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THE PERFORMANCE AND PERCEPTION OF WETLAND SYSTEMS FOR THE TREATMENT OF HIGHWAY RUNOFF

ARVIND S MUNGUR

Urban Pollution Research Centre
Middlesex University

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ABSTRACT

Constructed wetlands are increasingly being seen as a viable solution to the treatment of highway runoff although currently there are no established design and performance criteria for highway runoff treatment systems. In order to assess the heavy metal removal performance by different wetland systems receiving urban runoff, a natural and constructed wetland site were monitored for metal removal performance and metal accumulation by the sediment and four macrophyte species. Although there is active metal uptake by the sediment and macrophytes, aqueous metal concentrations remain unchanged in the natural wetland. The initial results from the constructed wetland system show variable metal removal performance although an improvement in performance is expected as the system becomes more established.

An experimental laboratory-based wetland system showed efficient treatment performance of water dosed with heavy metals. The distribution of metals in the substrate highlight the importance of the hydraulic design, and the need to reduce the possibility of shortcircuiting, in constructed wetlands for runoff treatment.

A questionnaire survey was used to assess the public's perception of the aesthetic and wildlife value of wetlands and their attitudes towards the use of wetland treatment systems for water pollution control. A predictive model for the visual preference of wetland landscapes was developed from the results of the survey. The results show that the public has a clear preference for clean natural looking wetland environments with landscape complexity, diverse vegetation and the presence of wildlife. The public have reservations about the use of wetlands for wastewater treatment indicating the need for background information to allay these concerns.

Design criteria are proposed for the engineering of the wetland that will be constructed by the Environmental Agency (EA) at the natural wetland site to treat highway runoff. The results of the survey provide recommendations for the landscaping design of treatment wetland systems.

CONTENTS

SECTION TITLES

CHAPTER 1 INTRODUCTION

CHAPTER 2 THE USE OF WETLANDS FOR WASTEWATER TREATMENT

CHAPTER 3 ASSESSMENT OF HEAVY METAL REMOVAL FROM HIGHWAY RUNOFF BY A NATURAL WETLAND

3.3.4 Metal Determination by AAS

3.4 RESULTS AND DISCUSSION

CHAPTER 4 ASSESSMENT OF HEAVY METAL REMOVAL BY A FULL-SCALE CONSTRUCTED WETLAND

4.4 RESULTS AND DISCUSSION

CHAPTER 5 ASSESSMENT OF HEAVY METAL REMOVAL PERFORMANCE OF A LABORATORY SCALE WETLAND

5.3 RESULTS AND DISCUSSION

CHAPTER 6 THE PUBLIC'S PERCEPTION OF THE AESTHETIC AND WILDLIFE VALUE OF WETLANDS AND THE USE OF WETLANDS FOR WATER QUALITY IMPROVEMENT

6.6.3 Results From the Assessment of Wetland Preference for Wetland Landscapes

6.6.6 Public Perception of the Use of Wetlands for Water Quality Improvement

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

TABLES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

FIGURES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

PLATES

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

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All the work detailed in this thesis has been carried out by myself, Arvind Mungur, with the following exception. The wetland in Braintree (described in Chapter 4) was monitored, and the samples analysed, at different times by the following persons:

Arvind Mungur & Karen Moody: August 1994 to December 1994
Arvind Mungur & Scott Lewis: January 1995 to July 1995
Caroline Fallon: March 1996 to September 1996

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Vegetated wetlands have long been employed for the treatment of municipal, industrial and agricultural effluents (Cooper *et al.,* 1996; Kadlec and Knight, 1996). However, the use of constructed wetlands is now being increasingly seen as a viable solution for the treatment of highway runoff since generally runoff is directly discharged to the nearest watercourse untreated. Such a system ignores the potential pollution loads of, for example, heavy metals generated from rainfall runoff and their impact on receiving waters.

Although there is considerable literature on the use of wetlands and vegetated detention basins for urban storm water quality control (Kadlec and Knight, 1996), few studies relate to highway runoff (Ellis, 1994; Martin and Smoot, 1988; Startin and Lansdown, 1994). Consequently, there are no established design and performance criteria for urban runoff treatment wetlands although there is considerable interest in the UK in the potential use of constructed wetlands to treat highway and surface runoff from the Environment Agency (EA) whose responsibilities include the control of polluting discharges to receiving waters.

There has been comparatively little research undertaken on public perception of the aesthetic and wildlife value of wetlands. Research has concentrated on the historical perception of wetlands (Jorgensen, 1971), the value of wetlands to humans (Williams, 1991) and the perception of the visual values of wetlands, where values are defined as the enjoyment derived by people in terms of scenery, recreation and nature education (Smardon, 1983). There have been very few studies on public perception of the use of wetlands for water quality improvement although many wetlands, both natural and constructed, are used for this purpose. Whilst the improvement of water quality remains the primary goal of constructed wetlands, there is growing recognition that treatment wetlands can provide ancillary benefits such as wildlife habitat and public use for recreation and environmental study.

It was against this background that this work, by the Urban Pollution Research Centre (UPRC) at Middlesex University, was undertaken and the results of which are presented in this thesis. The work also complements and further develops a previous study undertaken within the UPRC which investigated the use of macrophytes for heavy metal pollution control (Zhang, 1990). Current UPRC studies include monitoring of wetland systems for the treatment of urban runoff, the microbial accumulation of heavy metals in wetlands (Scholes *et al.*, 1995) and the microbial degradation of organics.

1.2 AIMS

The principal aim of the research programme was to assess heavy metal removal performance by different wetland systems receiving urban runoff. This involved monitoring the metal concentrations entering and leaving the systems and the uptake of metals by the substrate and wetland plants. A natural wetland and a full-scale constructed wetland were chosen as monitoring sites. Laboratory-based experiments were also undertaken to assess the impact of the soil, macrophyte species and hydraulic design on heavy metal removal by wetland systems. The second aim was to assess the public's perception of the aesthetic and wildlife value of wetlands and their attitudes towards the use of wetland treatment systems for water pollution control. A questionnaire survey was designed and implemented to achieve this.

The natural wetland has been selected by the Environment Agency (EA) as a site to introduce a constructed wetland to treat runoff from a major highway. The ultimate aim of the research is for the findings of this research to be incorporated into the performance and design criteria of this and future wetlands.

1.3 OUTLINE OF THE THESIS

The thesis is presented in seven chapters including this introduction. Chapter 2 presents a literature review of the use of wetlands for the treatment of highway runoff. In addition, the public's perception of wetlands is considered. In Chapter 3, the field methodologies and laboratory analytical techniques are given together with an assessment of heavy metal removal from highway runoff by a natural wetland. Chapter

4 assesses the heavy metal removal from surface runoff by a constructed wetland over a two year period. Heavy metal removal by a laboratory scale wetland was also undertaken. The results, presented in Chapter 5, provide a further understanding of the impact of soils, macrophytes and hydraulic design on heavy metal removal by wetland systems. Chapter 6 presents the results from questionnaire surveys to assess the public's perception of the aesthetic and wildlife value of wetlands and their use for water quality improvement and also includes sections on the design of the questionnaires. Chapter 7 summarises the findings and presents recommendations for further research in this field, as indicated by this thesis.

1.4 CONFERENCES

During the period of this research a number of conferences were attended and papers outlining different areas of the research were presented. Conferences at which presentations were made are listed below.

- *Fourth European Postgraduate Workshop on Urban Runoff-Sewer Systems, Treatment Plants and Receiving Waters.*
  Aalborg, Denmark, July 1993.
  ERASMUS.

- *Fourth International Conference on Wetland Systems for Water Pollution Control.*
  Guangzhou, People's Republic of China, 6-10 November, 1994.
  International Association of Water Quality (IAWQ).

- *Fifth International Conference on Wetland Systems for Water Pollution Control.*
  Vienna, Austria, 15-19 September 1996.
  International Association of Water Quality (IAWQ).

1.5 PUBLICATIONS

A number of publications were also produced and they are listed below. Those papers that have been peer reviewed are marked with an asterisk (*).

Mungur, A.S. (1993). The Use of Constructed Wetlands to Treat Highway Runoff. In *Abstracts from the Fourth European Postgraduate Workshop on Urban Runoff-Sewer Systems, Treatment Plants and Receiving Waters.* 5-9 July 1993, Aalborg University, Denmark.

Mungur, A.S., Shutes, R.B.E., Revitt, D.M. and House, M.A. (1994). A Constructed Wetland for the Treatment of Highway Runoff in the United Kingdom. In *International Association on Water Quality (IAWQ); Specialist Group on the Use of Macrophytes in Water Pollution Control Newsletter* **11**, p7-12.

Mungur, A.S., Shutes, R.B.E., Revitt, D.M. and House, M.A. (1995). An Assessment of Metal Removal from Highway Runoff by a Natural Wetland. *Wat. Sci. Tech.* **32(3)**, p169-175 (*).

Mungur, A.S. (1996). Contributing author to *Reed Beds and Constructed Wetlands for Wastewater Treatment.* Cooper, P.F., Job, G.D., Green, M.B. and Shutes, R.B.E. WRc Publications, Medmenham, 184pp.

Mungur, A.S. (1996). Perceptions of Wetlands and Their Use in Wastewater Treatment. In *Proceedings of the European Seminar on Water Geography*, London, UK, 6-11 September 1996, ERASMUS, p83-86.

Mungur, A.S., House, M.A., Shutes, R.B.E. and Revitt, D.M. (1996). Public Perception of Wetlands and Their Use in Wastewater Treatment. *Fifth International Conference on Wetland Systems for Water Pollution Control*, Vienna, Austria, 15-19 September 1996 (*).

Shutes, R.B.E., Mungur, A.S., Scholes L.N.L., and D.M. Revitt (1996). The Treatment of Urban Runoff by Wetland Systems. *Fifth International Conference on Wetland Systems for Water Pollution Control*, Vienna, Austria, 15-19 September 1996 (*).

Mungur, A.S., Shutes, R.B.E., Revitt, D.M. and House, M.A. (1997). An Assessment of Metal Removal Performance by a Laboratory Scale Wetland. *Wat. Sci. Tech.* **35(5)**.

Manuscripts Submitted for Publication

Mungur, A.S., Shutes, R.B.E., Revitt, D.M., House, M.A. and Fallon, C. (1997). A Constructed Wetland for the Treatment of Urban Runoff. *International Conference on the Remediation and Management of Degraded Lands*, Hong Kong, 2-5 December 1996 (*).

CHAPTER 2 THE USE OF WETLANDS FOR THE TREATMENT OF HIGHWAY RUNOFF

2.1 INTRODUCTION

This chapter is a review of the existing literature on the use of wetlands for the treatment of highway runoff and covers the following eight topics:

(1) Metal-contaminated highway runoff, its sources and impact.
(2) Definition of wetlands.
(3) Conventional non-wetland treatment methods.
(4) The components of a wetland that may function to improve highway runoff.
(5) The advantages and disadvantages of constructed wetlands in wastewater treatment.
(6) The processes of metal-removal in wetlands.
(7) The design, construction and operation of wetlands.
(8) The public's perception of the aesthetic and wildlife value of wetlands.

The reader is also referred to Kadlec and Knight (1996) who comprehensively cover all the aspects of treatment wetlands.

2.2 HIGHWAY RUNOFF QUALITY IN THE UK

2.2.1 Highway Drainage Waters

There is sufficient data available to indicate that drainage waters from highway surfaces are associated with pollutant levels which are generally comparable to urban runoff (Colwill *et al.*, 1984; Ellis, 1986; Hedley and Lockley, 1975; Mance, 1981; Muschack, 1990; OECD, 1978; Sartor and Boyd, 1972; Shaheen, 1975; US Dept. of Transportation, 1981). A summary of the range and concentrations of contaminants that have been recorded in highway drainage in the UK and Europe is given in Table 2.1.

In addition to the contaminants listed in Table 2.1, highway drainage can also carry

Table 2.1 UK/European highway drainage quality (After Hedley and Lockley, 1975).

Determinand	Concentration ranges (mg/l)	
	Suburban roads	Motorway and trunk roads
Suspended solids	11-40	(261) 110-5700
BOD	8-25	(24) 12.2-32
Chloride	1.3-27.0	(386) 159-2174
Total N	0.18-0.98	(1.8) 1.4-3.3
Total Zn	0.02-1.90	(0.41) 0.17-3.55
Total Pb	0.01-0.15	(0.96) 0.34-2.41
Total Cu	0.01-0.12	(0.15) 0.05-0.69
Oil/total hydrocarbons	2.8-31.0	(28) 7.5-400

Key
( ): Mean Values shown in brackets

pollutants such as bromide, pesticides, faecal coliforms, and PCBs (Ellis, 1989). However, as far as receiving water impacts are concerned, the principal pollutants are solids, metals and oils together with chloride and bromide during the winter months between November and March. The runoff concentrations of these pollutants can increase by an order of magnitude as a result of deicing operations. The effect of toxic metals on the environment is detailed in Förstner and Wittman (1981).

2.2.2 Sources of Highway Pollution

The highway system is obviously a potential source of a wide variety of pollutants to both the adjacent land surface through spray and deflationary action as well as to receiving waters as a result of direct surface discharge. Figure 2.1 illustrates pollutant sources, pathways and sinks for highway surface runoff for both the above and below-ground phases and Figure 2.2 illustrates the sources of metal pollution in urban stormwater. It must be noted that many of the secondary sinks act as temporary "reservoirs" for subsequent pollution within the highway drainage system. Table 2.2 presents a summary of the primary sources of the more common highway runoff contaminants. General vehicular wear and deposition is by far the largest contributor

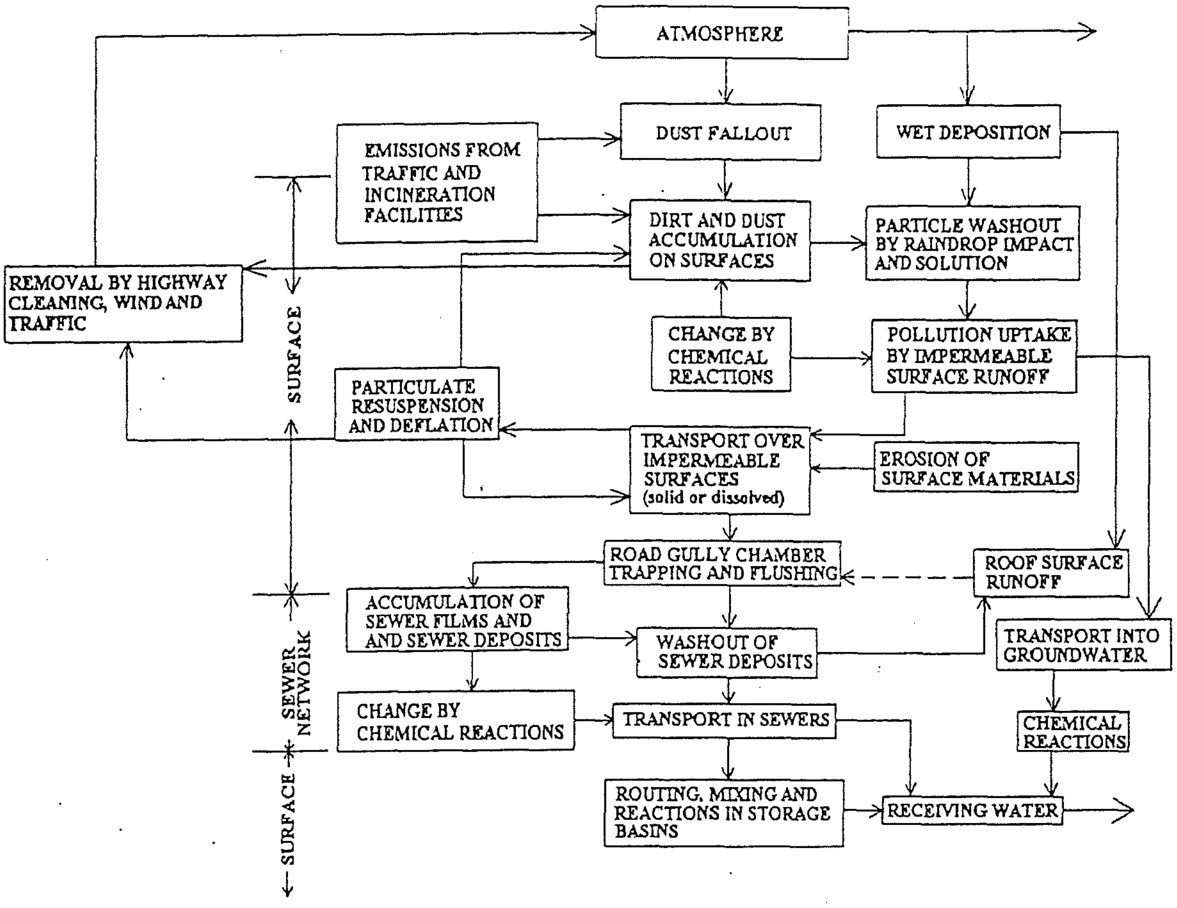


Figure 2.1 Pollutant sources and pathways of highway runoff (After Hall *et al.*, 1991).

of pollutants during non-winter periods although the percentage of direct traffic related contributions to total mass accumulation for some metals may be relatively small.

It is clear from an inspection of Table 2.2 that the principal sources of highway surface pollution include vehicle and tyre wear; vehicle lubrication system losses; vehicle exhaust emissions; deicing materials and additives; road surface wear; litter and spillages and atmospheric (wet and dry) deposition.

2.2.3 Pollution Impact of Highway Runoff

There are relatively few studies on the fate and impact of highway runoff contaminants on receiving waters (Ellis *et al.*, 1985; Gavens *et al.*, 1982 and Hamilton *et al.*, 1984) and on the biota of receiving waters (Baekken, 1994; Davis and George, 1987; Hvitved-

Spoil Heaps

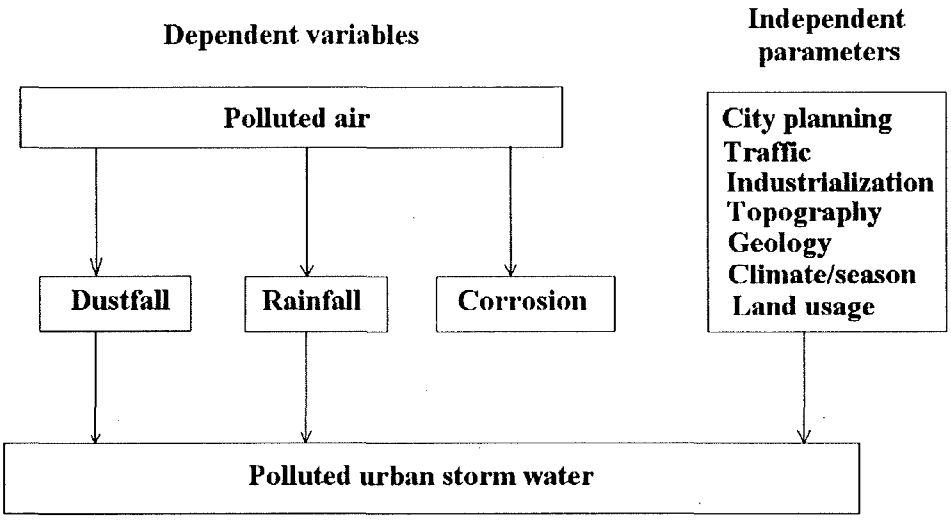


Figure 2.2 Sources of metal pollution in urban stormwater (After Malmquist, 1975).

Jacobson and Yousef, 1991; Maltby *et al.*, 1995 and Müller, 1987). Most of the contaminants in highway runoff are associated with the particulate form and accumulate in the sediments of the receiving waters where they may reach concentrations and magnitudes higher than those in the overlying waters (Catallo and Gambrell, 1987 and Ingersoll, 1991) and thus present the highest risk to members of the benthic community.

Drainage waters from highway surfaces are associated with pollutant levels which are generally comparable to those found in urban runoff (Colwill *et al.*, 1984; Ellis, 1986; Muschack, 1990). It is estimated that 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 inputs to the receiving watercourses (Ellis *et al.*, 1987). In urban receiving waters, the principal pollutants are suspended solids, heavy metals, hydrocarbons and deicing salts with the major sources of highway pollution arising from road and vehicle wear.

The heavy metals such as Cd, Cu, Pb, and Zn are persistent pollutants which are particularly damaging when short duration intense summer storms follow a long dry period during which these pollutants have accumulated upon the road surface, in verges and in the drainage system itself. A sudden flush of highway drainage can be very damaging to the stream ecology in these circumstances. More extensive rainfall would have less impact due to the greater dilution of pollutants in the runoff. The distribution

Table 2.2 Highway runoff constituents and their primary sources (After Rexnord Inc., 1984).

Constituent	Source
Solids	Road pavement wear, vehicles, atmosphere, maintenance, deicing operations
Pb	Petrol (exhaust emissions and leakage/spillage), tyrewear (lead oxide filler), lubricating oil and grease, bearing wear, underseal spray
Zn	Tyre wear (fillers), oil (stabilising additives), grease
Cd	Tyre wear (fillers), insecticide applications
Cu	Metal plating, bearing/bush wear, moving engine parts, brake lining wear, insecticide/fungicide applications
Cr	Metal plating brake lining wear, moving engine parts, roadway markings
Ni	Diesel/petrol, lubricating oil, metal plating, bush and brake lining wear, asphalt surfacing
Fe	Body rust, steel highway structures (guard rails, etc.), moving engine parts, soils
Mn	Moving engine parts, soils
Bromide	Exhaust, deicing compounds
Cyanide	Deicing compounds
Chloride	Deicing salts
Sulphate	Diesel/petrol, deicing salts, road dressing, acid rain
Hydrocarbons	Lubricating oil and grease, diesel/petrol, antifreeze/hydraulic fluids, asphalt surfacing
Rubber	Tyre/seal wear
PCBs/Pesticides	Tyre wear (PCB catalyst), herbicide spraying of highway right of way, atmosphere
Bacteria	Litter, bird and animal faeces, livestock yard waste and HGV livestock movements, spillages

of metals in highway runoff between the particulate and dissolved phases is important since the environmental mobility and bioavailability of metals largely depends upon their aqueous concentration. The soluble portions of Pb, Cu and Zn in highway runoff have been found to constitute 1-10%, 20-40% and 30-50% respectively of the total metal composition (Ellis *et al.*, 1987). Levels of soluble metals will tend to be low and toxicity thresholds highest in hard water areas such as London and the cr situation applies for soft water areas.

Total Cd concentrations are generally too low to have a significant ecological impact although where determined, the majority of the total Cd has been found to be in the soluble form (Ellis *et al.*, 1987). The bioavailability of Pb is generally believed to be reduced due to the high association of this metal with the particulate form, but a recent study of plant roots has shown that large amounts of Pb accumulate in root cell walls. This plant store of Pb can potentially be passed through the food chain to other organisms (Wierzbicka and Antosiewicz, 1993).

2.3 WETLAND ECOSYSTEMS

2.3.1 Definition Of Wetlands

A wetland is an *ecotone* - an "edge" habitat; a transition zone between dry land and deep water, an environment that is neither clearly terrestrial nor clearly aquatic (Hammer and Bastian, 1989; Kadlec and Knight, 1996). There is no single "correct" definition of wetlands for all purposes. Several definitions and classification systems have been devised for differing needs and purposes. Most tend to avoid the how wet-is-wet question by identifying wetlands in terms of soil characteristics and the types of plants these transitional habitats typically support. This is possible because shallow standing water or saturated soil can soon cause severe problems for all plants except hydrophytes, which are specifically adapted for these conditions. One working definition adopted describes a wetland as "land in which the water table is at or above the ground surface long enough each year to maintain saturated soil conditions and the related vegetation" (Reed *et al.*, 1988).

In 1979, the US Fish and Wildlife Service developed a definition and classification system capable of encompassing and systematically organizing all types of wetland habitats for scientific purposes (Cowardin *et al.*, 1979). It broadly recognizes wetlands as a transition between terrestrial and aquatic systems, where water is the dominant factor determining development of soils and associated biological communities and where, at least periodically, the water table is at or near the surface, or the land is covered by shallow water. Specifically it requires that wetlands meet one or more of three conditions:

- Areas supporting predominantly hydrophytes (at least periodically);
- Areas with predominantly undrained hydric soil (ie. wet for a period of time long enough to produce anaerobic conditions that limit the types of plant that can grow there);
- Areas with non-soil substrate (such as rock or gravel) that are saturated or covered by shallow water at some time during the growing season.

However, various legislation and agency regulations define wetlands in more general terms; for example areas flooded or saturated by surface water or groundwater often and long enough to support those types of vegetation and aquatic life that require or are specially adapted to saturated soil conditions. Such descriptions can be expanded, if necessary, to accomodate many of the scientific classifications. At the same time, they also conform to popular conceptions of what constitutes wetlands - salt and freshwater swamps, marshes, and bogs.

In popular usage, shallow-water or saturated areas dominated by water-tolerant woody plants and trees are generally considered *swamps*; those dominated by soft-stemmed plants are considered *marshes*; and those with mosses are *bogs*. Freshwater marshes are dominated by herbaceous plants. Submerged and floating plants may also occur, often in abundance, but it is the emergent plants that usually distinguish a marsh from other aquatic environments. Familiar emergents include reedmace or cattails (*Typha*), bulrush (*Scirpus*), reed (*Phragmites*), grasses and sedges (*Carex*).

2.3.2 Functions Of Natural Wetlands

The productivity of many wetlands far exceeds that of the most fertile farm fields (which in many cases are former wetlands). Wetlands receive, hold, and recycle nutrients continually washed from regions further upland (Figure 2.3). These nutrients support an abundance of macro- and microscopic vegetation, which converts inorganic chemicals to the organic materials required - directly or indirectly - as food for animals or man. In addition to their vegetative productivity, wetlands support fauna including zooplankton, worms, insects, crustaceans, fish, amphibians, reptiles, birds and mammals. Other animals are drawn from nearby environments to feed at the highly productive "edge" environment of wetlands and they in turn become prey for others from a greater distance, thus extending the productive influence of wetlands far beyond their borders.

Sport and commercial hunters and fishermen have brought public attention to the economic value of the fish and wildlife of wetlands. They were first to note the direct relationship between wetland destruction and declining populations of valuable species of shellfish, fish, reptiles, birds and fur-bearing mammals that are dependent on certain types of wetland habitats during part or all of their lives.

But perhaps the most important but least understood function of wetlands is water quality improvement. Wetlands provide effective, free treatment for many types of water pollution. Wetlands can effectively remove or convert large quantities of pollutants from point sources (municipal and certain industrial wastewater effluents) and non-point sources (mine, agricultural, and urban runoff) including organic matter, suspended solids, metals, and excess nutrients. Natural filtration, sedimentation, and other processes help clear the water of many pollutants. Some are physically or chemically immobilized and remain in the wetland permanently unless disturbed. Chemical reactions and biological decomposition break down complex compounds into simpler substances. Through absorption and assimilation, wetland plants remove nutrients (e.g. nitrates, phosphates, heavy metals) for biomass production. One abundant by-product of the plant growth process is oxygen production, which increases the dissolved oxygen content of the water and also of the substrate in the immediate vicinity of plant roots (see Section 2.7.4). This increases the capacity of the system for aerobic bacterial decomposition of pollutants as well as its capacity for supporting a wide range of oxygen-using aquatic organisms, some of which directly or indirectly utilize additional pollutants (Kadlec and Knight, 1996).

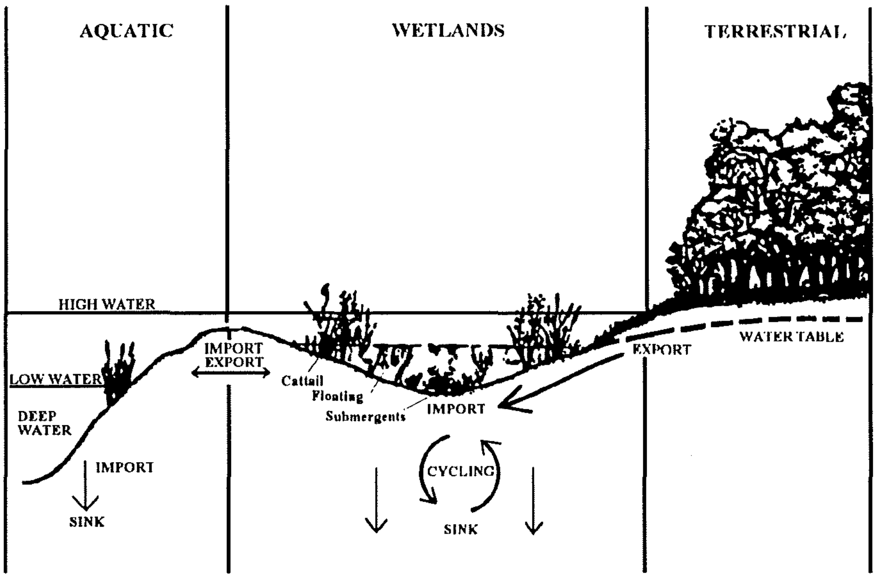


Figure 2.3 Wetlands are transition zones between terrestrial and aquatic environments and benefit from nutrient, energy, plant and animal inputs from neighbouring systems (From Hammer and Bastian, 1989).

Many nutrients are held in the wetland system and recycled through successive seasons of plant growth, death, and decay. If water leaves the system through seepage to groundwater or filtration, the soils may remove some pollutants. If water leaves via overland flow, nutrients trapped in the substrate and plant tissues during the growing season do not contribute to noxious algae blooms and excessive aquatic weed growths in downstream rivers and lakes. Excess nutrients from decaying plants released during the non-growing season have less effect on downstream waters (Hammer and Bastian, 1989).

The cumulative impacts on water quality functions of wetlands, ie. the multiple impacts whose effects on the wetland cannot be predicted by simply adding the effects of all the individual impacts, are discussed by Hemond and Benoit (1988) and Whigham *et al.* (1988) examine the cumulative impact from a landscape approach (given there are different types of freshwater wetlands in different positions in the landscape). A wetland ecosytem is shown in Figure 2.4.

2.3.3 Wetland Vegetation

The structure and form of aquatic macrophytes can be divided into two groups: free floating and rooted (Figure 2.5). The free floating plants include those with roots

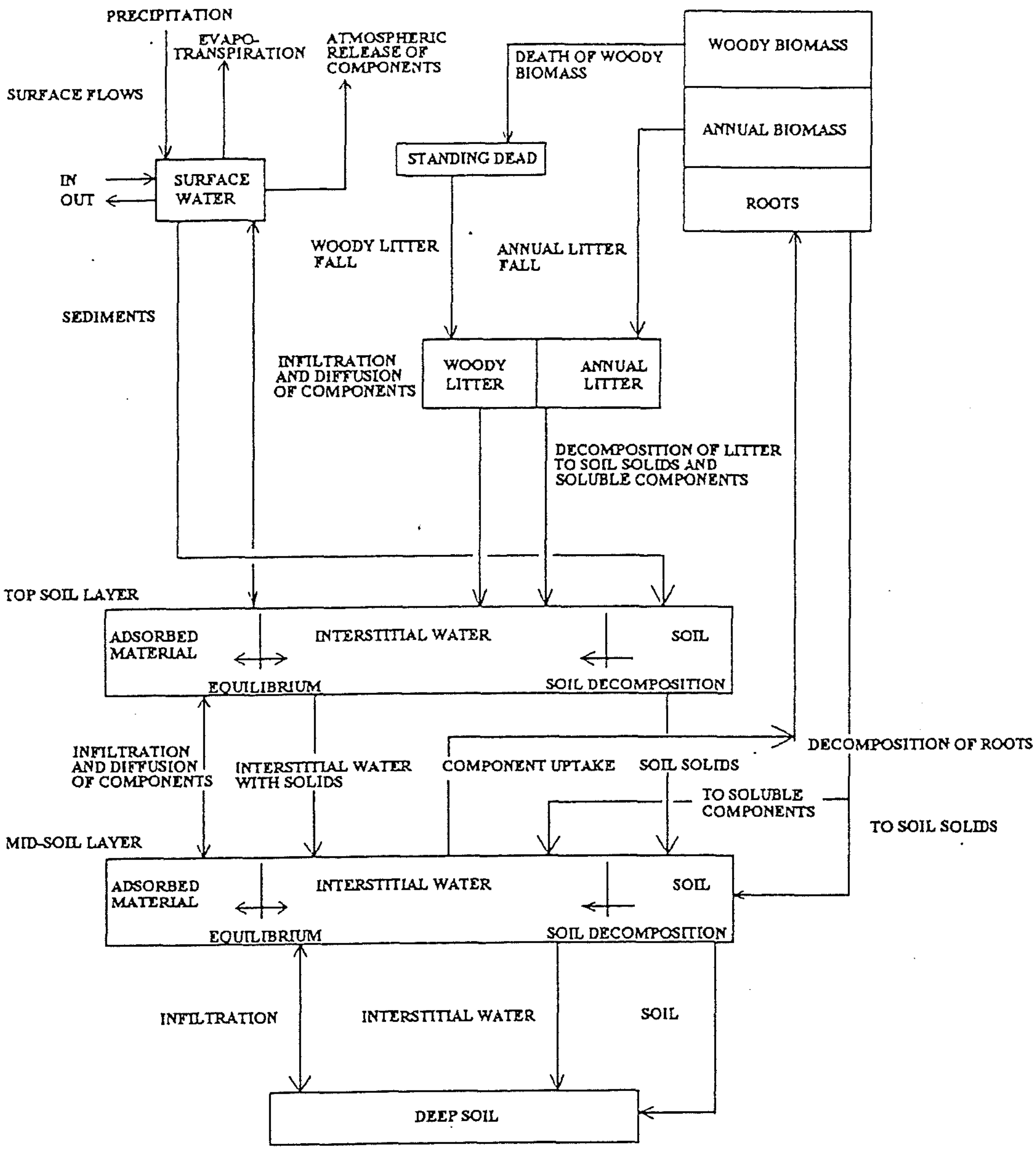


Figure 2.4 A wetland ecosystem model (After Kadlec and Hammer, 1988).

suspended in the water column of which there are those that float at the water surface (A), and those that float suspended in the water column itself (B). Of the rooted forms, some have parts which emerge from the water (C), others have leaves that float at the surface water (D), and others are fully submerged (E).

Wetlands have individual and group characteristics related to the plant species present and their adaptations to specific hydrological, nutrient, and substrate conditions. Because of this, a variety of plant species are used in constructed wetland systems (Table 2.3) (Guntenspergen *et al.,* 1989).

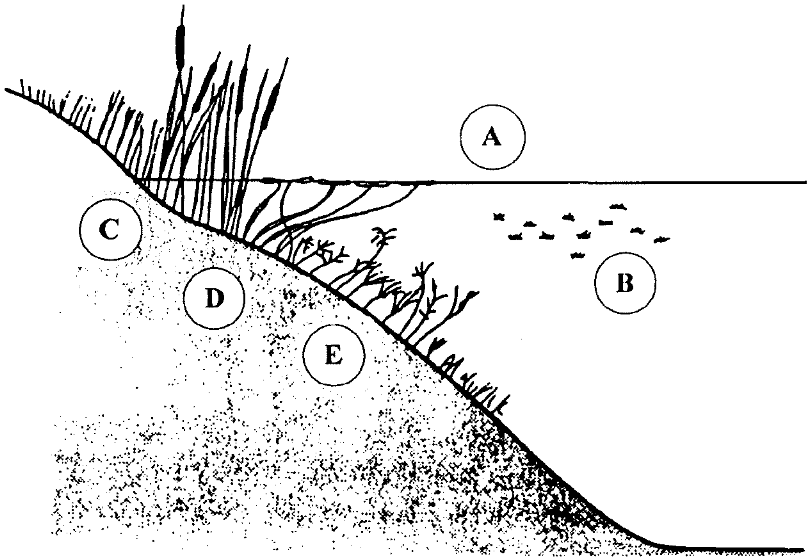


Figure 2.5 Major lifeforms of aquatic macrophytes. A - free-floating at surface; B - free-floating beneath surface; C - emergent (e.g. *Typha latifolia*); D - with floating leaves; and E - submerged.

Natural wetlands are populated by different plant types adapted for growth in water or saturated soil. Organization into clear-cut groups is difficult because of ambiguous definitions and the complexity of the classification schemes. Consequently, there are many terms referring to plants growing in the zone from terrestrial to aquatic habitats: *hydrophyte, aquatic macrophyte, vascular hydrophyte, aquatic plant,* and *vascular aquatic plant.*

Table 2.3 Plant species used in constructed wetlands for wastewater treatment (From Hammer and Bastian, 1989).

EMERGENT
Scirpus robustus
Scirpus lacustris
Schoenoplectus lacustris
Phragmites australis
Phalaris arundinacea
Typha domingensis
Typha latifolia
Canna flaccida
Iris pseudacorus
Scirpus pungens
Scirpus validus
Glyceria maxima
Eleocharis dulcis
Eleocharis sphacelata
Typha orientalis
Zantedeschia aethiopica
Colocasia esculenta

SUBMERGED
Egeria densa
Ceratophyllum demersum
Elodea nuttallii
Myriophyllum aquaticum

FLOATING
Lagorosiphon major
Salvinia rotundifolia
Spirodela polyrhiza
Pistia stratiotes
Lemna minor
Eichhornia crassipes
Wolffia arrhiza
Azolla caroliniana
Hydrocotyle umbellata
Lemna gibba
Lemna spp.

Only a few taxa of wetland plants (e.g. *Typha, Phragmites, Myriophyllum, Lemna*) are used in wastewater treatment studies (Table 2.3). There are over 1000 species found entirely in aquatic families (Sculthorpe, 1969). If aquatic species in otherwise terrestrial families and woody species found in forested wetlands are included, less than 1% of the available taxa have actually been used.

2.4 NON-WETLAND TREATMENT TECHNIQUES

2.4.1 Conventional Highway Runoff Treatment Systems

Studies in the UK and Europe that have investigated the use of conventional wastewater treatment unit designs for the removal of pollutants contained in highway runoff have primarily focussed on motorway locations and on systems that might be effective in removing solids, oils and metals. The principal operational designs that have been tested include sedimentation and oil chambers or tanks, lagoons and filtration basins. These techniques all involve the collection and treatment of wastewater and have had varying degrees of success.

2.4.2 Tanks/Chambers

Large storage tanks, where quiescent settling (achieved by plain sedimentation) is allowed over a certain length of time, will remove nutrients, metals and organic pollutants with varying efficiency (Bennett *et al.*, 1981; Ellis, 1985 and Whipple Hunter, 1981).

Studies in the UK commissioned by the Transport Research Laboratory have demonstrated that sedimentation tanks to treat runoff from a typical motorway would have relatively large dimensions. Together with their low trap efficiencies, particularly for the toxic dissolved and organic pollutants from highways, it was concluded that sediment tanks do not offer acceptable operational quality performances without resorting to further controls. Furthermore there can also be seasonal variations in efficiency and the need for frequent desludging of tanks (Ellis and Revitt, 1991).

2.4.3 Filtration Basins

A number of US (DeGroot, 1982; Schueler, 1987) and French studies (Balades, 1985; Cathelain *et al.*, 1981; Ranchet and Ruperd, 1983 and Ruperd, 1987) have reported on the use of filtration basins for the control and treatment of stormwater and highway runoff. While initial performance of such facilities demonstrates an effective removal of both soluble and fine particulate pollutants, their long-term capability is questionable. The conclusion drawn is that infiltration systems require regular and careful maintenance to sustain effective long-term quality performance.

2.4.4 Lagoons

Borch-Jenson (1978) investigated the removal efficiency of a lagoon receiving highway runoff. High removal rates were recorded for all the parameters investigated. Further studies (Colwill *et al.*, 1984; Perry and McIntyre, 1986 and Pope *et al.*, 1978) have shown that the annual average removal efficiency of lagoons is better than that of tanks and filtration basins.

A study by Martin (1988) indicates that detention of urban stormwater runoff in a system that combines both a detention pond and wetlands can provide, in certain respects, effective treatment of urban runoff (i.e. reducing both suspended and dissolved loads of solids and metals).

2.4.5 Non-Wetland Vegetative Systems

Vegetated wetlands have been used for 20 years (originally in Germany) in the treatment of municipal, industrial and agricultural effluents (Cooper and Findlater, 1990). Wetlands are the obvious systems, but the other non-wetland vegetative system are grass swales (Figure 2.6). Roadside swales or grassed channels are commonly used in the US and Canada to convey stormwater runoff from the impervious surface to selected off-site locations for storage prior to discharge into adjoining receiving waters. They also provide temporary retention for infiltration. Such grassed filter channels are viewed as low cost practices which offer some water quality benefits (Ellis, 1990)

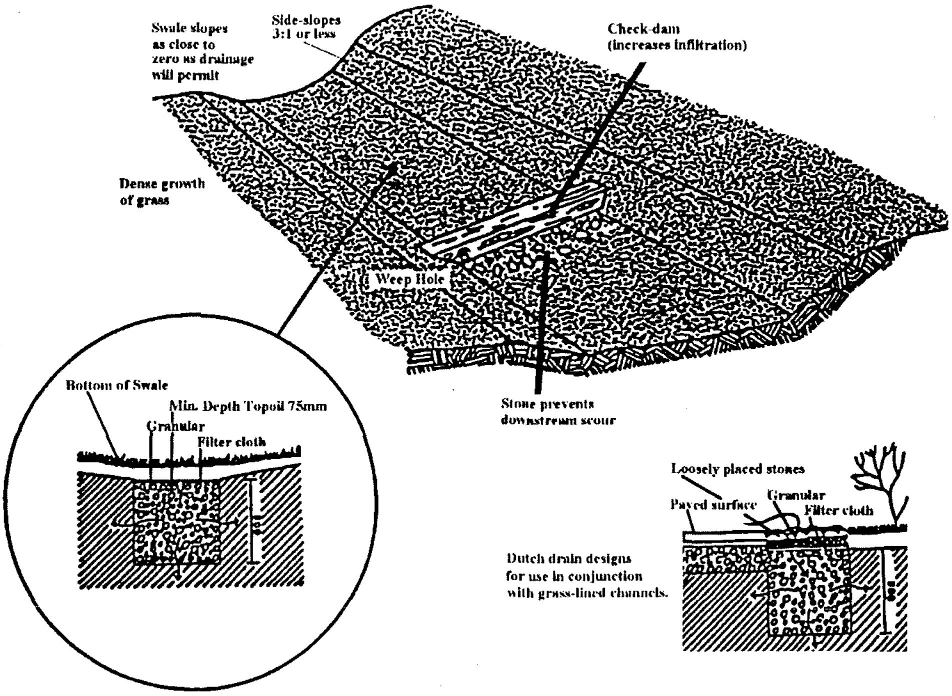


Figure 2.6 Schematic of a grass swale (After Ellis, 1990).

through filtration and deposition of solids by the grass cover during stormwater flow.

2.5 CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

2.5.1 Definition Of Constructed Wetlands

Constructed wetlands are defined as a designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life, and water that simulates natural wetlands for human use and benefits (Hammer and Bastian, 1989). Synonymous terms include *man-made, engineered,* and *artificial* wetlands. Although bogs and swamps have been constructed or used for wastewater treatment and consequently are included in the above definition, most constructed wetlands for wastewater treatment emulate marshes. Marshes with herbaceous emergent and, perhaps, submergent plants have the most promise for wastewater treatment. Flood-tolerant woody plants in swamps may require 5-20 years for development and full operational performance. Bogs dominated by mosses are difficult to establish, have limited retention capacity (Wieder, 1988) and limited adaptability to fluctuating water levels, and are likely to become marshes if water and nutrient inputs are increased (Kadlec, 1988). Conversely, marshes with reedmace or cattail (*Typha*), bulrush (*Scirpus*) or reed (*Phragmites*) are adapted to fluctuating water and nutrient levels and are more tolerant of high pollutant concentrations (Small, 1976).

For most purposes, the majority of natural or constructed wetlands have five principal components:

- substrates with various rates of hydraulic conductivity;
- plants adapted to water-saturated anaerobic substrates;
- a water column (water flowing in or above the surface of the substrate);
- invertebrates and vertebrates; and
- an aerobic and anaerobic microbial population.

Constructed wetlands appear to have very broad applicability as wastewater treatment systems for a range of water pollution problems (Watson *et al.*, 1989). The most common uses are for treatment of municipal wastewaters and acid mine drainage. Other applications include textile waste, photographic laboratory waste, pulp mill effluent, refinery effluent, swine farrowing and feeding waste, poultry rendering waste, landfill leachate, and of course urban runoff.

2.5.2 Processes Within Constructed Wetland Components

2.5.2.1 Microbes

Microbes - bacteria, fungi, algae, and protozoa - alter contaminant substances to obtain nutrients or energy to carry out their life cycles (Alexander, 1967). The effectiveness of wetlands managed for wastewater treatment is dependent on developing and maintaining the optimum environment for the required microbial populations. Fortunately, these microbes are ubiquitous, naturally occurring in most waters and likely to have large populations in wetlands and contaminated waters with nutrient or energy sources.

2.5.2.2 Plants

Wetland plants have two important but indirect functions: (1) within the water column, stems and leaves significantly increase surface area for attachment of microbial populations; and (2) wetland plants have the ability to transport atmospheric gases including oxygen down into the roots to enable their roots to survive in an anaerobic environment. Some incidental leakage occurs, producing a thin-film, aerobic region called the *rhizosphere* surrounding each root hair (Figure 2.7). Some chemical oxidation occurs in this microscopic region, but more importantly, the rhizosphere supports large microbial populations that modify nutrients, metallic ions, and other compounds. The juxtaposition on a microscopic scale of an aerobic region surrounded by an anaerobic region multiplied by the extensive area of the rhizosphere boundary is crucial to nitrification-denitrification and numerous other desirable pollutant transformations. The influence of rhizosphere aeration on nutrient removal from effluents by an artificial wetland is discussed by Bowmer (1987). It is known that wetlands can remove nitrate because of the anaerobic conditions created in the water-covered soil and a denitification capacity of as much as 4000 kg/ha yr has been observed in natural Danish wetlands (Hoffman, 1985). Relevant works on nitrogen removal from wastewater by wetlands and plants include those by Brodrick *et al.* (1988) and Gesberg *et al.* (1986).

For wastewater treatment, certain plant/substrate combinations appear to be more efficient in constructed wetland treatment systems (Gesberg *et al.*, 1986), and others may be more tolerant of high pollutant concentrations. Consequently, many projects have included a single plant/substrate combination (Brix and Schierup, 1989). But maintaining a monoculture may require unnecessary operational expenses or even be undesirable since an insect pest outbreak could seriously damage a monoculture system (Snoddy *et al.*, 1989), whereas a mixed-species system may be more resistant to pest attack and fluctuating loading rates and may remove a broader variety of pollutants. Furthermore a mixture of species can provide a more aesthetic wetland appearance.

Emergent and floating leaved species have been preferentially used in initial studies of constructed wetlands. Floating-leaved species such as duckweed (*Lemna*) have been used because of their high growth rates, large standing crops, and ability to remove

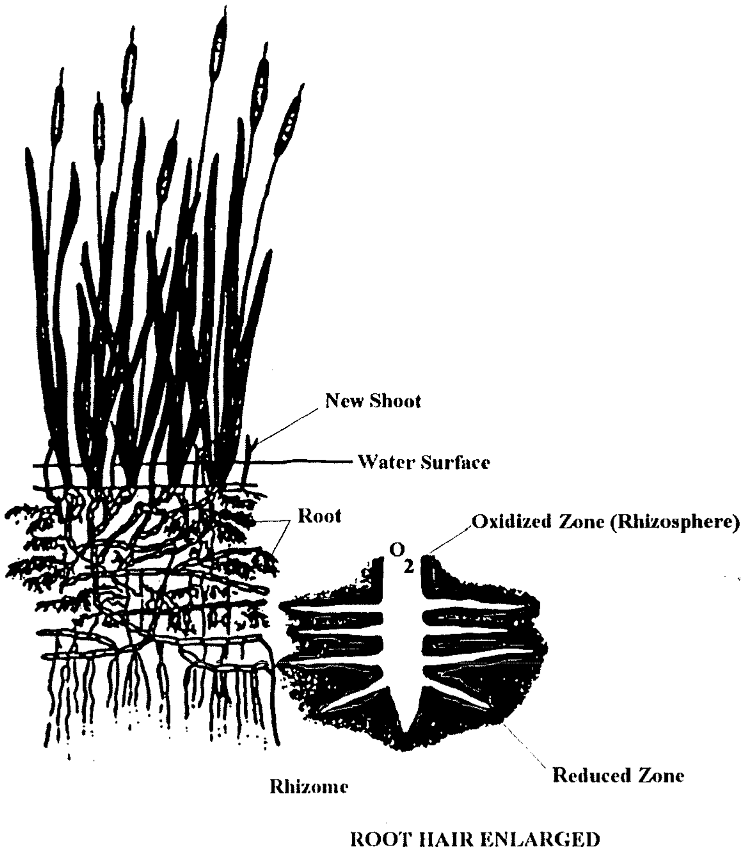


Figure 2.7 Wetland plants have the unique ability to transport oxygen to support their roots growing in a anaerobic substrates (From Hammer and Bastian, 1989).

heavy metals (Jain *et al.*, 1990) and nutrients directly from the water column.

Potentially useful emergent species include many members of the reedmace *(Typha)*, reed *(Phragmites)*, sedge *(Carex)*, reed canary grass *(Phalaris)*, and rush *(Juncus)* genera which all have potentially high uptake and production rates. They are widespread, able to tolerate a wide range of environmental conditions, and can alter their environment in ways suitable for wastewater treatment. Submerged aquatic plants do not appear to have the necessary requirements that are needed in wastewater treatment. They have low production rates and many species are intolerant of eutrophic conditions and/or have detrimental interactions with algae in the water column.

However, in addition to tolerance of wastewater, the effect of wetland plant species on their environment beyond their influence on wastewater alteration must also be considered. Although many aquatic plants have the potential to affect wastewater quality, certain species may be inappropriate: (1) nuisance plants well-adapted for use in wastewater treatment systems that may escape, spread and cause serious problems in natural wetlands (e.g. water hyacinth, *Eichhornia crassipes*); and (2) plants that produce undesirable environmental change.

Universal criteria to determine wetland species suitability for wastewater treatment are not possible because different facilities have different objectives and standards. Municipal wastewater treatment requires modification of organic material and nutrients; stormwater runoff carries heavy metals and refractory organic substances; and mine drainage contains metals and low pH conditions. One species or set of species will not be applicable for all cases. However, although only a few species are currently used, it is reasonable to assume that other species may be suitable. Therefore further studies on the ecology and physiology of candidate species should be carried out.

2.5.2.3 Substrates

Substrates - various soils, sand, or gravel - provide physical support for plants; considerable reactive surface area for complexing ions, anions, and other compounds; and attachment surfaces for microbial populations (see Section 2.7.5).

2.5.2.4 Water

Surface and subsurface water transports substances and gases to microbial populations, carries off by-products, and provides the environment and water for biochemical processes of plants and microbes (see Section 2.7.5).

2.5.2.5 Summary

The mechanisms that modify and/or immobilize pollutants, especially toxic substances, are poorly understood. Some wetland systems appear to remove or modify even complex toxics (Dornbush, 1989; Portier and Palmer, 1989), but disposal methods such as plant harvesting (and subsequent incineration) may be necessary. Long-term accumulation of heavy metals or unaltered toxic compounds in wetland vegetation or sediments may reduce their widespread distribution in the environment, but the concentrated deposits may contribute to detrimental effects of bioaccumulation and/or biotransport, may require periodic recovery/recycling procedures, or may restrict other uses of these areas.

2.6 THE ADVANTAGES AND DISADVANTAGES OF CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

Research and monitoring studies indicate that constructed wetlands offer an economical, largely self-maintaining, and therefore preferred alternative to conventional treatment of contaminated water. There is every reason to expect that these systems can continue to function reliably for long periods of time just as natural wetlands have, but only long-term operating data will confirm this expectation (Hammer and Bastian, 1989).

2.6.1 Advantages

If small communities are to meet the wastewater treatment requirements of the future, they must have treatment systems that are not only effective and reliable but also simple and inexpensive tp build and operate. Constructed wetlands, which appear to meet all these criteria, offer a promising alternative to conventional treatment plants and the advantages are summarized below:

- Constructed wetland systems are relatively inexpensive to construct and operate (low capital, construction, operational and maintenance costs (Hammer, 1989)).

- Systems are sustainable, generally self-maintaining and require little or no operator supervision.

- Systems provide effective and reliable wastewater treatment (ability to improve water quality is well-documented).

- Systems are relatively tolerant of fluctuating hydrological and contaminant loading rates.

- Systems may provide indirect environmental benefits such as green space, wildlife habitats, flood control and recreational and educational areas.

An exciting derivative of constructed wetlands is their benefit as wildlife habitats. Although wildlife cannot be the primary purpose, proper planning, implementation, and maintenance can enormously enhance the value of constructed wetlands for wildlife (Kadlec and Knight, 1996; Knight, 1996). For example, establishing vegetation for wildlife food and cover should be an integral design element. Constructed wetlands that maximize the edge area (see Section 2.3.1), provide transition zones into the upland areas, and use existing wildlife corridors, are examples of important design considerations.

2.6.2 Disadvantages

Because wetlands are naturally functioning ecosystems, there are some inconvenient factors which cannot be avoided. The disadvantages of constructed wetlands relative to conventional systems are summarized below:

- Land area requirements for treatment are relatively large (unit volume 50m^3 land per m^3 per day of flow).

- Slow rate of treatment in comparison to conventional systems.

- Treatment during winter is impaired - low temperatures slow biological reactions; freezing lowers water depth and prevents aeration and mixing of the water by the wind. Most commonly used plant species are seasonal in that shoots are produced in spring and die back in winter, so that their uptake of nutrients during winter is negligible.

- Most plant species commonly used for wastewater treatment die if the substatrum dries out.

- Design and operating criteria currently imprecise.

- The problems of biological and hydrological complexity and the lack of understanding of important process dynamics.

- Constructed wetlands take at least 2-3 years to become established; during this time treatment efficiency may be low.

- Substrate may eventually (tens of years) become saturated with metals and therefore need to be renewed. The fate of toxic contaminants is an obvious management concern. *Spent* substrate will need to be disposed of in a way that will minimize subsequent environmental impact. The wetland will need to be rebuilt (spent substrate may have economic potential for metal recovery). Harvesting and repeated cutting of emergent plants would have an effect of reduced growth as well as causing disturbance and mobilization of the contaminated substrate. However, general experience has shown that emergent macrophyte systems do not need frequent harvesting. Metals, as in the case of nutrients, appear to be locked into intractable organic material and are returned to the sediment when the plant tissue decomposes. It is these sites of organic sedimentation that support denitrification processes vital to the removal of nitrogen compounds (see Section 2.5.2.2). Regular monitoring of the macrophytic community is certainly necessary and at some stage harvesting may be required to restore vigour to old macrophyte stands.

- Some plant species are weeds in many areas, especially in irrigation, drainage and flood abatement channels where they can severely restrict water flow (Hocking, 1985).

- Possible problems with pests and odour (especially in tropical climates).

- Use of constructed wetlands may be limited by steep topography, shallow soils, a high water table, or susceptibility to severe flooding (especially in tropical climates).

- Impacts on wildlife are still unknown. While potential benefits of constructed wetlands as wildlife habitats are well known, full benefit realization is dependant on related issues and research needs. The possible impact that wetlands constructed for wastewater treatment might have on the short and long-term viability of wildlife attracted to these areas is difficult to assess as is the lethal and sublethal impacts of contaminants in water, vegetation and soils on wildlife. The question of who has legal responsibilty for potential impacts, especially in the case of migratory or threatened and endangered species, how these problems can be anticipated, avoided and remedied needs to be addressed. Obviously, there is a need to initiate long-term research to eliminate such uncertainities and to answer these and other questions on such systems.

2.7 PROCESSES OF METAL REMOVAL IN WETLANDS

2.7.1 Introduction

Wetland systems reduce many contaminants, including biochemical oxygen demand (BOD), suspended solids (ss). nitrogen, phophorus, trace metals, trace organics, and pathogens. This reduction is achieved by diverse treatment mechanisms: sedimentation, filtration, chemical precipitation and adsorption, microbial interactions (especially oxidation), and uptake by vegetation. These removal mechanisms are summarized in Table 2.4 (Stowell *et al.*, 1980).

Figure 2.8 illustrates the processes of metal removal that may take place in a wetland. Since this is a relatively new field, the various removal mechanisms, the relationship between them and their relative importance are not well understood and only limited information is available (Watson *et al.*, 1989).

General research on water quality functions of wetlands, as reviewed by Hemond and Benoit (1988), suggest that while some metal accumulation occurs due to plant uptake, significant removal occurs due to complex biogeochemical reactions within oxidized and reduced regions of wetland soils. Also experience with wastewater treatment by natural

Table 2.4 Containment removal mechanisms in aquatic systems employing plants and animals (After Stowell *et al.*, 1980).

Mechanism	Contaminant affected[2]	Description
Physical		
Sedimentation	P - Settleable solids S - Colloidal solids I - BOD, N, P, heavy metals, refractory organics, bacteria and virus	Gravity settling solids (and constituent contaminants) in pond/marsh settings
Filtration	S - Settleable solids, Colloidal solids	Particulates filtered mechanically as water passes through substrate, root masses, or fish
Adsorption	S - Colloidal solids	Interparticle attractive force (van der Waals force)
Chemical		
Precipitation	P - Phosphorus, heavy metals	Formation of or coprecipitation with insoluble compounds
Adsorption	P - Phosphorus, heavy metals	Adsorption on substrate and plant surface
Decomposition	P - Refractory organics	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation and reduction
Biological		
Microbial Metabolism[2]	P - Colloidal solids, BOD, N, refractory organics, heavy metals	Removal of colloidal solids and soluble organics by suspended, benthic and plant-supported bacteria; Bacterial nitrification and denitrification; Microbially mediated oxidation of metals
Plant Metabolism[2]	S - Refractory organics, bacteria and virus	Uptake and metabolism of organics by plants; Root excretions may be toxic to organisms of enteric origin
Plant Adsorption	S - N, P, heavy metals, refractory organics	Under proper conditions significant quantities of these contaminants will be taken up by plants
Natural Dieoff	P - Bacteria and virus	Natural decay of organisms in an unfavourable environment

Key

[1] P = Primary effect; S = Secondary effect; I = Incidental effect (i.e. effect occurring incidental to removal of another contaminant).

[2] Metabolism includes both biosynthesis and catabolic reactions.

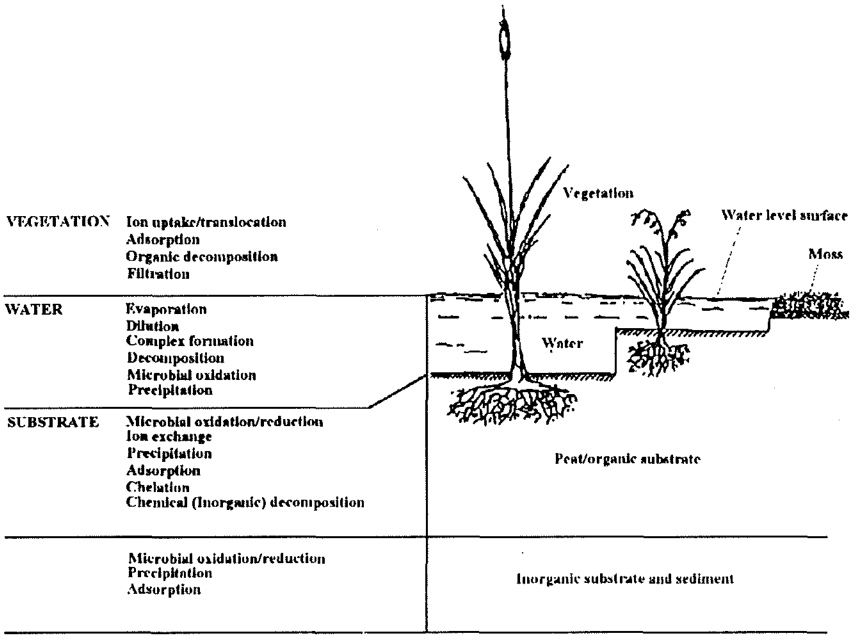


Figure 2.8 The processes of metal uptake that may take place in a wetland (From Kleinmann and Girts, 1987).

and artificial wetland systems indicates that pollutant removal can be enhanced by creating conditions that maximize surface area for water contact within the soil and plant root horizon (Crites *et al.*, 1988; Hammer, 1989 and Reed *et al.*, 1988).

2.7.2 Metal Chemistry In Aquatic Ecosystems

Metals are distributed amongst several phases and forms, which are more or less toxic and mobile. The main concentrations of metals in constructed wetlands are located in the substratum, in suspended particulate matter (arbritarily defined as being retained by a 0.45μm filter), in colloidal material, and in the water column as a soluble fraction consisting of hydrated ions and complexes, both organic and inorganic. The soluble fraction is considered to be most available and toxic to biota.

The distribution of metals in aquatic ecosystems, the significance of metal speciation and the range of analytical techniques available are described and discussed in several comprehensive reviews (Hart and Davies, 1978; Forstner and Wittman, 1981; Florence, 1982; Leppard, 1983; Salomons and Forstner, 1984; Batley, 1987, 1989).

Metals occur in either the soluble or particle associated form. The soluble form is most bioavailable, especially when the metal is present as either an ionic or weakly complexed species. Certain metals such as Cd and Zn have a stronger affinity for the dissolved phase whereas Pb is predominantly particulate associated (Morrison *et al.*, 1994).

The majority of metals present in aquatic ecosystems are found in suspended particulates and in bottom sediments, either incorporated into minerals, adsorbed, precipitated or complexed with organic matter. The sediment consists of a mosaic of solid phases, including quartz, layer silicate clay minerals, various oxides and hydroxides of iron, manganese and aluminium, carbonates, phosphates, sulphides and particulate organic matter, which together act as a large reservoir for metals. Particle size, which ranges from colloidal ($<0.1\mu m$ in diameter) to sand ($>20\mu m$) and gravel ($>2mm$), determines the surface area available for chemical reactions. Clay-size particles are highly reactive and usually consist of layer silicate clay minerals and quartz, often coated with hydrous oxides of iron and organic matter.

Metals are incorporated into the sediment by four main bonding processes:

(1) Cation exchange - a reaction where positively-charged metal ions in solution bind to negatively-charged sites on the surface of the plant matter. The cation exchange capacity (CEC) of a material is a measure of the number of binding sites per mass or volume. The attractive force for cation exchange is electrostatic and the size of this force depends on a wide range of factors. A cation in solution will displace a cation bound to a site on the surface if the electrostatic attraction of the site for the dissolved cation exceeds that for the bound cation, hence the term "cation exchange". Weider (1988) has shown that cation exchange does not represent a long-term method for wastewater treatment since all cation exchange sites quickly become occupied by heavy metals and cation exchange binding is a reversible process. For recently established wetlands, however, cation exchange may be an important mechanism whilst unoccupied cation exchange sites exist. The cation exchange properties of wetland vegetation is thought to be due to carboxyl functional groups (-COOH)

in humic acids of plant cellular tissue. The adsorption of metals to the surface of vegetation is a significant process in plants having a high surface area to volume ratio. Similarly, the CEC is influenced by the vegetative surface area for the displacement of cations by the more strongly positively charged metal ions in the wastewater (Cooper *et al.*, 1996).

(2) Adsorption - the binding of particles or dissolved substances in solution to sites on the plant surface - by hydrous iron and manganese oxides in sediments is thought to be a very important mechanism in controlling the distribution of trace metals in aquatic systems (Jenne, 1968). The sorption capacity of the various sediment fractions decreases in the order: hydrous manganese oxides > humic acids > hydrous iron oxides > clay minerals. However, in soils sorption capacity differs for different metals (Taylor *et al.*, 1983). For example, manganese oxides adsorb Co strongly, but Ni can be more strongly adsorbed by iron oxides. Cu and Zn are also strongly concentrated in iron oxide phases. Metals are complexed or chelated with a range of organic materials such as algae, bacteria, detritus, and organic matter coatings on layer silicate clay or other mineral surfaces.

(3) Precipitation and co-precipitation, and

(4) Complexation or chelation (formation of complex compounds by intra-molecular hydrogen bonding).

In addition, sedimentation and coagulation of particulate and colloidal matter result in metal fixation in bottom sediments. Adsorbed, precipitated, co-precipitated and complexed metals are considered potentially bioavailable, because they can be released back into solution to restore equilibrium, whereas metals incorporated into mineral lattices are considered essentially unavailable to biota. Therefore, measures of total metal concentration in sediments do not adequately reflect the potential for plant uptake and toxicity.

The distribution of metals between sediments and solution is very sensitive to changes in physicochemical conditions. The potential bioavailability of metals in sediments is favoured by increases in the following parameters:

(1) *acidity,* which increases dissolution of hydrous metal oxides and carbonates and intensifies competition for exchange sites;

(2) *reducing power,* which (i) causes dissolution of hydrous metal oxides, with release of any adsorbed or co-precipitated metals, and (ii) reduces production of dissolved organic compounds;

(3) *salinity,* which increases competition for surface binding sites; and

(4) *the concentration of either natural or synthetic organic ligands,* which form soluble complexes with metals that would otherwise be adsorbed on solid particles.

Generally, soluble metal species dominate in waters which are acidic, low in alkalinity, suspended solids and concentrations of dissolved organic carbon; and in sediments which are acid and reduced. It follows that less soluble metal species predominate in neutral to alkaline, oxidized sediments.

2.7.3 Plant Uptake and Tolerance

2.7.3.1 Plant Distribution and Development of Tolerant Ecotypes

Studies show that metal accumulation in plants correlates poorly with metal concentration in sediments. Such studies include the publications on metal uptake by emergent hydrophytes growing in metal-contaminated sediments (Babcock *et al.*, 1983; Egler and Lapakko, 1988; Hutchinson, 1975; Mudroch and Capobianco, 1978; Schierup and Larsen, 1981; Sencindiver and Bhumbla, 1988; Taylor and Crowder, 1983a and Wells *et al.*, 1980).

Metal-tolerant terrestrial ecotypes have evolved through genetic adaptation (Antonovics *et al.*, 1971), but mechanisms of metal tolerance in emergent wetland plants are not well understood. Some genera of emergent hydrophytes, notably *Schoenoplectus* and *Typha*, are more tolerant than others (Blake and Dubois, 1982). Taylor and Crowder (1983a;b) studied metal uptake by *Typha latifolia* in detail. In plants acclimatised to soils with a high Cu and Ni content, these metals were largely excluded fron the above-ground parts of the plant, but accumulated in the root stock. Fe and Mn were accumulated by the above- and below-ground parts. Leaf tissue metal concentrations for unacclimatised *Typha latifolia* plants exposed to high concentrations of heavy metals in solution culture may reach 460μg/g of Ni and 130μg/g Cu (Taylor and Crowder, 1983b). Leaf tissue metal concentrations of 190μg/g Cu and 240μg/g Zn have been noted in *Typha* plants receiving urban runoff (Zhang *et al.*, 1990). *Typha* root tissue concentrations of 440μg/g Pb (Lan *et al.*, 1990) and 2400μg/g Zn (Blake *et al.*, 1987) have also been noted. Studies of *Typha* species by McNaughton *et al.* (1974), Taylor and Crowder (1983a) and Dunbabin (1989) have found no evidence that the development of tolerant ecotypes is a prerequisite for colonising metal-contaminated sites.

