The universal design, operation and maintenance guidelines for farm constructed wetlands (FCW) in temperate climates

Aila Carty a, Miklas Scholz b,*, Kate Heal c, Fabrice Gouriveau c, Atif Mustafa b

a Independent Environmental Wetlands Consultant, County Cork, Ireland
b Institute for Infrastructure and Environment, School of Engineering and Electronics, The University of Edinburgh, William Rankine Building, The King’s Buildings, Edinburgh EH9 3JL, Scotland, United Kingdom
c School of GeoSciences, Crew Building, The King’s Buildings, The University of Edinburgh, Edinburgh EH9 3JN, Scotland, United Kingdom

Received 22 October 2007; received in revised form 22 January 2008; accepted 27 January 2008
Available online 24 March 2008

Abstract

This paper comprises the scientific justification for the Farm Constructed Wetland (FCW) Design Manual for Northern Ireland and Scotland. Moreover, this document addresses an international audience interested in applying wetland systems in the wider agricultural context. Farm constructed wetlands combine farm wastewater (predominantly farmyard runoff) treatment with landscape and biodiversity enhancements, and are a specific application and class of integrated constructed wetlands (ICW), which have wider applications in the treatment of other wastewater types such as domestic sewage. The aim of this review paper is to propose guidelines highlighting the rationale for FCW, including key water quality management and regulatory issues, important physical and biochemical wetland treatment processes, assessment techniques for characterizing potential FCW sites and discharge options to water bodies. The paper discusses universal design, construction, planting, maintenance and operation issues relevant specifically for FCW in a temperate climate, but highlights also catchment-specific requirements to protect the environment.

Keywords: Agriculture; Best management practice; Farmyard; Runoff; Water quality

1. Introduction

1.1. Foreword

Interest in the use of constructed wetlands has increased considerably during the past few years as a means of treating surface water runoff from farmyards (Poe et al., 2003; Scholz and Xu, 2002). This paper proposes therefore a universal design and management guideline for farm constructed wetlands (FCW) in a temperate climate addressing the ever more apparent requirement for a holistic approach to land and water management. The topic has national and international support as shown in the production of guidance documents concerning water management, nitrate, bathing water, groundwater, biological diversity and wetlands protection (Scholz, 2006a; UNEP, 2003). This paper is the scientific basis for the Farm Constructed Wetland Design Manual for Northern Ireland and Scotland (Carty et al., in press).

The FCW design guideline is intended for use by farm advisers, farmers, consulting engineers, landscape architects, environmental regulators, catchment managers, local authorities, farmers unions, academics and any organizations involved in water quality management in rural areas. The guide provides information necessary for the design, siting, construction and maintenance of sustainable FCW used to treat predominantly farmyard runoff, roof runoff and dairy parlor washings.

1.2. Agriculture and water quality management

The loss of nutrients and contaminants from agricultural land, farmyards, dairy parlors, tracks and roofs to...
rivers, lakes and groundwater, can have a detrimental impact on water quality. Both point and diffuse sources of pollution from agriculture contribute to the degradation of water quality and aquatic ecosystems (e.g. fish kills and loss of habitats) through eutrophication, contamination of groundwater, siltation and direct toxicity to organisms which consequently affect biodiversity, fisheries, recreation and public health. It also affects farmers, exposing them to fines and prosecutions, and the wider community by the subsequent degradation and loss of water supply within affected watersheds (Harrington and Ryder, 2002; Mantovi et al., 2003; Scholz et al., 2007).

There is a wide range of laws and policies at national and international levels (e.g. Zedler, 2003; Scholz, 2006a,b), which aim to control and mitigate the risks of water pollution caused by agricultural contaminants. Several Best Management Practices (BMP) are available for farmyard runoff treatment as part of ‘treatment trains’ (Scholz, 2006a,b); i.e. sets of measures that range from pollution source control to dirty water collection and treatment. The most common measures implemented at the farm scale include the following (Rice et al., 2002; Hilton, 2003):

- Animal diet improvement to reduce nutrient losses.
- Roofing of silage pits and areas of farmyards where excrements are expected to accumulate.
- Clean roof water diversion to drains to reduce the volume of dirty water to be stored and spread.
- Upgrading of buildings, and of manure, slurry, fuel and pesticide storages to avoid leaks and spillages.
- Basins and biobeds for pesticide wash water storage and treatment.
- Swales, buffer strips and wetlands to store and clean farmyard runoff before discharge to watercourses (Poe et al., 2003).

In addition to the previously mentioned BMP, FCW are recommended for the collection and treatment of farmyard runoff, before it is released into watercourses, to protect surface water and groundwater resources (Scholz et al., 2007). The US American and New Zealand approaches to FCW have been summarized by USEPA (1995a,b) and NIWA (1997), respectively.

2. Farm constructed wetlands: definition and background

2.1. Introduction

A FCW is defined as an ecologically engineered system comprising a series of shallow free surface flow constructed wetland cells (see below) containing emergent vegetation, which is designed to receive and treat farmyard runoff (Carty et al., in press; Scholz et al., 2007). Farm constructed wetlands are being developed to benefit both the environment and the farmers, by reducing the impact of potential pollution incidents, helping to manage farm effluents and by enhancing habitat, biodiversity and landscape, in a way that is practical, efficient, affordable and cost-effective (Harrington et al., 2005). Typical FCW design and operation contrast with that of constructed reed beds, which can be seen as being ‘closer’ to the traditional wastewater treatment philosophy based predominantly on civil engineering principles (Mantovi et al., 2003; Kantawanichkul and Somprasert, 2005; Sun et al., 2006).

