
Integrated Constructed Wetlands: concept, design, site evaluation and performance

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Abstract: ‘Integrated Constructed Wetlands’ (ICW) are a joined-up approach to land and water management. Significant synergies were achieved by explicitly combining environmental, ecological and aesthetic objectives. Intercepted precipitation was found to be the main factor determining treatment efficacy. Soil infiltration and evapo-transpiration combined to enhance hydraulic residence time. A wetland area and configuration were the principal factors determining effluent water quality. During periods of low precipitation ICW discharge tended to positive synchrony with the receiving waters. There were significant improvements to the ecology and water chemistry of receiving waters after five years of ICW intercepting about 75% of farmyard pollution.

Keywords: integrated constructed wetlands; ICWs; land-water interfaces; site assessment; phosphorus; nitrogen; ground water; surface water; sustainability; catchment; sub-catchment; precipitation; surface flow.

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1 Introduction

It is one of the paradoxes of life how inherently simple ideas can capture the imagination, develop and become unassailable; using land or 'farming' the land for its water is one. The 'Integrated Constructed Wetlands' concept and the associated '(ICWs) Initiative' of the Irish National Parks and Wildlife Service (Department of Environment, Heritage and Local Government) is one such simple idea based upon the use of the land-water interface to effect environmental and nature conservation management. The ICW concept developed from work started in the late 1980s and early 1990s to improve the management of natural resources for the rural-community in the 25 km²-water catchment of the Dunhill-Annestown stream in south county Waterford, Ireland (Harrington and Ryder, 2002). The working framework deployed in the catchment is similar to that of the 'small watershed technique' and associated ecosystem studies developed by Bormann and Likens (1981) at Hubbard Brook, New Hampshire, USA. As the ICW Initiative has its focus on an entire catchment it adheres to, and is strongly influenced by, the 'Ecosystem Approach' developed for the UN 1992 Convention on Biological Diversity (CBD), to which all countries of the European Union and its Commission are signatories. The specific naming of the concept as 'Integrated Constructed Wetlands' (ICWs) arose from the need to emphasise its joined-up approach to the management of natural resources.

The ICW concept is based on the holistic use of land to manage water quality. Because of climate, topography and soils, wetlands of various types were once ubiquitous throughout Ireland and most of Europe. These areas of land-water interfaces once formed an integral part of the environmental and ecological structure of the landscape. They acted as transition zones between dry and water-inundated land areas and functioned to control the transfer and storage of water and nutrients. They also provided habitats for diverse flora and fauna (Feehan and O'Donovan, 1996; Otte, 2003). So great has the loss of this environmental infrastructure been that there is now often little appreciation of their environmental and ecological roles. This is reflected in the continuing drainage and infilling of wetlands and, institutionally, by the caution or even indifference with which state regulatory agencies can view the use of wetland infrastructure for the management of water resources (Panel Summary and Concluding Remarks, 2005; Otte, 2005). The ICW initiative endeavours to promote the advantages of restoring some of wetlands' key environmental services and their associated habitat lost.

Wetland landscapes, in particular those dominated by emergent vegetation (helophytes), with seasonal, shallow water and nutrient enriched soils, have been especially vulnerable to drainage and conversion to agricultural land. The ICWs described in this paper mimic in large part the structure and processes found in this type of wetland.

The ICW Initiative of the National Parks and Wildlife Service is served by the authors of this paper, an interdisciplinary team comprising members with chemistry, ecology, engineering, environmental science and hydro-geology backgrounds. The initiative's remit is to demonstrate the working capabilities of ICWs and to promote their application, initially through the development of a 'National Guidance Manual' for their use in the management of farmyard waste water. The success achieved so far in managing the variable nature of farmyard effluents has seen the application of ICWs in the management of other effluents including those from the food industry (dairy and meat processing), landfill leachate, sewage grey-water and sewage-contaminated storm-water.

2 The Integrated Constructed Wetland (ICW) concept

The primary objective of ICWs is the explicit integration of:

- the containment and treatment of influents within emergent vegetated areas using wherever possible local soil material
- the aesthetic placement of the containing wetland structure into the local landscape towards enhancing a site's ancillary values
- enhanced habitat diversity and nature management.

