Carex* and invasive grasses in foreground with *Typha* and *Sparganium erectum* (bur-reed) in background

Pond 5 (area = 3,300 m$^2$) was planted with small random blocks of *Carex* (1000), *Sparganium* (2000), *Iris* (2000), *Typha* (500) and *Phragmites* (500). A small deepened area of open water was included to allow a fish population to develop naturally (Figure 12).

**Figure 12** Pond 5 with a mixed planting area containing *Iris pseudacorus* (yellow flag iris), *Typha* (bulrush), *Sparganium erectum* (bur-reed) and *Carex ripraria* (common sedge)

Small open water and vegetated areas existed in each pond after planting, which allowed for the free flow of water and encouraged biological diversity within the system.

### 4.1 Discharge consent

As with other industries, the use of ICW to treat PDW requires a discharge consent from the Northern Ireland Environment Agency (NIEA) under the Water (Northern Ireland) Order 1999, where application fees and annual charges are payable. It is an offence to use an ICW to treat any farm effluent, including FDW, without a Water Order consent being issued. If a non-consented discharge to a waterway or underground strata is found to have occurred, enforcement action may be taken. If an ICW is used on a farm, and found to be causing pollution, or to be non-compliant with its consent conditions, remedial action will be required and enforcement action may be taken.

Discharge consents contain numeric limits for various parameters, depending on the nature of the effluent discharged. In the case of a farm ICW for the treatment of FDW, limits are set for BOD and suspended solids (SS) in relation to receiving waters (water quality standards tables are shown in Section 14 (Appendix) of the report). The values will be as demonstrated in Table 1 below, providing the system is properly constructed to a design guide for ICW standards.

**Table 1** Acceptable and BOD and SS discharge water concentrations

| Discharge concentration | BOD (mg/l) | SS (mg/l) |
|---|---|---|
| Discharge limit* | 40 | 60 |

*To receiving water course- Sixmilewater, Antrim.

Monitoring TP will also be undertaken by NIEA, but no maximum discharge limit was determined to date for constructed farm ICW. This may change, however, subject to future legislative requirements.

# 5 Scientific monitoring

## 5.1 Soil sampling

Soil samples collected in 2004 from the newly formed pond bases before flooding and planting were analysed, to establish baseline values for nutrients and organic matter. Subsequent sampling was undertaken in 2007/8 for comparative analysis. Sediments and suspended organic “crust” from pond 1 were also sampled in 2007 to allow for examination of soil structure and nutrient content. Occasional testing of soil and water for heavy metal concentrations was also undertaken.

## 5.2 Vegetation recordings

First season establishment and survival was recorded within randomly located 1 $m^2$ quadrats throughout each pond. Latterly, 16 $m^2$ quadrats were established in each pond to allow data to be collected on plant growth and vegetation status. Measurements and counts were recorded during the growing and senescing seasons of all the different planted and invasive species. Figure 13 shows pond 1 with the 16 $m^2$ recording quadrat circled and part of pond 2.

**Figure 13** Pond 1 with 16 $m^2$ vegetation recording quadrat (circled)

## 5.3 Water sampling

Effluents were piped through a V-notch weir, where an ultrasonic meter continuously recorded daily and total flows and an automatic sampler periodically recorded samples from the inflow storing them (refrigerated) until collection (Figure 14), before the influent entered pond 1. Farmyard dirty water influent and pond outflow waters were grab-sampled weekly with subsequent standard laboratory analysis conducted for compounds of nutrients N, P, and $BOD^5$. TP, TSP, SPP, nitrate, nitrite and ammonium, conductivity and pH were also determined.

Three borehole sampling points were established to monitor groundwater quality, located between ponds 1 and 2 (GW1), between ponds 3 and 4 (GW2) and between pond 5 and the site perimeter drain (GW3). These were sampled intermittently throughout the monitoring period.

### 5.4 Pathogen sampling

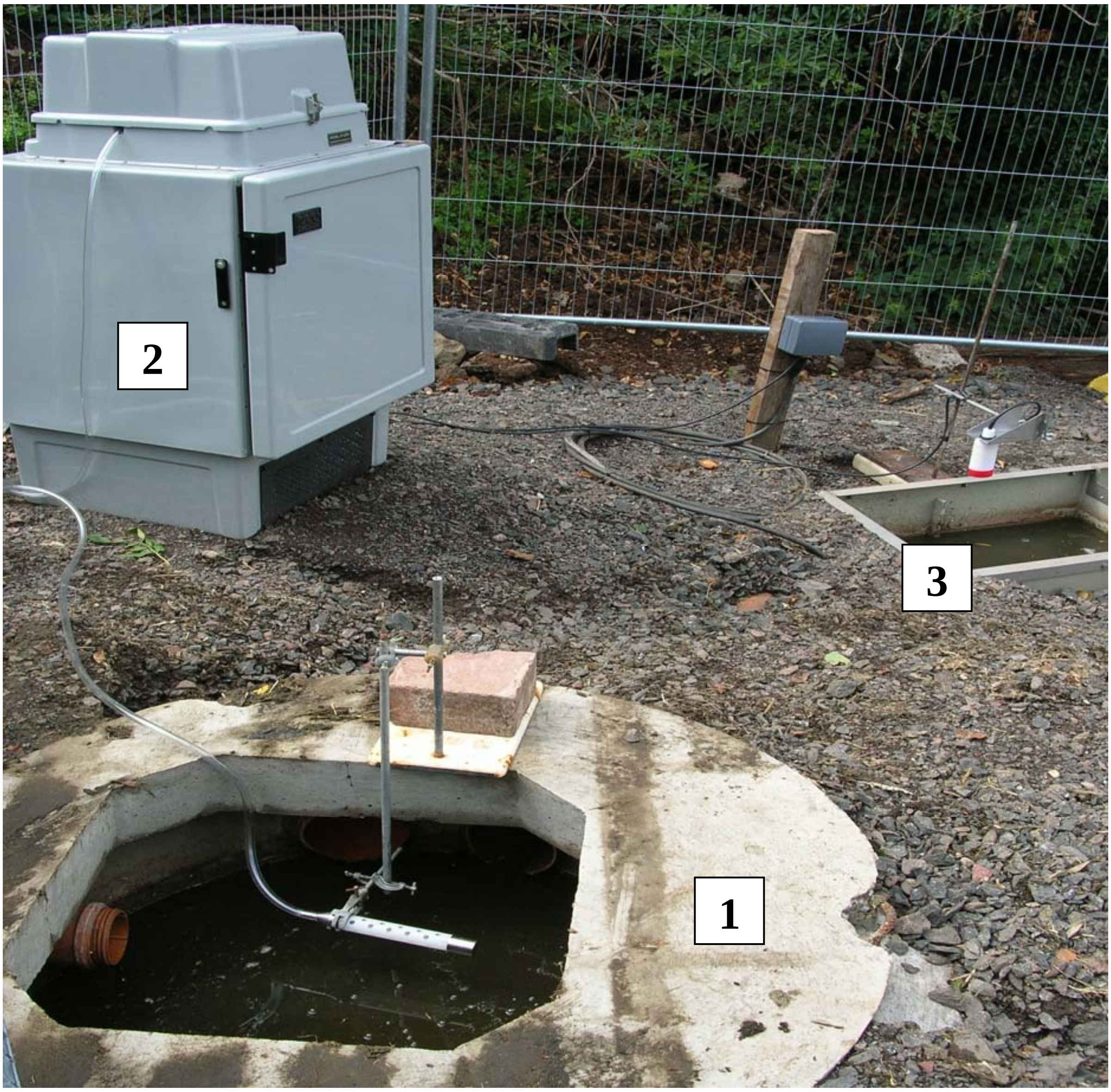
Northern Ireland Environment Agency (NIEA) (Water Quality Branch) staff sampled inlet FDW and pond waters at set points (outflows). The samples were chilled and then transported for faecal pathogen content analysis at the NIEA laboratories in Lisburn.

### 5.5 Problems and charges of the project, and consequences

i) Blockage of the V-notch weir affecting flow recordings at the ICW inlet
ii) Blockage of flow meter at the ICW discharge manhole affecting outflow recordings.

The subsequent actions to overcome these difficulties are described in section 6.3.2

**Figure 14** 1. Automatic sample intake equipment (foreground), 2. refrigerated automatic sampler cabinet (top left), 3. flow measuring sensor and V-notch weir tank (centre right)



# 6 Results and preliminary findings

For ease of use and continuity, milligram per litre (mg/l) is used for concentrations in this document except in original data tables where measuring units may be stated.

## 6.1 Plant survival and establishment

Successful establishment of the aquatic plants is essential for effective ICW performance and various authorities advised that the ICW plants have at least one growing season before the system is commissioned. All species planted in the ICW ponds demonstrated a high level of survival and re-emergence (>80%) in spring 2005 (Table 2). Despite suffering drought stress during the summer of 2005, all species recorded additional plant numbers in all sample areas.

**Table 2** Percentage of re-emergent plants (from winter 2004 to Spring 2005)

| Pond | Area ($m^3$) | Plant type | Number planted | Re-emergence (%) |
|---|---|---|---|---|
| 1 | 2245 | *Phragmites australis* | 1500 | 81.3 |
| 2 | 1415 | *Phragmites* | 2000 | 82.5 |
| | | *Typha latifolia* | 1000 | 93.9 |
| 3 | 2400 | *Carex riparia* | 2000 | 80.2 |
| | | *Typha latifolia* | 2000 | 92.4 |
| 4 | 3130 | *Sparganium erectum* | 2000 | 88.2* |
| | | *Typha latifolia* | 500 | |
| | | *Iris pseudacorus* | 2000 | |
| | | *Carex riparia* | 1000 | |
| 5 | 3300 | *Carex ripraria* | 1000 | 81.8* |
| | | *Sparganium erectum* | 2000 | |
| | | *Iris pseudacorus* | 2000 | |
| | | *Typha latifolia* | | |

*Mean value for all species

Biomass accumulation continued in 2006, with a similar trend noted for all ponds during the growing season. Between spring emergence and mid summer, plant stem numbers increased by over 100% in all recorded quadrats. This increase in vegetative growth of both planted and invasive grasses resulted in a reduction of open water areas in most ponds.

## 6.2 Pond Hydrology

### 6.2.1 Pond water accumulation

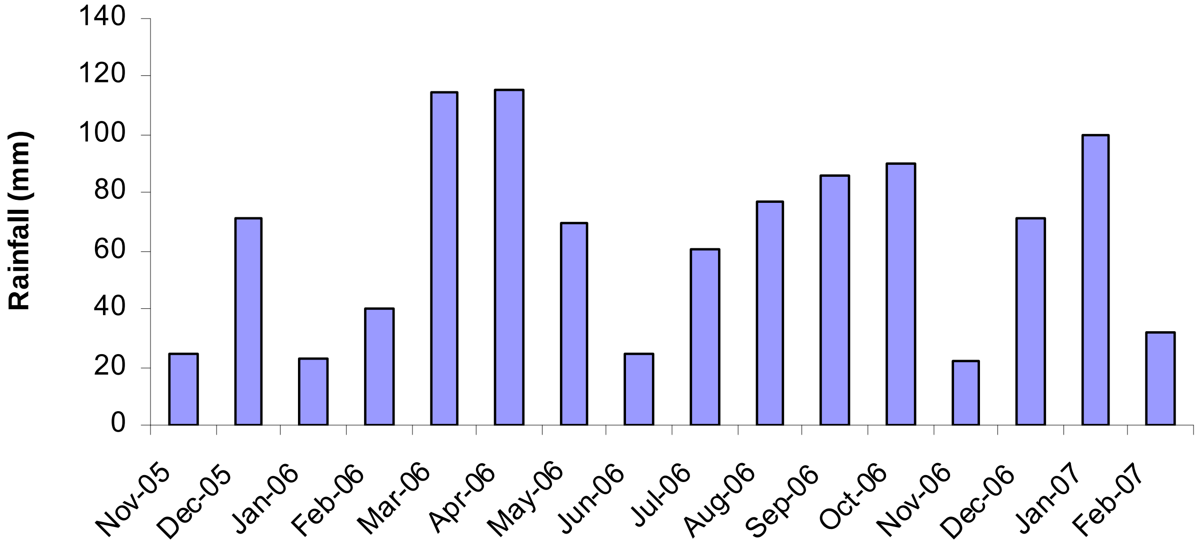
After planting in autumn 2004, the pond outflow pipes were lowered to just above soil level to prevent the plants becoming totally submerged over the winter months. At the beginning of April 2005, the outflows were raised to allow precipitation to accumulate and during the period until October 2005, the rainfall on the pond areas amounted to 6277 m$^3$, sufficient to bring the whole ICW (surface area 12490 m$^2$) to the required depth of 300 mm and fill the total capacity of 3747 m$^3$. However, potential evapotranspiration (PET) losses during summer would have been substantial (~80% based on a 26 year recorded average for individual months) and although actual water depths were not recorded at that time, it was noted that the ICW had a water deficit before FDW was introduced in November 2005.