The design approach for the construction of farm wetlands proposed in this universal guideline for temperate climate is largely inspired by the Integrated Constructed Wetland (ICW) concept (Harrington and Ryder, 2002; Scholz et al., 2007) pioneered in Ireland by the National Parks and Wildlife Service (Department of Environment, Heritage and Local Government, Ireland), and is based upon data on performance over the last ten years of 13 ICW constructed within the Anne Valley in southern Ireland. The ICW concept is based on the following principles (Harrington et al., 2005):

- The containment and treatment of influents within shallow vegetated ponds using local soil material, wherever possible.
- The aesthetic placement of the containing wetland structure into the local landscape (‘landscape fit’) to enhance a site’s ancillary values.
- The enhancement of habitat and biodiversity.

The design endeavors to optimize natural biological, chemical and physical processes of pollutant removal in a way that does not incur a negative impact on aquatic and terrestrial ecosystems (Scholz et al., 2007).

2.2. Effluent types

Farm constructed wetlands can be designed to treat various types of wastewater from farms including dairy, machinery, vegetable and mushroom washings, runoff from silos, yards and other areas of hard-standing (usually only lightly contaminated by manure or silage), and livestock access tracks (Poe et al., 2003; Scholz et al., 2007; Carty et al., in press). However, FCW are usually not designed for the treatment of more nutrient-rich effluent types such as slurries, raw milk, and washings from pesticide sprayer and dipping equipment.

2.3. Processes within farm constructed wetlands

Within a FCW, the contaminated effluent is treated through various physical, chemical and biological processes involving aquatic plants (predominantly macrophytes), algae, micro-organisms, water, soil and sun (e.g. direct process via photodegradation). The main processes for which detailed examples can be found elsewhere (Mantovi et al., 2003; Scholz and Xu, 2002; Scholz and Lee, 2005; Scholz, 2006a; Scholz et al., 2007; Zedler, 2003; Carty et al., in press) are as follows:
• Physical filtration of suspended solids by wetland vegetative biomass acting as a hydrological baffle to incoming flows (optimized by high vegetation density and low flow velocity).
• Settling of suspended particulate matter by gravity (optimized by low flow velocity, low wind speed, low disturbance and long residence time).
• Uptake, transformation and breakdown of nutrients, hydrocarbons and pesticides by biomass, plants and microbes (increased by a relatively high temperature, long residence time, contact with micro-organisms and plants, high micro-organism and plant density, and a relatively high organic matter content).
• Accumulation and decomposition of organic matter, which is important for nutrient cycling (optimized by low velocity and availability of adsorption sites on suitable aggregates).
• Microbial mediated processes such as nitrification (aerobic) and denitrification (anaerobic), which are important for the cycling of nitrogen (see also Poe et al. (2003)).
• Chemical precipitation and sorption of nutrients such as phosphorus (see also Braskerud, 2002) by soil (influenced by the availability of sorption sites, pH and redox potential).
• Predation and natural die-off of pathogens; e.g. Escherichia coli and Cryptosporidium (optimized by high diversity and density of natural predators (e.g. protozoa), and increased exposure to ultraviolet light).

2.4. Introduction to farm constructed wetland functions, values and principles

The profiles and infrastructural details required to support habitat development and biodiversity enhancement are, on the basis of experience, best addressed in the design and construction of the wetland. This is particularly relevant to the development of transitional habitats between the terrestrial embankment and wetland zones (Scholz and Lee, 2005; Scholz, 2006a).

Wide, shallow and low elevated embankments promote floral and faunal diversity. Shallow and deep wetland areas with either south- or north-facing aspects are also important to enhance the habitat. Local vegetation is best incorporated wherever possible. Care should be taken when locating a FCW immediately adjacent to woodland as problems may arise from shading and seepage of water via root systems. Farm constructed wetlands can be dynamic ecosystems and their habitats may change unless managed and maintained. For example, the management of water depth to facilitate optimal water treatment is particularly important in this regard (Dunne et al., 2005a,b; Scholz, 2007; Scholz et al., 2007; see also below).

Wetlands, including FCW, can have considerable aesthetic appeal. The combination of water, vegetation and associated wildlife are the principal elements of visual enhancement, and there are many examples of this throughout the world. The aesthetic appeal of a FCW can be maximized through appropriate land-forming design that is implemented during construction (Scholz, 2007).

The process of design ensures that the final wetland structure ‘fits’ well into the landscape; e.g. by designing curvilinear enclosing embankments that conform to the site’s topography. Subsequent vegetation development will further enhance the visual natural appearance of the system. Appropriate land-forming of the structure to fit the landscape also reduces FCW maintenance, thus enhancing a variety of amenity values and improving its sustained functionality (Dunne et al., 2005a,b; Scholz, 2006b; Scholz et al., 2007).

