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The performance of vegetated biofilters for highway runoff control

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Abstract

The design of highway drainage in the UK traditionally has provided for the rapid removal of surface runoff from the carriageway. The most commonly used methods are through direct and positive discharges to the nearest watercourse (perhaps routed through a detention pond) or into a soakaway system. Such systems pay little attention to the potential loads generated from rainfall-runoff events or their possible impacts upon receiving waters. This paper reviews the potential use of vegetative systems as appropriate control measures for highway discharge pollution and discusses design options. The uptake of total petroleum hydrocarbons (TPH), lead and zinc by five species of emergent macrophyte is discussed for a constructed experimental wetland receiving runoff from a large transit base and car parking area in Washington State, USA. The data suggest that *Typha latifolia* and *Sparganium* are the most suitable species for TPH, Pb and Zn uptake, storage and metabolism.

Key words: Highway runoff; Macrophyte; Wetland; Pollutant removal

1. Introduction

The specific threat of highway drainage to receiving waters traditionally has been included within the general context of urban runoff, the problems of which have been compared with those caused by secondary sewage effluents (Ellis, 1985). However, some studies have suggested that even though highways may only occupy some 5–8% of the urban catchment area, highway drainage waters can contribute as much as 50% of the total suspended solids, 16% of total hydrocarbons and between 35% and 75% of the total metal pollutant input budgets to the receiving stream (Ellis et al., 1987).

The construction of a highway within an urban catchment extensively modifies the local hydrological cycle with larger volumes of water having to be dealt with in a shorter period of time at receiving water sites close to the road. The effects are twofold and to some extent counteractive, as the increase in total pollutant load is buffered by the increased dilution volumes available. Nevertheless, the acute, slug impacts of highway surface drainage waters, as well as the chronic disturbance of downstream pollutant accumulations, can have a deleterious effect on receiving water quality and habitat (Hamilton and Harrison, 1991).

Recent work on highway runoff has dealt with its impact upon receiving water biota through the use of bioassay techniques on exposed organisms and algae (Bascombe et al., 1988). Recent studies

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have also reported on the design and effectiveness of roadside swales and flood storage basins for the control and treatment of highway runoff (Yousef et al., 1987; Ellis, 1991). In addition, there have been a number of limited studies comparing the efficiency of sedimentation tanks, lagoons and percolating filter devices for the de-oiling, de-sludging and general treatment of highway drainage (Ruperd, 1987; Stotz, 1990).

2. Vegetative systems

2.1. Pollutant removal mechanisms

Vegetated wetlands have long been employed for the treatment of municipal, industrial and agricultural effluents (Cooper and Findlater, 1990). Most of these constructed wetlands are basically derivations of the German designs originally developed by Seidel (1976) and Kickuth (1976). In these vertical and/or horizontal flow systems, macrophyte root zones become oxygen-rich microzones in an otherwise anoxic (no free oxygen but with nitrate present) or anaerobic (no free oxygen or nitrate) environment. These localised oxygen-rich root zones play an important part in the microbial process as the bacteria which proliferate in the aerobic root zone can stabilise organics in the wastewater effluent and nitrify ammonia to nitrate. As the wastewater then flows into anoxic zones within the wetland substratum, microbially mediated denitrification can convert the nitrate to nitrogen gas which is then released to the atmosphere. In simple terms, a constructed vegetative wetland can be considered as a low loaded biological feed-film filter with inbuilt sedimentation. Whilst the emergent plants absorb some of the pollutants directly, the main function of the plants is to supply oxygen to the microorganisms within the wetland. The root zone method has the additional advantage that physicochemical sediment reactions, including biochemical oxidation of organics, can also aid in the removal of pollutants from the effluent.

Although the use of both natural and artificial wetlands for the treatment of point source wastewater discharges is therefore fairly extensively documented, there is nevertheless only very limited information on the use of such facilities for treating non-point source pollution from stormwater runoff. There is general agreement on the dominant removal mechanisms operating in such vegetated systems although the relative significance of the various processes has not been satisfactorily assessed.