## 6.3 ICW Influent flows - FDW and precipitation- (November 2005 - February 2007)

### 6.3.1 Roof and yard run off and precipitation in pond

Rainfall records demonstrated that from November 2005 until February 2007, total precipitation at the ICW was 1024, mm with large variations in precipitation between and within monthly intervals (Figure 15). Rainfall flows from the yard and roofed areas (6600 m$^2$) equated to a volume of 6758 m$^3$ for the period. However, assumed PET losses of 0.5 mm/day (winter) and 2 mm/day (summer) would have reduced flow volume to the ICW to 4821 m$^3$. The contribution of rainfall to the ponds (minus PET) was calculated as 4803 m$^3$.

**Figure 15** Greenmount ICW rainfall record (November 2005 – February 2007)



### 6.3.2 Parlour flow volumes

Flow data from the inflow recording system indicated that on days with zero rainfall the lowest mean FDW daily flow rates that emanated from the milking parlour washings ranged from 3 - 5 $m^3$ day. Higher recorded daily FDW flow readings (mean 17.7 $m^3$, max 47.1 $m^3$) were deemed unreliable, as notes from site visit log books showed that the V-notch weir was prone to almost constant blocking by build up of FDW organic matter, thus corrupting recordings. Furthermore, during exceptional periods of sudden heavy rainfall, flow velocities exceeded the measuring capacities of the system, resulting in occasional inflows of unknown quantities from within the farmyard area, which also contributed to total inflow volume. To overcome these erroneous data and elucidate inflow volumes, a water balance (Table 3), constructed using data from pond water depth measurements, rainfall and evapotranspiration records, indicted that the lowest recorded inflow values of 3 - 5 $m^3$ day, were within the correct range for FDW inflow (Table 4) from the parlours (washings and flushings only).

**Table 3** ICW water balance (mm) derived from Greenmount environmental data

| Month | pT* | Rain days | Rainfall (mm) | Evaporation (mm) | Runoff potential (mm) | Cumulative deficit (mm) | Recorded deficit (mm) |
|---|---|---|---|---|---|---|---|
| **Nov-05** | 7 | 20 | 25 | -8.05 | 16.83 | 0.00 | |
| **Dec-05** | 4 | 11 | 71 | -4.39 | 66.46 | 0.00 | |
| **Jan-06** | 5 | 12 | 23 | -6.53 | 16.76 | 0.00 | |
| **Feb-06** | 13 | 16 | 40 | -16.19 | 24.21 | 0.00 | |
| **Mar-06** | 31 | 22 | 115 | -36.81 | 78.21 | 0.00 | |
| **Apr-06** | 52 | 23 | 115 | -62.38 | 52.71 | 0.00 | 0 |
| **May-06** | 79 | 17 | 70 | -95.21 | -25.36 | -25.36 | -26 |
| **Jun-06** | 89 | 10 | 24 | -106.46 | -81.99 | -107.34 | -81 |
| **Jul-06** | 88 | 9 | 61 | -105.02 | -44.13 | -151.47 | -180 |
| **Aug-06** | 70 | 22 | 77 | -84.14 | -6.93 | -158.40 | -84 |
| **Sep-06** | 43 | 22 | 86 | -52.18 | 33.99 | -124.41 | 34 |
| **Oct-06** | 22 | 22 | 90 | -26.87 | 63.48 | -60.93 | 78 |
| **Nov-06** | 7 | 8 | 22 | -8.05 | 14.44 | -46.49 | |
| **Dec-06** | 4 | 26 | 71 | -4.39 | 66.66 | 20.16 | |
| **Jan-07** | 5 | 27 | 100 | -6.53 | 93.17 | 0.00 | |
| **Feb-07** | 13 | 11 | 32 | -16.19 | 16.05 | 0.00 | |

(*Penman-Monteith correction for evaporation = 1.2)

The sudden change in water balance during September 2006 can be attributed to a drainage plug that was installed in pond 3 (during August 2006), to retain precipitation and FDW inflows, increase water levels there in pond 3 and in ponds 1 and 2, which had dried considerably. This in turn stopped outflows to ponds 4 and 5.

**Table 4** Predicted and actual wetland flow volumes based on 3 $m^3$ per day FDW inflow

| | Rainfall mm | Wet days mm | Yard evaporated* mm | Yard runoff $m^3$ | Wetland net rain $m^3$ | Parlour input $m^3$ | Predicted Water balance $m^3$ | Actual Deficit $m^3$ recorded |
|---|---|---|---|---|---|---|---|---|
| **Nov-05** | 25 | 20 | 10 | 98 | 210 | 90 | 398 | |
| **Dec-05** | 71 | 11 | 5.5 | 431 | 830 | 93 | 1354 | |
| **Jan-06** | 23 | 12 | 6 | 114 | 209 | 93 | 416 | |
| **Feb-06** | 40 | 16 | 8 | 214 | 302 | 84 | 600 | |
| **Mar-06** | 115 | 22 | 11 | 687 | 977 | 93 | 1756 | |
| **Apr-06** | 115 | 23 | 46 | 456 | 658 | 90 | 1204 | |
| **May-06** | 70 | 17 | 34 | 237 | -317 | 93 | 13 | |
| **Jun-06** | 24 | 10 | 20 | 30 | -1024 | 90 | -904 | -904 |
| **Jul-06** | 61 | 9 | 18 | 283 | -551 | 93 | -175 | -1080 |
| **Aug-06** | 77 | 22 | 44 | 219 | -87 | 93 | 226 | -854 |
| **Sep-06** | 86 | 22 | 44 | 278 | 425 | 90 | 793 | -61 |
| **Oct-06** | 90 | 22 | 11 | 524 | 793 | 93 | 1409 | |
| **Nov-06** | 22 | 8 | 4 | 122 | 180 | 90 | 392 | |
| **Dec-06** | 71 | 26 | 13 | 383 | 833 | 93 | 1309 | |
| **Jan-07** | 100 | 27 | 13.5 | 569 | 1164 | 93 | 1826 | |
| **Feb-07** | 32 | 11 | 5.5 | 176 | 200 | 84 | 461 | |

(*yard- winter mean PET 0.5 mm rain day, yard- summer mean PET 2 mm rain day)

Estimations of evapotranspiration in both natural and ICW are affected by many factors (Lott and Hunt, 2001). A study by Essery and Wilcock (1990) comparing modelled and actual PET observations, demonstrated differences between calculated and recorded deficits, therefore those (as seen in Table 3) would not be unexpected in this environment. The combined flows (minus PET losses) calculated from the water balance calculations are shown in Table 5.

**Table 5** ICW water through-flow volumes (November 2005 – February 2007)

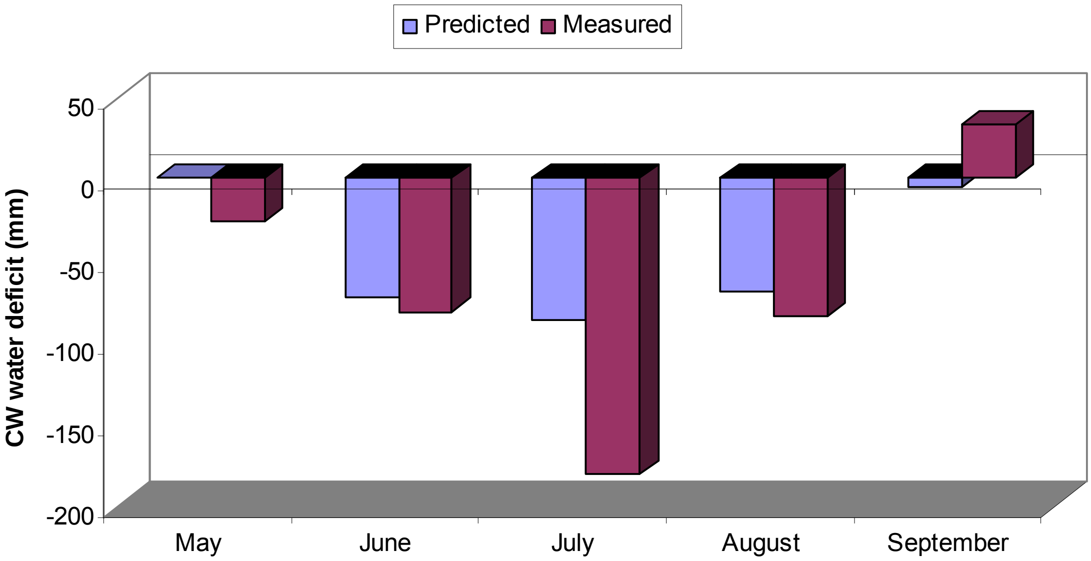
| Rainfall to ponds ($m^3$) | Rainfall to yard/roof ($m^3$) | Parlour washings ($m^3$) | ICW total inflow ($m^3$) |
|---|---|---|---|
| 4803 | 4821 | 1455 | 11079 |

Outflow from the ICW was discharged only from the final (pond 5) to the Sixmilewater river via a 200 m long, 150 mm Ø PVC pipeline. Data from the ICW outflow recording meter, having a reduced diameter pipe bore (150 mm down to 25 mm), proved to be very erratic, largely due to blockage within the small bore pipe caused by build up of organic detritus in the discharge waters. This in turn caused backing-up in the ponds and pipe work had to be disconnected on several occasions to allow water to flow out freely, resulting in the loss of data. Eventually both this and the v-notch weir flow monitoring equipment were disconnected completely.

## 6.4 Potential evapotranspiration (PET)

During the summer months (May – August 2006), a mean PET of 3.1 mm/day without rainfall would require that a minimum 6.9 $m^3$ FDW flowed into pond 1 daily (area = 2245 $m^2$) to be sufficient to just maintain water levels in this pond only. In order to adequately cover the total surface area of the ICW ponds (12490 $m^3$), a FDW inflow of 38.7 $m^3$ day would be required whereas the estimated inflow was only 3$m^3$ per day during the period. Water depth in ponds was recorded relevant to the lowest outflow point in each pond. During the period from May 2006 until September 2006, low rainfall and high PET (≤ 6.5 mm/day recorded) combined to lower pond water levels to such an extent that there was no flow between any of the ponds and a water deficit existed within all ponds. From early May 2006 onwards, all ponds suffered considerable drops in water level, especially during the July heatwave when maximum daily temperatures were consistently > 20°C. During September, when temperatures dropped, PET (more properly described as evaporation during winter months) decreased to < 2 mm day and rainfall increased. Figure 16 demonstrates the effect of high PET values and corresponding low rainfall on pond water levels during summer 2006 (the effect of the drainage plug described on page 24 can be seen in the surplus balance accumulated by September).