2.7.3.2 Distribution of Metals After Uptake into Plants

Typha domingensis growing on mine sites contained higher concentrations of metals than the same species growing on non-mine sites and yet remained healthy, demonstrating that it is capable of tolerating enhanced levels of metal in tissues without serious physiological damage (Dunbabin, 1989). Metal concentrations consistently decreased in the order roots > rhizomes > non-green leaves > green leaves (as confirmed by Zhang *et al.*, 1990). Under contaminated conditions the greater proportion of the metal taken up by the plants was retained in the roots. The low concentrations of Cd, Cu, Pb, and Zn found in the green shoots relative to roots and sediments indicates that, under field conditions, harvesting shoots to remove metals from wetlands is not worthwhile (Dunbabin and Bowmer, 1992).

2.7.4 Effect of Substrate

The substrate of a natural or constructed wetland will have an organic soil ecosystem; an upper aerobic portion underlain by a lower anaerobic layer with a thin transitional layer between the two (Sikora and Keeney, 1983). In the anaerobic layer, metabolic action of microorganisms leads to anaerobic conditions with the characteristic redox potentials and the predominance of reduced forms of carbon, nitrogen, phosphorus, manganese, iron and other elements. Large vertical gradients of oxygen, temperature, and redox potential as well as the amount of decaying organic matter present characterize the upper, aerobic layer indicating that it is chemically dynamic. The aerobic layer tends to be thin, due to oxygen diffusion being restricted by the high resistance of the substrate and the high demand for oxygen within this layer (Good and Patrick, 1987) although oxygenation of the substrate by wetland plants, a result of the oxidized zone around the roots of the plant - the rhizosphere, greatly increases the amount of the substrate that is aerobic.

Wetland sediments are characteristically reduced and rich in organic matter making them effective sinks for metals (Giblin, 1985). General methods of metal-removal in the substrate include the direct mechanisms of cation exchange and adsorption and physical filtration, and indirect ones - providing physical support for wetland plants and providing attachment surfaces for microbial populations including sulphate-reducing bacteria and actinomycetes which have been shown to bind to heavy metal ions (see Section 2.7.5) (Mattuschka and Straube, 1993) and selectively scavenge metals (Pradhan and Levine, 1992). Possible mechanisms of metal retention in sediments include ion exchange, precipitation, and complexation with organic matter (Chan *et al.*, 1982). Water depth, organic matter content, texture, and iron and manganese content have all been identified as important in determining sediment metal concentrations (Grieve and Fletcher, 1976; Mudroch and Copabianco, 1978 and Pita and Hyne, 1975).

As mentioned earlier, soil chemical reactions in natural wetlands are dominated by anaerobic conditions and wetlands are important reducing systems on the landscape. However, few freshwater wetland ecosystems are permanently flooded, so wetlands maintain a wide range of oxidation-reduction reactions on the landscape thus allowing them to function as effective sinks for nutrients and metals (Faulkner and Richardson, 1989).

2.7.5 Microbe-Metal Interactions

Wetland substrates can be separated into two zones: the aerobic zone (containing a high proportion of organic material), and the anaerobic zones (dominated by the inorganic matter). The presence of metal-oxidising bacteria in the aerobic zones and sulphate reducing bacteria in the anaerobic zones will cause the precipitation of metal oxides and sulphates respectively (Batal *et al.*, 1989). There are six distinct chemical processes between microorganisms and metals (Ford and Mitchell, 1992):

(1) Intracellular accumulation. Bacteria and microbial cells can concentrate metals by interaction with surface ligands followed by slow transport into the cell. Cu and Zn, for example, are incorporated into enzymes this way and thus detoxified.

(2) Cell wall-associated metals. The presence of certain functional groups allows many metals to bind to cell walls.

(3) Metal-siderophore interactions. Sideraphores are chelating agents which facilitate uptake of ferric ions mainly.

(4) Extracellular mobilization/immobilization of metals by bacterial metabolites. Microbial reduction can release acidic metabolites or toxic metals and cause leaching. Immobilization occurs because of formation of insoluble salts by bacterial activity.

(5) Extracellular polymer-metal interactions. Many microorganisms produce extracellular polysaccharides that strongly bind metals.

(6) Transformation and volatilization of metals.

2.7.6 Processes in Wetland Waters Affecting Metal Concentration

The effectiveness of a wetland to treat wastewater will depend on the rate at which metal contaminants and acidity are removed from the water column. The ultimate fate of any removed contaminants will be in the substrate. Seven processes affect the concentration of metals in the water of a wetland.

(1) *Dilution* is the simplest way to change metal concentration. Wetlands tend to be found at low points in the landform, so additional water inputs from surface drainage or precipitation will act to dilute the wastewater. Additional water inputs may contain alkalinity and thus raise pH.

(2) *Evaporation* from the water surface will increase the concentration of metals, lower the residence time and thus reduce treatment effectiveness.

(3) Dissolved metals may form *complexes* with the suspended matter which may subsequently settle in the substrate.

(4) Bacteria are thought to catalyse *oxidation and hydrolysis* of dissolved iron, causing it to precipitate.

(5) *Precipitation* of iron hydroxides can cause other metal ions to become precipitated (co-precipitation).

(6) *Neutralization* of acidic wastewaters by available alkalinity will cause metal ions to precipitate.

(7) *Acidification* generally converts metals into more soluble bioavaliable forms.

2.8 DESIGN, CONSTRUCTION AND OPERATION OF CONSTRUCTED WETLANDS

2.8.1 Introduction

Constructed wetland technology is emerging as a low-cost, easily operated efficient alternative to conventional treatment systems for a wide variety of wastewaters. Although use for a variety of wastewaters is increasing, information on design, operation, and performance is limited and, in some cases, confusing. The information available is adequate for system design to reduce targeted pollutants but inadequate to optimize design and operation for consistent compliance (Watson *et al.*, 1989).

2.8.2 Types Of Wetlands

The distinction between wetlands is based on whether or not flow is confined to the substrate. This is determined by the hydraulic conductivity of the substrate and by water level. The terminology is confusing in that subsurface water flow is likely to occur in a surface flow wetland but at a much lower rate than surface flow.

A constructed wetland designed for surface flow consists of basins or channels, soil or another suitable medium to support emergent vegetation, and relatively shallow water flowing through the unit. If seepage needs to be prevented, a liner is incorporated into the design.

A subsurface flow system consists of a trench or bed containing a medium that supports growth of emergent vegetation. Media used have included crushed stone, gravel, and different soils, either alone or in combination. Most beds are underlain by impermeable material to prevent seepage and assure water level control. Wastewater flows laterally and is purified during contact with media surfaces and vegetation root zones. The subsurface zone is saturated and generally anaerobic, but excess oxygen conveyed through the plant root system supports aerobic microsites adjacent to roots and rhizomes.

Of the two types, surface flow wetlands are simpler to design and construct and require simpler inlet distribution structures. Emergent wetland vegetation is used in surface flow systems. A water depth can be selected that is optimum for the chosen wetland species. Surface flow systems are, however, subject to ice-cover in cold climates. There has been limited research on the effects of snow or ice-cover, but treatment efficiency will be lowered because effective water depth is reduced and hence retention is reduced (Kadlec, 1989a).

Subsurface flow systems provide for greater contact between wastewater and substrate but are prone to clogging with precipitated metal hydroxides and may experience problems with invasive weeds. Design is more difficult and a constant flow rate is important to avoid breakthrough (resurgence of the water before the outlet). Influent distribution structures require closer attention as does the choice of substrate.

Constructed wetlands with subsurface flow are widely used in Denmark, West Germany, Austria, Switzerland, and other European countries to treat screened raw sewage or primary effluent. They have been described as root-zone systems, reed bed, hydrobotanical system, soil filter trench, biological-macrophytic, and other marsh beds by various proponents. All these systems use soil to support the vegetation. Most of these constructed wetlands are derived from the German designs based on the original work of Kickuth (1984). These are vertical and/or horizontal flow systems where macrophyte root zones become oxygen-rich microzones in an otherwise anoxic or anaerobic environment (Ellis, 1993).

2.8.3 Site Selection

Several research groups (Brodie, 1989; Reed *et al.*, 1988) have considered the factors involved at the site-selection stage. These include:

- Proximity to source of runoff;
- Proximity to suitable discharge point;
- Land availability (knowledge of property ownership, restrictions placed by previous, current or future land uses, public opposition);

- Hydrological factors (surface and groundwater flow patterns and water quality, drainage basin characteristics, implications for downstream users); a detailed water budget should be constructed;
- Access factors (access for construction equipment and personnel, and for delivery of equipment and materials, provision of long-term right of access for maintenance necessary);
- Availability of utilities (electricity, if pumping required);
- Geological considerations (character of surface materials and soils, depth of bedrock which must exceed excavation depth, availability of construction materials); and
- Topographic considerations (it must be possible to obtain a slope of 0-3% for the base of the wetland without extensive earthmoving); topography also affects drainage and erosion potential, access and slope stability.

Information and techniques available include soil surveys, geological, and topographic maps, aerial photographs, walkover surveys, and site investigations, such as auguring, test pit digging, percolation tests, and mapping.

2.8.4 Preliminary Design Considerations

Preliminary design considerations include:

- A knowledge of the chemistry of the drainage and hydrology of the area;
- Whether wetland treatment is necessary (comparison of drainage chemistry with regulatory requirements will enable the assessment of the degree of treatment required and partially answer this question);
- Possession of background information on runoff and good knowledge of the surface and ground water hydrology;
- Constructing a complete water budget for the site (this includes investigations of all inflows and outflows of surface water, rainfall, estimation of water losses by evapotranspiration and subsurface losses and gains);
- Availability and costs of plants and substrate;
- Treatment efficiency of the available substrates; and

- Long-term cost of the wetland compared to other treatment systems.

2.8.5 Construction Plans

Minimum contents of a construction plan for a wetland for wastewater treatment are given by Tomljanovich and Perez (1989). These can be used as the basis for a construction plan for urban runoff treatment. The minimum requirements are:

- Site clearing limits;
- Access roads;
- Utilities (overhead and underground);
- Erosion control measures;
- Location and boundaries of designated areas;
- Trees and existing vegetation to be left undisturbed;
- Wildlife habitat enhancement structures;
- Dyke location, length, top width, elevation, freeboard, and upstream and downstream slopes;
- Spillway location, elevation, and type (riprap, concrete, vegetation);
- Size, location, elevation, and type of water control structures;
- Permeability for substrate and dykes;
- Impermeable linings (type, location) where required;
- Placement of substrate materials;
- Species and spacing of vegetation to be planted;
- Liming and/or fertilizer requirements;
- Seeding, mulching, fertilizing, amd liming of dykes and disturbed land; and
- Inlet and outlet distribution piping (type, location, elevation).

The level of detail will depend on size and complexity of the wetland, site characteristics, and regulating requirements.

2.8.6 Preconstruction Site Activities

These should include marking and clearing the site, identifying any need for temporary diversion or pumping of water, and identifying materials that can be reused (Tomljanovich and Perez, 1989).

2.8.7 Cost Estimate Preparation

Preparation of cost estimates vary depending on whether the wetland will be constructed by the owner/operator or contracted out. In either case, cost estimates include the following items: engineering plan, preconstruction site preparation, construction (labour, equipment, bill of materials), supervision, and indirect and overhead charges.

2.8.8 Construction Details

Various authors (Howard *et al.*, 1989c; Kleinmann *et al.*, 1986; Steiner and Freeman, 1989; Tomljanovich and Perez, 1989) give useful details and suggestions for wetland construction:

Equipment: The correct type and size of construction equipment is critical and the equipment used should be appropriate for the ground conditions.

Liners: All components should be lined to isolate them from groundwater. A permeability of less than 10^{-6}cm/s is desired. Liners should be strong and thick and resistant to puncturing.

Dykes: Some dyke seepage is usually acceptable, therefore on-site borrow materials are often appropriate. Dykes should be compacted and sloped and together with other disturbed areas, should be revegetated as soon as possible after construction.

Inlets and Oulets: The distribution system of pipes and sumps should avoid sharp bends or traps which allow for the accumulation of precipitates and should provide adjustable delivery of the runoff. In cold climates, the distribution system should be insulated. Corrosive resistant coating should be used for pipes and sumps if pH <5.0.

In a research wetland, test wells should be installed to sample interstitial water (see Watson and Hobson, 1989).

Miscellaneous: Control of water is vitally important during construction. Design should be flexible enough to allow for on-site modification, for example, to account for new seeps discovered during construction. A polishing and treatment area downstream from the wetland may be needed to comply with discharge laws during construction.

2.8.9 Inspection, Testing And Startup

Before accepting the final product, the owner/operator should require a thorough test of all components to ensure proper operation of pumps and water control structures, sealing, water level, flow distribution, and plant survival. An initial maintenance program that includes frequent and thorough inspection and immediate correction of problems is critical to ensuring successful operation of wastewater treatment wetlands.

2.8.10 Considerations And Factors Influencing Wetland Establishment

Three important factors contribute to the diversity of natural wetlands and form the basis for any wetland development scheme. These are (1) hydrologic considerations, (2) substrate, and (3) vegetation. Variations in hydrology and substrate have a strong influence on vegetative diversity. By understanding the relation between these factors, it is possible to determine which species should be planted, by what means, and under which given environmental conditions (Allen *et al.*, 1989).

2.8.10.1 Hydrologic Considerations

Water depth and frequency of flooding or its periodicity are important in determining the plant species appropriate to a constructed system. Water depth causes different vegetation zones in a wetland partly because deeper water restricts oxygen from reaching the substrate (DuLaunie *et al.*, 1976). Water depth also influences the degree of light penetration and photosynthesis.

Periodicity, duration, and seasonality of flooding are important for selecting plant species to be used for wetland development. Wetland plants can withstand various degrees of flooding depending on when and for how long the flooding occurs. Many wetland emergent plants need a period of lower water level during the growing season, whereas in the dormant season the water level is not as important. Water quality factors affecting selection of wetland plants include such factors as water clarity (especially for submerged aquatic species), pH, salt concentration, and dissolved oxygen.

2.8.10.2 Substrate

Many substrates are suitable for wetland establishment. Loamy soils are especially good because they are soft and crumbly, allowing for easy rhizome and root penetration. But fine- textured soils such as clays may limit root and rhizome penetration. Low nutrient content may limit growth and development as may excessive nutrients. However, because of the nutrient-rich influent, substrates with low nutrient concentrations may be suitable in constructed wetlands for wastewater treatment if other requirements are met. Because hydrophytes grow well in a broad range of soil types, soil changes are usually not necessary. Other studies (Brodie *et al.*, 1988; Stillings *et al.*, 1988) further suggest that substrate type is unimportant once the wetland has become established.

Although peaty organic soils support wetland plants, they are not preferred for wetland development. They are low in nutrients because organic acids, yielding many hydrogen ions, occupy cation exchange sites, and once flooded they have a loose, soft texture that provides inadequate support for emergent aquatics. In such soil, it might be necessary to anchor each planting unit individually.

Site excavation for wetland establishment is likely to expose a subsoil that may not be as conducive to plant growth as the topsoil. Clays and gravels which frequently underly more favourable soils may be sufficiently dense or hard to inhibit root penetration, may lack nutrients found in topsoil, or may be impermeable to water needed by roots (Emerson, 1961; Wein *et al.*, 1987).

Sandy, coarse textured, and subsoil substrates often lack nutrients and may require fertilizers (Kadlec and Wentz, 1974). However, sandy soils hold plants well and prevent them from floating out of the planting surface, in contrast to peaty or silty soils. Planting in sandy soil can be efficient and inexpensive because of its ideal texture for hand planting; however, sand or gravel are prone to drying out quickly and may need irrigation if water levels cannot be maintained at the root level.

Nutrient conditions in constructed wetlands are improved by natural processes and by horticultural techniques. In coastal salt marshes, coarse-textured soils and subsoils frequently are nutrient-poor (Knutson and Woodhouse, 1983) and require fertilization.

The substrate should be analysed prior to use to assess hydraulic conductivity, pH, buffering capacity, plant nutrient concentrations, and microbial activity. Hydraulic conductivity is important if the purification processes are largely confined to the rhizosphere and root zones (i.e. areas of target accumulation). Good horizontal flows are required in these barrier zones and channeled short-circuiting must be avoided. Gravel might provide a more suitable substrate for emergent macrophytes within constructed wetlands since it would allow adequate root growth, support high hydraulic loadings and increase permeability (Howard *et al.*, 1989c).

The depth of substrate influences retention time in a subsurface flow wetland. In a surface flow wetland, water depth is the most important determinant of retention time. Factors influencing the selection of depth in a subsurface flow wetland include desired retention time, depth of root penetration, cost of substrate, and climate. A maximum root penetration of 0.3m has been observed for *Typha latifolia* and one of 0.6m for *Phragmites* (Reed *et al.*, 1988). In extreme cold climates, substrate depth may need to be increased further such that temperatures suitable for sulphate-reduction can be maintained all year round (3-5^{0}C minimum) (Howard *et al.*, 1989c).

2.8.10.3 Vegetation

The vegetative component is a major factor in successful wetland development. Which plants will grow given the hydrological and substrate conditions in the developed wetland? Which plants provide the appropriate attributes for wastewater treatment? How are plants to be selected? For wastewater treatment, plants selected should (1) be active vegetative colonizers with spreading rhizome systems; (2) have considerable biomass or stem densities to achieve maximum translocation of water and assimilation of nutrients; (3) have maximum surface area for microbial populations; (4) have efficient oxygen transport into the anaerobic root zone to facilitate oxidation of reduced toxic metals and support a large rhizosphere; and (5) be a combination of species that will provide coverage over the broadest spread of water depths envisioned for the terrain conditions. These above attributes must be intergrated with the hydrological and substrate conditions in choosing species for planting (Allen *et al.*, 1989).

Reedmace or cattail (*Typha*) marshes are probably the simplest types of wetland systems to create, due to their monotypic structure, aggressive and productive growth habits, and wide tolerance to hydrologic and edaphic conditions (Dobberteen and Nickerson, 1991).

It is important to understand how a particular species might react to given wetland conditions before that species is nominated for use in a wetland development project. The results of a study by Vedagiri and Ehrenfeld (1991) clearly show that the availability of metals to plants may be as strongly influenced by the plant community within which the plant grows as by the character of the soil and water of a site. As mentioned earlier, water depth dictates zonation of wetland plants, and species should be selected primarily on this criterion (Figure 2.9). *Typha latifolia* is in many ways an ideal plant species for constructed wetlands. Many factors influence this choice as listed below:

- Tolerance to high metal concentrations. *Typha* can tolerate high metal concentrations (Kleinmann, 1990).

- Effect of water level. The use of *Sphagnum* species was abandoned due in part of their poor tolerance of fluctuating water levels. *Sphagnum* only tolerates inundation for a short while (Kleinmann *et al.*, 1986). *Typha* may come to dominate if the standing water depth exceeds 0.15m; as depth increases sedges

(*Carex* species) give way to clubrushes (*Scirpus* species), clubrushes to *Typha* (Reed *et al.*, 1988). Maximum depth and other physico-chemical conditions for selected wetland plant species are given in Table 2.5.

- Oxygen transfer capability. The decreasing order of oxygen release per unit mass for five wetland plant species was found to be *Typha latifolia, Juncus effusus, Sparganium americanum, Eleocharis quadrangula,* and *Scirpus cyperinus* (Michaud and Richardson, 1989).

- Root proliferation. *Phragmites* and *Scirpus* provide the greatest root proliferation while *Typha* species have limited root proliferation and overwintering capacity (Wood, 1990).

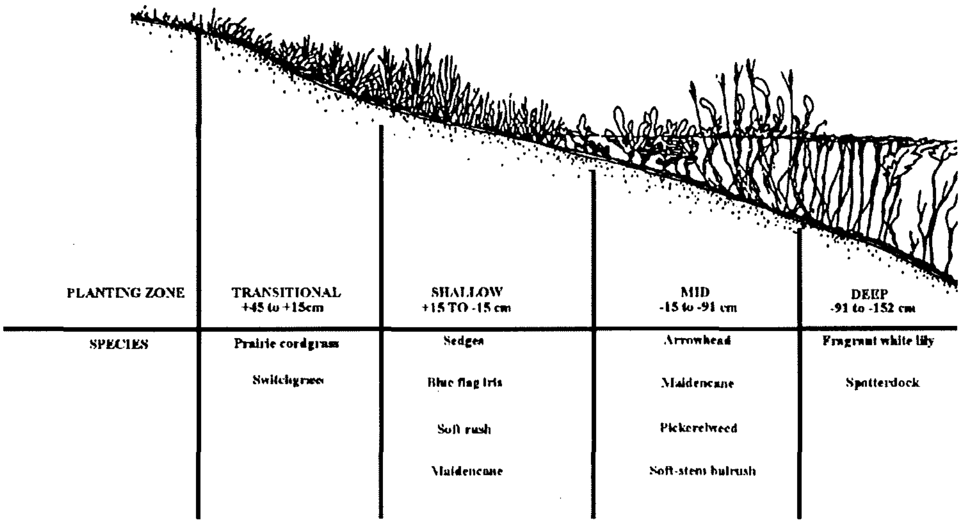
- Soil requirements. *Typha* will grow in a wide variety of media; sedges can be grown in silty clays (Reed *et al.*, 1988).

- Availability and transplantability. Local species of vegetation, tolerant to environment and climate, are recommended. *Typha, Phragmites,Juncus, Scirpus,* and *Carex* species are cosmopolitan in distribution (Reed *et al.*, 1988). *Typha* are easy to transplant, *Sphagnum* and other mosses are not easy to obtain or transplant (Kleinmann *et al.*, 1986).

- Availability of tolerant ecotypes. Use of metal-tolerant ecotypes (populations within a particular species) of a particular wetland plant will enable runoff with higher metal concentrations to be treated.

- Supply of organic matter to the substrate. Some wetland plants (e.g. *Molinia*) species die in the winter thus supplying a large amount of organic matter to the substrate.

- Diversity. There is usually no need to reproduce natural wetland diversity in surface flow wetlands since *Typha, Typha* and *Phragmites,* or *Typha* and *Scirpus* tend to dominate (Reed *et al.*, 1988). (Note: experiments by Nickerson and



PLANTING ZONE	TRANSITIONAL +45 to +15cm	SHALLOW +15 TO -15 cm	MID -15 to -91 cm	DEEP -91 to -152 cm
SPECIES	Prairie cordgrass	Sedges	Arrowhead	Fragrant white lily
	Switchgrass	Blue flag iris	Maidencane	Spatterdock
		Soft rush	Pickerelweed	
		Maidencane	Soft-stem bulrush	

Figure 2.9 Typical interior United States wetland by planting zone, as they are related to normal water level (0.0cm) (From NRA, 1992).

Dobberteen (1988) on growth of *Typha* species under the polluted environment at a landfill suggest that *Typha angustifolia* exhibits better growth than *Typha latifolia* in terms of maximum stem density and plant height).

Little is known about the nutrient requirements of individual hydrophytes, and consequently general fertility concepts are often applied.

2.8.10.4 Sources Of Plant Materials

Wetland plants can be purchased from nurseries, collected in the wild, or grown for a specific project. Most authors agree that for most projects, wild collected material is most desirable for the following reasons. Only a few commercial nurseries specialise in wetland plants for wetland construction and commercial suppliers carry only a limited number of species. Nursery-supplied plants are also genetically and physiologically adapted to their growing site and may be difficult to establish and maintain at locations with different edaphic and climatic characteristics. Finally, plants that have to be packaged, transported, and stored before planting may be stressed at the time of planting.

Plants collected from the wild are more closely adapted to local environmental conditions than nursery-acquired plants. They can also be planted with limited storage.

Table 2.5 Physico-chemical conditions for selected wetland plant species (From Warburton *et al.*, 1985).

Plants	Depth Range (m)	Salinity	Alkalinity (mg/l $CaCO_3$)	pH
Sedges (*Cyperus* spp. and *Carex* spp.)	<0.30	fresh-water	-	-
Rushes (*Juncus* spp.)	wet soil	-	-	-
Reedgrass (*Phragmites australis*)	-1 to 2	fresh or brackish water	0.5-298	3.7-9.0
River Bulrush (*Sparganium fluviatilis*)	<0.50	fresh or brackish water	30-220	7-9.1
Bur-reed (*Sparganium eurycarpum*)	<1.20	fresh-water	35-376	6.7-8.8
Cattail (*Typha latifolia*)	<0.30	fresh or brackish water	10-376	4.5-9.0

If a diverse natural ecosystem is desirable, natural populations can supply that diversity.

2.8.10.5 Other Considerations

There are still a number of areas and matters relating to vegetative systems that require further information. These include:

- Hydrology and loading effects; what is the long term effect of variable flows and shock loadings on the efficiency of the uptake mechanisms?
- The optimum properties of water depths, basin geometry and substrate sediment composition needed for differing vegetation species to maximize uptake.
- The long-term management strategies for maintaining operational effectiveness. There is still insufficient information on optimisation techniques for improving system efficiency.
- Insufficient knowledge of the uptake and release mechanisms for toxic metal and organic compounds.

These points and others are discussed in further detail in Hammer (1989) and Kadlec and Knight (1996). Whalen *et al.* (1989) describes in detail the design, construction and cost of a constructed bulrush wetland designed by Lombardo & Associates, Inc., Boston, Massachusetts, for the purpose of denitrifying septic tank effluent collected from 2000 homes. A simple combination marshland design for highway runoff treatment is given in Figure 2.10. Watson *et al.* (1989) describe the typical arrangement for a reed bed treatment system and Kadlec and Knight (1996) describe wetland project planning and design and wetland treatment system establishment, operation and maintenance.

2.9 PUBLIC PERCEPTION OF WETLANDS AND THE RESEARCH FRAMEWORK REQUIRED

2.9.1 Public Perception of Wetlands

2.9.1.1 Historical Perception of Wetlands

A negative image of wetlands can be traced back to ancestral European where the "bog-swamp" mythology developed, and where people believed strange mythical creatures lived in wetlands (Jorgensen, 1971). After the industrial revolution attitudes toward wetlands changed from fear to indifference. Wetlands were generally believed to be wastelands which caused disease and produced mosquitos (Smardon, 1975). Growth in wetland awareness is directly related to an increase in scientific knowledge (about the processes and functions of wetlands) and also by changing attitudes to wetlands which increasingly see them as valued environments.

The origin of this changed attitude is the USA where wetland awareness grew from many sources. First, recreation, wildlife and hunting enthusiasts, who had the support of the Fish and Wildlife Service (FWS), an agency of the Department of the Interior, stimulated interest in the value of wetlands from the mid-1930s. The decision by the FWS after 1934 to sell "duck stamps", which had to be purchased by wildfowl hunters to raise money for wetland preservation, created much publicity. Since then nearly one

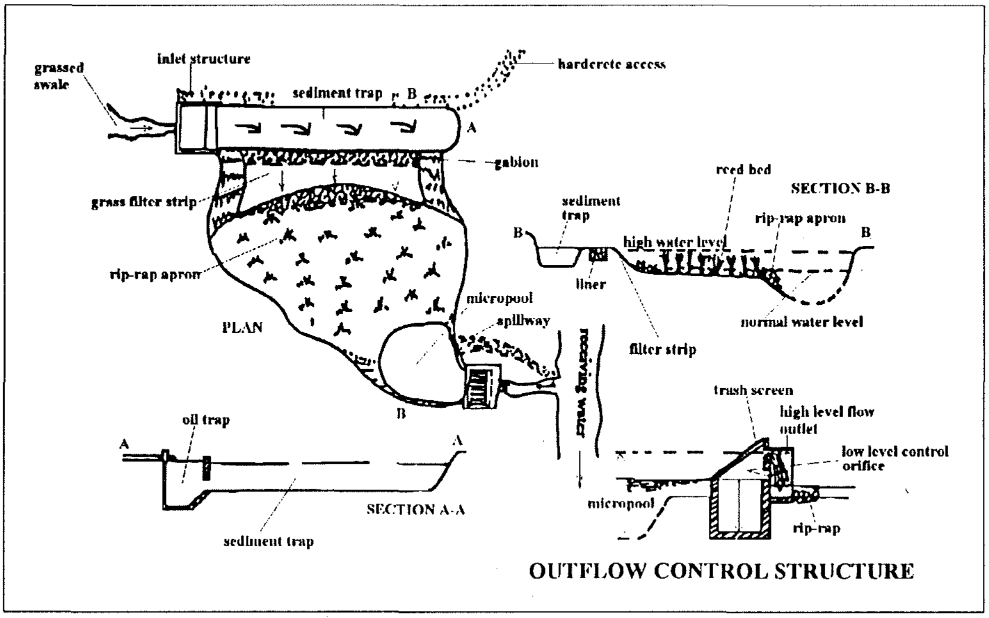


Figure 2.10 Combined wetland basin for highway runoff treatment (From Ellis and Revitt, 1991).

million ha of wetlands have been purchased. Additionally, the private duck hunting lobby, "Ducks Unlimited", which has over 600 000 members, promoted its aims through purchasing or creating 700 000 ha of wetland breeding grounds. The Audubon Society and the Nature Conservancy Council have also had a positive impact on public opinion by promoting wilderness preservation (Smardon, 1989).

Secondly, from the 1950s ecologists like Teal, Pomery and E. and H.T. Odum raised intellectual curiosity about wetlands. Thirdly, wetland research centres (Baton Rouge, LA, Sapelo Island, GA and Miami, FA) were setup. By the 1960s, the decade in which environmental issues became an agenda, all these different strands came together. In Europe, wetlands have been long recognised as being valuable habitats by ecologists (Purseglove, 1988) but it was not until the early 1970s that unchecked wetland drainage for agricultural purposes and thus wetland preservation became an issue (Smardon, 1989).

2.9.1.2 The Value of Wetlands

Natural environments - those that seem untouched by human activities - attract many people and wetlands offer opportunities for a "primitive" experience. Wetlands often rank high in aesthetic value against other landscape types, probably because of the broad appeal of the complex intermingling of the land-water interface. Because of the variety of water bodies, land forms, vegetation and animals, wetlands are full of different shapes and textures and allow for a distinctive sensual experience. The natural appeal is understandable since wetlands are often the last areas in the landscape to undergo development (Hammer, 1992).

The attempt to establish the natural processes and functions of wetlands and their resultant value to humans as an argument against their development and loss has a long history (Section 2.9.1.1; Williams, 1991). Proven and beneficial functions include physical, chemical, biological and hydrological processes. The biological functions lead on to a consideration of the socioeconomic consumptive benefits of the products of wetlands. Throughout the ages humans have been attracted by food production on reclaimed land, fuel from organic soils, fibre from hardwood forests, mangroves and reed swamps, and ubiquitously, fish, fowl and fauna (Chabreck, 1979; Crow and MacDonald, 1979; Palmisano, 1979).

Much more difficult to prove are the non-consumptive benefits. These include scenic or visual, recreational, educational, aesthetic, archaeological, scientific, heritage and historical benefits which are difficult to define, let alone quantify (Foster, 1979). These overlap and intertwine and consequently a precise definition is not possible (Leitch and Scott, 1977; Sather and Smith, 1984). They have thus been considered of secondary importance compared with the direct consumptive and economic products that can be quantified and have a monetary value put on them. Often the topic is approached through the media of literature and art (Fritzell, 1979; Niering, 1979), or through scenic and visual-cultural assessments (Haslam, 1973; Smardon, 1983; 1988). However, since it is not possible to measure these values objectively it is difficult to compare nonconsumptive with consumptive benefits, or even one non-consumptive type with another nonconsumptive type in the same wetland.

The one non-consumptive benefit that can sometimes be quantified is that of recreation, as the number of people participating and what they are willing to pay for the privilege of that participation in the form of license fees, equipment or travel, is a fairly accurate measure of its value. Thus it is estimated that 83.2 million Americans spent US $14.8 billion on observing and photographing wildlife in 1980-81 (Fish and Wildlife Service, 1982). But of course there is a fine dividing line between this type of passive, appreciative activity and the more active hunting and fishing activities, which fall firmly in the list of consumptive benefits of the products of wetlands.

2.9.1.3 Perception of Wetlands: Assessment of the Visual-Cultural Values of Wetlands

What little research there is on the public's perception of wetlands has focused on the monetary valuation of wetlands (Bateman *et al.*, 1992; Willis *et al.*, 1995) their visual-cultural values. Visual-cultural values are the finite natural resources available for human use and perception within or associated with wetland areas. They can thus be defined as the enjoyment derived from wetlands by people in terms of scenery, recreation and nature education (Smardon, 1983). Visual values place emphasis on visual perception and the visual quality of wetlands whereas cultural values place emphasis on the educational and recreational uses of wetlands. Wetlands are ideal areas for environmental education because of the ease with which important scientific principles can be observed and demonstrated. Basic principles of ecology - succession, trophic levels, food webs and nutrient and energy cycling - are more easily shown in a wetland than almost any other type of ecosystem. Wetlands support many types of direct recreation including hunting, trapping, fishing, wildlife watching, nature photography, berry picking, picnicking, hiking, walking and boating. These visual, recreational and educational values of wetlands are highly interdependent and correlate strongly (Levin, 1977).

A review of the literature shows that the assessment of the visual values of wetlands has been conducted by (1) comparing wetlands with other landscape types, (2) comparing specific types of wetlands with each other, (3) comparing wetlands with their immediate surroundings, (4) discussing the micro-landscape within wetlands, and (5) discussing the dynamic aspects of wetlands.

(1) Wetlands versus other landscapes: Wetlands rate high in aesthetic value compared to other landscapes. Tidal marshes, bogs and freshwater marshes rate fairly high in landscape quality in comparison to other landscape types (e.g. beach and water, suburban development, developed open land, commercial development and dense residential development) (Palmer, 1978; Steinitz *et al.*, 1978; Hammitt, 1978). The high scenic quality of wetlands is not paralleled by high recreational use. This could be partially explained by the difficulty of gaining physical access to or into wetlands which are composites of vegetation types and often densely vegetated and thus lacking in visual and physical access (Cheek and Field, 1977).

(2) Wetlands versus other wetlands: Little empirical work has been done on human preference for type of wetland. From the results of Smardon's fieldwork 1972, the average recreationist would prefer relatively open freshwater wetlands such as fresh meadows, shallow or deep freshwater marshes, bog mats, or low shrub swamps to thickly vegetated shrub swamps without visual clearance under the woody canopy. Other studies indicate the value of visually open ("spacious") wetlands (Palmer, 1978). The assumption that the larger a wetland is, the higher the visual-cultural value is not necessarily true. Small wetlands (less than 20 acres) may have high visual and educational values since from a visual and educational point of view, the most important quality is probably the diversity of attributes per unit area (Litton *et al.*, 1972; Steinitz *et al.*, 1978). However large wetlands can sustain a higher recreational use and may support more wildlife or a greater variety of wildlife.

(3) Wetlands and their immediate surroundings: The landform and types of vegetation surrounding the wetland are important in defining a visual image and sense of enclosed space. This spatial enclosure and edge contrast bordering a wetland is important to the wetland's scenic and recreational quality (Smardon, 1972, 1975). Preference testing shows that people in general prefer open water, forest and agricultural land adjacent to wetland areas. Wetlands adjacent to

rivers, small lakes, ponds and saltwater bays or inlets are optimum environments from a recreational and educational as well as visual perspective (Fabos *et al.*, 1975; Palmer, 1978).

(4) Wetlands and the micro-landscape within: When viewed in the context of the larger landscape (as in a photograph or from a car window) a wetland may be highly valued for providing openness and constrast in the landscape (Litton *et al.*, 1972; Palmer, 1978; Rodgers, 1970; Smardon, 1972, 1975). As the view shifts to the micro-landscape within the wetland, the scale changes as do the values. Work done by Hammitt (1978) on northern bogs indicates that people like to experience a mixture of open bog mat and wooded screens, which provide "mystery" or intrigue about areas yet to be explored. Access enhancements (e.g. boardwalks), if carefully sited and designed, may promote visual, recreational and educational values by providing access into an otherwise restricted and delicate area.

(5) Dynamic aspects of wetlands: Some dynamic aspects of wetlands include seasonal changes and their effects on vegetation (Rodgers, 1970; Smardon, 1972). Probably some of the most important aspects of wetlands in terms of visual-cultural values are those which are the hardest to assess. Rowntree (1976) notes the dynamic visual aspects of salt marshes, especially the tidal flow and how it influences the morphology of the vegetative community. Even more dynamic is wetland wildlife which in the US for example, may range from the glimpse of an occasional moose in nothern bogs or the American alligator in the Everglades to huge flocks of migrating waterfowl in wetlands along major flyways. Even in the cases of turtles basking on logs in the sun or kingfishers feeding, wildlife inevitably steals the show from its habitat.

2.9.1.4 Public Perception of Wetland Visual Values

A review of the literature shows that the visual preference in a landscape is related to a complex range of cultural, psychological and environmental factors. Past research has focused on the examination of information or stimuli provided by visual display. Lee

(1977), Smardon (1972, 1975) and Smardon and Fabos (1976) propose models using rating and ranking systems for evaluating visual-cultural values. From the study of visual preference values associated with river-swamp environments a model for visual preference has been developed. Four factors are identified as being important to visual preference in the environment, two informational variables (legibility and spatial definition) and two involvement variables (complexity and mystery). *Legibility* involves the clarity or coherence of a scene, aiding in individual recognition of visual elements. *Spatial definition* primarily involves the arrangement of three-dimensional space within the visual array and can be said to be a measure of the depth and enclosure of a scene. It affects orientation and has a definite influence on individual perception and preference. *Complexity* involves the number and relative distribution of landscape elements. *Mystery* concerns the promise of additional information and encourages an individual to enter a visual display in order to seek this additional visual data (Kaplan, 1975).

Levin (1977) attempted to test the validity of these concepts in application to analysis of riverscape preference. His study was founded upon the assumption that a visual experience on a river consists of a series of views or sequential glimpses down a river corridor. The general concepts proposed were used to create a model that could predict human preference for Louisiana river landscapes and other landscapes such as wetlands.These four variables appeared to be of value in the prediction of preference for river landscapes. These principles were then related to the primary landscape components - land, water and vegetation. Results indicate a strong interdependence between the evaluative factors. The strong interdependence indicates a scene will not possess exceptional preference value with one or two of the characteristics (legibility, complexity, spatial definition, mystery, distinction or disturbance) dominating.

A classification of wetlands by visual character provides an understanding of the distribution, nature and extent of different types of wetland landscapes in a given context. The physical attributes of wetlands that have been found to be important to visual values are water bodies, landform, surrounding land use and wetland vegetation. The key visual attributes identified are visual contrast and visual diversity of the wetland and its surroundings (Smardon, 1972).

Visual contrast and visual diversity are attributed to resource variables each of which is defined as follows: *Water-body size* is the existence and quantity of open water that borders, goes through, or is part of a wetland. *Surrounding land-use contrast* is the difference in edges, or height contrast, of the surrounding land uses. *Surrounding landform contrast* is the scale of the surrounding landform in relation to the size or scale of the wetland. *Internal wetland contrast* is the differences in vegetation edges or height and textural contrast of the internal edges of the wetland. *Water-body diversity* is the types of associated water bodies adjacent to or part of a given wetland. *Surrounding landform diversity* is the variety of landforms surrounding or adjacent to a wetland. *Surrounding land-use diversity* is the number of different land-use types that border a given wetland. *Wetland-type diversity* is the number of wetland types found within a wetland. *Wetland-edge complexity* is the complexity of the physical boundary of the wetland where it meets a landform or vegetation edge.

In classifying wetland visual attributes the following should be established based on the above assumptions: (1) To clearly and systematically identify and describe visual attributes important to wetlands and their surrounding landscape context, (2) to adapt and test a method of visual description in selected areas, and (3) to ensure that the descriptive classification is useful to planners and designers so that the visual attributes of wetlands can be protected.

2.9.1.5 Public Perception of the Use of Wetlands for Water Pollution Control

There is scant literature on the public's perception of use of wetlands for wastewater treatment. Literature reviews on perceived environmental quality has provided useful information as to how people will react to sensory environmental quality aspects of wetlands loaded with wastewater. It is known that perceived environmental quality hinges directly on the type of wetland use by the public. Smardon (1989) outlines a framework determining and enlisting public support for wetlands wastewater treatment projects and shows there is a need to understand the public perception of specific areas to be used for wastewater treatment by wetlands and using wetlands for wastewater treatment. There is also a need to collect physical site user data and determine whether wetland site(s) restrict or enhance usage and finally design interpretation/communication packages explaining the process of wastewater treatment by wetlands, including testing and re-testing to assess changes in attitudes or perceptions. Smardon (1986) has also developed a public use research programme for the Des Plaines River Wetlands Demonstration Project in Lake Country, Illinois.

2.9.1.6 Public Perception of the Wildlife Value of Wetlands

Although the presence of wildlife in wetlands is probably the most dynamic aspect of wetlands (see Section 2.9.1.3), ironically, little, if any, empirical perceptual or behavioural work exists on the aesthetic aspects of wildlife in wetland environments - the raison d'être behind popular demand for preservation of wetland environments. In view of the increasing emphasis on passive recreation and nonconsumptive values of wildlife, this is truly an overlooked area of research. The wildlife aspect is furthermore difficult to quantify economically, except as in the example of the calculations of the Fish and Wildlife Service (FWS) on how much was spent annually in the USA on, primarily, birdwatching (see Section 2.9.1.2).

2.9.2 Public Perception Research Framework

Questionnaire surveys are an efficient tool for studies on public perception (de Vaus, 1996). The research to develop a questionnaire that could measure public perception of the aesthetic and wildlife value of wetlands was divided into several stages. The aims of the study were closely defined (see Chapter 1) and previous research in this area was studied (see Section 2.9.1). Familiarisation with social survey techniques and methodology was achieved through several methods. An introduction into the topic was obtained from previous literature relating to survey methods (e.g. Bradburn *et al.*, 1979; de Vaus, 1996; Moser and Kalton, 1971; Oppenheim, 1966; Payne, 1951; Reynolds, 1990; Rossi, Wright and Anderson, 1983; and Youngman, 1978). An understanding of the methods and techniques utilised in question formulation, questionnaire design and interviewing was obtained from the literature and by undertaking a postgraduate diploma in survey research methods organised by the Department of Social Sciences (Middlesex University, 1993/94). The subsequent stages of the methodology as detailed in the literature are described in Chapter 6.

CHAPTER 3 ASSESSMENT OF HEAVY METAL REMOVAL FROM HIGHWAY RUNOFF BY A NATURAL WETLAND

3.1 INTRODUCTION

This chapter presents a preliminary assessment of the heavy metal removal performance of a natural wetland. The results are compared with the levels found in an adjacent stream which also receives runoff from the same major road (the A406 North Circular). Both the wetland and stream subsequently discharge effluent at proximal locations into the Brent Reservoir, a site designated as a Site of Special Scientific Interest (SSSI) in terms of both its flora and fauna by the Environment Agency, in NW London. It has a further role as that of a recreational source. The Brent or Welsh Harp Reservoir was constructed in 1835, to act as a storage reservoir for the Grand Union Canal, and is located at the confluence of the Silk Stream and River Brent.

In this chapter, the concentrations and temporal trends of Cd, Cu, Pb and Zn in the water, sediment and emergent macrophytes, of the wetland and stream are presented and intrepreted with respect to the treatment efficiency of the wetland. Due to the difficulty of setting up a flow meter at this site and the possibility of breakdown of equipment, it was not possible to record flow continuously at the discharge drain although flow was measured in the stream. The lack of flow data at the inlet of the wetland meant that heavy metal loads were impossible to calculate and removal efficiencies within the wetland could not be calculated over the monitoring period. The results described in this chapter show that although there is evidence of active metal uptake by the sediment and macrophyte species, water metal concentrations generally remained unchanged.

There is considerable interest in the UK, from both the Department of Transport and the Environment Agency (EA) whose responsibilities include the control of polluting discharges to receiving waters, in the potential use of constructed wetlands to treat surface runoff. This investigation of discharges from a major highway in NW London to the Brent Reservoir was commissioned by its conservation management commitee.

The site has been selected by the EA for the introduction of an experimental wetland to assess the removal efficiency of heavy metals from point source discharges and to reduce their toxic impacts on the biota of the Brent Reservoir, especially from the more bioavailable aqueous fraction.

3.2 SAMPLING LOCATIONS

The pollutant levels in the natural wetland (approximate area 2000m^2) were compared with the natural pollutant levels found in an adjacent stream. Four sites were chosen (Figure 3.1) - two sites in the natural wetland (Sites 1 and 2 - the designated inlet and outlet of the wetland; Plates 1i and 1ii) which receives runoff from a major highway, the A406 North Circular Road in NW London and two sites in the natural stream which also receives runoff from the same major road (Sites 3 and 4 - "upstream" and "downstream").

Site 1 is at the drain which discharges the runoff into the wetland (Plate 1i) and Site 2 is where the runoff discharges out of the wetland (Plate 1ii). Site 3 is upstream and Site 4 is downstream relative to the point where wetland flow joins the stream. Both the wetland and stream subsequently discharge effluent at proximal locations into the Brent Reservoir (Figure 3.1). Water samples were collected from the four sites at seasonal intervals between March 1993 and February 1994 and sediment samples were similarly collected between March 1993 and June 1994. Water samples only were collected in May 1993 during a storm event and sediment samples only were collected in June 1994, because of the lack of flow at the wetland sites. Plant samples were also collected close to Sites 1 and 2 at seasonal intervals. The following macrophyte species are found in the wetland: *Typha latifolia, Phragmites australis, Scirpus lacustris* and *Iris pseudacorus.*

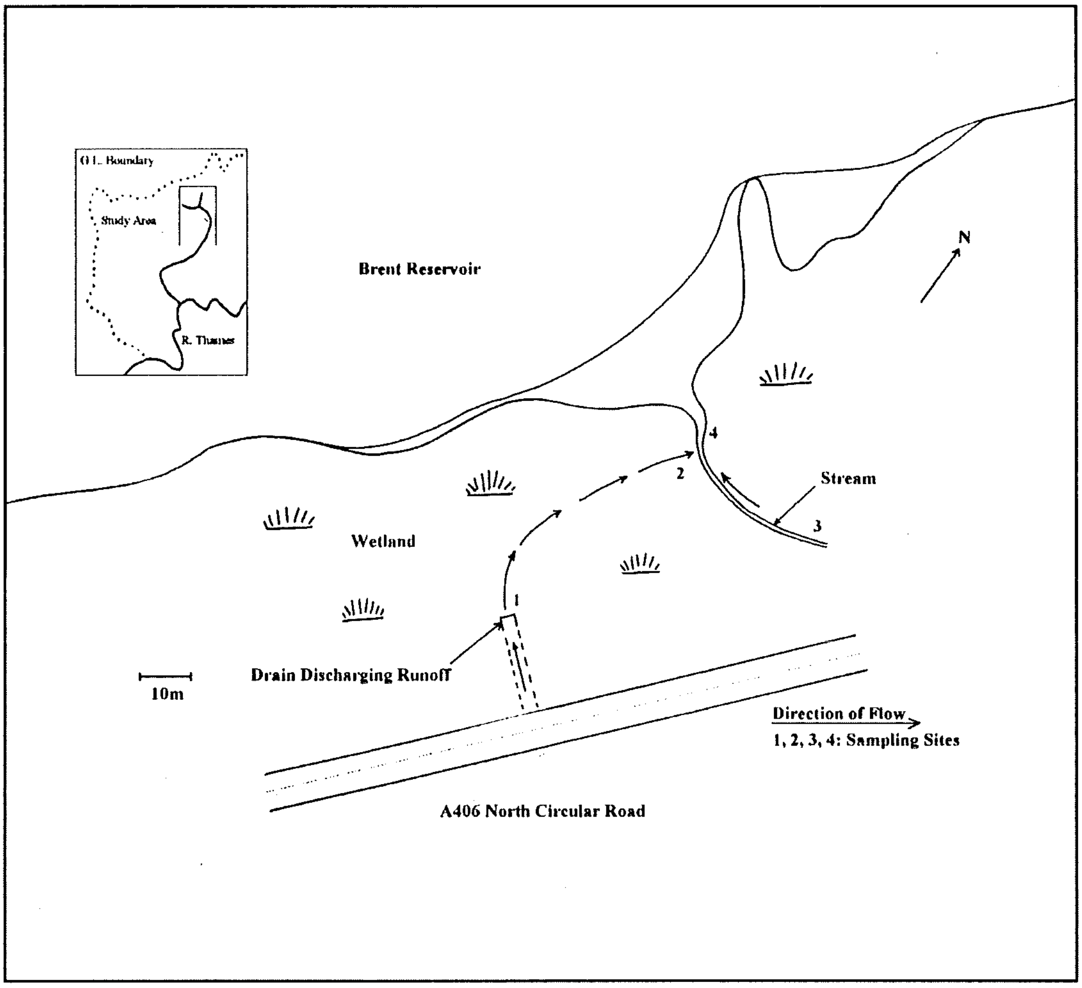


Figure 3.1 Location of the sampling sites.

Plate 1i Submerged drain at the inlet of the wetland (Site 1).

Plate 1ii Outlet area of the wetland (Site 2), outlet is on the left.

3.3 SAMPLING METHODS AND ANALYTICAL TECHNIQUES

3.3.1 Sampling Methods

Plastic sample bottles pre-washed with 10% nitric acid (for samples where metal determination was to be carried out), small plastic bags and large plastic bags were used to collect water samples, sediment and plant samples respectively. Water samples were collected in the plastic bottles which were pre-washed with sample water and then filled to near capacity. Surface sediments were collected using trowels and/or grab samplers. Plants were carefully dug out (ensuring a sufficient section of root and rhizome was collected) by spade and stored in the large plastic bags. The tools were wrapped in plastic bags and/or sediment samples were carefully removed from the areas where the sediment was not in direct contact with the tool to ensure there was no metal contamination of the samples. Samples were stored in freezers if preparation for analysis could not be carried out immediately.

3.3.2 Extraction Procedure for Total Metal Analysis

3.3.2.1 Water

Water samples (50ml) were extracted by heating to dryness on a hot sand-bath with 2ml concentrated nitric acid. The residue was taken into solution with 10% dilute nitric acid, filtered through Whatman No.42 filter paper and made up to a final volume of 50ml using double distilled deionised water. Duplicate samples were analyzed for Cd, Cu, Pb and Zn by inductively coupled plasma atomic emission spectroscopy.

3.3.2.2 Sediment

The sediment samples were oven dried at 100°C for 24 hours, sieved to the fraction less than 250μm, and 2g of sediment was digested with concentrated nitric acid and perchloric acid mixture (10ml) (9:1 by volume). This acid mixture was used since it has been shown to be an efficient method for metal extraction in sediments (Mulliss *et al.*, 1991). The residue was taken into solution with 10ml of 10% dilute nitric acid and warmed prior to centrifugation for 15 minutes at 6000 r.p.m. The supernatant liquid was pipetted off and 20ml of double distilled deionised water was added to the solid sample which was re-centrifuged as described above. The supernatant liquid was removed by pipetting and the combined supernatant liquids made up to 50 or 100ml. Duplicate samples were analyzed for Cd, Cu, Pb and Zn by atomic absorption spectrophotometry using flame atomization.

3.3.2.3 Plants

The plant samples were washed with tap water to prevent tissue damage and to remove all traces of attached sediment and separated into two parts comprising the aerial component (stem and leaf) and subsurface component (roots and rhizome). These plant components were oven dried at 100°C for 24 hours and ground samples (1-2g) were digested with concentrated nitric acid (10-15ml). The residue was made up to 50 or 100ml using the same procedure as for the sediment samples. Duplicate samples were analyzed for Cd, Cu, Pb and Zn by atomic absorption spectrophotometry using flame atomization.

3.3.3 Metal Determination by ICP-AES

3.3.3.1 Introduction

Inductively coupled plasma - atomic emission spectroscopy (ICP-AES) (Perkin Elmer Model Plasma 40 Instrument) was used to determine the total metal concentrations of Cd, Cu, Pb and Zn in water samples. The ICP-AES instrument performs sequential multi-element analyses of aqueous samples in a relatively short period of time. The detection limits of Cd, Cu, Pb and Zn are 2, 1, 40 and 3 μg/l respectively (Boss and Fredeen, 1989).

3.3.3.2 Inductively Coupled Plasma - Theory

The inductively coupled plasma instrument provides the energy to atomize the metal ions and promote atomic and ionic transitions which are observable at characteristic ultra-violet and visible wavelengths. The wavelength and intensity of this emitted radiation identifies the metal and determines its concentration in the original solution, when compared to the results from standard solutions.

Argon gas is directed through a torch consisting of three concentric quartz tubes as shown in Figure 3.2. A copper coil surrounds the top end of the torch and is connected to a radio frequency (RF) generator. When RF power (700 - 1500 watts) is applied to the coil, an alternating current oscillates at a rate corresponding to the frequency of the generator (27 or 40 megahertz). The RF oscillation of the current in the coil causes RF electric and magnetic fields to be set up at the top of the torch. An electric spark is applied to the argon causing some of the electrons to be stripped from their atoms. These electrons are then caught up in and accelerated by the magnetic field. This process of adding energy to electrons by the use of a coil is known as *inductive coupling*. These high-energy electrons in turn collide with other argon atoms stripping off more electrons in a chain reaction and resulting in a plasma consisting of argon atoms, electrons and argon ions and known as an ICP discharge.

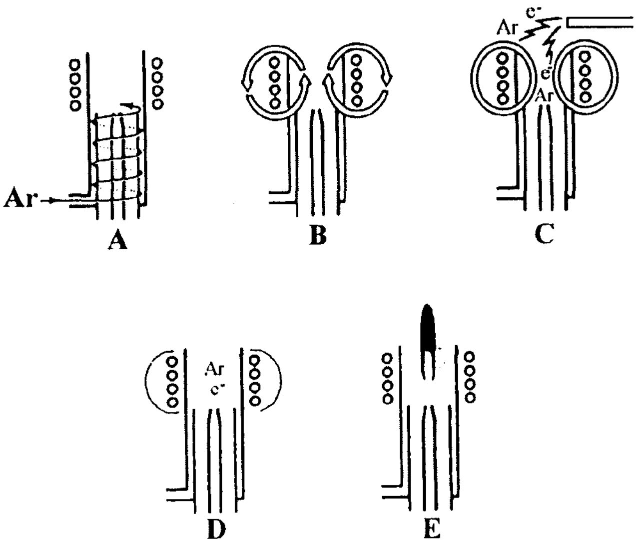


Figure 3.2 Cross section of an ICP torch and load coil depicting an ignition sequence. A - Argon gas is swirled through the torch. B - RF power is applied to the load coil. C - A spark produces some free electrons in the argon. D - The free electrons are accelerated by the RF fields, causing further ionization and forming a plasma. E - The sample aerosol-carrying nebulizer flow punches a hole in the plasma (From Boss and Freeden, 1989).

Figure 3.3 shows a cross-sectional representation of the discharge. The induction region (IR) is a doughnut-shaped ring (typical temperature ≈ 10 000K) formed by the sample-carrying nebulizer flow punching a hole through the centre of the discharge and is so-called because it is the region where the inductive energy transfer from the load coil to the plasma takes place. Pneumatic nebulizers using high-speed gas flows are used to create the aerosol. In the preheating zone (PHZ), the aerosol carrying the solvated ions is desolvated leaving the sample as microscopic salt particles which are vapourized into molecules and then atomized. Excitation and ionization processes take place in the initial radiation zone (IRZ) (temperature 8000K) and normal analytical zone (NAZ) (temperature range: 6500 - 6800K), the latter being the region where the analyte emission is typically measured.

The high temperature within the plasma is one of the important reasons for the superiority of the ICP over atomic absorption spectroscopy techniques using flames and furnaces. Gas temperatures in the centre of the ICP are over 6000K whereas flames and furnaces have upper temperature ranges of about 3000K. The higher temperature improves excitation and ionization efficiences and also reduces or eliminates many of the chemical interferences found in flames and furnaces.

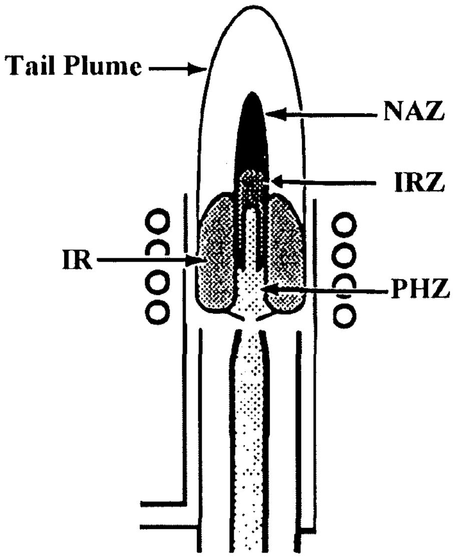


Figure 3.3 Zones of the ICP. IR - Induction Region, PHZ - Preheating Zone, IRZ - Initial Radiation zone, NAZ - Normal Analytical Zone (From Boss and Fredeen, 1989).

3.3.4 Metal Determination by AAS

3.3.4.1 Introduction

Atomic spectroscopy incorporates three different techniques: atomic absorption, atomic emission and atomic fluorescence. Atomic absorption techniques were used to analyse the total metal concentrations in sediment and plant samples.

3.3.4.2 Atomic Absorption Spectroscopy - Theory

Atomic absorption is the process that occurs when a ground state atom absorbs energy in the form of light of a specific wavelength and is elevated to an excited state. The amount of light energy absorbed at this wavelength will increase as the number of atoms of the selected element in the light path increases. The relationship between the amount of light absorbed and the concentration of analyte present in known standards can be used to determine unknown concentrations.

Table 3.1 AAS parameters used in flame analysis.

	Cd	Cu	Pb	Zn
Wavelength (nm)	228.8	324.7	217.0	213.9
Lamp current (mA)	3	3	6	5
Fuel	Acetylene	Acetylene	Acetylene	Acetylene
Background correction	Yes	Yes	Yes	Yes
Replicates	3	3	3	3
Integration time (secs)	4.0	4.0	4.0	4.0
Bandpass (nm)	0.5	0.5	0.5	0.5
Oxidant	Air	Air	Air	Air
Detection limits (μg/l)	6	3	20	2

Although the AAS detection limits for Pb and Zn (20 and 2μg/l) are better than those for the ICP-AES (40 and 3μg/l respectively), ICP-AES was used to analyse the water samples because the actual sensitivity of the AAS was found to be unsatisfactory for the water samples.

3.4 RESULTS AND DISCUSSION

3.4.1 Water and Sediment Samples in the Wetland

Average heavy metal concentrations in the wetland water samples (Sites 1 and 2) are listed in Table 3.2. The average aqueous Cu, Pb and Zn concentrations at Site 1 show levels that are more comparable to the concentrations recorded (in the UK and continental Europe) in highway drainage from suburban roads than from motorways and trunk roads (Table 3.3). Drainage waters from highway surfaces are also associated with pollutant levels which are generally comparable to those found in urban runoff (Colwill *et al.*, 1984; Ellis, 1986; Muschack, 1990). It is estimated that 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 inputs to the receiving watercourses (Ellis *et al.*, 1987). In urban receiving waters, the principal pollutants are suspended solids, heavy metals, hydrocarbons and deicing salts with the major sources of highway pollution arising from road and vehicle wear.

Table 3.2 Average heavy metal concentrations and standard deviations in wetland water and sediment samples (Sites 1 and 2).

Metal	Water concentration (μg/l)		Sediment concentration (μg/g)	
	Site 1	Site 2	Site 1	Site 2
Pb	84±46	112±55	980±476	929±310
Zn	67±40	149±112	653±205	583±110
Cu	24±13	34±20	323±185	373±106
Cd	6±4	7±4	8.7±5.3	4.8±2.7

Water metal concentrations show increases from Site 1 to Site 2. This is probably due to several factors. The flow of runoff into the wetland, which is dependent on the volume of highway runoff discharged and therefore precipitation, is intermittent and the retention time of the water (and subsequent treatment) in the wetland is therefore highly variable. The retention time between Site 1 and Site 2, measured using dye, was only between 16 and 21 minutes during the winter after a storm event. This indicates that the flow short circuits through the wetland (see Plate 2ii and Section 3.4.2) and short

Table 3.3 Comparison of quality of UK/European highway drainage with runoff from the A406 North Circular Road, London (After Hedley and Lockey, 1975).

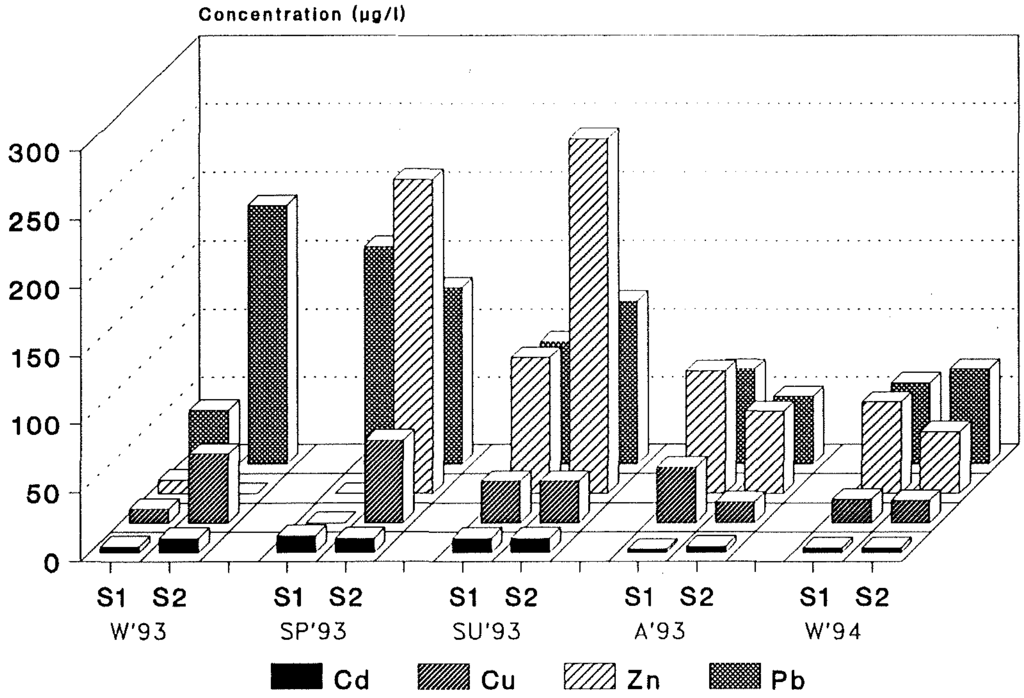
Metal	Concentration Ranges (mg/l)		
	Motorways	Suburban Roads	A406 Road (Site 1)*
Total Zn	0.17-3.55	0.02-1.90	0.01-0.10
Total Pb	0.34-2.41	0.01-0.15	0.04-0.16
Total Cu	0.05-0.69	0.01-0.12	0.01-0.04

Key
* Minimum to maximum range

retention times are enhanced by the gradient of the wetland between Sites 1 and 2. Furthermore, because the wetland sediment is relatively fine-grained, especially at Site 1 where 33% of the particle size is finer than 250μm, the water does not easily permeate through the sediment and this results in overland flow. Consequently runoff flow would be insufficiently attenuated by the vegetation, reducing contact time and hence the efficiency of metal uptake by the macrophytes from the polluted water. The macrophytes exposed to the flow are predominantly concentrated in a central area in the wetland (see Plate 2i) which is inadequate for effective treatment of flows during storm events.

Sediment concentrations of Cd, Cu, Pb and Zn in the wetland (Table 3.2) show considerable variation but there are no apparent concentration differences for each metal between the inlet and outlet sites of the wetland. Metal concentrations at both sites increase over the spring to autumn monitoring period except for Cu and this may reflect flushing of sediment following storm events and also the release of metals back into the sediment as the macrophytes die and decompose with the onset of autumn.

Figures 3.4 and 3.5 show the temporal variation of heavy metal concentrations in the water and sediment of the wetland at Sites 1 and 2 (the inlet and outlet of the wetland) over the whole monitoring period. Figure 3.4 shows that the heavy metal water concentrations at Sites 1 and 2 generally show lower levels in the autumn and winter. This can be explained by dilution caused by the higher flow rates seen in the colder months due to higher rainfall. Thus concentrations in the drain discharging highway runoff would be higher during periods of lowest flow, i.e. the spring and summer (not

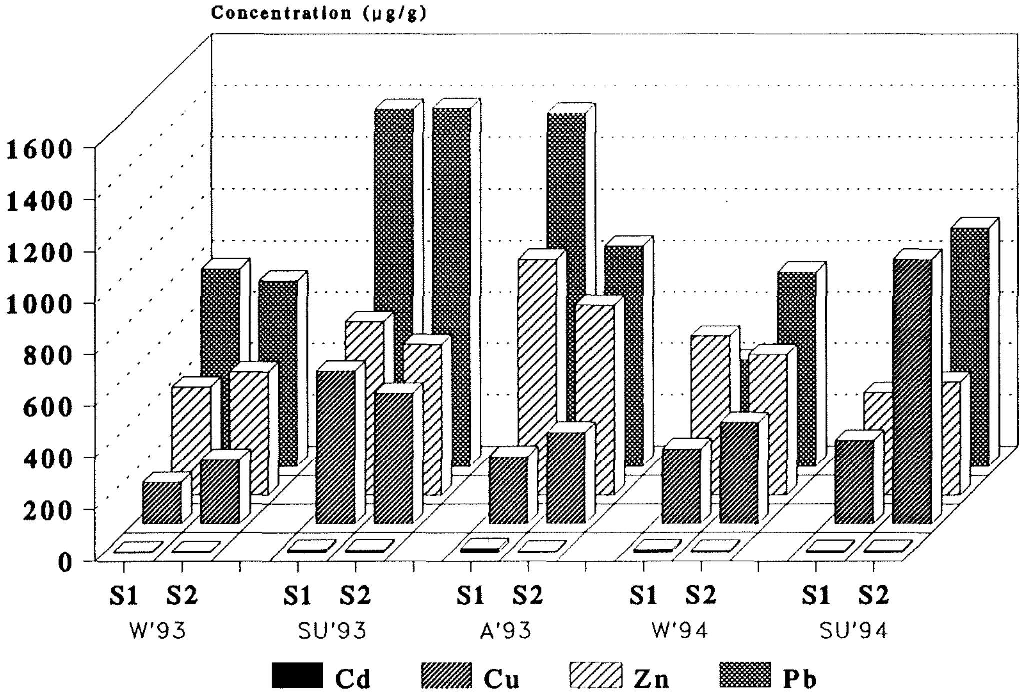


Key
W: Winter; SP: Spring; SU: Summer; A: Autumn

Figure 3.4 Temporal variation in heavy metal concentrations (µg/l) in water samples from Site 1 (S1) and Site 2 (S2).

including storm events) and the maximum water concentrations for Cd, Pb and Zn at Site 1 (12, 100 and 160µg/l respectively) are seen in the spring and summer.