2.2. Wetland basins

Although there is now a considerable literature available on the use of wetlands and vegetated detention basins for quality control of urban stormwater, very few relate specifically to runoff from trafficked surfaces (Verniers and Loze, 1985; Martin and Smoot, 1988). In the context of vegetative best management practice (BMP) treatment of highway runoff, it is possibly more appropriate to seek the integration of diverse control systems in order to provide an overall effective level of performance. This could involve, for example, the integration of grassed channels and filter strips with marshlands as well as front-end sediment/oil traps and perhaps even final sand filtration. At many sites, it may be feasible to utilise a creatively landscaped wooded filter strip. Such buffer zones will not provide much storage or sufficient filtration to reduce peak discharge and pollutant flushes by any substantial amount, but they will decrease runoff velocity (and consequently the time of concentration) and may offer some contributions to groundwater recharge.

Reed bed treatment in wetland marshes and marginal perimeter zones of flood storage ponds enables biological uptake mechanisms to achieve effective pollutant removal. Although most wetland species have fairly specific water depth requirements, an optimal depth of between 100 and 150 mm needs to be regulated and maintained within the marshland micropool. At least 25–30% of the total wetland surface area should remain as a permanent water body with minimum depths of 0.5–1.0 m. This combination of shallow reedmarsh and open water provides ideal habitat opportunities for waterfowl and marshbirds and will be more aesthetically appealing. The shoreline fringe also provides a marginal safety bench and can be sown with reed canary grass (*Phalaris arundinacea*). A small rip-rap or crushed rock dam can be established near the inlet to form a sediment forebay; this will prevent the marshland plants from being choked by excessive incoming coarse silt.

3. An experimental wetland system

The work described in this paper relates to an experimental wetland system installed to receive and treat surface runoff generated from the impermeable areas of a transit operating base in Tukwila, WA, USA. The heavy vehicle transit base is operated by the Municipality of Metropolitan Seattle (METRO) and stormwater inflows from the trafficked surfaces are directed into a redesigned detention pond of 0.10 ha (Fig. 1). The inflow at the eastern end of the South Base Pond represents the major contribution from the transit base with an additional but smaller inflow at the western end having its source in the employee car parking area. The objectives of the study were to identify the pollutant removal effectiveness of emergent macrophyte species in the constructed wetland and to determine the overall suitability and growth capabilities of native wetland species in surviving and treating toxic concentrations derived from highway traffic sources.

3.1. Experimental and statistical procedures

Approximately one-third of the total area of the detention pond was planted with ten species of emergent vegetation and this was sampled on four separate occasions during 1991. The initial sampling phase in July involved collecting three replicate samples of each species together with associated soil samples. The plant samples were separated into root and shoot components and each of these was analysed for total petroleum