**Figure 16** Changes in CW water levels during summer 2006

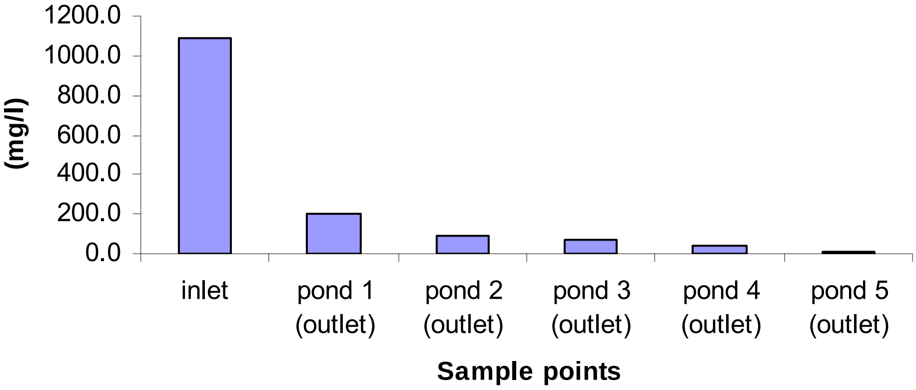


A serious consequence of this dry period was the colonisation of previously open water areas by grasses, especially annual meadow grass (*Poa annua*. spp). These grasses became well established, grew to seed and despite being eventually drowned out by rising autumn water levels, reappeared in 2007 and 2008. Pond water levels were less affected during the summer of 2007, when rainfall was frequently heavy enough to generally sustain flows. The imbalance of ICW water content due to leakage, was postulated and though no direct evidence was found to corroborate, inter-pond leakage via pipework gravel surround was considered possible.

### 6.5 BOD$^5$ reduction

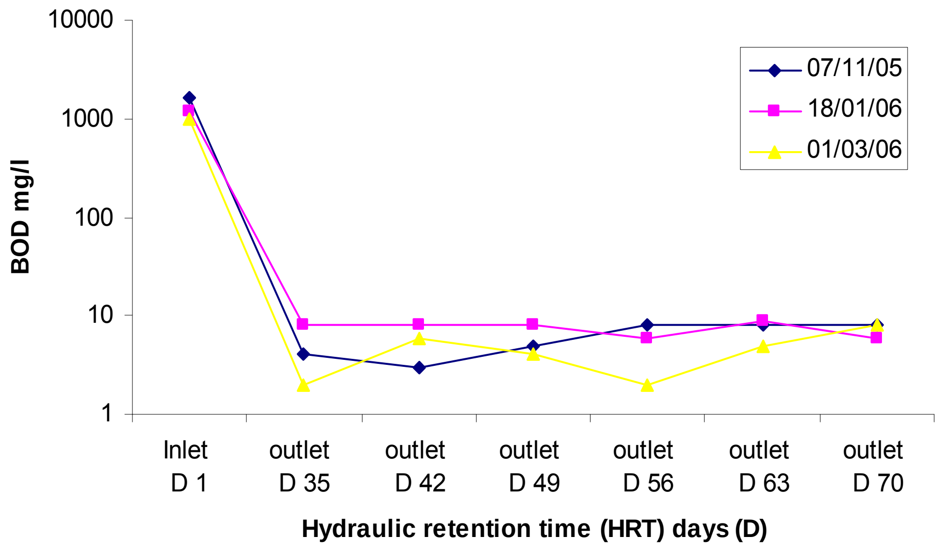
Biochemical oxygen demand of the influent was significantly reduced during water flow through the ponds and the performance was consistent over time. The BOD$^5$ was largely reduced in pond 1 with lesser reductions in subsequent ponds. Figure 17 shows the mean BOD$^5$ within each pond and demonstrates the reduction in BOD$^5$ between ponds.

**Figure 17** Mean BOD values recorded at CW pond outlets, Nov 2005 to Mar 2008



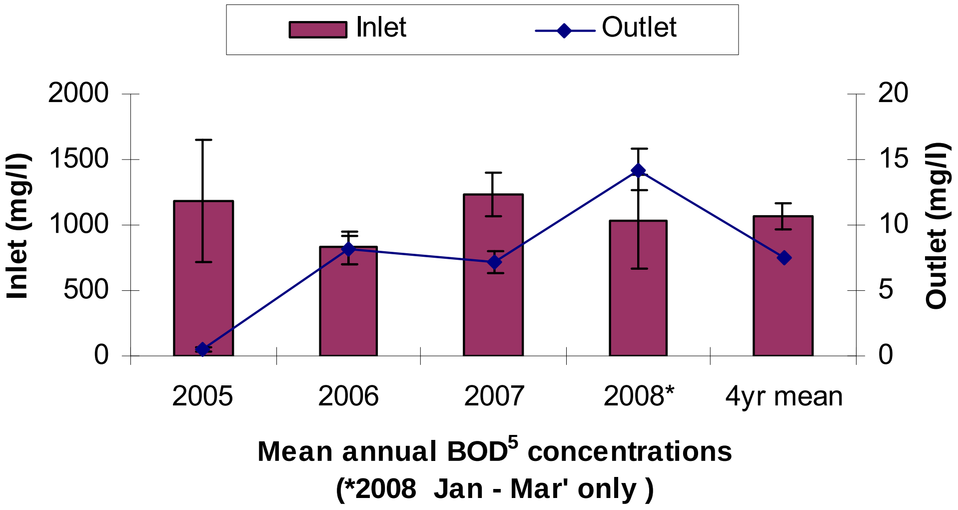
Inlet BOD$^5$ values ranged from 4913 mg/l to 124 mg/l. with a mean concentration of 1080 ± 104 mg/l. Discharge water from the ICW (pond 5) had BOD$^5$ levels ranging from 1 – 33 mg/l, with a mean 7.4 ± 0.5 mg/l. The highest pond 5 (non-discharge) BOD$^5$ value of 44 mg/l corresponded with the driest period during summer 2006, when there was no water flow between ponds and pond waters were stagnant with increasing amounts of plant detritus and algal growth, factors that have could contributed to the increased BOD$^5$ levels. During the autumn/winter periods, when water flowed between ponds, the mean BOD$^5$ concentration in the discharge waters was 7.6 ± 0.5 mg/l. Analysis of individual high inflow BOD$^5$ values during passage over time through the complete ICW system did not show any corresponding surges in discharge water BOD$^5$ values over prolonged periods. Figure 18 displays the changes in BOD$^5$ between the inflow and outflow points over 70 days for the example periods of time. Despite continuous high loadings the final discharge BOD$^5$ levels were consistently significantly ($P$<0.001) reduced by >99% and only on a few occasions exceeded the acceptable maximum discharge (40 mg/l) set by NIEA.

**Figure 18** Change in BOD$^5$ concentration from inlet to outlet during 70 days HRT for three example periods



Since initial recordings commenced in October 2005 until December 2007, the annual mean BOD$^5$ concentration at the inlet varied by 15 - 20 % but outlet point concentrations remained relatively steady during 2006 and 2007 until an increase was noted during the first three months of 2008 (Figure 19).

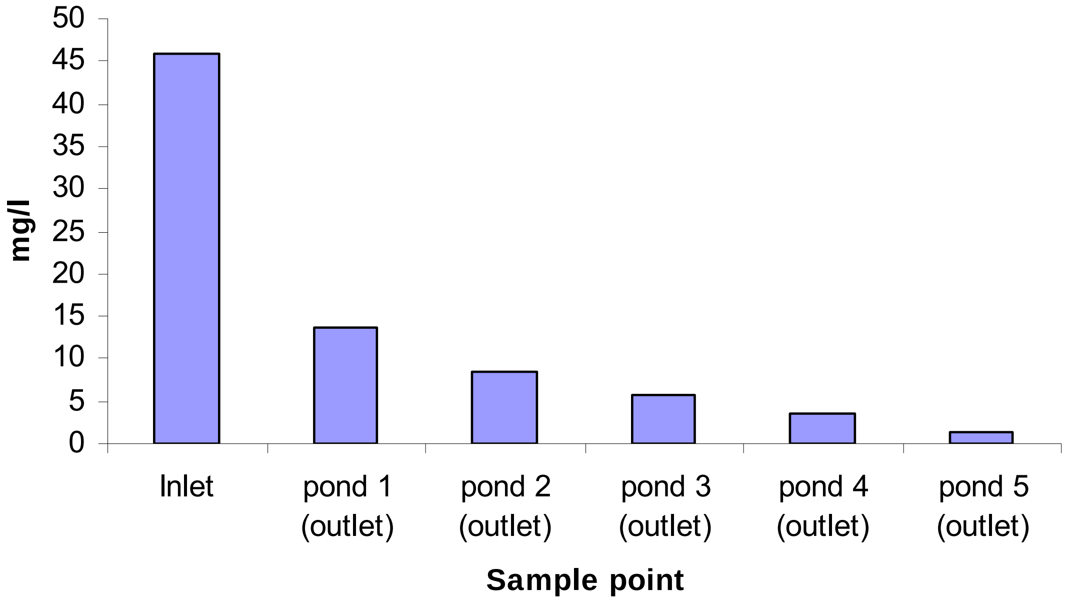
**Figure 19** Annual BOD$^5$ concentration (Error bar = 1 standard error (se))



## 6.6 Phosphorus retention

Phosphorus contained within the influent cannot be lost to the atmosphere in gaseous form and must be retained within the ponds, held within the plant root system, muds and organic matter, be utilised by the pond flora and fauna or carried out of the ICW by discharge waters. From November 2005 to March 2008, values recorded for TP in the FDW influent ranged from 1.0 mg/l to 246.5 mg/l with a mean of 45.92 ± 4.96 mg/l. Data for the outflow waters ranged from 0.05 mg/l to 5.8 mg/l, with a mean of 1.2 ± 0.15 mg/l, reductions that were consistent and highly significant ($P<0.001$). There were marked seasonal differences in outflow concentrations and the lowest monthly TP reduction value (82.6%) was recorded during March-April 2006, while the mean reduction during the overall period from February 2006 to March 2008 was 97.1%. Similar seasonal trends in TSP and SRP reductions were also observed. The mean water TP content at the ICW inlet and at the outflow point in each pond during the intensive monitoring period of November 2005 to March 2008 is shown in Figure 20.

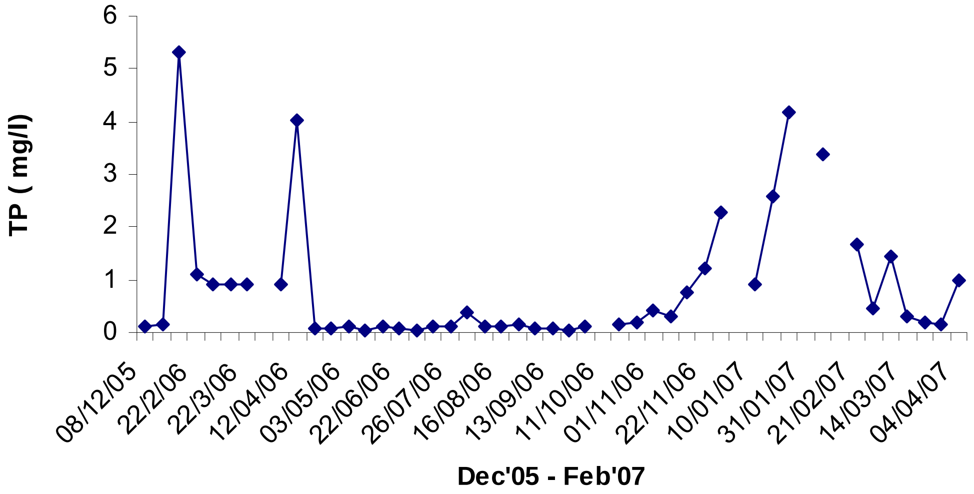
**Figure 20** Mean TP content of ICW pond waters, Nov 2005 – Mar 2008



As with $BOD^5$, the P content of discharge water also varies. These fluctuations in the outflow point P levels are possibly due to the well documented effects of heavy rainfall causing SRP to solubilise in the turbid water. During these conditions, ICW can become net contributors of P to water systems (Dunne *et al*., 2005a).