This explicit integration facilitates processing synergies, robustness and sustainability that are not generally available in other wetland treatment systems. These benefits are primarily due to the greater biological complexity and generally relatively larger land area and associated longer HRT. Fundamentally, the concept is focused upon creating ecological infrastructures that are largely self-managing, biologically self-designing and which have social and economic coherence. This robust, sustainable and multi-benefit yield from ICW systems is assured by appropriate assessment, design and construction (Kadlec and Knight, 1996).

3 Capture, containment and treatment

The ICW concept requires that all existing and potentially polluted water sources drain to the receiving constructed wetland. In the farmyard context such waters will typically include:

- dairy parlour and yard washings
- impervious farmyard curtilage and road surface runoff
- seepage from silage and dungsteeds
- roof water likely to be contaminated by avian faecal matter, dust and residues from roofing material
- accidental spillages and leakage of hydrocarbons, fertilisers and other farm-used chemicals.

Whilst good farmyard management will strive to minimise the degree to which water-vectored pollutants flow from the yard, their potential to escape to adjacent surface drains is reason enough to consider/recommend that all existing water flows and potential flows within a farmyard complex/curtilage are intercepted and directed to the wetland. Additionally, there are environmental risks associated with the conventional landspreading method of dirty water disposal. Several studies in Ireland (Richards, 1999; Bartley, 2003; Rodgers et al., 2003) have reported that land spreading of dirty water can lead (either directly or indirectly) to high nitrate levels in soil pore water and groundwater. Many farmyard infrastructures are inadequately serviced to manage all existing water flows from their curtilage and in the existing farm economic climate their management requires the development of cost-effective remedies to ensure the protection of surface and ground waters.

It is essential that any containment is secure and that only water free from polluting contaminants is discharged to surface or ground waters.

Containment of influents within the segmented structure of an ICW, with each sequential segment having its own contamination gradient, will progressively lead to improved water quality, which should ultimately meet the needs of the eventual receiving environment. The wetland's embankments retaining the through-flowing water must be sufficiently high to allow for the accumulation of sediments and detritus. The soil lining the base must adequately impede infiltration.

Precipitation-generated volumes from farmyard areas may be many orders of magnitude greater than that originating solely from farmyard and dairy washings. Typically, these are only about one third of the annual volume of water from intercepted precipitation on open farmyard areas. During 24 h extreme events, (e.g., 50 mm during a 24 h period) washings can be as little as 2% of the volume of water generated from precipitation on open farmyard areas (Harrington et al., 2005).

The episodic nature of precipitation and the continuous draw-off of water through interception by the tall emergent vegetation, evapo-transpiration and infiltration to ground has the capacity to arrest water flow between the individual segments of an ICW. This creates freeboard between the outlet level and the level of the water in an individual wetland segment. This provides each wetland segment with extra receiving hydraulic capacity before flow to the next segment can resume, consequently enhancing HRT.

Velocity of the water flow through the wetland is determined by the volumetric flow and cross-sectional area of the water channel. With the surface flow of ICWs this equates to volumetric flow across the width of each wetland segment. Minimising velocity enhances the precipitation of suspended solids and promotes a longer contact time with emergent vegetation whose surfaces support water-cleansing biofilms.

Wind and temperature differences have the potential to generate water movement between the different aquatic strata within a wetland segment. Emergent vegetation minimises mixing, thus allowing the cleaner water to flow preferentially along the surface especially during periods of large precipitation-generated flow. In the initial receiving wetland segment, floating vegetation may develop typically, *Glyceria maxima* and *Agrostis stolonifera*, and water flow will be partially subsurface, this has the added advantage of reducing odours.