2.5. Benefits of farm constructed wetlands

The main benefits of FCW as discussed by Zedler (2003), Scholz and Xu (2002), Scholz et al. (2007) and other researchers (see below) are summarized below:

• High level of treatment and robustness: Efficient treatment (up to 99% reduction by concentration) of contaminants such as phosphorus (Braskerud, 2002), nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, biochemical oxygen demand, suspended solids, hydrocarbons and pathogens.
• Runoff and flood management: FCW are designed sufficiently large to manage heavy rainfall events, providing attenuation for increased effluent volumes during storm events. By functioning as ‘buffer zones’ and attenuating peak flows, they contribute to the reduction of flooding incidents downstream (Scholz and Lee, 2005; Scholz, 2007).
• Relative low cost and simplicity of operation: FCW have minimal equipment needs and little, if any, energy use since water can be transferred by gravity through the system. They are also simple to operate and more cost-effective than alternative methods of disposing of farm runoff (Poe et al., 2003).
• Odor minimization: Odor can be a serious problem when handling and treating agricultural wastes. Odors are minimized in FCW by using a dense plant cover, appropriate and tall plant species, a shallow water level and maintaining surface flow.
• Aesthetically pleasing: FCW enhance the landscape by adding colors, texture, and by increasing the diversity of plants and habitats (Scholz, 2007).
• Habitat and biodiversity enhancement: FCW provide habitats for a wide variety of birds, mammals, reptiles, amphibians and invertebrates (e.g. Froneman et al., 2001).
• Contingency measures: FCW can help to mitigate the impact of accidental spillages, acting as buffer zones and giving time to implement emergency measures.
2.6. Limitations of farm constructed wetlands

Farm Constructed Wetlands have some limitations, although these can be managed by designing and maintaining FCW for their design goals, as outlined in this paper. The main limitations as discussed by Scholz et al. (2007) and Carty et al. (in press) are as follows:

- Farm constructed wetlands have a relatively large land requirement compared to conventional wastewater treatment systems (Scholz, 2006a,b).
- The removal of pollutants may vary during the year and in the long-term due to seasonal weather patterns (e.g. as reported by Dunne et al. (2005b)) and also variations in the inflow of pollutants. In some circumstances, pollutants might even be released (e.g. as reported by Thörén et al. (2004)), but this can be minimized by the use of a modular approach (i.e. using a series of FCW cells) and by designing the system for extreme rainfall events.
- Emission of greenhouse gases (e.g. methane and nitrous oxide as reported by Hefting et al. (2003)).
- Most FCW should be regarded primarily as water treatment systems and should be treated accordingly; i.e. not used for bathing, fishing or animal watering due to the possible presence of pathogens, toxins and parasites.
- Although safety and health concerns for humans and livestock may arise from FCW because they contain standing water, such concerns can be minimized by the use of gently sloping sides, marginal vegetation and by raising public awareness.
- Farm constructed wetland pollutants (e.g. heavy metals and pesticides) may cause harm to wildlife, but this impact can be mitigated by an appropriate design taking account of ecological aspects and by keeping certain types of effluents (e.g. pesticide washings) away from FCW.
- Some infiltration of water to groundwater may occur. However, infiltration is reduced by the use of shallow water depths and an adequate substrate such as clay (Hill et al., 2000), and it decreases over time through sealing of the bed of the wetland by accumulated organic matter and sediment (Harrington et al., 2005).

3. Farm constructed wetland site suitability

3.1. Effluent to be treated

In order to decide if a FCW is needed and appropriate for a given farm, a site-specific approach is required, usually involving the following steps (Zedler, 2003; Carty et al., in press):

1. Assessment of the type and volume of the effluent to be treated (present and future) and the infrastructure present on the farm.
2. Determination of the need for a FCW from assessment of existing on-farm measures and potential cost-effective alternatives for dirty water management.
3. Determination of the characteristics of the site available for FCW construction and assessment of any potential impacts that may result from FCW implementation.

It is recommended that specialist advice from a suitably qualified consultant and/or engineer is sought when assessing the need for a FCW and the suitability of a FCW site. To decide whether a FCW is an appropriate option for a farm, the farmer and/or farm advisor will need to assess the present effluent management, types of effluent, present storage facilities, the economics of developing a FCW, and the likelihood that a FCW will improve existing conditions. When assessing the type and volume of effluent to be treated, the present and possible future loading (e.g. increased stock numbers, impervious areas and shed roofs) should be considered.

Precipitation events are the primary factor affecting design, as there is almost no attenuation of farmyard-intercepted rain. The hydraulic flux in any year arising from storm events can be between 25 and 100 times the mean flow from the farmyard. It is this flux that must be appropriately managed within the FCW design (R. Harrington, Department of Environment, Heritage and Local Government, Ireland, personal communication, 15 September 2007).

The FCW are designed to deal with storm events and the variable composition of influents through including sufficient wetland area for flow attenuation and water treatment. The areas of yards, tracks and roofs within the farmyard must be calculated to determine the volumes to be treated. Each farmyard will have varying daily water usages (e.g. yard washings and parlor washings), which must be calculated as part of the total volumes of water and runoff produced on site (Carty et al., in press).

Before implementing a FCW design, it is necessary to ensure that BMP are employed to decrease the contamination of the farmyard runoff (e.g. improved cattle diet, roofing of feeding areas and separation of roof runoff). It is also important to look at potential alternatives available to the farmer to deal with the contaminated farmyard runoff (e.g. storage and subsequent land spreading (Bowmer and Laut, 1992), and overland flow) as discussed elsewhere (Harrington et al., 2005; Scholz et al., 2007).

