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The use of constructed wetlands for reducing the impacts of urban surface runoff on receiving water quality

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Abstract The design criteria for constructed wetlands for the treatment of urban runoff are described and particular attention is paid to pre- and post-treatment components, sizing considerations and the substrate structure. The pollutant removal performances of two constructed wetlands are discussed and the predicted maximum outflow pollutant concentrations are compared to existing water quality criteria. Suspended solids represent the main concern with higher outlet concentrations being discharged due to re-suspension processes. This problem highlights both the need for regular maintenance, particularly with respect to the emptying of sedimentation tanks, and the benefits of incorporating an overflow channel to reduce sediment mobilization during high flow conditions.

INTRODUCTION

Increasing urbanization, through the development of buildings, roads and other impermeable surfaces results, in alterations to the natural hydrological cycle, involving changes in peak flow characteristics and the volume and quality of the runoff. Traditionally in the UK, new urban sites have been engineered in such a way that surface water is drained directly and as quickly as possible to the nearest water course to prevent the possibility of flood occurrence. The design of such a system neglects the potential pollutant loads which can be generated in urban runoff, particularly after a prolonged antecedent dry period, and hence their impacts on receiving water quality.

The pollutant loads of urban drainage waters tends to be highly variable due to a dependence on factors such as land use, characteristics of the drainage system and catchment area, the nature and frequency of storms and the weather conditions between storms. The principal pollutants in urban runoff are BOD, suspended solids, heavy metals, hydrocarbons, nutrients and faecal coliforms. The impacts of these pollutants on receiving river waters are currently compared in the UK to the River Ecosystem Classification which comprises five hierarchical classes which are defined in order of decreasing chemical water quality by RE1 to RE5 (National Rivers Authority, 1994). Pollutants not currently covered within this classification system are required to comply with the appropriate EC Directive.

Control procedures for urban runoff can be considered to be scale-dependent such that they may be located within the boundary of an individual property, within the public sewer system or in the downstream channel (CIRIA, 1992). Downstream treatment facilities, such as detention storage ponds, need to be carefully sized and designed but offer potential benefits with regard to amenity improvements, recreational opportunities and environmental enhancement. The incorporation of macrophytic vegetation into detention ponds improves pollutant removal efficiencies through biofiltration and biological uptake processes. Treatment systems, which rely predominantly on reeds planted in constructed wetlands, are now being progressively used to reduce pollutant levels in stormwater derived from impermeable surfaces such as highways (Shutes *et al.*, 1999), airports (Revitt *et al.*, 1997) and general urban areas (Shutes *et al.*, 1997).

Two basic designs of constructed wetlands have been used to treat runoff, utilizing either horizontal surface water flow or horizontal subsurface water flow systems. Surface flow systems generally contain soils planted with emergent and/or submergent wetland macrophytes such that the water flows at shallow depths and at low velocities above and within the surface layers of the substrate. Within subsurface systems, the contaminated waters flow through a medium composed of soil, sand, gravel or artificial media. A wide range of emergent macrophytes have been used in constructed wetlands with reedmace (*Typha* species) and the common reed (*Phragmites* species) being extensively utilized because of their availability, pollution tolerance and root/rhizome matrix.

This paper will examine the establishment of design criteria for constructed wetlands to treat urban runoff, which is an emerging technology in the UK (Cooper *et al.*, 1996). The results obtained from two case studies, which have investigated the use of constructed wetlands to treat urban runoff, are discussed in the second part of the paper.

DESIGN CRITERIA FOR URBAN RUNOFF TREATMENT BY CONSTRUCTED WETLANDS

The factors that will determine the selection of the most appropriate design criteria include:

(a) local climate, topography and geology;
(b) catchment area and associated land uses, including specific attention to road surface areas and traffic loadings;
(c) land availability for construction;
(d) size/extent and type of receiving water body;
(e) water quality classification and objective (including water uses);
(f) environmental enhancement value;
(g) economic considerations.

A comprehensive treatment system for urban runoff which incorporates a constructed wetland should also ideally include an oil separator and silt trap, a settlement pond and associated control structures, a final settlement tank, an appropriate outfall into the receiving watercourse, and full vehicle access to each component.