Highest metal accumulation in the sediment (see Figure 3.5) occurs following shock loads of heavy metals flushed into the wetland during intense summer storms following a long antecedent dry period during which these pollutants have accumulated upon the road surface, in verges and in the drainage system itself. Thus the maximum Cu and Pb concentrations at Site 1 (589 and 1381µg/g respectively) as well as high Zn concentrations (670µg/g) are seen in the summer. The maximum Cd and Zn concentrations (15 and 913µg/g) are seen in the autumn and may have also been the result of shock loads.



Key
W: Winter; SU: Summer; A: Autumn

Figure 3.5 Temporal variation in heavy metal concentrations (µg/g) in sediment samples from Site 1 (S1) and Site 2 (S2).

3.4.2 Water and Sediment Samples in the Stream

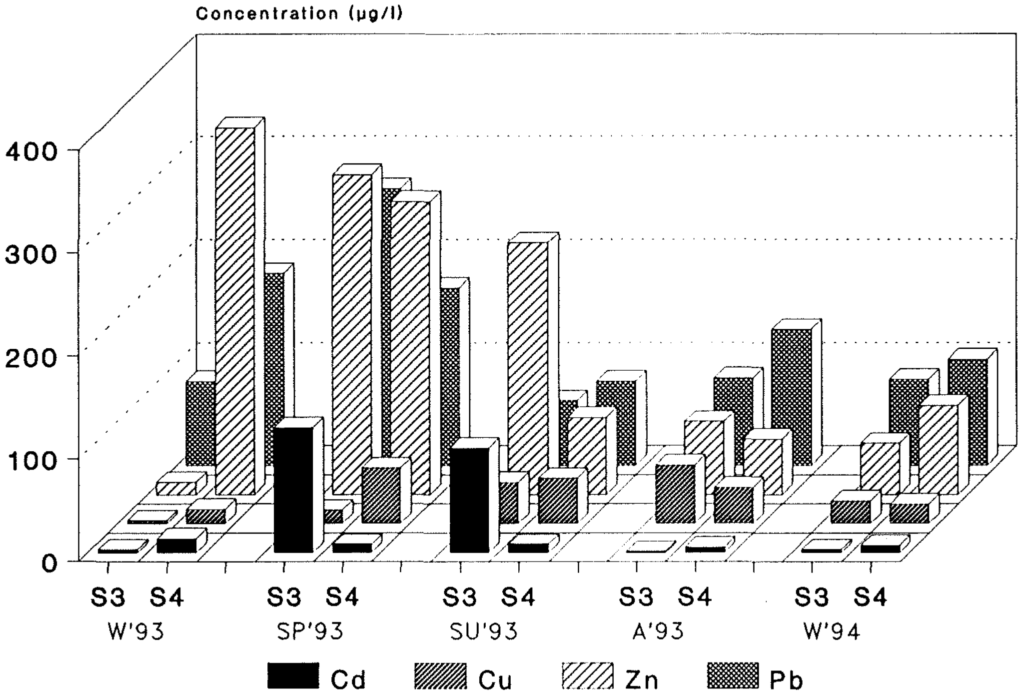
The concentrations of Zn, Pb, Cu and Cd in the stream (Table 3.4) are of the same order of magnitude but generally higher than those in the runoff discharged into the wetland. This is probably because the stream receives runoff from a larger surface area of highway as well as contaminated discharges from other sources including buildings. With the exception of Cd, the average water concentrations at Site 4 are higher than those at Site 3. This is to be expected because Site 4 also receives runoff discharged from the wetland via Site 2 thus elevating the overall metal levels in the water.

The sediment levels of Cu, Pb and Zn are consistently higher in the stream (Table 3.4) compared to the wetland. The high levels of Cu and Pb may reflect the influence of higher metal loads in the greater quantities of runoff discharged into the stream compared to the wetland.

Table 3.4 Average heavy metal concentrations and standard deviations in stream water and sediment samples (Sites 3 and 4).

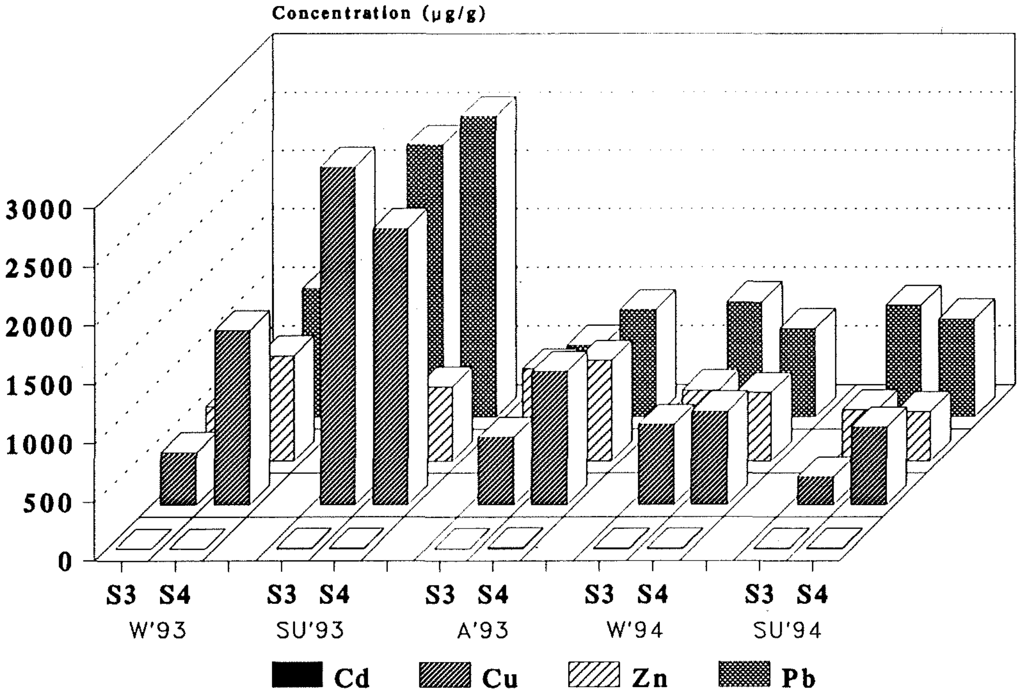
Metal	Water concentration (μg/l)		Sediment concentration (μg/g)	
	Site 3	Site 4	Site 3	Site 4
Pb	116±85	135±44	1076±864	1329±837
Zn	137±131	171±139	632±136	742±157
Cu	32±17	34±16	1147±1159	1441±668
Cd	46±61	8±3	2.9±2.4	4.5±3.3

Figures 3.6 and 3.7 show the temporal variations of heavy metal concentrations in the water and sediment of the stream at Sites 3 and 4 (upstream and downstream) over the whole monitoring period. The decrease in the autumn and winter heavy metal water concentrations (Figure 3.6) may be due to the dilution effects caused by the higher rainfall during these periods.



Key
W: Winter; SP: Spring; SU: Summer; A: Autumn

Figure 3.6 Temporal variation in heavy metal concentrations (μg/l) in water samples from Site 3 (S3) and Site 4 (S4).



Key
W: Winter; SU: Summer; A: Autumn

Figure 3.7 Temporal variation in heavy metal concentrations (µg/g) in sediment samples from Site 3 (S3) and Site 4 (S4).

The heavy metal sediment concentrations in the stream (Figure 3.7) are fairly consistent over the monitoring period except for the high levels seen at both sites for Cu and Pb (2879 and 2322µg/g respectively at Site 3 and 2351 and 2568µg/g respectively at Site 4) in the summer sample of 1993. These results may reflect flushing of the stream sediment following storm events during the winter. Overall sediment concentrations at Site 4 (i.e. downstream) are greater than at Site 3 (i.e. upstream). This may be explained by the fact that the flow is generally lower downstream in the vicinity of Site 4 than upstream (e.g. the flow velocities at Sites 3 and 4 were 0.243 and 0.115m/s respectively for the summer sampling date). The lower flow velocity allows a higher rate of sedimentation downstream and thus allows more potential for sediment metal accumulation.

3.4.3 Macrophyte Samples

Metal analyses of macrophytes collected from Sites 1 and 2 indicate bioaccumulation of Pb, Zn, Cu and Cd by *Typha latifolia, Iris pseudacorus* and *Phragmites australis.* The highest concentrations were recorded in *Phragmites australis* (Table 3.5) collected at Site 1 near the discharging drain. Tissue concentrations are generally higher in the roots and rhizomes compared to the leaves and stems of the macrophytes (Figure 3.8).

This is generally consistent with the results of previous studies on heavy metal uptake by macrophytes (Taylor and Crowder, 1983; Zhang *et al.*, 1990; Ellis *et al.*, 1994). In the wetland, *Iris pseudacorus* and *Phragmites australis* show higher uptakes of heavy metals and appear to be more efficient in this capacity than *Typha latifolia* (Figure 3.8). The maximum concentrations measured for the subsurface (roots and rhizomes) and above-surface (leaves and stems) components are shown in Table 3.5.

Table 3.5 Maximum heavy metal concentrations (μg/g) in wetland macrophytes.

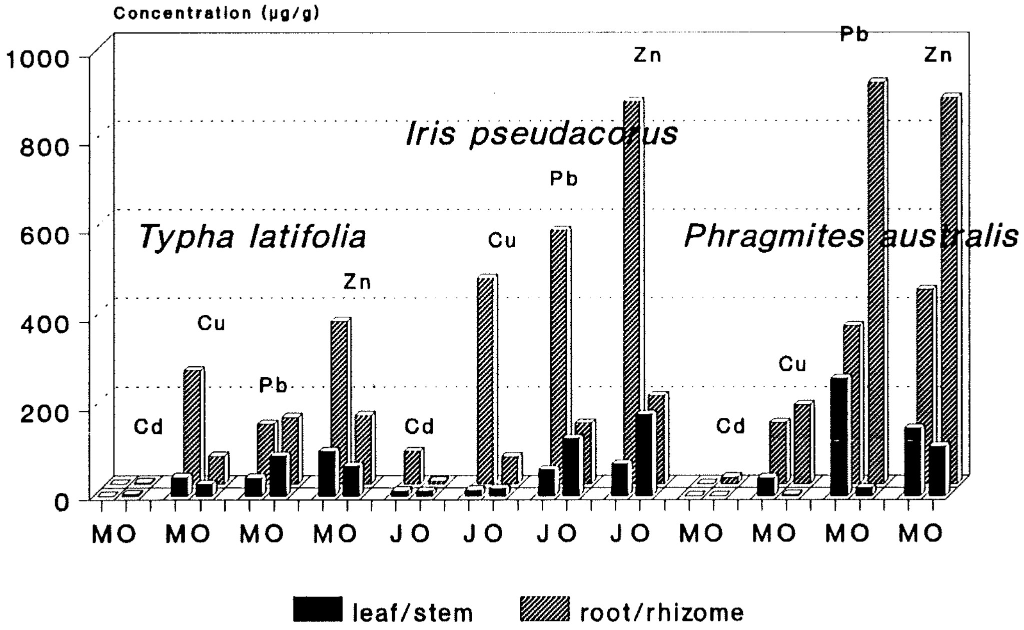
Metal	*Phragmites australis*		*Iris pseudacorus*		*Typha latifolia*	
	ss	as	ss	as	ss	as
Pb	905	264	571	129	150	90
Zn	871	152	862	184	366	154
Cu	178	41	462	17	256	42
Cd	15	*	73	12	3.4	4

Key

ss:	subsurface tissue
as:	above-surface tissue
*	below the detection limit

Metal accumulation in *Phragmites* shows an overall trend of metal concentrations decreasing in the order of Pb > Zn > Cu > Cd whereas Zn is preferentially accumulated over Pb, Cu and Cd by *Iris* and *Typha*. The high metal concentrations seen in all the macrophytes of this wetland are a function of the elevated loads found in the runoff discharged into the wetland (see Table 3.2). The high metal concentrations may also be explained by the formation of iron plaque on the roots of the macrophytes. *Phragmites* and *Typha* are both known to form an iron plaque (Crowder and St.-Cyr,

1991) which consists mainly of iron (hydr-) oxides and it is possible that such plants may be at an advantage with regard to the uptake of metals due to the adsorption and immobilization of heavy metals by the iron plaque although the tolerance mechanism is as yet unclear (Ye *et al.*, 1994). This property may also explain the high Zn concentrations seen especially in the subsurface tissues since the plaque seems to slow Zn transport to the above-surface tissues but does not reduce Zn subsurface uptake, thus concentrating Zn in this area.

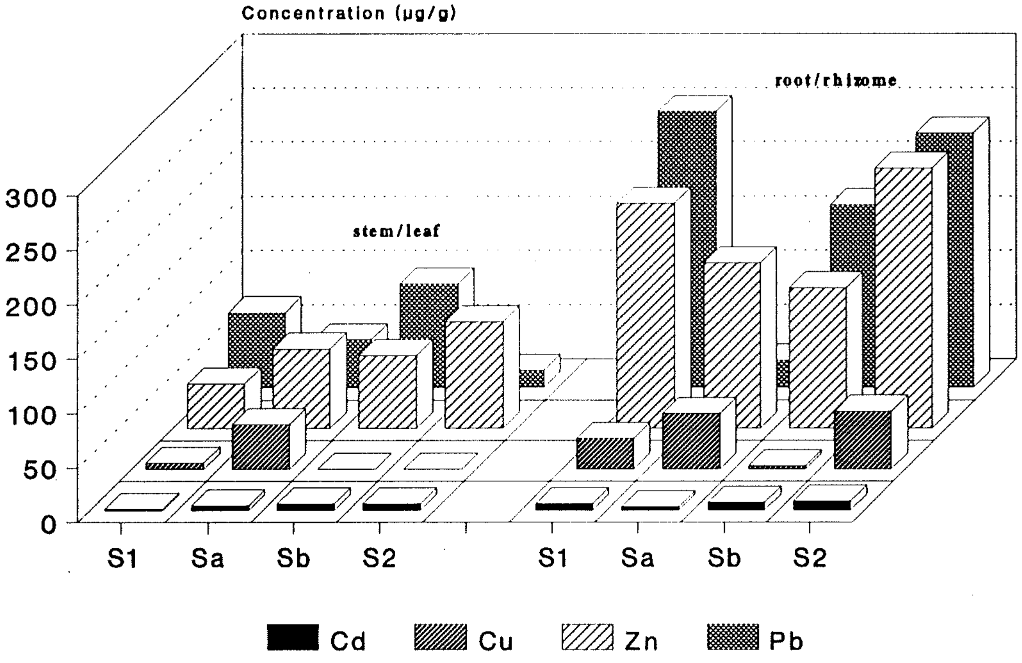


Key
M = May; J = June; O = October 1993

Figure 3.8 Variation of metal concentrations in macrophyte species over the monitoring period.

Figure 3.8 shows how the metal concentrations vary for each sampled macrophyte species over the monitoring period. The fall in tissue metal concentrations recorded between May and October for *Typha latifolia* and between June and October for *Iris pseudacorus* reflects the die back and eventual decomposition of the seasonal macrophytes. However, root and rhizome metal concentrations increase between May and October for *Phragmites australis* indicating that this species may have had a longer growing season than the other species in the wetland. The heavy metals, as in the case of nutrients, appear to be locked into intractable organic matter and are returned to the sediment when the plant tissue decomposes (Burgoon *et al.*, 1991). This may account for the sediment Pb and Zn concentrations remaining elevated in the wetland during the autumn (Figure 3.5).

The central area of the wetland (Plate 2i) is dominated by a dense population of *Typha latifolia*. Figure 3.9 shows the variation in metal concentrations in *Typha latifolia* moving from Site 1 (the designated inlet of the wetland) through the central area of the wetland, which is represented by Site a and Site b (Plate 2ii), to Site 2 (the designated outlet of the wetland). Simultaneous samples were collected from these sites in February 1994 when the central region of the wetland was accessible.



Key

S1:	Site 1
Sa:	Site located at the entrance to the central area of the wetland moving away from Site 1
Sb:	Site located at the exit to the central area of the wetland moving towards Site 2
S2:	Site 2

Figure 3.9 Variation of metal concentrations in *Typha latifolia* through the wetland.

Plate 2i The densely vegetated central area of the wetland.

Plate 2ii Short circuited runoff flows out of the central area of the wetland (Site b).

Subsurface tissue metal concentrations in *Typha* in the central wetland region (Sites a and b) are generally lower than those seen at the inlet and outlet (Figure 3.9). This may be explained by the flow characteristics within the wetland. The wetland has a short retention time (see Section 3.4.1) which is compounded by the gradient of the central wetland area (the wetland slopes from Site 1 to Site 2; the slope is evident during the winter when the macrophytes cover is sparse). The flow is extremely variable (water enters the natural wetland via runoff, groundwater discharge and precipitation) and the storm event gives a good estimation of the shortest retention time.

Thus in this case, a potential shock load of heavy metals would pass through the wetland rapidly and not allow sufficient time for metal uptake by the macrophytes. The short circuiting of flow hinders uptake and thus possibly reduces treatment efficiency. Higher macrophyte density throughout the wetland during the growing season would allow more attenuation by the macrophytes. But the temporal variation of heavy metal concentrations in the water (Figure 3.4) shows no obvious decrease from Site 1 to Site 2. The results suggest that the flow path through the wetland is well established and short circuiting probably occurs at times of high flow, compounded by the gradient of the wetland. Spreading the distribution of the flow at the inlet would therefore allow a more even flow throughout the wetland.

The high subsurface tissue concentrations (254 and 207μg/g for Pb and Zn respectively) measured at the inlet (Site 1) are expected since the drain discharging runoff into the wetland is usually submerged (Plate 1a). In times of little or no flow the inlet is usually an area of stagnant water and there is more time for uptake by macrophytes. The high subsurface tissue concentrations (243 and 239μg/g for Pb and Zn respectively) monitored near the outlet (Site 2) can also be explained by the flow characteristics. As flow approaches the outlet, it meanders at times of little or no flow due to the low gradient in this area of the wetland. Therefore, resulting standing water, as seen in Plate 1ii, allows more time for metal uptake by the macrophytes in this area.

3.4.4 Assessment of the Impact of Highway Runoff on the Natural Wetland and the Brent Reservoir

3.4.4.1 Water Quality of Runoff Discharging into the Brent Reservoir

The average metal concentrations in the water at Sites 2 and 4 which combine and discharge into the Brent reservoir exceed the European Community (EC) water quality standards for freshwater life (EC Freshwater Fisheries Directive, 1978) and are close to or exceed the EC directive on pollution caused by certain dangerous substances discharged into the aquatic environment (EC Dangerous Substances Directive, 1976; Halcrow, 1993) (Table 3.6).

Table 3.6 Comparison of average heavy metal water concentrations and standard deviations at Sites 2 and 4 (which discharge into the Brent reservoir) with water quality standards.

Metal	Water concentration (μg/l)			
	Site 2	Site 4	EC water quality standard[1]	RE water quality standard[2]
Cd	7±4	8±3	5	-
Cu	34±20	34±16	28AD	112P
Pb	112±55	135±44	20AD	-
Zn	149±112	171±139	125AT	500P

Key

[1] EC Dangerous Substances Directive. For a water hardness of at least 250mg/l (EA Thames Region water hardness). Metal concentration limits selected on the basis of their toxicity, persistence and liability to bio-accumulate in the food chain.

[2] River Ecosystem Classification Regulations (1994) for the hierarchical class of highest quality for a water hardness greater than 250mg/l.

A = Annual; D = Dissolved; T = Total; P = 95% of Samples

The average concentrations of Cd, Cu, Pb and Zn at Site 2 are comparable to or exceed the European Community standards for freshwater life. However, the average Cu and Zn concentrations are considerably less than the River Ecosystem Classification water quality criteria. Nonetheless, these results show that the natural wetland needs to be modified such it can remove the heavy metals in the runoff discharged into it to within acceptable and less harmful levels.

Table 3.6 also shows that the average concentrations of all the metals at Site 4 can exceed the European Community standards. This shows the effect of the cumulative influence of a number of discharges into the stream and emphasises the need to either prevent contaminated runoff from discharging into the stream or to modify the stream such that the water quality can be improved. The latter could be achieved by allowing shock loads in the stream to discharge into a treatment wetland constructed on the site of the current natural wetland (see Section 3.4.5).

3.4.4.2 Heavy Metal Loads in the Wetland and Stream

As previously mentioned in Section 3.1, flow could not be measured at the drain discharging runoff into the wetland due to the difficulty of setting up a flow meter at the site and also because the drain is usually submerged (Plate 1i) and there is discernable flow only during storm events. The lack of flow data at the inlet of the wetland meant that heavy metal loads were impossible to calculate and removal efficiencies within the wetland could not be calculated over the monitoring period.

However, heavy metal loads were estimated for the outlet and Sites 3 and 4 in the stream (for sampling date 6/05/93) to give an indication of the metal loads in the system and the results are shown in Table 3.7.

Table 3.7 clearly shows that the heavy metal loads are higher in the stream than in the outlet of the wetland. This probably reflects the higher volumes of runoff received by the stream compared to the natural wetland. The low metal loads flowing out of the designated wetland outlet can only give a lower estimation of the amount of metal that is regularly discharged into the Brent reservoir since the wetland may be discharging runoff into it via other pathways. Higher loads will also be discharged during storm events.

Table 3.7 Heavy metal loads at the wetland outlet (Site 2) and upstream (Site 3) and downstream (Site 4) for the sampling date in summer 1993 (during a dry period which accounts for the low flow velocities measured).

Parameters	Site 2	Site 3	Site 4
Flow velocity (m/s)	0.080	0.243	0.115
Cross sectional area (m^2)	0.020	0.096	0.495
Rate of flow (m^3/s)	0.0016	0.023	0.057
Cd concentration (μg/l)	10	102	8
Cu concentration (μg/l)	30	40	44
Pb concentration (μg/l)	260	244	75
Zn concentration (μg/l)	120	63	82
Cd load (μg/s)	0.016	2.38	0.45
Cu load (μg/s)	0.048	0.93	2.50
Pb load (μg/s)	0.416	5.69	4.27
Zn load (μg/s)	0.192	1.47	4.67

Cd and Pb loads in the stream decrease downstream whereas the Cu and Zn loads increase. These results shows that there is a significant toxic discharge into the reservoir and confirm the need for its treatment before it impacts on the ecosystem of the reservoir.

3.4.4.3 Comparison of Metal Concentrations in the Natural Wetland and in a Receiving Basin at the Northern End of the Brent Reservoir

The average metal concentrations of the water, sediment and macrophytes in the natural wetland were compared with those of a receiving basin at the northern end of the Brent reservoir which receives urban stormwater runoff from the Silk Stream (Zhang *et al.*, 1990) (Figure 3.10). Thus the impact of highway runoff on the natural wetland was compared with the impact of urban stormwater runoff on the receiving basin. Both sources of runoff ultimately discharge into the Brent reservoir, a Site of Special Scientific Interest, and this represents a risk to the flora and fauna of the reservoir due to the ability of heavy metals to bio-accumulate in the food chain.

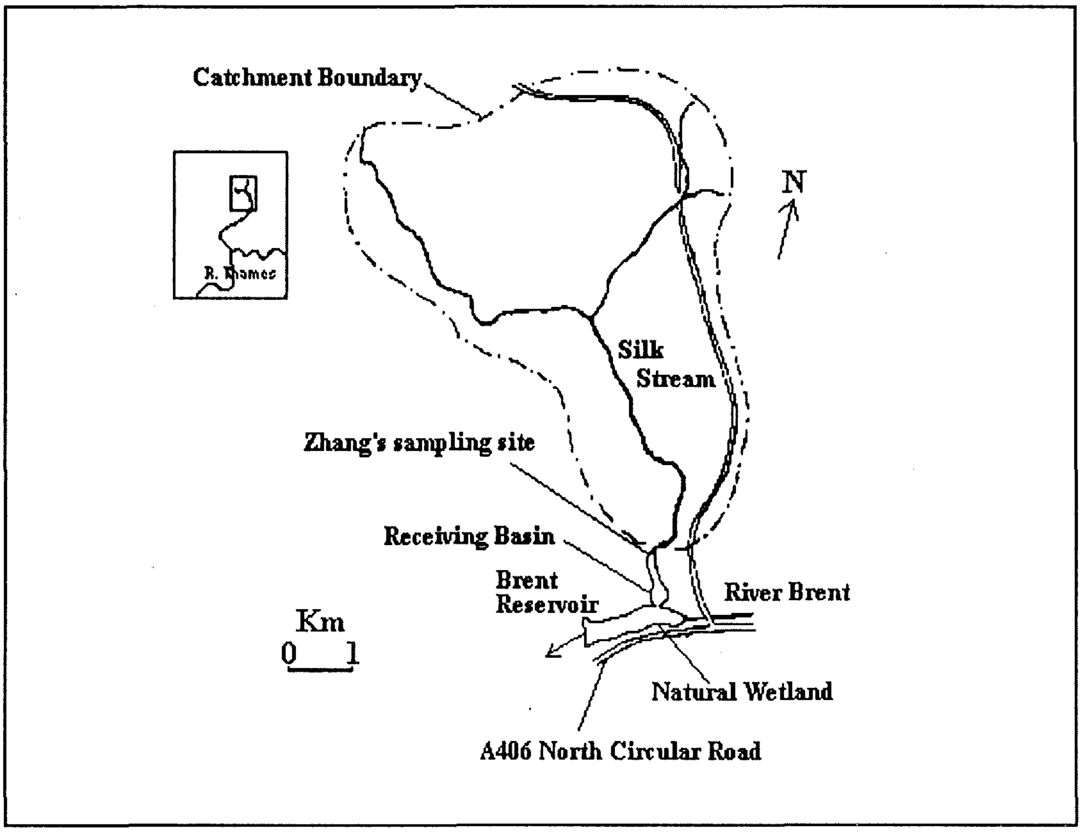


Figure 3.10 The location of the natural wetland and Zhang's sampling site with respect to the A406 North Circular Road.

Cd concentrations in the water discharged into the Brent reservoir (Sites 2 and 4) are comparable to the Cd levels discharged into the basin, whereas the Cu concentrations are lower (Table 3.8). However the Zn and especially Pb water concentrations are higher than those discharged into the basin. The metal concentrations regularly exceed the European Community Dangerous Substances Directive (see Section 3.4.4.1) and these comparisons show the significance of toxic discharges derived from highway runoff and emphasise the need for its treatment before it is discharged into the Brent reservoir.

Sediment concentrations in the wetland and stream are generally higher than in the receiving basin for all the metals except Cd and Zn at Sites 2 and 4 (Table 3.9). These comparisons highlight the higher levels of metals in the highway runoff and also the potential of the sediment to act as a sink for heavy metals.

Table 3.8 Average heavy metal water concentrations and standard deviations at Sites 2 and 4 compared with those of the receiving basin.

Metal	Water concentration (μg/l)		
	Site 2	Site 4	Basin*
Cd	7±4	8±3	9±4
Cu	34±20	34±16	60±46
Pb	112±55	135±44	36±16
Zn	149±112	171±139	137±107

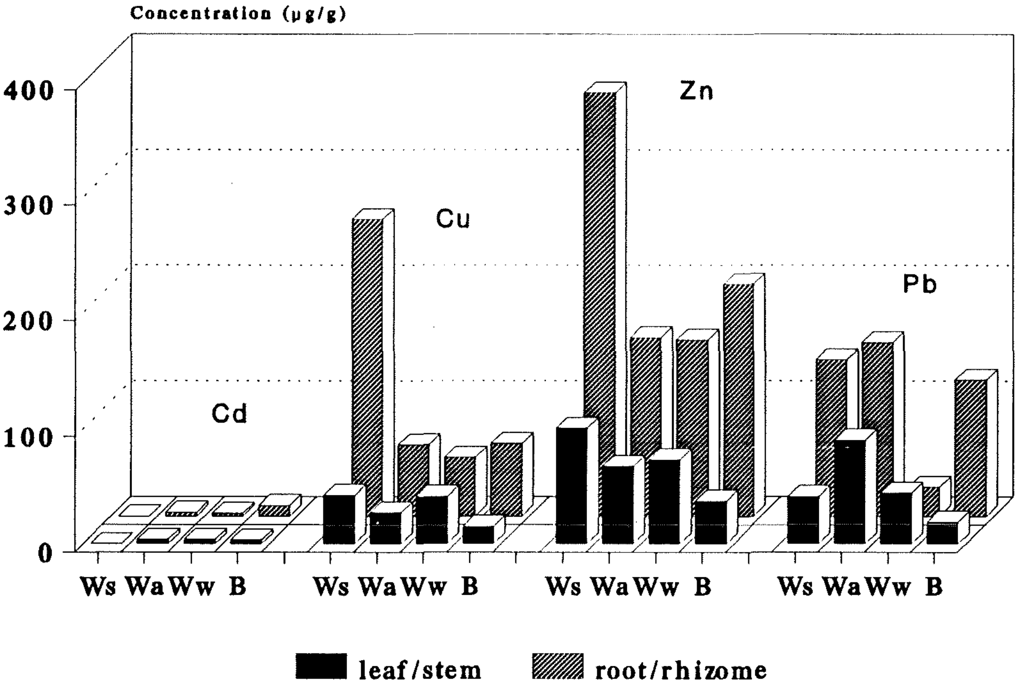
Key
* Data from Zhang (1990).

Table 3.9 Average heavy metal sediment concentrations and standard deviations at Sites 2 and 4 compared with those of the receiving basin.

Metal	Sediment concentration (μg/g)		
	Site 2	Site 4	Basin*
Cd	4.8±2.7	4.5±3.3	12.5±7.8
Cu	373±106	1441±668	220±45
Pb	929±310	1329±837	841±229
Zn	583±110	742±157	779±140

Key
* Data from Zhang (1990).

A comparison of the seasonal (summer and autumn 1993 and winter 1994) heavy metal concentrations in the tissues of *Typha latifolia* in the wetland with the average tissue metal concentrations in *Typha* in the basin show that higher metal concentrations are accumulated in the tissues of *Typha* in the wetland compared to the basin (Figure 3.11). The highest concentrations occur in the summer during the growing season when uptake is at a maximum and then fall with the onset of winter when the macrophytes die-back and eventually release the metals back into the sediment. But even the tissue concentrations during the autumn and winter are comparable to those in *Typha* present in the basin. These comparisons show how the higher levels of heavy metals, discharged into the wetland from highway runoff, are reflected by their bioaccumulation in the macrophytes of the wetland.



Key
Ws: *Typha* in wetland in summer 1993
Wa: *Typha* in wetland in autumn 1993
Ww: *Typha* in wetland in winter 1993
B: *Typha* in the receiving basin in the north end of the Brent reservoir during the growing season (see Figure 3.10)

Figure 3.11 Comparison of average *Typha latifolia* tissue metal concentrations in the wetland and the receiving basin.

Overall, higher metal concentrations are found in the water, sediment and plants of the wetland and stream which receives highway runoff in comparison to the concentrations found in the water, sediment and plants under the cumulative influence of a number of discharges to the receiving basin. This highlights the potentially detrimental impact which the toxic discharge from highway runoff may have on the Brent Reservoir and emphasises the need for its treatment.

3.4.5 Proposed Design of A Constructed Wetland

3.4.5.1 Introduction

The results of this assessment of heavy metal removal from highway runoff by the natural wetland show that, although the wetland has the potential to reduce toxic impacts to the Brent Reservoir, it needs to be modified to allow adequate treatment of the runoff to within acceptable standards. The runoff discharged into the stream also requires treatment since the higher metal levels also impact directly on the Brent Reservoir.

Thus the results support a proposal by the Environment Agency to construct a wetland planted with indigenous species of macrophyte to treat highway runoff on the current natural site. Successful design of the wetland treatment system requires adequate pretreatment and conservative hydraulic loadings and also the incorporation of natural wetland features to enhance plant community production and wildlife populations. Public perception and interest concerning the proposed treatment system are important during the proposal stages since the public who use the area may oppose any plans that would appear to alter the wetlands' perceived value. Thus the constituency involved should be considered when establishing the aesthetics of the constructed wetland and their feedback incorporated into the design criteria. The project to construct a wetland over the current site may actually enhance the resource value of the wetland since currently, it is sometimes used as a dumping ground for litter and consequently, has lost much of its aesthetic appeal.

3.4.5.2 Design Criteria

The following design criteria have been suggested to the Environment Agency with regard to the proposal to construct a wetland to treat the highway runoff from the A406 North Circular Road to within acceptable standards as shown in Figure 3.12.

- The area of the natural wetland limits the size of a constructed wetland to less than 2000m^2. The reed beds of a constructed wetland incorporating a sediment trap and settlement pond would cover over half the area of the current site (approximately 1000m^2). Based on the approximate area of the natural wetland through which the runoff currently flows through, this should be adequate to receive highway runoff discharges .

- The stream should be retained as a spillway for storm discharges. The wetland could also act in a similar way depending on its water storage capacity since the stream is more likely to overflow during a storm event as it receives runoff from more sources than the wetland. Thus when stream water levels rise above a designated level during storm events, the excess flow will discharge into the wetland for treatment and prevent the discharge of shock loads of toxins directly into the Brent Reservoir.

- The proposed design includes a sediment trap (approximate area 250m^2) between the oil booms and weirs at the inlet for highway runoff and at the passage for stream and/or wetland overflows. These design considerations would allow for the pretreatment of runoff. The sediment trap would be separated from the vegetated section by a rock-filled gabion bund which would distribute the flow evenly across the width of the bed. The frequency of dredging of the sediment trap would depend on the rate of sedimentation within it.

- The reed bed would be planted with locally available plant species and would consist of two compartments (approximatley 400 and 700m^2) with baffles to encourage mixing of the water and help minimize short-circuiting. Two smaller reed beds would also reduce short-circuiting since flow is more easily controlled in a smaller area and also facilitate maintenance due to the barrier between them allowing access to all areas of the reed beds.

- A mixed gravel and soil substrate at a gentle slope (approximately 1%) would allow subsurface flow through the wetland whereas baffles would direct surface flow across the wetland and reduce short-circuiting.

- There are currently no established design and performance criteria for constructed wetland systems for the treatment of highway runoff although the following guidelines have been proposed in the UK. The systems should always include grit and hydrocarbon traps. A minimum retention time of 30 minutes is required to achieve an ideal treatment efficiency and a maximum flow velocity of $0.7 ms^{-1}$ should not be exceeded to avoid damaging the vegetation and reducing the uptake efficiency of the plants (Halcrow, 1993). The criteria for selecting wetland systems for highway runoff treatment should be dependent on the degree of flow attenuation necessary and whether sufficient land is available (or new land required) within the highway boundary for wetland construction in addition to traditional pollution control structures.

  Thus a wall 0.74m high surrounding the $1100m^2$ treatment area would provide a 30 minute retention time for a maximum storm discharge of $0.45m^3/s$* (Halcrow, 1993).

* A flow rate of $0.45m^3/s$ corresponds to a volume of $810m^3$ for 30 minutes. A wall 0.74m high around the $1100m^2$ reedbed area would provide the required extra volume to retain the storm discharge for at least 30 minutes. This is based on the assumption that the flow does not continue at a rate of $0.45m^3/s$ for more than 30 minutes; an assumption based on the generally short-lived nature of storms in this region.

- A final settlement pond (approximately $800m^2$) after the reed beds would enhance further suspended solids removal and provide an open water body which would attract wildlife and possibly provide another nesting area for the large bird population of the Brent Reservoir (e.g. floating mats would encourage nesting).

- The results of a survey assessing the public perception of the aesthetic and wildlife value of natural and constructed wetlands (Chapter 6) would be integrated into the design criteria with a view to creating an aesthetically pleasing landscape and especially encouraging the flora and fauna to colonise the

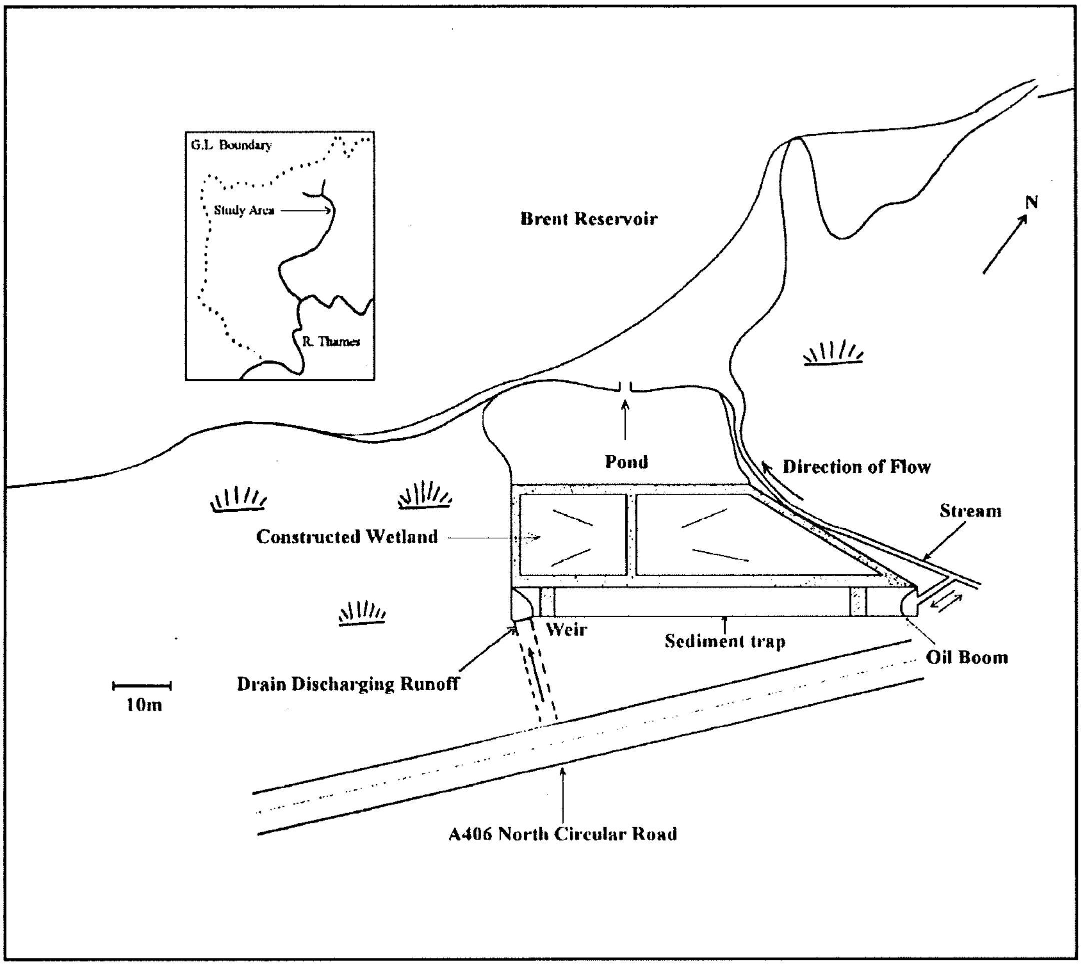


Figure 3.12 Proposed design of the constructed wetland.

wetland without interfering with its primary aim - to efficiently treat highway runoff (see Chapter 7).

3.5 CONCLUSION

The results of this study indicate that further heavy metal removal from the drain and stream is required to reduce the toxic impacts to the receiving basin. Although the rhizomatous species of macrophyte investigated have a limited metal uptake potential in comparison to the sediment, their foliage can attenuate the flow of surface discharges and facilitate the settlement of metal contaminated particles and the uptake of dissolved metal species. The rhizomes and roots provide a sediment sink which will reduce the resuspension of particles during intermittent discharges. The results provide a baseline study for the assessment of the pollution removal potential of the wetland which is planned for construction at this site.

The natural wetland exhibits severe hydraulic short-circuiting difficulties which result in inadequately treated water mixing with any treated water at the outlet of the wetland, thereby downgrading the quality of the discharge. The wetland is a natural system with a simple flow pattern and highly variable loading rates dependent on the amount of rainfall. Short-circuiting problems are inherent in continous flow systems and any future wetland design must take this into account as suggested by the use of baffles in the proposed design of the constructed wetland (Figure 3.12).

CHAPTER 4 ASSESSMENT OF HEAVY METAL REMOVAL BY A FULL-SCALE CONSTRUCTED WETLAND

4.1 INTRODUCTION

This chapter describes the introduction of a constructed wetland to a substantial residential development. The wetland represents an innovative example of environmental engineering utilising plants as an ecological method for treating pollution from surface runoff as well as providing an aesthetically appealing landscape design. The results of the monitoring programme to determine heavy metal removal provides a valuable baseline to which further studies can be compared in the future for the assessment of the metal removal performance of a constructed wetland.

4.2 SAMPLING LOCATIONS

The wetland is located adjacent to a residential development (188.18ha) in Braintree, Essex, which is currently being constructed by Countryside Properties plc and which will provide, by the year 2000, 2000 new homes and low density business space together with shopping, recreational and social facilities within a garden village environment (Mungur *et al.*, 1994). A bypass which discharges runoff into the wetland was opened in March 1996 although only one lane is currently operating (Figure 4.1).

The constructed wetland (7900m^2) has been designed to treat surface runoff in a greenfield housing development. The wetland incorporates two settlement trenches which are separated from the vegetated section by gabions containing crushed rock. A total of 33,750 plants have been introduced to the wetland including 18,000 *Typha latifolia* and 10,000 *Phragmites australis* and additional species including *Iris pseudacorus* and *Scirpus lacustris*. The wetland contains an initial section of *Phragmites* planted in a surface layer of gravel and underlying soil substrate. The gravel is designed to increase hydraulic conductivity and act as a friction layer and silt trap during intermittent storm events. The wetland effluent is discharged through six outfall pipes

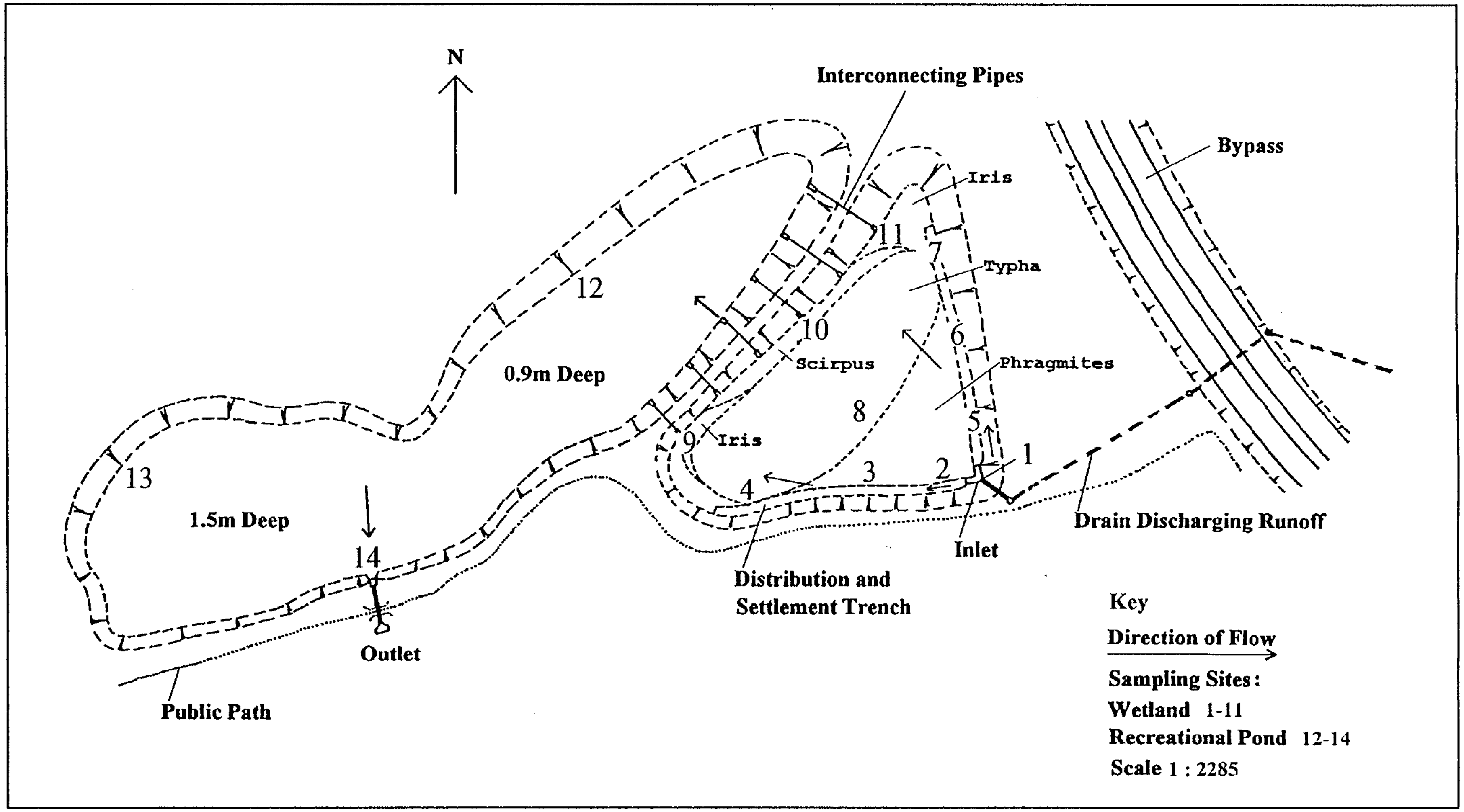


Figure 4.1 The constructed wetland and recreational pond in Braintree showing the 14 sampling sites.

to a pond (16,000m^2) designed for recreational activities. Water and sediment samples from up to 14 sites in the two ponds were collected and analysed for Cd, Cu, Pb and Zn as previously described in Section 3.3.2. The sites are described in Table 4.1. Plant samples were collected seasonally from the wetland and also analysed for Cd, Cu, Pb and Zn concentrations. Species availability was dependent on the degree of planting and delays in planting - *Phragmites australis* was planted in May 1995, a year after the introduction of the other plants. These delays were attributable to various problems including the plants not taking root and growing properly and damage caused by the feeding and nesting activities of geese. The plants could only be planted between March and May, the optimum period for initial growth.

A portable UF 1100 ultrasonic flow-meter was installed at the inlet to measure inflow from August to October 1994. The total monitoring period (August 1994 - September 1996) aimed to assess the total metal removal performance of the constructed wetland.

Table 4.1 Description of sampling sites.

Site(s)	Description	Nature of samples	Group
1[a]	Inlet pipe	Water and sediment	I
2-7[b]	Settlement trenches	Water and sediment	II
8-11[c]	Wetland interior	Water, sediment and plants	III
12-13	Recreational pond	Water and sediment	IV
14[d]	Outlet flume	Water and sediment	V

Key
a: Plate 3i; b: Plate 3ii
c: Plate 4i; d: Plate 4ii

4.3 CONSTRUCTION OF THE WETLAND SYSTEM

4.3.1 Design Considerations

The constructed wetland (7900m^2) and adjacent recreational pond (16,000m^2) were designed to provide treatment and act as a balancing pond to store surface water runoff from the catchment and discharge it into the outfall system of ditches at a controlled

Plate 3i Inlet pipe.

Plate 3ii Settlement trench.

Plate 4i Wetland interior.

Plate 4ii Outlet flume.

rate (Figure 4.1). The Environment Agency (EA), Anglian Region, was responsible for approving the discharge rate as well as setting standards for the quality of the discharged water. The EA required that the discharge to the outfall ditch should not exceed the rate that would be produced from the undeveloped site for storms having a return period of up to 100 years. The estimated gross area of catchment including the pond is 38.583ha, of which 23.11ha is impermeable surface. The permitted discharge rate from the undeveloped site authorised by the EA was 7.06 l/s/ha for a 1 in 100 year storm event, thus giving a permitted maximum flow rate of 272.4 l/s for the whole catchment area.

The maximum storage required was calculated for storm events ranging from a 1 in 1 year to a 1 in 100 year frequency. A projected rise in water level of only 0.366m is required as a result of the large surface area of the wetland and pond. Computations were made for flows obtained from flumes, weirs and V-notches, and a flume of width 0.7m was judged to be satisfactory (Table 4.2) by the consultants (Burrow-Crocker) who designed the wetland.

Table 4.2 Storage, head and flows calculated from the discharge devices considered (DHV UK, 1994).

Return Period	Storage (m^3)	Head (m)	Flow Allowed (l/s)	90° V-notch	0.6m Rect. Weir	0.7m Broad Crest	0.7m Flume
-	0	0.000	0	0.0	0.0	0.0	0.0
-	1000	0.040	40	1.3	10.1	9.5	9.4
-	2000	0.082	65	8.0	28.9	28.0	27.4
1	2932	0.121	92	21.1	51.5	50.2	49.2
2	3601	0.150	111	36.1	70.8	69.3	67.9
5	4408	0.183	140	59.4	95.2	93.4	91.6
10	5112	0.213	166	86.8	119.4	117.3	115.0
20	6009	0.248	191	127.0	149.9	147.4	144.4
	6750	0.276	210	166.6	176.3	173.5	170.0
50	7525	0.309	225	220.1	208.2	205.0	200.9
	8200	0.336	240	271.0	235.7	232.3	227.6
100	8953	0.366	250	366	268.1	264.3	259.0

The rational method for calculating the amount of runoff for storm sewer design, and ultimately maximum storage, is defined by the following relationship:

$$Q = 0.278CIA \qquad \text{(Equation 4.1)}$$

where Q = maximum rate of runoff (m^3/s)
C = coefficient of runoff based on type and character of surface (see Table 4.3)
I = average rainfall intensity, for the period of maximum rainfall of a given frequency of occurence having a duration equal to the time required for the entire drainage area to contribute flow (mm/hr)
A = drainage area (km^2)

Table 4.3 Coefficients of runoff for the rational method (Equation 4.1) for various areas and types of surface.

Description	Coefficient
Business areas depending on density	0.70 to 0.95
Apartment-dwelling areas*	0.50 to 0.70
Single-family areas	0.30 to 0.50
Parks, cemeteries, playgrounds	0.10 to 0.25
Paved streets	0.80 to 0.90
Watertight roofs	0.70 to 0.95
Lawns depending on surface slope and character of subsoil	0.10 to 0.25

Key
* The Braintree site could be classified under this header.

Rainfall may be intercepted by vegetation, retained in surface depressions and evaporate, infiltrate into the soil, or drain away over the surface. The coefficient of runoff is that fraction of rainfall that contributes to surface runoff from a particular drainage area. The coefficients given in Table 4.3 show that the majority of rainfall falling on paved and built-up areas runs off, while open spaces with grassed surfaces retain the bulk of rain water. The size of the drainage area is determined by field survey, or measurement from a map.

The rainfall intensity in the rational formula is the most complex parameter. Recording gauges maintained by weather services automatically chart rainfall rates with respect to time. These data can be compiled and organized statistically into intensity-duration curves. As an example, for storms with a duration of 30 minutes, the maximum average rainfall anticipated once every 5 years is 75 mm/h, and the 25-year frequency is 95 mm/h. In design, 5-year storm frequency is used for residential areas, 10-year frequency for business sections, and 15-year frequency for high-value districts where flooding would result in considerable property damage (Hammer, 1986). For the design criteria of this site a 100-year storm frequency was used as the upper limit in calculating the maximum storage capacity of the system and the computations gave a projected rise in water level of 366mm.

The other important design consideration was to decide what discharge device would best suit this system based on the maximum projected water level rise. This was done by measuring the rate of flow in the channel of each device. There are many methods of measuring the rate of flow in a channel. What method is used usually depends on the frequency of the observations, the duration of the measurement period, and the purpose of the measurements (Charlton, 1978).

Weirs can be used for measuring the flow of water in open channels. Water flowing over the sharp edge crest must discharge to the atmosphere, i.e. air must be allowed to pass freely under the jet. When these conditions are met, the rate of flow can be directly related to the height of water measured behind the weir. Most of the weirs developed and calibrated have V-notch or rectangular openings. The most common weir used for measuring wastewater is the 90° V-notch weir. It is particularly well adapted to recording wide variations in flow, and may be used in treatment plants too small to warrant continous flow recording and the more expensive Parshall flume. V-notch weirs are commonly installed on a temporary basis to make flow measurements associated with industrial wastewater surveys. Discharge over a 90° V-notch weir can be calculated using the following equation (Hammer, 1986):

$$Q = 1.4H^{5/2} \qquad \text{(Equation 4.2)}$$

Where Q = free discharge (m^3/s)
H = vertical head (m)

The flow of wastewater through an open channel can be also be measured by a venturi-type flume, such as a Parshall flume which is what was used for the outlet of the Braintree wetland system (Plate 4ii). Rectangular open channel flumes are simple, relatively cheap and particularly suitable for deep and narrow channels when the discharge and its range are small. Parshall flumes also have the advantages of a lower head loss than a weir and a smooth hydraulic flow preventing deposition of solids.

Under free-flowing (unsubmerged) conditions, the Parshall flume is a critical-depth meter that establishes a mathematical relationship between the stage h and discharge Q. For a flume with a throat width of at least 1 ft but less than 8 ft, flow can be calculated using the following equation (Viessman and Hammer, 1993):

$$Q = 4Wh^{1.522W*} \qquad \text{(Equation 4.3)}$$

Where
Q = flow, cubic feet per second
W = throat width, feet
h = upper head, feet
$*$ = to the power of 0.026

Using similar methods, Burrow-Crocker Consultancy calculated that for projected water level rises up to 0.366m, the flow through a 0.7m wide flume was the best discharge device able to cope with the demands of this particular system (see Table 4.2).

4.3.2 Construction of the Wetland

The base of the reed bed was constructed in impermeable boulder clay, to minimise any seepage, with a slope less than or equal to 1% to assist the water flow through the bed from the inlet to the outlets. The discharge from the inlet passes to two sediment forebays (approximately 2×100m) to allow settlement of suspended solids. The flow passes across a bund formed from a gabion wall. The gabion and the stone trenches at the inlet were filled with evenly-graded stones in the range of 50 to 200mm, with the optimum size being 60 to 100mm, and were planted with *Nymphaea* spp and *Elodea crispa*. The surface of the reed bed was made level to ensure even flow. Gravel of an even grade between 3 and 10mm was used for the *Phragmites australis* area to increase the hydraulic conductivity and act as a friction layer during intermittent storm events.

Clay and topsoil were made available by excavation of the site and a soil bed of 150mm was used for *Typha latifolia, Scirpus lacustris* and *Iris pseudacorus*. The topsoil was previously used for farming and had sufficient nutrient content to encourage initial plant growth.

4.3.3 Wetland Plants

A total of 10,000 *Phragmites* was supplied in half litre volume pots, which were removed prior to planting, at a density of four plants per square metre. It was essential to use containerised stock as the developed root balls provided initial sustenance for the plants in the gravel and provided support against flow and wind erosion. Once fully rooted, the *Phragmites* utilised nutrients from the water. *Typha* and *Scirpus,* planted at a density of four and six plants per square metre respectively, were supplied as well developed, short, stout plants with bare roots of at least one season's growth. Care was taken when planting to minimise root damage. For the settlement trenches near the inlet, *Nymphaea* plants of at least one season's growth were supplied in containers of two litre volume. *Elodea crispa* oxygenators were supplied in weighted bunches of a minimum three strands per bunch and firmly planted into the soil and where necessary, secured *in situ* with stones. Both *Nymphaea* and *Elodea* were only planted when there was sufficient water in the trench to support them. Similarly, reeds were not planted until the bed was at least moist. It is generally recommended that planting of reed beds in the UK takes place between March and May as this is the optimum period for initial growth with less possibility of transplant shock and desiccation.

The triangular gravel area (comprising over a third of the surface area of the wetland) which extends from the settlement trenches below the inlet, was planted with *Phragmites*. The remainder of the wetland was planted with *Typha, Iris* and *Scirpus* with alternating species in front of the six outlet pipes (Figure 4.1). A total 33,750 plants were eventually introduced to the wetland.

4.3.4 Flow Pathway

The wetland was constructed to allow both surface and subsurface flow. Water passes through the inlet into two settlement trenches. The trenches retain any large solids and thus reduce the need for maintenance. Each trench was planted with 50 *Nymphaea* spp lilies to reduce sunlight interaction and therefore prevent proliferation of algal blooms and stagnation of the water and 200 *Elodea crispa* to oxygenate and therefore improve water quality.

The water is encouraged to flow along the width of the trench and pass over a bund into the gravel section. The bund has a dual purpose. Firstly, it separates the trench from the gravel bed, acting as a retaining wall. Secondly it prevents surface erosion of the reed beds by acting as a buffer to the inflow of water and retains a constant water level thereby preventing reflux through the inlet pipe.

The water then flows onto a gabion line which acts as an initial physical filter and which extends across the width of the bed. It then passes through the subsurface system of the *Phragmites* bed planted in gravel. This system will assist the control of weed growth although the water level will periodically rise above the surface of the gravel. However, during dry periods, water will flow through the base of the bed encouraged by the slope of approximately 1%.

The water will then reach the soil bed which represents the surface flow system. Due to the poorer hydraulic conductivity of the soil compared to the gravel, surface flow will dominate through this section of the wetland containing *Typha latifolia* and *Scirpus lacustris* and *Iris*. Before reaching the outlet pipes, a stone trench collects and retains soil. A further separation layer ensures that the soil does not pass along and clog the outlet pipes.

Finally, the water passes through six outlet pipes into the recreational pond where it is subsequently discharged via a flume into the local river channel. The pipes are designed to enable retention of water to a depth of 5cm in the reed beds.

4.4 RESULTS AND DISCUSSION

4.4.1 Introduction

The monitoring period (August 1994 - September 1996) encompassed the construction of the housing development at Braintree and the opening of the bypass in March 1996 to traffic. As a result of delays in the planting of the wetland and the residential site construction, this is essentially a baseline study of the levels of heavy metals in the wetland and recreational pond. The heavy metal removal performance of the system from road and surface runoff was assessed for only a limited period and can only give an indication of the wetlands' performance when the bypass reaches full capacity and the housing development is fully constructed and functioning. A second carriageway may also be constructed in the future, if there is a need. It would indeed be advantageous if the monitoring was continued through this time since it would provide a valuable case study of how the wetland system and its removal performance has evolved prior to and after the completion of the construction of the housing development.

The monthly sampling programme was affected by relative inaccessibility of the wetland site - the site is situated over 80km from London and during the construction of the bypass, access to the wetland was often prevented or obstructed by deep mud. This meant that site visits at optimum times (e.g. a storm event) were not readily made being dependent on other factors beyond the control of this research programme.

4.4.2 Water Samples from the Inlet of the Wetland and the Outlet

The ranges of the average Cd, Cu, Pb and Zn water concentrations at the inlet pipe (Site 1) through the construction phase (Table 4.4) show levels that are comparable with the concentrations recorded in highway drainage from the A406 North Circular Road in London (see Chapter 3) indicative of vehicle densities up to 1500 vehicles per hour (Warren, 1987). These concentrations do not necessarily mean that the vehicle density on the bypass is comparable to that of a major motorway since the town of Braintree does not have a high traffic density. The high levels are probably due to flushes of highway drainage whereby the pollutants that accumulated upon the road surface during the construction of the bypass were flushed into the wetland once the bypass surface was cleaned for the official opening in April 1996. The metal concentrations are, in fact, lower after the opening of the bypass.

The Pb and Zn concentrations found in the waters in the inlet are higher than the Cd and Cu concentrations (Tables 4.4 and 4.5). The primary sources of heavy metals in highway runoff are vehicles (Rexnord Inc. 1984; also see Section 2.2) and construction vehicles were heavily used in the vicinity of the wetland during the construction of the bypass. The primary sources of Zn are tyre wear (fillers), galvanised materials, oil (stabilising additives) and grease (Rexnord Inc. 1984). Since the bypass was not being used for travelling by vehicles through the monitoring period, Zn derived from tyre wear is unlikely to be a major source. It is probable that the Zn in the inflowing runoff was derived from the oil and grease of the construction vehicles (Cd and Cu are not significant constituents). The Pb concentrations can be explained similarly although this metal has many other sources, petrol being a predominant one.

Average heavy metal concentrations with standard deviations in the water and sediment samples at the inlet (Site 1) and outlet (Site 14) during the construction phase are listed in Table 4.5. The variations of the heavy metal water concentrations at these sites throughout the monitoring period are shown in Figures 4.2 to 4.5. Inlet concentrations are generally higher than those in the outlet with the highest inlet concentrations of Cd (51μg/l) and Cu (72μg/l) observed in September 1996 (Figure 4.2) and October 1994 (Figure 4.3) respectively. The highest inlet concentrations of Pb occurred in October 1994 (152μg/l) and in April 1995 (149μg/l) (Figure 4.4) whereas the highest inlet concentration of Zn (305μg/l) occurred in April 1995 (Figure 4.5). In each of these cases, except for Zn, the higher concentrations can at least be partially explained by shock loads due to consistent rain events with high monthly totals prior to the sampling dates (see Figures 4.2 to 4.5). The higher Cd, Cu, Pb and Zn water concentrations in the inlet generally coincide with the autumn/winter period of 1994 and the spring of 1995 when the bypass was being constructed. This reflects the increased activity in construction near the wetland site since the vehicles used for construction would be sources of the heavy metals (see Section 4.4.3).

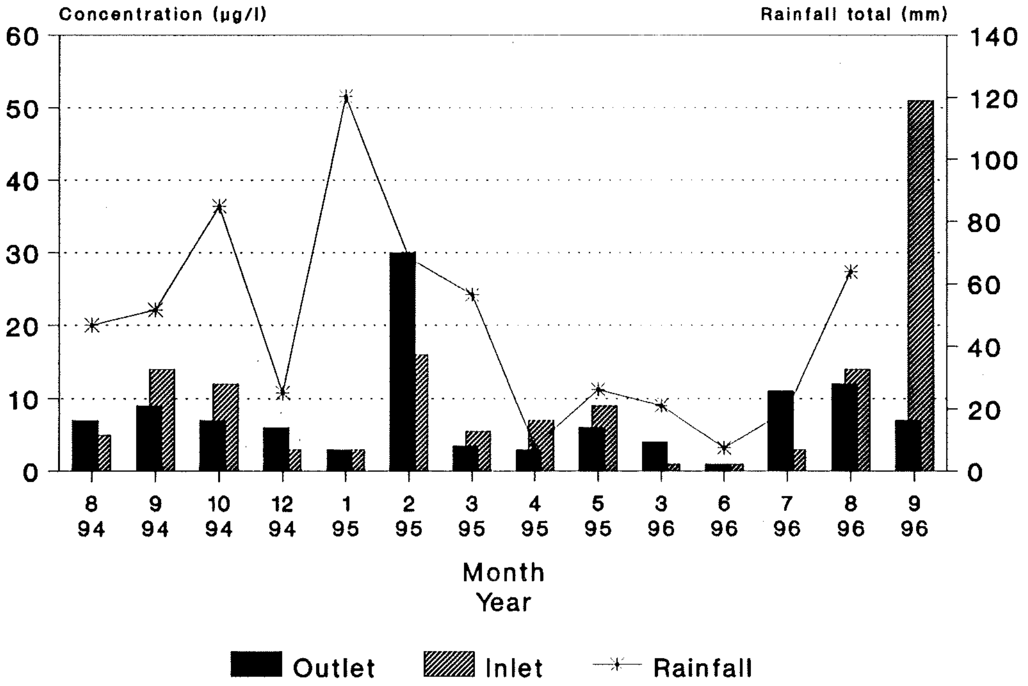


Figure 4.2 Temporal variation in inlet and outlet water concentrations for Cd (Rainfall data for 9/96 not included as sampling took place early in the month).

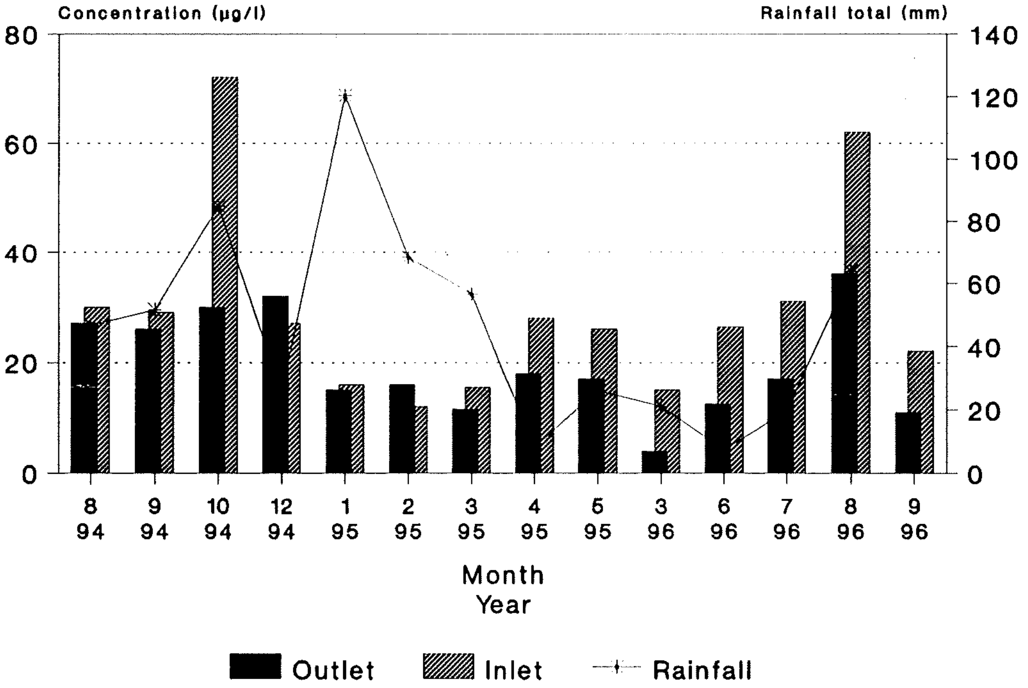


Figure 4.3 Temporal variation in inlet and outlet water concentrations for Cu (Rainfall data for 9/96 not included as sampling took place early in the month).