Fig. 1 provides a decision support tree for the treatment of farmyard and roof runoff with FCW. This tree can be used as a template, and might require modification to address differences in regional and national legislation.

3.2. Site characteristics

Each FCW design is site-specific requiring “expert judgment” as discussed by Scholz (2006a,b; 2007). Therefore, a comprehensive site-specific assessment combining site
Investigation and desk study is necessary to determine the site characteristics, assess any potential impacts, decide on any groundwater and surface water protection measures, and to provide data that will be used in the design of the FCW.

The site assessment should be undertaken by a person who is professionally qualified, has experience in all of the required disciplines and who can call in experts if necessary to clarify any anomalies that may arise. When assessing the site suitability, the relevant bodies and authorities should be consulted in the context of the prevailing legislation. The following existing characteristics of a site should be assessed: topography, geology, soils and subsoils, hydrogeology, hydrology, flora and fauna, archaeological and architectural features, and natural interest.
A number of trial holes should be dug on the proposed FCW site to a depth of at least 1 m should intercept any field drains, and divert their flow to surface water. Ideally, a FCW should be developed on gently sloping land (Harrington et al., 2005). Areas that are steeply sloping require larger wetland areas, deeper soils and subsoils, more excavation works, and probably increased costs of construction. When assessing the proposed site, consideration should be given to the approximate area of land required for the wetland, embankments and access (see below).

The location of a wetland down-gradient from the farmyard will allow for the effluent to flow by gravity and thus remove the need for pumping. Existing Irish FCW have been located at varying distances from 5 m to greater than 500 m from the farmyard. The FCW cells and embankments should be designed so that water flows through the FCW by gravity (Scholz et al., 2007).

A topographical survey of the farmyard and the proposed FCW site, at a scale of at least 1:500, is recommended. The survey should include contours (preferably 0.5 m contours), location and use of buildings, boundaries, hydrological features, and any features of archaeological and architectural interest.

A desk study should be undertaken in advance of the site visit to establish the geological context of the site. A number of trial holes should be dug on the proposed site to examine the type, depth and texture of the underlying soil and subsoil. Trial holes should be dug to a depth between 2 and 3 m, with a minimum of four trial holes per approximately 4000 m². Where the soil texture is not easily determined by hand assessment methods on site, a laboratory test can be conducted to determine soil permeability or particle size distribution or both.

Where low permeability soils suitable for the construction of a wetland (such as clays) are not found on site, alternative measures should be taken (Carty et al., in press):

- **Import suitable soils:** There may be a requirement to import soils for part or all of the FCW. Additional soils can sometimes be found on the farm or locally, but this may incur additional costs for transportation, particularly if located away from the farm. Importing soil from another site or farm may require a licence subject to national guidelines and laws.
- **Use of an artificial liner:** The use of an artificial plastic liner, similar to that required for a landfill, can also be considered. However, its use will incur a much greater cost and may require replacement in the future. Furthermore, the installation of an artificial liner requires the expertise of an engineer and consultation with the local authorities and regulators.

Field drains are widely used in agricultural land. All field drains must be located (through local knowledge or site excavation) to assess whether they are likely to conduct water to the FCW or provide a pathway for water to leave the FCW before completing treatment. A trench or drain dug during construction around the perimeter of the proposed FCW site to a depth of at least 1 m should intercept any field drains, and divert their flow to surface water.

Climatic conditions, including rainfall and evapotranspiration, will determine the volumes to be treated by the FCW system and the residence time within the FCW. Due to the sources of effluent (mainly precipitation-generated runoff) and the effects of climate, discharge from FCW may be confined to wet periods.

3.3. Discharge options

Any nearby surface water features such as rivers, streams, lakes and drains should be noted during the survey. In most cases, a local river, stream, ditch or even woodland will provide the final discharge point for the water that has been treated by the FCW. As well as assessing the suitability of a watercourse as a potential discharge point, consideration must be given to high water levels, other discharges upstream and downstream, water abstractions downstream and flooding. Where a FCW is to be developed in a floodplain, the potential impacts upstream and downstream must be assessed. In some instances, the floodplain may be protected, in which case a FCW may not be permitted. Regional and national authorities need to be consulted (e.g. UNEP, 2003; Zedler, 2003; Scholz, 2006a).

The final discharge should be to surface water with sufficient assimilative capacity such as a stream or river with significant flows throughout the year, rather than to a field drain which has low assimilative capacity and often dries out. The discharge of the treated waters should have a negligible effect on the receiving water (e.g. Zedler (2003); R. Harrington, Department of Environment, Heritage and...
Where a discharge to surface water is not possible or not suitable, a wet woodland or willow bed could be used. The woodland can be designed to have a zero discharge or minimal discharge; however, it must be noted that this may require a large area (Scholz, 2006a,b; Zheng et al., 2006).

It is recommended that a FCW should not be immediately adjacent to surface water to minimize the impact of any failure of the FCW. The buffer distance depends on the adjacent surface water and the ground conditions; a minimum of 5–10 m is recommended.