4 The aesthetic placement of the containing wetland structure into the local landscape towards enhancing a site's value

Wetlands, including constructed wetlands can have considerable aesthetic appeal. The combination of water, vegetation and associated wildlife, which constitute the wetlands, is the principal cause of their appeal and there are many examples of this throughout the world (<http://www.ramsar.org>). The ICW concept strives to incorporate aesthetic appeal through appropriate land-forming design, implemented during construction. Land-forming the ICW structure requires several levels of sensitivity to the existing topography and local landscape. It endeavours to ensure that the final structure 'fits' into the landscape, e.g., by making the enclosing embankments curvilinear, thus conforming to the sites' topography in order to visually enhance its appearance from both a distance and on site. Appreciation is further encouraged by providing ease of access and facilitation for visitor intimacy with the structures and habitats of the ICW. Subsequent

vegetation development will further enhance the visual appearance and its 'natural' sympathetic appeal. Appropriate land forming of the structure to fit the landscape usually has the added advantage of reducing ICW maintenance, enhancing a variety of amenity values and improving its functional longevity.

5 The facilitation of habitat diversity and nature management

The principles of 'restoration ecology' apply to ICWs (Jordan et al., 1987). The opportunities for habitat restoration and biodiversity require attention at the design stage. The profiles and infrastructural details required to support habitat development are, on the basis of experience, best addressed at the land-forming stage during construction. This is particularly pertinent to the development of ecotones (transitional habitats between the terrestrial embankment and the aquatic wetland zones). Wide, shallow and low elevated edges to the embankments were clearly best in facilitating floral and faunal diversity. Consideration should also be given to including shallow and deep areas with either south or north facing aspects. Existing vegetation, particularly trees and woodland, are best incorporated wherever possible. There is a general recognition that ICWs can be very dynamic ecosystems and that their habitats may be transient unless managed and maintained. The management of water depth is the most important in this regard.

The primary vegetation types used in ICWs are emergent plant species (helophytes). These species have evolved to enable them to root in soils with no available or limited oxygen supply, growing vertically through the water column, with most of their leaves in the air. They have specially adapted tissues that facilitate oxygen storage and its transportation from the leaves through the stem to the roots. Soil and water characteristics influence the type and performance of plant species for each wetland segment of an ICW. While more than a 100 native species can be used, in general, about 11 species are most commonly used. Their genera are: *Acorus*, *Carex*, *Eleocharis*, *Glyceria*, *Iris*, *Juncus*, *Phragmites*, *Ranunculus*, *Scirpus*, *Sparganium* and *Typha*.

Species selection depends upon: water depth, turbidity, pH, ammonium concentration and the electrical conductivity of the water in each wetland segment. Various mixes of species may be used throughout an ICW. Consideration must be given to the size, physical structure and physiology of the plants and their related adaptive capacity for survival in different water depths, or soil types. With time the wetland environment changes as its constituent species interact. Inter-specific competition and other biotic factors, especially waterfowl, influence long term vegetation development. Initial plant establishment exerts the dominant influence on the vegetation structure of an ICW during its early years. Overall plant establishment is ultimately dependent upon the nature and depth of the influent, plant species availability and physiological maturity and planting density.

Subsequent species enrichment through additional planting, may be possible or, indeed, be sometimes necessary. Nearly all farmers involved in the project have expressed their appreciation of having an area of visual beauty, tranquillity and wildlife interest that was not previously present adjacent to their farmyard. The consequences of this are for wider appreciation within the community, leading to curiosity and interest in the nature of wetlands. The encouragement of all those farming the land of the catchment to participate in building ICWs has been helped by the acquisition of these new values for their land.

6 Site assessment

Site assessment will determine the parameters for the design to provide the necessary protection to surface and ground waters and other aspects of the site's value, including those of archaeological and nature interest (Keohane et al., 2005).

The key factors in the construction of treatment wetlands are: HRT and velocity; nutrient cycling, retention and retrieval; retaining structures; site hydrogeology and soil characteristics; area availability and existing site values and influent characteristics. Water depth and influent ammonium concentration are the key factors determining vegetation establishment and development (Harrington, 2005). All of these factors require assessment to determine if an ICW can be safely built on a proposed site and whether its construction might have any negative impact. It is essential that the construction of a wetland does not itself become a source of pollution. To this end, the conditions agreed upon with regulatory authorities must be met. There are two general types of conditions; those dealing with water resources and those dealing with the intrinsic values of the site.

The conditions for protection of surface waters are:

- taking an ecosystem approach
- that discharge into sensitive waters should be at least neutral
- the assimilative capacity of the receiving surface water needs to be determined.

