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# Constructed wetlands for environmental pollution control: A review of developments, research and practice in Ireland

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**Abstract**

For the purpose of synthesizing a compendium of efforts aimed at environmental pollution control through the use of constructed wetlands systems (CWs) in Ireland, a detailed review of CWs was undertaken. Emphasis was placed on the diverse range of development, practice and researches on CWs technology, placing them in the overall context of the need for low-cost and sustainable wastewater treatment systems. The potential use of CWs in protecting estuarine quality within the current legislative framework is considered, as well as the emerging concept of integrated constructed wetlands (ICWs). In addition, an assessment of the efficiency of CWs in operation in Ireland towards abating environmental pollution was done, and compared with CWs operating in other European countries. The need for sufficient and appropriate data to assist in further development of CWs and modelling studies, and instilling confidence in the public is also highlighted.

*Keywords*: Constructed wetlands, dewatered alum sludge, environment, Ireland, phosphorus, pollution control, reed beds, wastewater treatment.

## Notations and Abbreviations

| | |
|---|---|
| $BOD_5$ | 5-day Biological oxygen demand |
| COD | Chemical oxygen demand |
| CWs | Constructed wetland treatment system |
| Co | County |
| ds | dried solids |
| EEC | European Economic Community |
| EPA | Environmental Protection Agency |
| EU | European Union |
| ICW | Integrated constructed wetland |
| N | Nitrogen |
| Ortho-P | Ortho-phosphate |
| pa | per annum |
| $P_{ads}$ | Phosphorus adsorption capacity (mg-P/g) |
| PE | population equivalents |
| RBTS | Reed bed treatment systems |
| RP | Reactive phosphorus |
| SD | Standard deviation |
| TSS | Total suspended solids |
| TP | Total phosphate |
| % Red | % Reduction |

**Contents**

## 1. Introduction

Ireland is a country located on the western borderline of the European Union, famously noted for its capricious weather. It is surrounded by Gulf stream currents, leading to the relative warm temperature in Ireland's coasts. Average annual rainfall in Ireland is 750-1000mm in the eastern half of the country, 1000-1250mm in the west and >2000mm in the mountainous areas (MET eirean, 2006). Inhabited by 4.21 million people (UNSD, 2006), Ireland is reputed to have the fastest transformed economy in Europe, having undergone series of vigorous economic growth and rapid social changes since the 1990s. Predominantly, Ireland is a rural, agricultural society with agriculture engaging about 70% of the land and 13% of the workforce. However, with the economic boom, there has been a significant increase in human population and industrial enterprise; increasing load on service systems and public utilities. The increased urbanisation and other development factors have all combined to add pressure on its environment (EPA, 2000).

As regards environmental pollution control and in particular, wastewater treatment, on-site systems (mainly septic tank systems and mechanical aeration systems) is the primary method used for the treatment and disposal of domestic wastewaters in the rural areas and in urban areas that are not connected to public sewer systems. In the rural areas, septic tanks and percolation areas are however mostly used with about 300,000 septic tanks in Ireland serving a population of 1.2million people and discharging approximately 80 million $m^3$ of effluent annually (Daly et al., 1993). In the urban areas, almost all the wastewater produced is treated and discharged into estuaries and freshwaters with about 70% of the wastewater receiving secondary treatment (EPA, 2004). As regards the use of Constructed wetlands (CWs) for wastewater treatment, the technology is noted to be in its infancy stage when compared to North America and other European countries (Healy and Cawley, 2002). CWs are engineered wastewater treatment systems that encompass a plurality of treatment modules including biological, chemical and physical processes, which are all akin to processes occurring in natural treatment wetlands. Although initially designed and used for domestic wastewater treatment, through the efforts of research and operation for over fifty years, CWs have now been successfully used for environmental pollution control, through the treatment of a wide variety of wastewaters including industrial effluents, urban and agricultural stormwater runoff, animal wastewaters, leachates, sludges and mine drainage (IWA, 2000; Scholz and Lee, 2005).

However, the last ten years has seen a significant introduction of this technology as a sewage treatment system to single households and small rural communities in Ireland and also as a tertiary system to larger villages and towns. Applications of CWs systems have also been extended to a wide range of types of wastewaters including urban stormwater runoff and mine wastewater. It has also been noted that CWs have now gained increased popularity in the treatment of agricultural wastewaters in Ireland (Healy et al., 2007). In addition, research interests in CWs technique have developed rapidly in recent years.

Several authors, such as Haberl et al., (1998); Lienard et al., (1998); Borner et al., (1998); Cooper et al., (1998); Greenway and Woolley (1999); Tanner et al., (2000); Vymazal et al., (2002) and Rousseau et al., (2004) have published papers relating to the state and application of CWs for environmental pollution control in their respective domains. In addition, Scholz and Lee (2005) gave a comprehensive and critical review of hydrobiological, physical and biochemical processes that aids chemical transformations in CWs. These are commendable efforts for three main reasons: (1) It brings to fore the state and understanding of CWs for environmental pollution control in such countries and in general. (2) It affords an opportunity to exchange ideas on CWS technology between different countries and (3) It forms part of contributions into a wide database of CWs operation and performances in different places and regions. This would be a ready tool in performance assessment and in harmonising design guidelines. A survey of literature shows that such review has been published in about 50% of the current 27-member state of the EU (Vymazal et al., 1998) and in several other parts of the world. However, there is no publication yet on such from Ireland. Therefore, in a concise manner, this paper aims to provide a review of CWs in Ireland, focusing on their use, treatment performances, research and challenges. The review was based on a desk-study, a limited number of interviews and site visits.

