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Chapter 20

Urban and Highway Runoff Treatment by Constructed Wetlands

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Abstract. The pollution removal performance of artificial or constructed wetlands is compared with natural wetland performance in the UK, US and Australia. The reported results for an experimental study of a highway runoff treatment system in the UK show good removal of pollutants during storm events but poor treatment during dry weather conditions. The latter is explained by reference to the relation of inflow pollutant concentrations to the background irreducible concentrations associated with the wetland system. A small-scale experimental wetland study of diesel oil treatment is also described. The design criteria, wetland sizing, optimal hydraulic loading, flow velocity, substrate structure, planting considerations and pre and post-treatment structures in systems incorporating a constructed wetland are discussed.

20.1. Constructed Wetland Types and Flow Systems

Although the design of artificially constructed wetlands varies making each system unique, the basic flow configurations can be divided into two categories:

Surface flow (SF) or *free water surface* (FWS) systems which are similar to natural marshes in that they are basins planted with emergent, submergent and/or floating wetland macrophyte plants. Such free surface water treatment wetlands mimic the hydrologic regime of natural wetlands. Almost all constructed wetlands in the UK for the treatment of urban runoff comprise SF systems, and resemble natural marshes in that they can provide wildlife habitat and aesthetic benefits as well as water treatment. The influent passes as free-surface (overland) flow (and/or at shallow depths) and at low velocities above the supporting substrates. Figure 1 shows a (3×80 m^2) linear SF design which has been retrofitted into a widened stream channel in Dagenham, East London to treat surface runoff from a 440 ha residential and commercial area (Scholes et al., 1999).

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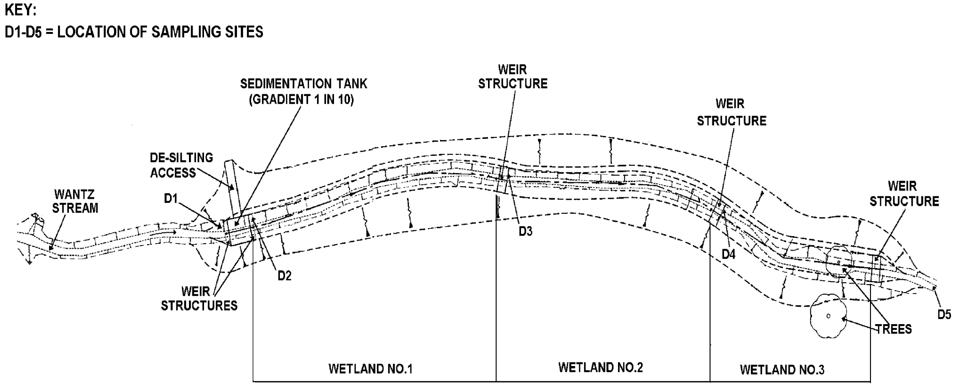

Figure 1: SF constructed wetland design (R Wantz, Dagenham, E London).

The 1,750 m^2 modular wetland system is designed to meet 50% removal efficiencies for targeted pollutants (BOD, Pb, Zn and SS). SF/FWS systems with low flow rates are susceptible to winter ice-cover in temperate climates such as the UK, and have reduced efficiencies during such times since effective water depth and retention time are reduced (Kadlec & Knight, 1996).

Sub-surface flow (SSF) systems operate with the influent flowing below the surface of the soil or gravel substrate. Purification occurs during contact with the plant roots and substrate surfaces, which are water-saturated and can therefore be considered to be oxygen-limited. The substrate in these systems is thermally insulated by the overlying vegetation and litter layer thus the wetland performance is not significantly reduced during the winter. Most of the earliest wetland treatment systems in Europe were SSF systems constructed to treat domestic wastewater. There are two basic flow configurations for SSF wetlands:

Horizontal flow (HF) systems where the effluent is fed in at the inlet but then flows slowly through the porous medium (normally gravel) under the surface of the bed in a more or less horizontal path to the outlet zone. These HF systems are also known in the UK as reedbed treatment systems (RBTS) as the most frequently used plant is the common reed (*Phragmites australis*).

Vertical flow (VF) systems, which usually have a sand cap overlying the graded gravel/rock substrate, and are intermittently dosed from above to flood the surface of the bed. The effluent then drains vertically down through the bed to be collected at the base. Such VF systems are similar in design and operation to conventional percolating filters, but are very rarely found on surface water drainage systems.

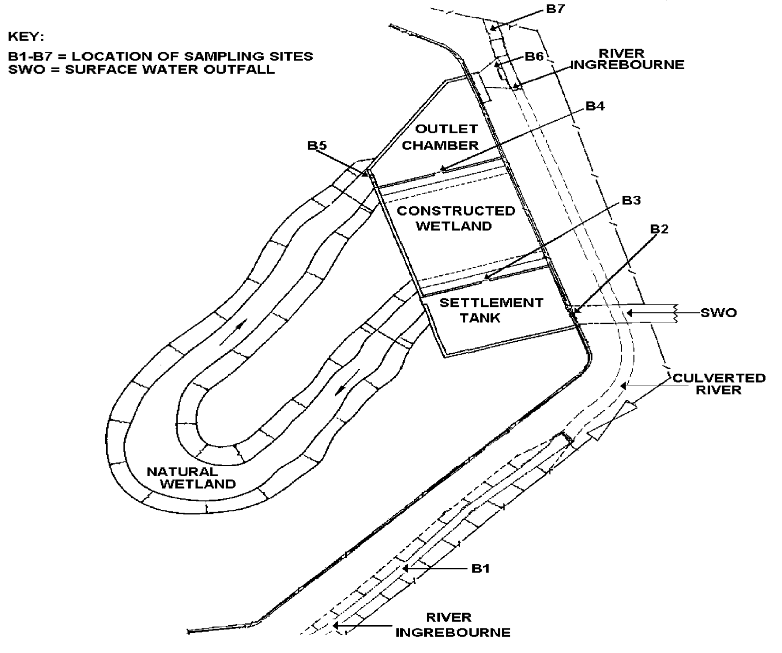

Figure 2: An SSF constructed wetland (Brentwood, Essex).

Fig. 2 illustrates an SSF constructed wetland system located at Brentwood, Essex to treat surface water discharges from a 400 ha mixed urban catchment prior to entry into the River Ingrebourne. During high flows, untreated effluent also overflows into a natural *Typha* wetland in addition to passing through the SSF *Phragmites* wetland before final discharge to the river. The total wetland area is 204 m^2 and the mean retention time is 50 min. Dry weather removals average 30–33% for Pb and Cu, 19% for Zn, 18% for SS, 26% for BOD and 50% for total ammonia with mean metal sediment removals varying between 17 and 33% (Revitt et al., 1999).