(If a surface water discharge is not possible, then an alternative needs to be examined, such as increasing post-treatment infiltration into the ground.)

The conditions for protection of groundwater are:

- prohibition within 60 m of a well or spring
- prohibition within the inner protection zone of a public well, where groundwater vulnerability is extreme
- that the ICW is underlain by at least 1.5 m of subsoil, with the upper 0.5 m enhanced where necessary to 1×10^{-8} m/s.

The site/sub-soil investigation comprises:

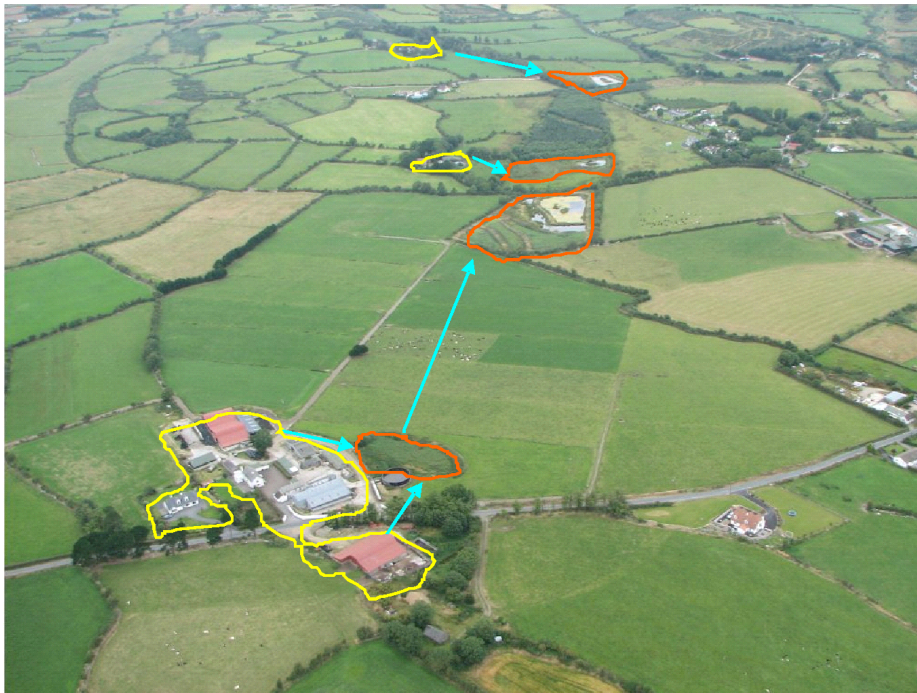
- excavation of trial holes
- description of each trial hole to BS5930 standard
- assessment of the workability of the material to achieve the necessary resistance to infiltration
- taking samples for Particle Size Distribution analysis to demonstrate a clay content of >10%.

Assessment of a site's intrinsic values comprises both desk and on-site study to identify any potential archaeological interest, areas of nature and wetland interest particularly Special Areas of Conservation (SACs) or Natural Heritage Areas (NHAs). Ideally the site should have no, or low, values for these interests. Landscape consideration is achieved through attention to topography and adjacent landscape features.

6.1 Performance assessment

The working framework deployed in the 25 km² Annestown-Dunhill catchment is similar to that of the 'small watershed technique' and associated ecosystem studies developed by Bormann and Likens (1981). The entire catchment is divided into a number of sub- or nested catchments recognising each farmyard curtilage of the 19 working farms in the catchment as a sub-catchment. In 1999/2000 12 ICWs were designed, planning permission from local government (Waterford County Council) applied for and received, and construction carried out to intercept and treat farmyard dirty water from 12 farmyards. These farm ICW systems, and additional planned systems, continue to provide valuable data on the functioning of an entire water catchment. In effect this catchment acts as a field laboratory with parallels to that of the Hubbard Brook catchments (Bormann and Likens, 1981). In this case it allows the assessment of the impact of the wide application of the ICW concept at river catchment scale (Figure 1).