## 2. History, application and prospects of constructed wetland systems in Ireland

In Ireland, much of the development in CWs has been taking place mainly in the last ten years although there was an isolated case in the 1880's when the British army set up a system at the Curragh camp in Co. Kildare (Costello, 1993). The CWs may have probably been rudimentarily designed based on intuition and not on well-founded design principles. In addition, no performance data could be obtained. Nonetheless, it was subsequently used as a template for the first reported application of CWs in Ireland to treat a private dairy farm wastewater in Co. Sligo (Costello, 1993). Thereafter, there was no reported development and application of the technology in Ireland for about thirty years until the early 1990s, when the owners of Sli na Bande, Co. Wicklow had a surface flow system installed by a Belgian company called PURE Milieutechniek in 1991 (Harty and Otte, 2003). Also between 1990 and 1993, two communities in Co. Kilkenny in need of effective sewage treatment in order to protect their wells and the environment, built gravel reed beds for sewage treatment. Designs for these systems came from similar communities in the UK and were prepared by Iris water and design (Harthy and Otte, 2003).

However, by the early 90's, which was the beginning of the rapid economic growth, there was gradual increase in the volume of sewage generated. Consequently, the need for low-cost and effective wastewater treatment by local authorities started to reverberate in most parts of the country. This initiated discussions on effective wastewater treatment and in 1993, the first and only conference so far on constructed wetlands for wastewater treatment in Ireland was held (Costello, 1993). Attendees included county councillors, engineering consultants, effluent treatment firms, environmental concern groups, farmers and others with interest in wastewater treatment and pollution control (Harthy and Otte, 2003). The conference gave the much-needed impetus to the interest and development of CWs in Ireland.

According to an inventory survey carried out in 2005 at the University College Dublin, there are now about 140 CWs sites in Ireland. Fig. 1 illustrates the geographic distribution of these CWs across the country. From Fig. 1, it is believed that CWs have been successfully established in all parts of Ireland without any exception. There is no reported negative effect from the Irish climate on the performance of the CWs. In particular, the systems show a particular advantage of aesthetical appearance with Irish climate and lower energy consumption for their performance. Fig. 2 indicates that the county with the highest number of CWs in Ireland is Wexford, followed by Cork. The two counties account for about 30% of all the CWs in Ireland. Both Wexford and Cork are predominantly rural areas. However, while 47% of the systems in Wexford are used for the treatment of wastewater emanating from dwellings, approximately the same numbers of systems (44%) are used for commercial purposes in Cork. In the urban areas, it would seem that conventional wastewater treatment technologies are still dominant e.g. in Co. Dublin, which has only about 2% of the total number of CWs.

**[Insert Fig. 1 here]**

**[Insert Fig. 2 here]**

Luederitz, et al., (2001) noted that depending on the organic loading regime, all wetlands types have a good nutrient processing efficacy under the European climatic conditions. Given the relatively mild Atlantic climate prevailing in Ireland, winter temperatures rarely reach sub zero and are usually averaged 2.5$^{o}$C while average summer temperature is 19$^{o}$C (MET eirean, 2006). This implies favourable conditions for microbial-mediated treatment in CWs. Thus, operation of CWs under the Irish climate should be highly prospective.

According to the EPA, there are over 412 agglomerations in Ireland and it is noted that almost 23% of the wastewater from these agglomerations receive no treatment while only 48% receives only preliminary and primary treatment (EPA, 2004). The highest numbers of these agglomerations (141) fall within the 500-1,000 population equivalents (PE) range and may need to treat their wastewaters in the absence of large-scale wastewater treatment plants which may be uneconomical. It is also noted that only about 18% of small agglomerations between 500-2000PE comply with effluent quality standards (EPA, 2007) and this implies that there is a huge potential of using CWs to meet the required standards in some of the remaining 82% of the small agglomerations.  This creates a huge potential for application of CWs in such areas (being the most imaginative option for small on-site treatment systems). CWs may even be more needed in order to help the small communities comply with article 7 of the Urban Wastewater Treatment Directive (UWWT, 1991), which requires agglomerations of 2000PE or less that discharges to freshwater or estuaries to have appropriate treatment by December 2005. This is targeted at protecting freshwaters and preventing environmental pollution. Pursuant to meeting this directive, the EU commission recognises and recommends constructed wetlands (in form of reed beds) as a means for effective wastewater treatment in such locations (EU Commission, 2006).

Also, in rural Ireland, agricultural practices predominate and N & P losses from such practices continue to diminish surface water quality (Cleneghan, 2003), leading to a continuous decline in the quality of Irish surface waters. However, the most prevalent on-site wastewater treatment system in the rural areas is septic tanks and even when properly designed, constructed and maintained, septic tanks are only able to remove 40-70% of organic substrates expressed as $BOD_5$ and only 5-15% N and P (Kowalik and Obarska-Pempkowiak, 1998). Viewed from the standpoint of the need for environmental pollution control and water protection, such performance is insufficient to prevent water pollution and more extensive treatment would obviously be needed. Daly et al., (1993) noted that approximately 40% of the Ireland is unsuitable for the use of septic tanks due to geological conditions. Therefore, given the economic constraints of installing conventional wastewater treatment systems in most cases, CWs would be a mitigative and cost-effective land use practice, which could help retain the nutrients, improve surface water quality and reduce environmental pollution. This represents another prospective use of CWs for water and environmental pollution control in Ireland.