20.1.1. Pollutant Removal Efficiency of Constructed Wetland Systems

Table 1 summarises the averages and ranges of removal percentages for various pollutants calculated from the data presented in Nuttall et al. (1997) for constructed wetlands treating domestic wastewater (negative values denote negative efficiencies). The percentage removal efficiency is in most cases simply defined as: $(C_{in} - C_{out})/C_{in} \times 100$, where C_{in} and C_{out} are the inflow and outflow

Table 1: Percentage pollutant removals for domestic wastewater and artificial stormwater wetland systems in the UK.

	SS	BOD	NH_4-N	NO_3-N	*E. coli*
Domestic wastewater					
Secondary treatment	83	82	18	45	68
	(69–94)	(70–92)	(5–29)	(7–68)	(60–75)
Tertiary treatment	68	71	33	55	84
	(25–92)	(50–95)	(0–77)	(40–76)	(46–99)
Urban runoff					
Wetlands	76	24	31	33	–
	(36–95)	(−57 to 81)	(0–62)	(−17 to 68)	(52–88)
Combined retention/	73			53	92
detention basins	(13–99)			(10–99)	(86–99)
Wet (retention) ponds	55	40		29	
(with marginal vegetation)	(46–91)	(0–69)		(0–80)	
Extended detention basins[a]					
Highway runoff					
Wetlands (combined	–	18		–	–
retention/detention)	(50–70)	–		(10–20)[b]	(50–90)
SF wetlands	–	15		45[b]	82
SSF Wetlands	(13–75)	(5–32)		(10–60)[b]	(75–99)
	73			53[b]	92
	(13–99)			(10–96)[b]	(86–99)
	85			44[b]	88
	(62–97)			(25–98)[b]	(80–97)

[a] From US data (Urban Drainage & Flood Control District, 1992).
[b] Data for Total Nitrogen.

pollutant concentrations, respectively. The table also shows summary data that have been recorded in the UK for wetland systems receiving urban and highway runoff (Ellis, 1991, 1997; Ellis & Revitt, 1991, 1994; Cutbill, 1994; Cooper et al., 1996). The data for extended detention basins are taken from US data UDFCD (1992) as there are no comparable data recorded for UK sites. The equivalent data for metal removal efficiencies (with ranges shown in brackets and negative values denoting negative efficiencies) that have been noted for various types of surface water wetland systems (Cutbill, 1994; Ellis et al., 1994; Mungur et al., 1995; Ellis, 1999; Heal, 1999; Revitt et al., 1999; Scholes et al., 1999; Halcrow/UPRC, 2000; Revitt & Ellis, 2000) are presented in Table 2.

Although the data exhibit very large ranges, it is clear that artificially constructed wetlands perform better than natural systems, and there is substantial evidence that water and suspended sediment metal concentrations are reduced in urban stormwater wetlands (Shutes et al., 1993; Cutbill, 1994; Hares & Ward, 1999). Some possible concern has been expressed over the ability of urban wetlands to sufficiently remove cadmium, with recorded storm outflow rates frequently exceeding the European Union/Environment Agency for England and Wales water quality standard of 5 μg/l (Revitt et al., 1999; Pontier et al., 2001; Sriyaraj & Shutes, 2001).

A review of a number of studies in the US and Europe suggested that maximum pollutant removal can be achieved in a pre-settlement pond which is equivalent to some 10–15% of the total wetland cell volume (Ellis, 1991). Constructed wetlands in the Environment Agency Midlands Region utilise a stilling pond and sedimentation trap of $10\,m^3$ capacity to capture influent stormwater debris/litter, grit and oiled sediment. This front-end basin can also serve as a back-up spillage containment facility. If sufficient land is available, a final settlement tank (concrete structure) with a minimum capacity of $50\,m^3$ extending across the width of the wetland can be installed. The tank will help prevent fine sediment from the wetland being transferred into the receiving water body. The final settlement tank is an idealised part of the overall system and only needs to be included in the overall design where greatest protection to sensitive receiving waters is required. Regular maintenance is recommended to prevent collected sediments being resuspended during high flows. The rate of sediment deposition will vary with each catchment so the frequency of sediment removal cannot be predicted. Annual inspections should be made to determine if sediment removal is required.

A review of the data reported from international studies broadly confirms the findings arising from the UK wetland database. The results from 26 studies conducted on constructed urban wetland systems in the US have been analysed (Strecker et al., 1992). Although good to high pollutant removal efficiencies were observed, the analysis identified the inherent random nature of the performance data with the absence of any meaningful direct relationships between performance and catchment parameters (Table 3) or with basin/runoff volumes. However, the WWAR and DAR values (see notes below Table 3), are very close to those recommended by European workers who have advocated for example, WWAR ratios of 2–3% and wetland basin volumes (V_b) equal to 4–6 times the mean storm runoff volume (V_r), (Hvitved-Jacobsen, 1990; Ellis, 1999).

Preliminary testing of the US EPA National Stormwater Standardised BMP Database confirms this variability that appears to characterise urban wetland performance (UWRRC & URS, 1999). Table 4, which has been calculated from this 1999 US EPA Database, suggests that this variability is independent

Table 2: Wetland metal removal efficiencies for natural and artificial wetlands in the UK.

	Metals		**Cadmium**	**Lead**	**Zinc**	**Copper**
	Total	**Dissolved**				
Natural wetlands			(−38 to 50)	(−50 to 82)	(−60 to 30)	(10–78)
Artificial wetlands						
Urban runoff						
Wetlands			–	62	57	51
			(5–73)	(6–70)	(−36 to 70)	(10–71)
Combined retention/detention basins			–	–	–	–
			(10–30)	(0–28)	(3–22)	(0–10)
Highway runoff						
Wetlands	–	–	–	69	42	–
	(40–90)	(−15 to 40)	(20–72)	(−41 to 89)	(−36 to 71)	(36–66)
Wet retention basins	–	–		52	38	
	(45–85)	(10–25)		(40–56)	(8–56)	
ED basins	–	–				
	(20–50)	(0–5)				
Dry detention basins (with infiltration)	–	–				
	(70–90)	(10–20)				

Table 3: Reported removal rates for US stormwater constructed wetlands.

	Pollutant removal rates (%)					**WWAR**	**DAR**
	SS	**NH_3**	**TP**	**Pb**	**Zn**		
Median	80.5	44.5	58.0	83.0	42.0	3.65	31.0
CV	27.7	49.4	48.5	56.1	38.8	94.6	156.2
Average	77.1	39.7	57.2	63.8	48.7	4.26	131.0

WWAR, % ratio of wetland surface area to catchment area; DAR, drainage area ratio; CV, coefficient of variation.

of the wetland flow system used although for solids and solids-related pollutants, SSF systems tend to perform better than SF systems.