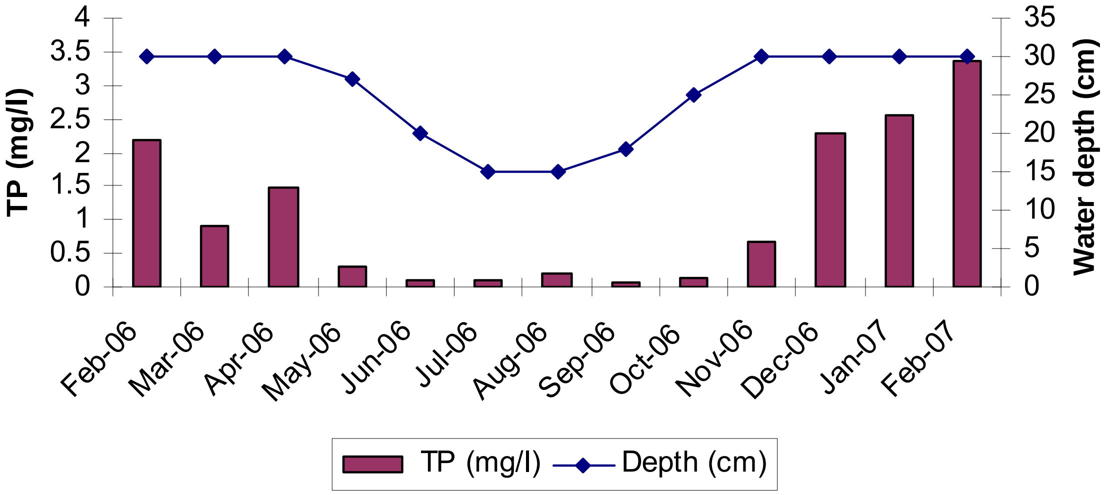
The variation in P concentration at the ICW outflow was lower during the dry spring and summer period in 2006 and higher in winter 2006/07 (Figure 21), values that correlated with the lack of flow between ponds during the summer and autumn periods. During that time the samples were taken from what were, in effect, stagnant waters. These conditions would have allowed nutrients, especially P, to precipitate onto sediments, accrete and adhere to organic matter and be adsorbed to root systems. Figure 21 also displays elevations of TP concentrations in the discharge waters from the pond 5 outflow that were first observed from samples taken in February 2006. This marker was quite distinct and accepted as giving a clear indication that the HRT was ~90 days, well within the designed range of 65 - 100 days.

**Figure 21** Outflow TP concentrations (pond 5)



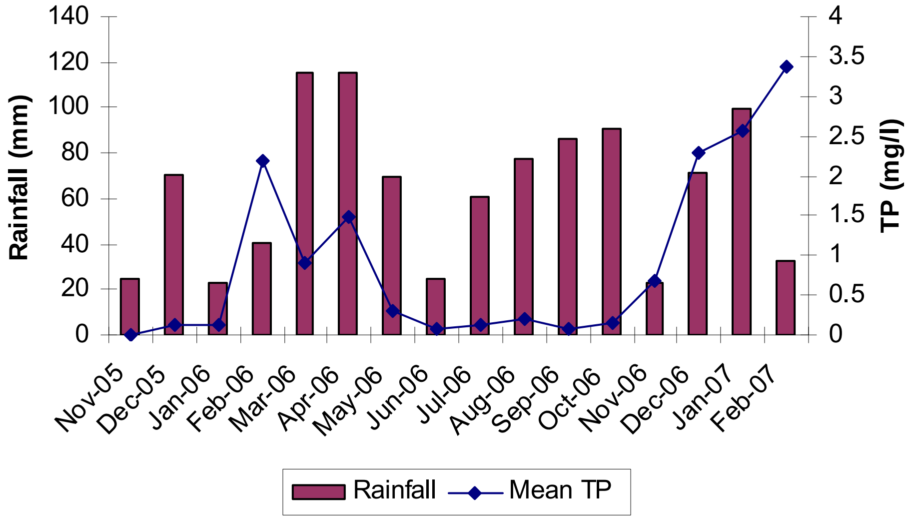
Close examination of data indicated that P outflow concentrations were affected by pond water levels (Figure 22) and that rainfall had an impact on outflow TP values except when pond water levels were insufficient to sustain inter-pond and final discharge flows (Figure 23).

**Figure 22** Pond water levels and Outflow (pond 5) TP concentration



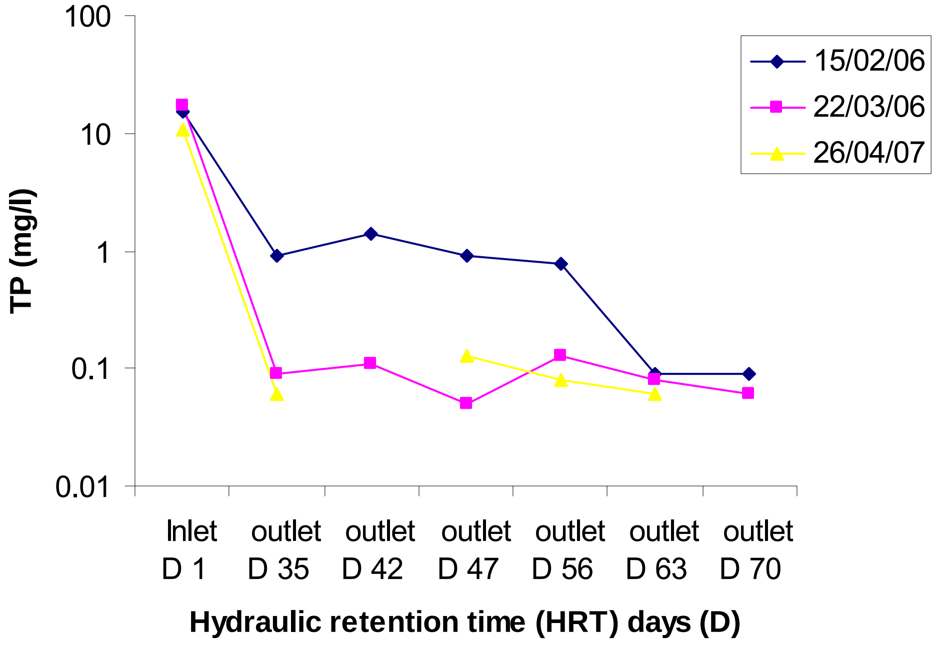
There was however little correlation ($R^2 = 0.1$) between rainfall amount and TP concentrations even at times when there was discharge from the ponds.

**Figure 23** Monthly rainfall and outlet (pond 5) TP concentration



Despite the observed seasonal and rainfall affected changes in TP concentrations, there was no evidence that high P levels in the FDW influent resulted in any surge effect at the outflow at any time during the HRT. Figure 24 demonstrates the consistently low P levels in the outflow waters compared with the initial influent P content over a HRT of 70 days for 3 different periods.

**Figure 24** Change in TP concentration from inlet to outlet during 70 days HRT for 3 example periods.

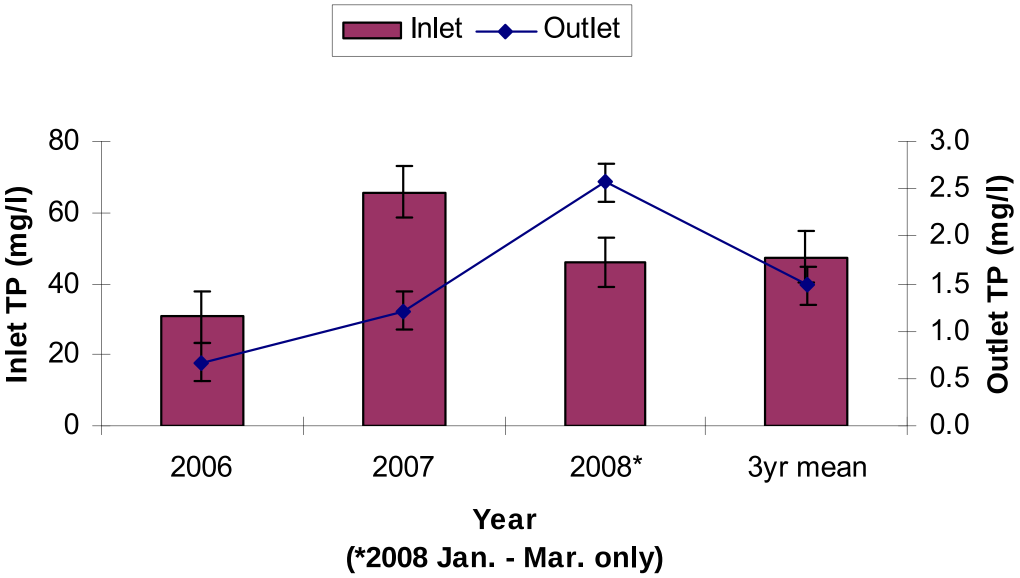


Data detailing TP concentrations at the pond 5 outlet sample point demonstrated clear seasonal differences, but these were not sustained trends. Mean TP concentrations in summer 2006 were much higher than during winter 2006-07 (1.35

mg/l and 0.42 mg/l respectively). By summer 2007 and 2008, concentrations were higher than during winter 2007/8 (2.4, 2.8 and 1.37 mg/l respectively). These changes may reflect 1) changes in pond hydrology or 2) higher summer precipitation levels solubilising P from sediments and plant detritus.

From the start of the sampling in November 2005, the reduction from inflow to outflow TP remained relatively constant (~96.5%) but this figure masked the fact that relative to 2006 both inflow and outflow concentrations had actually increased in 2007 and 2008 (Figure 25).