During the site assessment, information on the following should be collected: wells, springs, water table elevation, aquifers, nearby surface and groundwater supplies and connectivity with surface water features, since they will cause increased volumetric loading to the system, reducing residence time and treatment. Furthermore, sufficient distance must be provided between a FCW and up-gradient and down-gradient water supplies (Scholz, 2006a; Zedler, 2003).
The height of the water table must be recorded. The base of the FCW cells should be above the water table so sites with high water tables will not be suitable. The vulnerability of groundwater to pollution is assessed through combining information from groundwater vulnerability maps (where available) with a site-specific study and investigation of soil and geological conditions.

4. Design guidelines for farm constructed wetlands

4.1. Background

Once site assessment and selection has been completed, the detailed design of FCW can be conducted, taking account of the farm and farmyard structure and management practices. When designing FCW, the following aspects are therefore of major importance (Zedler, 2003; Harrington et al., 2005):

- Objectives behind the construction of the FCW.
- Characteristics of the farmyard runoff to be treated (volume and quality).
- Water quality targets to be achieved.
- Land availability to achieve the target water quality.

4.2. Water treatment requirements

Adequate pre-treatment, retention time, management and operation (e.g. removal of sediment and regular inspection) and design for efficient management (e.g. 6000 access) are required to achieve effective water treatment through a FCW. A FCW that is fit for purpose should have the following attributes (Harrington and Ryder, 2002; Rice et al., 2002; Scholz et al., 2007):

- Reliable and efficient in water treatment, particularly during storm events, extreme rainfall with increased hydraulic loadings, and also under relatively cold conditions.
- Capable of coping with accidental spillages.
- Flexible and versatile.
- Relatively simple to build.
- Low operation and maintenance requirements and costs.
- Low energy consumption.
- Good ‘landscape fit’.
- Enhance habitat and biodiversity (Froneman et al., 2001).
- Safe for farmers and for the public.

4.3. Runoff capture and conveyance

One of the early steps in FCW construction should be to ensure that any contaminated runoff, such as from roofs, farmyards and tracks, is captured properly. Runoff from adjacent land should usually not enter the FCW. However, regional recommendations may vary.

The conveyance of waters to, within and from the FCW must consider the following (Scholz, 2006a): collecting water from the farm; conveying that water to the wetland; water movement within the wetland; water movement out of the wetland. Where possible, the effluent should flow by gravity to minimize maintenance and energy costs.

It is essential that any containment is secure and that only water with acceptable concentrations of contaminants is discharged to watercourses or groundwater. The FCW embankments retaining the water flowing through the system must be sufficiently high to allow for the accumulation of sediment and detritus. The soil lining the base must adequately impede infiltration to protect groundwater (Dunne et al., 2005a,b; Keohane et al., 2005; Scholz et al., 2007).

4.4. Hydraulics, water balance and residence time

The periodic nature of precipitation and the interception and uptake of water by emergent vegetation, evaporation and ground infiltration has the capacity to retain water flow between the individual segments of a FCW. This creates a freeboard between the outlet level and the level of the water contained within an individual wetland cell. It also provides each wetland cell with ‘additional’ receiving hydraulic capacity before flow to the next segment can resume, thus enhancing the hydraulic residence time (Dunne et al., 2005a,b; Scholz et al., 2007).

The treatment effectiveness of surface flow wetland systems in comparison to sub-surface flow systems (Mantovani et al., 2003) is typically based on having appropriate hydraulic residence times, which depend very much on the specific site conditions (Harrington et al., 2005). In shallow, emergent and/or vegetated wetlands, such as FCW, this depends on having sufficient functional wetland area with an appropriate length to width ratio and a high emergent vegetation density. The hydraulic effectiveness of the FCW can be maximized by the following measures (Scholz et al., 2007):

- Segmentation of the wetland into a number of wetland cells of appropriate configuration (see below).
- Avoidance of preferential flow.
- Dense vegetation stand.
- Managing the water depth to ensure optimal functioning (Scholz, 2007).

The velocity of the water flow through the FCW is determined by the volumetric flow and the cross-sectional area of the water channel. Minimizing the velocity enhances the settling of suspended solids (D’Arcy et al., 2007) and promotes a longer contact time with emergent vegetation whose surfaces support biofilms (Scholz et al., 2002, 2007; Kantawanichkul and Somprasert, 2005).

Wind and temperature gradients can generate water movement between the different aquatic strata within a
wetland cell. Emergent vegetation minimize 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 cell, floating vegetation may develop (typically *Glyceria fluitans* and *Agrostis stolonifera*) and water flow will be partially sub-surface, thus having the additional advantage of reducing odors (Dunne et al., 2005a; Scholz and Lee, 2005; Scholz et al., 2007).

4.5. Wetland sizing

The design and sizing of FCW has often focused on phosphorus, which is recognized as one of the most difficult contaminants to remove from water and is a limiting nutrient in many freshwater ecosystems (Braskerud, 2002). For example, a catchment-specific study of 13 wetland systems in Waterford (Ireland) showed that, to achieve a mean molybdate reactive phosphorus (MRP) concentration at the outlet of 1 mg/l or less, the wetland area required was at least 1.3 times the farmyard area, and that each system should contain approximately four cells. The design is based on two assumptions: the larger a wetland, the more phosphorus removal can be expected; and all ICW studied near Waterford (Ireland) were at the designated threshold of failure for phosphorus (1 mg/l MRP for the outflow or near it in cases of no flow (Scholz et al., 2007)). This finding relating to MRP is, however, not universally applicable.