## 3. Current status of constructed wetland systems in Ireland

### *3.1 Types of* constructed wetland systems used *and wastewater treated*

The main types of CWs and the types of wastewaters treated in Ireland are shown in Fig. 3. It can be seen that most of the CWs in Ireland are designed for the treatment of municipal or domestic wastewater. However, some CWs mainly treat domestic wastewater exclusively while others do so in combination with other sewage such as dairy washings, restaurants, etc. It should be noted that due to the significant development of CWs especially in the last five years, CWs have been successfully applied to single households and small rural communities and as a tertiary system to larger villages and towns. There is also an increasing trend of application of CWs to farmyard waste management and urban stormwater runoff (in particular motorway runoff). For the particular case of urban stormwater treatment using CWs, updated and comprehensive information can be found in Scholz (2006). In addition, a number of experimental/novel CWs have also been reported and these are discussed in section 5.2. Fig. 3 particularly shows that surface flow (SF) and free water systems (FS) are the mostly used types of CWs in Ireland. SF is mostly used for single households while FS is mostly applied in agricultural cases. Costello (2006) noted that the climate, geology, population distribution and land use in Ireland, make the FS-type CWs an ideal technique for the solution of some of the Irish wastewater treatment problems. It is recommended that such CWs should consist of an inlet marsh for BOD and SS removal; a constructed pond with 500mm to 1000mm water depth for further reduction of BOD and for nitrification and denitrification and a second emergent marsh for further denitrification and to prevent floating plants or algae entering the discharge waters.

**[Insert Fig. 3 here]**

### *3.2 Treatment performances*

An attempt was made to evaluate the treatment performances of CWs in Ireland and compare them with CWs in some other parts of Europe. It must however be noted that due the desk-study nature of the review, time constraints and difficulty in obtaining long-term performance data of most of the CWs in operation, only a limited assessment could be made, based on thirteen CWs systems for which performance results were available. Therefore, inherent limitations as regards the interpretation, potential wider applicability, and extrapolation of the results outside those CWs should be taken into account. Table 1 summarises the results of the Irish CWs performance. Generally, wetlands are known to perform very well as regards $BOD_5$, COD and bacteria pollution reduction, but they show a limited capacity for nutrient (especially P) reduction. The high removal rate of $BOD_5$ and COD is caused by filtration/sedimentation of suspended solids and bacterial oxidation. A good knowledge of nutrient removing processes is however essential in optimizing their removal in CWs. N removal is mainly through bacterial transformations involving a sequential process of ammonification, nitrification and denitrification, although seasonal removal through volatilization and adsorption can also be equally important (IWA, 2000).

**[Insert Table 1 here]**

Results from Table 1 indicate an average removal of 76.8-99.8% ($BOD_5$), 76.3-99.7% (COD) and 67-99.9% ($NH_4$-N). The ranges of monitored parameters in the effluent (mean$\pm$SD) were: 12.3-38$\pm$9-39 mg/l for $BOD_5$, 28-90$\pm$9-58mg/l for COD, and 0.1-15$\pm$0.1-7 mg/l for $NH_4$-N. It can be seen that despite the wide range and variations of inlet concentrations of the pollutants (as evident from the high SD, refer to Table 1), most of the CWs can be adjudged to have performed well. More frequently, effluent $BOD_5$ values have been less than 20mg/l (9 out of 13 cases) while the average TSS concentration have been mostly less than 30mg/l (12 out of the 13 cases). A limited comparison was made between these performances and those reported for other countries. The result is presented in Table 2. At first hand, it seems conclusive that the Irish CWs have superior performance compared to the other CWs for which results were presented. For instance, while for the other countries, the average removal efficiency for $BOD_5$, COD and TSS ranged between 68.5-92.7%, 64.3-82% and 77.4-86.2%, respectively, the removal efficiencies for the Irish CWs were 94.1%, 93.3% and 91.0% respectively. It must however be noted that the removal efficiencies reported are based on inlet-outlet concentration basis and the average inlet concentrations in most cases were quite high for the Irish CWs. This may lead to considerable biased results as it has been well established that percental efficiencies increases with increasing inlet concentrations (Vymazal, 2002).

Unlike the current trend of assessing and predicting CWs treatment performance by applying novel and well-known modelling approaches such as self organizing maps (SOM) (Lee and Scholz, 2006); multiple regression analysis (MRA) (Volodymyr et al., 2007); and the CW2D model (Malte et al., 2007), most of CWs assessment are still limited to input-ouput data analysis only. While it is appreciated that most of the systems are still relatively young and data may be insufficient, it is well noted that such modelling approaches cannot be done without, in line with current trends. Scholz et al., (2007) have however successfully applied the self-organizing Kohonen map as a novel modelling approach to some CWs data in Ireland with great success.

**[Insert Table 2 here]**

## 4. Application of constructed wetland systems in Ireland: Case studies

### 4.1 *The Outokumpu Zinc-Tara mines CWs system*

In 1997, two pilot scale treatment wetlands were constructed and monitored to treat wastewater emanating from the Outokumpu Zinc-Tara mines (Tara mines) Ltd., Co. Meath, Ireland. The mines is the largest producer of Zinc in Europe. The CWs represent one of the rare cases of the application of CWs to mine tailings/industrial wastewater treatment in Ireland, contrary to its wider application in other parts of the world (Otte et al., 2003). In the UK, there are about 49 CWs treating mine wastewaters (Cooper, 2006). Generally, water quality of run-off and leachate from metalliferous mine tailings are not compliant with both Irish (O'Leary, 1996) and International discharge standards (Novotny, 1995). However, in the particular case of the Tara mines, the sulphuric acid used during the extraction of these metals from the ores contribute to the elevated sulphate levels in the discharge from the mine, with sulphate levels up to 3016mg/L being reported (Otte et al., 2003). Using the CWs, O'Sullivan et al., (2004a, b) reported that lead, zinc, iron and sulphate were removed from the wastewater passing through the wetland systems and were significantly retained in the substrates. It was further reported that the degree to which these contaminants are bioavailable depends on the biogeochemical conditions of the substrates. It was equally noted that majority of the metals and sulphur were retained in immobile residual forms, principally as metal-sulphides. Overall, based on available reported data, improvement of the tailings water is feasible using the treatment wetlands and the performance obtained is consistent with results obtained in other studies.