**Figure 25** Annual changes in TP concentration (Error bar = 1 se)

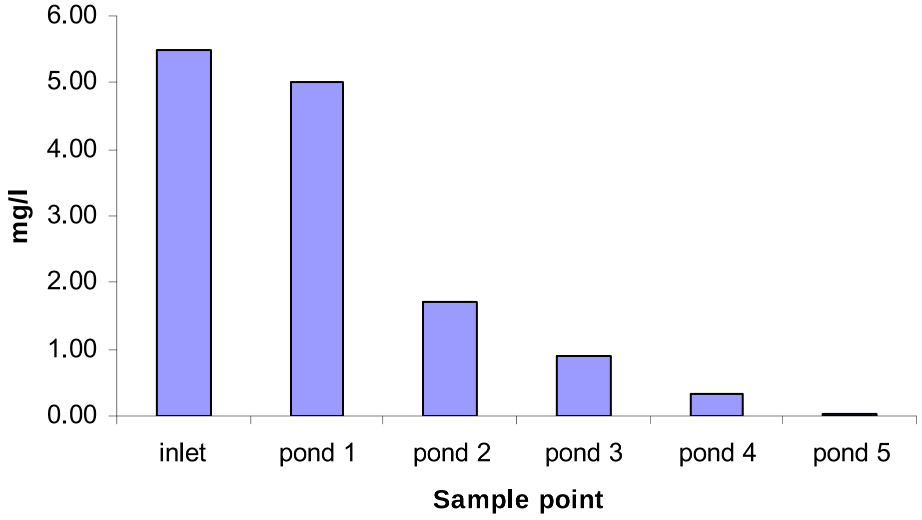


## 6.7 Nitrogen reduction

Nitrogen is another major component of FDW and is particularly difficult to remove using conventional methods as it is present in mostly soluble forms. However, ICW have been shown to be very effective at reducing N levels in discharge waters in many studies (Forbes *et al*., 2004). Analyses of the Greenmount FDW and pond water samples showed a considerable range in N content, measured as total oxidisable nitrogen (TON), ammonium nitrogen ($NH_4^-N$) and nitrite ($NO_2^-N$). V-notch (inflow) values for TON ranged from 0.05 mg/l to 9.3 mg/l, averaging 2.63 mg/l. The $NH_4^-N$ values ranged from 0.4 mg/l to 20.9 mg/l, with a mean of 5.6 ± 0.77 mg/l, and $NO_2$ values ranged from 0.006 mg/l to 0.24 mg/l, with a mean of 0.12 ± 0.02 mg/l.

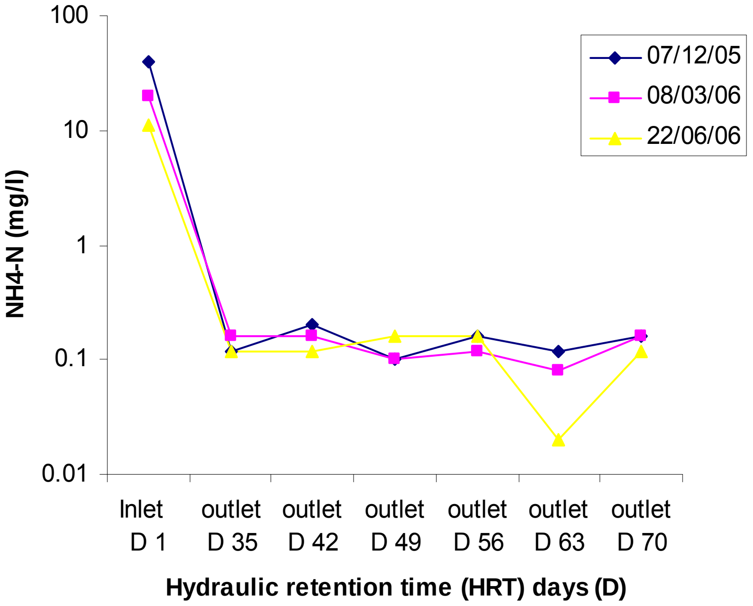
At the outflow, TON maximum, minimum and mean values were all <0.001 mg/l, $NH_4^-N$ values ranged from <0.01 mg/l to 0.15 mg/l, averaging 0.02 ± 0.006 mg/l. The $NO_2^-N$ values ranged from zero to 0.47 mg/l, with a mean of 0.05 mg/l. Figure 25 displays the mean $NH_4$ values recorded in each pond over the period.

**Figure 25** Changes in ammonium nitrogen ($NH_4$-N) levels between ponds in the ICW



The high $NH_4$-N values recorded in pond 1 reflected the build-up of soluble N salts in pond water, although it can be seen that this was largely retained within this pond and that there was a considerable drop in the recorded value from pond 2 onwards. The concentrations in the discharge waters remained very low and as with BOD$^5$ and TP, high inlet concentrations did not appear to increase discharge concentrations during the HRT (Figure 26).

**Figure 26** Change in $NH_4$-N concentration from inlet to outlet during 70 days HRT for 3 example periods



The concentration of the other N compounds (TON and $NO_2$) were also comparably reduced by 97% and 92% respectively.

### 6.8 Pond water characteristics

Table 6 shows the variation in the mean values for pond water pH, conductivity (COND), $BOD^5$ and nutrients across all ponds from the V-notch inlet to the outlet (pond 5), from pre-FDW introduction through and during the complete ICW monitoring period from November 2005 to March 2008.

**Table 6** Changes in mean concentration of $BOD^5$ and nutrients in ICW pond waters (November 2005 – March 2008)

| | **pH** | **COND** | **$BOD^5$ (mg/l)** | **SRP (mg/l)** | **TSP (mg/l)** | **TP (mg/l)** | **$NH_4$ (mg/l)** |
|---|---|---|---|---|---|---|---|
| Inlet | 6.85 | 757 | 1080 | 22.73 | 40.19 | 45.92 | 5.50 |
| Pond 1 | 7.31 | 614 | 202 | 9.09 | 12.46 | 13.58 | 5.01 |
| Pond 2 | 7.14 | 451 | 45 | 5.02 | 8.47 | 8.60 | 1.70 |
| Pond 3 | 7.26 | 418 | 38 | 4.32 | 5.06 | 5.87 | 0.90 |
| Pond 4 | 7.32 | 303 | 27 | 2.07 | 2.90 | 3.60 | 0.33 |
| Pond 5 | 7.61 | 291 | 8 | 1.14 | 1.15 | 1.21 | 0.02 |
| Pre-FDW | 8.89 | 203 | 1.2 | 0.06 | 0.02 | 0.03 | - |
| Significance | NS | * | *** | ** | ** | *** | * |

NS = Not Significant, * $P<0.05$, ** $P<0.01$, *** $P<0.001$

The mean annual Outflow concentrations for both TP and TSP increased by almost 100% and 50% in 2007 and 2008 respectively, compared to 2006.concentration values at the inflow and outflow points (± 1 se) are shown in Table 7.

**Table 7** Pond water concentrations (yearly)

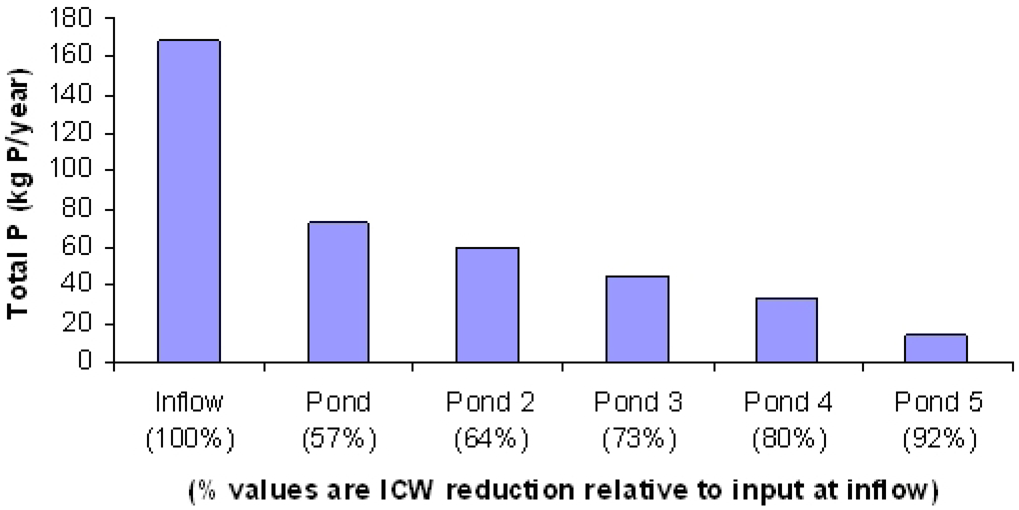
| Recorded parameter | | Inflow (mg/l) | Outflow (mg/l) |
|---|---|---|---|
| $BOD^5$ | 2005[a] | 1182 ± 467 | 0.5 (Pre-FDW flow) |
| | 2006 | 825 ± 118 | 7.4 ± 1.0 |
| | 2007 | 1227 ± 162 | 7.8 ± 1.0 |
| | 2008[b] | 1072 ± 384 | 4.0 ± 1.0 |
| TP | 2006 | 30.74 ± 5.27 | 0.67 ± 0.21 |
| | 2007 | 65.76 ± 8.17 | 1.21 ± 0.17 |
| | 2008 | 41.31 ± 6.68 | 2.57 ± 0.79 |
| TSP | 2006 | 24.81 ± 4.65 | 0.91 ± 0.33 |
| | 2007 | 55.15 ± 6.6 | 1.47 ± 0.29 |
| | 2008 | 33.22 ± 1.27 | 2.02 ± 0.60 |
| $NH_4$ | 2006 | 6.87 ± 1.66 | 0.04 ± 0.013 |
| | 2007 | 4.89 ± 0.77 | 0.006 ± 0.001 |
| | 2008[b] | 5.64 ± 0.77 | 0.019 ± 0.006 |

[a]2005 October – December; [b] 2008 January – March

### 6.8.1 Nutrient Loading

The total P load to the ICW during the 12 month period from March 2006 until February 2007, based on inflow FDW mean sample concentrations combined with flow volumes, was estimated to be 168 kg with ~92% of this being retained within the system (Figure 27). Of the 8% (13.6 kg) lost with outflow waters, the majority (~94%) was discharged during the winter months.

**Figure 27** Distribution of total P input and exports from the ICW ponds from March 2006 – February 2007

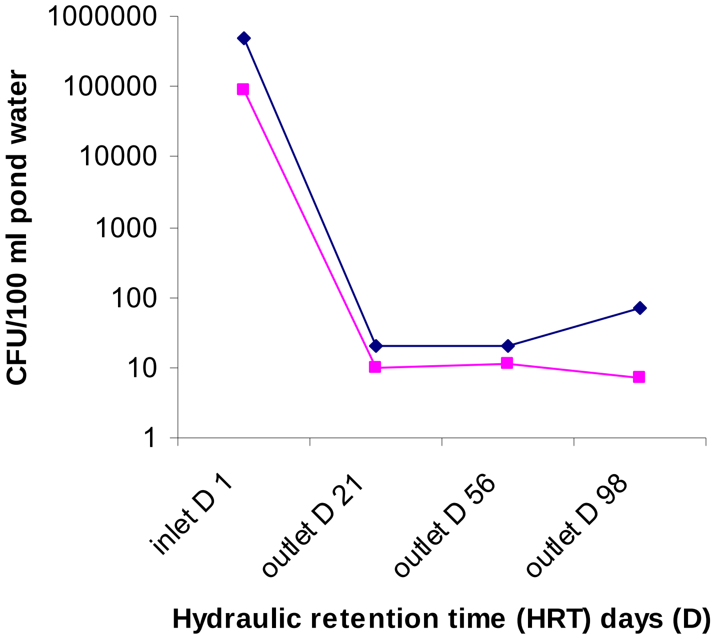


The mass loading of $BOD^5$ organic matter in FDW going to the ICW during the same period (March 2006 to February 2007) from the $BOD^5$ organic matter in the FDW was 1032.6 kg. Most of this (74.7%) was retained in pond 1 and the total discharged from the ICW was equivalent <2% of the total inflow loading. Nitrogen inputs were not estimated due to incomplete data for important periods.

## 6.9 Pathogen reduction

Analyses of faecal and total coliform pathogens showed reductions of up to log 5 in colony forming units (CFU). For both faecal and total coliforms, there was a mean reduction in CFU by ≤99% in pond 1, increasing to >99% in pond 2 and to very low numbers (<0.0001%) at the discharge outlet. Although these data were very consistent and significant ($P<0.001$) throughout the period with varying climatic and water conditions, the small sample numbers required that interpretation of the data was treated with caution. Figure 28 displays the trend in total and faecal coliform reductions between the initial FDW inlet and pond 5 outlet during one sampling episode.