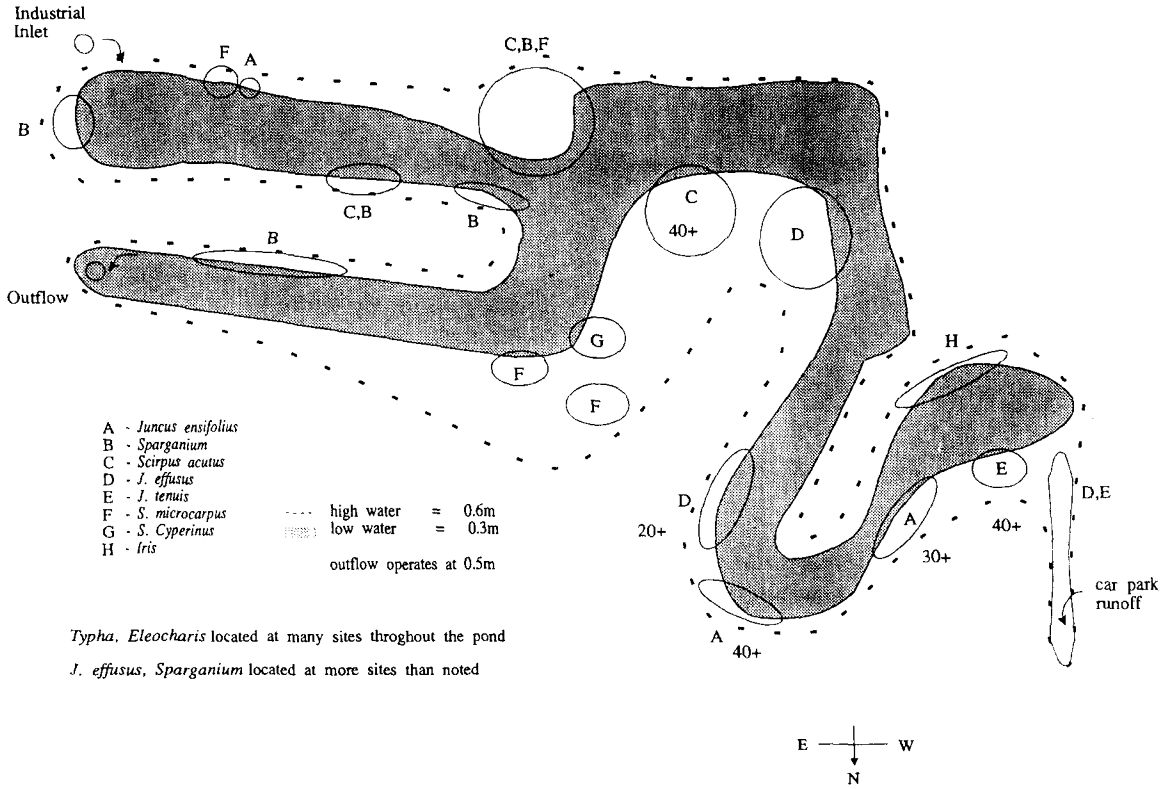

Fig. 1. Outline of South Base Pond and Location of Individual Species.

hydrocarbon (TPH), lead and zinc. Metals were determined by either graphite furnace atomic absorption spectrophotometry or inductively coupled plasma-atomic emission spectroscopy after acid extraction of the dried samples. The oil and grease components of TPH were extracted from the samples with freon (soxhlet extraction for plant tissues; ultrasonication for soils) and analysed by infrared methods.

The second sampling programme in September 1991 was revised substantially, following consideration of the initial results, by reducing the number of species analysed but increasing the number of replicate samples. The species demonstrating the greatest pollutant uptake potential in the first survey were identified to be *Typha latifolia*, *Iris*, *Scirpus acutus*, *Sparganium* and *Eleocharis*. To provide a more statistically valid assessment of the variability of the results, seven plants of each of these species (subdivided into root and shoot tissue) together with associated soil samples were collected from different locations within the pond. In addition, four replicates of each plant species together with soil samples were collected from reference control sites which were characterised by low metal and TPH inputs. These background sites were located at Lake Sammamish (for *T. latifolia*, *Iris* and *S. acutus*), Lower Cedar River (for *Sparganium*) and Pacific Wetland Nursery (for *Eleocharis*).

In the sampling survey carried out in October 1991, seven replicates of each of the identified important species and associated soil samples were collected from similar locations in the pond to those employed in the September sampling programme. Finally, in mid-November 1991, root and shoot samples from three measured areas within the pond were collected for each of the five species in order to calculate biomass per unit area values. At this late harvesting time, the biomass data will inevitably be reduced due to the presence of differing amounts of dead tissue for the various species. However, these data have been incorporated into the statistical analysis to estimate mean TPH, Pb and Zn loadings adjusted for biomass per plant matrix.

A range of statistical parameters (mean, standard deviation, variance and standard error of mean) are defined for each analyte in plant tissues and soils. Following the determination of the frequency distributions for the pollutant concentrations per matrix per plant over the experimental period, the results were log transformed to normalise the data sets so that parametric statistical tests could be performed. Analysis of variance was then used to determine the difference between the mean value of variables supported by t-tests to identify the values giving significant results.

