Protection of the Water Environment Using Balancing Facilities

R&D Technical Report P2-215/TR

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Statement of use
This report summarises the results from a 3 year monitoring period of two reedbeds incorporated as part of surface water storage ponds associated with the Newbury Bypass. It provides information to operational staff who are seeking advice on the construction and operation of constructed wetlands to treat road runoff.

Keywords
Vegetated pond, constructed wetland, reed bed, surface flow system, sub-surface flow system, pond retention time, removal efficiencies.

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EXECUTIVE SUMMARY

This report describes the results obtained during two phases of an extensive monitoring programme (December 1998 to August 2001) of the water quality during dry and wet weather conditions within the balancing ponds, adjacent to the A34 Newbury By-pass. In addition, during Phase 1 (December 1998 to December 1999) the sediment and aquatic plant quality was monitored in one of the ponds. The ponds, along with several others, were constructed for the storage and treatment of surface water run-off from the newly constructed bypass. Pond B is a vegetated pond (predominantly populated by *Phragmites australis*) and Pond F/G is a constructed wetland incorporating a sub-surface flow system and initially two reed species *(Phragmites australis* at the inlet end; *Typha latifolia* at the outlet end). *Phragmites* established itself most successfully in the gravel substrate and because of problems encountered with the development of the *Typha* bed, this was eventually replaced by replanting with *Phragmites*.

The temporal variability of monitored parameters, such as pH, dissolved oxygen, conductivity, BOD_5 and suspended solids, are described and explained in terms of the main influencing factors. There is a tendency for pH to increase slightly across both ponds and towards the end of the monitoring period there was evidence of the occurrence of anaerobic outlet conditions. The measured nutrients during the 24 visits to Pond F/G and the 16 visits to Pond B were chloride, nitrate, phosphate and sulphate. Phosphate was rarely detected and chloride concentrations mirrored the changes in conductivity due to winter salting activities. Initially higher nitrate concentrations at Pond F/G and higher sulphate concentrations at Pond B were not maintained throughout the programme. Total metal concentrations have remained consistently low in the road runoff throughout the monitoring period with only zinc exhibiting levels in excess of 30μg/l. This appears to be consistent with the findings of other workers examining performance of wetland systems associated with other parts of the Newbury By-pass. The seasonal variations of metal levels in the plant biomass are explained in terms of the relevant biological processes. A general decrease in sediment metal concentrations throughout Phase 1 of the monitoring period is encouraging in terms of the long term viability of Pond F/G.

The performances of both ponds are discussed for dry weather conditions and for storm events. Five storm events have been monitored for Pond F/G and for each of these the comparison of inlet and outlet pollutant loadings is based on the retention times determined through lithium dosing experiments. Following antecedent rainfall, the retention time of Pond F/G was of the order of 34 ± 12 hours and that of Pond B, 60 ± 20 hours. There is considerable variability in the parameters analysed in the collected inlet and outlet samples during the routine monitoring programme and this continues when dry weather only data is examined statistically. These results raise concerns about the use of analyses of grab samples for predicting treatment system performances. However, the results do suggest that the median overall removal efficiency for Pond F/G (8.6%) is more significant than the corresponding value (5.6%) for Pond B. The estimation of pollutant removal efficiencies for the 5 monitored storm events at Pond F/G gives more reliable data with good performances indicated for cadmium, chromium, nitrate and suspended solids and only slightly less positive performances for nickel, zinc and sulphate. A comparison of dry and wet weather removal efficiencies indicates that only copper demonstrated a higher removal during dry weather conditions with the release of copper from Pond F/G during 3 of the storm events being difficult to explain. The results suggest that accumulated salts arising from winter de-icing

activities may form complexes with certain metals and may be removed from the pond by increased flowrates associated with storm events.

Based on both the observations during the routine visits and the results obtained from the comprehensive monitoring programme, a range of recommendations have been made. These recommendations are divided into three categories that relate to:

- The future design and construction of wetlands for highway runoff treatment.
- Maintenance and management practices for preserving the operational integrity of existing systems.
- Future monitoring work which will extend our scientific understanding of the operational capabilities of wetland systems.

It is proposed that future monitoring should continue to assess the performances of the ponds as they become more established. However, this monitoring should be on a reduced scale in terms of the analytes to be investigated and it is suggested that chromium and nitrate would be appropriate as indicators of performance, particularly during storm events. It is also recommended that such investigations be made on the basis of inlet and outlet loads to the reedbeds taking into account the pond retention time rather than on the basis of grab samples which were the basis for the work previously undertaken.