However, retrofitted "packed bed" SF constructed wetlands in urban flood detention basins in Florida, City of Orlando (1995), have given consistently good pollutant removal rates for SS (78–90%), total nitrogen (63–70%), total phosphorus (62–82%) and total metals (55–73%). Similar horizontal SF wetland retrofitting on 24 sites in the Melbourne urban area of Australia has been successful in reducing pollutant outflow concentrations from detention basins and in improving downstream habitat status whilst maintaining existing flood attenuation capabilities (Wong et al., 1998). Studies in the Sydney region (Shatwell & Cordery, 1999), have indicated average retention in urban SF wetlands of 80 and 60% for SS and Total P, respectively, during small- to medium-sized storm events, but with very variable (and even negative) performance occurring during intense and/or large events.

Table 4: Removal rates for US stormwater SSF and SF wetlands.

	SS (%)	**Total N (%)**	**Total P (%)**	**Faecal coliforms (%)**
SSF systems				
Average	85.4	44.6	50.4	88.5
Range	67–97	25–98	20–97	80–97
SF systems				
Average	73.3	63.3	50.2	92.5
Range	13–99	1.6–99	7–98	86–99

20.2. Experimental Constructed Wetland Studies

20.2.1. Highway Runoff Wetland Treatment Study

The A34 Newbury Bypass in the UK is a 13.5 km porous asphalt surfaced dual carriageway which opened in November 1998. The drainage system includes a series of nine vegetated balancing ponds located adjacent to the highway. Each balancing pond incorporates a front-end oil interceptor and rectangular concrete sediment trap followed by a grassed slope to deliver the highway runoff to the treatment system. A vegetated pond exists as originally designed with a sloping profile which is able to support a variety of fringing macrophytes in the shallows with the predominant species in the main water body (depth: 0.05–1.0 m) being *Phragmites australis*. The original design of a second balancing pond has a constructed wetland which was amended by retrofitting to produce a SSF wetland containing a gravel substrate preceded by a small settlement pond. The constructed wetland was planted with both *Phragmites australis* (front half) and *Typha latifolia* (final half).

Both systems have been assessed by collecting inlet and outlet grab samples during wet and dry weather conditions and automatically controlled storm event samples have been obtained for the constructed wetland (Shutes et al., 2001). Removal efficiencies for suspended solids, Cd, Cr, Cu, Ni, Pb, Zn, nitrate and sulphate for the constructed wetland are shown in Table 5 for the trends observed

Table 5: Comparison of median and dry wet weather removal efficiencies for the constructed wetland.

Parameter	**Median dry weather removal efficiency**	**Median wet weather removal efficiency**
Cd[a]	0.0	84.7
Cr	47.2	42.8
Cu	4.0	−40.3
Ni	72.6	77.5
Pb	0.0	9.1
Zn	5.3	66.2
SS	9.7	57.7
NO_3[a]	5.3	65.5
SO_4	−5.4	44.1

[a] Indicates that the wet removal is significantly better than the dry removal (Mann–Whitney test).

under different weather conditions. The large variabilities in the removal efficiencies derived for both treatment systems, based on the analyses of grab samples, make accurate comparisons of the performances difficult and also raise concerns about using this type of sampling approach for this purpose. Treatment systems are required to function satisfactorily during the increased inlet loadings experienced during storm events, and this is shown to be the case for the constructed wetland for the majority of the monitored pollutants. Despite the existence of performance fluctuations, the generally low levels of inlet concentrations in the highway runoff indicated that the pond discharges did not threaten the environmental quality of the receiving waters.

Chromium and nickel appear to be removed equally well during both types of weather conditions, with Pb showing similar but poor removal performance during dry and wet conditions. In contrast, Cd and nitrate are removed more efficiently during storm events when the data are examined using the Mann–Whitney test, this difference is shown to be significant ($p < 0.05$). There is a similar emphasis on more favourable removal under wet weather conditions for Zn, suspended solids and sulphate although in each of these cases the comparison with dry weather conditions is not significantly different. Only Cu is predicted to have a higher removal during dry weather conditions and this is a consequence of the unexpected behaviour previously described for Cu during storm event monitoring.

The considerations described above assume that the analysis of grab samples obtained simultaneously from inlet and outlet positions during dry weather conditions can be compared directly to storm event monitoring. Ideally, a series of time-based inlet samples should have been collected and compared with similarly obtained outlet samples taking into account the residence time of the constructed wetland under dry conditions. This would have provided a direct comparison between the performances during the two types of extreme weather conditions. In the absence of such a comparison an explanation of the results is not straightforward. Thus, the indicated preferred removal of the two monitored nutrients (nitrate and sulphate) during wet weather would not have been expected as more time for plant uptake would be available during dry conditions and a previous study of the performance of a constructed wetland treating urban runoff has suggested that nitrate removal occurred primarily between, rather than during, storm events (Carleton et al., 2000). Similarly, the settling out of suspended solids should be more efficient under quiescent conditions whereas a higher removal during storm events is predicted by the results. However, this phenomenon is partly a function of the inlet suspended solids concentrations which did not exceed 20 mg/l for routine monitoring but regularly approached 100 mg/l during storm runoff conditions.

Lead is commonly found to be strongly associated with particulate material (Revitt & Morrison, 1987), but the absence of a marked inlet concentration difference between dry (maximum 4.5 μg/l) and wet (maximum 10.1 μg/l) weather conditions results in a median removal efficiency value (9.1%) for the latter conditions which is only slightly higher than the dry weather value (0.0%). Cadmium is the most effectively removed metal during storm events and is most significantly different from the obtained dry weather results ($p < 0.05$; Mann–Whitney test). This finding is again unexpected given the predicted high solubility of Cd in highway and urban runoff (Revitt & Morrison, 1987). Metal removal by a constructed wetland receiving highway runoff can generally be seen to be efficient during carefully designed storm event monitoring conditions (Table 5) with only Cu showing an aberrant behaviour and Pb demonstrating a small positive removal.

The results highlight the limitations of utilising analysed grab samples as the basis for estimating pollutant removal efficiencies between the inlet and outlet of a water treatment system. This is particularly true in wet weather although the automatically controlled sampling of storm events show good pollutant removal in the constructed wetland. There is only a marginal improvement when dry weather conditions prevail both before and during sampling on account of the low inlet concentrations. At such low inflow concentrations, it is difficult to achieve any enhanced removal effectiveness as they represent the minimum or "irreducible pollutant concentrations" (IPC). Such background concentrations (IPC) represent the best performance treatment that can be achieved under low flow conditions and may not be further reduced even if the wetland surface area or volume is increased. Fig. 3 illustrates the range of performance that can be achieved with very variable and even negative efficiencies being associated with inflows (C_0) at or near the background irreducible concentration levels (C^*).