4. Results

4.1. Pollutant uptake by plants and soil

A comparison of pond and control site data for TPH, Pb and Zn concentrations in soil, root and shoot matrices of *T. latifolia*, *Sparganium*, *S. acutus*, *Eleocharis* and *Iris* has been performed for the comprehensive data set gathered in September 1991. The soil samples collected from the South Base Pond show considerably higher TPH concentrations compared with the control sites ($P < 0.01$ or 0.05) except for soils associated with *Iris* where little difference can be observed. Zinc levels are consistently greater in the pond soil samples and this discrimination for all species other than *Iris* is strongly supported by the statistical data ($P <$ 0.01 or 0.05, Table 1) but in the case of Pb there is no clear difference between pond and control sites for soils collected with *Sparganium* (Lower Cedar River) and *Iris* (Lake Sammamish). The Pb concentrations in these soil samples are above those which would be expected to be associated with background sites.

T. latifolia showed clear evidence of greater uptake of TPH and Zn into the root or rhizosphere (root fibre + rhizome) compared with the shoot and there is evidence of enhanced pollutant accumulation at the pond site except in the case of Pb which exhibits concentrations close to the analytical detection limit for both pond and control species. The *Sparganium* tissue results indicate a pollutant enhancement at the pond site with this effect being particularly noticeable for root Pb levels, as for this metal there was no discrimination between pond and control soil concentrations. *S. acutus* demonstrates a lower pollutant accumulation ability with only shoot (TPH) concentrations

Table 1
Probability values (*t*-test) for control vs. South Base Pond samples by matrix, September 1991 data

Contaminant	Species	Soil	Root	Shoot
TPH	*Iris*	0.290	0.220	0.630
	T. latifolia	0.034	0.740	0.200
	Sparganium	0.011	0.280	0.001
	S. acutus	0.002	0.960	0.001
	Eleocharis	0.000	0.750	0.000
	Iris	0.630	0.100	Not defined
Pb	*T. latifolia*	0.460	0.390	Not defined
	Sparganium	0.630	0.002	0.230
	S. acutus	0.160	0.150	0.160
	Eleocharis	0.001	0.000	Not defined
Zn	*Iris*	0.008	0.330	0.032
	T. latifolia	0.033	0.009	0.035
	Sparganium	0.002	0.021	0.001
	S. acutus	0.002	0.790	0.001
	Eleocharis	0.004	0.021	0.000

($P < 0.001$, Table 1) showing evidence of increases in the pond compared with the control samples. *Eleocharis* appears to behave similarly to *T. latifolia* and *Sparganium* with regard to tissue uptake of TPH and Zn but the variability of the data makes conclusions difficult in the case of Pb. There is evidence for efficient and significant ($P < 0.01$) root accumulation of Pb at the pond site but shoot concentrations are consistently close to the analytical detection limit. *Iris* shows the least encouraging results with regard to pollutant uptake with only root TPH values showing evidence of elevation in the pond samples compared with those from the reference site. Both *Iris* root and shoot tissues exhibit Zn levels at the control site which are equivalent to those at the pond site and the inefficient Pb uptake is illustrated by concentration values which are at or close to the analytical detection limit.

Analysis of the pond data set for temporal variations across the July, September and October sampling dates indicates that the changes, where they exist, generally represent reductions in concentrations. These decreases in levels can be found for both soil and plant matrices, with TPH being the pollutant which most often follows this trend. The only significant difference occurs in *S. acutus* soil samples between September and October ($P < 0.05$). Soil TPH concentrations reduce markedly between September and October and in the same period shoot Zn levels fall from a mean value of > 10 mg/kg to less than the detection limit. The variations in pollutant soil levels may be due to reduced inputs into the pond or more probably a consequence of biased sampling whereas the lower plant tissue concentrations may occur as a result of reduced pollutant uptake towards the end of the growing season. In addition, there may well be biodegradation of TPH by plant and soil microorganisms.