Figure 1 Three ICWs in the Dunhill Landscape showing dirty water flows (light blue) from farmyard (yellow) to receiving wetland (red) (for colours see online version)



6.2 Methods

An extensive water quality monitoring programme was undertaken on these. This comprised sampling wetland influents and effluents, receiving surface and ground waters. Grab samples were taken on a monthly basis for each wetland influent and effluent. In the absence of effluent discharge, the surface water of the last wetland cell of each ICW system was sampled. The Anne River, which is the receiving waterbody for the ICW discharges, was sampled approximately monthly. Receiving groundwaters were

sampled monthly at three ICW sites from 4 m-deep piezometric tubes located 5 m downgradient of the ICW cells.

Flow meters were installed at one four-celled farmyard ICW. Influent and effluent flows into, between and from each wetland cell of the ICW were continuously recorded using flow meters and recording devices for the period March 2003–April 2004. Rainfall and evaporation were measured by an automatic weather station. This allowed water and nutrient budgets for each cell of this ICW to be calculated. Phosphorus and Nitrogen budgets were calculated by multiplying flow by concentration. Each wetland cell in this ICW system was sampled approximately weekly at the inlet and outlet, between April 2003 and December 2004. Discharge into the ground was calculated, using the average value of the inlet and outlet concentrations for each cell, to account for the concentration gradient along the length of the cell. Surface discharge calculations were based on the outlet concentration.

Molybdate Reactive Phosphate (MRP) was measured and a factor of 1.8 was applied to MRP concentrations to calculate Total Phosphorus (TP). This factor was determined using project data (unpublished), whereby samples were tested for both MRP and TP to establish a relationship. Uptake by vegetation was not considered in the P budget but, in the absence of harvesting, was likely to be neutral over time.

Nitrogen fluxes were calculated from ammonia plus nitrate concentration, multiplied by flow. Uptake by vegetation or emissions to atmosphere was not taken into account for the nitrogen budget; nevertheless, calculation of the nitrogen flux to ground and to surface waters was possible.

Sediment accumulations were measured for six ICW sites. Sediment samples were taken by manual grab from the first three cells of each of these ICWs; at the inlet, mid, and outlet areas of the first cell where heterogeneity was expected to be greatest, and at central areas of second and third cells.

Sediment samples were tested for TP using the ascorbic acid method following digestion using nitric acid/hydrogen peroxide. Water analysis was undertaken at Waterford County Council's laboratory using standard methods of analysis (APHA, 1992, 1996).

6.3 Results

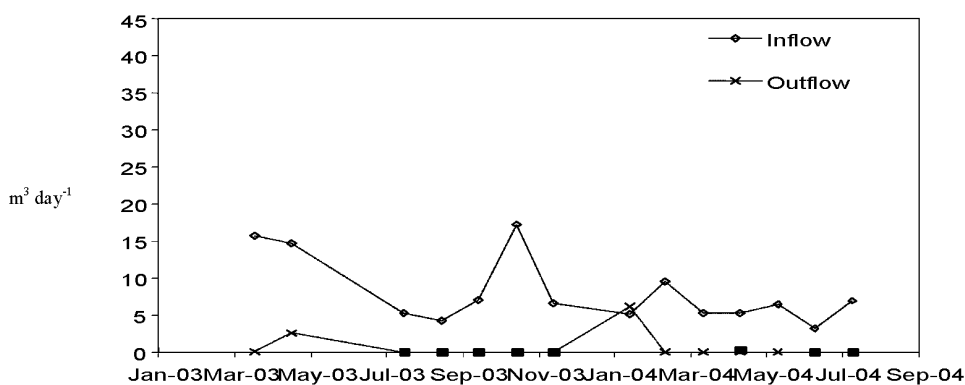
The BOD_5 of the influents entering the ICWs was $1200 \pm 5000 \text{ mg l}^{-1}$. Significant reductions in concentrations of organic material, suspended material, nutrients and faecal bacteria in the influents of all 12 ICWs sites was observed during monitoring, Table 1. No significant correlation was found between inlet and outlet concentrations for water quality parameters. The ICWs were constructed with some variations around the design template, and this allowed the relationship between configuration and performance to be considered. A wetland area based on an appropriate factor (>2) times the farmyard area, an aspect ratio for the individual wetland segments ($<4 : 1$ length to width) and having the first receiving wetland segment $>20\%$ of the overall wetland area, were found to be the principal factors determining good effluent water quality from ICWs (Carroll et al., 2005; Harrington et al., 2005).