### 4.2 *Village scale systems*

In Ireland, there are at least 20 village systems. An example of such systems is the Colecott village CWs. Colecott village is a small cluster of ten county council cottages and four mobile homes with a population of 48 (O'Hogain, 2003). A septic tank and a large percolation area previously served the village but these became ineffective due to clogging of the percolation area. Consequently, a hybrid RBTS was designed based on a modified Max Planck Institute

Process to replace the septic tank (O'Hogain, 2003). It was designed for 60PE allowing for future population development of 25%. The RBTS showed a very variable influent concentration but the system produced good quality effluents even at periods of high organic and hydraulic loads. There were however operational problems reported as a result of surface water input which affected the hydraulic load.

### *4.3 The Irish Integrated Constructed Wetlands (ICWs)*

ICWs are an initiative of Duchas, the Irish Heritage Service and they represent a specific design approach to the widely used concept of constructed wetlands. The approach strives to achieve 'landscape fit' and 'biodiversity' into the design of CWs. Fundamental to their design is water quality improvement and incorporation of the widest possible range of ecological conditions normally found in natural wetlands, (including those of soil, water, plant and animal ecology) (Dunne et al., 2005a,b). They are seen as a potential wastewater solution for agriculture, agribusiness, rural communities and the environment. They have also gained international acceptance, particularly in light of the recent European guidelines on preventing diffuse agricultural pollution (Carty et al., 2007). By virtue of their expanded functions, they typically have greater land area requirements than conventional surface flow wetlands, but their relatively larger footprint facilitates a greater range of physical, biological and chemical processes that occur in the wetland environment. (Harrington and Ryder, 2002). As part of a Duchas-led ecological restoration project in the Anne valley on the south coast of Co. Waterford, Ireland, 13 ICWs were constructed to enhance water quality management and prevent environmental pollution within the Anne valley. The Anne valley has a 7km mainstream with a catchment area of 25km$^2$. Twelve of the CWs treat farm effluent while one treats municipal wastewater. Scholz et al., (2007) reports that the principal design criteria leading to adequate effluent water quality (i.e., molybdate reactive phosphorus less than 1 mg/l) from the ICWs are that the wetland area needs to be sized by a factor of at least 1.3 times the farmyard area and the aspect ratio for the individual wetland segments needs to be less than 1:2.2 (width to length). It was further reported that within a year of the ICW commissioning, approximately 75% of farmyard runoff was intercepted, leading to improvements in the receiving surface waters of the catchment. Furthermore, a case study of ICWs suggested that phosphorus exported from an ICW system was similar to the typical background concentrations of phosphorus export rates from land to water. This demonstrates the robustness and efficiency of the ICWs in cleansing and managing water flow from farmyards while integrating the wetland infrastructure into the landscape and enhancing its biological diversity.

The EPA quality rating for the stream has reportedly improved significantly, ever since the introduction and operation of the wetland systems. However, the effluent quality of the ICW treating municipal wastewater (designed at $5m^2$/PE) showed decline in effluent quality due to recent development of about 40 housing units. Elsewhere, ICWs was also used at the Teagasc Research Centre (TRC), Co. Wexford, to treat primarily treated farmyard dirty water emanating from the farm. Details of the ICW design and construction are published in Dunne et al., (2005a,b). Results from both systems show that the ICWs performed successfully, especially in organics reduction. In addition, there was correlation between the measured farmyard dirty water inflow rate and rainfall leading to suggestion that rainfall on impervious surfaces may be an important component in the generation of farm yard dirty water that is collected, stored and subsequently discharged to the system.

### *4.4 Discussion*

The EPA document on wastewater treatment for single houses (EPA, 2000) is the accepted definitive guidelines for CWs in Ireland. The guideline is largely based on those contained in the "European Design and Operations Guidelines for Reed Bed Treatment Systems" edited by Cooper (1990). It is also noted that although public awareness and the number of systems in operation is growing daily, there are still some apprehensions as regards their reliability in Ireland. For instance, most of the operators suggest that majority of their clientele choose CWs/RBTS for economic reasons, not necessarily because they are convinced of their performance and reliability but because of their low running and maintenance costs. There is therefore an obvious need for a community-based participatory approach to foster understanding and address issues such as reliability and operation and maintenance problems.

The vast majority of CWs in Ireland are based on rooted emergent macrophytes-subsurface/surface flow with local soil, sand or gravel as substrate. The substrate of the reed bed is critical to the treatment performance. A fine substrate increases the efficiency of the filter but it causes it to clog easily. On the other hand, a coarser substrate is less prone to clogging but the treatment efficiency is reduced. Pre-treatment may be necessary and it consists of a wide variety of elements. Lining is provided in all the CWs and typical liners include heavy duty plastics and clays. In addition, some operators comply with the SR-6 standards (See NSAI, 1991) in relation to the distance between the CWs/RBTS and groundwater well or watercourses, while others simply follow guidelines as contained in the EPA guidelines (EPA, 2000)

Although CWs/RBTS is widely used in rural Ireland, which are agriculturally dominated areas, some operators argue that the use CWs/RBTS for agricultural wastewaters may not be feasible after all. They argue that the wastewater from agriculture is simply too strong for treatment by a CWs/RBTS. However, other operators believe that CWs could be used for preventing pollution from agricultural sources as long as they are located in low lying areas, downhill of a farm and where there is a suitable stream for the discharge of the effluents. Evidences however abound in scientific literature on the use of CWs/RBTS for the treatment of high strength wastewaters including agricultural wastewaters. For instance, Zhao et al., (2004a) reported on the use of a novel laboratory-scale reed bed system for the treatment of an animal farm wastewater with a $BOD_5$ value of 441-3150mg/l while Hunt et al., (2001) detailed the successful application of CWs to the treatment of wastewater from dairy and swine operations.