The effect of each of the two inflows into the South Base Pond has been separately investigated by dividing the pond into two halves (East and West) at a point approximately equidistant from both inflows. Mann–Witney *U*-tests were then carried out on the soil pollutant levels in each half (Table 2). In September there was a significant difference between the soil concentration of both TPH and Zn, both being highest in the eastern half of the pond ($P < 0.001$, $P < 0.05$, respectively). This was further supported by the highest Zn and the third highest TPH determination occurring closest to the transit base inflow, suggesting that this is the most important source of TPH and Zn.

Table 2
Soil pollutant levels in Western and Eastern halves of South Base Pond

	Median level East (p.p.m.)	Median level West (p.p.m.)	Mann–Whitney *P* value
September 1991 data			
TPH	7100	620	0.0003
Pb	83	34	0.2954
Zn	220	130	0.0424
October 1991 data			
TPH	830	360	0.0564
Pb	62	32	0.0034
Zn	170	150	0.0600

No significant difference could be found between Pb levels, although again, the highest Pb level occurred closest to the transit base inflow. This may be simply due to the larger drainage area contributing to the inflow as opposed to greater deposition from vehicle emissions as most motor fuels used in the USA are lead free. The October 1991 data broadly support these trends. The technique of sampling plants from different parts of the pond was therefore essential to overcome this bias in pollutant distribution.

4.2. Comparisons of plant biomass levels between species

The results of plant biomass/unit area for root and shoot tissue material were obtained for one sampling date (November 1991). Consideration of the combined tissue data for all sampling dates clearly indicates that *T. latifolia* was the dominant species with a significantly greater total plant mass per area than any other species ($P < 0.001$ or < 0.05). *T. latifolia* also provides a greater shoot mass per area than any other plant ($P < 0.001$ or < 0.05).

The biomass differences have important implications for the total pollutant loads and mean values have been calculated for the respective root and shoot tissues (Fig. 2). *T. latifolia* is clearly the dominant species with regard to storage of pollutants in both roots and shoots. The roots have at least a four-fold capability and the shoots a two-fold capability compared with the other plant

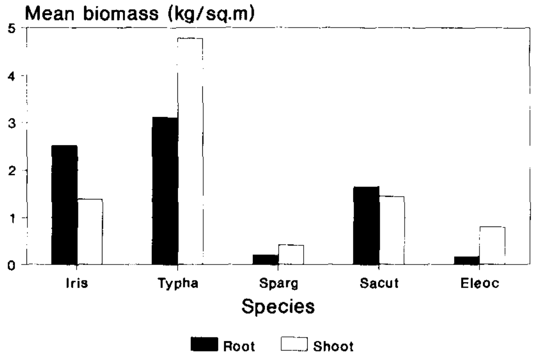

Fig. 2. Mean biomass per unit area.

species. *Iris*, which also possesses a rhizome system, and *S. acutus* roots also provide important storage capacities for TPH. For both the metals, *Sparganium* demonstrates the next most important storage capacity after *T. latifolia* in both root and shoot tissue. The shoot tissue is particularly important for *Sparganium* and this is closely followed by *Eleocharis* shoots.

4.3. Pollutant removal processes

An interpretation of the data is limited by the sampling period which was conducted during July–November and therefore excludes any reference to the winter and spring period. Pollutant uptake, particularly in the case of a soluble micronutrient such as Zn, will be reduced in parallel with slower plant growth during the winter period. A previous study has also indicated that there can be competitive interactions for plant cation uptake and this may explain some of the variations noted in Zn and Pb tissue levels during the September/October sampling period (Zhang et al., 1990). *T. latifolia*, *Sparganium* and *Iris* will show significant foliar decomposition with an associated release of contaminants into the water phase and the incorporation of detritus into the sediments during the winter. *S. acutus* and *Eleocharis*, on the other hand, have a relatively low level of foliar decomposition as confirmed by observations and measurements of tissue decay in the November 1991 data.