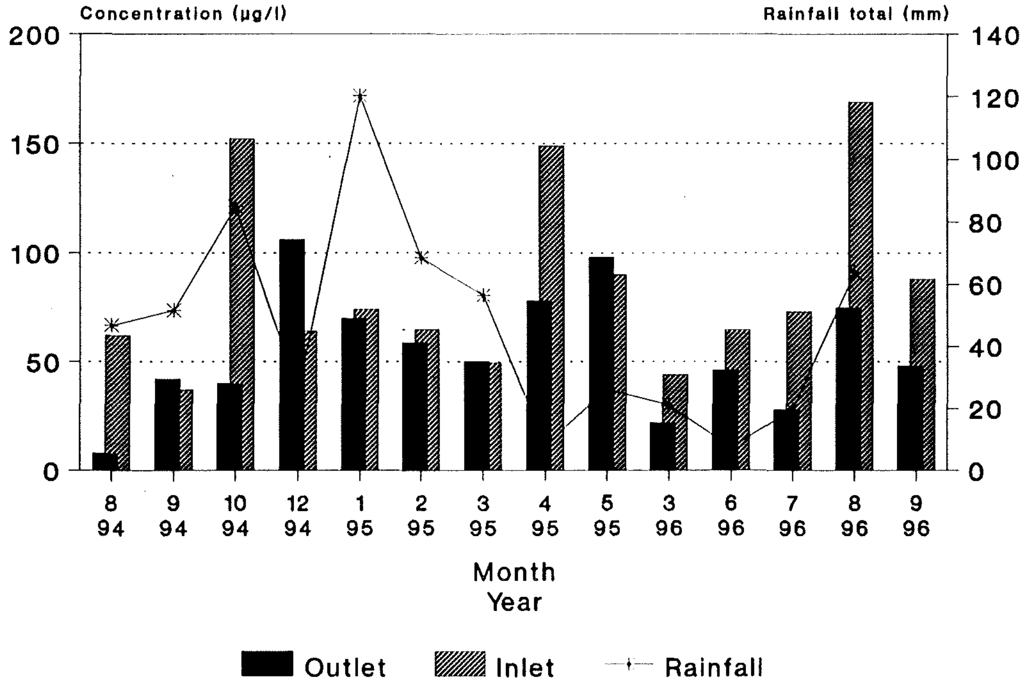


Figure 4.4 Temporal variation in inlet and outlet water concentrations for Pb (Rainfall data for 9/96 not included as sampling took place early in the month).

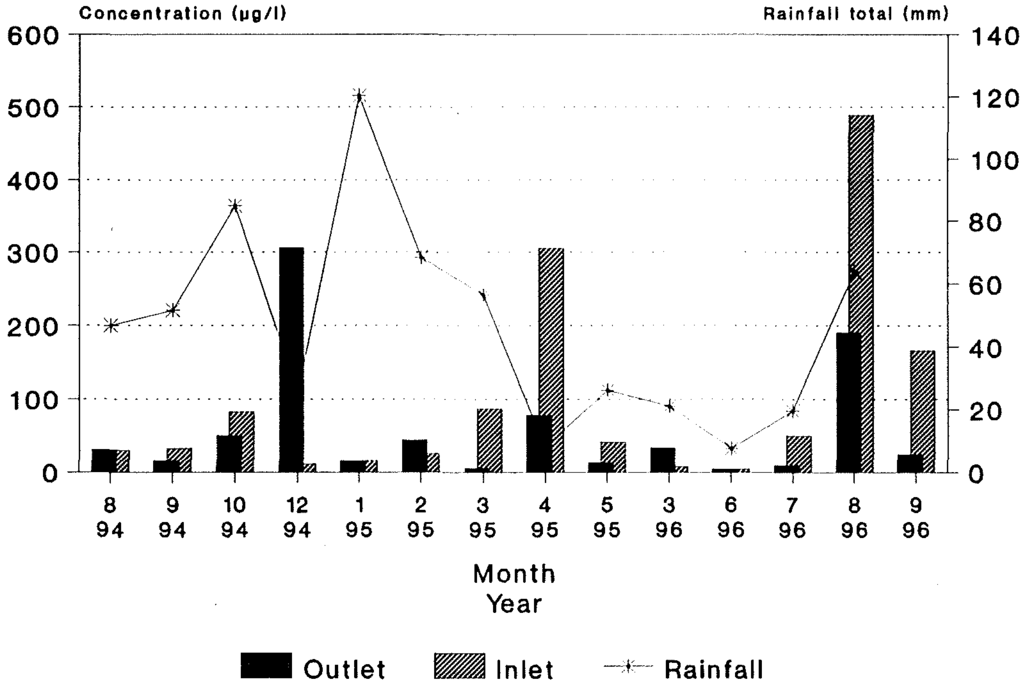


Figure 4.5 Temporal variation in inlet and outlet water concentrations for Zn (Rainfall data for 9/96 not included as sampling took place early in the month).

Table 4.4 Comparison of quality of UK/European highway drainage with runoff from the Braintree site.

Metal	Concentration Ranges (μg/l)				
	Motorways[1]	Suburban roads[1]	A406 Road[2]	Inlet (before the opening of the bypass)	Inlet (after the opening of the bypass)
Total Cd	-	-	2-12	3-16	1-3
Total Cu	50-690	10-120	10-40	12-72	26.3-31
Total Pb	340-2410	10-150	40-160	37-152	64.7-73
Total Zn	170-3550	20-1900	10-100	11-86	4.4-50

Key
1 Data from Hedley and Lockey (1975)
2 Data from Mungur *et al.* (1995) (see Chapter 3)

The effect of the opening of the bypass is not readily apparent with water concentrations at the inlet from March 1996 lying within the range of values seen in the period August 1994 to March 1996, before the bypass was opened to vehicles (Table 4.4). However there is a small but perceptible increase in the water concentrations of all the metals at the inlet from March to July 1996 (Figures 4.2 to 4.5). Although the later concentrations do not reach the levels seen previously, these concentrations are derived mostly from runoff resulting from vehicles using the bypass and not derived from heavy construction work. The remaining runoff is derived from surface runoff from the housing development. The bypass is not a major highway and will not have such comparable traffic densities. Even as it becomes more established, it is not likely that the concentration ranges of heavy metals in the resulting runoff will regularly exceed the highest concentrations seen in the runoff during the construction phase.

Outlet metal water concentrations are generally lower than the inlet concentrations in the case of all the metals (Table 4.5; Figures 4.2 to 4.5). Outlet water concentrations are higher than those in the inlet in December 1994 (6 versus 3μg/l) and February 1995 (30 versus 16μg/l) for Cd and December 1994 for Cu (32 versus 27μg/l), Pb (106 versus 64μg/l) and Zn (306 versus 11μg/l). This may reflect shock loads in the runoff from the catchment area around the recreational pond (and the outlet area) which, at those times, had not been planted or developed in any way and thus could not attenuate

Table 4.5 Average heavy metal concentrations and standard deviations in wetland water samples from the inlet (Site 1) and outlet (Site 14) during the monitoring period.

Metal	Water concentration (μg/l)	
	Inlet	Outlet
Cd	7.5±5.5 (2)	7.7±8.6 (6)
Cu	27.1±18.0 (28.7)	19.7±9.2 (14.8)
Pb	78.7±42.8 (68.9)	57.3±33.1 (37.1)
Zn	62.8±94.5 (27.2)	56.0±95.9 (7.1)

Key
( ): Average concentrations after the opening of the bypass in March 1996.

surface runoff. Therefore, during storm rain events, metal loads that had accumulated during construction around the pond were washed away by the runoff into the recreational pond (Figure 4.1) and eventually discharged out of the flume at the outlet (Site 14).

The inlet water concentrations (Table 4.5) of the Braintree wetland are comparable to, but generally higher than the levels seen in other wetland systems which receive urban runoff (Table 4.6) whereas the level of treatment (based on comparisons of the inlet and outlet concentrations) does not compare as well. The higher concentrations reflect the higher metal loads discharged into the wetland due to the construction activities occurring in the vicinity during most of the monitoring period. The lower apparent level of treatment can also be explained by surface runoff from the then undeveloped catchment area around the recreational pond (i.e. other than that from the inlet) which could not attenuate surface runoff efficiently.

Table 4.6 Comparison of inlet and outlet metal water concentrations (μg/l) in the Braintree wetland and other wetland systems receiving runoff.

	Cd		Cu		Pb		Zn	
Description	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Wetland receiving surface/urban runoff, Braintree, UK	7.5	7.7	27.1	19.7	78.7	57.3	62.8	56.0
Forested swamp receiving urban runoff, Sandford, FL*	3.9	-	19.9	-	24.7	-	3.9	-
Freshwater marsh receiving urban stormwater, Orlando, FL**	-	-	8.0	1.0	18.0	3.0	75.0	25.0

Key

* Data from Harper *et al.* (1986), ** Data from Schiffer (1989)

4.4.3 Sediment Samples from the Inlet of the Wetland and the Outlet

The sediment metal concentrations show similar trends to the water concentrations. They are generally lower at the outlet than at the inlet, with the exception of Cd, and do not show high variations (Table 4.7). Sediment samples from the *inlet* were not collected after March 1996.

Table 4.7 Average heavy metal concentrations and standard deviations in wetland sediment samples from the inlet (Site 1) and outlet (Site 14) during the monitoring period.

Metal	Sediment concentration (μg/g)	
	Inlet	Outlet
Cd	2.2±1.3	2.4±2.5 (1.3)
Cu	14.2±8.8	13.9±6.7 (5.6)
Pb	41.5±17.9	28.4±12.6 (13.7)
Zn	49.0±19.9	39.3±14.6 (11.3)

Key

( ): Average concentrations after the opening of the bypass in March 1996.

The sediment concentrations seen at the inlet and outlet are generally lower than the levels seen in other wetland systems (Table 4.8) and are in fact comparable to the concentrations seen in an unpolluted wetland (Zhang *et al.*, 1990). These results represent baseline levels and show that the Braintree wetland is still in its early stages and has the potential to become an efficient sink for heavy metals as it starts to receive higher loads of heavy metals once the bypass and housing development are fully established.

Table 4.8 Comparison of inlet/outlet average heavy metal sediment concentrations in the Braintree wetland with the sediments of other wetland systems receiving urban runoff.

Metal	Sediment concentration (μg/g)						
	Braintree wetland, UK		Freshwater marsh, Orlando, FL[1]		Swamp Forest, Sanford, FL[2]	Shallow lake with macrophytes, Tacoma, WA[3]	Unpolluted wetland, UK[4]
	Inlet	Outlet	Inlet	Outlet			
Cd	2.2	2.4	7	1	2.2	5.9	2
Cu	14.2	13.9	92	4	8.5	160	20
Pb	41.5	28.4	1300	40	48	3000	40
Zn	49	39.3	410	23	40	900	35

Key
Data from: [1] Schiffer (1989), [2] Harper and Livingston (Unpublished), [3] Wisseman and Cook (1977), [4] Zhang *et al.* (1990)

4.4.4 Water Samples from the Wetland and Recreational Pond

Water and sediment samples from a further 12 sites in the wetland and recreational pond (see Table 4.1) were collected over the monitoring period. The sites were grouped into five categories (including the inlet and outlet) as shown in Table 4.1 for a clearer representation of how the metal concentrations of the water and sediment samples varied through the system over the monitoring period. The temporal variation of the heavy metal water concentrations through the wetland and recreational pond are shown in Figures 4.6 to 4.9 and the average heavy metal concentrations with standard deviations in all the different grouped areas of the system are listed in Table 4.9.

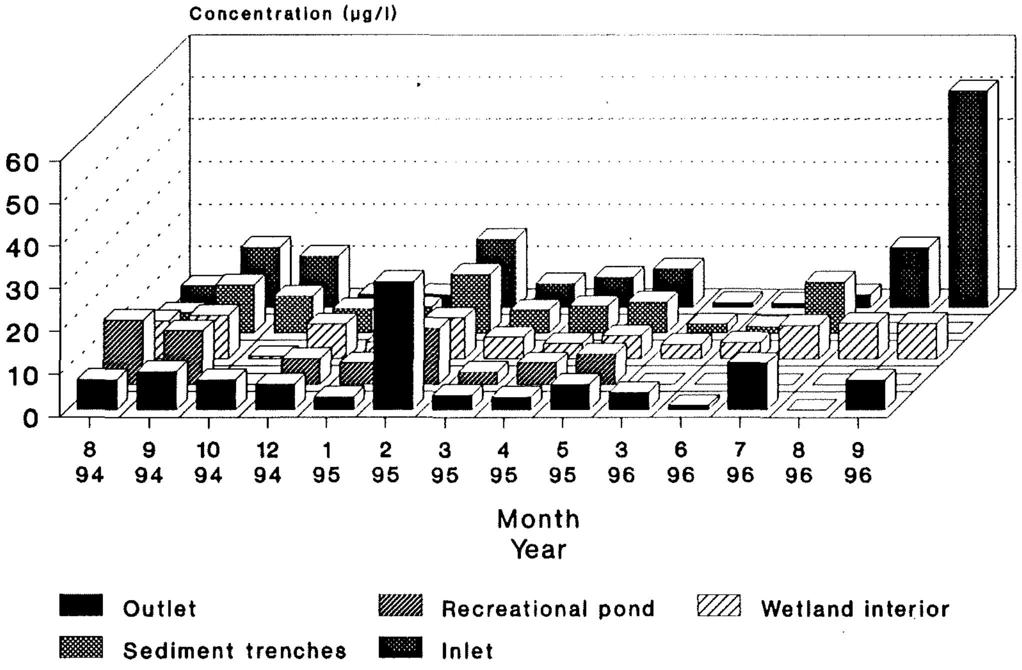


Figure 4.6 Temporal variation of water concentrations for Cd through the wetland and recreational pond.

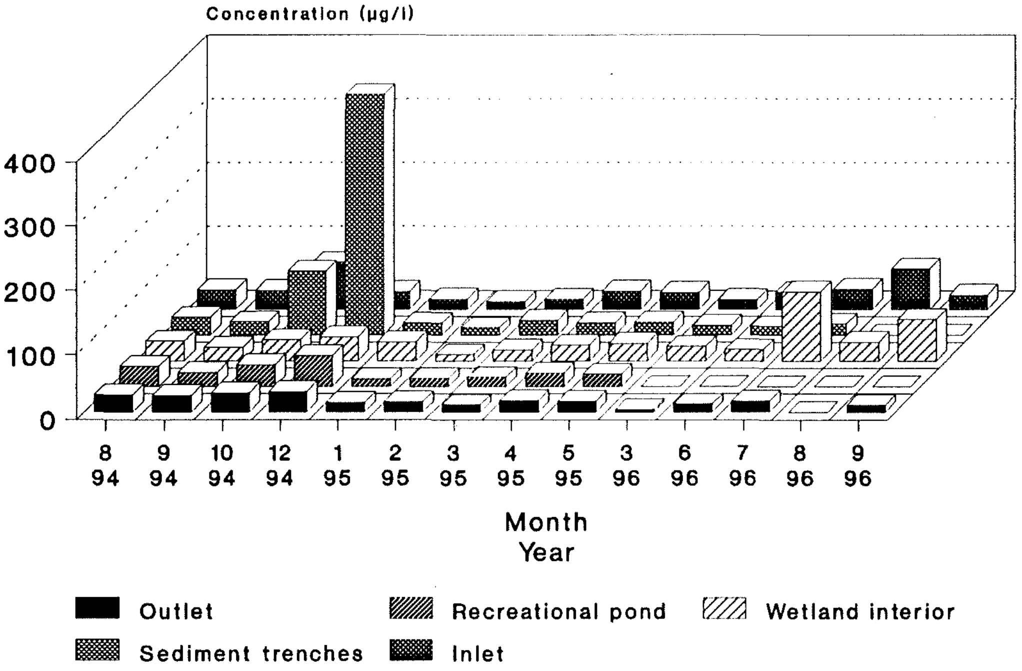


Figure 4.7 Temporal variation of water concentrations for Cu through the wetland and recreational pond.

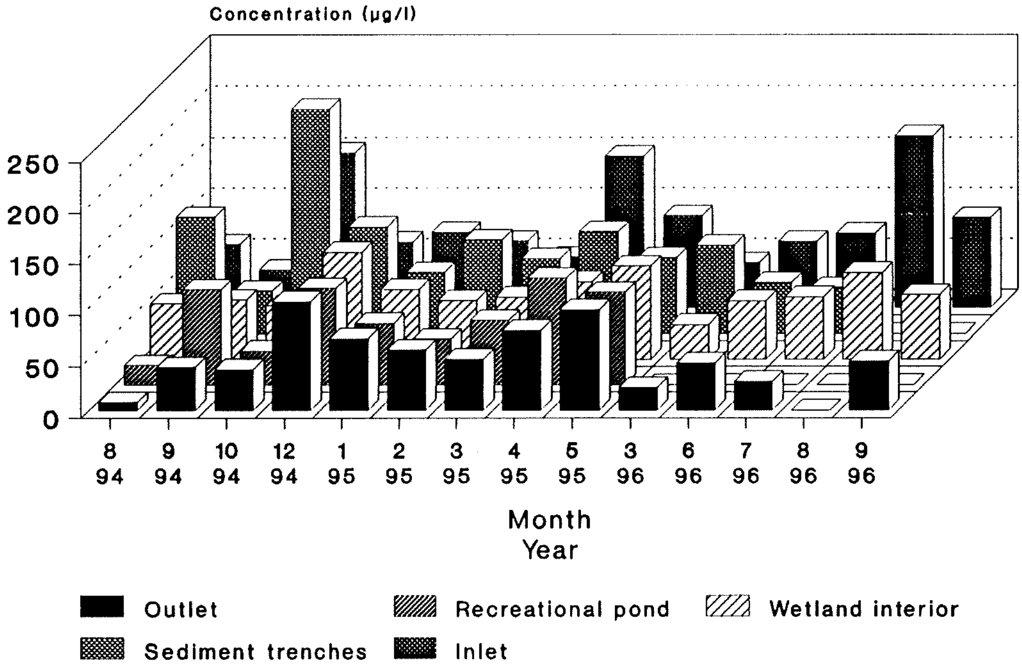


Figure 4.8 Temporal variation of water concentrations for Pb through the wetland and recreational pond.

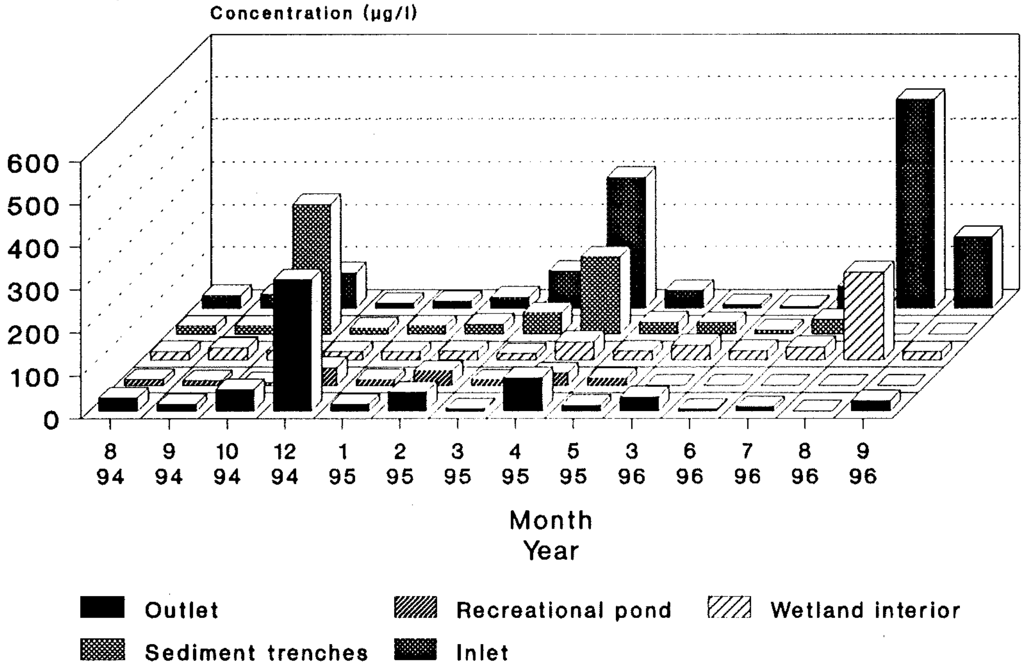


Figure 4.9 Temporal variation of water concentrations for Zn through the wetland and recreational pond.

Table 4.9 Average water metal concentrations and standard deviations (μg/l) in the grouped areas of the wetland.

Metal	Group I	Group II	Group III	Group IV	Group V
	Inlet	Sediment traps	Wetland interior	Recreational pond	Outlet
Cd	7.5±5.5 (2.2)	6.8±4.0 (5.3)	5.4±3.8 (4.9)	7.4±5.4	7.7±8.6 (5.3)
Cu	27.1±18.0 (24.1)	28.9±26.7 (15.3)	25.0±6.3 (48.8)	24.0±12.5	19.7±9.2 (11.2)
Pb	78.7±42.8 (60.6)	96.2±51.2 (60)	65.4±21.3 (50.2)	66.7±32.1	57.3±33.1 (32.0)
Zn	62.8±94.5 (20.8)	64.8±103.2 (23.1)	23.3±8.3 (28.6)	19.9±12.7	56.0±95.9 (15.7)

Key

( ): Average concentrations after the opening of the bypass in March 1996 are shown in brackets.

Table 4.9 and Figures 4.6 to 4.9 show that there are no clear trends in the water metal concentrations as the water flows from the inlet pipe to the outlet flume via the settlement trenches, the interior of the wetland and its interconnecting pipes, and the recreational pond (see Figure 4.1). The metal concentrations are not markedly different after the opening of the bypass in March 1996 although there is a slight increasing trend after March 1996.

Cd and Cu water concentrations are fairly constant through the system over the monitoring period (Figures 4.6 and 4.7 respectively) except for the elevated levels in February 1995 and December 1994 respectively. The higher Cu concentrations in the wetland interior (Sites 8 to 11) from July to September 1996 may be explained by the higher rate of evaporation though the summer. As a result, metal concentrations in the stagnant waters of the wetland interior would increase at times of low or no discharge into the wetland.

Pb water concentrations generally show more variation through the system over the monitoring period (Figure 4.8) than Cd and Cu. The Pb concentrations in the sediment trenches, the wetland interior and recreational pond generally vary with increases and decreases in the inlet and outlet Pb water concentrations. The Zn concentrations (Figure 4.9) are fairly constant except for the high levels in the sediment trench in October 1994 and in April 1995 (302.5 and 178.7μg/l respectively), and in the wetland interior (203.7μg/l) in August 1996. The irregular distribution of these peaks may suggest random shock loads or an irregular source of Zn derived from the construction vehicles.

To determine if the observed differences in the water metal concentrations in the different grouped areas of the wetland (e.g. the inlet and outlet) can be attributed to natural variability through the wetland or to another cause (i.e. determine the probability (p) of finding results as remote as the ones observed when, in fact, all the population means are equal), analysis of variance (ANOVA) was carried out to test the null hypothesis that the several population (grouped areas) means are equal (ANOVA examines the variability of observations within each group as well as the variability between the group means). The results are shown in Table 4.10.

Table 4.10 Analysis of variance: p-values of the metal water concentrations through the system over the total monitoring period.

Areas analysed	Cd	Cu	Pb	Zn
Inlet/Outlet	0.95	0.43	0.58	0.79
Inlet/Sediment trap	0.70	0.41	0.97	0.96
Sediment trap/Wetland	0.85	0.53	0.65	0.86
Wetland/Recreational pond	0.52	0.21	0.24	0.23

When $p > 0.050$, the null hypothesis cannot be rejected, i.e. observed differences *can* be attributed to the natural variability of the wetland. Thus the differences in the metal water concentrations in the separate grouped areas of the wetland (Table 4.9) can be attributed to the natural variation amongst the grouped areas of the wetland system that have been compared, i.e. the differences are not statistically significant. Also, as Figures 4.6 to 4.9 show, the metal concentrations in the water do not vary much.

4.4.5 Sediment Samples from the Wetland and Recreational Pond

The temporal variation of the heavy metal sediment concentrations though the wetland and recreational pond are shown in Figures 4.10 to 4.13 and the average heavy metal concentrations with standard deviations in all of the different grouped areas of the system are listed in Table 4.11. Table 4.11 and Figures 4.10 to 4.13 show that there is little variation within the metal concentrations through the system over the monitoring period. The opening of the bypass appears to have no clear effect on the concentrations of all the heavy metals in the sediment trenches, the wetland interior and the recreational pond after March 1996 although this may also be due to low rainfall contributing to less runoff into the wetland.

Table 4.11 Average sediment metal concentrations and standard deviations (μg/g) in the grouped areas of the wetland.

Metal	Group I	Group II	Group III	Group IV	Group V
	Inlet	Sediment traps	Wetland interior	Recreational pond	Outlet
Cd	2.2±1.3	2.5±1.3 (2.7)	2.0±1.9 (5.0)	1.7±1.0	2.4±2.5 (3.4)
Cu	14.2±8.8	25.9±11.8 (10.5)	23.8±19.4 (25.8)	16.8±5.0	13.9±6.7 (7.5)
Pb	41.5±17.9	44.0±14.1 (24.7)	31.0±10.3 (27.2)	32.4±7.0	28.4±12.6 (15.0)
Zn	49.0±19.9	62.1±7.8 (47.3)	65.0±49.7 (57.6)	41.0±9.2	39.3±14.6 (21.3)

Key

( ): Average concentrations after the opening of the bypass in March 1996 shown in brackets.

The highest sediment concentrations for each metal (4.8μg/g for Cd in March 1996, 49.2μg/g for Cu in April 1995, 76.7μg/g for Pb in October 1994 and 72.8μg/g for Zn in April 1995) were generally found in the sediment trenches following periods of consistent rainfall except for Pb in October 1994 (see rainfall data as shown in Figures 4.2 to 4.5). Higher inflow through the inlet into the sediment trenches introduces higher loads into the trenches causing higher metal accumulation in the trench sediment.

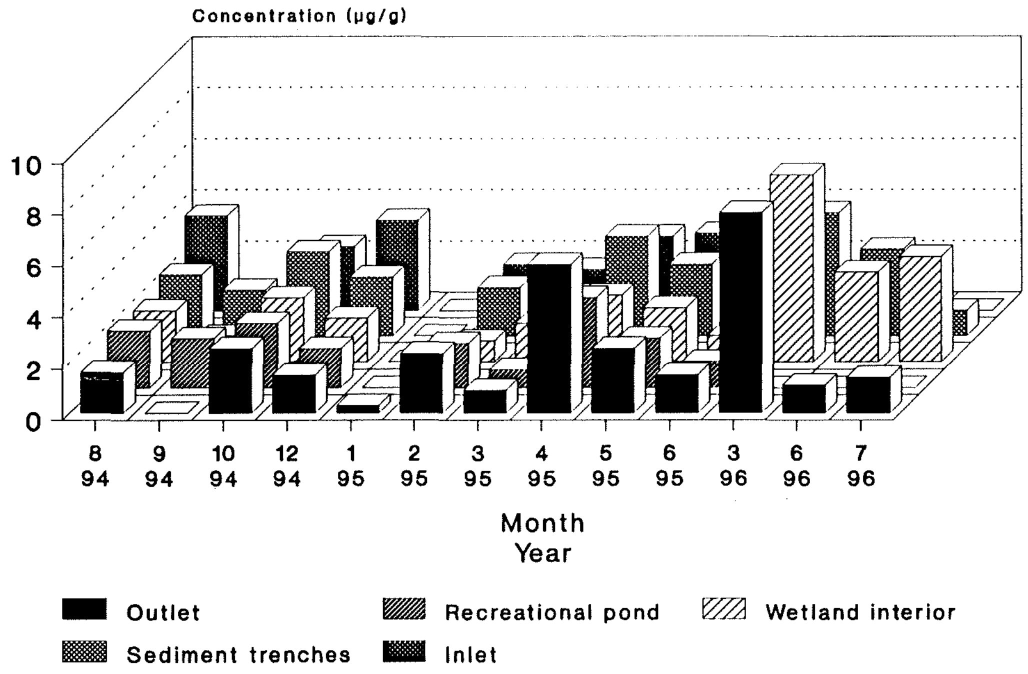


Figure 4.10 Temporal variation of sediment concentrations for Cd through the wetland and recreational pond.

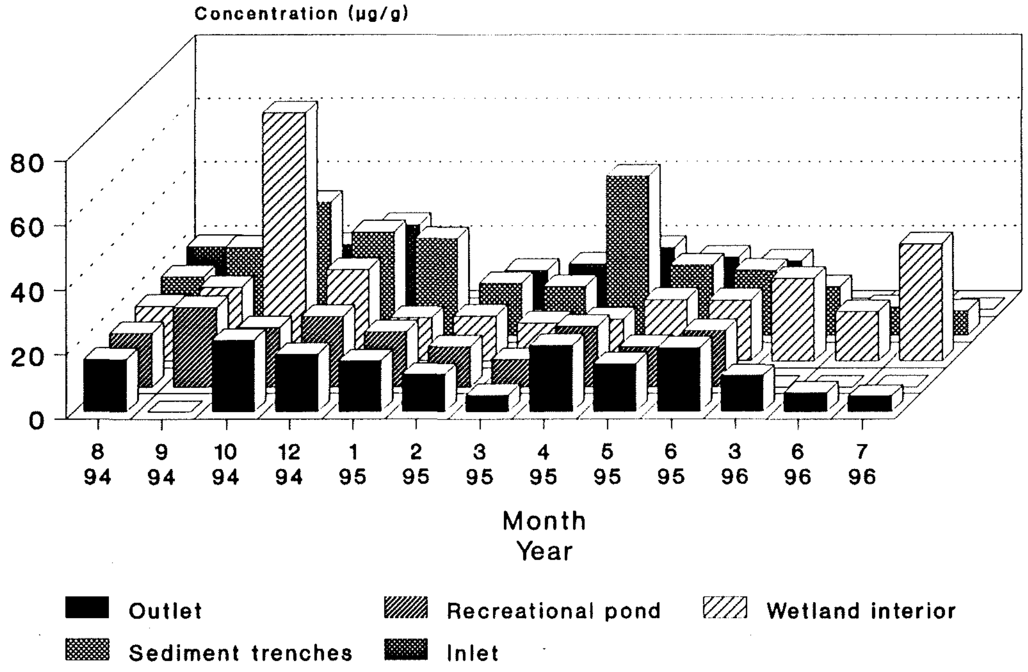


Figure 4.11 Temporal variation of sediment concentrations for Cu through the wetland and recreational pond.

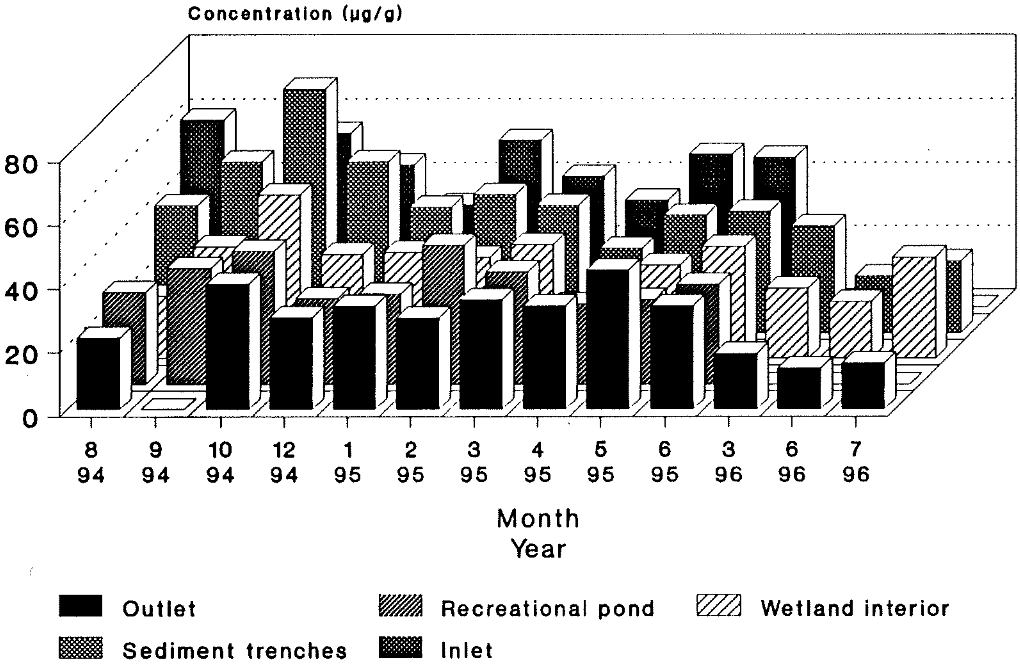


Figure 4.12 Temporal variation of sediment concentrations for Pb through the wetland and recreational pond.

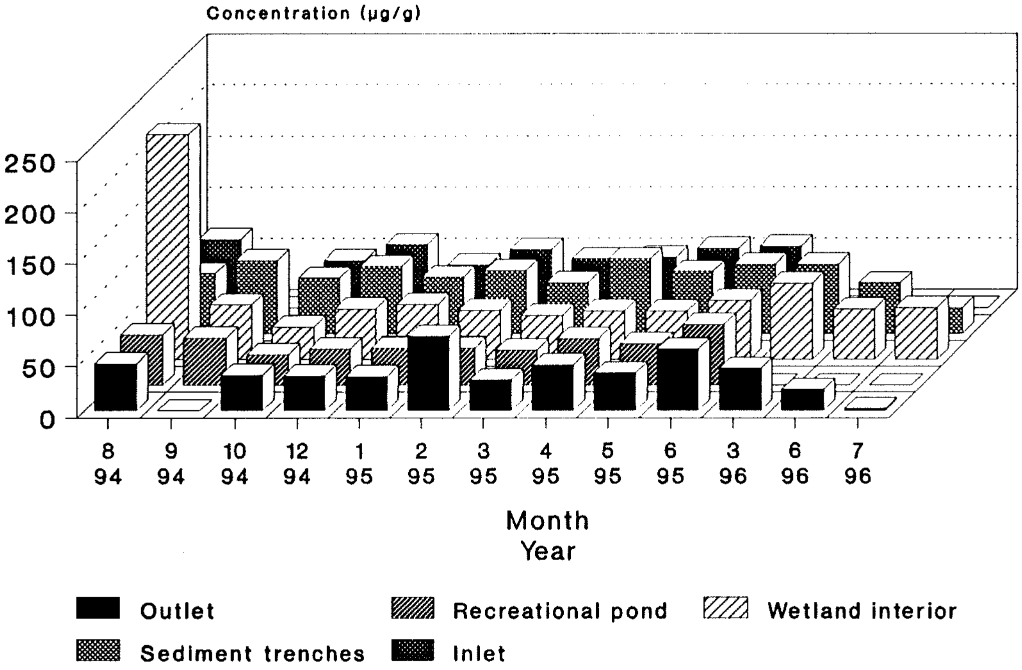


Figure 4.13 Temporal variation of sediment concentrations for Zn through the wetland and recreational pond.

ANOVA was carried out to determine if the observed differences in the sediment metal concentrations in the different grouped areas of the wetland (e.g. the inlet and outlet) could be attributed to natural variability through the wetland or to another cause. The results are shown in Table 4.12.

Table 4.12 Analysis of variance: p-values of the metal sediment concentrations through the system over the total monitoring period.

Areas analysed	Cd	Cu	Pb	Zn
Inlet/Outlet	0.32	0.91	0.08	0.26
Inlet/Sediment trap	0.37	0.01	0.62	0.07
Sediment trap/Wetland	0.87	0.88	0.05	0.73
Wetland/Recreational pond	0.68	0.31	0.96	0.19

When $p > 0.050$, the null hypothesis cannot be rejected, i.e. observed differences can be attributed to the natural variability amongst the species. From Table 4.12, the differences seen in the metal sediment concentrations in separate grouped areas can be attributed, in the majority of the cases, to the natural variation amongst the grouped areas of the wetland system that have been compared, i.e. the differences are not statistically significant. This may be because the wetland did not receive sufficiently high metal loads through the monitoring period to allow for metal concentration differences through the different areas of the wetland to become marked. Also, as Figures 4.10 to 4.13 show, metal concentrations in the sediment do not show significant variations.

However, the null hypothesis is rejected for the Cu concentrations in the sediment samples of the inlet and settlement trenches (Table 4.12). This may occur because the average Cu concentrations in the settlement trenches were consistently higher than those found in the inlet. This might indicate that the settlement trenches are effectively accumulating higher concentrations due to their design which allows sedimentation. Thus the differences in concentrations may not be attributable to the natural variability of Cu in this system. However the null hypothesis is not rejected for Cd, Pb and Zn in the same samples, as might be expected. This suggests that either more data over a longer period of time is required for to draw any conclusions from ANOVA or the Cu result may be anomalous.

4.4.6 Metal Removal Performance of the Wetland System

A disadvantage of the long monitoring period (2 years) was that equipment used in the initial stages of the monitoring could not always be available for use throughout the study. Therefore, other methods had to be employed for certain measurements such as the flow rate into the wetland. As previously mentioned in Section 4.2, a portable UF 1100 ultrasonic flow-meter was initially installed at the inlet of the wetland to measure inflowing rates from August to October 1994 (Table 4.13). Thereafter flow rates at the inlet were calculated by taking the average of the time taken to fill a container of known volume. Flow rates at the outlet were estimated when possible (Table 4.13).

Table 4.13 Flow rates measured at the inlet (Site 1), the interconnecting pipes between the wetland and recreational pond and at the outlet (Site 14).

Date	Site	Q (l/s)
08/94	Site 1	8.29
09/94	Site 1	3.40
10/94	Site 1	5.04
01/95	Site 1	0.41
02/95	Site 1	0.34
03/95	Site 1	0.20
04/95	Site 1	0.25
05/95	Site 1	0.19
03/96	Site 1	1.02
	Site 9	0.32
	Site 10	0.25
	Site 11	0.42
	Site 14	0.22
09/96	Site 1	3.36
	Pipe 1 (Site 9)	0.50
	Pipe 2	0.65
	Pipe 3	0.70
	Pipe 4 (Site 10)	0.50
	Pipe 5	0.81
	Pipe 6 (Site 11)	0.80
	Site 14	0.18

Heavy metal loading rates at the inlet were calculated using the following relationship:

$$L = [\,] \times Q \qquad \text{(Equation 4.4)}$$

Where:
L = Metal loading at inlet (mg/s)
$[\,]$ = Metal concentration at inlet (mg/m^3)
Q = Flow rate at inlet at that time (m^3/s)*

* Note, 1m^3/s corresponds to 1000l/s.

Table 4.14 lists the heavy metal loading rates calculated for the inlet (Site 1) over the monitoring period and Figure 4.14 shows the temporal variation of metal loading rates at the inlet (Site 1). It is clear from Table 4.14 and Figure 4.14 that the loading rates decreased dramatically between October 1994 and January 1995. This is interpreted as a direct result of the reduction in construction activity through the winter of 1994/1995 due to completion of house construction in the area of the wetland system and remaining construction activity lessening due to the difficulties of working through the winter. The increases in Pb and Zn in April 1995 follow the opening of the bypass in March 1996 and may reflect increased vehicle activity for construction purposes on the bypass. Metal loadings for June and July 1996 could not be calculated due to the lack of flow in the inlet pipe.

Table 4.14 Inlet (Site 1) heavy metal loadings (mg/s) over the monitoring period.

Date	Cd	Cu	Pb	Zn
08/94	41.5	248.7	514.0	248.7
09/94	47.6	98.6	125.8	108.8
10/94	60.5	362.9	766.1	413.3
01/95	1.2	6.6	30.3	6.6
02/95	5.4	4.1	22.1	8.5
03/95	1.1	3.1	9.9	17.3
04/95	1.8	7.0	29.8	76.3
05/95	1.7	4.9	17.1	7.8
03/96	1.0	15.2	44.7	8.1
09/96*	171.4	73.9	295.7	557.8

Key
* Storm event

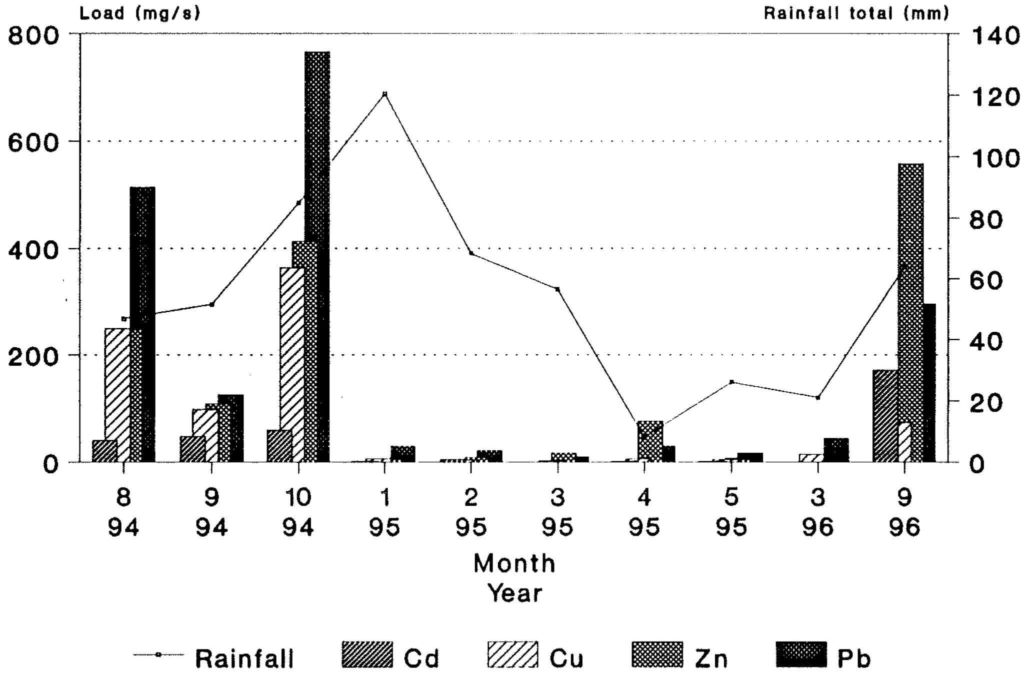


Figure 4.14 Temporal variation of heavy metal loading rates at the inlet (Site 1) (Rainfall total for 8/96 used in the graph for the 9/96 loadings as measurements took place early in the month).

Figure 4.14 shows that the highest loading rates tend to occur during times of consistent rainfall events. However, the higher loads seen in August and October 1994 are also probably associated with drainage derived from the construction activities during the building of the housing development. The very low loads seen in January 1995 concides with a decrease in heavy construction activity. The higher loads seen in September 1996 occurred after a relatively dry summer and are probably due to a shock load during the storm event that occurred when the measurements were taken.

Loading rates out of the wetland at the interconnecting pipes between the wetland and the recreational pond (Sites 9 to 11; see Figure 4.1) were measured in March and September 1996. Table 4.15 lists the removal efficiencies that were calculated at the various dates and Figures 4.15 and 4.16 show the heavy metal removal efficiency of the wetland for a non-storm event and a storm event respectively. The results show that the heavy metal removal efficiencies between the inlet (Site 1) and outlet (Site 14) range between 9.9 and 99.3%. The loadings at the interconnecting pipes were combined to represent the total load of metals transferring to the recreational pond. The heavy metal removal efficiencies between the inlet (Site 1) and the recreational pond range between -271.6 and 84.7%. The metal removal between the inlet and outlet is comparable to the removal efficiencies reported in full-scale wetlands by various researchers (see Kadlec and Knight, 1996) and are summarized in Table 4.16.

Table 4.15 Removal efficiencies for the inlet (Site 1) and recreational pond and inlet (Site 1) and outlet (Site 14) and based on metal loads at the sites.

Date	Sites	Removal efficiency (%)			
		Cd	Cu	Pb	Zn
03/96	Site 1/Pond	-170.0	-46.7	24.6	-271.6
	Site 1/Site 14	10.0	94.1	89.0	9.9
09/96*	Site 1/Pond	80.0	-281.6	26.8	84.7
	Site 1/Site 14	99.3	97.4	97.1	99.2

Key

* Storm event - water samples collected and flow measurements made at the outlet (Site 14) represent the first flush of water out of the system (3 hours after initial sampling at the inlet (Site 1) - i.e. the retention time).

Cd removal in wetlands is thought to occur because of the formation of its sulphide and subsequent sedimentation of the metal (Hendry *et al.*, 1979; Best, 1987; CH2M HILL, 1991, 1992). The wide range for Cd removal in the Braintree wetland (Table 4.15) may be attributed to the low concentrations of Cd usually found in runoff. Thus even small fluctuations in concentration will affect the removal efficiency greatly.

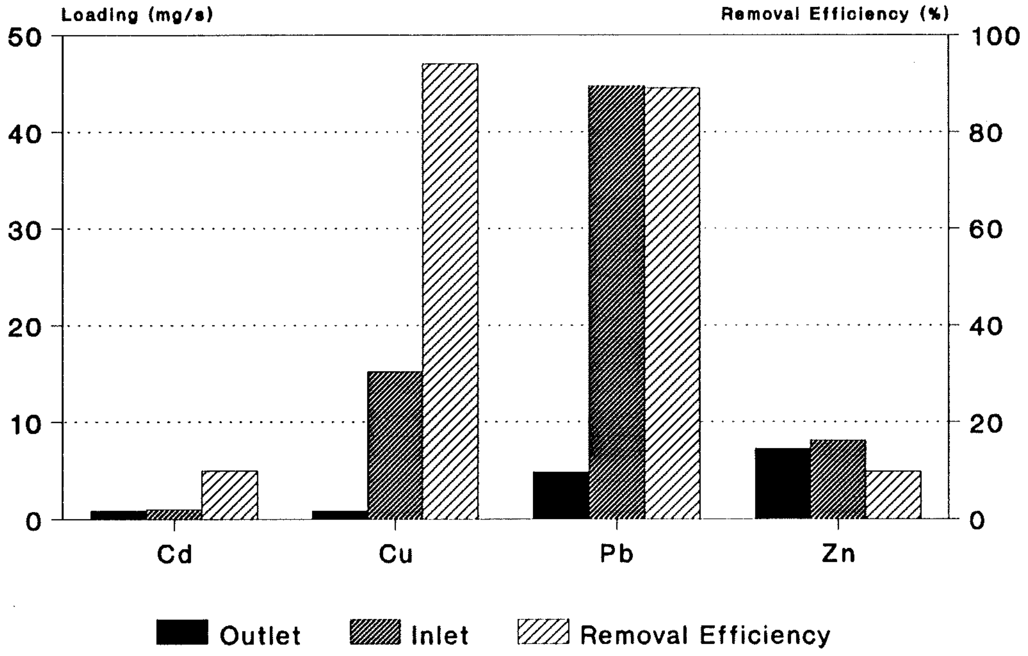


Figure 4.15 Heavy metal removal efficiency of the wetland during a non-storm event (3/96).

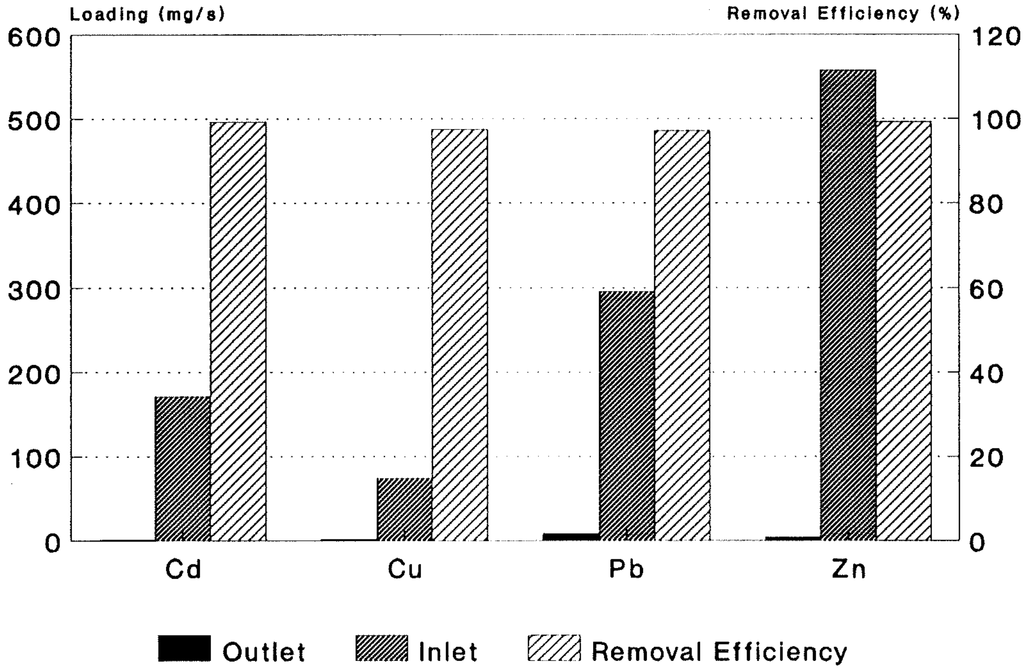


Figure 4.16 Heavy metal removal efficiency of the wetland during a storm event (9/96).

Table 4.16 Comparison of the heavy metal removal performance of the constructed wetland system at Braintree with other full-scale wetlands.

Metal	% Removal range between the inlet and outlet in the Braintree wetland system	% Removal range between inlet and outlet in other full-scale wetland systems (Kadlec and Knight, 1996)
Cd	10.0-99.3	0-98.7
Cu	94.1-97.4	38-96
Pb	89.0-97.1	-181-83.3
Zn	9.9-99.2	33-89.5

Cu, Pb and Zn removals appear to correlate with inflow concentrations with removal efficiency increasing with increasing inflow concentrations (Kadlec and Knight, 1996; see also Section 5.3). The high affinity of Cu for peat and humic substances (Kadlec and Keoleian, 1986) and, to a lesser degree, macrophyte tissues (Zhang *et al.*, 1990; Sinicrope *et al.*, 1992) appears to play an important role in its removal in wetlands and may explain the high Cu removal seen in the Braintree wetland. Pb removal appears to be mostly due to the formation of insoluble compounds followed by subsequent sedimentation. The wide range for Zn removal in the Braintree wetland (Table 4.16) compared to Pb may be attributed to Zn being present in water as a predominantly soluble bioavailable metal ion or weak complex (Revitt and Morrison, 1987). Sediment association/uptake for Zn is generally lower than Pb since the latter exhibits little remobilization once deposited (Meiorin, 1989) and this may affect the overall removal efficiency of Zn. However, this is not seen in the Braintree wetland where the average sediment Zn concentrations in the system are higher than those of Pb (see Table 4.11). Another possibility is that Zn removal varies more than Pb removal because of more variable inflow concentrations (see Figures 4.4 and 4.5).

4.4.7 Macrophyte Samples

Specimens of *Typha latifolia, Iris pseudacorus* and *Scirpus lacustris* were collected at Sites 8, 9 and 10 respectively (see Figure 4.1) for tissue heavy metal analysis as previously described in Section 3.3.2.3. Sampling took place initially in autumn 1993, prior to the start of the official monitoring period (August 1994 to September 1996) and prior to runoff discharging into the wetland, to establish background tissue concentrations.

Further macrophyte samples were collected in the growing seasons of 1994 and 1995 (*Typha* was not collected in 1994). *Phragmites australis* was not planted in the wetland until the spring of 1995 (collected near Site 8) and thus only one sample set was analysed.

Metal analyses of the macrophytes indicate bioaccumulation of Cd, Cu, Pb and Zn (Figures 4.17 to 4.19). Tissue concentrations are generally higher in the roots and rhizomes compared to the leaves and stems. This is consistent with the results of several other studies (see Chapters 2, 3 and 5). The highest metal concentrations for the subsurface (ss) and above-surface (as) components are shown Table 4.17. There is an increasing trend with time in heavy metal concentrations of Zn in the subsurface tissues of *Iris* (Figure 4.17). Pb in the leaves and stems of *Scirpus* (Figure 4.18) and Cu and Zn in all tissues of *Typha* show similar increases (Figure 4.19). Zn appears to be preferentially accumulated over Pb, Cu and Cd. This is consistent with other studies on metal uptake by macrophytes in wetlands receiving urban runoff (Simpson *et al.*, 1983; Meiorin, 1989; Zhang *et al.*, 1990) and may be explained by Zn being present in water as a predominantly soluble bioavailable metal ion (Revitt and Morrison, 1987) which may allow it to be taken up by the tissues more rapidly than the other metals.

The higher Zn concentrations may also be explained by the formation of an iron plaque on the roots of the macrophytes (Crowder and St.-Cyr, 1991). Iron plaque consists mainly of iron (hydr-) oxides (Chen *et al.*, 1980; Mendelssohn and Postek, 1982) and there is a possibility that plants forming an iron plaque could be at an advantage with regard to the uptake of metals due to the adsorption and immobilization of heavy metals by the iron plaque (Taylor and Crowder, 1983b) although the tolerance mechanism is as yet unclear (Ye *et al.*, 1994). The plaque seems to slow Zn transport to the above-surface tissue but not to reduce Zn uptake into the roots, thus concentrating Zn in this area.

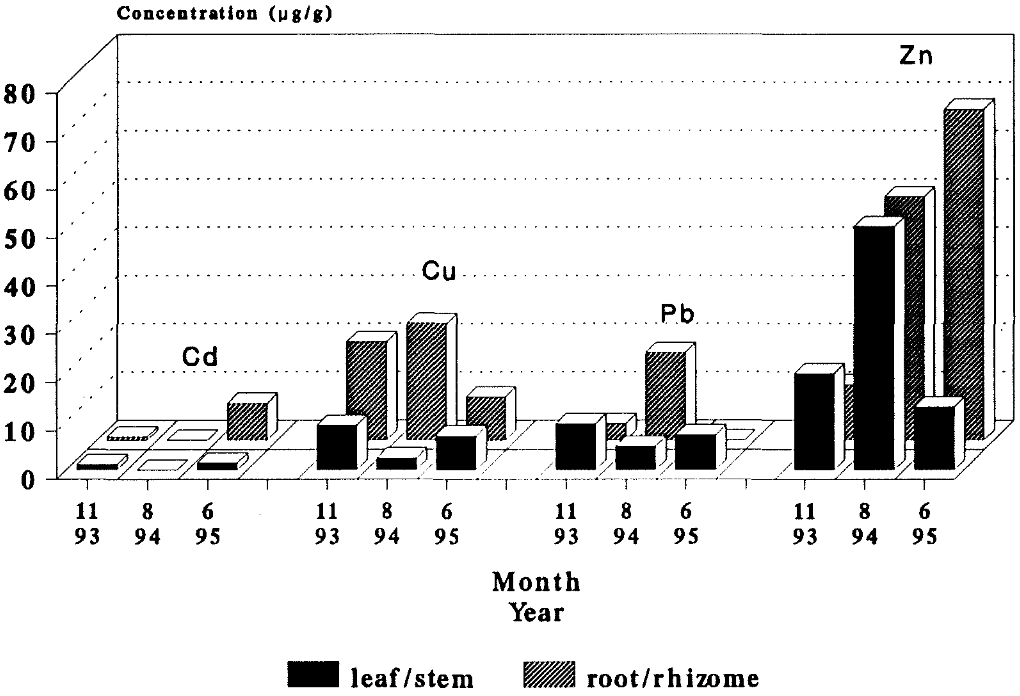


Figure 4.17 Temporal variation of heavy metals in the tissues of *Iris pseudacorus*.

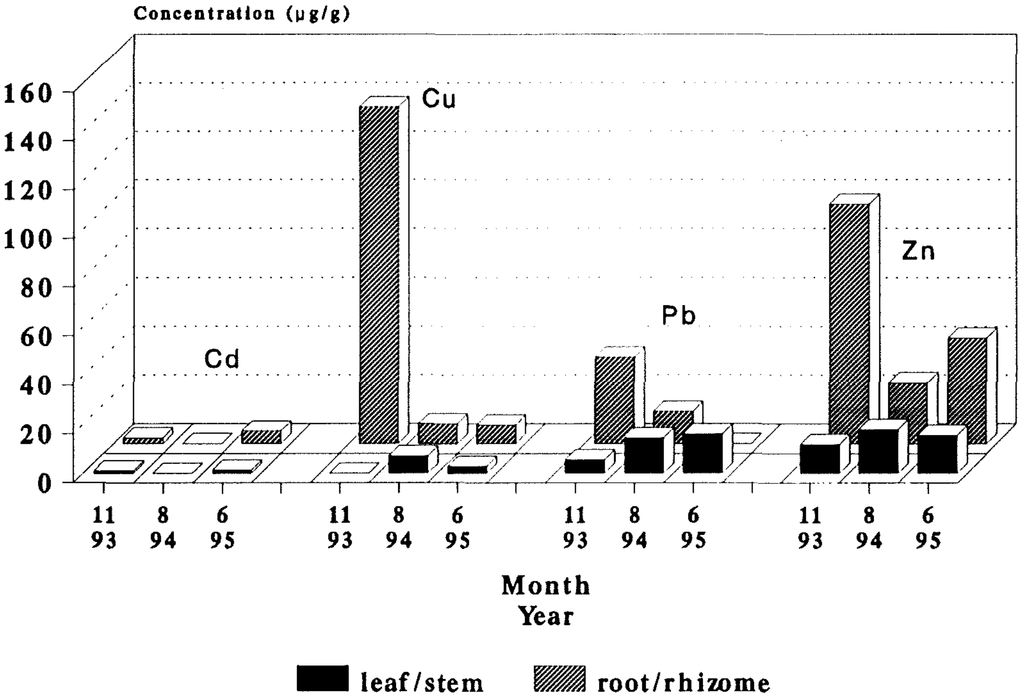


Figure 4.18 Temporal variation of heavy metals in the tissues of *Scirpus lacustris*.

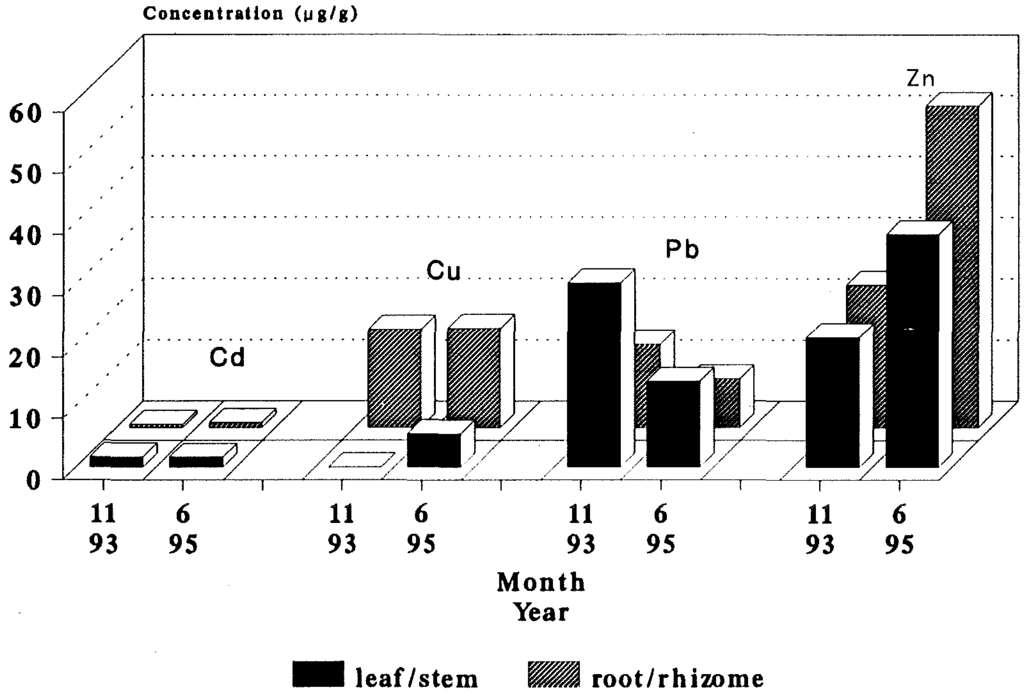


Figure 4.19 Temporal variation of heavy metals in the tissues of *Typha latifolia.*

Table 4.17 Maximum heavy metal concentrations (µg/g) in wetland macrophytes.

Metal	*Typha latifolia*		*Iris pseudacorus*		*Scirpus lacustris*		*Phragmites australis*	
	ss	as	ss	as	ss	as	ss	as
Cd	1.7	0.8	7.6	1.4	5.2	1.4	3.0	0.6
Cu	16.2	5.4	24.1	9.2	138.2	7.0	19.4	7.0
Pb	8.0	30.1	18.1	9.5	35.5	16.0	7.0	5.0
Zn	52.6	38.0	68.6	50.4	98.2	18.0	212.8	31.2

Key

ss:	subsurface tissue
as:	above surface tissue

The maximum metal concentrations in the macrophyte tissues (Table 4.17) are considerably less than the concentrations seen in the macrophytes of the natural wetland near the Brent reservoir which receives runoff from a major highway (Section 3.4.2). This is to be expected since the macrophytes in the Braintree wetland were sampled when the plants were relatively young and had not been completely established. This is clearly shown by a comparison of the maximum metal concentrations in *Typha latifolia* in the Braintree wetland with those in the natural wetland near the Brent reservoir and in a receiving basin at the northern end of the Welsh Harp reservoir (Zhang *et al.*, 1990) which lies just north of the Brent reservoir and also receives urban stormwater runoff (Figure 4.20). The comparison clearly shows that the concentrations are lowest in the *Typha latifolia* present in the Braintree wetland. Since macrophytes can accumulate high levels of heavy metals, as shown by the *Typha* in the natural wetland, it is envisaged that macrophyte tissue metal concentrations in the Braintree wetland will increase over successive growing seasons as the system becomes more established and the wetland receives runoff more consistently.

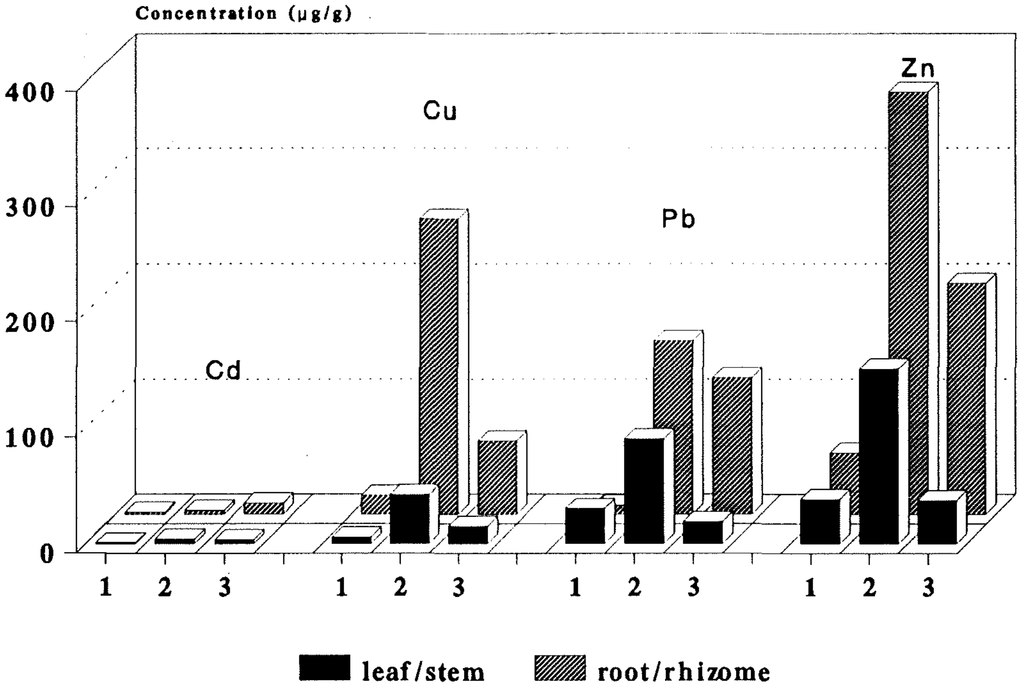


Figure 4.20 Comparison of maximum heavy metal concentrations in the tissues of *Typha latifolia* in (1) the Braintree wetland, (2) the natural wetland and (3) a receiving basin.

4.5 CONCLUSIONS

The results provide a baseline study for the assessment of the heavy metal removal performance of the constructed wetland system in Braintree. Delays in construction of the bypass and the housing development have meant that only limited results could be obtained after the opening of the bypass, which is the main source of runoff discharged into the wetland. These initial results show a variable metal removal performance by the constructed wetland. An improvement in performance is expected from:

- the growth to maturity of the plants and the accumulation of a litter layer;
- the reduction and eventual completion of construction activity; and
- the regular removal of sediment from the settlement trenches.

Heavy metal removal efficiencies between the inlet and outlet ranged from 9.9 to 99.3% and more consistent results are expected with time. A continuation of the study would provide a valuable case study of the performance of the wetland system before and after the completion of the bypass and the housing development from which surface runoff is anticipated to discharge into the wetland. The results will also influence the adoption of constructed wetlands in future residential developments in the UK.

CHAPTER 5 ASSESSMENT OF HEAVY METAL REMOVAL PERFORMANCE OF A LABORATORY SCALE WETLAND

5.1 INTRODUCTION

Although there has been a considerable amount of research on the role of macrophytes and substrates in metal uptake (see Chapter 2), comparatively little work has been carried out on the metal removal performance of experimental wetland systems (Kadlec and Knight, 1996). The majority of experimentation with wetland microcosms has investigated nutrient removal (Breen, 1990, 1992; Breen *et al.*, 1989; Breen and Chick, 1989; Rogers, 1990, 1991; Kadlec and Knight, 1996) although Dunbabin *et al.* (1988) demonstrated that heavy metal retention was higher in planted miniature gravel-based wetland filters than in those without plants. Overall the studies showed that there was little difference in performance between different species although the best results were obtained by the species producing the greatest biomass. The aim of the present study is to assess the removal of Cu, Pb and Zn within a laboratory scale wetland and the role of the substrate, the root zone and other subsurface tissues of the macrophytes with regard to metal uptake. This study complements research on the performance of full-scale natural and subsurface-flow wetlands treating runoff as described in Chapters 3 and 4 and the wetland design was loosely based on the wetland described in Chapter 4.