Pre- and post-treatment components

The incorporation of treatment facilities upstream of a constructed wetland will extend its operational life-span without involving major maintenance. Oil and phytotoxic chemicals in urban runoff can seriously affect the treatment efficiencies of constructed wetlands and the viability of plants (Shutes *et al.*, 1993) and suspended solids can produce damaging siltation effects in the wetland inlet zones. The finer and more mobile sediments, which can pass through the latest designs of oil and grit interceptors, can pose problems to a constructed wetland and, therefore, where land availability allows, a settlement pond should be located prior to the wetland. The ideal settlement pond size for maximum pollutant removal would have a surface area corresponding to 2 to 3% of the urban drainage area and a retention volume of 4 to 6 times the mean total storm runoff volume (Hvitved-Jacobsen, 1990). The land space necessary to satisfy these requirements is not usually available and compromises have to be made. In situations where a serious pollution potential exists, it may be advantageous to install wetland forebays or lagoons fitted with oil booms to reduce the initial flush of pollutants into the main wetland (CIRIA, 1994). Spillage containment facilities are recommended in urban catchments where roads and industrial/commercial areas contribute significantly to the drainage area.

Where a constructed wetland discharges treated urban runoff to a sensitive receiving water, a final settlement tank extending across the width of the wetland can prevent fine sediment from being transferred from the wetland. Regular maintenance is required to prevent collected sediments from being re-suspended during high flows and it is recommended that inspections should be made on, at least, an annual basis.

Sizing consideration

The maximum potential treatment efficiency is achieved by sub-surface flow systems (Revitt *et al.*, 1997) but these provide minimal flood storage and therefore where this is required, separate storage must be provided. The balance attained between storage and treatment requirements in a constructed wetland is dependent on the land space available. If this is not limited, the wetland can be sized to receive the design flood (normally with a return period of 10 years) at an attenuated flow rate regulated by the settlement/balancing pond outlet structure. Where land space is limited, the constructed wetland can be sized to treat only the first flush of the runoff, which usually contains a high proportion of the pollutant load for a specific storm event. To achieve this situation the settlement/balancing pond outlet structure would need an overflow incorporated to divert excess flows directly to the watercourse following detention.

High rates of urban runoff may discharge onto constructed wetlands during storm events but optimal loading rates should not exceed 1 $m^3\ m^{-2}\ day^{-1}$ in order to ensure effective treatment. Flow velocities should be carefully controlled with relatively low values (0.3–0.5 $m\ s^{-1}$) ensuring efficient sedimentation. Ideally, the influent flow should be distributed evenly across the width of the wetland and this can be achieved by using slotted inlet pipes or a weir gate. A rip-rap or gabion zone at the front of the reedbed helps to dissipate high water flows.

Hydraulic residence time is an important factor in determining the pollutant removal performance of constructed wetlands for urban runoff treatment. It is influenced by the aspect ratio (width/length), the vegetation, the substrate porosity and hence hydraulic conductivity, depth of water and flow, and the slope of the bed.

Hydraulic conductivities in the range 10^{-3} m s^{-1} to 10^{-2} m s^{-1} are recommended for constructed wetlands for the treatment of urban runoff. Water level and flow control structures, such as flumes and weirs, are required to keep the hydraulic regime within desired parameters. The optimum design of constructed wetlands should retain the average storm volume, which can be calculated from the average rainfall, runoff coefficient and catchment area, for a minimum of 3–5 hours and preferably 10–15 h to achieve good removal efficiencies. A maximum retention time of 24 h has been suggested (Shutes *et al.*, 1999).

Wetland substrate

Kadlec & Knight (1996) and Cooper *et al.* (1996) have reviewed the different substrates and associated planting procedures, which have been used in constructed wetlands. The correct combination should be selected which for a specific situation will best support the sedimentation, filtration, biological uptake and microbial degradation processes by which the pollutants in urban runoff can be removed. For sub-surface systems a suitable substrate is washed pea gravel or a mixture of organic topsoil and gravel (1:6) to a depth not exceeding 0.6 m. This depth is sufficient for deep rooting macrophytes, such as *Phragmites*, and also prevents physical damage to the plants during the highest recommended flows and under the coldest conditions typically occurring in the UK. Selected reeds may be mixed or segregated within the entire reedbed system at typical planting densities of 4 plants per square metre. In addition, a range of emergent and floating aquatic plants around the edges of the wetland is recommended to enhance the ecological and visual interest, which should complement the natural environment.

Case Study 1: Brentwood constructed wetland

Site description The total treatment system is located at Brentwood, a small town situated northeast of London, consists of a constructed wetland of sub-surface design (144 m^2) and a natural, surface flow system (minimum capacity 45 m^2). Urban runoff from a 150 ha catchment area initially discharges from a surface water outfall into a settlement tank and then either passes through the constructed wetland (planted with *Phragmites australis*) or through a natural wetland (colonized with *Typha latifolia).* Both wetlands discharge into a combined post-treatment settlement tank before joining the River Ingrebourne. The water level is controlled throughout the system by stoplogs.