The period of plant establishment is only of the order of 1–2 years and is insufficient for maximum rhizome and root penetration to occur in the case of *T. latifolia*. This is an important factor influencing biofiltration efficiency, contaminant uptake rates and sediment accumulation. Furthermore, the populations of micro-organisms involved with hydrocarbon metabolism and metal uptake, which are considered to be most abundant at the aerobic/anaerobic interface, will not yet have reached their peaks. *Iris* also has a rhizome whereas the other species have relatively shallow root systems.

The initial criteria for selecting species of aquatic macrophytes for pollutant treatment removal include the surface area of the root system, the persistent sub-surface and above-ground biomass and the biomass accumulation rate. *T. latifolia* meets all but one of these criteria which therefore favours its selection for pollutant removal. The ability of *T. latifolia* to trap sediment in its rhizosphere is an additional benefit, but this can lead to a reduction of the hydraulic throughflow and pollutant removal efficiency and could have long-term management implications for locations subject to occasional high flow volumes which require efficient hydraulic routeing. The invasive vegetative spread of *T. latifolia* may out-compete other plant species whose presence may be desirable for both pollutant treatment and uptake and for the provision of a more visually varied and aesthetically pleasing environment which will attract more invertebrate and wildfowl species.

The availability of rainfall data and the dates, duration and intensity of discharges to the pond would assist the interpretation of temporal trends in the soil and plant tissue concentrations of TPH, Pb and Zn. A fall in the tissue concentrations of the three parameters may also be a consequence of plant growth in the period between sample collection dates and for TPH, the additional effect of biodegradation, especially in the soil, by aerobic and/or anaerobic bacteria.

The decrease in *Sparganium* TPH soil concentrations from July to September suggests the complementary effects of biodegradation and plant uptake. Oxygen transfer from plant to soil, which regulates the rate of aerobic degradation, will fall in the autumn as the foliage decomposes in this species. The same trend is observed for *T. latifolia* soil and tissue, although concentrations are lower than in *Sparganium*. However, when loadings are adjusted for biomass they are higher for *T. latifolia* (Figs. 3–5).

Although some variation in the concentrations recorded will clearly be influenced by the location of the plants sampled and their exposure to con-

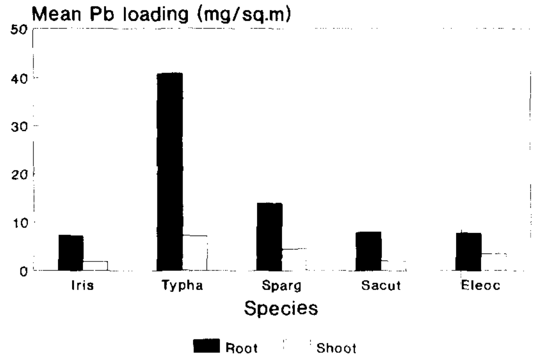

Fig. 4. Mean Pb loads.

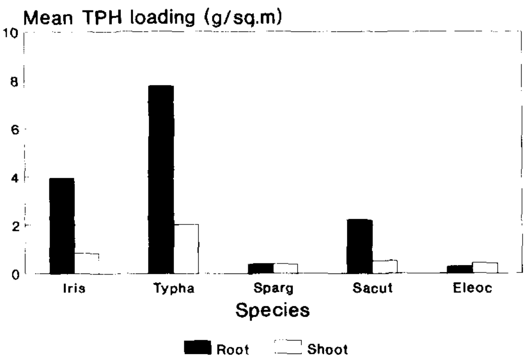

Fig. 3. Mean TPH loads.