5.2 MATERIALS AND METHODS

5.2.1 Design and Construction of Laboratory Scale Wetlands

Two laboratory scale wetlands were constructed as gravel-substrate subsurface flow systems in a continuous recirculating mode with fluorescent ultraviolet lamps simulating daylight conditions (Figure 5.1). Two flow experimentation tanks measuring 2.24m long × 0.60m wide × 0.30m deep were used; one tank was employed for dosing experiments and the other acted as a control. The tanks were sectioned off by fine-meshed gabions to create inlet and outlet areas measuring 0.40m × 0.60m × 0.30m

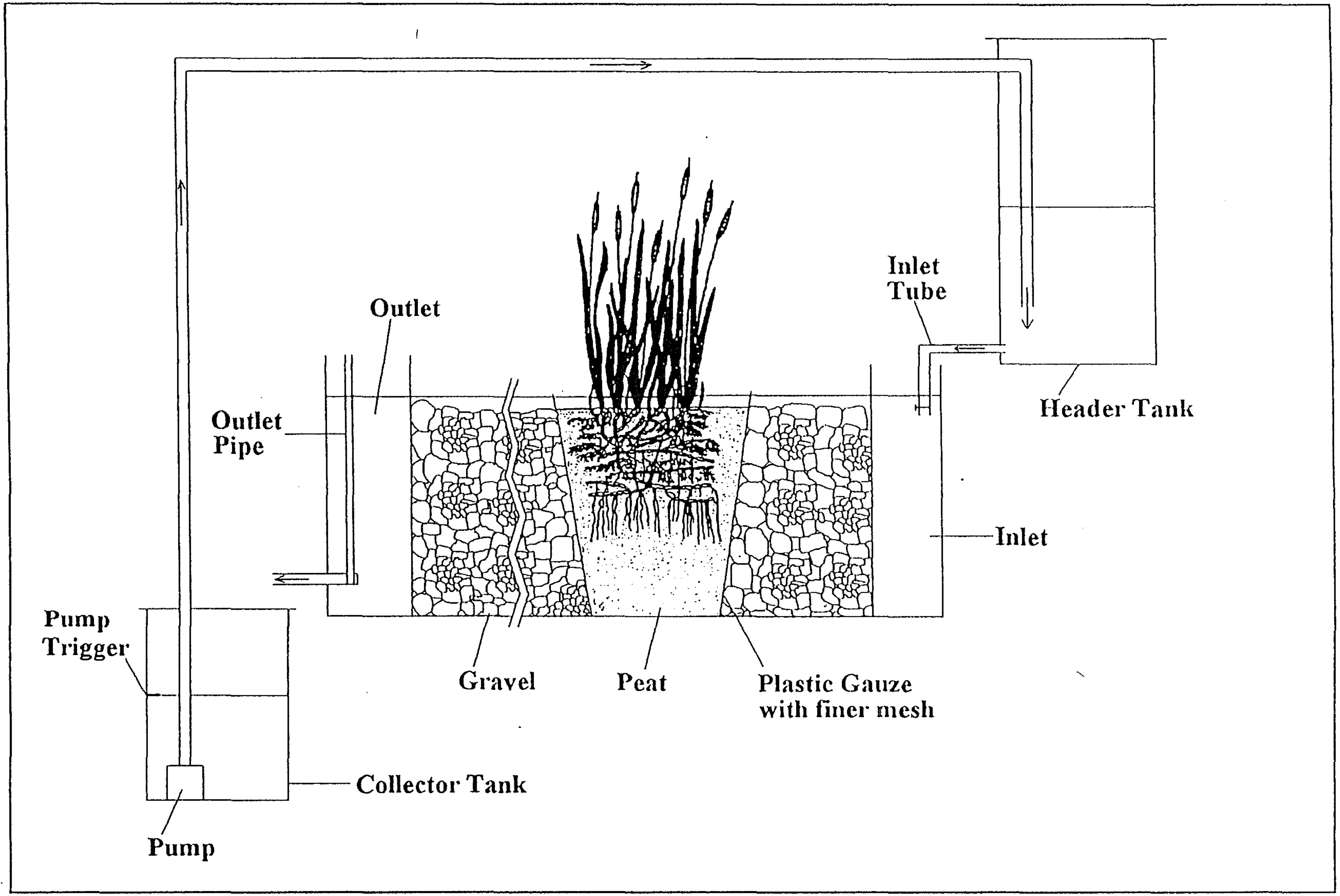


Figure 5.1 Schematic diagram of the experimental laboratory scale wetland.

and 0.16m × 0.60m × 0.30m respectively (Plates 5i and 5ii). The central sections of the tanks (measuring 1.68m × 0.60m × 0.30m), which consisted of washed gravel of diameter less than 10mm to a depth of 0.25m, contained 12 plants placed in sampling baskets (made from plastic gauze and lined with a fine mesh) which were placed at approximately equal intervals in the media (Plate 6i). This enabled samples of the media, complete with entrained solids and roots, to be removed without disturbing the rest of the media and damaging the root sections of the plants. The baskets were filled and compacted with commercial peat, also to a depth of 0.25m, prior to planting (Figure 5.1), which was chosen over sediment from the field because of its relatively low background metal content (7.7, 7.1 and 26.2μg/g for Cu, Pb and Zn respectively).

To establish a circulatory flow regime, it was necessary to have a header tank through which polluted water could be introduced, and discharged in a regulated manner into the inlet area of the wetland. Therefore, there was also a need for a tank which would collect the water discharged from the outlet pipe. Finally, when the water level in the collector tank reached a designated level, a trigger was required to set off a pump in the collector tank to pump the water back into the header tank. The outlet hole was thus drilled near the bottom of the tank and a tube and a pipe was fitted (Figure 5.1).

The last stage of the construction involved setting up fluorescent ultraviolet lamps to simulate outdoor daylight conditions. Two 1.5m long cool white Thorn fluorescent tubes were installed side-by-side above each wetland and were attached to a timer so that it was possible to set the length of time the lamps would remain on (Plate 6ii). Because the experiment took place over early summer the timer was set for 14 hours of light over the day once the wetlands had been established.

5.2.2 Determination of Retention Times

The system was filled with water (approximately 223 l) to immediately below the gravel surface. The flow characteristics and retention times (RT) of the wetland were determined using fluorescein dye and a variety of flow rates into and out of the wetland. The selection of flow rates was determined using the wetland design criteria discussed below.

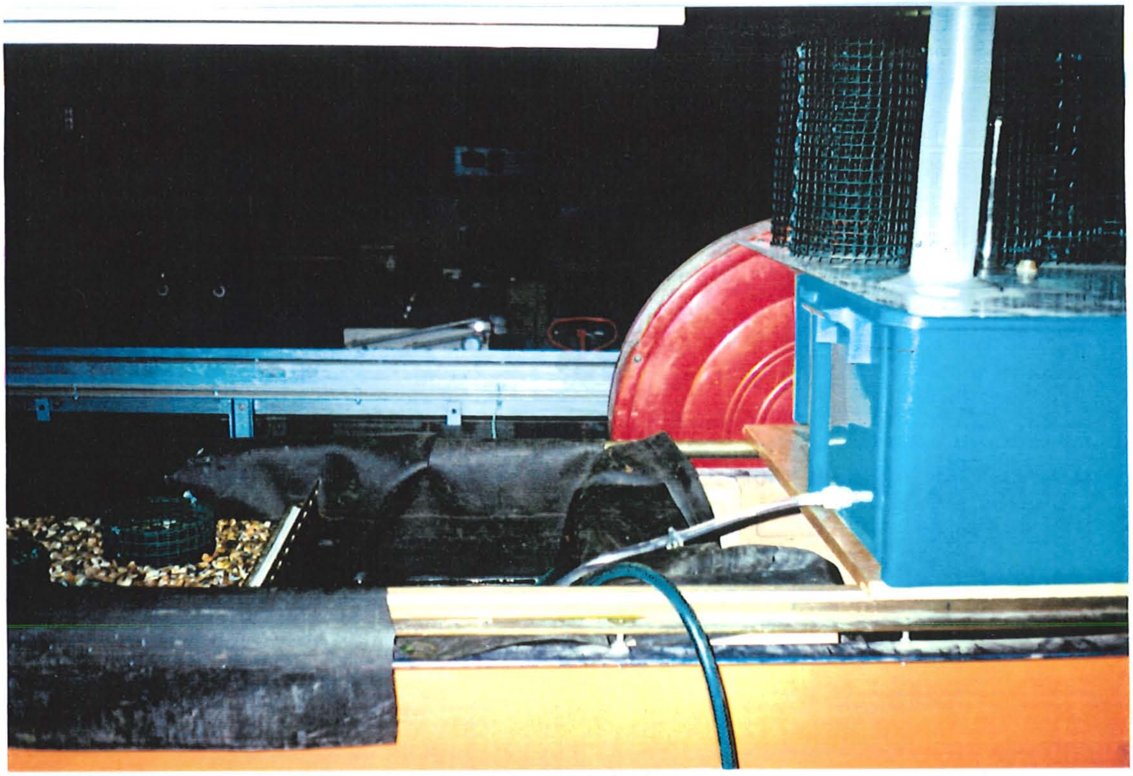


Plate 5i The inlet of the experimental wetland.

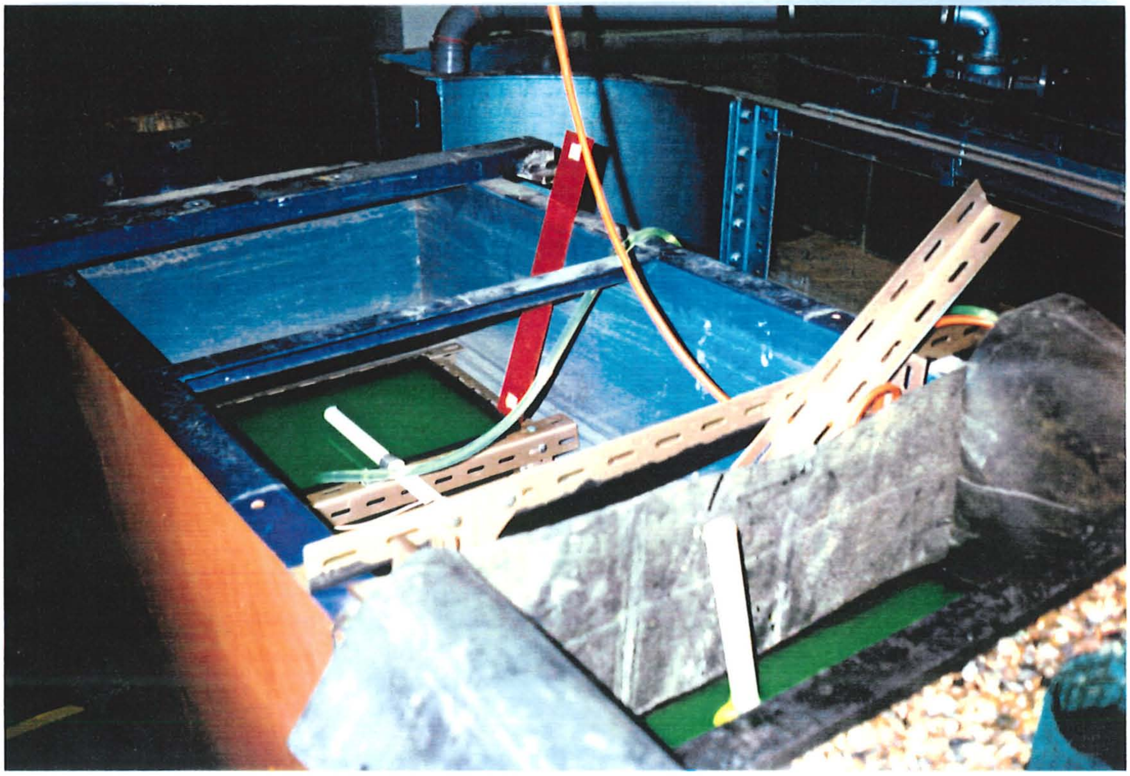


Plate 5ii The outlet of the experimental wetland (green colouration of the water due to dye used for retention time determination).

Plate 6i The plants were planted in sampling baskets which were placed at approximately equal intervals in the media.

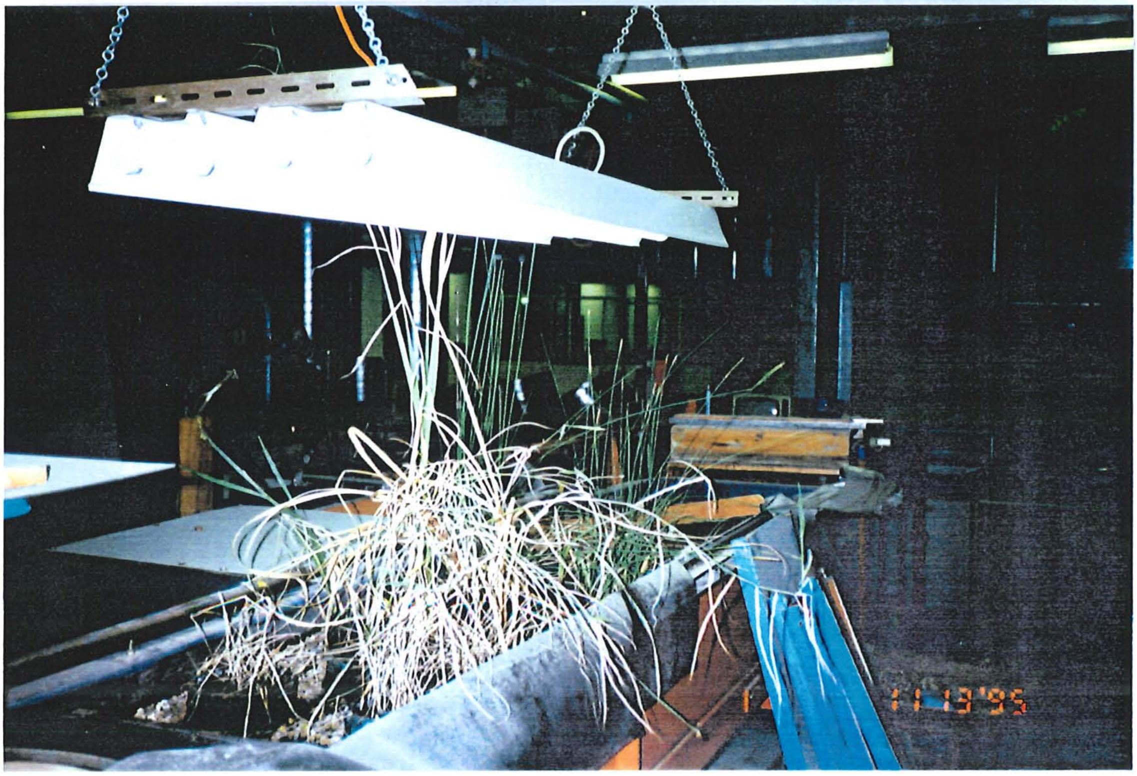


Plate 6ii The planted wetland showing the fluorescent ultraviolet lamps.

For subsurface flow reedbeds designed for the treatment of domestic wastewater, a surface area of $5m^2$ per population equivalent (pe) has been generally applied (Cooper and Findlater, 1990). At its maximum, a population equivalent is defined as 200l ($0.2m^3$) of wastewater per day, containing 300mg/l BOD. In this study the wastewater being treated was tap water dosed with Cu, Pb and Zn, but the same hydraulic targets were used.

Therefore:

$5m^2$ ⇒ 1pe ⇒ $0.2m^3$ hydraulic loading per day

$1.01m^{2*}$ ⇒ 0.202pe ⇒ $0.0404m^3$ hydraulic loading per day

(* Surface area of planted section of the wetland = $1.01m^2$)

Thus the hydraulic target of the wetland would be 40.4 litres per day based on identified treatment rates of domestic wastewater. Experience of operating wetlands in Europe and USA has identified a velocity of flow in subsurface flow systems above which disruption of the rhizome structure will take place (Watson *et al.,* 1989). This figure of 8.6m/day (0.358m/hr) was used to calculate target hydraulic loading using the following equation:

$$Q = VA \qquad \text{(Equation 5.1)}$$

where Q = discharge, m^3/day

V = velocity of flow, m/day

A = cross-sectional area, m^2

Thus for the laboratory scale wetland, $A = (0.25m \times 0.60m) = 0.15m^2$ and the hydraulic target (Q) based on the maximum disruption velocity $= (8.6 \times 0.15) = 1.29m^3$/day.

Hydraulic loading has a direct relationship to retention time within the system. There are currently no established design and performance criteria for constructed wetland systems for the treatment of urban runoff, although a minimum retention time of 30 minutes for ideal treatment efficiency and a maximum flow velocity of $0.7ms^{-1}$ over and through the wetland have been proposed for use in the UK (Halcrow, 1993). However, given that 12 hours is generally regarded as adequate time for the effective treatment in full-scale constructed wetlands (Worrall, 1994), it was possible to calculate hydraulic loadings using the following equation:

$$t = LWnd/Q \quad \text{(Equation 5.2)}$$

where t = hydraulic residence (retention time), days

L = length of system, m

W = width of system, m

n = porosity of bed (as a decimal fraction)

d = depth of substrate, m

Q = average daily flow, m^3/day

Therefore using a retention time of 12 hours (0.5 days):

$$Q = LWnd/t$$

where $Q = (1.68 \times 0.60 \times 0.36^{*} \times 0.25)/0.5$

therefore $Q = 0.1814m^3/day$ (126ml/min)

* Initial porosity of gravel substrate of 10mm diameter is 36% and eventual porosity is 18% after film growth and binding. With time, the substrate may regain its initial porosity due to the growth of the reed roots and rhizomes (Worrall, 1994) although Conley *et al.* (1991) reported that the roots and rhizomes of aquatic plants do not open up hydraulic pathways in rootzone systems. Thus a porosity of 0.18 (producing a value of Q = 63ml/min) would only apply once the reedbed had become relatively well established after the period of the investigations.

Thus theoretical hydraulic loadings based on population equivalents and maximum disruption range between $0.0404m^3$/day (28ml/min) and $1.29m^3$/day (896ml/min) and theoretical hydraulic targets using retention times of 12 hours should range between $0.0907m^3/day$ (63ml/min) and $0.1814m^3/day$ (126ml/min). However, given the constraints of this experiment, retention times of at least 4 hours were deemed sufficient for efficient treatment especially as the polluted water would be recirculating continuously. Retention times (RT) based on an assumed initial gravel porosity of 0.36 are shown in Table 5.1.

Table 5.1 The variation of theoretical retention times with flow rate.

Q (ml/min)	28	126	378	896
RT (hrs)	53.9	12	4	1.7

Although theoretical retention times were calculated, it was essential that the *real* retention time characteristics were identified. This information would enable the sampling regime to appropriately link inlet and outlet concentrations of the various determinands and also relate to the hydraulic manipulation/treatment performance relationship. Thus *real* retention time characteristics were determined using fluorescein dye and applying previously calculated flow rates as guidelines (Table 5.2).

Table 5.2 *Real* retention times.

Q (ml/min)	30	150	350	1000
RT (hrs)	>72	4	2	0.5

These results show that the actual retention times of the constructed wetland are generally shorter than the calculated theoretical retention times. The flow rate of 30ml/min is an exception since it corresponds to a longer RT of >72 hours which is probably the RT of the main plug of dye and not that of the initial (and almost imperceptible) trickle of dye which is probably retained for <72 hours by the wetland, and thus has an RT closer to the theoretical value of approximately 50 hours. The generally lower RT's and hence lower resistance to flow in the wetland may be explained by two factors. Firstly the system may be short-circuiting with preferential flow along the base and sides of the tank (as indicated by the flow pattern of the dye). Secondly the substrate may have a higher porosity (i.e. $n<0.36$) than that estimated from the gravel size (<10mm). From Tables 5.1 and 5.2, a flow rate of 150ml/min corresponds to a real retention time of at least 4 hours and a theoretical retention time of under 12 hours. Substituting the first two values into Equation 5.2 gives a porosity of 0.14. Similarly, substituting flow rates of 350 and 1000ml/min and real retention times of 2 and 0.5 hours respectively into Equation 5.2, gives porosities of 0.17 and 0.12 respectively. Thus the actual porosity of the substrate would appear to lie in the range 0.12 to 0.17. The results show that a hydraulic loading of 150ml/min allowed an RT of 4 hours although subsequent accumulation of solids in the wetland, partly due to the planting of macrophytes, would increase the RT .

5.2.3 Planting of the System

The plants were introduced after the retention times and flow rates appropriate for the laboratory scale constructed wetland were established. The wetland had a surface area of about 1m^2 and three plants of each of four species (*Phragmites australis, Typha latifolia, Schoenoplectus lacustris* and *Iris pseudacorus*) were planted in a similar sequence to the plants in the Braintree wetland (Chapter 4) as shown in Figure 5.2.

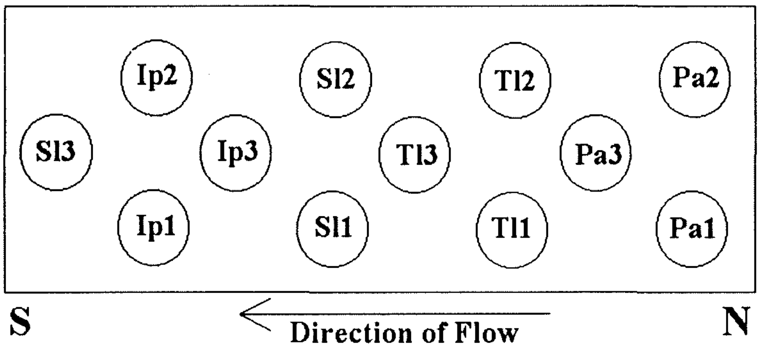


Figure 5.2 Schematic diagram illustrating the planting configuration within the experimental wetland (Pa = *Phragmites australis*, Tl = *Typha latifolia*, Sl = *Schoenoplectus lacustris* and Ip = *Iris pseudacorus*). *Scirpus* and *Iris* plants are mixed, similar to the planting in the constructed wetland at Braintree.

Prior to planting, the wetland which had been used to determine retention times was thoroughly flushed to remove any traces of the dye as well as any of the dosed water used in the determination of the heavy metal removal performance of the substrate only (see Section 5.5). Both wetlands were then drained and fresh peat was introduced into the sampling baskets. The plants obtained from a nursery (London Aquatic Co. Ltd, Enfield, North London) were relatively young specimens and were immediately planted in the sequence shown in Figure 5.2. Once the wetland was planted (30 May 1995), the system was slowly filled with tap water ensuring there was no flushing of the substrate or any other damage to the system until the water level reached just below the surface of the substrate. The flow rate into and out of the wetland was set to about 150ml/min to achieve the desired retention time of 4 hours and the plants were allowed to establish themselves whilst the water level was monitored and maintained by replacing water lost by evapotranspiration.

After two weeks, it became clear that the *Phragmites australis* and *Typha latifolia* plants were in poor health (symptoms included wilting, necrosis, leaf chlorosis and curling of tips) and were not growing satisfactorily. Therefore on the third week of this "establishing" period, the unhealthy plants were replaced by new specimens from the same batch as the initial plants (25 July 1995). Measurements of the light intensities in the wetland using an LX-101 Lutron lux meter showed that the plants were not receiving enough light for healthy growth. Optimum lux values for indoor growth range between 6000 and 10,000 whereas the levels at a height of 0.90m (near the tops of the plants) were measured at between 2000 and 3000. Thus the light intensity had to be increased by a factor of at least 2 and two more ultraviolet/natural light fluorescent tubes were installed above each wetland. The resulting four lamps provided sufficient light (lux values >6000 near the tops of the plants) for healthy growth in each wetland.

The plants not only suffered from insufficient light initially but, especially in the case of *Phragmites australis* and *Typha latifolia*, also from an infestation of whiteflies and aphids. This problem was solved by using a common garden pesticide although the insects proved hardy and difficult to eradicate completely.

The plants reached peak heights in August 1995 and started to wilt and die in late September although *Schoenoplectus lacustris* and *Iris pseudacorus* persisted well into the winter. The temperatures measured at the surface of the substrate in the wetland ranged between 20^{0}C and 26^{0}C through a particularly hot summer and as a result evapotranspiration rates reached an estimated 10 litres per day from each wetland during the warmest periods.

5.2.4 Dosing and Sampling Strategy

The planting, heavy metal dosing and sampling strategies are shown in Table 5.3.

Table 5.3 The planting, heavy metal dosing and sampling strategies used for the experiment.

Experiments	Date
Dosing of substrate only with 2mg/l dose of Cu, Pb, Zn	27/04/95
Planting	30/05/95
1mg/l dosing with Cu, Pb and Zn	15/06/95
1mg/l dosing on control wetland with Cu, Pb and Zn	26/06/95
5mg/l dosing with Cu, Pb and Zn	26/06/95
Planting of 2nd set of *Phragmites* & *Typha* spp	25/07/95
10mg/l dosing with Cu, Pb and Zn	26/07/95
Storm event simulation (20mg/l shock load of Cu, Pb and Zn)	22/08/95
Sampling of plant root sections and peat	08/-09/95

5.2.4.1 Dosing Experiments

In the dosing experiments, Cu, Pb and Zn were supplied as a nitrate mixed standard solution (1000mg/l) and diluted to the required concentration with tap water. Water samples were collected from the outlet at timed intervals at a flow rate of 150ml/min over time periods ranging between 4 and 72 hours (where the total dosed volume of 123 l passed through the wetland at least 5 times). Removal efficiencies were calculated by comparing input metal loadings with output metal loadings. The second wetland was initially used as a control and also used to replicate the 1mg/l dosing experiment on 26/06/95 (Table 5.3). Water samples were digested with concentrated nitric acid and analysed for Cu, Pb and Zn by inductively coupled plasma emission spectroscopy (see Section 3.2).

5.2.4.2 Peat and Macrophyte Sampling

After the completion of the dosing experiments, core samples of the peat were taken in each of four directions relative to the flow around the sampling basket at depths of about 10cm below the surface (Figure 5.3). This was to identify any patterns in peat

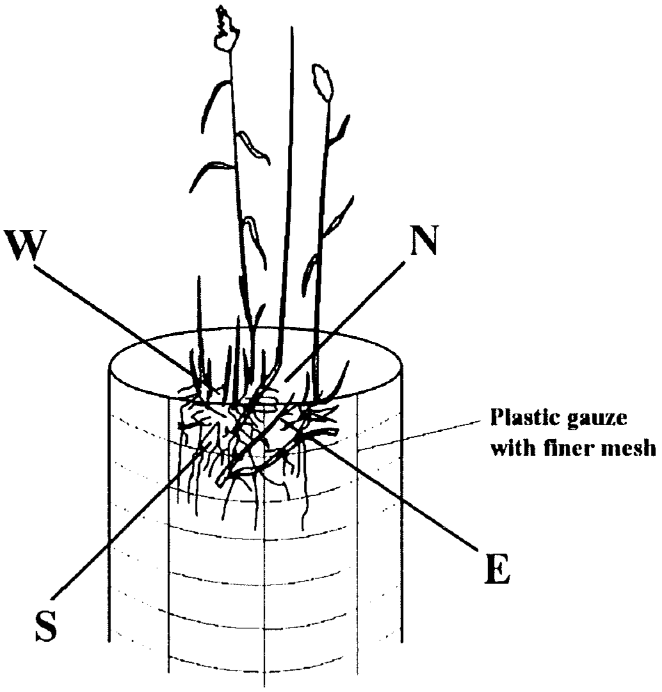


Figure 5.3 Core peat samples were taken from the N, S, E and W sections of the sampling basket (direction of flow from N to S).

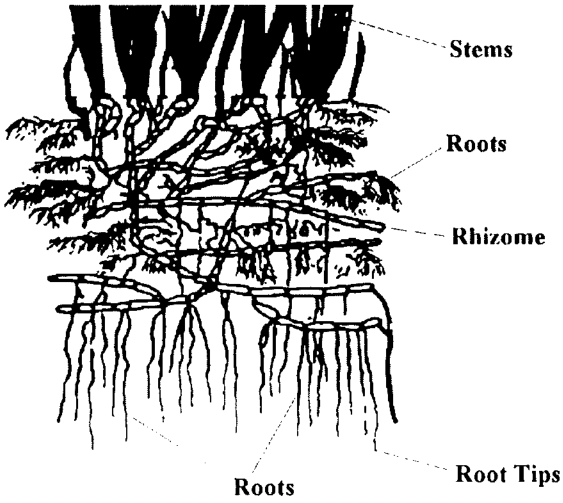


Figure 5.4 The three separate components of the subsurface plant tissue - root tips, roots and rhizome (a rhizome structure was present in all the species except the immature *Phragmites australis* specimens).

metal uptake within the wetland. Peat surrounding the root system of each plant was carefully removed to expose the rhizome (not present in the immature *Phragmites australis* plants), root and root tips (defined as the last 5mm of the root tendril) (Figure 5.4) which were then detached from the stem and carefully washed in distilled water to remove any traces of the peat. Representative samples were also taken from the control wetland for analysis. The plant components and peat samples were digested with concentrated nitric acid and with a concentrated nitric acid and perchloric acid mixture respectively and analysed for Cu, Pb and Zn using inductively coupled plasma emission spectroscopy (see Section 3.2).

5.3 RESULTS AND DISCUSSION

5.3.1 Removal Efficiencies

The Cu, Pb and Zn standard solution (1000mg/l) was diluted to the required concentrations (1, 2, 5, 10 and 20mg/l; see Table 5.3) with tap water for each of the dosing experiments. The water in the collector tank, the header tank and the inlet (a total volume of 123 l) was dosed (see Figure 5.1) to ensure that the concentration discharging into the wetland remained constant over the time the experiments were running. Thus a 1mg/l dose corresponded to a load of 123mg of each metal, a 2mg/l dose corresponded to a load of 246mg of each metal and so on. The 20mg/l dose was introduced as an approximately 22 l shock load which corresponded to a metal load of approximately 446mg. The metal loads present in the outlet at any one time were estimated by plotting the variation of the concentration of each metal over time (Figures 5.5 to 5.10) and calculating the area under the curve using the graphical sigma plot package. The results are presented and discussed in the following sections.

5.3.1.1 Removal Efficiency of the Substrate

Prior to planting, a 2mg/l mixed metal solution was added to one wetland to assess the removal efficiency of the gravel and peat substrate. The substrate exhibited high removal efficiencies of 99.3%, 93.9% and 98.3% for Cu, Pb and Zn respectively using

Table 5.4 Removal efficiencies for the 2mg/l dose of Cu, Pb and Zn by the gravel substrate only over a monitoring period of 4 hours (i.e. polluted water passes through the wetland once).

Mixed standard dose (mg/l)	2
Load in (mg)	246
Load out - Cu (mg)	1.683
Load out - Pb (mg)	15.030
Load out - Zn (mg)	4.095
% Removal - Cu	99.3
% Removal - Pb	93.9
% Removal - Zn	98.3

an retention time (RT) of 4 hours at a flow rate of 150ml/min (Table 5.4). After the first dosing experiment, the system was flushed with tap water to remove any traces of contamination before the plants were introduced. The levels of metals present in the outlet at 0 hours probably are the background levels of the water used to fill the wetland but may possibly be due to contamination from the materials used to construct the wetland. The temporal variations of outlet metal concentrations over the monitoring period are shown in Figure 5.5.

5.3.1.2 The 1mg/l Dosing Experiment

The results obtained over the sampling periods of 4 to 72 hours for the dosing experiment of 1mg/l indicate the ability of the wetland system to act as an efficient sink for heavy metals during the investigation (Table 5.5). To confirm that the results of the initial 1mg/l dose were not anomalous, this dose was repeated on the control wetland. The removal efficiency results proved to be comparably high and are reproducible (Table 5.5).

The results indicate that the metal removal efficiencies and removal rates decrease with time (Table 5.5). The high removal efficiencies seen after 4 hours may possibly reflect the first flush of 1mg/l dose not having passed through the wetland. The removals after 72 hours at a flow rate of 150ml/min correspond to the dosed volume (123 l) of water having passed through the system at least 5 times and thus gives a more accurate

Table 5.5 Removal efficiencies for the 1mg/l dose of Cu, Pb and Zn by the wetland systems.

Monitoring period	4 hours		72 hours	
Mixed standard dose (mg/l)	1	1[†]	1	1[†]
Load in (mg)	123	123	123	123
Load out - Cu (mg)	0.480	1.548	12.246	37.984
Load out - Pb (mg)	1.500	1.764	29.775	48.645
Load out - Zn (mg)	0.960	1.332	21.165	26.617
% Removal - Cu	99.6	98.7	90.0	69.1
% Removal - Pb	98.8	98.6	75.8	60.5
% Removal - Zn	99.2	98.9	82.8	78.4
Removal rate - Cu (mg/m^2/d)	-	-	36.6	28.1
Removal rate - Pb (mg/m^2/d)	-	-	30.8	24.5
Removal rate - Zn (mg/m^2/d)	-	-	33.6	31.8

Key:
[†] Dosing carried out in control wetland.

reflection of the metal removal efficiencies and removal rates of the experimental wetland. However, the lower removals after 72 hours may indicate that the metals in the wetland which are not taken up by the peat and gravel substrate may slowly be flushed out with each successive cycle of water passing through. Thus the results after 72 hours give a more realistic assessment of the treatment capacity of the experimental wetland. The temporal variations of the outlet metal concentrations for the 1mg/l dose over the full monitoring period of 72 hours are shown in Figure 5.6 and the resulting removal efficiencies are shown in Figure 5.9. Although the system was flushed with tap water to remove any traces of of the previous dose, some metals were probably retained in the system as shown by the metal levels in the outlet at 0 hours for each dosing experiment (Figures 5.6 to 5.8).

5.3.1.3 The 5 and 10mg/l Dosing Experiment

The results obtained over the sampling periods of 4 to 72 hours for the dosing experiment of 5 and 10mg/l can be interpreted similarly to the results of the 1mg/l dose and thus also indicate the ability of the wetland system to act as an efficient sink for heavy metals during the investigation (Table 5.6). The temporal variations of the outlet metal concentrations for the 5 and 10mg/l dose over the full monitoring period of 72 hours are shown in Figures 5.7 and 5.8 respectively. The resulting removal efficiencies are also shown in Figure 5.9.

Table 5.6 Removal efficiencies for the 5 and 10mg/l dose of Cu, Pb and Zn by the wetland system.

Monitoring period	4 hours		72 hours	
Mixed standard dose (mg/l)	5	10	5	10
Load in (mg)	615	1230	615	1230
Load out - Cu (mg)	5.094	3.870	112.482	100.701
Load out - Pb (mg)	2.484	2.682	60.183	57.523
Load out - Zn (mg)	3.618	8.496	58.775	132.800
% Removal - Cu	99.2	99.7	81.7	91.8
% Removal - Pb	99.6	99.8	90.2	95.3
% Removal - Zn	99.4	99.3	90.4	89.2
Removal rate - Cu ($mg/m^2/d$)	-	-	165.8	372.7
Removal rate - Pb ($mg/m^2/d$)	-	-	183.1	387.0
Removal rate - Zn ($mg/m^2/d$)	-	-	183.5	362.1

5.3.1.4 The Storm Simulation

The 20mg/l storm dose was introduced at an initial rate of 5 l/min as a 22.3 l shock load in an attempt to simulate a storm event. Results show that in the time taken (2.75 hours) for the water level to subside to its original level (just below the substrate surface) at an outlet flow rate of 150ml/min, the metal loadings leaving the system remained negligible (Figure 5.10). The wetland system retained 99.5%, 99.7% and 99.5% of the Cu, Pb and Zn entering the system (Table 5.7). It seems improbable that the very high removal efficiencies were due solely to effective treatment. Thus the possibility of the high metal loads not having had the time to pass through the complete wetland during the short monitoring period cannot be discounted. The experiment was not repeated due to constraints of time and equipment.

Table 5.7 Removal efficiencies for the 20mg/l shock load of Cu, Pb and Zn by the wetland system in the time taken for the water level to subside to levels prior to the simulated storm event.

Mixed standard dose (mg/l)	20
Load in (mg)	446.429
Load out - Cu (mg)	2.293
Load out - Pb (mg)	1.457
Load out - Zn (mg)	2.232
% Removal - Cu	99.5
% Removal - Pb	99.7
% Removal - Zn	99.5

5.3.1.5 Summary

The results obtained over the total monitoring period of 72 hours for the dosing experiments of 1, 5 and 10mg/l indicate the ability of the wetland system to act as an efficient sink for heavy metals during the investigation and to remove loads of Cu, Pb and Zn at rates of 36.6 to 372.7, 30.8 to 387 and 33.6 to 362.1 mg/m^2/d respectively (Tables 5.8 and 5.9). The results after 72 hours (Table 5.9) suggest that the wetland may eventually become saturated with metals since the removal efficiencies for each metal decrease as the RT increased from 4 to 72 hours. This suggests that the metals in the wetland not taken up by the peat may slowly be flushed out with each successive cycle of water passing through. However, the possibility of the high metal loads not having passed through the wetland after 4 hours cannot be discounted.

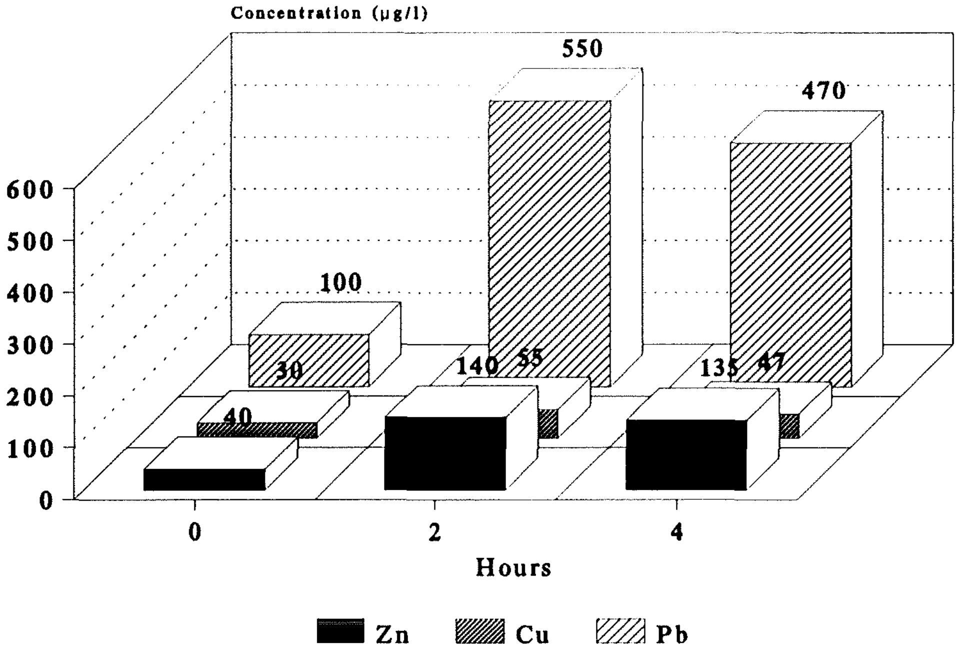


Figure 5.5 Temporal variation of outlet metal concentrations for the 2mg/l inlet dose prior to planting.

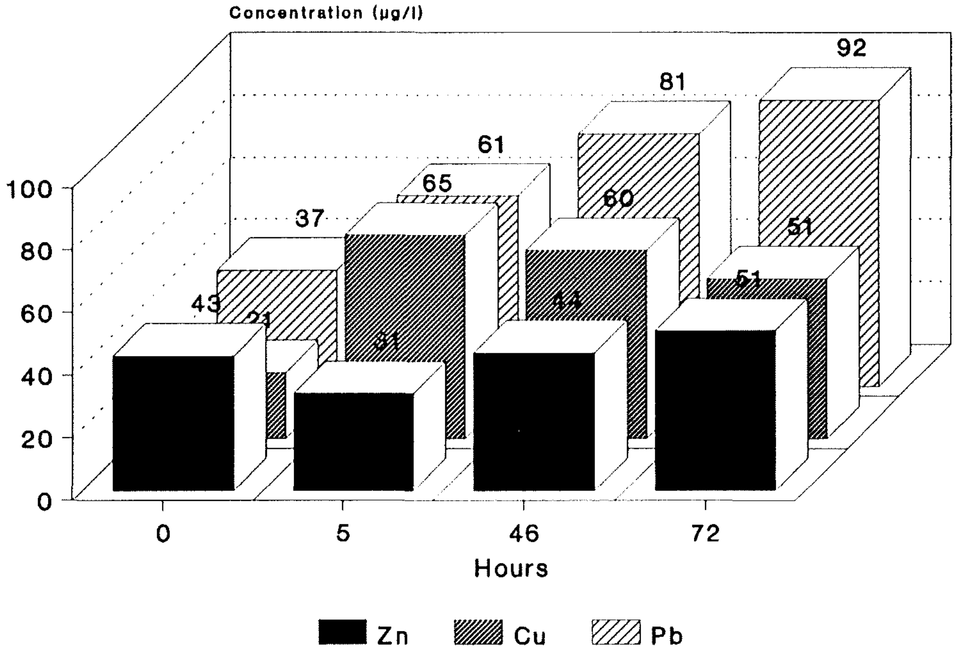


Figure 5.6 Temporal variation of outlet metal concentrations for the 1mg/l inlet dose after planting.

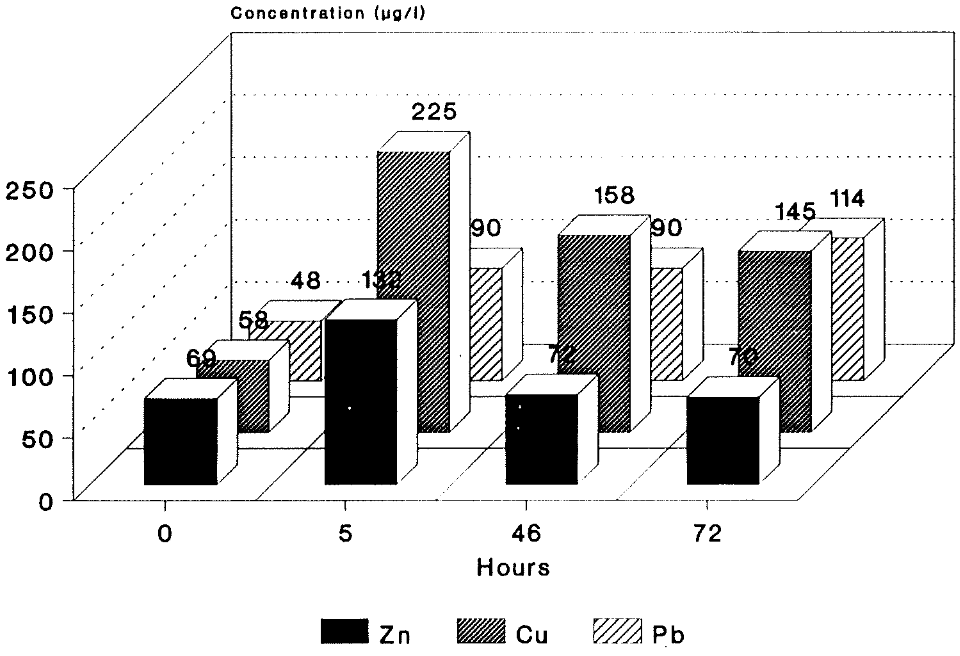


Figure 5.7 Temporal variation of outlet metal concentrations for the 5mg/l inlet dose.

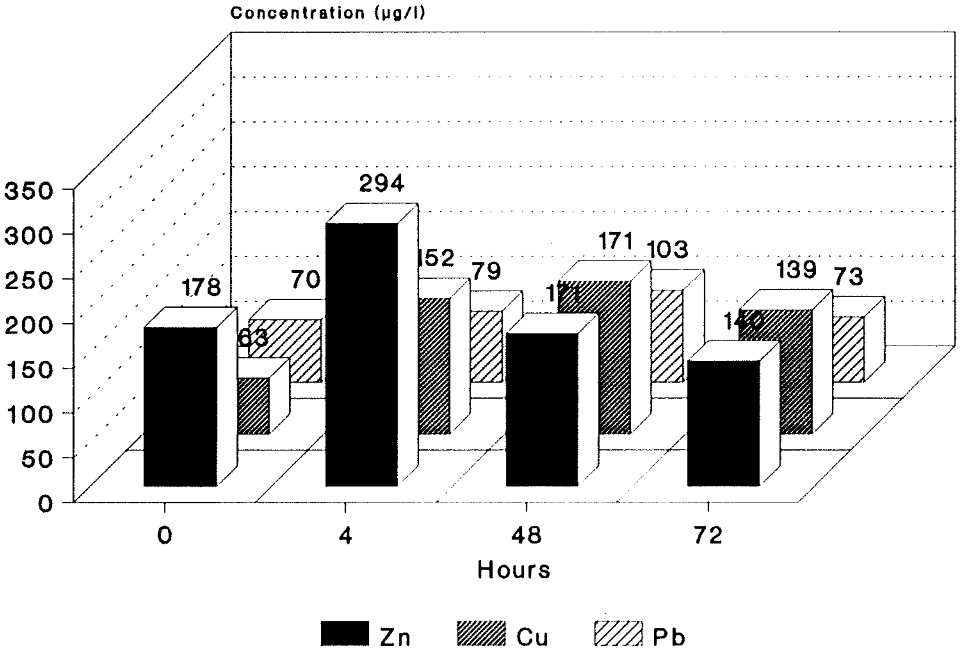


Figure 5.8 Temporal variation of outlet metal concentrations for the 10mg/l inlet dose.

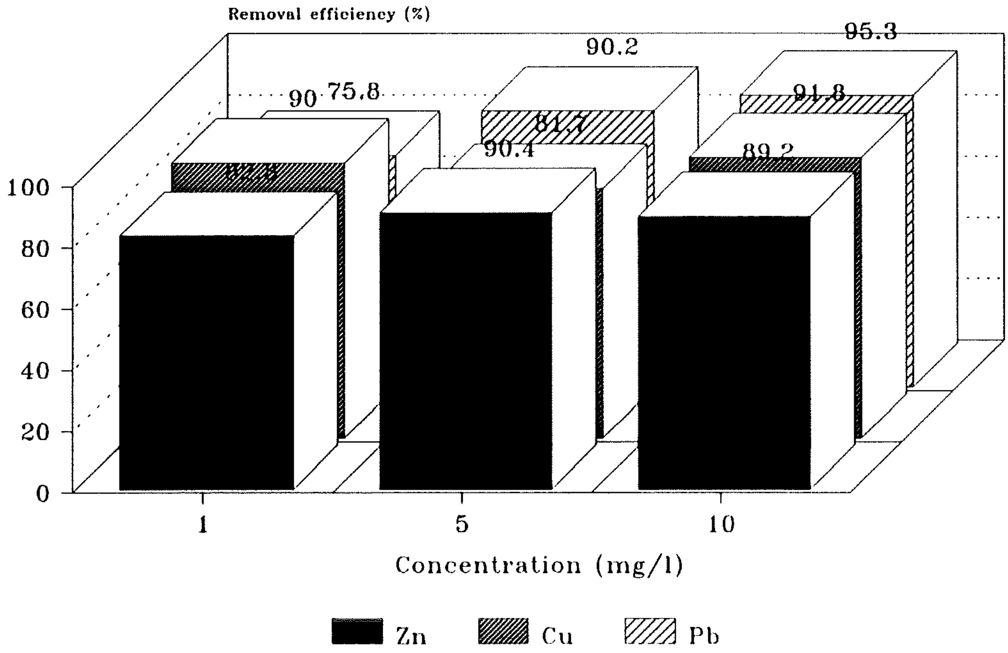


Figure 5.9 Heavy metal removal performance of experimental wetland for the 1, 5 and 10mg/l doses after 72 hours.

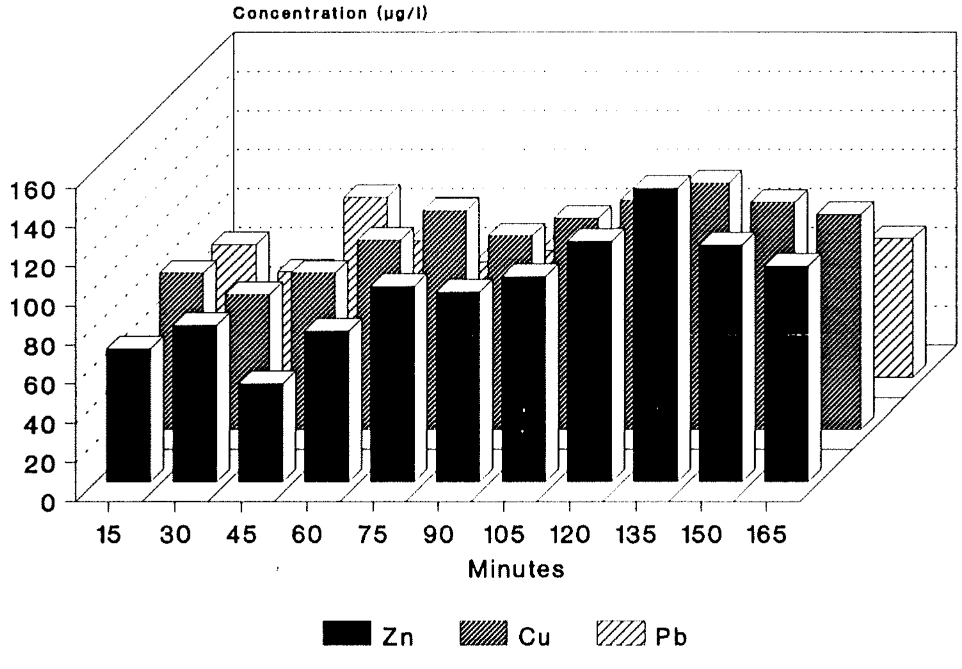


Figure 5.10 Temporal variation of outlet metal concentrations for the 20mg/l inlet storm event simulation dose.

Table 5.8 Removal efficiencies for Cu, Pb and Zn by the wetland system over a monitoring period of 4 hours (i.e. polluted water passes through the wetland once).

Mixed standard dose (mg/l)	2*	1	5	10
Load in (mg)	246	123	615	1230
Load out - Cu (mg)	1.683	0.480	5.094	3.870
Load out - Pb (mg)	15.030	1.500	2.484	2.682
Load out - Zn (mg)	4.095	0.960	3.618	8.496
% Removal - Cu	99.3	99.6	99.2	99.7
% Removal - Pb	93.9	98.8	99.6	99.8
% Removal - Zn	98.3	99.2	99.4	99.3

Key:
* Dosing carried out in gravel substrate only

Table 5.9 Removal efficiencies for Cu, Pb and Zn by the wetland system over a monitoring periods of 72 hours (allows time for repeated treament).

Mixed STD dose (mg/l)	1	5	10
Load in (mg)	123	615	1230
Load out - Cu (mg)	12.246	112.482	100.701
Load out - Pb (mg)	29.775	60.183	57.523
Load out - Zn (mg)	21.165	58.775	132.800
% Removal - Cu	90.0	81.7	91.8
% Removal - Pb	75.8	90.2	95.3
% Removal - Zn	82.8	90.4	89.2
Removal rate - Cu ($mg/m^2/d$)	36.6	165.8	372.7
Removal rate - Pb ($mg/m^2/d$)	30.8	183.1	387
Removal rate - Zn ($mg/m^2/d$)	33.6	183.5	362.1

Key:
† Dosing carried out in control wetland.

High removal efficiencies have been reported in full-scale wetlands by various researchers (see Kadlec and Knight, 1996). Removal efficiencies and removal rates of 88% and 65mg/m^2/d, 60% and 15mg/m^2/d and 71% and 109mg/m^2/d for Cu, Pb and

Zn respectively (based on inlet concentrations of 1.2mg/l, 0.3mg/l and 2.5mg/l respectively) have been reported for a subsurface flow wetland and removal rates of 63%, 86% and 79% (based on inlet concentrations of 0.06mg/l, 0.3mg/l and 0.4mg/l), for *Scirpus* planted in gravel (Sinicrope *et al.*, 1992).

A freshwater marsh receiving urban stormwater showed removal rates of 87.5%, 83.3% and 66.7% for Cu, Pb and Zn respectively (Schiffer, 1989). Similarly high removal rates for Cu and Zn from different types of wetlands have been reported by CH2M HILL (1991), Eger *et al.* (1993) and Hendry *et al.* (1979) whilst Noller *et al.* (1994) has reported high removal rates for Cu, Pb and Zn. All the literature and the results of this study show that metal removal efficiency increases with increasing inlet concentrations and that the removal rates (Figure 5.11) for the 1mg/l dose (after the total monitoring period of 72 hours) are consistent with those seen in other predominantly subsurface-flow systems with similar inlet concentrations.

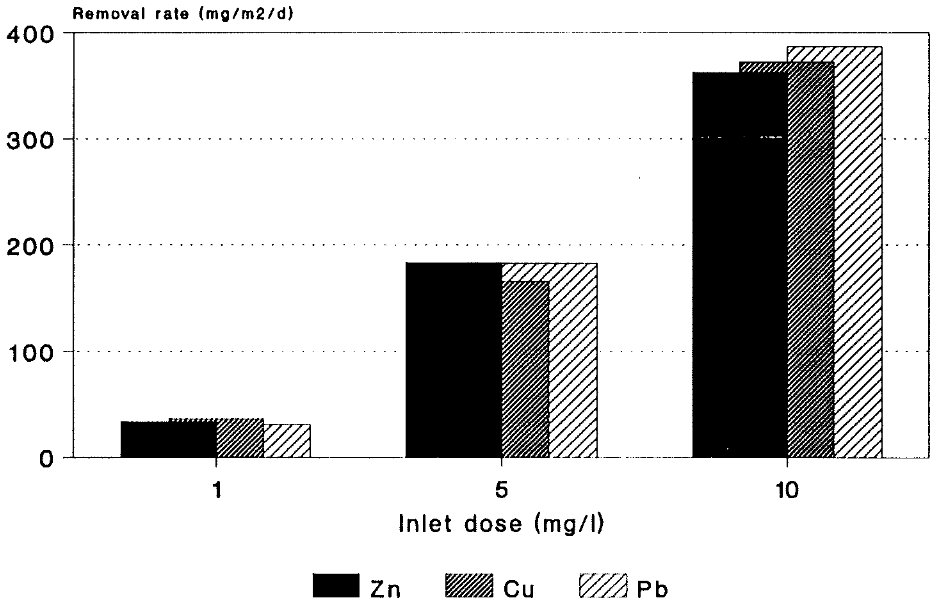


Figure 5.11 Heavy metal inlet doses (mg/l) versus removal rates (mg/m^2/d).

The removal rates seen in this study are at least one order of magnitude higher than the maximum loads deposited on major UK highways (Warren, 1987) indicating that such subsurface-flow wetland systems would possess the ability to treat metal-contaminated highway runoff efficiently (Table 5.10). However, these results are the initial responses

Table 5.10 Comparison of laboratory scale wetland heavy metal removal rates with maximum loads (mg/m^2/d) deposited on highways.

Metal	Laboratory scale wetland removal rates	UK urban highway loads*	UK/European highway loads**
Cu	36.6-372.7	0.14-0.78	0.11-1.0
Pb	30.8-387	1.1-13.0	0.3-3.6
Zn	33.6-362.1	1.9-19.0	0.52-5.2

Key

* Data from Warren (1987); Highway Pb loads will be lower in 1996 due to the introduction of Pb-free petrol in the UK in 1985.

** Data from Hedley and Lockley (1975)

of the experimental wetland to the metal doses. Subsequently, the system may become saturated with heavy metals and its removal rates may decrease. Further research needs to be carried out to assess the long-term heavy metal removal capacity of such wetland systems.

5.3.2 Peat Samples

Heavy metal peat concentrations from each of the four directions relative to the flow around the sampling baskets (the North, South, East and West samples as shown in Figure 5.3) ranged from 8 to 56, 6.9 to 138.1 and 7.8 to 623.4μg/g with mean concentrations and standard deviations of 34.2±14.9, 50.2±50.1 and 130.3±173.3μg/g for Cu, Pb and Zn respectively (Figure 5.12). The high percentage of organic matter in peat favours the binding of heavy metals in forms that may exhibit little remobilization and/or bioavailability (Giblin, 1985; Tam and Wong, 1994) by the mechanisms detailed in Section 2.5.2.3. However, the relationship between organic accumulation and metal concentrations in peat is not well understood with some studies having found little or no correlation between them (Orson *et al.*, 1992) suggesting that the adsorption mechanism varies between metal species.

In this study, peat heavy metal concentrations show that Zn is taken up in preference to Pb and Cu. This is contrary to what might be expected since Zn is present in water as a predominantly soluble bioavailable metal ion or weak complex (Revitt and Morrison, 1987) and sediment association/uptake for Zn is normally lower than Pb since the latter exhibits little remobilization once deposited (Meiorin, 1989). Harter (1979) has found that soils adsorbing large quantities of Pb also adsorb large quantities of Cu while Kadlec and Keoleian (1986) report that Cu and other divalent metal cations are known to bind strongly to peats and humics. The amount of metal adsorbed may be reduced by competitive interactions with other species (e.g. there is competition between Fe, Cu, Zn and Mn) for similar types of organic binding sites (Machemer and Wildeman, 1992). Thus there may be a possibility that Zn has been preferentially adsorbed over Cu in the experimental wetland although all the metals in this study were introduced as soluble ionic forms. Since the background Zn content is relatively high (26.2μg/g), it might be expected that Zn levels, after the dosing experiments, would be lower since the background content could have already occupied some of the available adsorption sites, but this is not the case. Another possible explanation of the high Zn concentrations may be that the cation exchange capacity (CEC) for Cu and Pb in the peat was less permanent. Thus these metals may have been released back into the water (the cation exchange binding process is reversible (Cooper *et al.* (1996)); also see Section 2.6.1) whereas the adsorption of Zn was more permanent.

The ranges of concentrations in the peat indicate significant variations throughout the wetland and the distribution of the highest Cu, Pb and Zn peat concentrations per basket (68.9, 140.5 and 280.6μg/g respectively) suggests that preferential uptake of metal occurs in the west sides of *Pa1, Tl1, Sl1* and *Ip1* and the east sides of *Pa2, Tl2, Sl2* and *Ip2* (see Figure 5.13). The lowest mean peat concentrations for Cu and Pb are found in the central row parallel to the direction of flow (i.e. the baskets planted with *Pa3, Tl3* and *Ip3* - refer to Figure 5.13 for key), whereas the lowest mean Zn concentrations are only seen in the basket planted with *Pa3.* Metal uptake increases as the flow of dosed water moves away from the inlet, reaches a maximum near the middle of the wetland (where *Sl1* and *2* were planted), and then decreases towards the outlet. These results indicate that the amount of metal uptake is not uniform within the wetland and is dependent on the flow characteristics within it. Short-circuiting of flow hinders uptake in the central row of the wetland parallel to flow and thus possibly reduces treatment efficiency. The *average* peat metal concentrations shown in Figure 5.12 reflects that preferential uptake generally occurs along the side rows of the wetland.

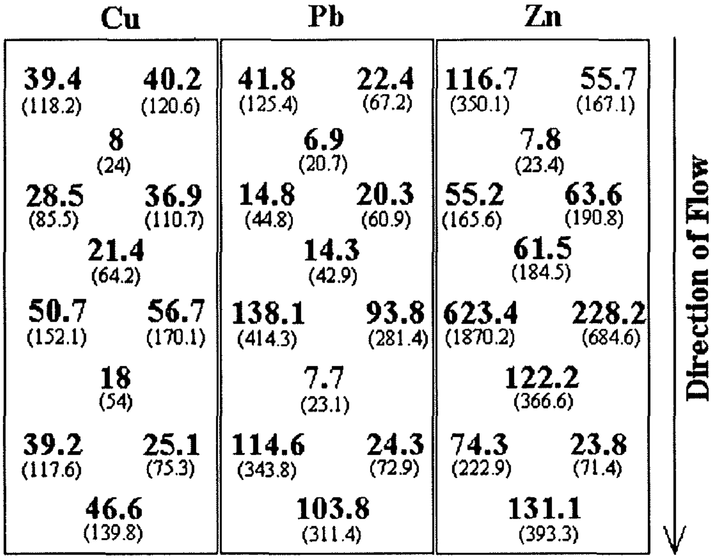


Figure 5.12 Mean peat metal concentrations (μg/g) and loads (mg) (in brackets) in the wetland.

Each basket contained approximately 3000g of peat and the resulting metal loads per basket are also shown in Figure 5.12. Uniform concentrations were assumed throughout the 20 - 25cm depth of the peat since most flow in peatlands occurs across and within 30cm of the surface (Romanov, 1968) giving an active removal depth of no more than 30cm, and most metal removal (>80%) occurs within the top 20cm (Eger and Lapakko, 1989).

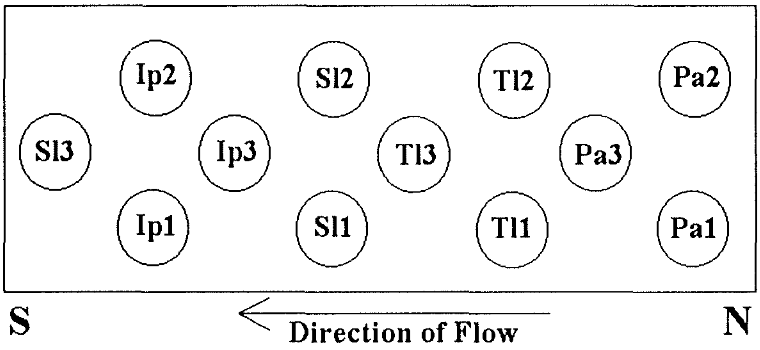


Figure 5.13 Schematic diagram illustrating the planting configuration within the experimental wetland (Pa = *Phragmites australis*, Tl = *Typha latifolia*, Sl = *Schoenplectus lacustris* and Ip = *Iris pseudacorus*).

5.3.3 Macrophyte Samples

5.3.3.1 Heavy Metal Concentrations in Macrophyte Samples

Tables 5.11 and 5.12 show the average and measured heavy metal concentrations in the subsurface tissues of each of the dosed plant species respectively. The results show an overall trend of metal concentrations decreasing in the order of root tips > roots > rhizome.

In the three dosed *Phragmites australis* plants (Table 5.12), which did not have a rhizomatous structure (possibly because the plants were immature), Cu concentrations ranged from 88.5 to 245.6 and 61.2 to 224.9μg/g in the root tips and roots respectively. Pb concentrations ranged from 44.5 to 72.2 and 12 to 41.3μg/g in the root tips and roots respectively, and Zn concentrations ranged from 144.5 to 383.3 and 157.6 to 172.2μg/g in the root tips and roots respectively. Cu concentrations (Table 5.11) are significantly higher than those recorded in root samples of *Phragmites* collected from polluted sites whilst the Pb and Zn concentrations are comparable (Haberl and Perfler, 1989; Kadlec and Knight, 1996; Lan *et al.*, 1990 and Surface *et al.*, 1993). These results are lower than the maximum Cu, Pb and Zn concentrations (178, 905 and 871μg/g respectively) accumulated by the subsurface tissues of *Phragmites australis* in a natural wetland receiving highway runoff (Mungur *et al.*, 1995). The latter values demonstrate the high heavy metal tolerance exhibited by *Phragmites* and suggest that more mature plants than the ones used in the experiments would have accumulated higher metal concentrations. This shows the importance of using plant species at similar levels of maturity.

Phragmites has been shown to evolve distinct metal tolerant populations in relation to other environmental influences (Mansfield, 1990) and is more dependent on edaphic factors than on the amount of heavy metals present in the sediment (Schierup and Larsen, 1981). Like *Phragmites, Typha latifolia* is known to form an iron plaque on its roots (Crowder and St.-Cyr, 1991). Iron plaque consists mainly of iron (hydr-) oxides (Chen *et al.*, 1980; Mendelssohn and Postek, 1982) and there is a possibility that plants forming an iron plaque could be at an advantage with regard to the uptake of metals due

Table 5.11 Average heavy metal concentrations (μg/g) in all dosed macrophytes species.

Macrophyte	Sample	Cu	Pb	Zn
Phragmites australis	Root	143	27	165
	Root tips	167	58	264
Typha latifolia	Rhizome	23	9	128
	Roots	163	59	201
	Root tips	231	161	970
Schoenoplectus lacustris	Rhizome	18	11	78
	Roots	92	47	260
	Root tips	168	72	469
Iris pseudacorus	Rhizome	6	8	9
	Roots	53	22	53
	Root tips	87	210	64

to the adsorption and immobilization of heavy metals by the iron plaque (Taylor and Crowder, 1983b) although the tolerance mechanism is as yet unclear (Ye *et al.*, 1994). Ferrous iron, Fe(II), is the dominant soluble form under reduced conditions in wetland sediments and is usually present in peat. Thus the formation of iron plaque in the experimental wetland is possible.

This property may help explain the high Zn concentration (2375μg/g) seen in the root tips of *Tl 2* since the plaque seems to slow Zn transport to the above-surface tissue but not reduce Zn uptake into the root, thus concentrating Zn in the roots. Thus *Typha latifolia* is able to accumulate and tolerate high levels of Zn, as confirmed by McNaughton *et al.* (1974), and subsurface tissue concentrations in the dosed *Typha* are comparable with those noted in other studies (Mungur *et al.*, 1995).

In the three dosed *Typha latifolia* plants (Table 5.12), where the root hair network was too entwined with the root system to be satisfactorily isolated, Cu concentrations ranged from 85 to 385, 68.4 to 235.6 and 22.4 to 68.4μg/g in the root tips, roots and rhizomes respectively.

Pb concentrations ranged from 51.9 to 315, 15.1 to 93.8 and 4.8 to 15.1μg/g in the root tips, roots and rhizome respectively, and Zn concentrations ranged from 123.8 to 2375, 110.7 to 289.1 and 102.9 to 152.1μg/g in the root tips, roots and rhizome respectively. These root concentrations are comparable with those noted in other studies (Blake *et al.*, 1987; Lan *et al.*, 1990; Meiorin, 1989; Mungur *et al.*, 1995 and Zhang *et al.*, 1990).

In the three dosed *Schoenoplectus lacustris* plants (Table 5.12), Cu concentrations ranged from 120.6 to 245.0, 55.5 to 134.1 and 8.3 to 25.2μg/g in the root tips, roots and rhizomes respectively. Pb concentrations ranged from 61.3 to 77.5, not detected to 84.1 and 9.6 to 11.4μg/g in the root tips, roots and rhizome respectively, and Zn concentrations ranged from 291.1 to 731.3, 201.6 to 330.5 and 42.9 to 100.7μg/g in the root tips, roots and rhizome respectively.

There is comparatively little data on metal uptake by *Schoenoplectus* but Pb concentrations have been found to be comparable with those found in *Scirpus*, the non-rhizomatous genus related to *Schoenoplectus* (Burton, 1983), whilst Zn concentrations are much higher. *Typha* and *Schoenoplectus* have been shown to be more metal-tolerant than other genera of emergent hydrophytes (Blake and Dubois, 1982) and this is shown by the fact that generally, the highest average Cu, Pb and Zn concentrations are seen in their respective subsurface tissues (Table 5.11).

In the three dosed *Iris pseudacorus* plants (Table 5.12), Cu concentrations ranged from 53.3 to 120, 25.2 to 88.3 and 4.4 to 7.9μg/g in the root tips, roots and rhizomes respectively. Pb concentrations ranged from 46 to 450, 8.6 to 41.4 and 4.4 to 13.1μg/g in the root tips, roots and rhizome respectively, and Zn concentrations ranged from 40 to 87.3, 26.6 to 96.8 and 5.7 to 12.3μg/g in the root tips, roots and rhizome respectively. *Iris* accumulates the lowest subsurface tissue metal concentrations, except for Pb in the root tips, indicating low metal uptake although field studies have shown it to be tolerant of much higher concentrations (Mungur *et al.*, 1995). These results are consistent with those of a study by Ellis *et al.* (1994) where *Iris* showed poor metal performance uptake in comparison to other plant species.

Table 5.12 Heavy metal concentrations (μg/g) in each dosed (refer to Figure 5.13 for locations of *species 1, 2, and 3*) and control (c) *Phragmites, Typha, Schoenoplectus* and *Iris* subsurface tissue.