1. INTRODUCTION

A comprehensive monitoring programme, covering a period of 33 months, has been carried out on a sub-surface flow constructed wetland (known as Pond F/G, see Figure 1.1) adjacent to the A34 Newbury By-pass. Although nominally a sub-surface flow system, the size and layout of Pond F/G mean that storm flows could over-top the substrate and therefore could turn the system from sub-surface flow to surface flow part way through a storm event. Sub-surface flow systems differ from surface flow systems in that wastewaters flow horizontally or vertically and remain below the level of the substrate. Purification occurs during contact with substrate surfaces and plant roots. The sub-surface substrates are water saturated and may develop anaerobic characteristics except for aerobic micro sites created by the supply of oxygen around plant roots. A view of Pond F/G in May 2001 is shown in Figure 1.4 and this also identifies the limited *Pragmites* growth in the re-planted reed bed. A consecutive monitoring programme of a vegetated balancing pond (known as Pond B, see Figure 1.2) has also been carried out. Ideally, this would have been a vegetation free system so that deductions could have been drawn about the degree of additional treatment, if any, provided by vegetated systems. Photographs of Pond B during spring and early summer are shown in Figures 1.5 and 1.6, respectively. In reality, the reported comparisons represent the difference in treatment performances between a partial sub-surface flow system and a vegetated pond.

Two separate phases, in terms of timing and the types of monitoring, have been achieved. The first of these, involving sampling between December 1998 and December 1999, is referred to in this report as Phase 1. Phase 2 of the overall monitoring programme took place between May 2000 and August 2001. Phase 1 involved 20 routine monitoring visits to Pond F/G and a more limited monitoring programme (12 monitoring visits) for Pond B. In addition to the routine monitoring, the performance of the constructed wetland during two storm events was investigated by taking manual water samples at the inlet to Pond F/G as well as automatically collecting samples from the outlet over the 54 hour period following each storm. The first storm event, on 25 August 1999, coincided with a planned routine monitoring visit and represented the behaviour of the wetland during late summer conditions. The second storm event was representative of the performance of the constructed wetland under winter conditions as it occurred on 8 December 1999.

The objectives of Phase 2 of the monitoring programme were to carry out 4 quarterly sampling visits to both ponds and also to automatically collect inlet and outlet water samples from Pond F/G during 3 distinct storm events. To assist this and to enable a full inlet flow record to be kept, a V-notch weir was installed along the sill of the silt trap at the inlet to Pond F/G. A pressure transducer probe was used to record water height in the silt trap relative to the weir crest and this was calibrated to inlet flow rate (see Figure 1.3). Automatic samplers located at both the inlet and outlet to Pond F/G were connected to a trigger switch which initiated operation when a water height of 15 mm above the weir crest was attained. The inlet sampler was set to sample every 5 minutes for a period of 2 hours whereas the outlet sampling programme involved a delay of 6 hours and a sample collection every 2 hours giving an overall sampling time of 54 hours. Storm events were sampled on the following dates: 26 February 2001, 22 April 2001 and 17 July 2001.

The removal performances, with regard to suspended solids, six metals and four nutrients, for Pond F/G during wet weather conditions, are described in this report and compared with dry weather removal performances. The latter were derived from data obtained from nine of the routine monitoring visits when no or negligible rainfall had occurred during the previous 48 hours. Dry removal efficiencies are also reported for Pond B based on the data collected from seven monitoring visits.

This final report was preceded by a report describing Phase 1 of the monitoring programme (Protection of the Water Environment using Balancing Facilities (Final Field Studies Report), E Mulhall, I Lagerberg, M Revitt and B Shutes, December 2001). In this report, the results of Phase 2 of the monitoring programme are combined with the major findings from Phase 1 to deduce overall interpretations and conclusions from the complete monitoring programme. Phase 2 has been previously described in seven interim reports, of which four cover routine monitoring visits (September 2000, March 2001, September 2001 and March 2002) and three reports deal with the flow monitoring data and results from the three specific storm events which were analysed (March 2002 (2 reports) and June 2002). Sections 2 and 3 of this report explain the ‘Sampling Programme’, and the ‘Sample Collection and Field Measurement’ protocols used. The ‘Laboratory Methodology’ section (Section 4) outlines the techniques employed in the extraction and analysis of water, sediment and plant samples. The ‘Monitoring Results and Discussion’ are covered in Section 5 and this report reviews the trends in the data collected over both Phases of the overall monitoring period (Phase 1; December 1998 to December 1999; Phase 2; May 2000 to August 2001). The report concludes with two sections covering ‘Conclusions’ and ‘Recommendations’ with the latter concentrating on suggestions for updating the Guidelines identified in Treatment of Highway Run-off Using Constructed Wetlands-An Interim Manual (published in 1999).