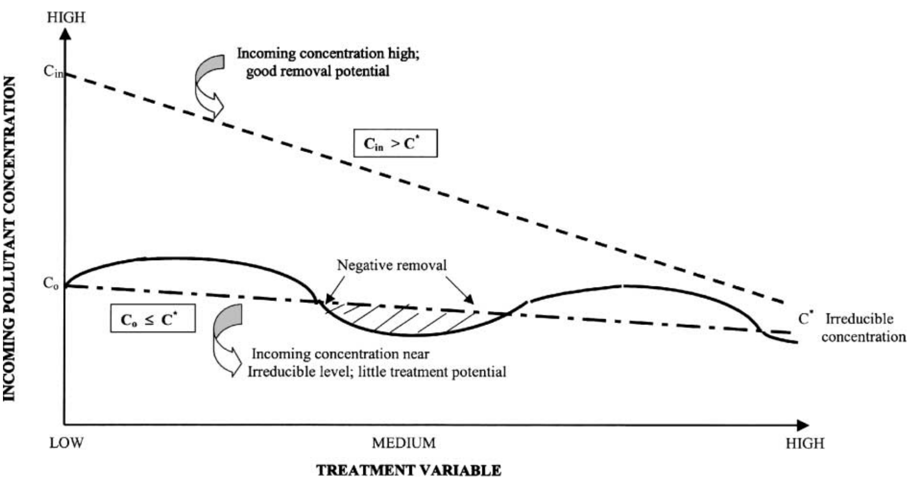

Figure 3: Treatment performance as a function of incoming concentrations.

20.2.2. Small-Scale Experimental Hydrocarbon Treatment Study

The use of constructed wetlands is not yet widely adopted for the treatment of hydrocarbon effluents (Salmon et al., 1998). A monitoring study by Farmer & Roberts (1995) showed 94% removal of oil and grease from cascading ponds colonised by *Typha* spp. and *Scirpus* spp.

The performance of a small-scale constructed wetland for the treatment of oil polluted water was assessed in comparison with an unvegetated system using two outdoor SSF beds (control and experimental, $10 \times 1\ m^2$) filled with a substrate of pea gravel (3–6 mm) to a depth of 60 cm (Omari et al., 2003). The experimental

Table 6: Hydrocarbon removal efficiencies in the top, middle and bottom depths of the experimental and control beds.

	Experimental system			**Control system**		
	Top	**Middle**	**Bottom**	**Top**	**Middle**	**Bottom**
June 1999	60.7	64.2	55.2	57.6	53.2	48.9
Overall	60.0			53.2		
July 1999	72.0	67.5	58.0	63.9	57.3	50.5
Overall	65.8			57.2		
August 1999	91.8	88.8	82.0	88.3	78.0	58.6
Overall	87.5			75.0		
September 1999	85.4	80.2	79.6	84.2	80.5	69.3
Overall	81.7			78.0		
June 2000	78.6	75.5	69.8	71.7	67.7	66.0
Overall	74.6			68.5		
July 2000	83.2	80.2	73.5	78.4	70.9	69.1
Overall	79.0			72.8		
August 2000	89.8	87.2	82.5	81.6	83.4	78.4
Overall	86.5			81.1		
September 2000	74.5	70.7	67.2	71.1	65.9	63.9
Overall	70.8			66.9		
December 2001	85.1	87.9	76.6	54.3	64.7	65.5
Overall	83.2			61.5		
Average overall	80.1 $\pm$ 9.8	78.0 $\pm$ 9.1	71.6 $\pm$ 10.0	72.3 $\pm$ 11.9	69.1 $\pm$ 10.3	63.4 $\pm$ 9.4

bed or small-scale constructed wetland was originally planted with *Typha* seedlings at a density of 7.5 plants/m^2.

Both beds (experimental and control) were treated with the same aqueous concentrations of diesel oil under identical dosing conditions. The average overall hydrocarbon removal efficiencies at the three monitored depths (top, middle and bottom) in the sub-surface systems were 80.1 $\pm$ 9.8%, 78.0 $\pm$ 9.1% and 71.6 $\pm$ 10.0% in the experimental bed, and 72.3 $\pm$ 11.9%, 69.1 $\pm$ 10.3% and 63.4 $\pm$ 9.4% in the control bed (Table 6). The differences in the hydrocarbon removal efficiencies between corresponding months in 1999 and 2000 were statistically analysed and are generally not significant.

The individual hydrocarbon removal efficiencies exceeded 60% in the top sections of both beds except for C-11 and C-25, with C-23 and C-26 also reduced in the control bed (Fig. 4). Overall differences in the removal efficiencies of the planted and the unplanted beds as well as at different depths in both systems, indicate that *Typha*-related removal processes complementing adsorption onto the gravel substrate are occurring.

The results of these two studies of experimental constructed wetlands for highway runoff and diesel oil treatment highlight the need for appropriate and standardised methods of wetland system data collection in terms of sampling equipment, timing and frequency and the location of sampling collection points. Valid comparisons can then be made between the pollutant removal performance of different wetland treatment systems.

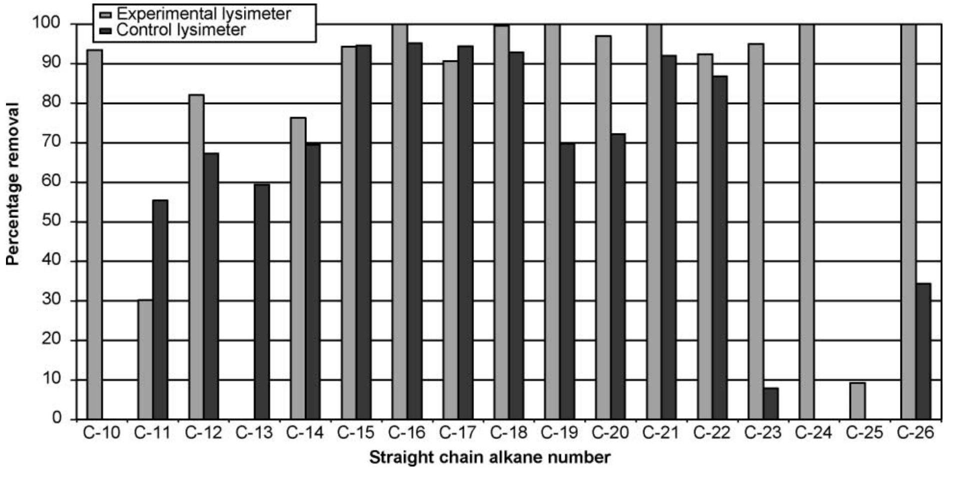

Figure 4: Hydrocarbon removal efficiencies after dosing at the top levels in the experimental lysimeter.