Macrophyte	Sample	Cu	Pb	Zn
Pa1	Whole root section*	97.5	55	697.5
Pa2	Root	224.9	12	172.2
	Root tips	88.5	44.5	144.5
Pa3	Roots	61.2	41.3	157.6
	Root tips	245.6	72.2	383.3
Pac	Whole root section*	140.9	33	63.1
Tl1	Root/Rhizome*	68.4	15.1	110.7
	Root tips	85	51.9	123.8
Tl2	Rhizome	22.9	4.8	102.9
	Root	90.8	24.2	112.9
	Root tips	385	315	2375
Tl3	Rhizome	22.4	12.4	152.1
	Root	235.6	93.8	289.1
	Root tips	221.4	117.1	410.7
Tlc	Rhizome	11.8	3.7	163
	Root	77.1	46.8	113.2
	Root tips	56.7	83.3	400
Sl1	Rhizome	25.2	9.6	90.5
	Roots	55.5	-	201.6
	Root tips	120.6	77	291.1
Sl2	Rhizome	20.1	10.9	100.7
	Roots	134.1	58.2	330.5
	Root tips	245	77.5	731.3
Sl3	Rhizome	8.3	11.4	42.9
	Roots	85	84.1	250.7
	Root tips	139.4	61.3	385.6
Slc	Rhizome/Root*	20.4	13.8	69.8
	Root tips	10	55	40
Ip1	Rhizome	7.9	6	8.9
	Roots	45.3	15.3	26.6
	Root tips	86.7	133.3	63.3
Ip2	Rhizome	5.8	13.1	12.3
	Roots	25.2	41.4	36.4
	Root tips	120	450	40
Ip3	Rhizome	4.4	4.4	5.7
	Roots	88.3	8.6	96.8
	Root tips	53.3	46	87.3
Ipc	Rhizome	7.9	4.5	15.4
	Roots	26.1	56.5	136.2
	Root tips	60	210	370

Key:

*	Tissues could not be separated satisfactorily
-	(<) detection limit

5.3.3.2 Heavy Metal Biomass Accumulations in Macrophyte Samples

Heavy metal biomass loadings per root subsection were calculated by multiplying the concentration of metal found in the tissue by the biomass of that tissue. The measured biomasses of all the subsurface tissue sections are shown in Table 5.13. *Typha latifolia* showed the highest subsurface tissue biomass of the four species (55.3g) followed by *Scirpus lacustris* (27.8g), *Iris* (10.2g) and *Phragmites* (6.9g). The variability in the biomass of the *Typha* tissues is probably due to differences in growth of the roots and rhizomes of each *Typha* plant. The relatively low biomass of *Phragmites* is considered to be a consequence of the plants being immature (see Section 5.2.3).

Table 5.13 shows that all four species showed great variability, with respect to each other, in the growth of their roots and rhizomes. Waterlogging of soil causes oxygen depletion and chemical reduction of certain compounds and at low redox potentials plant toxins such as ferrous and manganese ions are produced (Parr, 1990). Macrophytes survive these conditions and toxins due to the diffusion of oxygen from the roots to the rhizosphere (see Section 2.5.2.2). In gravel substrates, macrophyte may be unable to transport sufficient oxygen into the rhizosphere (or the oxygen diffuses away from the rhizosphere too rapidly) to avoid the effects of the toxins. Thus in the plants with a low root and rhizome biomass at the end of the growing season, growth was possibly inhibited by a lack of oxygen and thus confined to the aerobic zones of the peat profile. This may be due to the peat not being compacted sufficiently during planting and gaps in the peat profile allowing oxygen to diffuse away before a rhizosphere could develop around the root system. Alternatively, the lower biomasses may simply reflect unhealthy plants.

Tables 5.14 and 5.15 show the total and actual heavy metal loadings (μg) in the root sections of the dosed plants. The results show the highest accumulations occurred in *Typha latifolia* followed by *Schoenoplectus lacustris, Phragmites australis* and *Iris pseudacorus*. There is, in general, a trend of metal loads decreasing in the order of roots > rhizome > root tips reflecting the high biomass of the root matrix.

Table 5.13 Biomass (g) of each dosed (refer to Figure 5.13 for location of *species 1, 2,* and *3*) and control (c) *Phragmites, Typha, Schoenoplectus* and *Iris* subsurface tissue.

Species	Root tips	Roots	Rhizome
Pa1	-	0.08	-
Pa2	0.05	0.49	-
Pa3	0.09	6.80	-
Pac	0.93*		-
Tl1	0.04	9.09*	
Tl2	0.01	52.05	3.25
Tl3	0.07	36.76	2.81
Tlc	0.03	0.31	1.17
Sl1	0.09	0.64	12.24
Sl2	0.02	0.51	4.91
Sl3	0.04	17.46	10.3
Slc	0.04	13.94*	
Ip1	0.03	1.40	2.63
Ip2	0.01	0.64	0.90
Ip3	0.15	7.77	2.30
Ipc	0.01	0.92	1.32

Key:

* Combined biomass of subsurface tissues that could not be separated satisfactorily.

Table 5.14 Total accumulation of metals in subsurface tissues of each dosed macrophyte species (μg).

Species	Total Cu	Total Pb	Total Zn
Phragmites australis	561.4	299.4	1253.9
Typha latifolia	14168.7	4908.8	18329.3
Schoenoplectus lacustris	2092.8	1797.8	6775.2
Iris pseudacorus	813.5	167.6	876.0

Table 5.15 Heavy metal loadings (μg) in each dosed (refer to Figure 5.13 for locations of *species 1, 2,* and *3*) and control (c) *Phragmites, Typha, Schoenoplectus* and *Iris* subsurface tissue.

Macrophyte	Sample	Cu	Pb	Zn
Pa1	Whole root section*	7.8	4.4	55.8
Pa2	Root	101.9	5.9	84.4
	Root tips	4.4	2.2	7.2
Pa3	Root	415.9	280.5	1072
	Root tips	22.1	6.5	34.5
Pac	Whole root section*	131	30.7	58.7
Tl1	Root/Rhizome*	621.8	137.3	1006.3
	Root tips	3.4	2.1	5.0
Tl2	Rhizome	74.4	15.6	334.4
	Root	4726.1	1259.6	5876.5
	Root tips	3.9	3.2	23.8
Tl3	Rhizome	62.9	34.8	427.4
	Root	8660.7	3448.1	10627.3
	Root tips	15.5	8.2	28.8
Tlc	Rhizome	13.8	4.3	190.7
	Root	23.9	14.5	35.1
	Root tips	1.7	2.5	4.0
Sl1	Rhizome	308.5	117.5	1107.7
	Roots	35.5	0	129
	Root tips	1.1	6.9	26.2
Sl2	Rhizome	98.7	53.5	494.4
	Roots	68.4	29.7	168.6
	Root tips	4.9	1.6	14.6
Sl3	Rhizome	85.5	117.4	441.9
	Roots	1484.6	1468.9	4377.3
	Root tips	5.6	2.5	15.4
Slc	Rhizome/Root*	284.3	192.7	973.3
	Root tips	0.4	2.2	1.6
Ip1	Rhizome	20.8	15.8	23.4
	Roots	63.4	21.4	37.3
	Root tips	2.6	4	1.9
Ip2	Rhizome	5.2	11.8	11.1
	Roots	16.1	26.5	23.3
	Root tips	1.2	4.5	0.4
Ip3	Rhizome	10.1	10.1	13.1
	Roots	685.8	66.6	752.4
	Root tips	8	6.9	13.1
Ipc	Rhizome	10.4	5.9	20.3
	Roots	24	52	125.3
	Root tips	0.6	2.1	3.7

Key:

* Tissues could not be separated satisfactorily.

5.3.3.3 Distribution of Heavy Metal Loadings Within the Subsurface Tissues

The distribution of metal loadings within the subsurface tissues (i.e. rhizome, roots and root tips) were investigated using boxplots which compare distribution of values in several groups (Figure 5.14 to 5.16). The median value gives the central tendency and the length of the box gives the spread or variability of the observations (Norusis, 1988). Overall, the boxplots showed that the highest accumulations of Cu, Pb (to a lesser extent) and Zn occurred preferentially in the roots of *Typha latifolia* and that Zn was accumulated in preference to Cu and Pb in all the subsurface tissues. It is known that there is competition amongst Cu, Fe, Mn and Zn (Machemer and Wildeman, 1992) for similar types of organic binding sites and results from the peat samples show that Zn is accumulated preferentially in the wetland. There may be a possibility that a similar form of competition occurred in the subsurface tissue of the plant species. However,

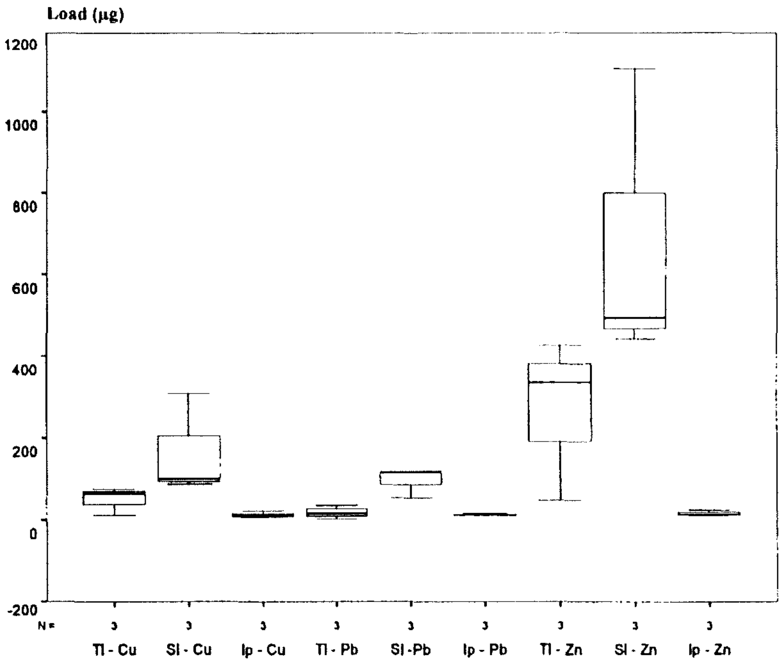


Figure 5.14 Metal load (μg) variations in rhizomes of each plant species (Tl = *Typha latifolia*, Sl = *Schoenoplectus lacustris* and Ip = *Iris pseudacorus*).

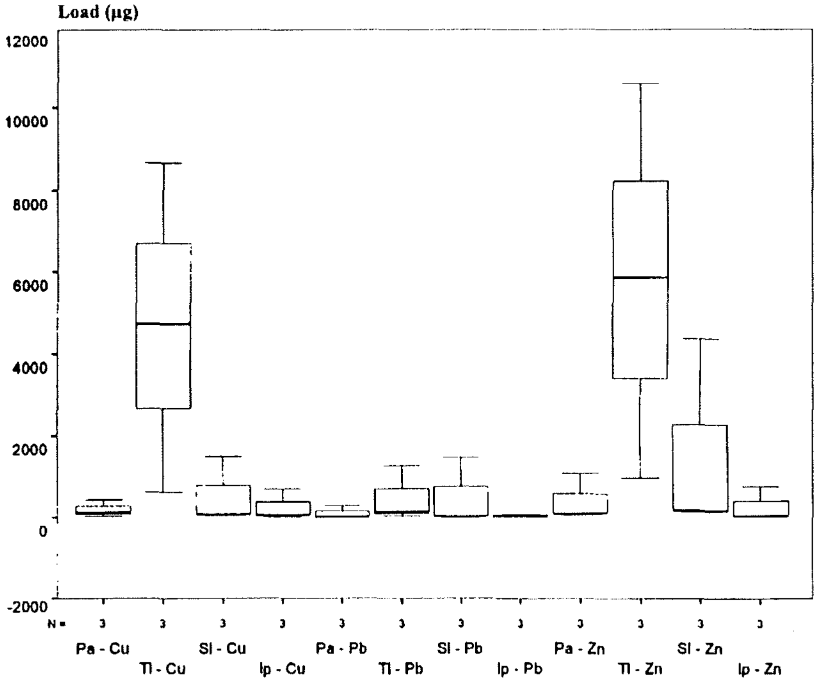


Figure 5.15 Metal load (μg) variations in roots of each plant species (Pa = *Phragmites australis*, Tl = *Typha latifolia*, Sl = *Schoenoplectus lacustris* and Ip = *Iris pseudacorus*).

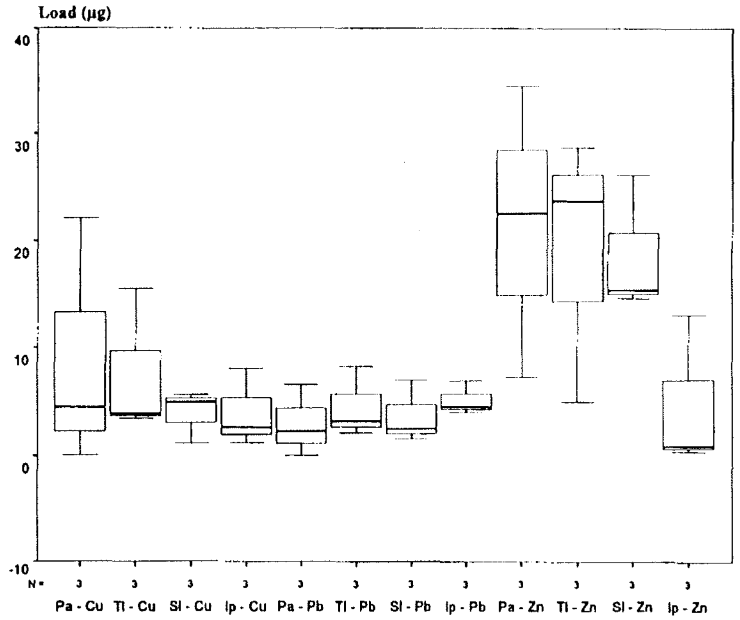


Figure 5.16 Metal load (μg) variations in root tips of each plant species (Pa = *Phragmites australis*, Tl = *Typha latifolia*, Sl = *Schoenoplectus lacustris* and Ip = *Iris pseudacorus*).

analysis of variance (ANOVA) showed that the differences seen in the metal loads in the subsurface tissues can be attributed to natural variations amongst the four plant species. There may be a possibility that the metal uptakes seen were influenced by metal tolerant genotypes (Macnair, 1981; 1983).

5.3.3.4 Assessment of the Relationship Between Heavy Metal Peat and Macrophyte Subsurface Tissue Loads

Table 5.16 shows the total heavy metal loads accumulated in the peat and subsurface tissues associated with each macrophyte.

Table 5.16 Total accumulation of Cu, Pb and Zn (μg) in the subsurface tissue of each plant and respective surrounding peat (refer to Figure 5.13 for key).

Macrophyte	Cu sediment load	Cu total subsurface tissue load	Pb sediment load	Pb total subsurface tissue load	Zn sediment load	Zn total subsurface tissue load
Pa1	120600	8	67200	4	167100	56
Pa2	118200	106	125400	8	350100	92
Pa3	24000	438	20700	287	23400	1107
Tl1	110700	625	60900	139	190800	1011
Tl2	85500	4804	44400	1278	165600	6235
Tl3	64200	8739	42900	3491	184500	11084
Sl1	170100	345	281400	124	684600	1263
Sl2	152100	172	414300	85	1870200	678
Sl3	139800	1576	311400	1589	393300	4835
Ip1	75300	87	72900	41	71400	63
Ip2	117600	23	343800	43	222900	35
Ip3	54000	704	23100	84	366600	779

Plots of the metal peat and subsurface plant tissue loads (Figures 5.17 to 5.19) show that the highest subsurface tissue loads are associated with lower peat loads for *Typha latifolia 2* and *3*. As the metal peat load increases, there appears to be a tendency for total subsurface tissue loads to decrease for each metal although there are no clear trends (the correlation coefficients, r, for Cu, Pb and Zn are -0.3133, -0.1646 and -0.1592 respectively). This is consistent with past studies which show that heavy metal accumulation in plants correlates poorly with metal loads in sediments (Babcock

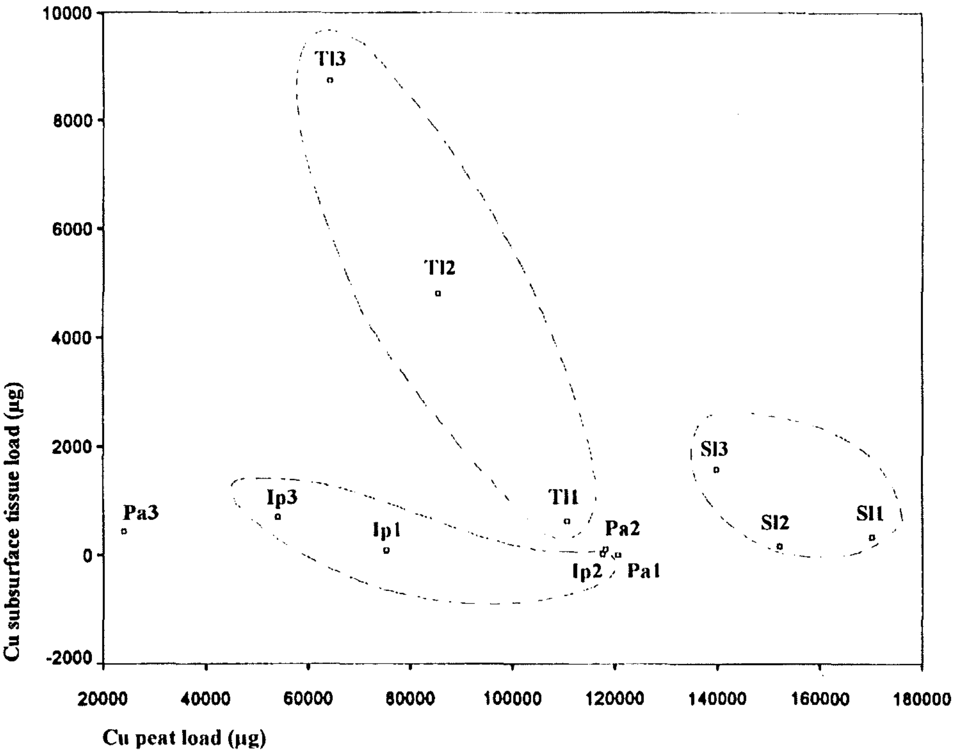


Figure 5.17 Plot of Cu loads in peat versus Cu loads in subsurface plant tissue.

et al., 1983; Eger and Lapakko, 1988; Hutchinson,1975; Mudroch and Capobianco, 1978; Schierup and Larsen, 1981; 1983; Sencindiver and Bhumbla, 1988; Taylor and Crowder, 1983a and Wells *et al.*, 1980). The lack of plant-sediment correlation is also consistent with the results of a study of Cu, Pb and Zn accumulation in *Typha latifolia* (Taylor and Crowder, 1983). Similar results are seen when the peat metal loads are plotted versus the loads of the individual subsurface tissue components (i.e. the rhizome, roots and root tips).

Pa3 (refer to Figure 5.13 for key) showed the highest metal subsurface tissue loads for this macrophyte (438, 287 and 1107μg for Cu, Pb and Zn respectively) although the peat surrounding *Pa3* had the lowest metal loads compared to the peat in the other *Phragmites* sampling baskets. However, *Pa1* and *2* had lower metal subsurface tissue loads (8, 4 and 56μg for Cu, Pb and Zn for *Pa1* and 106, 8 and 92μg for *Pa2* respectively) surrounded by higher peat concentrations (Table 5.16 and Figures 5.17, 5.18 and 5.19). These results are consistent with other studies which suggest that *Phragmites* is more dependent on edaphic factors than on the amount of heavy metals present in the sediment (Schierup and Larsen, 1981). This suggests that *Phragmites*

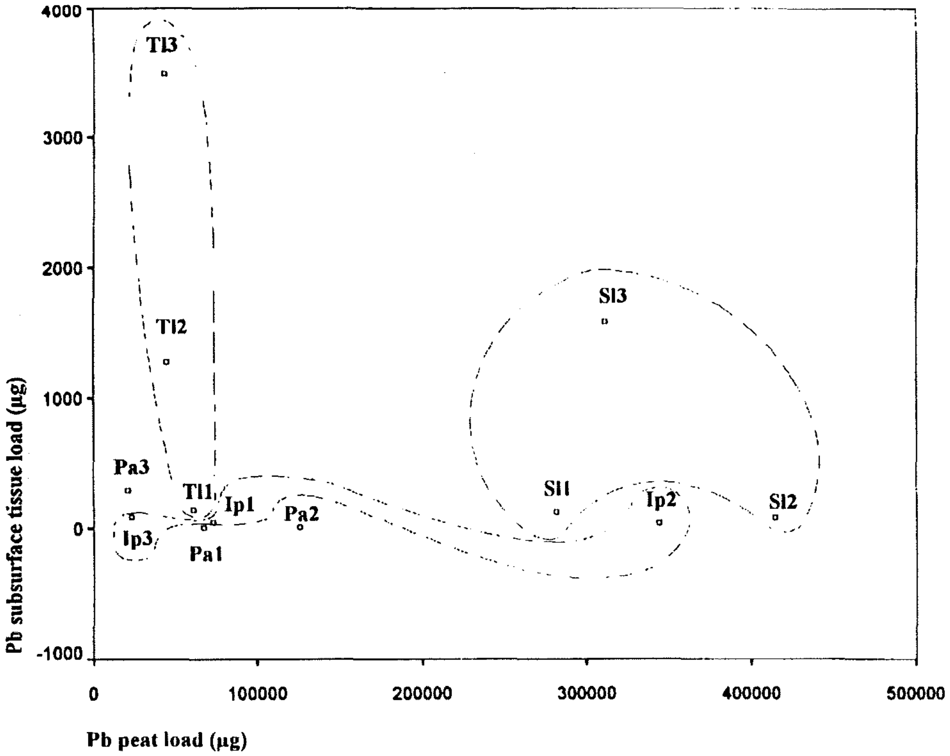


Figure 5.18 Plot of Pb loads in peat versus Pb loads in subsurface plant tissue.

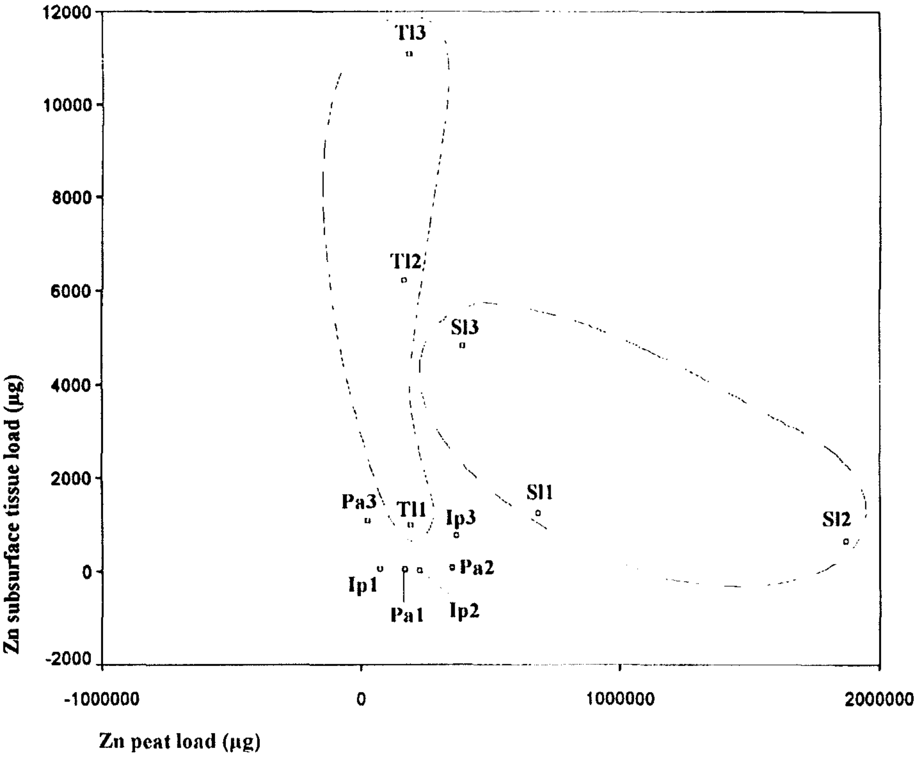


Figure 5.19 Plot of Zn loads in peat versus Zn loads in subsurface plant tissue.

should be planted, initially at least, near the inlet of wetlands designed to treat runoff containing significant levels of heavy metals since the plants of this species will efficiently remove metals regardless of the metal levels in the sediments near the inlet (which may vary more than in other areas of the wetland due to their proximity to the inflowing discharge and resulting variable metal load).

The high maximum loads recorded in the subsurface tissues of *Typha* (8739, 3491 and 11084μg for Cu, Pb and Zn respectively; see Table 5.16) were probably due to their high biomass, assuming uniform metal distribution throughout the system, as supported by past studies on the heavy metal tolerance of emergent hydrophytes including *Typha* (Blake and Dubois, 1982). Thus a large and extensive root network would be advantageous in accumulating high metal loads, metal uptake being proportional to root weight (Dushenkov *et al.*, 1995).

Metal loads were more evenly distributed between the *Schoenoplectus* plants than in the other species although the higher loads in the subsurface tissue of *Sl3* (1576, 1589 and 4835μg for Cu, Pb and Zn respectively) were not only attributed to its higher root biomass, but also to its position immediately next to the outlet (Figure 5.13) - the flow of the dosed water temporarily interrupted by the barrier forming the end of the wetland allowed more time for uptake.

5.3.3.5 Distribution of the Highest Subsurface Tissue Heavy Metal Loads Within the Wetland

The highest subsurface tissue metal loads (Table 5.17) were accumulated in the plants in the central row parallel to the direction of flow (i.e. *Pa3, Tl3, Ip3* and *Sl3*; see Figure 5.13) where flow was irregular due to shortcircuiting (see Section 5.2.2). This suggests that macrophytes planted in the areas of lowest flow were more likely to accumulate higher levels of metals since the lower flow rate was sufficiently attenuated by the vegetation to increase contact time and hence the efficiency of metal uptake by the macrophytes from the polluted water. The highest heavy metal total root loads for Cu, Pb and Zn were seen in *Typha latifolia,* which was planted behind the first line of *Phragmites australis* (Figure 5.13) in the wetland. This suggests that either optimium

Table 5.17 Highest subsurface tissue metal loads accumulated in each macrophyte species (μg) (refer to Figure 5.13 for key).

Species	Cu	Pb	Zn
Phragmites australis 3	438	287	1107
Typha latifolia 3	8739	3491	11084
Schoenoplectus lacustris 3	1576	1589	4835
Iris pseudacorus 3	704	84	779

uptake took place in this central area of the wetland or that *Typha latifolia* has the most efficient metal uptake mechanism. Since metal uptake is proportional to root weight and the *Typha* subsurface tissues had a higher biomass (mean of 34.7g) than those of *Phragmites* (mean of 2.5g), the latter reason is more probable as confirmed by studies on the heavy metal tolerance of *Typha* (Blake and Dubois, 1982).

The distribution of macrophytes within the plots of plant subsurface tissue loads and surrounding peat loads can be separated into groups showing interspecies affinity as shown in Figures 5.17 to 5.19. *Typha* and *Schoenoplectus* in the middle row of the wetland (*Tl3* and *Sl3*) accumulate the highest metal loads per species. Metal loads decrease in the order of Zn > Cu > Pb in the peat and subsurface tissue of *Phragmites, Typha* and *Iris.* The metal loads in *Schoenoplectus* decrease in the order of Zn > Pb > Cu. These trends, consistent with previously discussed results, show preferential uptake of Zn over Cu and Pb by the peat and subsurface tissues. Further experimentation is needed to see if this trend was due to the high bioavailability of Zn or whether other factors were influencing its preferential uptake.

As previously shown in Figures 5.17 to 5.19, the heavy metal load distribution within the *Typha* plants shows that metal loads decreased in the order *Tl3* > *Tl2* > *Tl1*. A similar order, whereby the plants in the central row of the wetland showed the most efficient uptake, is seen with *Pa3, Ip 3* and *Sl3*. High metal accumulations due to high subsurface tissue biomass can provide a partial explanation for the high loads in *Pa3* and *Ip3* since the biomasses of *Tl3* and *Sl3* are not much greater than the other plants of their species. This further suggests that short circuiting operated in the central row of the wetland allowing *Pa3, Tl3, Sl3* and *Ip3* more time for uptake. However, peat metal uptake through the central row of the wetland was less efficient (see Section 5.3.2). A possible explanation is that short-circuited water accumulated around the centre row baskets whilst flow continued along the base and around the sides of the peat cylinders. Metal uptake and bioaccumulation by plants in the centre row appears to increase whereas peat uptake is reduced because transpiration is maintained although flow rates through the substrate are reduced. This suggests that high accumulations would occur when the plants removed metals from an aqueous solution (such as the dosed water in areas of low flow) as shown by the studies carried out by Delgado *et al.* (1993), Makos and Hrncir (1995) and Srivastav *et al.* (1994).

5.4 CONCLUSIONS

The main conclusions of this study can be summarized as follows:

- The wetland system acted as an efficient sink for heavy metals during the investigation and removed loads of Cu, Pb and Zn at rates of 36.6 to 372.7, 30.8 to 387 and 33.6 to 362.1 mg/m^2/d respectively. Removal rates were generally most efficient for the highest inlet dosing concentration (10mg/l).

- Preferential uptake of metals by the peat occurred in the west sides of sampling baskets *Pa1, Tl1, Sl1* and *Ip1* and the east sides of sampling baskets *Pa2, Tl2, Sl2* and *Ip2* (Figure 5.13) where irregular flow allowed more time for uptake indicating short-circuiting of flow. Zn was taken up in preference to Cu and Pb by the peat.

- Cu, Pb and Zn concentrations in all four plant species decreased in the order of root tips > roots > rhizome. Zn was taken up in preference to Cu and Pb by the subsurface plant tissue.

- *Iris pseudacorus* accumulated the lowest subsurface tissue heavy metal concentrations whereas *Typha latifolia* accumulated the highest subsurface tissue heavy metal concentrations.

- The highest heavy metal loads occurred in *Typha latifolia* followed by *Schoenoplectus lacustris, Phragmites australis* and *Iris pseudacorus* and loads decreased in the order of roots > rhizome > root tips.

- Macrophytes planted in the areas of lowest flow were more likely to accumulate higher levels of metals since increased contact time increased uptake efficiency.

- Plant subsurface tissue metal loads correlated poorly with peat metal loads. Plant suburface tissue metal uptake was highest where the peat metal uptake was lowest (in the central sampling baskets - *Pa3, Tl3, Sl3* and *Ip3* - of the wetland) indicating that plant metal uptake was not influenced by the amount of metal in the peat but was more dependent on the amount of metals in the aqueous solution.

This study demonstrates that the experimental wetland system treated water dosed with Cu, Pb and Zn to simulate maximum runoff concentrations from major highways efficiently. The uneven distribution of metals in the peat highlights the importance of the hydraulic design, and the need to reduce the possibility of shortcircuiting, in constructed wetlands for runoff treatment. Flow regimes of such wetlands need to be studied and optimized for minimal shortcircuiting before and after planting takes place to ensure efficient treatment once the wetland is operational. However, it must be emphasized that these results are the initial responses of the laboratory scale wetland to the metal doses. Subsequently, the system may become saturated with heavy metals and its removal efficiency may decrease. Thus it would be necessary to determine the occurrence of any optimal removal efficiency for the wetland. Therefore the ultimate step would be to replicate the success of the laboratory-scale wetland with a full-scale wetland although very few examples of full-scale systems, including the wetlands currently being monitored, have achieved their full potential or matched the success of laboratory scale systems (Mitchell *et al.*, 1995).

CHAPTER 6 THE PUBLIC'S PERCEPTION OF THE AESTHETIC AND WILDLIFE VALUE OF WETLANDS AND THE USE OF WETLANDS FOR WATER QUALITY IMPROVEMENT

6.1 INTRODUCTION

In this Chapter, the methods used to design the pilot and main questionnaire surveys to assess the public's perception of the aesthestic and wildlife value of wetlands and the use of wetlands for water quality improvement are described in Section 6.2. The rationale behind pilot testing is described in Section 6.3 and the results from the pilot survey are presented and interpreted in Section 6.4. The resultant modifications made for the main survey are described and explained in Section 6.5. The results from the main survey are presented and interpreted in Section 6.6 and the conclusions of the study are presented in Section 6.7.

6.2 METHODOLOGY

6.2.1 Methods Used for Surveys

An introduction into the topic was obtained from previous literature relating to survey methods and an understanding of the methods and techniques utilised in question formulation, questionnaire design and interviewing was obtained from the literature and by undertaking a postgraduate diploma in survey research methods organised by the Faculty of Social Sciences (see Section 2.9.2).

Approaches to the study of the public's perception of wetlands were partly based on studies of the visual preference of landscapes (e.g. Lee, 1977; Levin, 1977 and Smardon, 1972, 1975, 1983; see Section 2.9.1) and additionally on the studies of water quality perception and recreational preference where on-site questionnaire surveys have been used to assess the public perception of different landscape types using members of the public who use "natural" open spaces (e.g. rivers, parks) regularly for recreational purposes (Barker, 1971; de Bettercourt and Peterson, 1981; David, 1971;

Davis and Parker, 1982; Fordham, 1991a; Fordham, 1991b; Kooyoomjian and Clesceri, 1974; Scherer and Coughlin, 1971; Tapsell *et al.,* 1991; Tunstall *et al.,* 1989 and Tunstall and Fordham, 1990). Thus the methodology was derived from the literature, the diploma and from studies carried out by the Flood Hazard Research Centre (Middlesex University). The methods are described in Sections 6.2.1.2 to 6.2.1.7.

6.2.1.2 The Nature of Questionnaire Surveys

Surveys are a method of social research characterised by a structured set of data. The function of survey analysis is to collect, organise, analyse and thus describe the characteristics of a set of data. The relevant data can be collected by a variety of techniques and appropriate research methods can be found for most studies (de Vaus, 1996). The most appropriate method for research into public perception of the value of wetlands, given the time constraints, involved the use of a questionnaire.

Qualitative research methods, such as the use of focus groups, are often used as a tool to refine research objectives, but were not used in this study due to time constraints. Quantitative research methods involve the use of questionnaires. A questionnaire is a highly structured data collection technique where each respondent is asked an identical set of questions. Questionnaires are the most widely used method of collecting survey data, mainly because they provide an extremely efficient way of creating and exploring variables by using case matrices for large samples (de Vaus, 1993). They are usually constructed in several stages: the information required is defined; the questions are devised, written and organised into a structured and logical order before the questionnaire is revised, evaluated and rewritten. This procedure is repeated until a satisfactory text and layout is created. Figure 6.1 summarises the various stages of the development of a questionnaire to assess the public perception of wetlands.

6.2.1.3 Practically Based Questionnaires

Questionnaire studies can be divided into those which are practically based (i.e. on-site, laboratory and household based) and those which are theoretical in nature. Practically based questionnaires are discussed in Sections 6.2.1.3.1 to 6.2.1.3.3. Theoretical

(1) DEFINE AIMS AND OBJECTIVES (Chapter 1)

(2) PRELIMINARY RESEARCH (Section 6.2.1)
- Literature review
- Background reading
- Attending relevant courses
- Discussion with other researchers

(3) PREPARATION OF DRAFT QUESTIONNAIRE (Section 6.2.2)
- Consideration of target groups
- The value of questions (from literature)
- Methodology (e.g. question wording, classification of possible answers)
- Testing and re-evaluation

(4) PREPARATION OF PILOT QUESTIONNAIRE (Section 6.2.2)
- Methodology considerations
- Presentation (e.g. use of interview or show cards)
- Testing and re-evaluation

(5) PREPARATION OF PILOT SURVEY (Section 6.2.2)
- Site selection
- Gaining permission to use site for interviewing purposes
- Training of interviewers
- Printing of questionnaires, show and id cards
- Preparation of interview card folders
- Methodology considerations (e.g. interviewer attire, positioning of interviewers at site)
- Testing and re-evaluation

(6) PILOT SURVEY (Section 6.3 and 6.4)
- Collection of data
- Organisation of data
- Analysis of data

(7) CHANGES TO SURVEY BASED ON PILOT EXPERIENCE (Section 6.5)
- Correct mistakes, oversights, etc.
- Preparation of main survey
- Testing and re-evaluation

(8) MAIN SURVEY (Section 6.6)
- Collection of data
- Organisation of data
- Analysis of data

Figure 6.1 The various stages of the development of a questionnaire to assess the public's perception of wetlands (After Williams, 1994).

studies to evaluate user preferences for water-based recreational sites include the construction of either mathematical models (Holman and Bennett, 1973; Stevens, 1966 and Turner, 1977) or Environmental Threshold Curves (de Bettencourt and Peterson, 1981) based on data collected from questionnaires.

6.2.1.3.1 On-Site Questionnaires

On-site questionnaire surveys involve interviewing the site users at one or more chosen location(s). They have been frequently used for studies of water quality perception and recreational preference carried out by the Flood Hazard Research Centre at Middlesex University (e.g. Fordman, 1991a; 1991b; Green and Tunstall, 1992; House, 1986; House and Herring, 1994; Tunstall *et al.,* 1989; Tunstall and Fordman, 1990) and for studies of visual preference of different landscapes (Smardon, 1983). The research has identified a number of advantages and disadvantages in using on-site questionnaires.

Advantages

On-site questionnaires allow the interviewer(s) to interview site users. This can be an effective time-saving strategy if the site users are the target group since this removes the need to contact potential respondents beforehand. Furthermore, people actually using a site will be more interested in their surrounding environment and thus generally more perceptive and aware of changes in the surrounding environment (e.g. water quality changes) than non-users. Thus they may be more willing to take part in an interview concerning the recreational environment they use. Site users are also generally better judges of what changes would increase or decrease the aesthetic and recreational nature of an area and what management strategies could be used for any improvements (Davis and Parker, 1982 and Ditton and Goodale, 1973).

Disadvantages

The effects of time of day and the angle of the sun can cause people's perception to vary since most of the sites appear more attractive and aesthetically pleasing in bright sunlight than under overcast skies (Coughlin, 1975). The completion of an on-site questionnaire may cause the respondents to notice aspects of their surrounding environment that they would not have noticed otherwise and this may confuse the issues under investigation. Furthermore, in cases where respondents have to move between a number of separate sites (e.g. different view points of a site), the route taken to the site and weariness may affect one's opinion when the last few sites are viewed. In addition, over-exposure to too many sites in one interview may lead to confusion and overlapping of impressions of one site onto the next. The approach taken when moving toward sites may influence perception, and the order in which the sites are viewed will influence perception (e.g. increasingly unattractive sites will lead the respondent to assume that the next sites will also be increasingly unattractive and they will respond as such) (House, 1986).

6.2.1.3.2 Laboratory-Based Questionnaires

Laboratory-based questionnaires are surveys that are carried out in closed surroundings with groups of respondents at one time. They involve targetting respondents beforehand and inviting them for interviews in groups at one location. Because there is no dependence on the visitors at a site, ideal populations can be targetted. This usually allows different socio-economic or recreational groups to be utilised within laboratory-based studies thus ensuring a diverse range of opinions. The setting also allows different number of scenarios (e.g. assessing the perceptions of a wide range of different landscapes) to be investigated in a relatively short time by the use of visual aids and/or slide or overhead projectors. The main drawback of a laboratory-based study is the considerable time and expense spent planning such an exercise and the lack of flexibility inherent in such an exercise since respondents will only be available for a limited time and, if absent, cannot be replaced, unlike in the field.

Many researchers (Coughlin and Goldstein, 1970; Dearinger, 1968; Herrington and Tocher, 1967; Herzog, 1985 and MacConnell and Stoll, 1968, House and Herring, 1994) have employed black and white or colour photographs and slides as a stimulus for laboratory based questionnaire studies investigating various aspects of the public's perception of recreational environments. This allows the perceptions of a wider range of landscapes to be determined without having to carry out the surveys at each landscape. This also provides controlled conditions for variables such as light, shade, weariness and the approach towards and exit from the sites. However, the conditions under which the photographs or slides are taken have to be consistent otherwise well-lit photographs/slides (e.g. those taken in sunny conditions), for example, will be perceived more favourably than poorly-lit photographs/slides.

Photographs can be used on-site thus combining the merits of both methods. This would allow the study of the public perception of wetland landscapes using an actual site as well as the perception of a range of other wetland landscapes depicted in photographs carefully selected beforehand.

Herzog (1985), Ittelson (1973) and Ulrich (1983) have all undertaken experiments to assess the importance of the length of time to which respondents are exposed to sites and their perceptions of those sites. In each instance, it was found that people decide upon their preference for a particular environment over an extremely short viewing time - usually the initial first few seconds. When the viewing time is increased to allow for a period of thought and consideration, the initial impression does not usually change, and if anything, is strengthened. Furthermore, the use of on-site respondents and the effect of the approach towards and away from the sites may give rise to another problem - first impressions of the site may overlap onto the perceptions of the next site allowing a predetermined image to be formed in the respondents' mind.

6.2.1.3.3 Household Based Questionnaires

As the name suggests, household based questionnaires involve carrying out the questionnaire survey by interviewing respondents, who have been previously approached, in their homes. Household based questionnaires are generally used in instances where the opinion of the general public is required, i.e. the persons do not necessarily have any prior knowledge of the subject. In the case of this study, persons who used wetland type environments in some way were required, i.e. site users who have some knowledge of their surrounding environment. Thus household based questionnaires were not appropriate for this study. Furthermore, this method is inherently time consuming since it requires the interviewer(s) to travel to all the homes once the respondents have agreed to be interviewed (de Vaus, 1996).

6.2.1.4 Method Used for this Study

The methods detailed in the literature show that the use of on-site questionnaires and the use of photographs and slides are seen as an excellent way of evaluating the public's perception of specific environments as a whole. Couglin and Hammer (1973) used the combined approach of photographs and visiting respondents to assess total significance of water quality to environmental preference for recreation and this approach was used for the assessment of the public perception of wetlands.

A laboratory-based survey was initially proposed for this study since it would have allowed bulk interviewing of, for example, 30 respondents at a time and thus would have considerably reduced the time required to interview a large number of respondents on a one-to-one basis. However, the logistics of a laboratory-based survey proved to be complicated and discouraging since there was a need to identify a target population of potential respondents who satisfied the following criteria:

- Respondents with the appropriate characteristics were required (e.g. people who regularly visit "natural" areas for recreational purposes, people who have an interest in their surrounding "natural" environment, etc.) for the survey. This criteria could be achieved by approaching visitors present at appropriate sites (i.e. wetland environments), and seeing whether they would be interested in partaking in the survey at a future date. Alternatively, it would be necessary to contact residents in the vicinity of appropriate sites (and who also used the sites for recreational purposes) via telephone or post in order to interest them in taking part in the survey. Another option would involve contacting members of recreational or outdoor groups who used sites appropriate for the purposes of the survey. It would also be necessary to keep the potential respondents unaware of the contents of the survey to prevent any bias, whatever the method of approach.

- Most importantly, there was a need to ensure that the respondents who did show an interest in taking part in the survey would indeed attend the arranged questionnaire sessions. This would be done by providing adequate inducements (e.g. payment, payment of travelling costs, food and drink, etc.) so that the potential respondents would give up at least an hour of their time to take part in the survey.

- Finally, the survey would be held in a place where potential respondents would be able to arrive without much difficulty. The place used to carry out the survey need not be in the vicinity of a wetland site although proximity to such an environment might provide a further incentive to the respondents to partake in the survey since they could visit the site before or after completing their questionnaire. In the instances where members of a recreational group were targetted for a survey, their club house would be an ideal venue.

Satisfying all the above criteria was prohibitively time-consuming and expensive given the constraints of the research programme (principally time and funds). By contrast, the criteria for an on-site survey were to identify an appropriate site in London which had many visitors, examples of the types of wetland landscapes being investigated, and facilities to allow for easy interviewing between the respondents and interviewers (i.e. pathways, benches, areas of shade for when the sunshine might cause discomfort during the summer, areas where respondents would not mind stopping for the duration of the interview). Finally, the site needed to have enough visitors and be large enough such that a number of interviewers could carry out the survey without targetting the same respondents. These criteria were far more easily satisfied. Section 6.2.1.5 addresses further considerations for questionnaire design.

6.2.1.5 Questionnaire Design and Development

Since it is often very difficult to go back to respondents to collect additional information, it is extremely important to plan ahead and ensure all the relevant questions are asked in the first place. Questionnaires can be divided into four sections (de Vaus, 1996):

- Measure of the dependent variable(s): development of questions to measure what is trying to be clarified.

- Measure of the independent variable(s): development of questions to identify the "causal" variables.

- Measure of the test variable(s): variables which help clarify the nature of the links between independent and dependent variables.

- Background measures: age, gender, occupation, education, etc.

The phrasing of questions is one of the most important aspects of questionnaire design. Question content, the wording of questions, the selection of question type, questionnaire layout and other considerations (language, length, format (open or closed; direct or indirect), bias, clarity, saliency, detail and tone) are variously covered by de Vaus (1996), Dillman (1978), Gallup (1947), Gowers (1962), Oppenheim (1968) and Strunk and White (1972). With these guidelines and the survey objectives in mind, a large number of draft questions were prepared, tested and revised.

As mentioned previously, an important aspect of question construction is the response format - should the questions be open or closed? A closed or force-choiced question is one in which a number of alternative answers are provided from which the respondents are to choose one or more. An open-ended question is one for which respondents formulate their own answers (de Vaus, 1996).

The main disadvantage of closed questions is that in some issues they can create false opinions by providing too few alternative answers or prompt respondents to choose "acceptable" answers. However, a well-developed closed question can be answered quickly, is easier to code (converting answers to questions into numbers for computer analysis) and does not discriminate against less talkative and inarticulate respondents.

There is no definitive approach - it is usually worth using a combination of open and closed questions for key variables or use open questions in a pilot survey to devise closed questions in the main survey. Gallup (1947) suggested the following combination:

- a closed question to see if the respondent has thought about or is aware of the issue;
- an open question to get at general feelings on the matter;
- a closed question to get at specific aspects of the issues;
- open or closed questions to find out respondents' reasons for their opinions;
- closed question to find out how strongly the opinion is held.

6.2.1.6 Sample Size

The required sample size depends on three key factors (de Vaus, 1996):

- what degree of accuracy is required from the sample;
- to what extent there is a variation in the population with regards to the key characteristics of the study; and
- cost and time.

The degree of accuracy depends on how much error can be tolerated. Table 6.1 shows the sample sizes required to obtain samples of varying accuracy. The figures are calculated such that there is a 95% confidence level that the results in the population will be as in the sample plus or minus the sampling error.

There are three points to note about the relationship between sample size and accuracy. First, the sample size has to be quadrupled to halve the sampling error. Second, the size of the population from which the sample is drawn is not important for the accuracy of the sample, except where the sample size represents a sizable proportion of the population (Moser and Kalton, 1971). It is the absolute size of the sample that is important. Third, the population is assumed to be heterogeneous. For a population where most respondents will answer a question in a particular way, a smaller sample is sufficient.

One problem that can arise is when subgroups need to be analysed separately (e.g. looking at the perceptions of different age groups). Thus from Table 6.1, a sample of 1100 (sampling error of 3.0% at 95% confidence levels) might only have 277 respondents in the 18-24 age group. Thus figures for that age group will have a sampling error of +6.0%. Hoinville *et al.* (1977) suggests that the smallest subgroup has at least 50 to 100 cases. Therefore the final sample size is a compromise between cost, time, accuracy and sufficient subgroup numbers for subgroup analysis (if required).

Table 6.1 Sampling errors for various sampling sizes at a 95% confidence level (Adapted from de Vaus, 1996).

Sampling error	Sample size*	Sampling error	Sampling size
1.0	10000	5.5	330
1.5	4500	6.0	277
2.0	2500	6.5	237
2.5	1600	7.0	204
3.0	1100	7.5	178
3.5	816	8.0	156
4.0	625	8.5	138
4.5	494	9.0	123
5.0	400	9.5	110
		10	100

Key

* This assumes a 50/50 split on a variable (sample sizes would be smaller for more homogeneous samples.

6.2.1.7 Analysis of Data

Once data are collected, they are generally subjected to some form of statistical analysis, e.g. multiple regression (Coughlin and Goldstein, 1970 and Coughlin *et al.*, 1972), step-wise regression (Holman and Bennett, 1973), Chi-Squared tests (Ditton and Goodale, 1973), cluster analysis (de Bettencourt and Peterson, 1981 and Knopp *et al.*,

1979) and factor analysis (Herzog, 1985). These data can also be presented in terms of percentage response rates (Barker, 1971; David, 1971; Davis and Parker, 1982; Ditton and Goodale, 1973 and Kooyoomjian and Clesceri, 1974). In many respects the latter form is of greater significance and meaning as it allows the importance of the individual variables to be expressed in relation to the total population sampled. However, the use of statistics may be revealing in the importance of variables to, for example, the preference of a wetland site and in this study the statistical package used was SPSS/PC+ (Norusis, 1988). Whichever techniques are used, it is essential that the data collected are carefully analysed.

6.2.2 Development of the Questionnaire

A review of the literature on the methodology (Section 6.2.2) showed that the best method to collect data to assess the public's perception of the aesthetic and wildlife value of wetlands was to carry out an on-site questionnaire survey (see Section 6.2.1.3), incorporating carefully selected photographs of wetland landscapes, at a carefully selected site (see Section 6.3.2) and interviewing the site users. The stages of the development of the questionnaire are described in Sections 6.2.2.1 to 6.2.2.4.

6.2.2.1 Preparation of Draft Questionnaire

A questionnaire survey assessing the public's perception of the aesthetic value of wetlands was to be carried out at a wetland site used for recreation. It was assumed that the site users would have an interest in their surroundings. A series of photographs depicting a range of wetland environments (see Sections 6.3.2 and 6.5.2 for detail on the photographs selected for the pilot and main questionnaires respectively) were used in conjunction with the questionnaire to assess how the wetland-using public perceived the different wetland-types (since the on-site wetland is not representive of all types of wetlands).

6.2.2.2 Site Selection

The criteria used in the selection of the site were:

- the presence of wetland environments which showed the range of visual attributes defined by the literature (see Section 2.9.1.4);
- diverse flora and a significant wildlife presence (i.e. a variety of different and easily identifiable fauna); and
- the regular use of the site for recreation and amenity by a range of user groups (see Section 6.2.3).

Several sites were identified which fulfilled some of the criteria, but few fulfilled all three. Sites investigated as possible for on-site surveys were: the Kenwood and Parliament Hill area of Hampstead Heath in North London, the Trent Park Country Park in Enfield Chase in North London and the Welsh Harp in North West London.

Hampstead Heath (Figure 6.2) is a large, popular and relatively unspoilt green space and receives a large number of visitors for recreational purposes (a very important consideration with regards to finding the required number of people to be interviewed). Hampstead Heath has a variety of wetland-type environments of which the largest and most conveniently situated contains the primary landscape components (land, water and vegetation) important in defining the visual attributes of wetlands as well as supporting a variety of wildlife including several types of birds and many examples of aquatic life. This wetland (Plate 7i) is not easily accessible since it is partially surrounded by a footpath (which has metal railings on one side to prevent access into the wetland) which leads to the swimming ponds of the Heath although it is easily seen and close by. Thus passers-bys have a very good visual example of what a wetland is. The area is also convenient for carrying out interviews since the path that partially surrounds the wetland is long enough to allow a number of interviewers to operate without getting in the way of each other or having the problem of respondents listening to the answers of other respondents being interviewed simultaneously. The path is also convenient for

Figure 6.2 Site of the questionnaire surveys in Hampstead Heath.

both the interviewers and respondents since it has seats and areas of shade which allow them to carry out the interviews in relative comfort. Colleagues and students were recruited for interviewing purposes and they were appropriately trained. A maximum of three interviewers operated at any time in the area.

The Trent Park Country Park attracts a lot of visitors but does not have good examples of wetland environments which are conveniently situated for interviewing purposes. The Welsh Harp (and Brent reservoir) is a Site of Special Scientific Interest (SSSI) with a bird sanctuary and thus has very good examples of wetland environments and wildlife. However, potential interviewees, such as walkers, are sparse due to poor facilities for walking and the relative inaccessability of the reservoir. Hence the wetland site on Hampstead Heath was selected as the location for the on-site questionnaire surveys (see Figure 6.2).

6.2.2.3 User Groups

During the summer months when the survey was carried out, the majority of the respondents in the area were involved in some form of walking as well as cycling and picnicking. The site users were sub-divided into the following categories: walking the dog, walking the children, strolling, walking two miles or more, cycling, picnicking and on a nature ramble. Walkers were divided into four subgroups since those walking children and walking two miles or more have been shown to be more aware of their surroundings than those out for a stroll and walking the dog (Burrows and House, 1989). Similar user groups have previously been used in other public perception surveys (e.g. Burrows and House, 1989; Ditton and Goodale, 1973; Green *et al.,* 1989; 1992 and House and Herring, 1994).

The survey did not target specialist users (e.g. boaters, fisherman, etc.) due to the time constraints of the research, but instead targetted the public who were attracted to open areas for recreational purposes, including people who visited Hampstead Heath rarely.

The sample size chosen for this survey was 300 (sampling error of between 5.5 and 6.0% at 95% confidence levels - see Table 6.1) given the time constraints, length of the questionnaires (20-25 minutes interviewing time) and method used to collect data (one-on-one interviews). The survey was carried out in the immediate surroundings of the site (so that all the respondents, regardless of where they are being interviewed, could see the wetland clearly) over the summer of 1995. Eventually, 284 persons were interviewed and this was deemed sufficient for statistical analysis.

The survey was carried out by approaching or stopping respondents in the vicinity of the on-site wetland and interviewing the willing respondents. The use of convenient spots (e.g. near benches, in the shade, overlooking the wetland) for interviewing reduced the problems associated with moving respondents (e.g. weariness, boredom, etc).

Due to time constraints, random respondent selection on site (e.g. approaching every 5th person for interviewing) was not strictly adhered to and an estimation of non-response was not carried out either.

6.2.2.4 Outline of the Questionnaire

The aim of the questionnaire survey was to evaluate the public's perception of the aesthetic and wildlife value of wetlands and their perception of, and attitude towards, the use of wetlands for wastewater treatment. The pilot and main questionnaires (Appendices 1 and 2 respectively) can be divided into the following general categories:

- General use of site. This section assessed why the respondents were there, how often they visited that site, the time spent at the site and how far they had travelled to get there. This was done to assess the importance (if any) of these characteristics on the perception of wetland environments since frequent visitors who spend a long time at a site are generally the most critical of environmental quality (Green *et al.,* 1989; House and Herring, 1994).

- Club membership. This section used club membership as a measure of how strongly the respondents were interested in environmental issues (i.e. are they members of, or do they donate to, any environmental/recreational clubs). This was also carried out to see if there is any relationship between group membership and wetland perception.

- Elements of wetland environments. This section used photographs to assess the public's perception of the visual attributes of wetlands which, in combination, indicate the overall preference of a scene (see Section 2.9.1.4).

- Value and uses of wetland environments. The value of the components that define wetland ecosystems and the benefits of the main products of wetlands were evaluated to assess the importance of wetlands.

- Wildlife value of wetlands. This section measured the importance of wildlife and the types of wildlife deemed important for the public's enjoyment of a visit.

- Use of wetlands for water quality improvement. This section explained how wetlands could improve water quality with the help of a visual aid (Figure 6.3) and measured what the respondents thought of using natural and constructed wetlands for water quality improvement as well as their reasons for their respective answers.

- Respondent information. This section compiled gender, age and employment status (or otherwise) of the respondents to see if this information influenced wetland perception at all.

These categories were incorporated into the pilot questionnaire described in Section 6.3 and shown in Appendix 1. After the pilot questionnaire had been tested, the modifications resulted in the main questionnaire which is described in Section 6.5 and shown in Appendix 2.

In most cases, these variables listed above were rated on a variety of numeric scales (e.g. 1 to 5, 0 to 6, -3 to +3, 0 or 1) where the lowest value generally denotes the lowest rating (i.e. the most negative response) and the highest value, the highest rating (the most positive response). The variables were measured using multiple indicators rather than one because multiple indicators can:

(1) tap the complexity of most variables;

(2) assist in preventing distortions and misclassifications which can arise from the use of only single-item measures of complex variables (e.g. how someone votes); and

(3) increase reliability and precision (de Vaus, 1996). The final score for each variable was determined using some form of statistical analysis like means, standards deviations or medians.

Some of the variables were presented in the form of lists (the visual attributes and the uses of wetlands). The disadvantage of providing lists (of possible answers) of any sort at all is that they may prompt responses to variables that have never been considered by the respondents before since people are very open to suggestions and may easily be influenced by the presentation of a list of potential views. There is no real solution to this problem except, perhaps, to precede such questions by a more open question concerning their perceptions of the site in question and thus encourage the respondent to form their own views before they are shown any lists of potential views. Thus there may sometimes be a need to ask a question in two different ways to ensure there is no prompting of reponses. The reply to this general question can then be compared to those of the more detailed category questions to assess the degree of influence exerted upon the respondents (House, 1986).

6.3 THE PILOT SURVEY

6.3.1 The Value of Pilot Tests

The first step in carrying out a large-scale questionnaire survey is to develop a questionnaire and rigorously evaluate each question and the questionnaire as a whole before final administration. This process is known as pilot testing or pretesting (Converse and Presser, 1986; de Vaus, 1996).

The pilot questionnaire as a whole needs evaluating if it is to be of most use. The following questions need to be asked: does the questionnaire flow (i.e. do the questions fit together); are the transitions from one section to another smooth; is each question necessary; what is the relationship between the questions; is the questionnaire too long; does the questionnaire hold the respondent's interest and attention; how are the data to be analysed? (de Vaus, 1996).

Another important question that needs to be asked is: do the questions lead to where they are intended? A flow diagram is a very useful tool to create a model of the questionnaire and the expected inter-relationships between the questions. Such a model can highlight whether the set of questions fulfill the research objectives in a coherent and logical manner and are adequate to collect the relevant and desired information.

Thus there is a need to identify the following (Converse and Presser, 1976):

- questions that made the respondent uncomfortable;
- questions that had to be repeated;
- questions that appeared to be misinterpreted;
- questions that were difficult to read or questions particularly disliked by the interviewee;
- sections that dragged;
- sections where the respondent seems to want to say more.

Conducting pilot test questionnaires are thus vital for good questionnaire design.

6.3.2 Design of the Pilot Questionnaire

The objective of the on-site pilot survey overall was to test the pilot model (Figure 6.3) which assessed the public's perception of the aesthetic and wildlife value of wetlands and their use for water quality improvement. The pilot survey instrument was a structured questionnaire which incorporated coded questions, photographs of nine wetland environments, show cards and an illustration (Appendix 1). The pilot questionnaire can be divided into the following main categories:

- General use of site (see Section 6.2.4).

- Club membership (see Section 6.2.4).

- Perception of wetland environment with respect to enjoyment of visit. This section rated (1) the attractiveness and naturalness of the wetland site in Hampstead Heath as well as the cleanliness of the water in the wetland and the attractiveness of its vegetation cover; (2) the importance of the various wetland attributes (e.g. the water body, vegetation, wildlife types, etc., see Figure 6.2); (3) the components for an ideal natural setting and (4) what was liked/disliked about the wetland water body, all with respect to the enjoyment of a visit. Thus the wetland was broken down into its primary components of water, land, vegetation and wildlife which allowed the preference value of each component to be individually assessed.

- Perception of nine photographs of different wetland environments (Table 6.2). The photographs were rated for attractiveness and what was liked/disliked about them. This also allowed the value of wetland visual components to be assessed.

- The final section investigated attitudes towards the use of wetland systems to improve water quality. This was investigated using a visual aid (see Section 6.4.3) to explain the process of wastewater treatment by wetlands.

- Respondent information (see Section 6.2.4).

The aim of the pilot survey was therefore to test the model and highlight any faults in the structure of the questionnaire.

Photographs of wetland landscapes showing the primary components of water, land and vegetation (scenes A to I - Plates 1ii to 5ii) were taken from the Welsh Harp in NW London and the Walthamstow marshes in NE London. These nine scenes were deemed appropriate for the pilot questionnaire since they each showed at least one important aspect of wetland landscapes, i.e. the factors identified as being important to visual preference in the environment - legibility, spatial definition, complexity, mystery and disturbance (see Section 2.9.1.4). Although there was an effort to obtain "ideal" photographs (i.e. taken under controlled conditions of light, shade, etc., see Section 6.2.1.4), in practice, this proved difficult since the photographs from the two sites were taken on different days, using different cameras operated by different people (the chosen nine photographs were picked from a choice of over 200 photographs). Table 6.2 describes the main features of scenes (Scenes A to I - Plates 7ii to 11ii) used in the pilot survey.

The questionnaire also incorporated *open* questions (see Section 2.9.2.6) which allowed the public to express freely their opinions, attitudes and feelings towards particular aspects of wetland landscapes.

Table 6.2 The main features of scenes (Scenes A to I - Plates 1ii to 5ii) used in the pilot survey.

Scene	Main features (Reasons why photograph selected for the pilot survey)
A	Human activity (houses visible), sparse vegetation with no cover, floating debris in the water.
B	Fairly high vegetation diversity, presence of wildlife, human activity (telephone poles and lines).
C	Presence of water plants, vegetation diversity and variable vegetation cover.
D	High vegetation diversity and vegetation cover (overhanging branches), human activity.
E	Good vegetation cover, diversity and sense of enclosure.
F	Large expanse of water.
G	High vegetation diversity and cover, flowing water.
H	High vegetation diversity, vegetation colour, litter amongst the reeds.
I	Marsh-like conditions.

Many of the questions used rating and ranking systems to evaluate the visual attributes of the wetland (see Appendix 1). The use of the aforementioned wetland in Hampstead Heath was desirable since it allowed the measurement of the preference value of the wetland components with respect to the enjoyment value of the visit. Thus in addition to the photographs, the public was required to view the wetland and its components, and assess its value with respect to the enjoyment of their visit to this part of the Heath.

Pretesting was conducted on people who would resemble the types of respondents to whom the final questionnaire would finally be given. Because of the intensive nature of creating the questionnaire, it is not often possible to test large numbers of people. De Vaus (1996) recommends 75 to 100 respondents for a pilot test. However a pilot test number of 30 respondents (similar number have been used in studies, e.g. Green and Tunstall, 1992; House and Herring, 1994) was used because of the length of the pilot questionnaire (30-40 minutes) and resulting time constraints. The pilot survey was carried out over two weekends in May 1994 and 30 persons visiting the area for recreational purposes were interviewed.

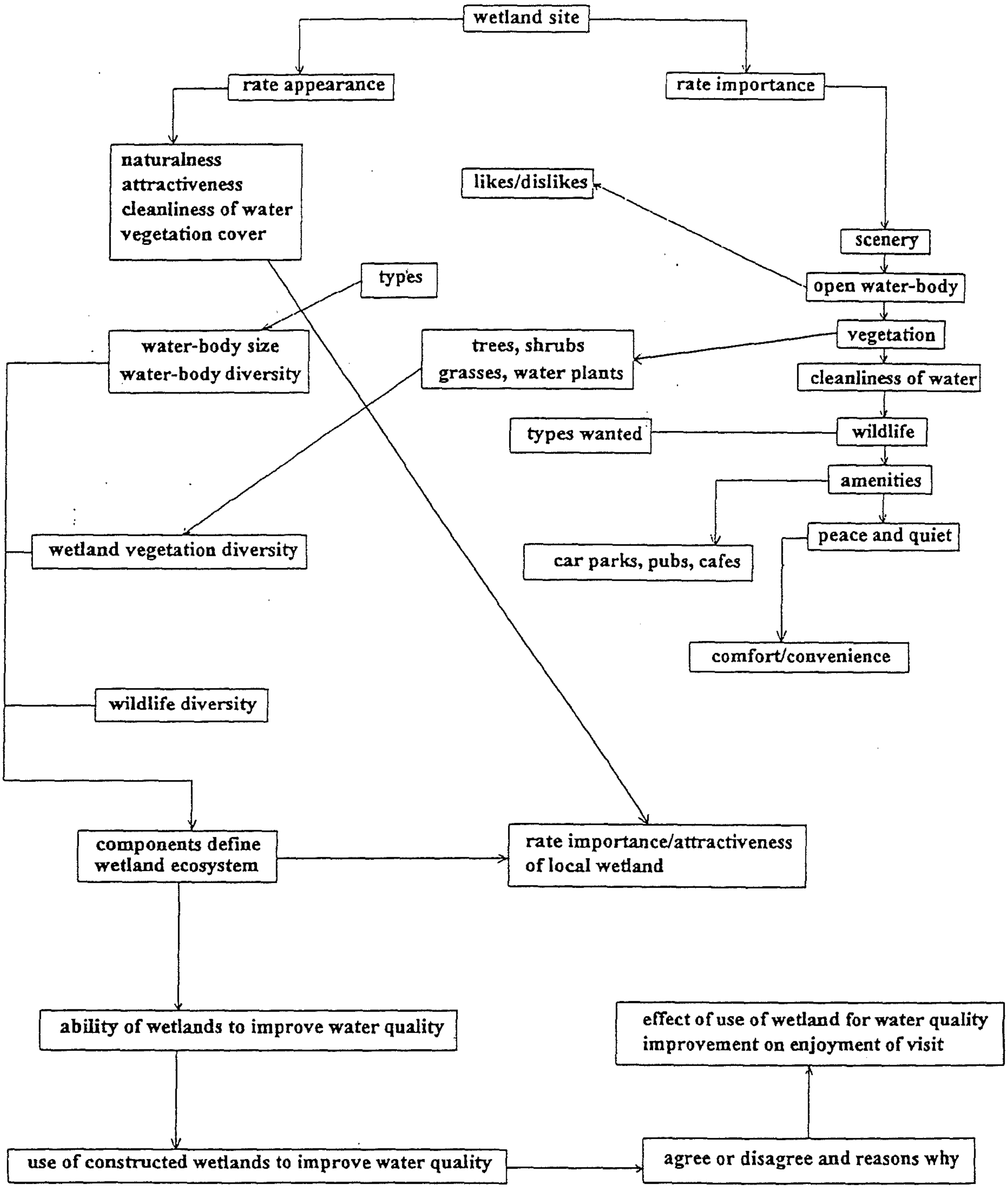


Figure 6.3 Flow diagram showing the development of the pilot questionnaire and expected inter-relationships.

Plate 7i Wetland at survey site in Hampstead Heath.

Plate 7ii Scene A.

Plate 8i Scene B.

Plate 8ii Scene C.

Plate 9i Scene D.

Plate 9ii Scene E.

Plate 10i Scene F.

Plate 10ii Scene G.

Plate 11i Scene H.

Plate 11ii Scene I.