Table 1 Characteristics of ICW influents, effluents, and receiving surface and groundwaters (mean \pm 1 standard deviation)

	<i>Influents</i> <i>n = c300</i>	<i>Effluents</i> <i>n = c300</i>	<i>Anne river,</i> <i>downstream</i> <i>of ICWs</i> <i>n = c25</i>	<i>Groundwater</i> <i>downgradient</i> <i>of ICWs</i> <i>n = c80</i>
BOD ₅ (mg l ⁻¹)	1200 \pm 5000	20 \pm 20	2 \pm 1.4	–
Ammonia (mg l ⁻¹ N)	80 \pm 170	0.5 \pm 2	0.06 \pm 0.04	4 \pm 4
Nitrate (mg l ⁻¹ N)	<1	1.5 \pm 3	4.2 \pm 1.4	0.2 \pm 1.5
MRP (mg l ⁻¹ P)	25 \pm 70	0.5 \pm 0.8	0.03 \pm 0.02	<0.01 \pm 0.04
<i>E coli</i> cfu (100 mls)	200,000 \pm 380,000	500 \pm 1320	–	25 \pm 27

6.4 Annual water balance

Direct water flow from the sampled farmyard contributed to 26% of total inflow. The remainder came from rainfall directly falling onto the wetland (58%) and extraneous water (15%), possibly from grassland up-gradient of the first wetland cell. Twenty three percent of water exited the wetland through evapo-transpiration, with 73% discharging into the ground; most of the water discharging to ground (46% of the total) was lost at the fourth pond in the system. Only 4% of the total water inflow (11% of the farmyard water) discharged to surface. Influent and effluent flows are presented in Figure 2. The seasonal pattern can be seen, with flow from the ICW only occurring for a short period in the winter/spring.

Figure 2 Water flow into and out of ICW system number 11, April 2003–2004

6.5 Phosphorus budget

Over the one year period 90 kg of phosphorus was estimated to have entered the ICW from the farmyard; 50 kg was deposited as sediment in the first cell, 7.6 kg was discharged to ground from cell 2, 12.9 kg from cell 3 and 19.0 kg from cell 4. The phosphorus discharged to the ground is expected to be quickly bound to the receiving soils of the area (acidic volcanic rhyolitic and host shale material derived). Only 0.5 kg of P was discharged to surface waters during the year.

6.6 Nitrogen budget

155 kg of nitrogen was estimated to have entered the ICW from the farmland over the one year study period. Of this, 60 kg was discharged to ground, and 2.5 kg to surface water. The remaining 90 kg is assumed to have been taken up by vegetation or emitted to the atmosphere.

6.7 Sediment phosphorus build-up

The velocity of the water seems to be critical for capture of phosphorus. There was a strong positive relationship observed ($r^2 = 0.99$), at three Anne Valley ICW sites examined, between the area of the first cell (and thus the horizontal velocity of the water) and depth of phosphorus-rich (circa 3 gP/kg dry wt) sediment.

The amount of P building up in the wetlands' sediment per annum (Table 2) ranged between 1–9% of annual farm P requirement, based on a requirement of 9 kg/ha as recommended by Coulter (2004).

Table 2 Sediment-P accumulation

<i>ICW system</i>	<i>Total sediment-P (kg) after five years operation</i>	<i>Annual sediment-P accumulation (kg)</i>	<i>Farm size (ha)</i>	<i>Annual farm P needs at 9 kg ha⁻¹ (%)</i>
3	246	49.2	61	9
4	151	30.2	121	3
9	228	45.6	56	9
10	26	5.2	78	1
11	367	73.4	130	6
12	41	8.2	158	1