20.3. Urban Wetland Design

The successful design of constructed wetlands for urban surface runoff management requires the adoption of an integrated multi-disciplinary approach as performance criteria are difficult to set given the inherent random fluctuations in discharge and pollution loadings which characterise stormwater runoff. This temporal and spatial variability makes it difficult to define retention time and hydraulic loading, and thus general design rules for urban stormwater wetlands have been developed from empirical performance data and using "single-number" techniques such as drainage area ratio (see Table 3). Thus no UK urban stormwater constructed wetlands are alike in every design respect: a feature readily confirmed from site inspections.

Consideration of water quality issues at the preliminary planning stage can help to mitigate or prevent stormwater management problems in urban catchments and reduce the magnitude and difficulty of surface water treatment. Hydrological effectiveness reflects the competing (and sometimes conflicting) factors of retention time, inflow characteristics and storage volume, and defines the long-term percentage of catchment runoff which enters the wetland basin. Hydraulic efficiency is strongly influenced by basin shape and depth; hydraulic structures such as inlets, outlets and berms; and by the type, extent and distribution of wetland vegetation. Wetland plants are adapted to specific wetting and drying cycles which also significantly influence the organic content and nutrient cycling in the basal sediments. A major factor in determining wetland hydro-cycling (and the overall treatment efficiency) is the interaction between catchment hydrology, basin bathymetry and the hydraulic behaviour (and location) of the outlet structure.

20.3.1. Design Criteria

The most important criterion for the design of a constructed wetland is the selection of the design storm and this in turn determines the wetland size and volume. The objective of the selection process is to determine the critical storm event causing the greatest pollution threat, with this storm event being described in terms of its duration, intensity and frequency of occurrence. In this analysis, it is assumed that the selection process will be based upon single rather than multiple event occurrences. Constructed wetlands can be designed to:

- Retain short duration storms (e.g. less than the 1:1 annual storm event) for the maximum retention time, ensuring that the high flows can be accommodated by the constructed wetland without overland flow in the case of SSF systems or

short-circuiting in the case of SF systems. For example, a wetland basin sized to capture 90% of the average annual runoff with a 24-h drawdown would be likely to overflow between 3 and 8 times per year. This would suggest that a feasible design storm for water quality control purposes might be in the order of a 2–4 month storm event.
- Retain longer duration storms ensuring that the initial first flush volume (equivalent to 10–15 mm effective rainfall runoff) containing the heaviest pollution loads receives adequate treatment. It is important that the constructed wetland is large enough to capture the first flush of the larger storm events in order to achieve such partial treatment and to delay outflow discharges to the watercourse, via the wetland and an overflow bypass system, until natural dilution flows have risen.

Where the availability of land and finance is not problematic, the constructed wetland should be designed to treat storms with a return period of 10 years, although the design of attenuation could be up to the 100-year return period. If a compromise is necessary requiring a design based on a shorter return period, the system should be capable of treating the polluted first flush of any storm event. Retention time is an extremely important factor in the treatment performance by constructed wetlands, and even a minimum retention time of only 30 min will help to remove the coarse sediment fractions. Considerations affecting the retention time include the aspect ratio (width: length), the vegetation, substrate porosity and hence hydraulic conductivity, depth of water, and the slope of the bed. Water level and flow control structures, for example flumes and weirs are also required to keep the hydraulic regime within desired parameters. An "ideal" retention time is dependent on the pollutant removal processes operating in the wetland system. Solids sedimentation can be achieved relatively quickly, and a 3–5 h retention will remove a substantial proportion of the coarse solids. However, in order to achieve removal of degradable organics, bacteria and other toxic species associated with the finer solids fractions, much longer retention periods of at least 24 h will be required (Shutes et al., 1997; Halcrow/UPRC, 1998, 2000;). When calculating the retention time in a SSF constructed wetland system, the volume of the bed media must also be taken into account.

20.3.2. Wetland Sizing

The principal problem of wetland design for the treatment of urban and highway runoff is that of optimum sizing given the episodic and random nature of discharge occurrence and the possibility of a rapid succession of inflow events. Sizing is crucial in controlling both the hydraulic loading and retention times needed to give maximum contact and biofiltration/uptake opportunities. The pollutant removal efficiency of an urban stormwater wetland will be directly affected by the frequency, spacing and duration of storm events, all of which are extremely difficult to pre-define. This explains why empirical approaches to the sizing of urban wetlands have been widely adopted. The utility and appeal of such approaches lies in their ability to provide a rapid and robust initial screening methodology for potential wetland alternatives at the early design stages but considerable caution must be exercised in extending them to final design (Kadlec, 2000).

One such approach is to consider the relative percentage of the contributing catchment area or connected impervious area and typically figures of between 1 and 5% have been suggested by Strecker et al. (1992) and Ellis (1999) for this wetland/watershed area ratio (WWAR). Assuming a 2–3% WWAR value, for a 10 ha development site and with retention times equal to 4–6 times the mean storm runoff volume:

$$\text{Surface area} = 100{,}000\ \text{m}^2 \times 2/100 = 2{,}000\ \text{m}^2$$

$$\text{Retention volume} = 10 \times 100 = 1{,}000\ \text{m}^3$$

$$\text{Average wetland depth} = 1{,}000\ (\text{m}^3)/2{,}000\ (\text{m}^2) = 0.5\ \text{m}$$

Such sizing criteria would pose considerable land-take difficulties and in any case does not account for any performance considerations.

Nevertheless, it has been shown that such an approach derives hydraulic loading rates (HLR) which are equivalent to the range of HLR values quoted in the national US database (NADB) for point-source SF treatment wetlands (Kadlec & Knight, 1996). They state that as the average annual HLR is close to the mode of the distribution of point-source wetland HLRs, it is reasonable to expect that stormwater wetlands designed using WWAR criteria would perform somewhere near the average quoted for the emergent marsh database set in the NADB. In addition, comparison of the 50 point-source NADB wetland data set with that of 17 urban SF constructed wetlands included in the review by Strecker et al. (1992) for the US Environment Protection Agency, showed very similar efficiency rates when examined on the basis of such empirical design criteria. The mean reduction of total phosphorus in the NADB marsh cells was 57% at an average HLR of 42 mm/day compared to a similar mean reduction of 57% for urban SF constructed stormwater marshes having a 4.3% WWAR value. The equivalent reduction rates for total SS were 81 and 77.1% for the NADB and US EPA wetlands, respectively.