The aspect ratio is defined as the mean length of the wetland system divided by the mean width. The study conducted in Ireland showed that to obtain an outlet MRP concentration of 1 mg/l or less, the FCW aspect ratio should be less than 2.2. In fact, the closer the aspect ratio is to 1 (i.e. the more the FCW shape is square or round), the better the wetland treatment (Scholz et al., 2007).

Sizing must also take account of the footprint of the upper embankments which should be between 2 and 3 m wide to ensure stability and to provide easy access for maintenance and monitoring. For safety reasons, inner embankments should be gently sloping.

4.6. Inlet and outlet structures

Inlets and outlets should be kept as simple as possible and avoid the use of concrete and over-engineered structures. Pipe diameters should be at least 150 mm to avoid clogging. Stone chippings should be placed beneath the inlet and outlet pipes to prevent scouring. Elbow pipes fitted to linear ones can be used to control the water level and the outflow of each cell (Carty et al., in press).

4.7. Landscape fit and biodiversity enhancement

The potential visual aspect of the FCW system design is important for achieving empathy from both farm dwellers and the local community. Farm constructed wetlands with curvilinear shaped and virtually level embankments have a more ‘natural’ appearance.

Several measures can improve the landscape fit and biodiversity of the FCW. Through BMP on the farm, the level of contaminated water discharging to the ponds can be reduced (Scholz, 2006a; Zheng et al., 2006). Wherever possible, the FCW should be located near (but not connected to) existing wetlands, ponds and lakes to allow for natural colonization by plants and animals. The FCW cells should be irregular in shape, with gently sloping embankments, areas of deeper water, and contain islands, where sufficient area is available. The use of locally occurring wetland plant species for establishing habitats and enhancing biodiversity appropriate to the locality is also likely to further increase the robustness and sustainability of the system (Froneman et al., 2001; Scholz, 2007; Scholz et al., 2007).

The area surrounding the FCW can be planted with trees and shrubs, but tall trees are not recommended on the FCW embankments. If possible, small pools around the main system should be created to collect runoff from adjacent fields and create additional aquatic habitat (Froneman et al., 2001; Carty et al., in press).

4.8. Life span of farm constructed wetlands

Wetland embankment height, in-flowing solids and accumulating detritus determine the functional life span of each segment of the FCW. With detritus accumulation and a minimum embankment height of 1 m, a life span between 50 and 100 years is expected. However, the life span can virtually be indefinite if detritus removal takes place regularly as discussed by Scholz et al. (2007) and in the section on maintenance below.

5. Construction and planting

5.1. Construction

Ideally, the construction of the FCW should be undertaken during the dry season and the involvement of the farmer is encouraged. Construction of a FCW should be undertaken by a competent machine operator and signed off by a qualified engineer on completion, although regional and national requirements for construction vary. The main stages of construction are as follows (McCuskey et al., 1994; Scholz et al., 2007):

(1) Topsoil is stripped from the FCW area and retained for later use (if applicable).
(2) Excavation of subsoil.
(3) Layering and compaction of soils for cell liner (laying of an artificial liner if required).
(4) Creation of gently sloping embankments (at least 1 in 3), with height >1.0 m and tops 2–3 m wide to guarantee stability and sufficient access around the wetland.
(5) Potential re-distribution of topsoil (if nutrient poor) over the base of the ponds.
(6) Pipe laying between the cells.
(7) Placement of stones or chippings beneath the inlet and outlet pipes.
(8) Planting of the FCW cells.

The machinery required for construction comprises a tracked excavator, bulldozers and a vibrating roller where a higher degree of soil compaction is required. The topsoil is stripped from the FCW area and retained for later use. The depth of excavation will vary depending on the depth of the overlying topsoil (McCuskey et al., 1994; Carty et al., in press).

Subsoil is excavated to form the base of each pond and to provide material for the embankments. The depth of excavation will depend on the topography and elevations required between each pond; typically, an excavation of 0.5 m below the ground level is required for flat sites. Where surrounding land slopes towards the FCW system, a drain or an embankment should be constructed around the system to divert potentially large volumes of runoff away from the system (McCuskey et al., 1994; Carty et al., in press).

The amount of compaction and layering will depend on the type of material being used to construct the FCW and should be determined during the site assessment of the soils. Where the soil permeability is sufficiently low, no layering is required. Medium to low permeable soils will require layering and compaction to ensure a permeability of approximately $10^{-8}$ m/s. Regional and national guidelines on soil permeability thresholds should be consulted by the designers.

Pipe ducting and elbows are placed at the inlet and outlet points for each FCW cell (see above) to ensure that the movement of water in each cell is across the maximum distance from the point of inflow to the exit. Furthermore, piping should be positioned in locations that are accessible and be placed as low as possible to the base of the exit point of the upper cell to ensure that any drainage is possible. In FCW discharging to surface waters prone to flooding a non-return valve should be placed on the outlet pipe to prevent any flood water entering the wetland system. Stones or chippings should be placed beneath the inlet and outlet pipes to prevent scouring of the wetland floor and to provide access for monitoring (McCuskey et al., 1994; Carty et al., in press).

The banks and floor of the wetland cells should normally be compacted and smoothed off using tracked excavators which are suitable for use on difficult wet terrain. Where a greater degree of compaction is required, rollers are used.

Measures should be employed during the construction of a FCW to limit the impact on surface water (runoff and siltation) and groundwater through proper management and supervision following national guidelines.