6.8 Receiving stream water quality

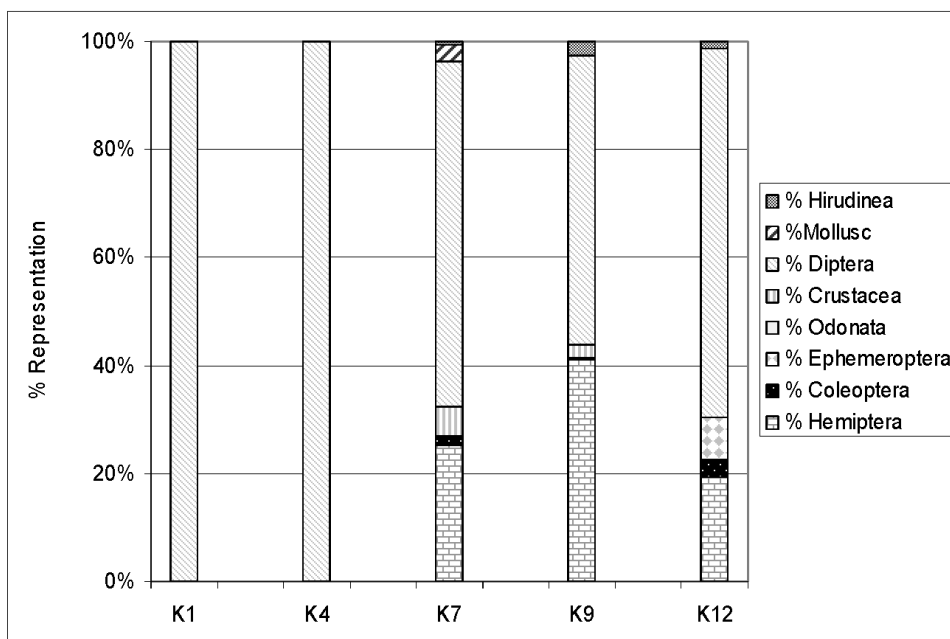
Improvement in the Annestown stream's water quality has coincided with the construction (in 1999–2000) of the ICW farm systems. These ICWs treat about 75% of all farmyard dirty water generated within the watershed. Biological water quality status of the stream has improved from an overall water quality rating of Q2 (seriously polluted) in 1999 to a water quality rating of Q3/4 (slightly polluted) in 2001 (EPA, 2002). Further evidence suggests that water quality has since improved to Q4 (unpolluted) (Mary Kelly-Quinn, Department of Zoology, University College Dublin, personal communication, May, 2004). Sea trout (*Salmo trutta*) have returned to the stream after many decades of absence. The common newt (*Triturus vulgaris*) has become abundant in all ICWs of the catchment.

Although our results from invertebrate monitoring within the catchment, individual ICWs and along the catchment's streams are on-going, preliminary results indicate significant ecological enhancement. A study of a representative ICW within an adjacent watershed suggests that there is a wide range of macroinvertebrate organisms present in the latter segments of ICWs. One site-specific study showed that in upper wetland (proximal) segments macroinvertebrate diversity was low, represented only by flies

(Diptera); however, in the latter (distal) segments of the system macroinvertebrate diversity was represented by several orders that included Diptera (flies), Hemiptera (true bugs), Ephemeroptera (mayflies) and Coleoptera (beetles) (Figure 3).

These findings indicate that the addition of an ICW system within agricultural landscapes, such as the Anne valley watershed, provide suitable environments, primarily due to the presence of appropriate water quality for local ecologies, such as macroinvertebrates.

Figure 3 Percent representation of different orders of macro-invertebrate biodiversity with distance from ICW influent. Numbers on x-axis represent individual wetland cells in the ICW system



7 Conclusions

The ICW concept, by applying basic understanding of wetland ecology and associated land-water interfaces developed a new paradigm for land and water management. Our findings suggest that ICWs are capable of treating farmyard dirty water and that they provide a sustainable management option to effectively reduce nutrient and contaminant loss from farmyards to water resources whilst also providing additional new values for the acquired wetland site.

The success of the ICW demonstration projects in the Anne Valley has attracted the interest of farmers and regulators throughout Ireland and the UK for the management of dirty water. The authors, the team serving the ICW initiative, are engaged in preparing a national guidance document to provide the necessary guidance to regulators, designers and constructors.

The intensive application of the ICW concept at a river catchment level has provided a unique opportunity to assess the value of a catchment-wide approach. The results so far

are encouraging and there is a strong anticipation that the approach undertaken will provide an effective template for the management of land and water resources on a wider scale.

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