**Figure 28** Coliform count reductions at the inlet and outlet points of the ICW during a 98-day HRT



Tables 8 and 9 demonstrate coliform counts from a number of sampling dates during the monitoring period.

**Table 8** Faecal coliform (presumptive) counts (‘000 cfu/100 ml)

| Date | Inlet | Pond 1 | Pond 2 | Pond 3 | Pond 4 | Pond 5 | Significance |
|---|---|---|---|---|---|---|---|
| 31/05/06 | 90 | 0.6 | <0.1 | <0.1 | <0.1 | <0.1 | ** |
| 06/09/06 | 270 | 2.4 | <0.1 | <0.1 | <0.1 | <0.1 | ** |
| 23/05/07 | CG | 0.3 | 0.7 | 0.4 | <0.1 | <0.1 | ** |
| 24/10/07 | 100 | - | <0.1 | <0.1 | <0.1 | >0.1 | ** |
| 04/02/09[!] | 23 | 6.6 | 1.0 | <0.1 | <0.1 | <0.1 | ** |

[!] Data supplied during report compilation. CG=Confluent growth; ** *P*<0.001

**Table 9** Total coliform (presumptive) counts (‘000 cfu/100 ml)

| Date | Inlet | Pond 1 | Pond 2 | Pond 3 | Pond 4 | Pond 5 | Significance |
|---|---|---|---|---|---|---|---|
| 31/05/06 | 500 | 22 | 0.3 | 0.1 | <0.1 | <0.1 | ** |
| 27/07/06 | 420 | 1.1 | 0.4 | <0.2 | 0.3 | <0.1 | ** |
| 06/09/06 | 1400 | 13 | <0.2 | <0.1 | <0.1 | <0.1 | ** |
| 23/05/07 | CG | 1.5 | 0.7 | <0.1 | <0.1 | <0.2 | ** |
| 24/10/07 | >1000 | - | 1.2 | <0.1 | <0.1 | <0.1 | ** |

** *P*<0.001;

Although there are no defined permitted levels for either faecal or total coliforms in inland waters, the Bathing Water Directive (76/160/EEC) defines the standards, as in table 10

**Table 10**

| | Guideline | Mandatory |
|---|---|---|
| Total coliforms CFU/100 ml | 500 | 10000 |
| Faecal coliforms CFU/100 ml | 100 | 2000 |

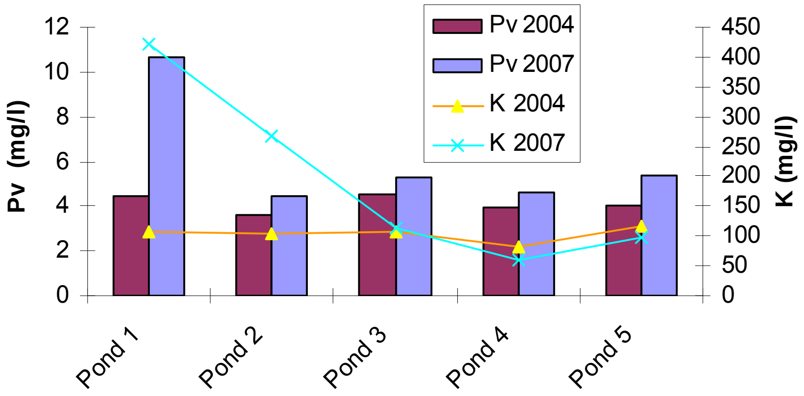
(Personal Communication; Devina Park, NIEA)

# 7 Constructed Wetland pond soils

## 7.1 Soil analyses

Soil analyses from the pre-flooded pond bases were compared with soil/sediment samples taken from the ponds after 24 months of FDW inflow. These data show a significant increase (Figure 29) of plant available phosphorus (Pv) (Olsen) and potassium (K) levels in pond 1 (*P*<0.05), with smaller increases of Pv in the remaining ponds and small (NS) reduction of K concentration in ponds 4 and 5.

**Figure 29** Plant available P (Olsen) and K in ICW soils in 2004 and 2007



The increase in nutrients was much lower than would be expected from the inputs of P and K to pond 1. This may reflect (1). that much of the P and K was not in plant available form or (2). an effect of sampling soils from the bottom of the ponds without root and plant detritus. Previous research (deBusk *et al.*, 2004) has shown that much of the nutrients remain either in solution, in the top layer of sediment/plant detritus or within the root and soil matrix of the plants where a proportion of it is adsorbed and utilised for growth.

Analysis (EDTA) for the trace metals Copper (Cu), Cadmium (Cd), Aluminium (Al), Zinc (Zn), Manganese (M) and Iron (Fe) in pond soils demonstrated significant differences (except for Cd) in the concentration between ponds (Table 11).

**Table 11** Mean concentration of trace metals in pond soils (2007)

| **Pond Number** | **Cu (mg/l)** | **Zn (mg/l)** | **Al (mg/l)** | **Cd (mg/l)** | **Fe (mg/l)** | **Mn (mg/l)** |
|---|---|---|---|---|---|---|
| 1 | 12.7 | 2.8 | 208.0 | 0.1 | 2315.8 | 117.6 |
| 2 | 9.1 | 3.5 | 217.0 | 0.0 | 2952.3 | 91.1 |
| 3 | 10.3 | 3.2 | 204.3 | 0.0 | 2133.0 | 154.8 |
| 4 | 14.9 | 5.6 | 222.0 | 0.1 | 2606.8 | 128.5 |
| 5 | 11.9 | 11.1 | 253.0 | 0.1 | 3363.5 | 172.5 |
| Significance | * | ** | * | NS | ** | * |

NS = Not Significant, * *P*<0.05, ** *P*<0.005

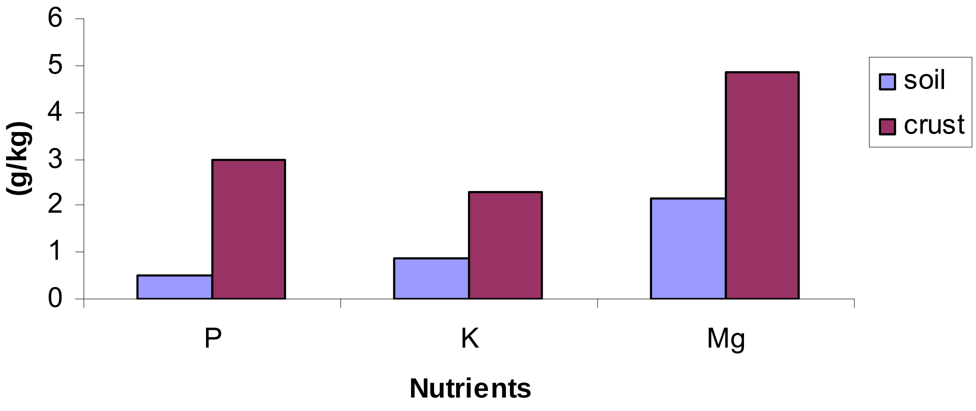
### 7.2 Organic matter surface accumulation (pond 1)

Surface accumulation of organic matter (derived from solids in the FDW) within pond 1 was particularly marked. Approximately 10% of the open water area directly underneath the inflow pipes (Figure 30) developed a surface “crust” several centimetres thick, suspended on the water surface, which was colonised by grasses that grew luxuriously upon it. Samples of the crust and soil-sediment cores (from the top 150 mm of the pond base) were taken for analysis in October 2007.

Analysis of this material indicates that compared to the pond soil-sediments, the surface crust had significantly ($P<0.001$) elevated levels of major nutrients (Figure 31). Soil (Kjeldahl) N was 2.28 ppm (DM) compared to 19.4 ppm (DM) in crust.

**Figure 30** Grasses growing on the surface “cake” layer adjacent to pond 1 inlet pipes

**Figure 31** Major nutrient levels in pond 1 sediments and organic matter crust



Some trace elements were present in significantly increased proportions (Table 10).

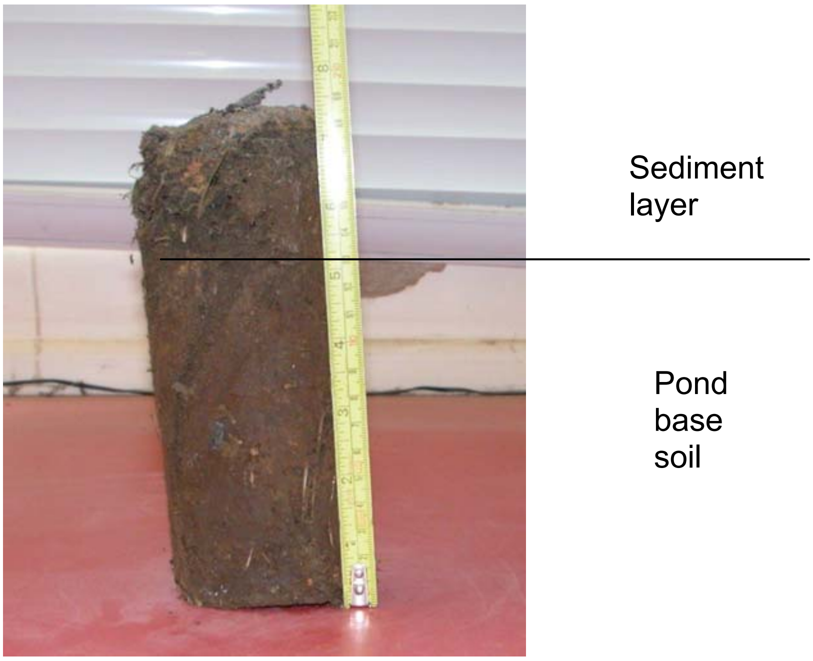
**Table 12** Trace element concentrations in Pond 1 organic matter crust and sediments

| | Zn (mg/kg) | Cu (mg/kg) | Mo (mg/kg) | Mn (mg/kg) | Fe (mg/kg) | Ca (mg/kg) | Se (mg/kg) |
|---|---|---|---|---|---|---|---|
| Crust | 357.5 | 78.3 | 1.1 | 160.6 | 9879.3 | 9636.7 | 24.7 |
| Sediment | 17.6 | 7.0 | 0.1 | 55.3 | 5120.9 | 6809.3 | 21.8 |
| Significance | ** | ** | ** | ** | ** | ** | * |

* *P*<0.05 ; ** *P*<0.01

The structure of the surface "crust" (~40 mm deep) and sub-soil of a dried core sample collected from this area of pond 1 during 2007 is shown in Figure 32.

**Figure 32** Soil core taken from pond 1 showing the organic sediment top layer (the darker top 40 mm)



# 8 Ground water

## 8.1 Ground water analyses

Analysis of ground water samples nutrient content indicated that only K showed a significant increase at sample points (SP) 1, 2 and 3 during the monitoring period. The higher values recorded on the last sample date for SP 3 could be probably attributed to contamination from the soil washed into the downpipe after it was exposed during landscaping work. Table 13 displays the concentration of each monitoring point on the days sampled.