Depending on the location of the site, there may be a need for fencing to restrict access to humans and livestock. When determining the type of fencing, the farmer will need to consider the extent of fencing, costs, and human and machinery access. In most cases, fencing similar to that already used on the farm will be suitable (Carty et al., in press).

5.2. Planting

The primary vegetation used in FCW is composed of emergent aquatic plant species (helophytes). These species have evolved to enable them to root in soils with little or no available oxygen, growing vertically through the water column with most of their leaves in the air. They have specially adapted tissues and physiologies that facilitate oxygen storage and its transportation from the leaves through the stem to the roots. The soil and water characteristics influence the type of helophyte species and their treatment performance (Scholz, 2006a; Scholz et al., 2007). Helophytes in FCW have important functions such as the following (Scholz and Lee, 2005; Jiang et al., 2007):

- Provision of a support structure for microbial colonies to develop.
- Facilitation of aerobic microbial activity (principal treatment removal process).
- Uptake of nutrients.
- Source of organic matter.
- Reduction of the flow of water to increase the residence time and settlement.
- Reduction of final volumetric discharge through plant transpiration and interception.

While more than a hundred native helophyte species can be used, about 20 species are actively planted in constructed wetland systems (Scholz and Lee, 2005; Scholz, 2006a,b). Initial plant establishment is the dominant influence on the vegetation structure on a FCW during its early years. Plant establishment is dependent upon the nature of the influent and water depth, plant species and physiological maturity, and planting density (Scholz et al., 2007; R. Harrington, Department of Environment, Heritage and Local Government, Ireland, personal communications, 16 October 2007). Inter-species competition and other biotic factors, especially waterfowl, influence long-term vegetation development (Froneman et al., 2001; Scholz, 2006a,b).

Plants should be sourced from existing (constructed or natural) wetlands where permitted or from accredited plant nurseries. Care must be taken to ensure that non-native species are not introduced. Seedlings are usually not recommended as they are more vulnerable to pollution and water level variations, and take longer to establish (Carty et al., in press).

If plants are sourced from existing wetlands, sufficient rhizome and/or root material should be obtained to allow the plants to establish, while also ensuring that the
root system of the original plant can regenerate. The harvesting should be carried out ideally by hand and over a sufficiently large area to minimize disturbance to the plants and its environment (R. Harrington, Department of Environment, Heritage and Local Government, Ireland, personal communication, 11 January 2007).

Planting of mature macrophytes should be carried out by hand into water or suitably saturated soils, ideally with 50–100 mm of water above the topsoil. Water levels should be maintained between 100 and 200 mm for at least the first six weeks after planting and the wetland should not be allowed to dry out below the soil surface. Shallow waters (<100 mm) will encourage establishment of grasses and weeds, which can restrict the growth of the wetland vegetation. Water may need to be sourced from nearby surface water features during planting, as the effluent from the farmyard may only provide sufficient cover for the first cell (McCuskey et al., 1994; Scholz and Lee, 2005).

The area of each wetland should be planted with various wetland species to increase biodiversity. The first wetland cell will receive a higher pollution load, often with a high ammonia-nitrogen concentration, so a minimum of three plants per m² is recommended to increase plant success. Subsequent cells will have reduced effluent loadings and a minimum of two plants per m² is therefore recommended. The farmer may wish to allow areas within the final cells to colonize naturally. Provided that planting is carried out at the beginning of the growing season and water levels are maintained between 100 and 200 mm for the initial few months, a desirable vegetation cover of at least 80% after two years should be attained. To establish a dense cover in a shorter period, the initial planting densities should be doubled (Carty et al., in press).

Prior to the commissioning of the FCW, the system should be signed off by a competent engineer (depending on regional guidelines), and have all monitoring and maintenance features and fencing in place. During the first few months, water levels within the wetland ponds should be at a minimum, approximately 100–200 mm, to provide favorable conditions for plant establishment. It is possible that some effluent may need to be diverted away from the FCW during the start-up stage; e.g. stored and/or land spread (McCuskey et al., 1994; Carty et al., in press).

6. Maintenance and operation

6.1. Pipe maintenance

The success of a FCW will depend on the maintenance and operation of the system. While a FCW is designed to be as self-maintaining as possible, it is crucial that a maintenance program is adopted to ensure continued effective water treatment and ‘rejuvenation’ of the system.

All inlet and outlet pipes within the FCW system should be visually inspected weekly for blockages, sediment accumulation and debris. Blockages will affect the hydraulics of the FCW system, while sediment accumulation may indicate inadequate solids separation further up in the system. Any blockages and sediment or debris accumulations around the inlet or outlet pipes should be cleared (Harrington et al., 2005; Scholz, 2006a).

6.2. Flow control

During prolonged dry periods, water depths within the ponds will decrease, especially in down-gradient regions of the wetland. It is essential to ensure that soils are flooded (to at least 50 mm). Farm constructed wetlands should usually not be allowed to dry out as cracks may form in the base, which may cause higher infiltration rates in the short term when effluent re-enters the cell. Once the emergent vegetation is established, FCW in temperate regions should be able to cope with reduced water depths, and even drying out, for periods of several months (R. Harrington, Department of Environment, Heritage and Local Government, Ireland, personal communications, February 2007).