Stormwater wetlands have also been sized to retain water volumes associated with storm events of a specified return period or probability of occurrence. It has been proposed that urban stormwater wetlands should be sized to contain effective runoff up to the 90th percentile value of the design storm event distribution

(Scheuler, 1992). This particular “single-number” design approach has the advantage of allowing a variable percentage of contributing catchment, depending upon the annual rainfall pattern and annual rainfall total. As in the case of the WWAR ratio approach (see above), the derived loading and detention times for SF urban constructed wetlands correspond well with the mean values for point-source treatment wetlands. This is implicitly acknowledged in the listing of pollutant reductions which lie in the mid-range for other types of treatment wetlands, e.g. total phosphorus and total SS removals are quoted as 45 and 69% compared to the 57 and 81% mean cited for the NADB wetland marshes (Scheuler, 1992).

In addition to the design storm and retention time, the following criteria are also recommended:

Aspect ratio (width:length) : 1:4–1:5
Slope of Wetland Bed : 1%
Minimum substrate bed depth : 0.6 m
Hydraulic conductivity of substrate : 10^{-3}–10^{-2} m/sec

Once the design storm and retention time choice has been made, the size of the conceptual constructed wetland can be calculated using Darcy’s Law and the above criteria as:

$$\text{Average daily flow rate } (Q_\mathrm{d};\ \mathrm{m^3/sec}) = \mathrm{A_c} \times k_\mathrm{h}(\partial H/\partial x)$$

where $\mathrm{A_c}$ is the cross-sectional area of the bed, k_h is the hydraulic conductivity of the substrate (m/sec) and $(\partial H/\partial x)$ is the slope or hydraulic gradient of the bed (m/m). Darcy’s Law assumes laminar uniform and constant flow in the media bed and clean water. In an SF wetland, flow will be channelled and short-circuited and the media will be covered with biological growths, and therefore the equation has only limited usefulness in such wetland design. Nevertheless Darcy’s Law does provide a reasonable approximation of flow conditions in SSF constructed wetland beds if moderate sized gravel (e.g. 10 mm pea gravel) is used for the support medium. Fig. 5 provides a schematic section through a SSF constructed wetland illustrating some of these design criteria.

20.3.3. Optimal Hydraulic Loading

During storm events, high rates of stormwater runoff may discharge onto constructed wetlands, but optimal HLR should not exceed 1 m^3/m^2/day in order to achieve a satisfactory treatment (Ellis, 1991). It has been suggested that an arbitrary HLR breakline appears to be about 2.7 ha catchment area/1,000 m^3 storage volume/day, with wetlands having a large area per flow unit (a lower loading

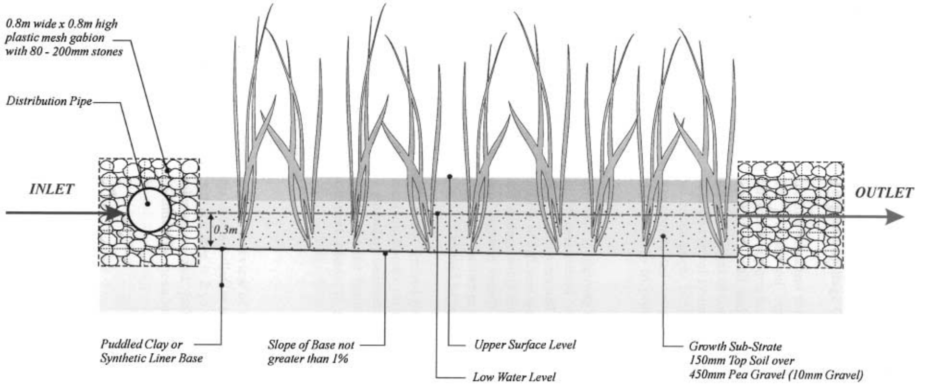

Figure 5: Section through subsurface constructed wetland.

rate) being normally SF systems and smaller areas (with higher loadings) associated with SSF systems (Watson et al., 1989).

20.3.4. Flow Velocity

Flow velocity should not exceed 0.3–0.5 m/sec at the inlet zone if effective sedimentation is to be achieved. At velocities greater than 0.7 m/sec, high flow may damage the plants physically and cause a decline in system efficiency. The inlet pipe should be constructed in such a way that influent flow is evenly distributed across the width of the bed. The level at which the outlet is set is determined by the lowest water level required in the constructed wetland. An additional source of water may be needed to supply the reedbeds during dry periods. Ideally the outlet structure should incorporate control measures which allow the water level in the bed to be varied; a flexible plastic pipe linked to a chain is an appropriate low cost option (Cooper et al., 1996).

An aspect ratio (length:width) of 4:1–5:1 for SSF wetlands and 10:1 or higher for SF wetlands has been recommended for domestic wastewater treatment wetlands. However, any aspect ratio with a good inlet distribution can be applied (IWA, 2000) as previous assumptions that wetlands with high aspect ratios would function more efficiently and be closer to plug flow have not been confirmed from tracer studies. Problems of short-circuiting can be minimised by careful construction, intermediate open-water zones for flow distribution, and the use of baffles and islands.

A grid of slotted plastic pipes (say diameter of 100 mm) should be installed vertically in the substrate (100 mm protruding above the surface, and penetrating the full depth of the substrate) at 5 m centres, to serve as static ventilation tubes and aid aeration of the root zone. Plastic poles should be erected to support lines of bunting to discourage birds from feeding on young plants. The height of the bunting should be about 1.5 m above the substrate surface. Non-metallic items should be incorporated into the construction of the wetland so that metals in the wetland only come from stormwater runoff. Therefore gabions should be encased with geotextiles and the poles supporting bunting should be plastic.

20.3.5. Substrate Structure

Horizontal SF wetlands utilise a natural soil substrate to provide organics and nutrients for plant growth, whereas SSF wetland substrates should primarily provide a good hydraulic conductivity. Nutrient supply can be supplemented to the SSF if required. A combination of organic and clay-based soils, sand, gravels and stones are used in SSF constructed wetlands to provide support for plants, reactive surfaces for complexing of ions and other compounds, and attachment surfaces for microbes which directly or indirectly utilise pollutants. The type of substrate used will have an effect on the hydraulic conductivity and efficiency of the constructed wetland, and must allow for a sufficiently high hydraulic conductivity to enable wastewater to flow at a sufficient rate for treatment without backing up and causing overland flow.