Removal efficiencies and pollutant concentrations The concentrations of all monitored pollutants during storm events at the inlet to the constructed wetland are shown in Table 1 together with average removal efficiencies and predicted outflow concentrations, which are compared to relevant water quality standards. The pollutant removal efficiencies within the wetland treatment system are higher during storm events with notable exceptions being the behaviour of nitrates and suspended solids. Although the mean value for suspended solids only indicates a small positive contribution from within the wetland, it is of concern that this could result in outflow

Table 1 Treatment potentials of Brentwood and Dagenham constructed wetlands in relation to maximum measured inflow pollutant concentrations during storm events.

Pollutant	**Brentwood Wetland**			**Dagenham Wetland**			**Water quality standard**
	Maximum measured inflow concentrations (for storm events unless indicated)	Mean percentage removal efficiencies for storm events	Predicted outflow concentrations	Maximum measured inflow concentrations (for storm events unless indicated)	Mean percentage removal efficiencies for storm events	Predicted outflow concentrations	
BOD	29.6 mg l^{-1}	26	21.9 mg l^{-1}	17.6 mg l^{-1}	24	13.4 mg l^{-1}	25[a] mg l^{-1}
SS	408.0 mg l^{-1}	–4	424.3 mg l^{-1}	89.4[b] mg l^{-1}	–99	178.0 mg l^{-1}	35[a] mg l^{-1}
Zn	221.0[b] g l^{-1}	55[c]	99.5 g l^{-1}	632.0 g l^{-1}	70	189.6 g l^{-1}	2[d] mg l^{-1}
Cd	8.9 g l^{-1}	29	6.3 g l^{-1}	9.6 g l^{-1}	73	2.6 g l^{-1}	5[e] g l^{-1}
Pb	109.8 g l^{-1}	40	65.9 g l^{-1}	31.9 g l^{-1}	70	9.6 g l^{-1}	250[f] g l^{-1}
Cu	59.9 g l^{-1}	39	36.5 g l^{-1}	42.8 g l^{-1}	66	14.6 g l^{-1}	112[g] g l^{-1}
Ni	21.2 g l^{-1}	34	14.0 g l^{-1}	58.5[b] g l^{-1}	39	24.0 g l^{-1}	200[f] g l^{-1}
Cr	15.6 g l^{-1}	38	9.7 g l^{-1}	13.8 g l^{-1}	83	2.3 g l^{-1}	250[f] g l^{-1}
Nitrate	20.9[b] mg l^{-1}	–21	25.3 mg l^{-1}	33.0[b] mg l^{-1}	44	18.5 mg l^{-1}	50[h] mg l^{-1}
Phosphate	0.2[b] mg l^{-1}	48	0.1 mg l^{-1}	1.4[b] mg l^{-1}	–18	1.7 mg l^{-1}	393[i] g l^{-1}

[a] Maximum discharge level according to Directive concerning urban waste water treatment (91/271/EEC) (Council of European Communities, 1991).

[b] Maximum inflow concentration monitored during dry weather.

[c] Zn removal efficiency for a specific event (October 1997).

[d] 95 percentile value for total Zn in hard water conditions for RE4 category river water according to River Ecosystem Classification (National Rivers Authority, 1994).

[e] Total concentration as annual average in hardest waters for protection of coarse freshwater fish (Council of European Communities, 1978).

[f] Soluble concentration as annual average in hardest waters for protection of coarse freshwater fish (Council of European Communities, 1978).

[g] 95 percentile value for dissolved Cu in hard water conditions for RE4 category river water according to River Ecosystem Classification (National Rivers Authority (1994).

[h] 95 percentile value for nitrate in surface water intended for abstraction for drinking water supply (Council of European Communities, 1975).

[i] Annual average concentration of phosphate for the protection of coarse freshwater fish (Council of European Communities, 1978).

concentrations in excess of 400 mg l^{-1}. This is far greater than the recommended European Community receiving water quality value (Table 1) and would require a dilution factor of over 12 to achieve conformity with this standard. The design of this constructed wetland requires further consideration, such as raising the stoplog at the outlet to the natural wetland, to address the lack of ability to retain suspended solids during storm conditions despite the existence of settlement areas both before and after the reedbed. Although the results indicate the contribution of nitrate to the stormflow, the maximum predicted outlet concentrations are not of concern with regard to causing a deterioration in water quality relative to drinking water abstraction requirements.