6.4 RESULTS FROM THE PILOT SURVEY

6.4.1 General Use of Site

Walking was the main reason given for visiting the site with strolling the main form of walking undertaken. Most of the respondents (60%) visited the area regularly (once-a-week or more) but spent no more than two hours there. Those who visited less regularly were more likely to spend less than two hours in the area. 53% of the respondents were local (i.e. living within two miles of the area) and 43% were members of an environmental group (e.g. Greenpeace, Friends of the Earth, National Trust, etc.) with 53% of respondents making donations to such groups. The high environmental organisation membership suggests a degree of environmental awareness in the population sampled and thus restricts the findings of the surveys to such groups.

6.4.2 General Perception of Aesthetic and Wildlife Value of the Wetland

Respondents were asked to rate the attractiveness of the wetland landscape, its vegetation cover, the water quality and the naturalness of the wetland on a scale of 0 (very unattractive/very polluted/very unnatural) to 6 (very attractive/very clean/very natural). Most of the respondents who were interviewed found the wetland and its vegetation cover attractive (mean 4.7 and 4.5 respectively); 53% thought the water was neither very clean nor very polluted (mean 3.5); and 80% found the wetland natural-looking (mean 4.6). These results indicate that the site users interviewed were more likely to find the wetland attractive, clean and natural-looking. Crosstabulations show that respondents who visit the site at least weekly are more likely to appreciate the aesthetic value of the site.

Respondents were asked to rate twelve features of the area in terms of their importance with regard to their enjoyment of a visit on a scale of 0 ("presence not important at all") to 6 ("presence very important"). The results in Table 6.3 show the mean scores given to each feature and their ranked order of importance. The latter is based on a significant difference being recorded between the mean scores obtained for each subgroup. Table 6.3 clearly shows that those features which form parts of the natural

Table 6.3 The importance of different features in contributing to the enjoyment of a visit to Parliament Hill.

Feature	Mean scores
Absence of litter	5.6
Trees	5.2
Peace and tranquility	5.2
Scenery	5.2
Wildlife	5.0
Grasses	4.9
Clean water	4.7
Shrubs	4.6
Open water body	4.4
Water plants	4.3
Parking	2.2
Pubs and cafes	1.7

N = 30 Scale: 0 (not important at all) to 6 (very important)

Question: How important are each of the following with regard to the enjoyment of your visit at this location?

environment are considered to be of greater importance than those which relate to human activities. This indicates the importance of a clean, peaceful, natural environment with limited access and limited human activity.

Respondents were asked what types of wildlife would increase their enjoyment of a visit to the wetland at Hampstead Heath. Based on the number of like responses, the ranked order was as follows: (1) water birds (e.g. ducks and swans), (2) fish-eating birds (e.g. kingfisher), (3) land mammals, (6) insects/amphibians/pondlife and (7) water mammals. The preference for birds is to be expected since they are amongst the most visible of fauna in this type of environment. Cross-tabulations showed that regular site visitors (at least weekly) are more more likely to appreciate the wildlife value of the site.

Respondents were asked to rate 18 features which could be part of a natural environment in terms of importance placed on the presence of each within their perceived *ideal* natural setting on a scale of 0 ("not important at all") to 6 ("very important"). The results in Table 6.4 show the mean scores given to each feature and their ranked order of importance of each subgroup.

Table 6.4 Important features for ideal natural setting.

Feature	Mean score
Trees	5.4
Peace and quiet	5.3
Water birds	5.2
Diversity of flowering plants and grasses	5.0
Small birds	5.0
Water plants	4.6
Butterflies	4.4
Water mammals	4.3
Fish	4.3
Dragonflies and other insects	4.0
Frogs	3.9
Seats	3.3
Parking	3.3
Safe area for paddling and swimming	3.1
Picnic facilities	2.8
Pubs, cafés and other social activities	1.5
Provision for fishing	1.4
Provision for boating	1.1

N =30 Scale: 0 - not important at all; 6 - very important

Question: In thinking of your ideal natural setting, how important would it be for each of the following to be present?

As in Table 6.3, it is clear from Table 6.4 that respondents value features of the natural environment over those which relate to human activities and recreation with peace and quiet being very important. These results are consistent with the finding of other studies on the perception of water environments such as House and Sangster (1991).

Respondents were asked what they liked and disliked about the water-body at the wetland site with regards to the enjoyment of their visit. Based on the number of similar answers, the results are shown in Table 6.5, ranked in order of main likes/dislikes. It was clear that respondents preferred clean natural-looking open water bodies with an abundance of different types of vegetation and wildlife and an absence of human activities as also shown by House and Sangster (1991). There was a definite preference for landscape complexity in terms of vegetation type, colour and spatial heterogeneity; of structural diversity (i.e. height), as well as clarity as in uncluttered and clearly visible expanses of water (scenes E, F, G and H - Plates 9ii, 10i, 10ii and 11i) as also shown by Kaplan (1975), Levin (1977) and Lee (1978).

Table 6.5 Respondent's likes and dislikes of the open water-body at the wetland site.

Likes		Dislikes	
(1)	Diversity of flora/fauna (41.9%)	(1)	Litter/dirty water Human interference/fence/noise Lack of access (9.7%)
(2)	Naturalness (38.7%)		
(3)	Undisturbed/lack of access and fishing (35.5%)		
(6)	High aesthetic quality Tranquility/stillness Openness/reflects light (19.4%)	(4)	Lack of wildlife Low colour diversity in vegetation Low plant diversity (6.5%)
(7)	Relaxing/soothing (12.9%)	(7)	Lack of height variation in vegetation Overgrown Untidy (3.2%)
(9)	Clean Landscape diversity (6.4%)		
(10)	Breeding site for birds(3.2%)		

As expected, a quiet waterbody with natural sounds giving a sense of relaxation was preferred. However, many respondents expressed the wish to gain more access into the wetland and approach the water's edge. Cross-tabulations of variables show that regular visitors (daily/a few times a week/weekly) were more likely to notice and mention detailed likes (e.g. lack of disturbance/fishing) and dislikes (e.g. low colour diversity of vegetation, overgrown vegetation) thus indicating they were familiar with their environment. Less frequent visitors especially liked the soothing and relaxing qualities of the water-body indicating that city dwellers, getting away from urbanized areas, appreciated the peacefulness of the surroundings.

It would probably have been more useful if the questions determining the likes and dislikes of the open water-body at the wetland site had been asked before the respondents were asked to rate the important features for their ideal natural setting. This would have allowed the respondents to consider in detail what they really liked about a natural setting with an open-water body (i.e. a wetland-type environment) and thus be able to say with more assurance what they considered to be the important features for their ideal natural setting (see Table 6.4).

Respondents were next asked to rate the attractiveness of nine scenes as a place to visit on a scale of 0 (very unattractive) to 6 (very attractive) using specially chosen photographs of wetland environments (scenes A to I - Plates 7ii to 11ii). This section allowed the respondents to view a range of wetland types which were different from the Hampstead Heath wetland (Plate 7i) and thus provided a more representative idea of what a wetland was as well as information on the public's perception of each type of wetland. They were then asked to name up to two visual features they liked and disliked about each scene. The results shown in Table 6.6 show that photographs H, F, E and G (in descending order) were found to be most attractive with no very clear preference for one particular scene. This is also reflected in their mean scores which range between 4.6 and 4.2.

There is a fairly consistent pattern amongst the features or attributes the respondents liked and disliked about the nine scenes. Scenes H, F, E and G were preferred because they "looked nice" and were "natural". Hence their overall look was perceived as attractive and these scenes can be said to have a high aesthetic quality and a high level of perceived naturalness. Other frequently mentioned likes were what was perceived as the tranquility of the scene and the presence, diversity, colour variation and distribution of the vegetation. Any sign of wildlife, such as ducks, was liked. The most common dislike was any feature that indicated human interference or activity (e.g. pylons, signs, fences, boats, etc.) - particularly pylons and litter, the perceived flatness of the landscape, barren or desolate landscapes, untidyness and overgrowth of vegetation (although overgrown vegetation is can be perceived as being "natural"). These results indicated the respondents preferred natural-looking landscapes with diverse and colourful (i.e. seasonal) vegetation which varied in height and broke the monotony of a flat barren landscape (see Table 6.6).

The presence of features in the photographs indicative of human activity or interference are perceived negatively and detract attention away from the other natural attributes of the photographs. The human interference in these photographs acts as a control towards which the natural attributes can be measured. Since it was clear that they were perceived negatively and were replaced for the main questionnaire (see Section 6.5.2).

The variation in vegetation type, height and colour increased the aesthetic value of the scene and thus enhanced its interest value and evoked a sense of "mystery" (a word used to favourably describe scenes H, E and G) or the encouragement to acquire additional visual information. These results are consistent with the work done by Levin (1977) who attempted to develop a model for visual preference for riverscapes (see Section 2.9.1.4). The four factors identified as being important to visual preference (as mentioned previously) in the environment (legibility, spatial definition, complexity and mystery) are all present to certain degrees in H, F, E and G.

These results show that overgrown vegetation and perceived untidyness are disliked and underline the respondent's preference for scenes where there is some visual clarity, i.e. the various components of vegetation - colour, type, height - can be distinguished relatively clearly (legibility). The fact that the flatness and perceived desolation of the landscape was disliked while the height variation of vegetation (e.g. low shrubs juxtaposed with taller trees with overhanging branches) and the presence of the three principal wetland components (land, water and vegetation) together was preferred, indicated that the *arrangement* and *variety* of the elements or components within the landscape were important in breaking up the monotony of the landscape and introducing visual interest (spatial definition/complexity). Finally the word "mystery" was actually used to describe scenes H, E and G.

The four visual preference factors (legibility, spatial definition, complexity and mystery)

Table 6.6 Perception of the visual values of (wetland) scenes A to I.

Scene	Mean score	Likes	Dislikes
H	4.6	1) Plant colour variation 2) Aesthetically pleasing 3) Naturalness 4) Plant diversity 5) Openness/Mystery	1) Litter 2) Human interference 3) Lack of access 4) Overgrown
F	4.4	1) Openness 2) Aesthetically pleasing 3) Naturalness/Tranquil 4) Plant diversity/Clean	1) Flatness 2) Boring 3) Desolate/Lack of access
E	4.3	1) Mystery 2) Aesthetically pleasing 3) Tranquil 4) Plant height variation 5) Openness/Plant diversity	1) Aesthetically not pleasing 2) Marshy 3) Desolate/Lack of access 4) Overgrown/Dead trees
G	4.2	1) Aesthetically pleasing 2) Naturalness 3) Openness/Clean 4) Plant colour variation 5) Tranquil/Mystery	1) Flat/Boring 2) Human interference 3) Desolate/Lack of access 4) Marshy/Stagnant water
C	3.7	1) Vegetation 2) Aesthetically pleasing 3) Naturalness 4) Openness 5) Plant colour variation 6) Tranquil/Clean/Interest	1) Litter 2) Flatness 3) Human interference 4) Lack of access/Untidy 5) Boring
D	3.5	1) Aesthetically pleasing 2) Vegetation/tranquil/clean 3) Plant diversity 4) Variation in height/colour 5) Overhanging branches	1) Human interference 2) Litter/Pollution 3) Flatness/Boring
I	3.3	1) Vegetation/Colour var. 2) Aesthetically pleasing 3) Naturalness/Marshy 4) Openness/Clean	1) Overgrown 2) Marshy 3) Stagnant/Boring 4) Litter
A	2.2	1) Naturalness/Openness 2) Plant colour var/diversity	1) Human interference 2) Litter/Overgrown 3) Desolate/Barren/Stark/Flat
B	2.1	1) Wildlife 2) Naturalness/Vegetation 3) Plant diversity	1) Human interference 2) Flatness/Desolate/Boring 3) Untidy/Marshy/Overgrown

Question: What two things do you like/dislike most about each scene? (N = 30) are strongly interdependent and scenes H, F, E and G all show these characteristics to various degrees but with none of the factors actually dominating as the mean values for attractiveness for H, F, E and G (4.2-4.6) show. These findings are also confirmed by the results obtained from the use of adjectives to describe the nine scenes A to I where the respondents were asked to select three adjectives from a list of twelve that best described their feelings when asked to view the nine scenes (Table 6.7).

Table 6.7 Adjectives most chosen to describe scenes A to I in decreasing order.

Scene	Adjectives used
H	*Natural, Interesting,* Overgrown, Secluded, *Tranquil/Wilderness,* Dull, Clean
F	*Natural, Tranquil, Interesting,* Clean, *Wilderness*/Secluded/Dull
E	*Natural, Wilderness/Interesting*/Secluded, *Tranquil,* Overgrown, Clean
G	*Natural, Interesting,* Clean, *Wilderness, Tranquil,* Busy, Overgrown/Dull
C	*Natural, Tranquil, Interesting,* Secluded, Dirty, *Wilderness,* Derelict, Dull
D	*Tranquil,* Busy, Clean, *Interesting,* **Dirty**/Overgrown, *Natural*/**Boring/Dull**
I	*Natural/Interesting, Wilderness,* **Dull/Boring, Derelict, Dirty**, Secluded
A	**Dull, Derelict, Dirty, Boring,** *Natural, Tranquil,* Overgrown, Secluded,Busy
B	Overgrown, **Dull**, *Natural,* Busy, **Boring, Derelict, Dirty,** *Wilderness,* Clean

Key
Italics: adjectives used for attractive scenes.
Bold: adjective used for unattractive scenes.

The results show that certain adjectives were repeatedly used to describe the four scenes (H, F, E and G) found most attractive and found least attractive (D, I, A and B) by the respondents. Table 6.7 shows that these were *natural, interesting, tranquil* and *wilderness* and **dirty, dull, boring** and **derelict** respectively. These results are similar to the words used to describe what was liked and disliked about those same scenes.

Having assessed the public's perception of the many features that make up a wetland environment, the respondents were asked to rate the attractiveness of the site again (on a scale of 0 to 6) having this time been informed that it is an example of a *wetland* environment. Thus the aim was to assess any change in perception once the term "wetland", which traditionally has evoked a negative image (Jorgensen, 1971; Smardon, 1975), was used. In this case, the mean score of 5.0 for attractiveness of the *wetland* was a slight improvement on the initial mean score of 4.7 for attractiveness of the *location*. This indicates that, on the whole, that the respondents do not have a negative image of wetlands. The importance of the wetland environment in this area, with regards to the enjoyment of the respondent's visit, rated highly with a mean score of 5.2 on a scale of 0 to 6 whereas the importance of having access *into* the wetland received a mean score of 3.3 on the same scale. This suggests widely varying opinions and that at least half the respondents were aware that human access into the wetland would only serve to spoil its aesthetic and wildlife value although the latter result may also indicate that respondents were not very concerned about having access into the wetland.

6.4.3 Perception of the Use of Wetlands for Water Quality Improvement

The concept of using wetlands to improve water quality was introduced by means of a simple explanation used in conjuction with a visual aid (Figure 6.4). The explanation was worded as follows:

"Contaminated water often passes through wetlands before entering rivers and lakes. Wetland systems can improve water quality by filtering out, trapping and breaking down pollutants found in the water. Thus wetlands can prevent certain pollutants from entering the natural environment."

The respondents were then asked if they would be in favour of using specifically constructed wetlands to improve water quality using a scale of -3 (strongly not in favour of) to 3 (strongly in favour of). The mean score of 2.7 indicates a highly favourable response. Reasons for their answers are shown in Table 6.8.

Reasons 1, 2 and 3 made up 75% of all the responses and showed that the use of constructed wetlands to improve water quality was perceived as being a natural and beneficial way to treat wastewater. The only reservations came from 5% of the respondents who felt they needed more information about this method and one respondent expressed concern over the effects of the pollutants, which would be trapped

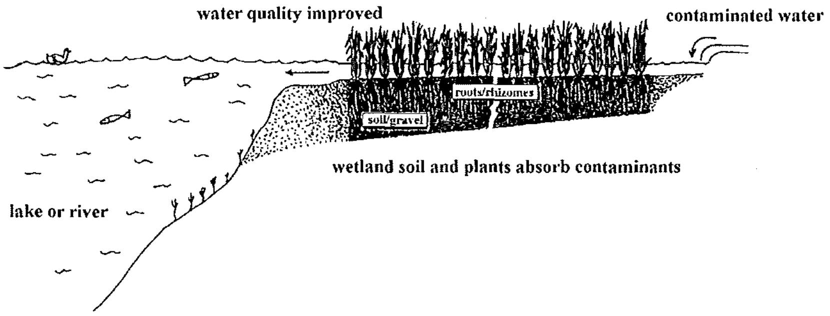


Figure 6.4 The visual aid used to help explain the concept of using wetlands to improve water quality.

in the wetland, on the flora and especially fauna of the wetland.

Finally, the respondents were asked if the use of the wetland at the site where the interviews were taking place for improving water quality would lessen their enjoyment of a visit to the site using a yes/no scale. Out of the 30 respondents interviewed, only one respondent said such a use of the wetland would lessen their enjoyment.

These results suggest that whilst there would be a favourable response to the use of wetlands for water quality improvement, background information must be provided to ensure the public understands what exactly is involved and also to allay whatever

Table 6.8 Reasons stated to justify feelings to use of constructed wetlands to improve water quality.

Rank	Reasons given
(1)	"Good for the natural environment/eco-friendly"
(2)	"Good for the water quality"
(3)	"Treatment method is natural"
(4)	"Nice way to clean water/aesthetically pleasing"
(6)	"Method encourages flora/fauna to thrive" "Need more information about this method"
(7)	"Method is low cost"
(8)	"Concern over effects of pollutants on life cycles"

concerns they may have.

6.4.4 Conclusions from the Pilot Survey

Several conclusions can be drawn from this pilot study and many of them are consistent with past studies on visual preference in the landscape (Levin, 1977). The main conclusions drawn are as follows:

(1) Respondents visit the site principally for the purpose of walking. Respondents who visit the site regularly (at least weekly) are more likely to appreciate the aesthetic and wildlife value of the site. Birds are the type of wildlife most preferred.

(2) Features which form part of the natural environment are considered to be of greater importance than those which relate to human activities. Peace and quiet and cleanliness receive high preference values.

(3) Perception of wetland visual attributes show that there is a definitive preference for factors which can be summarized as diversity and complexity (i.e. the order and structure apparent in the landscape) and involvement or interest factors in the landscape (Kaplan, 1973; 1975, Newby, 1971 and Wohlwill, 1966). These evaluative factors are strongly interdependent and highly interrelated (Levin, 1977).

(4) The use of the word "wetland" does not evoke a negative image.

(5) While there is a favourable response to the use of wetlands for water quality improvement, background information must be provided to ensure the public understands what is exactly involved and to also allay whatever concerns they may have.

Respondents had relatively little problem answering the questionnaire and most of them found the topics interesting and illuminating; especially the section concerning the use of constructed wetlands for water quality improvement. So overall the questionnaire worked well. However, certain sections and questions did not work and were changed, restructured or omitted to fulfill the objectives of the main survey (see Section 6.5.1). The photographs were replaced with more suitable ones (see Section 6.5.2). Overall the procedure of implementing the survey itself was fairly effective.

6.5 THE MAIN SURVEY

6.5.1 Introduction

The primary objectives of the survey questionnaire were to provide information on:

- the public's perception of wetlands by focusing on visual-cultural values linked to the use of wetlands for recreation and amenity;
- how this relates to their perception of, and attitude towards, the use of wetlands for wastewater treatment; and
- how this will provide guidelines to wetland construction for urban runoff treatment.

The secondary objective was to investigate factors influencing these perceptions: the purpose, frequency and length of their visit(s) to the location; and demographic information concerning the respondents gender, age and status.

6.5.2 Changes Made for the Main Survey

The pilot questionnaire rated the appearance of an actual wetland at the Hampstead Heath site and the importance of the visual attributes of the wetland as well as those of 9 wetland scenes demonstrated in photographic form. This allowed the measurement of the factors that made the wetland attractive (or unattractive).

The next step was to determine if there was a correlation between the visual attributes and the attractiveness of a series of photographs of wetland environments or scenes as a place to visit (i.e. how important were each of the visual attributes to the visual preference of each wetland scene). Thus the section of the questionnaire assessing wetland visual perception was reduced to questions rating the visual attributes only. This shortened the questionnaire thus saving time.

The number of photographs used was reduced to eight (Scenes A to H - Plates 12i to 15ii) since the chosen eight showed all the visual attributes being investigated satisfactorily. This also helped reduce the length of the questionnaire. All the photographs used in the pilot survey (except for scene G) were replaced by other photographs of wetland environments.

The pilot survey showed that the presence of features in the photographs indicative of human activity or interference were perceived negatively and probably detracted attention away from the natural attributes of the wetland landscapes depicted in the photograph (see Section 6.4.2). These scenes (A, B and D - Plates 7ii, 8i and 9i) were instead replaced with photographs of three constructed wetlands which ranged from very artificial to fairly natural in appearance (see scenes C, F and G - Plates 13i, 14ii and 15i). These scenes were included in the main survey to assess the public's perception of constructed wetlands in practice (i.e. visually) as well as in theory (Section 6.6.6). Furthermore, the initial respondent perception of these three wetlands could then be retested in the final section of the questionnaire when it became clear they were all constructed for water quality improvement. Scene B was also replaced because the presence of the birds also detracted attention from the other features of the scene.

Scene C (Plate 8ii) in the pilot was not well lit and was replaced with scene H (Plate 15ii). Scene E (Plate 9ii) in the pilot was replace by scene E (Plate 14i) which demonstrated a greater sense of mystery. Scene F (Plate 10i) in the pilot was replaced with scene B (Plate 12ii) since the latter portrayed more detail of vegetation as well as a large water body. Scene G from the pilot was retained (Plate 10ii) and this became scene D in the main survey (Plate 13ii). The colour diversity in scene H (Plate 11i) in the pilot was a strong positive feature and may have detracted from other features. It was replaced by scene A (Plate 12i) which was less colourful but demonstrated more visual attributes such as water/land contrast and enclosure of water by vegetation (see Section 6.5.3). Scene I (Plate 11ii) in the pilot was not used in the main survey. The main features of the eight scenes used in the main survey (i.e. the reasons why these photographs were selected) are described in Table 6.9.

Table 6.9 The main features of scenes (Scenes A to H - Plates 6i to 9ii) used in the main survey.

Scene	Main features (Reasons why photographs were selected for the main survey)
A	High vegetation diversity with variable contrast with water. High shoreline complexity with vegetation height variation giving a sense of enclosure and mystery.
B	Water contrasts strongly with land/vegetation and results in low shoreline complexity. Large expanse of water gives a feel of uniformity and impression of artifice (e.g. a reservoir).
C	Artificial structure with strong water/land contrast. Fairly high vegetation diversity. Low interest value and no sense of enclosure and mystery.
D	Low lighting gives impression of overgrown, tangled vegetation. Trees in the background and on the edges give a sense of enclosure. Flowing water.
E	Low water/land/vegetation contrast. Overhanging branches and low lighting give a strong sense of mystery. Reflections of vegetation in the water also give a sense of enclosure. Natural looking.
F	Components of land, water and vegetation easily discernable. Lack of vegetation height variation and low vegetation diversity monotonous and artificial. Artificial structure (outflow channel on the right) fairly well hidden.
G	High vegetation diversity, shoreline complexity and interest value. Artificial outflow structure prominent. Still water body.
H	Good water/land/vegetation contrast. Fairly high vegetation diversity.

The questions in the pilot questionnaire that measured features that contributed to the enjoyment of a visit and the important features for an ideal natural setting (Tables 6.3 and 6.4) predictably showed that the features which formed part of the natural environment were of far greater importance than those which related to human activities. Thus there was little additional value in further investigation of these variables and these questions were dispensed with to save time. Instead, attitudes to the actual uses of wetlands were measured since this section incorporated the use of wetlands for water qality improvement and thus introduced this topic to the respondent. The measure of the likes and dislikes of wetland scenes (Table 6.6) was unnecessary since the perception of the factors that determine visual preference and attractiveness were to be measured. The use of adjectives (Table 6.7) was also dispensed with since this proved to be the most unpopular and time-consuming section of the pilot questionnaire with the respondents and also because their perception of wetland visual attributes were to be comprehensively measured in the new questionnaire.

The perception of the use of wetlands for water quality improvement was expanded to include perception of the use of natural wetlands for water quality improvement, as well as the use of specifically constructed wetlands, and the aforementioned photographs of the three constructed wetlands. The latter linked in with the initial rating of the photographs early in the questionnaire and thus allowed changes in the perception of constructed wetlands to be assessed once it was clear what their function really was.

As a result of all the changes made, the main questionnaire (Section 6.5.3, Figure 6.4 and Appendix 2) flowed better, was less repetitive and thus less tedious and took less time per interview - 20 to 25 minutes as opposed to 30 to 40 minutes for the pilot questionnaire. Informal pretests were carried out on the questionnaire with the help of colleagues.

Plate 12i Scene A.

Plate 12ii Scene B.

Plate 13i Scene C.

Plate 13ii Scene D.

Plate 14i Scene E.

Plate 14ii Scene F.

Plate 15i Scene G.

Plate 15ii Scene H.

6.5.3 Design of the Main Questionnaire

The main questionnaire (Appendix 2) was designed with three separate research aims.

The first aim was to establish the relationship (if any) that existed between the visual attributes and the attractiveness or preference ratings. Thus photographs of natural and constructed wetlands (scenes A to H - Plates 12i to 15ii) were carefully chosen to allow the measurement of the following visual attributes: vegetation variety, contrast between water and the surrounding land, naturalness, shoreline clarity, interest value, vegetation openness, inclination to enter/explore the scene, enclosure of water by vegetation and amount of human activity. Statistical comparison of the measurements of these visual attributes with the preference value of each scene as a place to visit would thus determine if a significant correlation existed between them.

Having measured the influence of the visual attributes, the next step was to measure the socioeconomic benefits of wetlands or uses of wetlands that could possibly affect the perception of wetlands, including the use of wetlands for water quality improvement, using appropriate questions. Assessment of the wildlife value of wetlands was then carried out by measuring the importance of wildlife and what types of wildlife would contribute to the enjoyment of a visit to a wetland-type environment.

Finally the perception of the use of wetlands for water quality improvement was assessed. This section of the questionnaire included testing and re-testing with the use of more coded and open questions to assess changes in attitudes or perception towards wetlands.

Thus the questionnaire was designed in such a way that each section built upon the information derived from the previous section. Figure 6.5 shows a flow diagram of the development of the main survey questionnaire and the expected inter-relationships and Table 6.10 shows the variables that were measured.

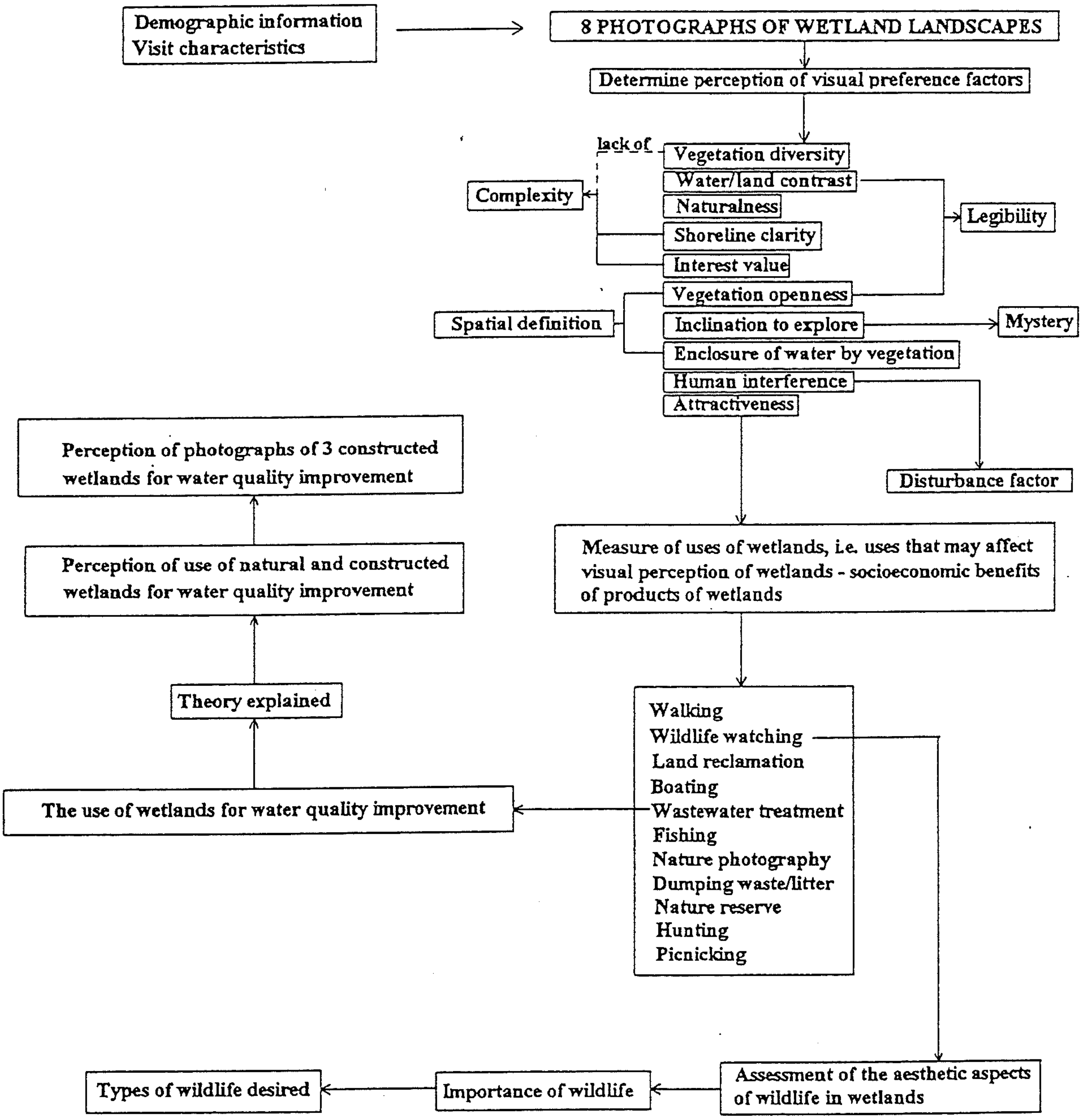


Figure 6.5 Flow diagram showing the development of the main questionnaire and the expected inter-relationships.

The questionnaire was divided into the following categories as shown in Figure 6.5:

- General use of site (see Section 6.2.4).
- Club membership (see Section 6.2.4).
- Elements of wetland environments. This section used photographs to assess the respondents perception of the following nine visual attributes which, in combination, indicate the overall preference (or attractiveness) of a scene:

  (1) vegetation diversity,
  (2) the contrast between water and land,
  (3) how natural or artificial the scene appeared,
  (4) the clarity of the water's edge,
  (5) how interesting the scene was,
  (6) how open did the vegetation appear,
  (7) did the appearance of the scene make the respondent want to explore the site further,
  (8) how enclosed was the water by the vegetation, and finally
  (9) how much human interference did there appear to be.

  The attractiveness of each scene as a place to visit was rated separately so that the attractiveness ratings could be correlated with the ratings of the above attributes.

- Uses of wetland environments. The socio-economic benefits of main products of wetlands were evaluated next - the use of wetlands for walking, wildlife watching, land reclamation, boating, wastewater treatment, fishing, nature photography, dumping waste/litter, as a nature reserve, hunting and picnicking.
- Aesthetic aspects of wetlands. Following on from the measure of the use of wetlands for wildlife watching, this section measured the importance of wildlife and the types of wildlife deemed important for enjoyment of a visit.

Table 6.10 Variables measured as part of perception studies.

Use of site	Reason for being there (Q.1) Frequency of visit (Q.2) Time spent there (Q.3) Distance travelled to get there (Q.4)
Club membership	Members of/donate to any environmental /recreational clubs (Q.5)
Visual attributes of each scene	Vegetation diversity (Q.6) Contrast between water and land (Q.7) Naturalness (Q.8) Clarity of water's edge (Q.9) Interest value (Q.10) Vegetation openness (Q.11) Inclination to explore (Q.12) Enclosure of water by vegetation (Q.13) Amount of human interference (Q.14) Attractiveness (Q.15)
Uses of wetlands	Hiking and strolls Wildlife watching Land reclamation Boating Nature photography Dumping waste/litter Fishing Nature reserve Bird watching Picnicking (All Q.16)
Aesthetic aspects of wildlife	Importance of wildlife (Q.17) Types of wildlife deemed important (Q.18)
Wetlands for water quality improvement	Use of natural wetlands (Q.19,20) Use of constructed wetlands (Q.21,22) Assessment of scenes of constructed wetlands (Q.23)
Respondent information	Gender (Q.24) Age (Q.25) Employment status (or otherwise) (Q.26, 27)

- Use of wetlands for water quality improvement. Following on from the measure of the use of wetland for wastewater treatment, this section explained how wetlands could improve water quality with the help of a visual aid (Figure 6.3) and measured what the respondents thought of using natural and constructed wetlands for water quality improvement and the reasons for their respective answers as well as their thoughts on photographs of actual constructed wetlands.

- Respondent information (see Section 6.2.4).

6.6 RESULTS FROM THE MAIN SURVEY

6.6.1 Introduction

The target number of 300 questionnaires was almost reached with a total of 284 questionnaires completed. Up to three interviewers undertook the interviews between May and August 1995, with an average interview time of 25 minutes per questionnaire. The interviewers were positioned in the same area where the pilot survey was undertaken since it was convenient for interviewing purposes. This area overlooked an actual wetland with wildlife (a variety of water birds, terrapins) and thus attracted visitors as well as giving the respondents a good example of a wetland landscape.

The same criteria used to select the respondents for the pilot survey were used for the main survey (see Section 6.2.2.3).

6.6.2 Demographics and Visit Characteristics

6.6.2.1 Gender, Age and Vocation

An almost equal split of respondents between males (50.2%) and females (49.8%) was obtained. 46.1% of respondents were from the 26 to 44 years age group, 28.4% from the 45 to 64 years age group and the remaining 25.5% were fairly evenly distributed between the 18 to 25 and over 64 years categories. 58.7% of all respondents were in some form of employment (Table 6.11) with 11.9% working in some form of administration, 11.9% in the arts and over 10% working in sales or in education.

6.6.2.2 Characteristics of Visits and Residency

Walking was the main reason given for visiting this area of the Heath by 84% of the respondents with strolling (38.4%) the main form of walking being undertaken while 9.6% of the respondents were on a nature ramble (Table 6.12). 66.5% of the respondents were relatively local, i.e. living within two miles of the area (Table 6.13). Respondents who visited less frequently (21.5% visit monthly or less) were more likely to spend more time on site (40.1% spend over 2 hours in the area) (Tables 6.14 and 6.15 respectively). The response to the question on club and society membership revealed that 58.1% of respondents did not belong to any user or environmental groups (Table 6.16).

The relative importance of these demographic and visitor characteristics to the public's perception of wetlands is discussed in Section 6.6.3.6.

Table 6.11 Demographic characteristics of the respondents.

Gender	Female	141
	Male	142
N		283
Age	18 - 24 Years	42 (14.9%)
	26 - 40 Years	130 (46.1%)
	45 - 64 Years	80 (28.4%)
	>64 Years	30 (10.6%)
N		282
Are you currently...	in full-time employment	129 (45.6%)
	in part-time employment	37 (13.1%)
	unemployed	26 (9.2%)
	retired	39 (13.8%)
	student	28 (9.9%)
	other	24 (8.5%)
N		283
If employed (full-time or part-time), what type of work do you do?	Marketing/Sales	18 (11%)
	Management/Finance	16 (9.8%)
	Teaching/Lecturing	17 (10.4%)
	Artist	19 (11.9%)
	Community Care	13 (7.9%)
	Administration/Clerical	19 (11.9%)
	Science/Engineering	8 (4.9%)
	Health Profession	14 (8.5%)
	Technical Work	9 (5.5%)
	Writing	7 (4.3%)
	Law	5 (3%)
	Media	5 (3%)
N	Miscellaneous	14 (8.5%)
		164

Table 6.12 Main reason for being in the area.

Reason	Frequency
Walking the dog	57 (20.3%)
Walking the children	12 (4.3%)
Strolling	108 (38.4%)
Walking 2 miles or more	59 (21%)
Cycling	8 (2.8%)
Picnicking	10 (3.6%)
Nature ramble	27 (9.6%)
N	281

Question: Which of the following is your main reason for being here today?

Table 6.13 Distance travelled to reach site.

Distance	Frequency
< 1/2 mile	73 (25.7%)
1/2 - 1 mile	46 (16.2%)
> 1 - 2 miles	70 (26.4%)
> 2 miles	95 (33.5%)
N	284

Question: How far did you travel to get here today?

Table 6.14 Frequency of visits to site.

Frequency	n
At least daily	55 (19.4%)
At least a few times a week	75 (26.4%)
At least weekly	61 (21.5%)
At least fortnightly	32 (11.2%)
At least every month	34 (12%)
At least 5 to 11 times a year	13 (4.6%)
Yearly or less often	6 (2.1%)
Never been here before	8 (2.8%)
N	284

Question: How often on average do you come here or other similar open spaces?

Table 6.15 Amount of time spent at site.

Time	Frequency
0 - 15 minutes	2 (0.7%)
16 - 30 minutes	13 (4.6%)
31 - 60 minutes	38 (13.4%)
1 - 2 hours	117 (41.2%)
2 - 3 hours	70 (24.6%)
3 - 4 hours	30 (10.6%)
> 4 hours	14 (4.9%)
N	284

Question: How much time do you plan to spend here today?

Table 6.16 Club and Society Membership.

Club/Society/Group	n
Angling club or association	6
Canoeing club	4
Rambling club	7
Bird watching society	3
Rowing club	3
Friends of the Earth	24
Local or county wildlife trust	5
National Trust	44
Greenpeace	25
Royal Society for the Protection of Birds	17
Council for the Protection of Rural England	9
Civic or community association	4
World Wide Fund for Nature	18
Other environmental or recreational groups	29
None	165

N = 284; Multiple response question - Totals >100% possible.

Question: Do you belong to any of the following clubs, societies or groups?

6.6.2 Methods Used to Assess Visual Preference of Wetland Landscapes

The assessment and explanation of visual preference for wetland landscapes was carried out in two parts (Table 6.17):

1) Assessment and explanation of wetland landscape preference by the visual attributes (Section 6.6.3):

- Looking at the mean scores obtained by each scene for each of the visual attributes factors (Section 6.6.3.1).
- Investigating correlations between two variables (e.g. attractiveness of a scene and each of the nine visual attributes) using statistics based on rank (Section 6.6.3.1) and determining the significance of the correlations[1]. The results will aim to provide a model for the visual preference of wetland landscapes (Section 6.6.3.3).
- Applying factor analysis to the visual attributes to identify the attributes that can explain wetland preference (Section 6.6.3.5).

2) Explanation of wetland landscape preference by respondent type and respondent characteristics:

- Looking for any relationships between visual preference and respondent characteristics using factor scores (which shows how much weight is attributed by the respondent to each factor), t-tests and crosstabulations - thus see if differences between respondents explain visual preferences (Section 6.6.3.6).

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[1] Measures of correlation and their tests of significance (Section 6.6.3.2): How two sets of scores are related and the degree of their relation can be established using measures of correlation. These statistical tests determine the probability associated with the occurrence of a correlation as large as the one observed in the sample under the null hypothesis that the variables are unrelated in the population. Thus these statistical tests determine the *significance* of the observed association (Siegel, 1956).

Thus the aim was to attempt to explain the preference value of scene A to H (defined by their attractiveness rating) by each of the nine visual attributes listed on the right of Table 6.17 and by each of the ten respondent characteristics/information listed on the left of Table 6.17 respectively.

Table 6.17 Analytical method for assessment of visual preference for wetland landscapes.

Evaluation of preference* of scenes A to H by respondent type		Wetland scenes	Evaluation of preference* of scenes A to H by nine visual attributes
Site usage	-Reason for being there	A to H	Vegetation diversity (Complexity)
	- Frequency of visit		Water/land contrast (Legibility)
	- Time spent there		Naturalness (Disturbance factor)
	- Distance travelled		Shoreline complexity (Complexity)
Group membership			Interest value (Complexity)
Demographic information	- Gender		Vegetation openness (Legibility/Spatial Definition)
	- Age		Inclination to explore (Mystery)
	- Employment status		Enclosure of water by vegetation (Spatial Definition)
	- Type of employment		Degree of human activity (Disturbance factor)

Key:

* Preference defined by attractiveness of each scene.

( ): Visual attributes are grouped into respective visual preference factors.

The ultimate aim of this part of the study was to develop a model for the prediction of visual preference of wetland landscapes. The predictive model would predict what types of visual attributes (and thus visual preference factors) would be preferred by the public when they viewed wetland landscapes. Past studies on the visual preference of river landscapes (Lee, 1978; Levin, 1977; Smardon, 1983) have shown the landscapes preferred by respondents rate highly in terms of legibility and complexity of the landscape components of water, land and vegetation, enclosing or space-defining elements (spatial definition), feeling of mystery or anticipation and lack of human disturbance. These visual factors are all found in wetland landscapes and it was theorized that the highest ranking or most preferred wetland scene would possess a good mix of these vital factors since for a scene to be of superior visual quality, it must maintain a mix or balance of factors - one factor cannot dominate the others.

However, wetlands tend to have a wide variety of vegetation-types (macrophytes, trees, shrubs, grasses, mosses, etc.) which enhance the complexity of the scene. The density and varied morphology of the vegetation serves to reduce vegetation legibility since the plants all grow in the same vicinity and thus obscure individual plant forms and internal vegetative structures like tree limbs and trunks. The lack of visibility (and thus legibility) is a characteristic of wetland landscapes and assumed to be a virtue in wetland preference.

Based partly on studies of the visual preference of river landscapes, it was theorized that a model wetland landscape would have the following visual factors: low legibility, high complexity, significant enclosing or space-defining elements, a sense of mystery creating anticipation as to what lies beyond the obscured parts of the wetland, and finally, a definite lack of human disturbance or activity (as shown by the results of the pilot study in Section 6.4.2). The assumption is that these visual factors explain the visual preference (defined for the purposes of the study as attractiveness of a landscape as a place to visit) of a scene and the assumptions were tested as follows.

The nine visual attributes defining the visual preference factors of legibility, complexity, spatial definition, mystery and disturbance factors (see Table 6.10 and 6.17) were explored and analysed with respect to the overall preference by the respondents for each of the eight wetland scenes (defined by how attractive it was as a place to visit) A to H (Plates 12i to 15ii) which each showed some of the visual attributes investigated (see Section 6.5.3 and Table 6.9). It was thus theorised that the visual attributes which correlated significantly with the attractiveness ratings of the eight wetland scenes would be valuable in the prediction of wetland visual preference.

The ultimate aim of this section of the study would be for the model predicting visual preference to be incorporated into future design criteria for the construction of wetlands for water quality improvement.

6.6.3 Results From the Assessment of Wetland Preference for Wetland Landscapes

6.6.3.1 The Mean Scores of the Visual Attributes of each Wetland Scene

The respondents were asked to look at eight photographs (scenes A to H - Plates 6i to 9ii) and rate the nine visual attributes on a scale of 1 to 5, and the attractiveness of each scene as a place to visit on a scale of 0 to 6. The respondents were given a wider range scale for this question since they were more likely to have stronger opinions on the attractiveness of a scene as a place to visit than on some of the visual attributes. Thus they could easily pick a score from a wider range of responses. The results are presented in the form of mean scores in Tables 6.18 to show how each visual attribute rated for wetland scenes A to H. Table 6.19 shows the range of the mean scores recorded for each visual attribute. This provides an indication of which attributes gave the widest range of responses.

Table 6.18 shows that there is generally little difference in the mean scores between the top five or six ranked scenes. The greatest differences are between the highest ranked scenes (generally scenes A and E) and the lowest ranked scenes (generally scenes C and F). Table 6.19 shows that the visual attributes with the widest range of mean scores from the eight scenes are, not suprisingly, the lack of human interference in a scene and the naturalness of the scene. This is consistent with the results of the pilot study whereby features of an environment that relate to human activity are regarded as least important to the enjoyment of a visit (Section 6.4.2). These wide ranges are also to be expected since these features prominently distinguish between the constructed wetlands and the more natural wetlands. The lower range of mean scores for some of the visual attributes such as vegetation diversity or inclination to explore the scene (Table 6.18)

Table 6.18 Mean scores per variable measured per scene ranked in descending order.

Variable	Vegetation diversity (1 = not varied at all; 5 = very varied)							
Scene	G	E	A	D	C	H	B	F
Mean	3.82	3.61	3.58	3.58	3.51	3.48	2.99	2.63
Variable	Lack of discernable contrast between water and land (1 = a lot of constrast; 5 = no contrast at all)							
Scene	E	G	F	A	D	C	H	B
Mean	3.40	2.89	2.84	2.69	2.52	2.28	2.20	2.11
Variable	Naturalness (1 = very artificial; 5 = very natural)							
Scene	E	A	D	H	B	G	F	C
Mean	4.55	4.36	4.18	4.11	3.98	3.13	2.62	1.29
Variable	Shoreline clarity (1 = very clear; 5 = not clear at all)							
Scene	E	A	G	F	D	H	B	C
Mean	3.89	3.01	2.89	2.52	2.22	2.09	1.75	1.63
Variable	Interest value (1 = very uninteresting; 5 = very interesting)							
Scene	E	A	D	H	G	B	C	F
Mean	3.96	3.71	3.59	3.53	3.36	3.23	2.94	2.36
Variable	Lack of vegetation openness (1 = very open; 5 = not open at all)							
Scene	E	A	D	B	G	H	C	F
Mean	4.00	3.29	2.78	2.60	2.58	2.57	2.28	2.05
Variable	Inclination to explore scene (1 = not at all; 5 = very much)							
Scene	E	A	D	H	G	B	C	F
Mean	3.78	3.49	3.41	3.36	3.30	3.16	2.59	2.28
Variable	Enclosure of water by vegetation (1 = not enclosed at all; 5 = very enclosed)							
Scene	E	G	C	F	A	D	H	B
Mean	4.05	3.65	3.16	3.16	3.15	2.82	2.66	2.25
Variable	Lack of human interference (1 = a lot of interference; 5 = none at all)							
Scene	E	A	D	H	B	G	F	C
Mean	4.53	4.41	4.17	3.94	3.74	2.59	2.47	1.17
Variable	Attractiveness (0 = very unattractive; 6 = very attractive)							
Scene	E	A	H	D	B	G	C	F
Mean	4.30	4.01	3.94	3.76	3.60	3.37	2.06	2.04

Table 6.19 Range of mean score per visual attribute.

Visual Attribute	Range of Mean Scores	Difference in Ranges
Lack of human interference	1.17-4.53	3.36
Naturalness	1.29-4.55	3.26
Attractiveness	2.04-4.30	2.26
Shoreline clarity	1.63-3.89	2.16
Lack of vegetation openness	2.05-4.00	1.95
Enclosure of water by vegetation	2.25-4.05	1.80
Interest value	2.36-3.96	1.6
Inclination to explore scene	2.28-3.78	1.50
Lack of discernable contrast between water and land	2.11-3.40	1.29
Vegetation diversity	2.63-3.82	1.19

indicate that there are less widely varying opinions for these variables. The importance or weight carried by each visual attribute with respect to the attractiveness of a scene is discussed next in Section 6.6.3.2.

6.6.3.2 Developing the Model for the Prediction of Visual Preference of Wetland Landscapes

In addition to the mean scores of each visual attribute shown in Table 6.18, Table 6.20 shows the method used to analyse the eight wetland scenes. Table 6.20 shows a sample rating for *one respondent* whereby the highest attainable score for each visual attribute for a particular scene (e.g. scene A) was 5 and the lowest, 1. Thus in this example, the respondent thought scene A had a high vegetation diversity (a score of 4), low shoreline clarity (a score of 1), a high interest value (a score of 5), etc. The mean scores ascribed to the visual attributes were additionally used to calculate a numerical average, termed an *assessment ratio*, for each of the wetland scenes. This was calculated as the sum of the mean scores ascribed to each of the nine visual attributes divided by 45, the highest sum of the ratings (i.e. 5, the most positive response for each attribute, multiplied by 9, the total number of attributes). By examination of the assessment ratios of the wetland scenes, it was possible to see how preference of the wetland scenes varied

Table 6.20 Evaluative model system used to rate wetland scenes showing a sample rating for one wetland scene.

Visual Variable	Visual Preference Factor	Rating Scale 1*	2	3	4	5**	Rating
Complexity	Vegetation diversity				X		4
Complexity	Shoreline clarity	X					1
Complexity	Interest value					X	5
Legibility	Water/land constrast		X				2
Spatial definition /legibility	Vegetation spacing /clarity	X					1
Spatial definition	Enclosure of water by vegetation			X			3
Mystery	Inclination to explore scene				X		4
Disturbance Factor	Naturalness		X				2
Disturbance Factor	Human interference			X			3
	Total Points						25
	Total Possible Points						45
	Assessment Ratio***						0.555

* The lowest score indicates the most negative response.
** The highest score indicates the most positive response.
*** The assessment ratio ranges from 0 to 1 (very unattractive to very attractive).

Note:
Total points = Sum of ratings for all factors.
Total possible points = Number of factors rated × 5.
Assessment ratio = Total points ÷ Total possible points

based on the combination of the visual attributes. The calculated assessment ratios ranged between 0.463 and 0.627 for the constructed wetlands (scenes C, F and G - Plates 13i, 14ii and 15i) and 0.574 to 0.795 for the natural wetland scenes (Table 6.21). Table 6.22 shows the rankings of the wetland scenes by their assessment ratios.

Table 6.21 Assessment ratio of each wetland scene.

Wetland scene	A	B	C	D	E	F	G	H
(1) Total points	31.69	25.81	20.85	29.27	35.77	22.93	28.21	27.94
(2) Total possible points	45	45	45	45	45	45	45	45
Assessment ratio (1÷2)	0.704	0.574	0.463	0.650	0.795	0.510	0.627	0.621

Note:

Sum of ascribed mean ratings = Sum of the ascribed mean ratings for the nine visual attributes for each scene (derived from Table 6.18).

Maximum rating possible = N(Variables) × Highest rating

= 9 × 5

= 45

Table 6.22 Ranking of the wetland scenes by their assessment ratios.

Rank	1	2	3	4	5	6	7	8
Scene	E	A	D	G	H	B	F	C

Scene E is ranked first and is thus the most preferred scene whereas C, ranked eighth (last) is the least preferred scene.

Using this form of analysis in the development of a predictive model of public preference for wetland landscapes ensures that the combinations of the various visual attributes are accounted for by the model rather than the influence of one attribute being allowed to dominate. This is important as it is hypothesized that the combination of visual attributes are more significant in the prediction of preference than the analysis of a single attribute (Lee, 1978). Thus, through the analysis of the individual attributes relevant to visual preference, it is possible to gain an understanding of what constitutes the overall impression of a view and ultimately, the positive or negative perception of that view.

The next step in the development of the model was to validate the results by seeing how well the calculated assessment ratios correlated with the ascribed mean ratings for the attractiveness of each of the eight scenes (i.e. test the assumption that attractiveness can be explained by the visual attributes; see Section 6.5.2). Thus the final stage in the development of the predictive model of wetland landscape preference required the determination of the importance of each of the individual visual attributes to the overall rating of the attractiveness of each of the wetland scenes.

For this purpose the wetland scenes were placed in rank order based on the calculated assessment ratios with a ranking of 1 indicating the highest preference value and 8 indicating the least preference value (Table 6.22). The rankings for the attractiveness variable and the nine visual attributes were statistically compared to determine if there were any significant correlations between them using the Kendall rank correlation coefficient (τ - tau) - a statistic based on rank - which was used to analyse the degree of agreement between attractiveness of each wetland scene and firstly, the combination of the visual attributes. Finally the correlations were tested to determine which attributes were most statistically significant. The method used to determine the correlations is described in Appendix 3 (multiple regression analysis, which would use the actual scores rather than the derived ranks, may give more accurate information).

6.6.3.3 Model for the Prediction of Visual Preference for Wetland Landscapes

The results in Table 6.23 show that the visual attributes which correlate strongest with attractiveness (i.e. high ratings for these factors for a given scene are likely to indicate that the respondents find said scene attractive) are the naturalness and interest value of the scene, the respondents' inclination to explore the scene, the lack of human interference in the scene and the lack of vegetation openness (or spacing/clarity) in that scene. The next step was to test the significance of these correlations using the null hypothesis to determine which factors were most statistically significant.

The null hypothesis (H_0) is a hypothesis of no difference which is usually formulated for the express purpose of being rejected. If rejected, an alternative hypothesis (H_1) may be accepted. Thus H_1 is the operational statement of the experimenter's research hypothesis and the research hypothesis is the prediction derived from the theory under

Table 6.23 Comparison of rankings for each visual attribute and the Kendall rank coefficient between attractiveness and each of the 9 other visual factors.

Scene	E	A	H	D	B	G	C	F	τ
Visual attribute									
Attractiveness	1	2	3	4	5	6	7	8	n/a
Naturalness	1	2	4	3	5	6	8	7	0.85
Interest value	1	2	4	3	6	5	7	8	0.85
Inclination to explore scene	1	2	4	3	6	5	7	8	0.85
Lack of human interference	1	2	4	3	5	6	8	7	0.85
Lack of vegetation openness	1	2	6	3	4	5	7	8	0.78
Vegetation diversity	2	3	6	4	7	1	5	8	0.42
Shoreline complexity	1	2	6	5	7	3	8	4	0.42
Lack of discernable contrast between water and land	1	4	7	5	8	2	6	3	0.14
Enclosure of water by vegetation	1	5	7	6	8	2	3	4	0.07
All 9 above factors	1	2	5	3	6	4	8	7	0.71

test (Siegel, 1956).

There are two types of errors which may be made in arriving at a decision about H_0. The first, the Type I error, is to reject H_0 when it is in fact true. The second, the Type II error, is to accept H_0 when it is in fact false. The probability for a Type I and Type II error are denoted by α and β respectively and α is generally set at a value of 0.1.

When a decision needs to be made based on these differences, H_0 is tested against H_1. H_1 constitutes the assertion that is accepted if H_0 is rejected. Thus for H_0, the two variables are *unrelated* in the population and for H_1 the two variables are *related* or associated in the population. Therefore in this case if the attractiveness of the scenes are ranked X and the visual preference factors are ranked Y, then for any given order of the X ranks all possible orders of the Y ranks are equally likely. That is, for a given order of the X ranks, any one possible order of the Y ranks is just as likely to occur as any other possible order of the Y ranks.

If the X ranks are ordered in natural order, (i.e. 1, 2, 3, 4, 5, 6, 7, 8), for that order, all the 8! (i.e. 8×7×6×5×4×3×2×1) possible orders of the Y ranks are equally probable under H_0. Therefore any one particular order of the Y ranks has the probability of occurrence under H_0 of 1/8!.

When N is 10 or less (in this case N, the number of scenes analysed, is 8), Table 6.24 may be used to determine the exact probability associated with the occurrence (one-tailed - detecting a difference in one direction only) under H_0 of any value as extreme as an observed S (actual score). The sampling distributions of S and τ are identical in a probability sense. Given that τ is a function of S (see Appendix 3), either might be tabled, but it is more convenient to tabulate S (Siegel, 1956).

Table 6.24 Table of probabilities associated with values as large as observed values of S in the Kendall's rank correlation coefficient (adapted from Kendall, 1948).

S	N = 8
0	0.548
2	0.452
4	0.360
6	0.274
8	0.199
10	0.138
12	0.089
14	0.054
16	0.031
18	0.016
20	0.0071
22	0.0028
24	0.00087
26	0.00019
28	0.000025

If the probability $p \leq \alpha$, H_0 may be rejected (where α is set at a value of 0.1). Thus the null hypothesis is rejected at $p \leq 0.1$. Therefore for $S = 2$, an $S \geq 2$ has a probability of occurrence under H_0 of $p = 0.452$. Thus for the Kendall's rank correlation coefficients between attractiveness and each of the nine visual attributes:

1) When $S = 2$ (enclosure of water by vegetation), for $S \geq 2$, $p = 0.452$ ($\tau = 0.071$).
2) When $S = 4$ (lack of discernable contrast between land and water), for $S \geq 4$, $p = 0.360$ ($\tau = 0.143$).
3) When $S = 12$ (vegetation diversity/shoreline complexity), for $S \geq 12$, $p = 0.089$ ($\tau = 0.429$).
4) When $S = 22$ (lack of vegetation openness), for $S \geq 22$, $p = 0.0028$ ($\tau = 0.786$).
5) When $S = 24$ (naturalness/interest value/inclination to explore scene/lack of human interference), for $S \geq 24$, $p = 0.00087$ ($\tau = 0.857$).

If it is hypothesized that there is no significant correlation between the rankings, an S value of 12 has p(occurrence) = 0.089 which is less than the set α value of 0.1. Thus H_0 can be rejected at a level of significance of 0.089 and it can be concluded that the attributes with $p \leq 0.089$ (vegetation diversity, shoreline complexity, lack of vegetation openness, naturalness, interest value, inclination to explore scene and lack of human interference) are strongly associated with attractiveness whereas the attributes with $p \geq 0.089$ (lack of discernable contrast between water and land and enclosure of water by vegetation) are less so.

Thus the alternative hypothesis (H_1), that there is a highly significant correlation between attractiveness and the aforementioned seven visual attributes, can be accepted. If the null hypothesis (H_0) is really true, the probability of drawing a random sample producing the same result is 0.089.

The results from these analyses show that the visual attributes which are most statistically significant, and thus positively associated with the attractiveness of a wetland scene, are naturalness, interest value, inclination to explore scene, lack of human interference, lack of vegetation openness, vegetation diversity and shoreline complexity. The preference of the visual values of diversity and complexity and involvement and interest in wetlands are consistent with other studies on the visual preference of other landscape types (Kaplan, 1973, 1975; Newby, 1971 and Wohlwill, 1966). The results suggest that a model for the prediction of the visual preference of wetland landscapes should include the visual attributes of vegetation diversity, shoreline complexity and interest value (complexity), lack of vegetation openness (illegibility), inclination to explore scene (mystery) and naturalness and lack of human interference (lack of disturbance factors).

6.6.3.4 Discussion of Visual Factors in Wetland Scenes

Section 6.6.3.3 identified the visual preference factors of complexity, illegibility, mystery and disturbance factors as being significant for the visual preference of wetland landscapes. Each factor is discussed next with respect to each of the eight scenes used in the main questionnaire survey (scenes A to H - Plates 12i to 15ii) to emphasize how these factors influenced visual preference (Table 6.25).

Legibility

The top two scenes chosen according to the model format and by the respondents were scenes E and A (Table 6.25) rated low in terms of legibility because of the unclear presentation of individual plant forms and internal vegetative structures (e.g. trunks, tree limbs) as shown in E especially. The vegetation is clearer in scene A but the darkness of the thick growth behind the reeds suggests high vegetation density and therefore low legibility. Visual penetration (the ability to see into the shoreline environment) was obstructed by tangled masses of vegetation (scenes A and E especially) and the darkness of the photographs.

A strong edge contrast between water and land and/or vegetation (scenes B, H and D) increases legibility which consequently lowers their preference ratings. The top scenes (E and A) showed low edge contrast whereas the constructed wetlands (scenes C, F and G) show strong edge contrast and consequently rate poorly. These results thus show that

Table 6.25 Rankings of the scenes for all visual factors.

Variable	High							Low
Model	E	A	D	G	H	B	F	C
Attractiveness	E	A	H	D	B	G	C	F
Legibility								
Vegetation openness*	F	C	H	G	B	D	A	E
Water/land contrast	B	H	C	D	A	F	G	E
Lack of enclosure of water by vegetation	B	H	D	A	F	C	G	E
Spatial definition								
Lack of vegetation openness*	E	A	D	B	G	H	C	F
Enclosure of water by vegetation	E	G	C	F	A	D	H	B
Complexity								
Interest value	E	A	D	H	G	B	C	F
Vegetation diversity	G	E	A	D	C	H	B	F
Shoreline complexity	E	A	G	F	D	H	B	C
Lack of disturbance factors								
Naturalness	E	A	D	H	B	G	F	C
Lack of human interference	E	A	D	H	B	G	F	C
Mystery								
Inclination to explore	E	A	D	H	G	B	C	F

Key

* Vegetation openness (or the lack of it) can fall under two visual preference factors.

illegibility positively influenced wetland visual preference because it increases the interest value and the level of mystery.

Lee (1977) showed that the visual preference factors of complexity, legibility, spatial definition and mystery positively influenced visual preference of river landscapes.

Legibility is important since it enhances ones' ability to see the river's edge or shoreline environment. However, *illegibility* is important in the visual preference of wetlands because the perception of wetlands is different from that of rivers - the ability to see the edge environment of a wetland and gain access into it is not as important to the public since they are less likely to use a wetland-type environment for recreation. This is reflected by the study by Cheek and Field (1977) who, comparing the recreational use of different environments, found fewer types of recreational activities and less activity overall associated with wetland-type environments. Thus even wetlands of high scenic quality (partly due to their visual illegibility) are not likely to be used for recreational purposes and this may be partially explained by the difficulty of gaining physical access to and into wetlands (Smardon, 1983). The lack of access does not seem to reduce the allure of wetland environments since it suggests wilderness, naturalness and mystery - attributes which all contribute to the attractiveness of a scene.

Complexity

The top two scenes (E and A) chosen by the model and the respondents rated highly in terms of complexity (Table 6.25). An irregular shoreline (and skyline) (as seen in scenes A, E and D but not in F, B and C) leads to greater visual interest. This is clearly demonstrated in scene A where the shoreline is obscured by the clump of macrophytes which seem to extend away from the shoreline into the water (i.e. towards the viewer) thus making it unclear whether it is part of the shoreline or not. Scene G rated fairly high for shoreline complexity because it shows an enclosed pond-like area with the vegetation obscuring the shoreline. However scene G rates low for visual preference because of the artificial structure (see Disturbance Factors). The complexity of scenes A and E is also enhance by the darkness of those photographs since the low lighting makes the vegetative components of the scenes less easily distinguishable.

Scenes G, A and E rated highly for vegetation diversity. Scene G showed different macrophytes enclosing a water-body which reflects their image. The water-body also contains floating plants. The vegetation diversity is further enhanced by the colour differences between the various vegetation types. Scene A also showed marked vegetation colour differences as well as vegetation height variations not obviously seen in scene G. Water surface complexity (i.e. degree of calmness) can have an influence on visual preference (Lee, 1977) and can partly explain the preference of scene A over scene G (where the water surface is mirror calm). Scene E has high vegetation diversity but because the scene is very shaded and enclosed by trees, vegetation colour differences are not readily apparent. But the low legibility and wide height variation of the vegetation gives a strong sense of tangled, dense vegetation and thus a sense that there are many types of vegetation present.

The influence of complexity in wetland visual preference of wetlands is consistent with studies (Niering, 1967; Rowntree, 1976 and Smardon 1972, 1975) which showed the importance of the textual contrast of aquatic vegetation and water, the complexity and richness of emergent aquatic-vegetative patterns in wetlands, and the interspersion of the components of vegetation and open water. The complexity of vegetation includes its dynamic aspects such as seasonal changes and resulting changes in colour and diversity and these are also very important in determining visual preference of wetlands (Rodgers, 1970; Smardon, 1972).

Spatial Definition

The highest rated scene (E) has significant enclosing or space-defining elements (primarily trees) which positively influence visual preference. Scene F shows a low-lying landscape with no feel of enclosure. The water reeds define space within the water but do not have sufficient height variation to create a feeling of enclosure. The uniformity of the different vegetation types in scene B and the strong edge contrast between the vegetation and land and the large water-body reduces complexity but heightens legibility giving the scene a monotonous feel.

The constructed wetlands (scenes C, F and G) all rate fairly high on enclosure of water by vegetation since they all feature water-bodies clearly enclosed by vegetation (Table 6.25). However, these scenes rate poorly for visual preference due to the obvious presence of human activity, their high legibility and lack of complexity.

Various studies (Litton *et al.,* 1972; Palmer, 1978; Smardon, 1972 and Steinitz *et al.,* 1978) have shown that recreationists preferred relatively open wetlands (e.g. meadows, shallow or deep marshes, bog mats, low shrub mats) to thickly vegetated shrub and wooded swamps without visual clearance under the woody canopy. These results contrast with the results of this study since the most preferred scene (E) is a complex composite of different visual attributes which are not easy to assess visually or physically access whereas the visually open wetlands rate lower. However, Smardon's studies (1972, 1983) anticipates the latter results by acknowledging that such complex landscapes may come to be valued as the public learns about the desirable characteristics of denser shrubbed and wooded wetlands.

Mystery or Anticipation

Scene E demonstrates the mystery factor very well. Dense, overhanging vegetation and strong reflections in the water obscure but do not totally obstruct the view. The jutting mass of trees on the right of the photograph partially blocks out the view behind it. Thus the further reaches of the wetland move out of sight, creating anticipation. The feeling of mystery is further enhanced by the illegibility of the scene, the lack of clarity (i.e. high complexity), and the strong sense of enclosure afforded by the trees all which contribute to the darkness of the scene. Scene E thus demonstrates all the most preferred visual preference factors (Table 6.25) and these results are consistent with the work on bogs carried out by Hammitt (1978) who showed that the public preferred a mixture of open bog mats and wooded screens which provided mystery or intrigue about areas yet to be explored. The importance of a mixture of mystery and openness has also been suggested by More *et al.* (1977) and Rodgers (1970).

By constrast, scene F (rated lowest for the *inclination to explore* attribute) does not show any features of mystery since it is highly legible, has low complexity and few space-defining elements. Although scene F has a low water/land edge constrast like scene E, this attribute cannot influence the overall visual preference; only a mix of attributes will give the true preference.

Disturbance Factors

Disturbance of the environment has a negative influence on visual preference of wetland landscapes and this borne out by the results. The rankings for the naturalness of the scenes and whether or not they show signs of human interference are identical (Table 6.25). They correlate strongly with the rankings for how attractive the wetland scenes are as a place to visit ($\tau = 0.857$). Thus the presence of artificial structures influence the visual preference rating of scene C negatively. Because scene C is a wetland constructed solely to treat wastewater, its design engineers have not given any thought to aesthetics considerations which might offset its artificial features. Scene C thus shows most of the visual values which negatively influence visual perception - high vegetation legibility, strong water/land edge contrast, no sense of enclosure by the vegetation, low complexity enhanced by the uniform constructed water edge, and finally no mystery. Scene C does rank higher on the enclosure of water by vegetation and on vegetation diversity, but the former attribute does not correlate significantly with attractiveness whilst the latter factor has less influence on visual preference than the disturbance factors.

The low preference ranking can be similarly explained for scene F. Although scene F is less obviously artificial than scene C (the only visible artificial structure is an outflow channel in the right of the picture) it rates poorly because of very low complexity (especially in terms of vegetation diversity and interest value) and a resulting lack of mystery. By contrast, scene G is a wetland constructed with some attempt to making it appear more natural and as a result rates highest for vegetation diversity, relatively high for water/land and water/vegetation illegibility, high for shoreline complexity, and has middle scores for interest value and sense of mystery (Table 6.25). But the constructed outlet structure in the left of the photograph lowers the overall preference of scene G. Scene B is probably perceived as having a high disturbance factors because the large expanse of water and edge contrast with the vegetation gives an impression of an artificial water-body not unlike a reservoir.