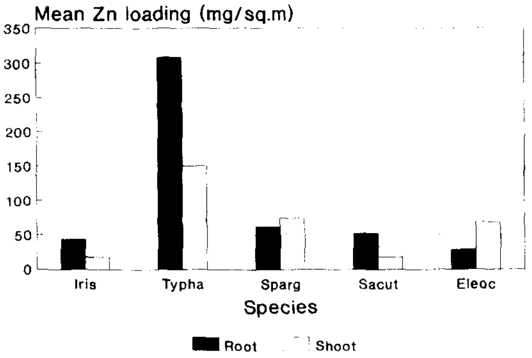

Fig. 5. Mean Zn loads.

taminated discharges, the data suggest that *T. latifolia* and *Sparganium* are the most suitable species for TPH, Pb and Zn uptake, storage and metabolism. *Eleocharis* and *S. acutus* have similar and lower uptake capabilities and *Iris* is the least effective species for pollutant uptake. The experimental study would therefore indicate that emergent macrophytic species can be highly effective in providing a control and treatment buffer for toxic discharges associated with trafficked surfaces in urban areas. However, further work is needed to establish the longer term operational effectiveness of such bioengineered systems and to determine their relative cost advantages.

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6. References

Bascombe, A.D., J.B. Ellis, D.M. Revitt and R.B. Shutes, 1988. The role of invertebrate biomonitoring for water quality management within urban catchments. In: J.C. Hooghart (Ed), Hydrological Processes and Water Management in Urban Areas. IHP/UNESCO, The Netherlands, pp. 404–412.

Cooper, P.F. and B.C. Findlater, 1990. (Eds), Constructed Wetlands in Water Pollution Control. Pergamon Press, Oxford.

Ellis, J.B. 1985. Urban runoff quality and control. In: T.H.Y. Tebbutt (Ed), Advances in Water Engineering. Elsevier Applied Science, London.

Ellis, J.B., 1991. The design and operation of vegetation systems for urban source runoff quality control. In: Procedings of the 3rd Standing Conference Stormwater Source Control. Coventry Polytechnic.

Ellis, J.B., D.M. Revitt, D.O. Harrop and P.R. Beckwith, 1987. The contribution of highway surfaces to urban stormwater sediments and metal loadings. Sci. Total Environ., 59: 339–349.

Hamilton, R.S. and R.M. Harrison, 1991. (Eds), Highway Pollution. Elsevier Science, London.

Kickuth, R., 1976. Degradation and incorporation of nutrients from rural wastewaters by plant rhizosphere under limnic conditions. In: J.H. Voserburg (Ed), Utilisation of Manure by Land Spreading. Rpt. EUR 5672e, Euroepan Commission, London, pp. 335–343.

Martin, E.H. and J.L. Smoot, 1988. Constituent-load changes in urban stormwater runoff routed through a detention pond wetland system in central Florida. J. Environ. Eng., ASCE., 114(4): 226–249.

Ruperd, M., 1987. Efficacite des Ouvrages de Traitement des Eaux de Ruissellement. Service Tech. l'Urbanisme, Div. Equp. Urbains, Paris.

Seidel, K., 1976. Macrophytes and water purification. In: J. Tourbier and R.W. Pierson (Eds), Biological Control of Water Pollution. Pennsylvania University Press, Pennsylvania, pp. 109–121.

Stotz, G., 1990. Decontamination of highway surface runoff in the FRG. Sci. Total Environ., 93: 507–514.

Verniers, G. and H. Loze, 1985. Etude ecologique des bassins d'Orage autoroutiers. Ann. Trav. Publics Belg., 2: 14–21.

Yousef, Y.A., T. Hvitved-Jacobsen, M.P. Wanielista and H.H. Harper, 1987. Removal of contaminants in highway runoff through swales. Sci. Total Environ., 59: 391–399.

Zhang, T., J.B. Ellis, D.M. Revitt and R.B.E. Shutes, 1990. Metal uptake and associated pollution control by *Typha latifolia* in urban wetlands. In: P.F. Cooper and B.C. Findlater (Eds), Constructed Wetlands in Water Pollution Control. Pergamon Press, Oxford, pp. 451–459.