Design wise, the hydraulic model proposed in the Guidelines used to define the shape of the bed is based on Darcy's equation. Typically, the EPA recommends a plan area ($A_p$) of $5m^2$/PE for $BOD_5$ removal in a HF bed. The width of the CWs can be calculated from Eq. (1). This would imply that the $A_p$ for a reed bed for a four person household would be $20m^2$, and the wetland with a 0.6m depth, a media permeability of 50m/d (sand) laid at a gradient of 1% and a suitable width of 2.5m would be 8m long (EPA, 2000).

$$A_c = \frac{Q}{k \times i} \qquad (1)$$

Where, $A_c$ is the cross sectional area ($m^2$) of the wetland at the inlet, $Q$ is the average wastewater flow rate ($m^3$/d), $K$ is the permeability (m/d) of the wetland media and $i$ is the hydraulic gradient equal to the slope of the bed. Some operators already argue that a sizing of $5m^2$/PE is too high in the Irish context. However, the EPA design recommendation could be reduced to $1m^2$/PE for tertiary treatment and $0.5m^2$/PE for storm water treatment with 0.6m depth and a 0.5-2% bottom slope. Contrarily, some operators recommend and use $10m^2$/PE and $5m^2$/PE for secondary and tertiary treatment respectively. In Europe, one population equivalent (PE) means the organic biodegradable load having the $BOD_5$ of 60 g of oxygen per day. The more recently CWs in Europe have been designed for 5 to 10m$^2$/PE. In the Czech republic, Vymazal (1996) reports that most of the CWs are designed at about 5 m$^2$/PE, primarily for the removal of organics and SS, but they are reported to be insufficient for nutrient removal. Based on a survey of 109 Danish CWs, Schierup et al. (1990) suggested that a specific area of between 15 and 30 m$^2$/PE would be necessary to achieve a total N effluent concentration below 8 mg/l while to achieve an effluent total P concentration less than 1.5mg/l, a specific area of 40-70 m$^2$/PE was recommended.

In Ireland, most of the systems have been operating for a little over five years but efficient and stable removal of organic matter has been relatively achieved. Operation and maintenance problems have been varied and somewhat localised. Such problems are however typically related to hydraulic constructions and loadings, clogging, supervision, misconceptions and/or bad design.

## 5. Research on constructed wetlands in Ireland

### *5.1 Research output*

A comparative analysis was done to evaluate research output on CWs in Ireland in comparison to other countries. Research output based on the numbers of papers published in over 67 journal sources, and papers accepted for publication from presentation in the bi-annual international conference on constructed wetlands for water pollution control were used as assessment tools. The bi-annual international conference on constructed wetlands for water pollution control is arguably the leading conference on CWs in the world. The number of published papers were statistically analysed using the "Web of Science" performance indicator charts (2005). The performance indicator charts had a database search output of 67 journal sources, covering 1,107 CWs papers published between 1992 to 2002 worldwide. The results are shown in Table 3. It can be inferred that not much has been done in Ireland as regard publication of either research findings or treatment performances of operating CWs. Unlike the leading countries such as the USA, UK, Australia and Germany, that have 551, 96, 70 and 56 papers respectively on CWs published in 67 journals, Ireland has only 3 published papers and one published paper from conference presentations. It can also be seen that research output presented at conferences on CWs in the leading countries have mostly been university-led with some collaboration with the government and/or the private sector. It is therefore expected that with the current economic prosperity of the country, more grants will be dedicated to University-led research in the development, experimentation and optimisation of CWs in Ireland towards mitigating environmental pollution. There is also an obvious need for improved dissemination of research findings and treatment performances.

**[Insert Table 3 here]**

### *5.2 Novel developments*

#### *5.2.1. Tidal flow constructed wetland systems*

Tidal flow CWs refers to the rhythmical filling and draining of constructed wetland matrices with wastewater. It is an innovative engineering operation strategy aimed to improve the removal of organic matter and nutrients in CWs and it is currently being investigated in Ireland. Originally reported by Green et al., (1997), tidal flow constructed wetlands (particularly sub-surface vertical flow) is an engineering solution, enabling the treatment of high strength wastewaters in CWs. During the draining of the wetland matrices in the tidal flow system, the retreating wastewater acts as a passive pump that draws air into the wetland matrices. This leads to enhanced aeration of the CWs and improved biodegradation of pollutants in the system. Experimental results have shown that under hydraulic and organic loading rates as high as 0.43 $m^3/m^2 \cdot d$ and 1055 $gCOD/m^2 \cdot d$, removal efficiencies of 77%

(COD), 78% ($BOD_5$), 66% (SS), 68% ($NH_4$-N) and 38% (P) can be achieved using a multi-stage 'tidal flow' reed bed system (Zhao et al., 2004a). In a separate study, Lee and Scholz (2006) also employed the tidal flow concept to encourage air penetration through the aggregates of CWs filters treating gully pot liquor in a cold climate. The CWs filters were periodically inundated (100%) with pre-treated inflow gully pot liquor and partially drained (50%) or entirely drained (0%). Substantial metal removal efficiencies (>92%) were reportedly obtained. The tidal flow mechanism has also been demonstrated in other studies such as Austin (2006) and Sun et al., (2006).