**Table 13** Mean concentrations of ICW ground water samples

| Sample point | Date | TON-N (mg/l) | P (mg/l) | K (mg/l) | Mg (mg/l) | Cu (mg/l) |
|---|---|---|---|---|---|---|
| SP 1 | 05-04-06 | 1.12 | 0.18 | 1.72 | 22.70 | 0.05 |
| SP 1 | 11-10-06 | 0.28 | 0.40 | 1.60 | 28.12 | 0.07 |
| SP 1 | 11-07-07 | 1.26 | 0.12 | 1.24 | 21.95 | 0.05 |
| SP 2 | 05-04-06 | 0.42 | 0.19 | 4.23 | 21.13 | 0.06 |
| SP 2 | 11-10-06 | 0.00 | 0.11 | 4.14 | 20.90 | 0.05 |
| SP 2 | 11-07-07 | 0.07 | 0.07 | 4.32 | 21.19 | 0.05 |
| SP 3 | 05-04-06 | 0.28 | 0.17 | 2.99 | 32.24 | 0.05 |
| SP 3 | 11-10-06 | 0.14 | 0.25 | 2.97 | 35.98 | 0.06 |
| SP 3* | 11-07-07 | 1.26 | 1.04 | 3.83 | 58.78 | 0.26 |
| Significance | - | NS | NS | * | NS | NS |

NS = Not Significant , * $P<0.05$

# 9 Wildlife and ecosystems

The vegetation in all of the ICW ponds became very well established, providing cover and a source of food for wildlife. Wading birds were very quick to colonise the ponds and the ICW became an established breeding site for some common species. Several pairs of moorhen (*Gallinula chloropus*) and coot (*Fulica atra*) reared broods in the ICW and were in constant residence. Mallard ducks (*Anas platyrhynchos*) and Canada goose (*Branta canadensis*) were frequent visitors to the ICW while common snipe (*Gallinago gallinago*) were winter visitors (up to 14 were counted flighting from a single pond when disturbed). Stickleback fish (*Gasterosteus aculeatus aculeatus*), which were not introduced artificially into the ponds, have been recovered from the outflow screens of pond 5 and for most of the year, insect life was abundant, with large numbers of damselflies and dragonflies during warm summer days.

## 10 Discussion

From the FDW inlet to outlet discharge the reduction of $BOD^5$, P, N concentration and pathogens counts were very consistent, although P outflow increased significantly during wet winter periods. The fluctuations seen in FDW contaminants concentration at inlet were due to an interaction of several factors and might be expected to display a wide range of concentrations up to defined limits (Cumby *et al.,* 1999), above which they should be reclassified as slurries. Factors such as the time of sampling, precipitation levels, washing times and wash-water volumes were all relevant to the concentrations/dilutions of the samples when they were collected.

The concentration of $BOD^5$ in FDW for land spreading in Northern Ireland is normally expected to or is required to fall below $BOD^5$ 2000 mg/l. Though not applicable to the ICW, during the 2005/07 monitoring period the range of values recorded at Greenmount ICW inlet exceeded this only occasionally (max 2703 mg/l) and the mean $BOD^5$ at inlet was 943 ± 149 mg/l. The values recorded at the outlet (pond 5) ranged from 3.0 to 17.0 mg/l with a mean of 8 mg/l, values that fall well below the acceptable discharge maximum of 40 mg/l agreed by NIEA. By March 2008 the overall inlet value had increased 25% to 1080 ± 104 mg/l while the outlet value remained relatively constant (7.4mg/l ± 0.5). These mean inlet concentrations correspond well with expected predictions of 1000 to 1500 mg/l $BOD^5$ for Northern Ireland dairy FDW (DARD, 2003).

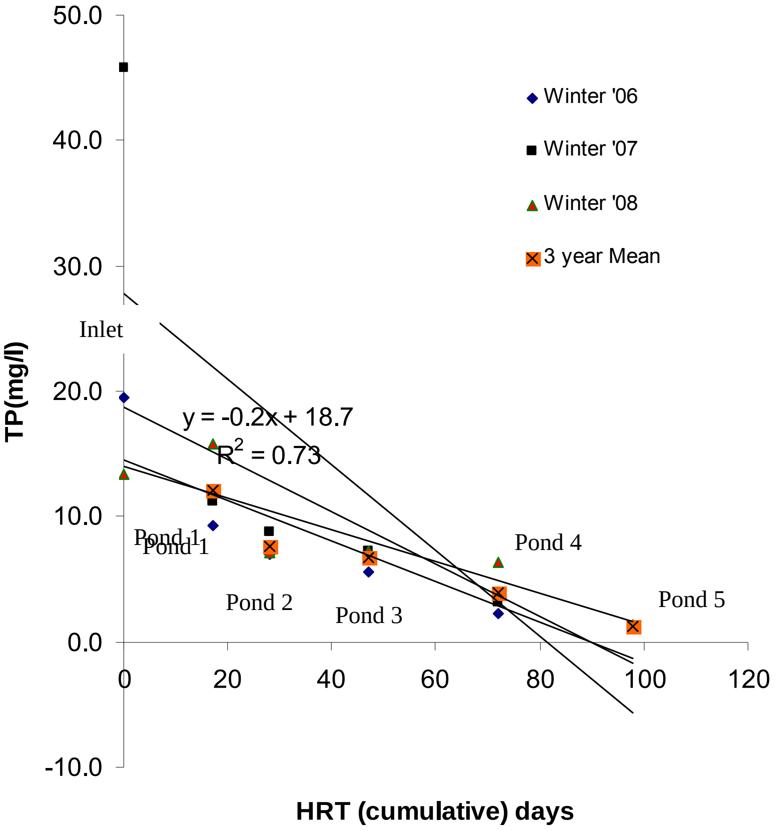
Changes in pond water total phosphorus (TP) concentrations from FDW inflow mean 45.92 ± 4.96 mg/l to average ICW outflow (discharge) concentrations of 1.2 ± 0.15 mg/l. Corresponding percentage reductions ranged 82.6 - 98.2% with a mean 97.1%. Substantial reductions of 94.9% in soluble reactive phosphorus (SRP) and 95.9% total soluble phosphorus (TSP) were also achieved. Though there were considerable seasonal variations, actual outflow P concentrations increased each year. The P values recorded and the percentage changes between inflow and outflow waters reflect higher reductions than those recorded in other comparable studies studies (Dunne *et al*., 2005a; Harrington *et al*., 2007). A review of relevant ICW literature (Forbes *et al*., 2004) concluded that the normal reductions recorded for P (as SRP and TP) ranged between 35-65%. However, between these studies many pertinent differences exist, for example in ICW to watershed size ratio, hydraulic load and retention time, nutrient load and many other factors that can affect reductive efficiency (Kadlec and Knight, 1996). The clear differences in P outflow concentrations during periods of water flow when P concentrations were generally higher, and non-flow between ponds when P concentrations were lower, may be important for future determinations of ICW farm:watershed ratios.

The $NH_4$-N inflow mean concentrations of 5.5 ± 0.77 mg/l were reduced at outflow by 96.4% to a mean of 0.02 ± 0.006 mg/l. This reduction is of a similar high percentage to those recorded from other ICW studies (Dunne *et al*., 2005a; Poach *et al*., 2003) and experimental work by Sun *et al*. (1999) who recorded inflow to outflow $NH_4$-N reductions from 330 mg/l down to 23 mg/l (93%). However, other studies by Sun *et al*. (1998) and Tanner *et al.* (2003) recorded maximum reductions of only 62 and 41% respectively.

The large reductions seen in the nitrogen ($NO_2$, TON, $NH_4$) content in the final discharge waters demonstrate the ability of the ICW to dissipate N. However it can also be lost to the atmosphere in gaseous form through wetland natural microbial processes (Hunt and Poach, 2001) and as $N_2O$ and $NH_3$ contributes to greenhouse gas (GHG) emissions. Concern on this aspect of wetlands is noted by Dampney *et al*. (2002) that when this occurs, this could be viewed (in their words) as a “straight swap” from nitrate pollution of water to atmospheric nitrous oxide pollution. The relative stability of pH in the ponds (~pH 7.5) would have limited the dis-association of the aqueous ammonium ion ($NH_4^+$) to $NH_3$, which can result in high emission of $NH_3$ $^+H$ (gaseous ammonia).

The bioremedial performance of the Greenmount ICW is undoubtedly influenced by the size of the ICW proportionate to its watershed area (~2:1), the hydraulic retention time (HRT) and inflow concentrations, which all effect influence on contaminant reductions. Regression analysis of results show that even with the large contaminant concentration changes in pond 1 there was a good linear relationship between contaminant reduction and pond area ($r^2$ = 0.84) and also HRT ($r^2$ = 0.73). Figure 32 demonstrates the latter for P (3 year mean values) and HRT in the ICW.

**Figure 32** Regression ($R^2$) plot of TP (mg/l) concentration and time (days) in ponds



Water loss due to evapotranspiration (annual mean PET ~450 mm May to September) was shown to greatly reduce pond water levels and interrupt flow patterns during the summer periods, factors that had a direct influence on pollutant concentrations. This resulted in slightly higher pond $BOD^5$ recordings in the summer months when the waters were stagnant, as no flows occurred between ponds and increased with greater flows during winter months, though remaining within the acceptable discharge limit. Conversely, P concentrations decreased during summer and increased significantly during winter high flow conditions. Though fluctuations may be expected in yearly rainfall patterns, the long term effects of prolonged dry conditions and subsequent wet periods cannot be predicted. However, a hydrologic model of a 14 year study of an agricultural ICW (Arnold *et al*., 2001) suggests that ideally, a wetland should be at or above 85% capacity for at least 60% of the time.

Studies of smaller ICW with shorter HRT, report much smaller reduction/removal of $BOD^5$ and nutrients. Tanner and Sukias (2003) reported a 33-67% $BOD^5$ reduction in a six-day HRT dairy ICW system but the efficacy of Greenmount ICW for $BOD^5$ reduction of 98-99% is not unexceptional with other studies reporting similar large reductions from high $BOD^5$ initial loadings to low values in outflow waters. Dunne *et al*. (2005a) reported 95-99% BOD reduction in ICW located on a dairy farm at Wexford, ROI. A predictive model (Sun *et al*., 1998) suggests that as $BOD^5$ loadings increase (up to a maximum of 1500 mg/l), $BOD^5$ content can be reduced by up to 98%.

Faecal and total coliform pathogens are reduced to very low levels in the ICW, comparable to those found in natural wetlands (Fox *et al*., 1984). This effect has also been found in other studies (Harrington *et al*., 2005; Shilton *et al*., 2003). The reduction to less than 100 cfu/100 ml recorded at Greenmount on several occasions, is contrary to the suggestions of Tanner and Sukias (2003) that reductions below 300-500 cfu/100 ml are probably unrealistic. However, the reductions at Greenmount were repeated consistently for both coliform types over a several years of recording.

Different soils can have a wide variation of nutrient retention capacity, especially for phosphorus (Dunne *et al.,* 2005b). Though a complete nutrient mass balance was not undertaken during this study the results of the soil analysis data does indicate some enrichment of P and K in pond 1 base soils. These increases do not reflect the nutrient load, especially of P, from the FDW and the proportion of the nutrients (and heavy metals and trace elements) taken up by the plants may be a relatively small percentage (Tanner, 2004). Gottschall *et al.* (2007) reported that *Tyhpa latifolia* in an agricultural ICW, utilised ~9% of TKN, 21% $NH^4$ and 5% of TP removed from the influent during its passage through the ICW. *Iris pseudacorus* was found to be the largest remover of P in a study that included *Phragmites australis* and two other macrophytes (Ansola and Fernandez, 1995). A review of 35 ICW studies, (Brisson and Chazarenc, 2008), found that while many reported differences between plant species in pollutant removal efficiencies, results were inconsistent and occasionally contradictory.

The ponds soil/sediment analysis did show that a considerable concentration of nutrient is accumulated in the root zone in pond 1, especially in the sediments and detritus, a finding previously reported of other studies (Longhi *et al*., 2008; Graetz *et* *al*. 2004; Qualls and Richardson, 2000) and there is also build-up of the organic matter “crust” in pond 1 (covering about 15% of the open water area). It is uncertain that these may have any detrimental effects on ICW performance, a possibility noted in studies, Langergraber *et al*. (2003) and Tanner and Sukias (2003) though it may be some years before these are manifested (Tanner *et al.,* 1998). However, this “crust” is relatively high in nutrients and may at some stage reach over-saturation which could result in nutrients being released into the pondwaters over time, creating the possibility of export through the system and discharge to receiving waters.