20.3.6. Planting Considerations

Constructed wetlands have traditionally utilised plant species commonly occurring in water bodies and watercourses, which were known to thrive in nutrient-rich situations and were generally pollutant tolerant. The main plant species utilised in sewage wastewater treatment has been the common reed (*Phragmites australis*), which led to the systems being known as RBTS. Reedmace (*Typha latifolia* and *Typha angustifolia*) has been increasingly used, both in sewage-derived wastewater treatment and particularly in the treatment of surface runoff and industrial effluents. Other plant species have played a lesser role in wastewater treatment, such as flag iris (*Iris pseudacorus*), bulrush (*Schoenoplectus* spp.) and sedges (*Carex* spp.).

It is recommended that vegetation for stormwater wetland treatment systems should be selected using the following criteria:

- a rapid and relatively constant growth rate;
- high biomass, root density and depth;
- ease of propagation;
- capacity to absorb or transform pollutants;
- tolerance of eutrophic conditions;

- ease of harvesting and potential of using harvested material;
- growth form (visual appearance);
- ecological value; and
- local retail (or nursery) availability.

20.3.7. Pre- and Post-treatment Structures

Traditional pollution control measures for urban and highway stormwater runoff in the UK have included grit and oil separators for the reduction of sediments and hydrocarbons. They are, however, inefficient in removing the majority of the pollution load and the finer and more mobile sediments and solid-associated pollutants including oil (which clog some designs of constructed wetland treating road runoff). Integrated pollution control systems including a combination of oil separators, silt traps/infiltration trenches, spillage containment facilities and wetland-forebays or lagoons, located prior to the constructed wetland cell(s), can provide for pre-treatment of raw stormwater runoff and help to prevent siltation in wetland inlet zones (Fig. 6) (Halcrow/UPRC, 1998; Shutes et al., 1999; Ellis et al., 2003).

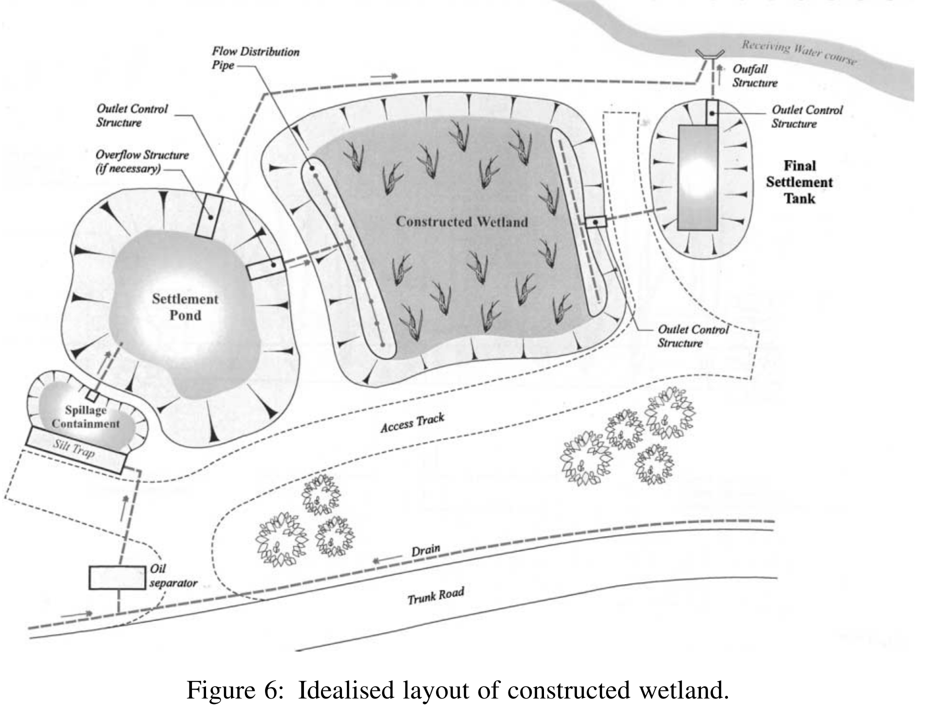

Figure 6: Idealised layout of constructed wetland.

20.4. Conclusion

The current focus on the development of sustainable urban drainage systems (SUDS) in many countries has raised awareness of the advantages of integrating constructed wetlands into urban and highway runoff treatment systems. However, it is essential that the criteria for the selection and design of constructed wetlands are rigorously applied, in order to maximise their pollution treatment performance and maintain and enhance their status as a valuable treatment option.

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References

Carleton, J. N., Grizzard, T. J., Godrej, A. N., Post, H. E., Lampe, L., & Kenel, P. P. (2000). Performance of a constructed wetland in treating urban stormwater runoff. *Water Environment Research*, **72**, 295–304.

City of Orlando Stormwater Utility Bureau. (1995). *Packed bed wetland stormwater treatment system*, Final Report. Florida Dept of Environmental Regulation, Tallahassee, FL, USA.

Cooper, P. F., Job, G. D., Green, M. B., & Shutes, R. B. E. (1996). *Reed beds and constructed wetlands for wastewater treatment*. WRc, Swindon.

Cutbill, L. B. (1994). The potential for urban stormwater treatment by constructed wetlands. In: *Proceedings of the IAWQ Fourth International Conference on Wetland Systems for Water Pollution Control, Guangzhou, China* (pp. 677–686). IAWQ, London.

Ellis, J. B. (1991). The design and operation of vegetative systems for urban runoff quality control. In: *Proceedings of the Third Standing Conference on Stormwater Source Control* (pp. 1–12). Coventry University, Coventry.

Ellis, J. B. (1999). Design considerations for the use of vegetative controls for the treatment of highway discharges. In: J. B. Ellis (Ed.), *Impacts of urban growth on surface water and groundwater quality* (Publ. No. 259, pp. 357–364). IAHS Press, Wallingford, Oxon.

Ellis, J. B., & Revitt, D. M. (1991). *Drainage for roads: control and treatment of highway runoff*, Report NRA 43804/MID.012. National Rivers Authority, Reading.

Ellis, J. B., Revitt, D. M., Shutes, R. B. E., & Langley, J. M. (1994). The performance of vegetated biofilters for highway runoff control. *Science and Total Environment*, **146–147**, 543–550.

Ellis, J. B., Shutes, R. B. E., & Revitt, D. M. (2003). *Constructed wetlands and links with sustainable drainage systems*, R&D Technical Report P2-159/TR1. Environment Agency for England and Wales.

Farmer, J. M., & Roberts, P. (1995). *Constructed wetlands for treatment of terminal wastewater*, British Petroleum (BP) Internal Report.