The variabilities of the metal concentrations, and consequently of the metal loadings, are typical of those expected in urban runoff due to the influence of a range of factors including the weather, urban surface types, traffic density etc. (Ellis & Revitt, 1991). The influence of wet weather conditions is clearly indicated by comparing the mean inlet loads which, for example, increase by factors of between 13 (for Zn) and 83 (for Pb). The mean removal efficiencies are positive for all metals except Zn, for which the high variability strongly influenced the average value. The highest mean removal efficiency was for Pb (40 ± 22%) followed closely by Cu and Cr (39 ± 47% and 38 ± 27%, respectively). The variabilities in the removal efficiencies are consistent with those which have been reported previously with ranges of –29 to 82% for Zn, 10 to 99% for Cd, 27 to 94% for Pb, –10 to 32% for Cu, 40 to 83% for Ni and 20 to 53% for Cr (Kadlec & Knight, 1996). The predicted outlet metal concentrations did not threaten to jeopardize compliance with European Community/ Environment Agency water quality standards except for Cd where the 5 μg l^{-1} value was exceeded. However, given the subsequent dilution following discharge to the receiving water, there is unlikely to be a downstream problem although there is an indicated requirement to carefully monitor the Cd levels throughout this constructed wetland system.

The performance of a constructed wetland with regard to metal removal during storm conditions can be best appreciated by consideration of the trends within specific events. The temporal pattern of metal loadings at the inlet and outlet to the Brentwood wetland during the same storm event shows that the maximum metal loadings were recorded at the inlet 22 min after the commencement of the storm. The highest loadings at the outlet, for most metals, occurred after 73 min. This indicates that the retention time for this wetland system under inflow rates approaching 100 l s^{-1}, was approximately 50 min. Comparison of the metal inlet and outlet loadings relative to this retention time gives the following removal efficiencies: Zn, 55%; Pb, 62%; Cu, 85%; Ni, 77%; and Cr, 63%. There was an overall increase in Cd of 3% which is partly explained by the small changes relative to low input loadings but also suggests different behaviour and mobilization of this metal within the constructed wetland during storm conditions.

Case Study 2: Dagenham constructed wetland

Site description This is a 250 m long, surface flow system which has been built in a specifically widened section of the Wantz Stream in East London. The total area of the constructed wetland is 1750 m^2 and the catchment area served occupies 440 ha.

The construction of a sub-surface flow system was not possible because of limited land availability. The wetland consists of three separate beds separated by flow control weirs and with *Typha latifolia* in the first bed and *Phragmites australis* in the second and third beds. Immediately upstream of the first bed is a settlement zone for the removal of suspended solids.

Removal efficiencies and pollutant concentrations The mean pollutant removal efficiencies for the Dagenham wetland during storm conditions are generally higher than those monitored at Brentwood (Table 1). This is surprising given the expected increased efficiencies associated with sub-surface systems and emphasizes the design limitations of the Brentwood wetland. The increased surface area of the Dagenham system is also significant as it represents 0.04% of the urban drainage area compared to 0.001% for the Brentwood wetland. Exceptions to the improved efficiencies exist for suspended solids and phosphates which both demonstrate negative net removals. In the case of suspended solids, this equates to almost a doubling of the inlet concentration and the predicted maximum outflow concentration clearly poses problems with respect to the water quality downstream. Because of the design of the Dagenham wetland there is no dilution effect and therefore the consequences of the high discharged suspended solid load are more serious. This highlights the requirement for regular emptying of the sediment tank and ideally the incorporation of an overflow channel to reduce excessive disturbance of retained sediments during high flow conditions. The high concentration of phosphate leaving the constructed wetland is also of concern and is probably linked to the high suspended solids level because of the affinity of phosphate for the particulate phase.

The BOD mean removal efficiencies are almost identical for both wetlands (Dagenham, 24%; Brentwood, 26%) but the monitored higher inlet concentrations to the Brentwood system mean that removal is more critical at this location. The predicted outlet BOD concentrations at both locations are below the required level of the European Community Urban Waste Water Treatment Directive (Table 1) and the higher discharge concentrations for Brentwood will be compensated for by the receiving water dilution.

The Dagenham wetland functioned efficiently with respect to metal removal during storm events with removal efficiencies in the range of 39% (for Ni) to 83% (for Cr). Efficient removal was most critical for Zn for which maximum inflow concentrations of 632 $\mu g\ l^{-1}$ were monitored. An average 70% removal efficiency reduced the concentration of this metal to 190 $\mu g\ l^{-1}$ which is well below the 95 percentile value for hardest waters under the River Ecosystem classification for the highest quality water (500 $\mu g\ l^{-1}$).

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