These results show that disturbance factors dominate the other visual preference factors in determining visual perception of wetland landscapes. However attractive and interesting the wetland scene may appear, obvious signs of human disturbance (e.g. construction) will negatively influence visual preference as the significant correlation of the *lack* of disturbance factors with the attractiveness of the wetland scenes shows ($\tau = 0.857$).

6.6.3.5 Factor Analysis of the Visual Preference Factors

"Factor analysis is a statistical technique used to identify a relatively small number of factors that can be used to represent relationships among sets of many interrelated variables" (Norusis, 1988). Factor analysis of the attractiveness of scenes A to H (Plates 12i to 15ii) identified two factors defining the natural wetland scenes (Factor 1 - scenes A, B, D, H and E) and the constructed wetland scenes (Factor 2 - scenes C, F and G), as expected. Since one of the goals of factor analysis is to reduce a large number of variables to a smaller number of factors, it is often desirable to estimate factor scores for each case. Thus factor scores for factors 1 and 2 for each of the 284 respondents relate to differences between respondents based on their responses to the attractiveness of scenes A to H and thus each score indicates how much weight is attributed to each factor. Thus factor 1 indicates the *attractiveness* of the wetland environment and factor 2 indicates the *unattractiveness* of the wetland landscape and high or low factor scores for one respondent indicates that the respondent attributed a lot of weight or little weight to the factor. Factor analysis was also carried on each of the nine visual attributes. In nearly each instance two factors were identified which defined how natural or artificial the scenes are.

Factor analysis on the attributes denoting diversity and variety of the vegetation in the scenes resulted in factors F1 (scenes A, B, D, E, F, G, H) and F2 (scene C). Although scene C (the most artificial-looking wetland) shows a variety of vegetation (mean score of 3.5 on a scale - see Table 6.18), it falls under a separate factor. As expected, this shows that the influence of the artificial construction is much more important than the influence of the variety of vegetation on visual perception.

Factor analysis on the variables denoting the level of contrast between water and land in scenes A to H resulted in three factors. Scenes E, F and G were isolated as one factor because their mean scores showed they have the least contrast of all. The strong artificial features of scene C separated it as a second factor (further underlined by the very low correlation this factor shows with the other two factors) whereas the third factor (scenes A, B, D and H) indicated good contrast.

Factor analysis on the variables denoting how natural or artificial the scenes appear, how interesting the scenes appear, the inclination to explore the scenes, the degree of enclosure of water by vegetation and the amount of human interference all resulted in two factors which separate out the natural and constructed scenes.

Factor analysis on the clarity of the water's edge or shoreline of the scenes resulted in three factors similar to the results for the variables denoting the level of contrast between water and land. However, in this case factor 1 (A, B, D and H) and factor 2 (E, F and G) show some correlation whereas factor 3 (C) has little or no correlation with the other two factors indicating the influence of the artificial structures in scene C.

Factor analysis on the variables denoting openness of vegetation of the scenes resulted in two factors. The mean scores of scenes C and F (factor 2) also rate highest out of the 8 scenes in terms of openness (Table 6.18). Correlation between factors 1 and 2 is very low. In this case the influence of open vegetation is greater than that of the artificial features since factor 2 includes scene F which is not so obviously artificial.

The results of factor analysis on the visual attributes expectedly show little or no correlation between natural and constructed wetland scenes. The strong artificial nature of scene C is a dominant negative influence on the public's visual perception. A plot of the weighted individual differences between scenes A to H (Plates 12i to 15ii) by a Euclidean distance model (Figure 6.6) clearly shows how the constructed wetland scenes (scenes C, F and G) are separated from the other more natural scenes. Scene G lies in a separate category from scenes C and F because it has a higher preference rating than either of them. But scene G still has an obvious artificial construction which does not include it with the other scenes.

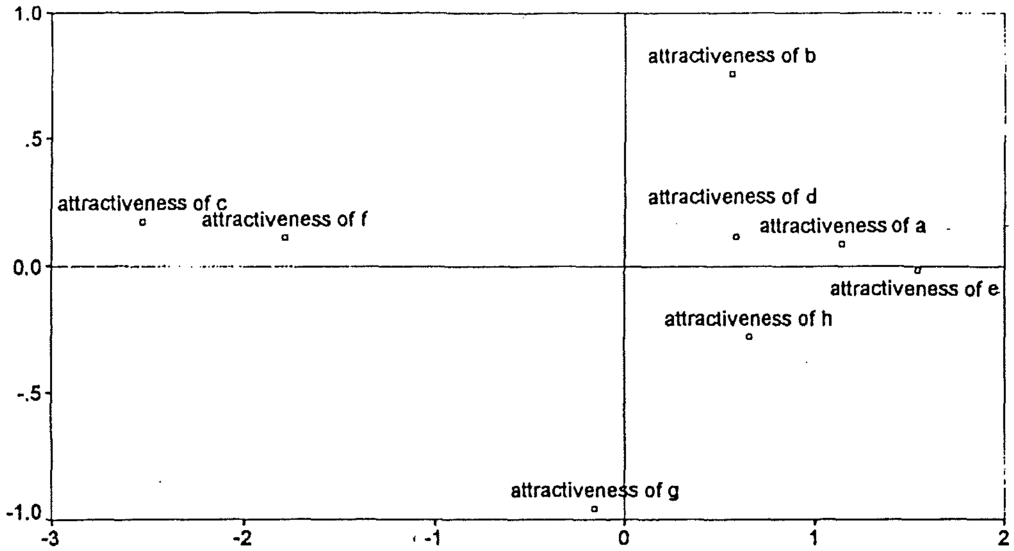

Figure 6.5 A plot of the weighted individual differences between scenes A to H by a Euclidean distance model (The Euclidean distance is the distance between two cases computed as the square root of the sum of the squared difference in values for each variable (Norusis, 1988)).

6.6.3.6 Explaining Visual Preference of Wetland Scenes by Respondent Characteristics

Visual preference of the wetland scenes (defined by how attractive each scene is as a place to visit) can be explained by a range of visual attributes. The possibility that they can also be explained by respondent characteristics (site usage, group membership and demographics) was explored using factor scores derived from factor analysis, t-test statistics and crosstabulations.

Since one of the aims of factor analysis is to reduce a large number of variables to a smaller number of factors, it is often desirable to estimate factor scores for each case.

The factor scores can be used to represent the values of the factors (Norusis, 1988). Thus for factors 1 and 2 (see Section 6.6.3.5) which indicated the attractiveness and unattractiveness of the wetland landscape respectively, the regression factor scores for factors 1 and 2 (the value of the factors for *each* of the respondents) show how much weight is attributed by each respondent to that factor. This relates to differences between respondents based on how attractive they found each wetland scene. Thus the factor scores for each of the other nine visual attributes show which respondents reacted strongly in one way or another to the visual attributes. The theory is that the identification of these respondent characteristics may help establish a profile of respondents who are more observant of the natural environment and its aesthetic aspects.

A study of the factor scores of all the visual attributes showed that respondents less than 45 years old were more likely to be more critical of the "naturalness" of a site (like Hampstead Heath, the site used for the on-site survey), probably because they are aware that most "natural" urban areas have been landscaped and altered. Respondents who visited green open spaces like Hampstead Heath regularly (at least once-a-week), and spent at least one hour there, were likely to be familiar with their surroundings and thus more aware of its aesthetic value (Green *et al.,* 1989; House and Herring, 1994). No clear conclusions could be drawn from the other respondent characteristics.

The t-test statistic, which is used for testing the null hypothesis that two population means are equal, was carried out between respondent characteristics and the factor scores for attractiveness of the wetland scenes. The results show that there is little significance between age groupings, gender, employment status and reason for being at the site and the factors emphasizing attractiveness and unattractiveness (significance > 0.1). However, frequency of visit, the time spent at the site and the distance travelled to the site all have significances < 0.1. This is explained by the fact that these three characteristics all influence perception with time spent at a site having the strongest significance (0.035) suggesting that awareness of surroundings increases with the time spent there (House and Herring, 1994) which is due to an interest in that surrounding.

Crosstabulation did not show many clear conclusions with only gender differences being relevant. In the measure of the socio-economic benefits of wetlands (see Section 6.6.4), females preferred the use of wetland for walks and bird watching whereas males preferred the use of wetlands for fishing (usually a male past-time). Males were more likely to agree with the use of natural wetlands for water quality improvement whereas the constructed wetlands of scenes C and F were more likely to lessen the enjoyment of a visit by females to a site where they would be present. These results suggest that females may have more concerns about the aesthetic aspects of their natural environments and is consistent with other studies which show that females are more critical of environmental quality (Green *et al.,* 1989; House and Herring, 1994).

6.6.4 Attitude Towards the Use of Wetlands

A measure of the perceived benefits associated with the use of wetlands was assessed by asking the respondents if they strongly disagreed or agreed (using a scale of 0 to 6) with a number of potential uses of wetlands, including their use for wastewater treatment.

The results demonstrated a clear preference for uses which involved minor modifications to wetlands and focused mainly on an appreciation of a wetlands' natural attributes (Table 6.26). For example, uses for bird and wildlife watching, nature conservation and photography received ratings of 5.27 to 5.40. Uses which resulted in more human activity and interference were given a lower rating. The use of wetlands for wastewater treatment scored a very low mean score of 1.17 indicating a strong negative attitude towards such a use. The use of the word "wastewater", with its connotations of sewage, instead of water quality improvement probably helped lower the score.

The results demonstrate the public's appreciation of the wildlife value of wetlands and the fact that are not supportive of any activities that will disturb the wildlife and allow the public to actively use the wetland (the four most popular uses of wetlands are sedentary activities). Birdwatchers like wetlands because of the greater number of bird species associated with them. The promotion of birdwatching could become an important secondary benefit in the development of constructed wetlands for wastewater treatment since such wetlands usually have a greater or more regular water inflow than natural wetlands and hence frequently provide more habitats for water birds (Kadlec and Knight, 1996).

Table 6.26 Ideal uses of wetlands.

Use of wetland	Mean score
Ideal location for bird watching	5.40
Ideal location for a nature reserve	5.36
Ideal location for wildlife watching	5.31
Ideal location for nature photography	5.27
Ideal location for hiking/strolls	3.67
Ideal location for picnicking	3.49
Ideal location for fishing	3.29
Ideal location for boating	2.83
Used for land reclamation	1.55
Used for wastewater treatment	1.17
Used for dumping waste/litter	0.26

Scale: 0 - strongly disagree with statement N = 284
6 - strongly agree with statement

Question: Could you please indicate whether you strongly agree or disagree with the following statements.

6.6.5 The Wildlife Value of Wetlands

Although the primary goal of most constructed wetland systems is to improve the water quality of a wide variety of wastewater types, there is increasing recognition of the ancillary benefits for wildlife habitat and public use (Knight, 1996). All treatment wetlands have emergent wetland plants and an adequate supply of water, either in the subsurface environment or as surface water. These two environmental components provide the essential foundation of an ecological foodweb which attracts a wide variety of wildlife species to all treatment wetlands. The public are attracted, directly or indirectly, to these systems as a result of the flora and fauna present in the wetlands either for recreation or environmental study. There is now an increasing amount of information available to wetland designers on how to attract wildlife to different types of wetlands and combine that with the resulting public use benefits (Knight, 1992, 1996; Merritt, 1994; Sather, 1989; US EPA, 1993; and Worrall, 1996).

This section of the questionnaire assessed the expressed value of wildlife and wildlife types in wetland environments to the visiting public. Respondents were asked how important the presence of wildlife with regards to the enjoyment of a visit to a wetland site was on a scale of 0 (not important at all) to 6 (very important). The mean score of 5.15 is consistent with the results shown in Table 6.26 and shows the high wildlife value of wetlands.

Respondents were next asked what types of wildlife would increase their enjoyment of a visit to a wetland site and the results are shown in Table 6.27. The results showed that birds were the most popular types of wildlife with waterbirds such as swans, ducks, moorhens, water fowl, grebes, coots and cranes especially popular. The preference for water birds is to be expected since they are amongst the most visible and aesthetically appealing types of wildlife found in the vicinity of water bodies which themselves tend to command the most visual interest in a landscape.

The large number of wildlife types which the public say would increase enjoyment of a visit to a wetland site shows how wildlife species provide a convenient focus on the value and health of wetlands (Kadlec and Knight, 1996) and shows that the public appreciate that wetlands provide habitat for a vast array of animal species. For example, an estimated 900 species of wildlife in the US require wetlands as habitat for a large part of their life cycles (Feierabend, 1989). Birds are typically the most important visual feature of wetlands (Kadlec and Knight, 1996) with about 600 different North American bird species (one third of the resident bird species) dependent on wetlands for some part of their life history (Kroodsma, 1978). The abundance and diversity of birds in and around wetlands attracts birdwatchers and in wetland water bodies which are enriched by nutrients and organic matter from wastewater and stormwater discharges, birds are often even more abundant (Kadlec and Knight, 1996). Thus given the popularity of birds, wetlands for wastewater treatment should be designed, where possible, to provide habitats for indigenous bird species found in the area.

Table 6.27 Types of wildlife that would increase enjoyment of a visit to wetland environment.

Responses for wildlife type	n	Rank
Waterbirds	144 (21.0%)	1
Small flying birds	140 (20.4%)	2
Fisheating birds	126 (18.4%)	3
Land mammals	61 (8.9%)	4
Wide variety	41 (6.0%)	5
Flying insects	33 (4.8%)	6
Water mammals	28 (4.1%)	7
Water insects	27 (3.9%)	8
Fish	24 (3.5%)	9
Nothing in particular	20 (2.9%)	10
Amphibians	17 (2.5%)	11
Reptiles	11 (1.6%)	12
Don't care	8 (1.2%)	13
Rare species	5 (0.7%)	14

Wildlife plays a subtle but important role in wetlands used for water quality improvement since they are all consumers that keep nutrients in circulation and regulate the populations of lower trophic levels in a manner that maximizes system function (Odum, 1983) and enhance the aesthetic aspects of the wetland considerably as the results above show. Thus greater consideration must be given to wildlife populations during design, construction and operation of wetland treatment systems. The studies by Payne (1992), Smith *et al.* (1989), Weller (1978) and Wengrzynek and Terrell (1990) cover the current state of the knowledge on enhancing wildlife use of constructed and natural wetlands. The ancillary benefits potentially achieved when treatment wetlands are built to attract wildlife may be an added value at a relatively low cost (Kadlec and Knight, 1996).

However, in the case of wetlands which receive highly loaded wastewater, the fate and effect of toxic heavy metals (e.g. Cd, Pb) and organics in treatment wetlands is an important consideration since the portion of potential toxins retained by the treatment wetland will eventually become incorporated into biological tissue leading to biomagnification up through the ecological food chain of that wetland. Thus there is a concern that wildlife attracted to a treatment wetland might be exposed to dangerous and potentially fatal levels of toxins (Friend, 1985). Adequate dissolved oxygen must also be maintained to prevent anaerobic conditions which would affect the foodchain. Generally the most effective and cheapest way to avoid problems of toxicity in a treatment wetland which has established an ecological food chain is to pretreat the wastewater to an appropriate level before it is discharged into the treatment wetland thus preventing an environmental hazard. However, designing a wetland which incorporates pretreatment is dependent on the amount of land space available and may thus only be cost effective for larger systems with ecosystems that would potentially be at risk from untreated wastewater.

Wetlands must also always be treated as ecosystems. There is no size threshold for encouraging ecosystems and only in the cases of wetlands treating very toxic wastewaters will an ecosystem not thrive. Microbes and algae generally colonize wetlands with no help. Problems associated with the build up of algae and duckweeds would occur if the water discharged into the wetland has high nutrient loads and would require management to ensure parts of the wetland do not become clogged up. Planting of trees such as emergent woody trees around the wetland and plant species in different depth zones (including floating plants) will increase the vegetative height variation and enhance the aesthetic value of the wetland. Plant species of the same family can be used to give diversity and prevent the problems of monocultures (see Table 6.28). Plant diversity will enhance the complexity of the wetland and thus increase its aesthetic value (see Section 6.6.3.4). Ensuring the water reeds are not in the shade where they will not grow properly is an important design consideration.

The presence of an established plant ecosystem means that all levels of the food chain could be supported, especially in the outflow areas where the water would be of a higher quality. Even in the instance where the wastewater is anaerobic fish species that are adapted to low oxygen levels will also control mosquito larvae and will in turn attract birds of prey.

Table 6.28 Summary of wildlife habitat design considerations for treatment wetlands.

Wildlife Habitat Considerations	**Comments**
Ability to control the water level*	Plant growth and water quality can be controlled by adjusting the water level
Presence of deep water zones without creating hydraulic short circuiting*	Deep water zones can improve hydraulic mixing, increase retention times, allow for solid settlement/storage and provide a perennial habitat for fish and birds
Wetland plant diversity	Polycultures are more resilient to pests, disease and operational changes
Plant species with known benefits to wildlife species*	Each plant species benefits different wildlife species/groups
Vegetative height variations	Vertical structural diversity provides a variet of habitats for feeding, roosting and nesting wildlife
Varying water regimes	Littoral shelves and benches and deep water zones promote specific plant species diversity
Irregular shorelines	Irregular shorelines provide visual cover and a greater ecotone which promotes wildlife diversity
Islands in open water areas*	Islands provide refuge for prey where predators are present
Nesting platforms*	There are few suitable habitats for nesting in newly constructed wetlands

Key
* Adapted from Knight (1996).

Table 6.28 summarizes many of the design considerations that are important in creating wildlife in treatment wetlands. Plant diversity, vegetative height variations as well as irregular shorelines all encourage wildlife and also contribute to the attractiveness of a wetland environment (see Section 6.6.3.4). Wherever possible, wildlife habitat considerations should be incorporated into the design criteria of treatment wetlands. This would generally involve the introduction of vegetative and open water zones of varying dimensions to the treatment wetland with the designer being able to influence the water level and plant species diversity which would in turn attract the desirable wildlife species which would rapidly colonize the wetland and show high diversity (Worrall *et al.,* 1996).

6.6.6 Public Perception of the Use of Wetlands for Water Quality Improvement

6.6.6.1 Public Perception of the Use of Natural Wetlands for Water Quality Control

The perception of the use of wetlands for water quality improvement was assessed. This section of the questionnaire explained how wetlands could improve water quality with the help of a schematic diagram (Figure 6.4) of a treatment wetland (also see Section 6.4.3) and sought to gain an insight into the publics' motivations behind decisions to adopt, or not to adopt, natural and/or constructed wetlands for wastewater treatment. This included an evaluation from the photographs of the attractiveness and use of the three constructed wetlands (Scenes C, F and G - Plates 13i, 14ii and 15i).

The respondents were asked if they would be in favour of using *natural* wetlands to improve water quality using a scale of -3 (strongly against) to 3 (strongly agree). The mean score of 0.22 indicates that there was considerable uncertainty concerning this use. Those who agreed with the use of natural wetlands for wastewater treatment (46.6% of the respondents) did so with reservations (Table 6.29). For example, 17.9% agreed only on the condition that there was no risk of the pollutants damaging the natural environment; however 15.8% of the respondents considered it to be a "good natural method" of improving water quality. Of those that were not sure of using natural wetlands to improve water quality (26%), 17.6% said that they needed more information. Of the 27.4% of the respondents who disagreed with this use, 13.7% stated that the pollutants would still be in the natural environment and so the problem would not be solved, whilst a further 9.5% simply felt that natural wetlands should not be interfered with.

Overall these responses indicate that there is concern over the effect of pollutants on a natural wetland and therefore major reservations about supporting any proposal to use natural wetlands for water quality improvement.

Table 6.29 Reasons stated to justify feelings in answer to the question "Would you agree with the use of *natural* wetlands to improve water quality?" (includes number of responses and response percentage).

-3	-2 -1 0 1 2	3
strongly disagree	not sure	strongly agree
Problem not solved, pollutants still in the natural environment (52, 13.7%)	Need more information (67, 17.6%)	If pollutants do not damage the wetland ecosystem (68, 17.9%)
Natural wetlands should be left alone (36, 9.5%)	Only if controlled (16, 4.2%)	Good natural method (60, 15.8%)
Should use artificial methods to treat wastewater (6, 1.6%)	Depends on what is being treated (11, 2.9%)	Allows cleaner water to be discharged into the natural environment (19, 5%)
Not enough natural wetlands in needed areas (6, 1.6%)	Only as a last resort (4, 1.1%)	Better than a wastewater treatment plant (14, 3.7%)
Should control source not effect (3, 0.8%)	Depends on how many wetlands are used (1, 0.25%)	Aesthetically pleasing treatment method (8, 2.1%)
Will create bad odours (1, 0.25%)		Low cost method (4, 1.1%)
		Wetlands do not have any other good uses (3, 0.8%)
		Self-maintaining method (1, 0.25%)

N = 380

Balance of responses:
Disagree (-1 to -3): 27.4% (n=104)
Not sure (0): 26.0% (n=99)
Agree (1 to 3): 46.6% n=177)

6.6.6.2 Public Perception of the Use of Constructed Wetlands for Water Quality Control

The respondents were next asked if they would be in favour of using *specifically constructed* wetlands to improve water quality using the same scale of -3 (strongly against) to 3 (strongly agree). The mean score of 1.63 indicates a much more positive response to this question as borne out by the reasons for their answers (Table 6.30). 10.6% of the respondents were not sure of using specifically constructed wetlands to improve water quality and all of them stated they needed more information. Those who disagreed to some degree (11.8% of the respondents) did so mostly because they believed that this form of pollution control would damage the environmnent in the long term and because they thought constructed wetlands were not aesthetically pleasing (5.8% and 2.3% of the respondents respectively), a perception based on the constructed wetlands depicted in three of the photographs used within the survey (Scenes C, F and G). However, 77.6% of the respondents agreed with the use of constructed wetlands for wastewater treatment with responses such: "good idea if it works" (26.1%), "systems could be controlled and monitored" (7.5%) and because it is a "a good natural method" (5.5%).

Most of the other positive responses came with reservations - 7% on the condition that the wetland "looked natural"; 6.8% on the condition that there would be no risk of the pollutants damaging the natural environment; 4% on the condition that the wetlands were constructed properly (i.e. pollutants did not leach out); and 2.5% on the condition that wetlands were only constructed on former wastelands. The value constructed wetlands as being a more aesthetic way of treating water as well as creating a new ecosystem was appreciated by 5.5% of the respondents.

These results are consistent with the results from the pilot study (Section 6.4.3) and suggest that the public is much more comfortable with the thought of using specifically constructed wetlands for water quality improvement but that they still have reservations as to the fate of the pollutants that will be retained in the wetland. Therefore, background information must be provided to ensure that the public understands exactly what is involved and to also allay their concerns.

Table 6.30 Reasons stated to justify feelings in answer to the question "Would you agree with the use of *specifically constructed* wetlands to improve water quality?" (includes number of responses and response percentage).

-3	-2	-1	0	1	2	3
strongly disagree			not sure			strongly agree
Damages environment in the long term (23, 5.8%)			Need more information (42, 10.6%)			Good idea if it works (104, 26.1%)
Not aesthetically pleasing (9, 2.3%)						System can be controlled and monitored (30, 7.5%)
Land area requirements large (4, 1%)						Only if it looks natural (28, 7%)
Will create bad odours (3, 0.75%)						Only if pollutants do not damag the wetland ecosystem (27, 6.8%)
Waste of money - enough wetlands already (3, 0.75%)						Good natural method (22, 5.5%)
Costly (2, 0.5%)						Creates a new aesthetic ecosystem (22, 5.5%)
Wastewater treatment plants should be enough (2, 0.5%)						Preferable to using natural wetlands (16, 4%)
Not suitable for swimming (1, 0.25%)						Only if constructed properly, ie. pollutants contained (16, 4%)
						Better than a wastewater treatment plant (13, 3.3%)
						Only if wastelands are being replaced by the wetlands (10, 2.5%)
						Only where this system is appropriate (6, 1.5%)
						Better than nothing (3, 0.75%)
						Have knowledge of such system (3, 0.75%)
						Will not affect wildlife as there is none there to begin with (3, 0.75%)
						Low cost method (2, 0.5%)
						Self-maintaining method (2, 0.5%)
						Only if isolated, eg. fenced off (1, 0.25%)
						Prevents silting in discharge areas (1, 0.25%)

Disagree (-1 to -3): 11.8% (n=47); Not sure (0): 10.6% (n=42); Agree (1 to 3): 77.6% (n=309)
N=398

Table 6.31 summarizes many of the design considerations that are important in creating public use benefits in treatment wetlands and which should be carried out in conjunction with the design considerations important in creating wildlife in treatment wetlands (Table 6.28). In the case of treatment wetlands which will be accessible to the public, access and use of the wetland will inevitably increase if it is aesthetically pleasing and not a nuisance or hazard. Thus the designer should ensure that the wastewater is not odorous and does not attract mosquitoes (a level of pretreatment may be required) or if it does, then take steps to control the mosquito larvae population (see Section 6.6.5); that the wetland is accessible and safe (e.g. minimize contact with potentially dangerous species such as pathogens and biting insects; handrails and shallow zones surrounding deep water zones), provides public information about the wetland (its nature, functions, wildlife, wastewater treatment capacity). Involving the public in such projects will educate and help publicize the benefits of treatment wetlands.

The treatment efficiency and aesthetic and wildlife value of wetlands constructed to improve water quality are not mutually exclusive but can be obtained simultaneously with good management and public participation. As the results from Section 6.6.3 show, the visual attributes preferred by the public are those attributes that will attract wildlife. With this knowledge, and with established design criteria for wetland water treatment, it is possible to design sustainable treatment wetlands that will serve the environment and the public alike without conflict.

6.6.6.3 Reassessment of the Perception of Constructed Wetlands

The final section of the questionnaire reassessed the public's perception of the aesthetic value of constructed wetlands by asking the respondents whether constructed wetlands for water quality improvement would lessen their enjoyment of a visit to a wetland-type environment based on scenes C, F and G.

The results (Table 6.32) show that despite the low preference for scenes C, F and G (which rated 7th, 8th and 6th respectively for attractiveness - see Table 6.17), the respondents did not unanimously say that these constructed wetlands would lessen enjoyment of a visit. Slightly more of the respondents (between 51.9% and 53.4%) said

Table 6.31 Summary of public use design considerations for treatment wetlands (Adapted from Knight, 1996).

Public Use Considerations	**Comments**
Parking and safe access to wetlands	A safe and secure environment will attract humans
Boardwalks and blind observation points	The public can enter and observe wetland flora and fauna without interference
Interpretative displays	A valuable educational tool concerning the nature and function of wetlands
Collection of public comment/volunteer participation	The public like to be involved and their suggestions may be useful for improvements
Access to monitoring records	The public has a right to know about any hazards or benefits due to a treatment wetlan
Incorporating visual preference factors	Creates an aesthetically pleasing wetland landscape

it *would not* lessen their enjoyment of a visit. This contrasts with the perception of the use of wetlands for water quality improvement (Section 6.6.4) where only 9% of the respondents agreed to this use. These results suggest that knowledge of the function of these wetlands enhances their value, aesthetic or otherwise, and the respondents favourably reassess their perceptions of treatment wetlands. Thus in this case, greater knowledge seems to influence perceptions positively even though it must be remembered that scenes C, F and G rated poorly for attractiveness a place to visit (see Table 6.18) and any increase in the public's perception of the aesthetic value of scenes C, F and G was probably very small.

Table 6.32 Would treatment wetlands lessen enjoyment of a visit?

Photograph	Yes	No	Don't know	N
C	122 (43.1%)	147 (51.9%)	14 (5%)	283
F	118 (41.7%)	150 (53%)	15 (5.3%)	283
G	117 (41.3%)	151 (53.4%)	15 (5.3%)	283

Question: Would the use of wetlands for improving water quality lessen your enjoyment of a visit to a wetland-type environment?

6.7 CONCLUSIONS

The main conclusion of this study can be summarized as follows:

- A predictive model for the visual preference of a wetland landscape should include the following visual attributes (in order of most statistical significance):

    (1) Naturalness and lack of human interference (lack of disturbance factors), interest value (complexity) and inclination to explore scene (mystery).

    (2) Lack of vegetation openness (illegibility).

    (3) Vegetation diversity and shoreline complexity (complexity).

- With regards to the uses of wetland environments, there is a clear preference for uses which involve minor modifications to wetlands and focus mainly on an appreciation of a wetlands' natural attributes. Uses which result in more human activity and interference (including the use of wetlands for wastewater treatment) in wetlands receive low preference ratings.

- The presence of wildlife is very important to the public's enjoyment of a visit to a wetland site. Birds are the most popular types of wildlife with waterbirds especially popular. This indicates that the design criteria for wetlands constructed for wastewater treatment should incorporate the visual attributes which will attract wildlife as well as increase the aesthetic value of a wetland landscape.

- The public have major reservations about the effect of pollutants on natural wetland systems used for wastewater treatment. Although there is far less resistance to the use of constructed wetlands for wastewater treatment, there is a definite need for background information to allay the public's concerns.

- Knowledge of the function of the treatment wetlands appears to improve the public's perception of treatment wetlands. This suggests that public involvement or participation in the design of treatment wetlands will allay public concerns, allow for more co-operation between treatment wetland designers and the public.

- There appears to be no significant relationship between respondent characteristics and their visual preference of wetland landscapes.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 HEAVY METAL REMOVAL PERFORMANCE OF A NATURAL WETLAND

The heavy metal concentrations found in a natural wetland in NW London were compared to the concentrations found in an adjacent stream which also receives runoff from the same major highway. The results show that although there is evidence of active metal uptake by the sediment and macrophytes, aqueous metal concentrations remained unchanged.

The results provide a baseline study for the assessment of the pollution removal potential of the wetland and support a proposal by the Environment Agency to construct a wetland planted with indigenous species of macrophytes to treat highway runoff on the current site. The natural wetland exhibits severe hydraulic short-circuiting difficulties which result in inadequately treated water mixing with any treated water at the outlet of the wetland, thereby downgrading the quality of the discharge into the Brent Reservoir receiving basin. Short-circuiting problems are inherent in such horizontal surface flow systems with intermittent flow. Any future wetland design must take this into account as suggested by the use of baffles in the proposed design of the constructed wetland.

7.2 HEAVY METAL REMOVAL PERFORMANCE OF A FULL-SCALE CONSTRUCTED WETLAND

A recently constructed wetland system in Braintree, Essex showed a variable metal removal performance. There were delays in construction of the housing development and a bypass, which is the main source of runoff discharges to the wetland, and therefore the results represent a baseline study. An improvement in performance and more consistent results are expected with time as the wetland becomes more established (i.e. growth to maturity of the plants, accumulation of a litter layer, completion of construction activity and the regular removal of sediment from the settlement trenches).

7.3 HEAVY METAL REMOVAL PERFORMANCE OF A LABORATORY SCALE WETLAND

An experimental laboratory scale wetland system treated showed efficient treatment of water dosed with Cu, Pb and Zn to simulate maximum runoff concentrations from major highways. The wetland system acted as an efficient sink for heavy metals during the investigation and removal rates generally increased with higher inlet dosing concentrations. Increased subsurface tissue contact time with the dosed water increased uptake efficiency, although plant subsurface tissue metal loads showed low correlations with peat metal loads. *Typha latifolia* accumulated the highest subsurface tissue metal concentrations and loads whereas *Iris pseudacorus* accumulated the lowest subsurface tissue metal concentrations and loads. Metal loads decreased in the order of roots > rhizome > root tips and Zn was taken up in preference to Cu and Pb by both peat and the macrophyte subsurface tissues.

The uneven distribution of metals in the peat highlights the importance of the hydraulic design and the need to reduce the possibility of shortcircuiting, in constructed wetlands designed for runoff treatment. Flow regimes within such wetlands need to be studied and optimized for minimal shortcircuiting before and after planting takes place to ensure efficient treatment when the wetland is fully operational.

7.4 PUBLIC PERCEPTION OF THE AESTHETIC, WILDLIFE AND TREATMENT VALUE OF WETLANDS

The main aim of this research was to develop a model to assess the visual preference of wetland landscapes. The methodology was developed and tested at an urban wetland site in North London. From the 284 completed interviews it is clear that the public has a preference for clean, natural looking open water bodies and for landscape complexity with diverse and colourful vegetation which varies in height and thus breaks the monotony of a flat, barren landscape. The variation in vegetation type, height and colour increases the aesthetic value of the scene and thus enhances its interest value and evokes a sense of mystery. The preferred visual attributes can be classified into four visual preference factors which make up the model: (1) a lack of disturbance factors (naturalness and lack of human interference); (2) complexity (interest value, vegetation diversity and shoreline complexity); (3) illegibility (lack of vegetation openness) and (4) mystery (inclination to explore scene).

The presence of wildlife is very important to the public's enjoyment of a visit to a wetland site. Birds are the most popular types of wildlife with waterbirds being especially popular.

Respondents were found to be unsure of the use of natural wetlands for the treatment of polluted water commenting that "the pollutants are still in the natural environment" and that polluted water should be controlled at the source, suggesting that the objections were based on the moral issue of pollution. There was stronger support for the use of constructed wetlands with respondents commenting that it is a "natural way to clean the water"; "it is cheap"; and "a preferable alternative to wastewater treatment plants or the use of natural wetlands".

Interpreting the results of the use of wetlands for water quality improvement indicates that the design criteria should incorporate the visual attributes which will attract wildlife as well as increase the aesthetic value of a wetland landscape. The visual attributes preferred by the public are often those that attract wildlife. Knowledge of the function of the treatment wetlands appears to improve the public's perception of these wetlands. This suggests that public involvement or participation in the design of treatment wetlands will allay their concerns and allow for more co-operation between treatment wetland designers and potential user groups.

Therefore, treatment efficiency and aesthetic and wildlife value of wetlands constructed to improve water quality are not mutually exclusive but can be obtained simultaneously with good management and public participation. With this knowledge, and with established design criteria for wetland water treatment, it is possible to design sustainable treatment wetlands that will serve the environment and the public alike without conflict.

7.5 DESIGN OF WETLAND SYSTEMS FOR URBAN RUNOFF TREATMENT

The constructed wetland discussed in Section 7.2 does not currently meet the proposed outcomes of the research discussed in Sections 7.3 and 7.4. On the positive side, the wetland is located in a newly created country park which will attract wildlife and enhance the original environment of arable fields and it is also planted with four species of macrophyte which improves its aesthetic value. It is also associated with an irregular-shaped ornamental lake which complements its environmental and aesthetic value. Furthermore, the baseline monitoring results indicate that the runoff treatment performance should improve as the system becomes more established. However, the wetland has a regular triangular shape which decreases its aesthetic value and the flow is possibly shortcircuiting in the wetland and thus reducing treatment potential.

The results summarised in Section 7.4 will be incorporated into the design of the wetland discussed in Section 7.1 with modifications to the shape of the proposed wetland (Figure 3.12) and its overall integration into the surrounding environment. The monitoring of the constructed wetland (Section 7.2) and the results summarised in Section 7.3 will influence design features such as the use of baffles to minimize shortcircuiting, pretreatment considerations (e.g. sediment traps, oil booms, etc.) at the inlet and establishing flow criteria (e.g. retention times, hydraulic loading rates, flow control structures, etc.).

The results summarised in Sections 7.1 to 7.4 thus propose design criteria for engineering and suggestions for landscaping design for treatment wetlands.

7.6 RECOMMENDATIONS FOR FURTHER MONITORING AND RESEARCH

Public participation of the recreational users of the Brent Reservoir and surrounding area should be encouraged in the design of the wetland that will be constructed over the natural wetland site near the Brent Reservoir by the Environment Agency since their feedback concerning the aesthetic and wildlife value of the wetland could be incorporated into the design criteria.

The resulting wetland should be monitored for heavy metal removal performance to ensure the quality of the discharges into the Brent Reservoir fall within acceptable standards. The runoff in the stream should also be treated since the higher metal levels impact directly on the Brent Reservoir. The wetland could also be monitored for hydrocarbon removal performance and ecological development such as a regular species count (e.g. birds, insects, plants). The impact on the wildlife of the site and the wetland treatment performance will provide a valuable case study and influence future adaptations of sites for water treatment and accompanying ancillary benefits.

A continuation of the monitoring of the constructed wetland in Braintree would also provide a valuable case study of the performance of the wetland system before and after the completion of the bypass and the housing development, from which surface runoff is anticipated to discharge into the wetland. An investigation into the flow characteristics of the wetland could possibly help improve its overall removal performance. The results will also influence the adoption of constructed wetlands in future residential developments in the UK. Further research could investigate the degradation and removal of hydrocarbons by the wetland sediments and plants. A study of the microbial populations in the wetland will provide an understanding of heavy metal and hydrocarbon removal processes.

The results of the performance of the laboratory scale wetland show its initial responses to the metal doses. Subsequently, the system may become saturated with heavy metals and its removal efficiency may decrease. Thus it would be necessary to determine the occurrence of any optimal removal efficiency for the wetland by carrying out the dosing experiments over longer periods of time. The study also needs to be repeated to verify the findings and to explore the mechanisms of metal uptake by the substrate (including the gravel) and the macrophytes and associated microorganisms and biofilms. Experimentation with the wetland design would also help determine flow characteristics and establish methods of reducing shortcircuiting. Research in these areas could help achieve the ultimate step of replicating the success of laboratory scale wetlands in full-scale wetlands.

There is a need for the survey of the public's perception of wetlands to be carried out in other wetland locations to verify the results of this research. Further investigations into the preference value of other visual attributes would provide more detailed visual preference models for all types of wetland landscapes. The aesthetic value of constructed wetlands also needs to be further investigated, particularly in areas where treatment wetlands are planned. Surveys carried out through the establishing years of a treatment wetland would help monitor (and therefore allow any steps to be taken to improve the wetlands' aesthetics) its value over time.

The high membership of environmental/outdoor groups of the Hampstead Heath visitor population indicates fairly high environmental awareness and thus they are probably not representative of average recreational groups. Therefore different wetland settings and different populations need to be investigated. Social surveys of the public's perception of wetlands need to be repeated in urban areas on a regular basis so that changes in public perceptions and opinions may be monitored alongside changes in the appearance of wetlands over different seasons. For comparative purposes, surveys in semi-urban, rural and heavily industrialised areas should also be carried out. On a larger scale, a European-wide survey would provide much information on public perceptions within different cultures.

Finally, comparisons of wetland treatment systems with other non-wetland treatment techniques may also be valuable since in many instances, other treatment techniques may be incorporated into a treatment wetlands' design to maximize treatment efficiency.

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APPENDIX 1 A PILOT STUDY TO ASSESS THE PUBLIC PERCEPTION OF THE AESTHETIC AND WILDLIFE VALUE OF WETLANDS AND THEIR USE FOR WATER QUALITY IMPROVEMENT

MIDDLESEX UNIVERSITY, URBAN POLLUTION RESEARCH CENTRE, CONFIDENTIAL

For Office Use Only

Questionnaire number .... _____

Location ____________________

Interviewer ____________________

Interview number .... _____

Date ....../....../1994

Day ____________________

Time interview started (24 hour clock) .... _____

Time interview finished (24 hour clock) .... _____

Length of interview (minutes) .... _____

Weather Conditions **(CIRCLE CODE THAT APPLIES)**

sunny	1
broken cloud	2
overcast	3
warm	1
mild	2
cold	3
dry	1
drizzle/showers	2
persistent rain	3
calm	1
breezy	2
windy	3

GENERAL USE OF THE SITE

[Q. 1] Which of the following is your main reason for being at <u>this site</u> today?

(READ OUT) **(CIRCLE ONE ONLY)**

walking:	
- the dog	1
- children	2
- strolling	3
- 2 miles or more	4
cycling	5
fishing	6
canoeing	7
rowing	8
picnicking	9
on the way to somewhere else	10

[Q. 2] How often on average do you come here?

at least daily	1
at least a few times a week	2
at least weekly	3
at least fortnightly	4
at least every month	5
at least 5 to 11 times a year	6
yearly or less often	7
never been here before	8

[Q. 3] How much time do you plan to spend at <u>this site today</u>?

0 - 15 mins	1
16 - 30 mins	2
31 - 60 mins	3
1 - 2 hours	4
2 - 3 hours	5
3 - 4 hours	6
> 4 hours (specify)	7

[Q.4] How far did you travel to get to this site today?

< 1/2 mile	1
1/2 - 1 mile	2
> 1 mile - 2 miles	3
> 2 miles (specify)	4

[Q. 5] Do you belong to or make donations to any of the following clubs, societies, or groups? **SHOW CARD A**

(CIRCLE YES OR NO)	**Member**		**Donate**	
	YES	**NO**	**YES**	**NO**
an angling club or association	1	0	1	0
a canoeing club	1	0	1	0
a rambling club	1	0	1	0
a bird watching club or society	1	0	1	0
a rowing club	1	0	1	0
Friends of the Earth	1	0	1	0
a local or county wildlife trust	1	0	1	0
National Trust	1	0	1	0
Greenpeace	1	0	1	0
Royal Society for the Protection of Birds	1	0	1	0
Council for the Protection of Rural England	1	0	1	0
a civic or community association	1	0	1	0
World Wide Fund for Nature	1	0	1	0
other environmental or recreational groups	1	0	1	0
(please specify) ________________				
none	1	0	1	0

PERCEPTION OF WETLAND ENVIRONMENT WITH RESPECT TO ENJOYMENT OF VISIT

Would you please rate the following questions on the scales below? **SHOW CARD B**

[Q. 6] How attractive is this location?

very unattractive						very attractive
0	1	2	3	4	5	6

[Q. 7] How clean do you think the water is at this location?

very polluted						very clean
0	1	2	3	4	5	6

[Q. 8] How attractive is the vegetation cover at this location?

very unattractive						very attractive
0	1	2	3	4	5	6

[Q. 9] How natural is this location?

very unnatural						very natural
0	1	2	3	4	5	6

[Q. 10] How important are each of the following with regard to the enjoyment of your visit <u>at this location</u>? **SHOW CARD C**

not important at all						very important
0	1	2	3	4	5	6

(a) scenery .... ___
(b) the open water body .... ___
(c) trees .... ___
(d) shrubs .... ___
(e) grasses .... ___
(f) cleanliness of the water .... ___
(g) presence of plants in the water .... ___
(h) presence of wildlife .... ___
(i) pubs & cafes .... ___
(j) parking facilities .... ___
(k) peace and tranquility .... ___
(i) absence of litter .... ___

[Q. 11] What types of wildlife <u>at this location</u> would increase your enjoyment of a visit? **(RECORD VERBATIM AND PROBE)**

[Q. 12] In thinking of your ideal natural setting, how important would it be for each of the following to be present? **SHOW CARD D**

not important at all ... very important

0 1 2 3 4 5 6

(a) safe area for paddling and swimming .... ___
(b) trees .... ___
(c) many fish in the water .... ___
(d) seats .... ___
(e) butterflies .... ___
(f) pubs and other social facilities .... ___
(g) provision for fishing .... ___
(h) diversity of flowering plants and grasses .... ___
(i) dragonflies and other water insects .... ___
(j) picnic facilities .... ___
(k) many kinds of small birds .... ___
(l) peace and quiet .... ___
(m) ducks and other water birds .... ___
(n) provision for boating .... ___
(o) frogs and frog spawn .... ___
(p) water mammals .... ___
(q) parking facilities .... ___
(r) water plants .... ___
(s) other (please specify) ....

[Q. 13] Overall, what do you like about the water-body at this location with regard to your enjoyment of a visit?

(RECORD VERBATIM AND PROBE)

____

____

[Q. 14] Overall, what do you dislike about the water-body at this location with regard to your enjoyment of a visit?

(RECORD VERBATIM AND PROBE)

____

____

____

PHOTOGRAPHS OF WETLAND ENVIRONMENTS

(READ OUT)

The following questions relate to photographs of landscapes some of which are found in this area.

[Q. 15] Could you please look at these photographs and rate attractiveness of each as a place to visit on the scale below? **SHOW CARD E**

(SHOW PHOTOGRAPH SET)

very unattractive						very attractive
0	1	2	3	4	5	6

Photograph A .... ___
Photograph B .... ___
Photograph C .... ___
Photograph D .... ___
Photograph E .... ___
Photograph F .... ___
Photograph G .... ___
Photograph H .... ___
Photograph I .... ___

(READ OUT)

Could you please look at these photographs and answer the questions for each of them?

(ASK THE FOLLOWING QUESTIONS FOR EACH PHOTOGRAPH)

PHOTOGRAPH A **(RECORD RESPONSE)**

[Q. 16] What two things do you like most? ____________________

____

[Q. 17] What two things do you dislike most? ____________________

____

PHOTOGRAPH B

[Q. 18] What two things do you like most? ____________________

____

[Q. 19] What two things do you dislike most? ____________________

____

PHOTOGRAPH C

[Q. 20] What two things do you like most? ____________________

____

[Q. 21] What two things do you dislike most? ____________________

____

PHOTOGRAPH D

[Q. 22] What two things do you like most? ______________________________

____

[Q. 23] What two things do you dislike most? ______________________________

____

PHOTOGRAPH E

[Q. 24] What two things do you like most? ______________________________

____

[Q. 25] What two things do you dislike most? ______________________________

____

PHOTOGRAPH F

[Q. 26] What two things do you like most? ______________________________

____

[Q. 27] What two things do you dislike most? ______________________________

____

PHOTOGRAPH G

[Q. 28] What two things do you like most? ______________________________

____

[Q. 29] What two things do you dislike most? ______________________________

____

PHOTOGRAPH H

[Q. 30] What two things do you like most? ______________________________

____

[Q. 31] What two things do you dislike most? ______________________________

____

PHOTOGRAPH I

[Q. 32] What two things do you like most? ______________________________

____

[Q. 33] What two things do you dislike most? ______________________________

____

[Q. 34] Which three of the following adjectives (1 - 12) best describe your feelings when looking at each scene?

(SHOW CARD F AND PHOTOGRAPH SET)

(TICK THE APPROPRIATE BOXES)

	A	B	C	D	E	F	G	H	I
natural									
busy									
tranquil									
dull									
wilderness									
overgrown									
boring									
secluded									
derelict									
dirty									
interesting									
clean									

(READ OUT)

The photographs you have just seen show various components of wetland environments. The next questions relate to wetland environments. **SHOW CARD B**

[Q. 35] How attractive is the wetland <u>at this location</u>?

very unattractive						very attractive
0	1	2	3	4	5	6
☐	☐	☐	☐	☐	☐	☐

[Q. 36] How important is the wetland environment at this location to your enjoyment of a visit?

not important at all						very important
0	1	2	3	4	5	6
☐	☐	☐	☐	☐	☐	☐

[Q. 37] How important is it to have access to the wetland at this location?

not important at all						very important
0	1	2	3	4	5	6
☐	☐	☐	☐	☐	☐	☐

WETLANDS FOR WATER QUALITY IMPROVEMENT

Contaminated water often passes through wetlands before entering rivers and lakes. Wetland systems can improve the water quality by filtering out and trapping pollutants found in the water. Thus wetlands can prevent certain pollutants from entering the natural environment. **SHOW CARD G**

The following questions relate to the use of wetlands by man to improve the quality of contaminated water that runs through them.

[Q. 38] Would you be in favour of using specifically constructed wetlands to improve water quality? **SHOW CARD H**

strongly not in favour of						strongly in favour of
-3	-2	-1	0	1	2	3
☐	☐	☐	☐	☐	☐	☐

[Q. 39] Would you please give reasons for your answer.

(RECORD VERBATIM AND PROBE)

____

____

____

[Q. 40] Would the use of <u>this wetland</u> for improving water quality lessen your enjoyment of a visit to this location?

yes 1
no 0

RESPONDENT INFORMATION

(READ OUT)

The following questions are standard for most questionnaires and are used <u>only</u> for our own classification purposes. Your answers are entirely confidential.

[Q. 41] Gender

female ... 1
male 2

[Q. 42] To which of the following age categories do you belong?

(READ OUT)

18 to 24 1
25 to 44 2
45 to 64 3
over 65 4

[Q. 43] Are you currently ......

in full-time employment 1
in part-time employment 2
unemployed 3
retired 4
student 5
other 6

If respondent is employed (full-time or part-time), ask [Q. 44]

[Q. 44] What type of work do you do?
(RECORD VERBATIM, PROBE IF NECESSARY)

____

____

(READ OUT)

This is the end of the questionnaire and I would like to thank you for taking the time to answer our questions. Do you have any questions you would like to ask me?

(RECORD ANY QUESTIONS VERBATIM)

____

____

ADDITIONAL NOTES:

____

____

____

____

....

....

FOR OFFICE USE ONLY:

QUESTIONNAIRE NUMBER: ______________

CARD A

(a) an angling club

(b) a canoeing club

(c) a rambling club

(d) a bird watching club

(e) a rowing club

(f) Friends of the Earth

(g) a local or county wildlife trust

(h) National Trust

(i) Greenpeace

(j) Royal Society for the Protection of Birds

(k) Council for the Protection of Birds

(l) Council for the Protection of Rural England

(m) a civic or community association

(n) World Wide Fund for Nature

(o) other environmental or recreational groups (please specify)

CARD B

0	1	2	3	4	5	6

CARD C

not important
at all

very
important

0	1	2	3	4	5	6

(a) scenery

(b) the open water body

(c) trees

(d) shrubs

(e) grasses

(f) cleanliness of the water

(g) presence of plants in the water

(h) presence of wildlife

(i) pubs & cafes

(j) parking facilities

(k) peace & quiet

(l) litter

CARD D

not important at all						very important
0	1	2	3	4	5	6

(a) safe area for paddling and swimming

(b) trees

(c) many fish in the water

(d) seats

(e) butterflies

(f) pubs and other social facilities

(g) provision for fishing

(h) diversity of flowering plants and grasses

(i) dragonflies and other water insects

(j) picnic facilities

(k) many kinds of small birds

(l) peace and quiet

(m) ducks and other water birds

(n) provision for boating

(o) frogs and frog spawn

(p) water mammals

(q) parking facilities

(r) water plants

(s) other (please specify)

CARD E

very unattractive						very attractive
0	1	2	3	4	5	6

Photograph A

Photograph B

Photograph C

Photograph D

Photograph E

Photograph F

Photograph G

Photograph H

Photograph I

CARD F

natural

busy

tranquil

dull

wilderness

overgrown

boring

secluded

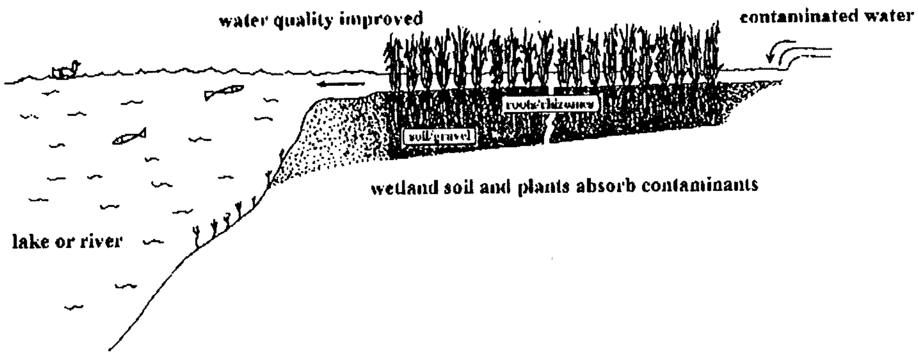
derelict

interesting

clean

dirty

CARD G


water quality improved
contaminated water
roots/rhizomes
soil/gravel
wetland soil and plants absorb contaminants
lake or river

CARD H

-3	-2	-1	0	1	2	3

APPENDIX 2 A STUDY TO ASSESS THE PUBLIC PERCEPTION OF THE AESTHETIC AND WILDLIFE VALUE OF WETLANDS AND THEIR USE FOR WATER QUALITY IMPROVEMENT

MIDDLESEX UNIVERSITY, URBAN POLLUTION RESEARCH CENTRE
CONFIDENTIAL

For Office Use Only

Questionnaire number .... __________
Location ...._________________
Interviewer .... ________________
Interview number .... ____
Date ....../....../1995
Time interview started (24 hour clock) ...._________
Time interview finished (24 hour clock) ...._______
Length of interview (minutes) ...._______

GENERAL USE OF THE SITE

[Q. 1] Which of the following is your main reason for being <u>here</u> today? **(READ OUT) (CIRCLE ONE ONLY)**

walking:	
- the dog	1
- children	2
- strolling	3
- 2 miles or more	4
cycling	5
picnicking	6
nature ramble	7

[Q. 2] How often on average do you come here or other similar open spaces?

at least daily	1
at least a few times a week	2
at least weekly	3
at least fortnightly	4
at least every month	5
at least 5 to 11 times a year	6
yearly or less often	7
never been here before	8

[Q. 3] How much time do you plan to spend <u>here today</u>?

0 - 15 mins	1
16 - 30 mins	2
31 - 60 mins	3
1 - 2 hours	4
2 - 3 hours	5
3 - 4 hours	6
> 4 hours (specify)	7

[Q.4] How far did you travel to get <u>here</u> today?

< 1/2 mile	1
1/2 - 1 mile	2
> 1 mile - 2 miles	3
> 2 miles (specify)	4

[Q. 5] Do you belong to or make donations to any of the following clubs, societies, or groups? **(SHOW CARD A)**
(CIRCLE YES OR NO)

	Member		**Donate**	
	YES	**NO**	**YES**	**NO**
an angling club or association	1	0	1	0
a canoeing club	1	0	1	0
a rambling club	1	0	1	0
a bird watching club or society	1	0	1	0
a rowing club	1	0	1	0
Friends of the Earth	1	0	1	0
a local or county wildlife trust	1	0	1	0
National Trust	1	0	1	0
Greenpeace	1	0	1	0
Royal Society for the Protection of Birds	1	0	1	0
Council for the Protection of Rural England	1	0	1	0
a civic or community association	1	0	1	0
World Wide Fund for Nature	1	0	1	0
other environmental or recreational groups	1	0	1	0
(please specify) ______________________				
none	1	0	1	0

SLIDES OF WETLAND ENVIRONMENTS

(READ OUT)

The following questions relate to photographs of landscapes some of which are found in this area. Could you please look at these photographs and answer the questions for each of them using the rating scales given. **(SHOW CARD B)**

[Q. 6] Do you consider the vegetation to be varied?

	not varied at all				very varied
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 7] Do you think there is a contrast between the water and the surrounding land?

	no contrast at all				a lot of contrast
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 8] Does this scene appear to be natural or artificial?

	very artificial				very natural
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 9] Can you see the water's edge clearly?

	not clearly at all				very clearly
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 10] Do you consider this scene to be interesting?

	very uninteresting				very interesting
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 11] How open is the vegetation?

	not open at all				very open
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 12] Does this scene make you want to explore the area further?

	not at all				very much
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 13] How enclosed is the water by the vegetation?

	not enclosed at all				very enclosed
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 14] Is there much human interference in this scene?

	none at all				a lot of interference
Photograph A	1	2	3	4	5
Photograph B	1	2	3	4	5
Photograph C	1	2	3	4	5
Photograph D	1	2	3	4	5
Photograph E	1	2	3	4	5
Photograph F	1	2	3	4	5
Photograph G	1	2	3	4	5
Photograph H	1	2	3	4	5

[Q. 15] Could you please look at these slides again and this time <u>rate the attractiveness of each as a place to visit</u> on the scale below? **(SHOW CARD C)**

	very unattractive						very attractive
Photograph A	0	1	2	3	4	5	6
Photograph B	0	1	2	3	4	5	6
Photograph C	0	1	2	3	4	5	6
Photograph D	0	1	2	3	4	5	6
Photograph E	0	1	2	3	4	5	6
Photograph F	0	1	2	3	4	5	6
Photograph G	0	1	2	3	4	5	6
Photograph H	0	1	2	3	4	5	6

The photographs you have just seen show various components of wetland environments. The following questions relate to wetland environments.

[Q. 16] Could you please indicate whether you strongly agree or disagree with the following statements using the scale below. **(SHOW CARD C)**

strongly disagree   strongly agree
0 1 2 3 4 5 6

Wetlands are an ideal location for hiking/strolls ....___

Wetlands are an ideal location for wildlife watching ....___

Wetlands could be used for land reclamation ....___

Wetlands are ideally suited to boating ....___

Wetlands could be used for wastewater treatment ....___

Wetlands are an ideal location for nature photography ....___

Wetlands could be used for dumping waste/litter ....___

Wetlands are an ideal location for fishing ....___

Wetlands are an ideal location for a nature reserve ....___

Wetlands are an ideal location for bird watching ....___

Wetlands are an ideal location for picnicking ....___

[Q. 17] How important is the presence of wildlife with regard to the enjoyment of your visit to a wetland site? **(SHOW CARD C)**

not important at all
very important
0 1 2 3 4 5 6

[Q. 18] What types of wildlife would increase your enjoyment of such a visit? **(RECORD VERBATIM AND PROBE)**

WETLANDS FOR WATER QUALITY IMPROVEMENT

Contaminated water often passes through wetlands before entering rivers and lakes. Wetland systems can improve the water quality by filtering out and trapping pollutants found in the water.

Thus wetlands can prevent certain pollutants from entering the natural environment. **(SHOW CARD D)**

The following questions relate to the use of wetlands by society to improve the quality of contaminated water that runs through them.

[Q. 19] Would you agree with the use of natural wetlands to improve water quality? **(SHOW CARD C)**

strongly disagree
strongly agree
-3 -2 -1 0 1 2 3

[Q. 20] Would you please give reasons for your answer.
(RECORD VERBATIM AND PROBE)

[Q. 21] Would you agree with the use of <u>specifically constructed</u> wetlands to improve water quality? **(SHOW CARD C)**

strongly disagree						strongly agree
-3	-2	-1	0	1	2	3

[Q. 22] Would you please give reasons for your answer.
(RECORD VERBATIM AND PROBE)

Could you please look at these three photographs and answer the following question. **(SHOW PHOTOGRAPHS C, F AND G)**

[Q. 23] Would the use of wetlands for improving water quality lessen your enjoyment of a visit to a wetland-type environment?

yes 1
no 0

RESPONDENT INFORMATION

(READ OUT)

The following questions are standard for most questionnaires and are used only for our own classification purposes. Your answers are entirely confidential.

[Q. 24] Gender

female	...	1
male	....	2

[Q. 25] To which of the following age categories do you belong?

18 to 24	....	1
25 to 44	....	2
45 to 64	....	3
over 65	....	4

[Q. 26] Are you currently ...

in full-time employment	....	1
in part-time employment	....	2
unemployed	....	3
retired	....	4
student	....	5
other	....	6

If you are employed (full-time or part-time), then please answer Q. 27.

[Q. 27] What type of work do you do?

(READ OUT)

This is the end of the questionnaire and I would like to thank you for taking the time to answer our questions. Do you have any comments you would like to record below?

CARD A

(a) an angling club

(b) a canoeing club

(c) a rambling club

(d) a bird watching club

(e) a rowing club

(f) Friends of the Earth

(g) a local or county wildlife trust

(h) National Trust

(i) Greenpeace

(j) Royal Society for the Protection of Birds

(k) Council for the Protection of Birds

(l) Council for the Protection of Rural England

(m) a civic or community association

(n) World Wide Fund for Nature

(o) other environmental or recreational groups (please specify)

CARD B

[Q. 6]

not varied at all				very varied
1	2	3	4	5

[Q. 7]

no contrast at all				a lot of contrast
1	2	3	4	5

[Q. 8]

very artificial				very natural
1	2	3	4	5

[Q. 9]

not clearly at all				very clearly
1	2	3	4	5

[Q. 10]

very uninteresting				very interesting
1	2	3	4	5

[Q. 11]

not open at all				very open
1	2	3	4	5

[Q. 12]

not at all				very much
1	2	3	4	5

[Q. 13]

not enclosed at all				very enclosed
1	2	3	4	5

[Q. 14]

none at all				a lot of interference
1	2	3	4	5

CARD C

[Q. 15]

very unattractive

very attractive

0	1	2	3	4	5	6

[Q. 16]

strongly disagree

strongly agree

0	1	2	3	4	5	6

[Q. 17]

not important at all

very important

0	1	2	3	4	5	6

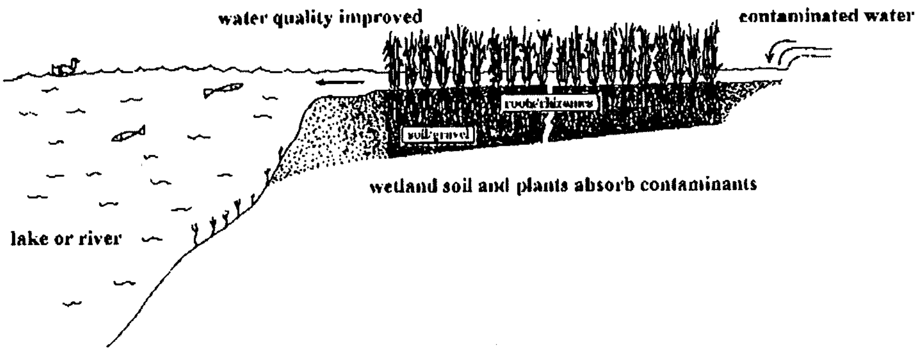
[Q. 19/21]

strongly disagree

strongly agree

-3	-2	-1	0	1	2	3

CARD D


water quality improved
contaminated water
roots/rhizomes
soil/gravel
wetland soil and plants absorb contaminants
lake or river

APPENDIX 3 DETERMINATION OF KENDALL'S RANK CORRELATION COEFFICIENT (τ)

The Kendall rank correlation coefficient is determined as follows:

$$\tau = S/0.5N(N-1) \qquad \text{(Equation A3-1)}$$

$$= \text{actual score/maximum possible score} \qquad \text{(Siegel, 1956)}$$

Where:
τ = Kendall rank correlation coefficient
S = Actual score
N = Number of scenes being ranked

The Kendall rank correlation coefficient, τ (tau), is used as a measure of correlation with data where at least ordinal measurement of variables X and Y has been achieved such that every subject can be assigned a rank on both X and Y. τ gives a measure of degree of association or correlation between the two sets of rank (Siegel, 1956). The sampling distribution of τ under the null hypothesis is known and is subject to tests of significance. In this study for example the variable X is the ranking of the attractiveness of the wetland scenes, and Y, the ranking of the assessment ratios of the wetland scenes. X and Y could also be the rankings of any two visual preference factors whose degree of correlation or agreement is being investigated. This method of correlation allows all the visual preference factors to be analysed with respect to attractiveness together as well as apart. The Kendall rank correlation coefficient ranges from 0 (no correlation at all) to +1 or -1 (correlates perfectly).

To obtain the degree of agreement between the attractiveness (X) of each wetland scene and the combination of the nine visual attributes (i.e. the assessment ratios) (Y) for the wetland scenes, the rankings (from Tables 6.17 and 6.20) are established as follows.

Scene	A	B	C	D	E	F	G	H
Attractiveness (X)	2	5	7	4	1	8	6	3
Assessment ratios (Y)	2	6	8	3	1	7	4	5

The next step is to arrange the order of the scenes so that ranks of attractiveness appear in their natural order (i.e. 1, 2,..., N).

Scene	E	A	H	D	B	G	C	F
Attractiveness (X)	1	2	3	4	5	6	7	8
Assessment ratios (Y)	1	2	5	3	6	4	8	7

To determine the degree of correspondence between variables X and Y, the number of pairs of ranks in Y's set which are in their correct (i.e. natural) order with respect to each other, are determined.

Firstly, all possible *pairs* of ranks in variable Y which ranks 1, the rank farthest to the left of the set, are considered as one member. The first pair, 1 and 2, has the correct order: 1 precedes 2. Since the order is natural, a score of +1 is assigned to this pair. Ranks 1 and 5 constitute the second pair which is also in the correct order and thus earns a score of +1. The remaining pairs of ranks (1 and 3, 1 and 6, 1 and 4, 1 and 8, 1 and 7) are all in the correct orders and all earn scores of +1. Thus for all pairs which include the rank 1, the total score is:

$$(+1) + (+1) + (+1) + (+1) + (+1) + (+1) + (+1) = +7$$

Considering all the scores that begin with the rank 2 (which is second rank from the left in variable Y's set) and the succeeding rank gives six pairs of ranks that are in correct orders and thus a total score of +6.

Considering all the scores that begin with the rank 5 (which is third rank from the left in variable Y's set) and the succeeding rank gives five pairs of ranks: (5 and 3); (5 and 6); (5 and 4); (5 and 8); and (5 and 7). The first and third pair are not in correct order and the score for those pairs is -1. The other three pairs of ranks are in correct orders and all earn scores of +1. Thus the total of the scores which include the rank 5 is:

$$(-1) + (+1) + (-1) + (+1) + (+1) = +1$$

Thus the total of the scores which include the remaining ranks 3, 6 and 5 are +4, +1 and +2 respectively. The rank 8 has only one succeeding rank and therefore only one pair: 8 and 7. The two members of this pair are in the wrong order and thus receive a score of -1.

Thus the actual score (S) is:

$$(+7) + (+6) + (+1) + (+4) + (+1) + (+2) + (-1) = +20$$

(The calculation of S can be considerably shortened from the method shown above by starting with the first number on the left and counting the number to its right which are larger. The number of ranks to its right which are smaller are then subtracted from this. If this is done for all the ranks, S is the sum of the results).

The maximum possible total for the scores assigned to all the pairs in variable Y's ranking would have been achieved if the rankings of variables X and Y matched perfectly. So when the rankings of X were arranged in their natural order, every pair of Y's ranks would also be in the correct order and thus every pair would receive a score of +1. Thus the maximum possible total would be the total of +1's for each rank which would be:

$$(+7) + (+6) + (+5) + (+4) + (+3) + (+2) + (+1) = +28$$

The maximum possible total score can be expressed as $0.5N(N - 1)$.

The degree of association between the two sets of rank is indicated by the ratio of the actual total sum of +1's and -1's (S) to the maximum possible total. This ratio is the Kendall rank correlation coefficient:

$$\begin{aligned}\tau &= \text{actual total/maximum possible total}\\ &= S/0.5N(N-1) = 20/28 = +0.714\end{aligned}$$

Where N is the number of objects or individuals ranked on both X and Y.

Therefore the measure of agreement or correlation between the ranks assigned to variables X and Y is +0.714 (τ can thus be thought of as a coefficient of disarray) indicating that it is reasonable to assume that the *combination* of the nine chosen visual preference factors can help explain the overall attractiveness of a wetland landscape.

Having determined the statistical correlation between the combination of the visual preference factors and the attractiveness of the wetland scenes, the rankings of each individual factor was then correlated with the rankings of attractiveness of the wetland scenes. Thus the order of the scenes were arranged so that the ranks of attractiveness of the wetland scenes appeared in their natural order (i.e. 1, 2,..., N) and the ranks for all the other factors listed below and the Kendall rank correlation coefficient were calculated to see which visual preference factor correlated significantly with the attractiveness of the scenes (Table 6.22).