*5.2.2 'Anti-sized' constructed wetland systems*

It is widely acknowledged that clogging of the filter surface is by far the biggest operational problem of vertical flow constructed wetlands (Austin et al., 2006 and Sun et al., 2007). Clogging reduces the infiltration capacity as well as the oxygen supply into a wetland system, leading to an extremely fast failure of the treatment performance. Although several means of mitigating clogging have been suggested (Platzer and Mauch, 1997; Spychala and Blazejewski, 2002; Langergraber et al., 2003) the problem still persists. Therefore, in order to counteract clogging, the concept of "anti-sized" media arrangement was introduced, leading to the development of the so called "anti-sized" CWs (Zhao et al., 2004b, 2005). The anti-sized arrangement refers to the use of coarse grains in the top layer and smaller grains in the middle or bottom layers of multi-layer substrates. Lab-scale experiments have demonstrated the greater ability of the anti-sized CWs system to counteract the problem of clogging with comparable treatment efficacy to the conventional CWs systems regarding the removal of COD, $BOD_5$, $NH_4$-N and P. The anti-sized arrangement of media allowed the top layer to remove a greater amount of suspended solids due to larger void space before the wastewater reached the lower layer. As a result, the solids are deposited deeper and the solid-storage capacity of the reed beds is more effectively utilized.

### *5.2.3 Dewatered alum sludge based constructed wetland*

Dewatered alum sludge is the by-product of drinking water treatment plants that use aluminium sulphate as the primary coagulant. The sludge has a gelatinous appearance and typically contains high concentrations of aluminium with a mixture of organic and inorganic materials and hydroxide precipitates. In Ireland, about 20.1kt-ds/pa is being generated at its largest water treatment plant and it costs about €3 million/pa to dispose through landfilling. Experimental results have however shown that the dewatered alum sludge can significantly adsorb P from aqueous solution through complexation and ligand exchange mechanism (Yang et al., 2006a). In order to optimise this potential, series of laboratory scale experiments were carried out in University College Dublin for the purpose of (1) exploiting the effectiveness of the reuse of dewatered alum sludge as an adsorbent for P immobilization (Yang et al., 2006b; Razali et al., 2007), and (2) developing the alum sludge-based CWs with dewatered alum sludge as main substrate (Zhao et al., 2006, Babatunde et al., 2006, 2007).

## 6. Conclusions and Recommendations

It is noted that CWs are now being increasingly used for environmental pollution control in Ireland. At present, there are about 140 CWs in Ireland and most of them are local soil/gravel based systems with either horizontal or vertical flow planted mostly with common reeds (*phragmites australis).* Predominantly, domestic wastewater is treated and there is a huge potential for its application in the over 141 agglomerations in Ireland with a PE between

500-1000. Removal of organics and SS in the systems is quite appreciable but a single conclusion on P removal cannot be drawn. While there is growing interest on the use of CWs in Ireland, gaps in current knowledge and awareness need to be plugged and convincing treatment performances presented and published to encourage more widespread adoption of the technology. On the basis of this review, the following recommendations are also made:

(1) A database of Irish constructed wetlands is highly essential, similar to the databases developed in the UK (Cooper, 2006), Belgium (Rousseau, 2005) and in North America (Knight et al., 1993). Such a database is particularly needed to: (i) Avoid duplication of efforts and mistakes, as it would provide appropriate reference for all wetland operators, (ii) afford a specific design approach for Ireland, and (iii) stimulate and optimise future application of constructed wetland technology in the country.

(2) More information should be made available to both the public and the operators and effort should be made to harmonize design approaches, avoid controversies and allow for discretionary flexibility to design, fitted to the Irish situation.

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Fig. 1 Geographic distribution of CWs across Ireland