Any adjustment of pipes must be carried out gradually as these movements may cause huge surges of effluent to subsequent wetland cells or receiving surface or groundwaters, reducing residence time and treatment within the system.

6.3. Vegetation maintenance

Water levels should be maintained at less than 300 mm to ensure good plant growth. However, most macrophytes tolerate short periods of increased water depth (up to 500 mm), such as associated with high rainfall, as well as low water depths or even no water during dry weather. Major changes in vegetation cover and composition should be noted as a possible indicator of change (i.e. degradation or improvement) in wetland performance. Pest control might be required if unwanted plant species take over a wetland (Asa Hedmark, Scottish Environment Protection Agency, personal communication, 21 May 2007).

6.4. Removal of sediment

Sediment accumulating within the wetland comprises organic material from the influent and dead plant matter, and also mineral sediment from eroded tracks. Existing constructed wetlands have shown varying accumulation rates depending on the type of loading and the amount of vegetation cover within the wetland. The removal of accumulated sediment is usually confined to the first cell (Scholz et al., 2007).

For a heavily loaded system, the inclusion of an open water pond at the initial stage of the FCW as a sediment trap may extend the operational life of subsequent cells before the removal of material is required. Any pond located within the initial wetland cell would require relatively frequent material removal (most likely biannually), but could be configured to be as accessible as a standard slurry storage tank (Scholz, 2006a; Scholz et al., 2007).
The most appropriate way of managing the material removed is likely to be land spreading on the farm in accordance with good farm management practice. Information on the solid content and nutrient composition, particularly phosphorus, are required to ensure that the usage complies with farm nutrient management requirements (Bowmer and Laut, 1992; Carty et al., in press).

As the farm’s nutrient management requirements may not allow the full amount of removed sediment to be spread on the land during one year, it is likely that occasional storage of removed sediment would be required for some sites. The storage requirements specified in good agricultural practice regulations with respect to farmyard manure should also suffice for FCW sediment to ensure environmental protection (Bowmer and Laut, 1992; Asa Hedmark, Scottish Environment Protection Agency, personal communication, 7 June 2007).

6.5. Inspection of pond embankments

The authors recommend that the farmer should undertake regular visual inspection of the internal and external faces of the wetland embankments to check for any water leakage, slippage or distortion. The internal embankment face can be checked by walking along the embankment crests and external embankment faces by walking along the external boundary of each cell. Any defects such as leakages, slippages or distorted areas should be addressed immediately.

6.6. Access and security checking and maintenance

Access around the wetland should be maintained by managing vegetation growth on the embankments. Under normal operating conditions, growth on some pond crests will need to be cut biannually using a mower or topper. Security and safety considerations for both humans and livestock should be incorporated into the design of the FCW subject to national guidelines. Access to the influent-receiving segment of the FCW may have to be limited through fencing or by existing hedgerows around the FCW (R. Harrington, Department of Environment, Heritage and Local Government, Ireland, personal communication, 5 June 2007).

6.7. Monitoring of the final effluent and receiving watercourses

The monitoring of the FCW and the final effluent will allow the farmer to assess the performance of the wetland system and to detect any malfunction. The general appearance of the final effluent should be noted, paying particular attention to water color, the presence of ‘sewage fungi’ (Scholz, 2006a), smell and any evidence of plant material in the discharge. If the final discharge water appears to be heavily discolored, polluted or contains plant material, then the outlet pipe should be isolated immediately by closing the gate valve. However, water that is visibly clear may also have a high nutrient load, which can only be determined by laboratory analysis.

The condition and appearance of the receiving waters at the point of discharge should be checked on a monthly basis and following extreme events such as high rainfall. The farmer should assess the condition and appearance of water, both upstream and downstream of the discharge location. Heavily discolored water or the appearance of sludge type material may indicate an upstream pollution source. Foaming immediately downstream of the discharge point may indicate pollution in the final effluent. The outlet pipe from the FCW should be isolated immediately by closing the gate valve in the event of any suspected pollution incident. The farmer should obtain advice from a suitable agricultural advisor and the regulator (Scholz, 2006a; Carty et al., in press).

7. Conclusions

This paper proposes for temperate climates universal design, operation and maintenance guidelines for a Farm Constructed Wetlands (FCW), which is a specific application of Integrated Constructed Wetlands (ICW). Guidelines have been proposed for assessing the need for FCW and their site suitability. The overall design of FCW is empirical, site-specific and predominantly based on expert judgment. The guideline is based on minimizing costs for the benefit of the farm owner but not at the expense of the environment. Therefore, the FCW may require considerably more land than conventional treatment technologies, which are usually associated with more maintenance and capital costs.

Acknowledgements

The research is associated with the Farm Constructed Wetland design Manual, which was funded by the Department of Environment in Northern Ireland (DoE NI) and the Scottish Environment Protection Agency (SEPA). The technical support of J. Keohane (Carlow Institute of Technology and Geotechnical and Environmental Services Ltd., Ireland) and E. J. Dunne (The University of Florida, USA) is acknowledged. B. D’Arcy, R. Morris, R. Audsley, S. Field, D. Crothers and A. E. Hedmark (SEPA), R. Harrington (Department of Environment, Heritage and Local Government, Ireland), F. Wilson (DoE NI) and P. Carroll (Waterford County Council) provided feedback. The content of this paper is not necessarily official policy of DoE NI and SEPA.

References