# 11 Conclusions

The initial establishment, high survivability and continued re-emergence of the various vegetation types and the development of a diverse flora and fauna within the ICW, indicates a sustainable environment for plant growth and wildlife occupation. While some plant species have begun to appear in ponds where they were not planted, there is no indication yet of dominance and encroachment by any particular species other than grasses.

Results from the records of the various ICW parameters sampled and analysed indicate that during the monitoring period, the bioremedial capacity of the wetlands was amply sufficient to meet the requirements for the outflow $BOD^5$ 40 mg/l discharge limit set by NIEA. Nutrient retention within the ICW was also of a very high level, and consistently much higher than those reported in studies of many other ICW. Phosphorus retention, considered here key criteria for FDW treatment, has been especially high, even allowing for seasonal fluctuations and P outflow concentrations which have increased each year.

Pathogen reduction performance was consistently excellent, regardless of initial coliform concentrations or pond water levels, with both faecal and total coliforms reduced to very low counts, equivalent to low background levels of natural wetland water.

Groundwater monitoring did not indicate that leakage occurred from the ponds into the surrounding earth. However, the falls witnessed in pond water levels during the 2006 summer months exceeded those attributable solely to reduced precipitation and PET losses alone. That might be due to leakage through the gravel bedding and surround of the distribution pipe work that links the ponds, a possibility that is currently under investigation.

The ICW:watershed ratio was sufficient to meet the initial contaminant removal requirements, resulting in changing nutrient status of the pond soils with a gradual increase in nutrient content, especially in pond 1. The discharge concentrations of all contaminants from pond 4 were on average twice those of pond 5, which indicates that any less than the 5 pond 1.25 ha system to service the FDW output, would have been unlikely to have achieved acceptable results.

The efficiency of the wetlands has been very consistent during the monitoring period, even during the drier summer months when little or no flow occurred between ponds. This scenario was not fully anticipated during the ICW planning stage and may be a major factor in the high contaminant retention performance of the wetland, *vis a vis* no outflow = no nutrient discharge.

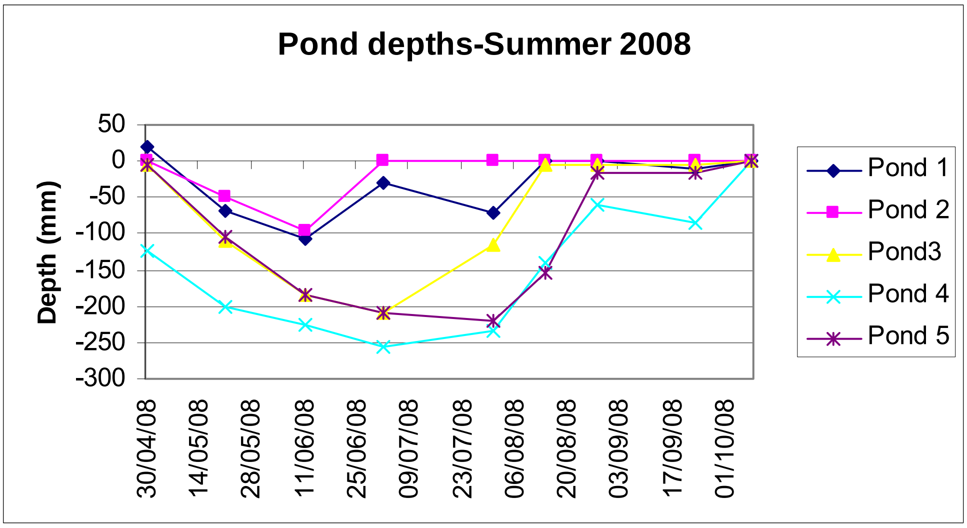
Overall, this constructed wetland has been exceptionally effective at bio-remediation of the farmyard dirty water as it has passed through the system of ponds. Indeed the levels of the contaminant reduction and nutrient retention have exceeded those reported from studies of many other agricultural ICW and the efficacy of the system has been very reliable and consistent.

Nutrient concentrations in the pond soils and sediments will, most likely, increase with time, a trend that if it continues may cause concern. In particular, continuous addition of substantial amounts of phosphorus (~154 kg (± 10%) per annum) could represent a negative aspect to the ICW in that it will create a substantial reservoir and potentially an export source of this element, a major factor in surface water eutrophication in Northern Ireland. This in turn may also affect the longevity of the ICW as an efficient, sustainable bio-remedial system for the dirty water produced at the farm. How long this ICW can continue to perform reliably will only become apparent after further years of prolonged use and this is an aspect of the ICW that will, most essentially, require continued monitoring.

## 2008 – 2009 Update

Monitoring and analysis continued through 2009 and changes in FDW contaminant concentrations were recorded. Overall mean values for inflow $BOD^5$ increased to 1311 ± 113 mg/l while outflow concentrations remained relatively constant at mean 7.4 ± 0.5 mg/l. During 2009 mean concentration of both inflow and outflow TP increased 97.48 ± 12.58 mg/l and 2.43 ± 0.015 mg/l respectively. Nitrogen data are currently being compiled. Vegetation growth remained strong except in pond 2 where *Typha latifolia* under competition from invasive grasses showed restrained growth, signs of disease and early senescence in 2008 and, for causes yet undetermined, complete die-back of some plants during the 2009 growing season. The pond water balance was again in deficit during summer 2008 (Figure 33) except pond 2 which recovered its optimum level by July. Though it is still uncertain, there is a possibility that there is leakage from pond 1 into pond 2, resulting in lower water levels in the former and sustained levels in the latter. This may also be the situation in ponds 4 and 5 where even larger discrepancies occurred.

**Figure 33** Pond water depths- spring and summer 2008



(0 = optimum water depth - pondwaters level with top of outflow)

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Stephen Sturgeon, Laboratory Manager, AFBI, Loughgall

John Archer, Laboratory supervisor, AFBI, Loughgall

Orla Ruddle, NIEA

Richard Coey, NIEA

NIEA Marine Assessment and Licensing Team – Microbiology Laboratory

NIEA River Ecology Section

Dr Fiona Wilson, NIEA

NIEA Marine Assessment and Licensing Team – Microbiology Laboratory

Dr Crawford Jordan, AFBI

Dr Sally Watson, Statistical Development, Biometrics, AFBI

Ashley Uprichard, Statistical Development, Biometrics, AFBI

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Belfry Construction, (Mr Pat Conway), Lakeview House, Ballycassidy, Enniskillen
*ie*Consulting Engineers, Innovation Centre, Green Road, Carlow
ieconsulting@eircom.net

## 13 Glossary of terms

### Terms and Abbreviations

| | |
|---|---|
| **BOD** | Biochemical oxygen demand (refers here to $BOD^5$) - the consumption of oxygen by biological/chemical reactions |
| **$BOD^5$** | 5-day biochemical oxygen demand |
| **DAIRY WASHINGS** | Washings from milking parlours |
| **DARD** | Department of Agriculture and Rural Development, N.I. |
| **DARD[1]** | Code of good Agricultural practice for the prevention of pollution of water. DARDNI, 2003 |
| **DEFRA** | Department of Environment, Farming and Rural Affairs, UK. |
| **EC** | European Commission |
| **EHS** | Environment and Heritage Service, DOE, N.I. |
| **EUTROPHIC** | Waters high in nutrients often resulting in plant and algal growth which can eventually reduce aquatic life |
| **FDW** | Farmyard dirty water – water resulting from washing of stock houses, milking parlours and yards |
| **HF** | Horizontal Flow |
| **HRT** | Hydraulic Retention Time (time effluent is in CW) |
| **HYDROPHYTES** | Plants able to withstand constant or frequent submergence of roots and stems |
| **MACROPHYTE** | Plants (& higher algae) large enough to be seen by eye |
| **mg/l** | milligram per litre |
| **N** | Nitrogen-nitrogenous compounds |
| **NIEA** | Northern Ireland Environment Agency |
| **µg/l** | Microgram per litre |
| **P** | Phosphorus- Phosphatic compounds |
| **PET** | Potential evapo-transpiration, a combination of evaporation and water transpired by plants to the atmosphere |
| **PPM** | Parts per million |
| **ROI** | Republic of Ireland |
| **SE** | Standard error – statistical term, i.e. normally indicates that ~68% of observations lie within ± 1 se |
| **SF** | Surface Flow |
| **SS** | Suspended solids |
| **TN** | Total nitrogen |
| **TP** | Total phosphorus- soluble and insoluble |
| **TSP** | Total soluble phosphorus |
| **SRP** | Soluble reactive phosphorus |
| **WFD** | Water Framework Directive |

# 14 Appendices

**Table 14** Standards for the Chemical GQA

| GQA Class | Dissolved Oxygen (% saturation) 10-percentile | BOD (mg/l) 90-percentile | Ammonia (mg N/l) 90-percentile |
|---|---|---|---|
| A (Very good) | 80 | 2.5 | 0.25 |
| B (Good) | 70 | 4 | 0.6 |
| C (Fairly good) | 60 | 6 | 1.3 |
| D (Fair) | 50 | 8 | 2.5 |
| E (Poor) | 20 | 15 | 9.0 |
| F (Bad) | < 20 | - | - |

**Table 15** GQA Classification (Based on rolling 3 year basis
e.g. 2006 = 2004 - 2006

| GQA Class | Dissolved Oxygen (% saturation) 10-percentile | BOD (mg/l) 90-percentile | Ammonia (mg N/l) 90-percentile |
|---|---|---|---|
| A (Very Good) | 80 | 2.5 | 0.25 |
| B (Good) | 70 | 4 | 0.6 |
| C (Fairly Good) | 60 | 6 | 1.3 |
| D (Fair) | 50 | 8 | 2.5 |
| E (Poor) | 20 | 15 | 9 |
| F (Bad) | < 20 | - | - |

**Table16** Freshwater Fish Directive

| | **Salmonid (Guideline Standard)** | **Salmonid (Mandatory Standard)*** ** | **Cyprinid (Guideline Standard)** | **Cyprinid (mandatory Standard)*** ** | **Mean for Garvary 2006** | **PASS FFD** |
|---|---|---|---|---|---|---|
| Dissolved Oxygen (mg/l $O_2$) | 50% >=9<br>100% >=7 | 50% >=9 | 50% >=8<br>100% >=5 | 50% >=7 | Pass | Yes |
| pH | | 6 - 9 | | 6 - 9 | 7.13 | Yes |
| $BOD^5$ (mg/l $O_2$) | <= 3 | | <= 6 | | 1.356 | Yes |
| Nitrites (mg/l $NO_2$) | <= 0.04 mg/l | <= 1 mg/l | <= 0.02 mg/l | <= 1 mg/l | 0.011 | Yes |
| Non-ionized ammonia (mg/l $NH_3$) | <= 0.005 | <= 0.025 | <= 0.005 | <= 0.025 | 0.0012 | Yes |
| Total ammonium (mg/l $NH_4$) | <= 0.04 mg/l | <= 1 mg/l | <= 0.02 mg/l | <= 1 mg/l | 0.021 | Yes |

(Courtesy of Orla Ruddle, NIEA)

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*ie ie*Consulting Engineers, Innovation Centre, Green Road, Carlow. ieconsulting@eircom.net Tel: 00353 50333084, Fax 00353 503 40499.

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Department of
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AFBI Headquarters, Newforge Lane, Belfast, Northern Ireland BT9 5PX
Tel: +44 28 9025 5636
email: info@afbini.gov.uk
www.afbini.gov.uk