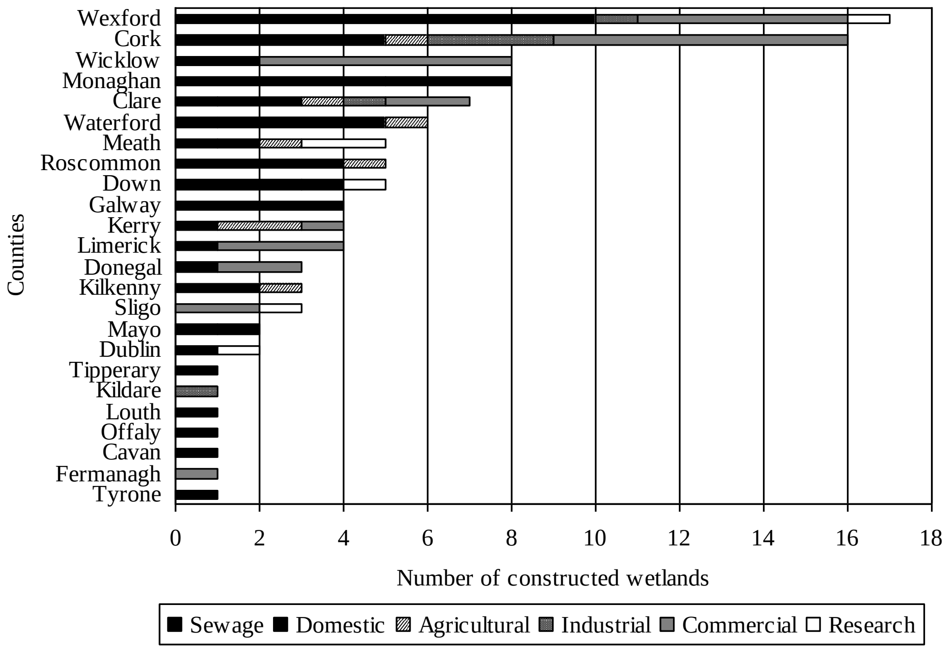


Fig. 2 Distribution and application of CWs across Irish counties

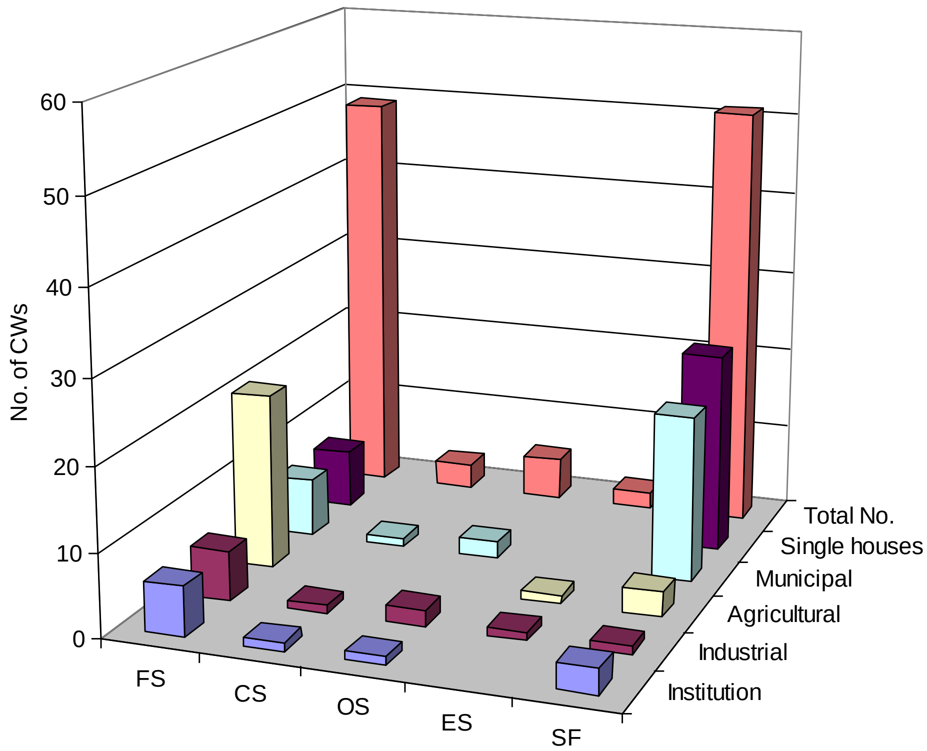


Fig. 3 Types of CWs and wastewaters treated in Ireland (FS--free water systems; CS--combined systems; OS--other systems such as sludge drying systems and stream filtration basins; ES--experimental systems; SF--surface flow systems)

Table 1 Summarized treatment performance of some selected Irish CWs (All parameters except pH are expressed in mg/l)

| Parameter (Mean ±SD) | Constructed wetland systems | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| $BOD_5$ | | | | | | | | | | | | | |
| In | 7058 ±17081 | 484 ±587 | 443 ±700 | 555 ±406 | 266 ±368 | 224 ±293 | 62 ±63 | 606 ±1176 | 69 ±54 | 635 ±1166 | 2544 ±2681 | 2308 ±9301 | 269 ±126 |
| Out | 12.3 ±9 | 13.6 ±11 | 27.5 ±18 | 38 ±26 | 20 ±23 | 20 ±16 | 13 ±10 | 14 ±11 | 16 ±11 | 24 ±23 | 18 ±39 | 17 ±16 | 27 ±23 |
| % Red | 99.8 | 97.2 | 93.8 | 93.2 | 92.5 | 91.1 | 79.0 | 97.7 | 76.8 | 96.2 | 99.3 | 99.3 | 89.0 |
| COD | | | | | | | | | | | | | |
| In | 9261 ±23482 | 768 ±724 | 1036 ±1423 | 1404 ±1053 | 903 ±1621 | 622 ±676 | 139 ±88 | 952 ±1681 | 184 ±151 | 1433 ±2799 | 8133 ±13866 | 3523 ±14345 | 462 ±244 |
| Out | 28 ±10 | 38 ±14 | 78 ±21 | 90 ±32 | 43 ±35 | 55 ±30 | 33 ±9 | 42 ±15 | 42 ±32 | 62 ±30 | 40 ±58 | 34 ±18 | 47 ±30 |
| % Red | 99.7 | 95.0 | 92.5 | 93.6 | 95.2 | 91.2 | 76.3 | 95.6 | 77.1 | 95.7 | 99.5 | 99.0 | 88.0 |
| TSS | | | | | | | | | | | | | |
| In | 1168 ±3277 | 159 ±121 | 152 ±157 | 1519 ±3827 | 133 ±136 | 222 ±506 | 45 ±61 | 585 ±1154 | 116 ±297 | 79 ±106 | 3730 ±9140 | 276 ±475 | 53 ±32 |
| Out | 13 ±12 | 26 ±35 | 22 ±18 | 51 ±44 | 13 ±9 | 23 ±26 | 9 ±7 | 14 ±8 | 20 ±21 | 22 ±19 | 25 ±31 | 22 ±23 | 0.5 ±1 |
| % Red | 98.9 | 83.7 | 85.5 | 96.7 | 90.2 | 89.4 | 80.0 | 97.6 | 82.8 | 72.2 | 99.3 | 92.0 | 99.0 |
| $NH_4$-N | | | | | | | | | | | | | |
| In | 131 ±190 | 45 ±44 | 40 ±29 | 91 ±57 | 39 ±56 | 33 ±34 | 18 ±67 | 36 ±44 | 21 ±42 | 29 ±41 | 275 ±364 | 64 ±227 | 45 ±13 |
| Out | 0.1 ±0.1 | 0.3 ±0.6 | 0.2 ±0.6 | 2.9 ±4.4 | 0.5 ±0.9 | 0.2 ±0.3 | 0.2 ±0.2 | 0.3 ±0.4 | 0.3 ±0.5 | 0.3 ±0.6 | 0.2 ±0.5 | 0.1 ±0.1 | 15 ±7 |
| % Red | 99.9 | 99.3 | 99.5 | 88.1 | 98.7 | 99.4 | 98.8 | 99.2 | 98.6 | 98.9 | 99.9 | 99.8 | 67.0 |
| RP | | | | | | | | | | | | | |
| In | 86 ±227 | 14.7 ±7 | 19 ±10 | 26 ±13 | 13.5 ±23 | 11 ±10 | 1.5 ±1.0 | 11.4 ±27 | 6.6 ±9 | 7.8 ±10 | 83 ±89 | 23 ±91 | 18 ±77 |
| Out | 0.1 ±0.3 | 0.2 ±0.2 | 1 ±0.8 | 1.4 ±1.4 | 0.3 ±0.8 | 0.1 ±0.2 | 0.04 ±0.2 | 0.4 ±0.2 | 0.1 ±0.5 | 0.8 ±0.5 | 0.1 ±0.3 | 0.05 ±0.1 | 11 ±3 |
| % Red | 99.9 | 98.6 | 94.7 | 94.5 | 97.8 | 99.1 | 97.3 | 96.5 | 98.5 | 89.7 | 99.9 | 99.8 | 26.0 |
| pH | | | | | | | | | | | | | |
| In | 6.4 ±1.2 | 7.3 ±0.4 | 7.1 ±0.4 | 7.4 ±0.5 | 7.3 ±0.3 | 7.6 ±0.5 | 7.0 ±0.2 | 7.1 ±0.7 | 6.9 ±0.3 | 7.1 ±0.9 | 7.1 ±0.7 | 6.8 ±0.5 | 7.4 ±0.4 |
| Out | 7.5 ±0.4 | 7.4 ±0.4 | 7.5 ±0.6 | 8 ±0.7 | 7.4 ±0.6 | 7.8 ±0.6 | 7.6 ±0.5 | 7.7 ±0.4 | 7.2 ±0.4 | 7.8 ±0.6 | 7.1 ±0.4 | 7.3 ±0.5 | 7.5 ±0.1 |