Halcrow/UPRC. (1998). *Treatment of highway runoff using constructed wetlands: an interim manual*. Halcrow & Urban Pollution Research Centre (UPRC), Middlesex University, Environment Agency Thames Region, Reading.

Halcrow/UPRC. (2000). *Protection of the water environment using balancing facilities*, Final Field Studies Report. Halcrow & Urban Pollution Research Centre (UPRC), Middlesex University, Environment Agency Thames Region, Reading.

Hares, R. J., & Ward, N. I. (1999). Comparison of the heavy metal content of motorway stormwater following discharge into wet biofiltration and dry detention ponds along the London orbital (M25) motorway. *Science and Total Environment*, **235**, 1–3, 169–178.

Heal, K. (1999). Metals in sediments of sustainable urban drainage structures in Scotland. In: J. B. Ellis (Ed.), *Impacts of Urban Growth on Surface Water and Groundwater Quality*, Publ. No. 259. IAHS Press, Wallingford, Oxon.

Hvitved-Jacobsen, T. (1990). Design criteria for detention pond quality. In: H. C. Torno (Ed.), *Urban Storm Quality Enhancement* (pp. 111–130). American Society of Civil Engineers, New York.

IWA. (2000).In: R. H. Kadlec, R. L. Knight, J. Vymazal, H. Brix, P. Cooper, & R. Haberl (Eds), *Constructed wetlands for pollution control: processes, performance, design and operation*, Scientific & Technical Report No. 8. IWA Publishing, London.

Kadlec, R. H. (2000). The inadequacy of first-order treatment wetland models. *Ecological Engineering*, **15**, 105–119, .

Kadlec, R. H., & Knight, R. L. (1996). *Treatment wetlands*. CRC Press, Lewis Publishers, Boca Raton, FL.

Mungur, A. S., Shutes, R. B. E., Revitt, D. M., & House, M. A. (1995). An assessment of metal removal from highway runoff by a natural wetland. *Water Science and Technology*, **32**, 3, 169–175.

Nuttall, P. M., Boon, A. G., & Rowell, M. R. (1997). *Review of the design and management of constructed wetlands*, Report 180. Construction Industry Research and Information Association, London.

Omari, K., Revitt, D. M., Shutes, R. B. E., & Garelick, H. (2003). Hydrocarbon removal in an experimental gravel bed constructed wetland. *Water Science and Technology*, **48**, 5, 275–282.

Pontier, H., May, E., & Williams, J. B. (2001). Constructed wetlands for the treatment of runoff from the Newbury Bypass. *Journal of Chinese Institute of Water and Environmental Management*, **15**, 125–129.

Revitt, D. M., & Ellis, J. B. (2000). Drainage, runoff and groundwater management. In: G. Mudge (Ed.), *The Environmental Management of Highways*. Institution of Highways and Transportation, London, Chapter 4.

Revitt, D. M., & Morrison, G. M. (1987). Metal speciation variations within separate stormwater systems. *Environmental Technology Letters*, **8**, 373–380.

Revitt, D. M., Shutes, R. B. E., & Scholes, L. (1999). The use of constructed wetlands for reducing the impacts of urban surface runoff on receiving water quality. In: J. B. Ellis (Ed.), *Impacts of Urban Growth on Surface Water and Groundwater Quality* (Publ. No. 259, pp. 349–356). IAHS Press, Wallingford, Oxon.

Salmon, C., Crabos, J. L., Sambuco, J. P., Bessiere, J. M., Basseres, A., Caumette, P., & Baccou, J. C. (1998). Artificial wetland performances in the purification efficiency of hydrocarbon wastewater. *Water Air and Soil Pollution*, **104**, 313–329.

Scheuler, T. R. (1992). *Controlling urban runoff: a practical manual for planning and designing urban BMPs*. Washington Council of Governments, Washington, DC.

Scholes, L. N. L., Shutes, R. B. E., Revitt, D. M., Purchase, D., & Forshaw, M. (1999). The removal of urban pollutants by constructed wetlands during wet weather. *Water Science and Technology*, **40**, 3, 333–340.

Shatwell, T., & Cordery, I. (1999). Nutrient storage in urban wetlands. In: J. B. Ellis (Ed.), *Impacts of urban growth on surface water and groundwater* (Publ. No. 259, pp. 339–348). IAHS Press, Wallingford, Oxon.

Shutes, R. B. E., Ellis, J. B., Revitt, D. M., & Zhang, T. (1993). The use of *Typha latifolia* for heavy metal pollution control in urban wetlands. In: G. Moshiri (Ed.), *Constructed wetlands for water quality improvement*. Lewis Publishers, London.

Shutes, R. B. E., Revitt, D. M., Mungur, A. S., & Scholes, L. N. L. (1997). The design of wetland systems for the treatment of urban runoff. *Water Science and Technology*, **35**, 5, 19–25.

Shutes, R. B. E., Revitt, D. M., Lagerberg, I. M., & Barraud, V. C. E. (1999). The design of vegetative constructed wetlands for the treatment of highway runoff. *Science and Total Environment*, **235**, 189–197.

Shutes, R. B. E., Revitt, D. M., Scholes, L. N. L., Forshaw, M., & Winter, B. (2001). An experimental constructed wetland system for the treatment of highway runoff in the UK. *Water Science and Technology*, **44**, 11, 571–578.

Sriyaraj, K., & Shutes, R. B. E. (2001). An assessment of the impact of motorway runoff on a pond, wetland and stream. *Environment International*, **26**, 5–6, 433–439.

Strecker, E. W., Kersnor, J. M., Driscoll, E. D., & Horner, R. R. (1992). *The use of wetlands for controlling stormwater pollution*, Report EPA/600. The Terrane Institute, Washington DC, USA.

Urban Drainage & Flood Control District (UDFCD). (1992). *Urban storm drainage criteria manual, volume 3; Best management practices (BMP) database*. Urban Drainage & Flood Control District, Denver, CO, USA.

Urban Water Resources Research Council (UWRRC) and URS Greiner Woodward Clyde. (1999). *National stormwater best management practices (BMP) database*. Environmental Protection Agency, Office of Water, Washington, DC.

Watson, J. T., Reed, S. C., Kadlec, R. H., Knight, R. L., & Whitehouse, A. E. (1989). Performance expectations and loading rates for constructed wetlands. In: D. A. Hammer (Ed.), *Constructed Wetlands for Wastewater Treatment* (pp. 319–352). Lewis Publishers Inc., Chelsea, MI.

Wong, T. H. F., Breen, P. F., Somes, N. L. G., & Lloyd, S. D. (1998). *Managing urban stormwater using constructed wetlands*, Co-operative Research Centre for Catchment Hydrology, Report 98/7. Monash University, Victoria, Australia.