Table 2 Average influent (In) and effluent (Out) concentrations (mg/l) and removal efficiencies (Eff, %) of selected pollutants in some CWs in Ireland and other countries

| Parameter | In ± SD | Out ± SD | Eff |
|---|---|---|---|
| $BOD_5$ | | | |
| Ireland | 361 ± 259.7 | 21.31 ± 17.2 | 94.1 |
| Czech Republic | 87.2 ± 63.1 | 10.5 ± 9.9 | 88.0 |
| Denmark and UK | 97.0 ± 81.0 | 13.1 ± 12.6 | 86.5 |
| North America | 27.5 | 8.6 | 68.5 |
| Germany-L.Saxony | 248 ± 233 | 42.0 | 83.0 |
| Germany-Bavaria | 106 ± 62.1 | 21.6 ± 16.4 | 79.6 |
| Poland | 110 ± 87.8 | 18.1 ± 14.3 | 83.5 |
| Slovenia | 107 ± 30.2 | 11.3 ± 2.5 | 89.0 |
| Sweden | 80.5 ± 55.0 | 5.9 ± 4.5 | 92.7 |
| COD | | | |
| Ireland | 790 ± 313.8 | 53 ± 24.8 | 93.3 |
| Czech Republic | 211 ± 160 | 53 ± 48.3 | 75.0 |
| Denmark | 264 ± 192 | 64.7 ± 27.9 | 75.0 |
| Germany-L.Saxony | 430 ± 348 | 133.0 | 69.0 |
| Germany-Bavaria | 234 ± 124 | 69.4 ± 39.1 | 70.3 |
| Poland | 283 ± 170 | 101 ± 23.6 | 64.3 |
| Slovenia | 200 ± 41.5 | 35.7 ± 3.1 | 82.0 |
| TSS | | | |
| Ireland | 228 ± 197.8 | 20.5 ± 18.8 | 91.0 |
| Czech Republic | 64.8 ± 46.7 | 10.2 ± 6.9 | 84.3 |
| Denmark and UK | 98.6 ± 81.6 | 13.6 ± 11.1 | 86.2 |
| North America | 48.2 | 10.3 | 78.6 |
| Poland | 140 ± 77.2 | 38.6 ± 23.5 | 77.4 |
| Total P | | | |
| Ireland | 13 ± 10.4 | 1.53 ± 0.78 | 88.2 |
| Czech Republic | 6.57 ± 3.6 | 3.22 ± 2.1 | 51.0 |
| Denmark and UK | 8.6 ± 4.5 | 6.3 ± 3.5 | 26.7 |
| North America | 4.41 | 3.0 | 32.7 |
| Germany-L.Saxony | 11.4 ± 9.6 | 4.0 | 65.0 |
| Poland | 7.65 ± 4.3 | 4.1 ± 1.5 | 46.4 |
| Sweden | 5.03 ± 1.4 | 2.1 ± 1.2 | 58.3 |

Data sources: Vymazal (2002); O'Hogain (2003) and authors data

Table 3 Research outputs on constructed wetlands in selected countries

| Country | No. of journal publications | Conference presentations | | | |
|---|---|---|---|---|---|
| | | Cumulative papers | Author affiliation | | |
| | | | Academic | Collaboration | Govt./Private |
| USA | 551 | 68 | 29 | 13 | 26 |
| UK | 96 | 34 | 23 | 2 | 9 |
| Australia | 70 | 41 | 19 | 5 | 17 |
| Germany | 56 | 18 | 12 | 3 | 3 |
| Canada | 45 | 6 | 3 | 1 | 2 |
| Sweden | 30 | 8 | 8 | 0 | 0 |
| New Zealand | 28 | 14 | 8 | 2 | 4 |
| Norway | 23 | 10 | 6 | 3 | 1 |
| Spain | 20 | 3 | 3 | 0 | 0 |
| Netherlands | 17 | 2 | 2 | 0 | 0 |
| Austria | 14 | 11 | 6 | 0 | 5 |
| France | 14 | 8 | 5 | 0 | 3 |
| Denmark | 11 | 11 | 8 | 2 | 1 |
| Belgium | 4 | 4 | 2 | 2 | 0 |
| Ireland | 3 | 1 | 1 | 0 | 0 |
| Slovenia | 2 | 4 | 2 | 2 | 0 |