Figure 1.1 Plan and cross section of Pond F/G

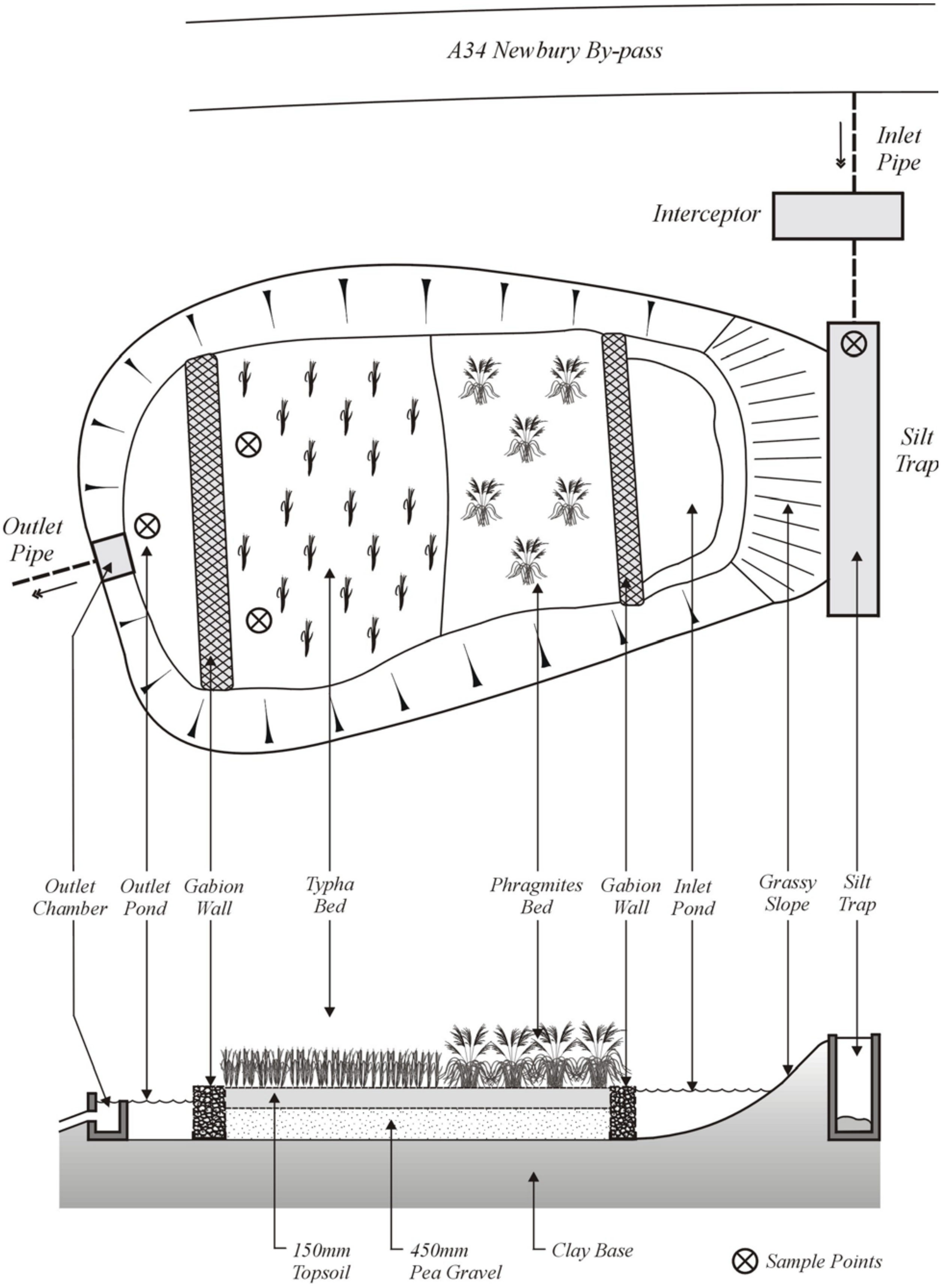


Figure 1.2 Plan and cross section of Pond B

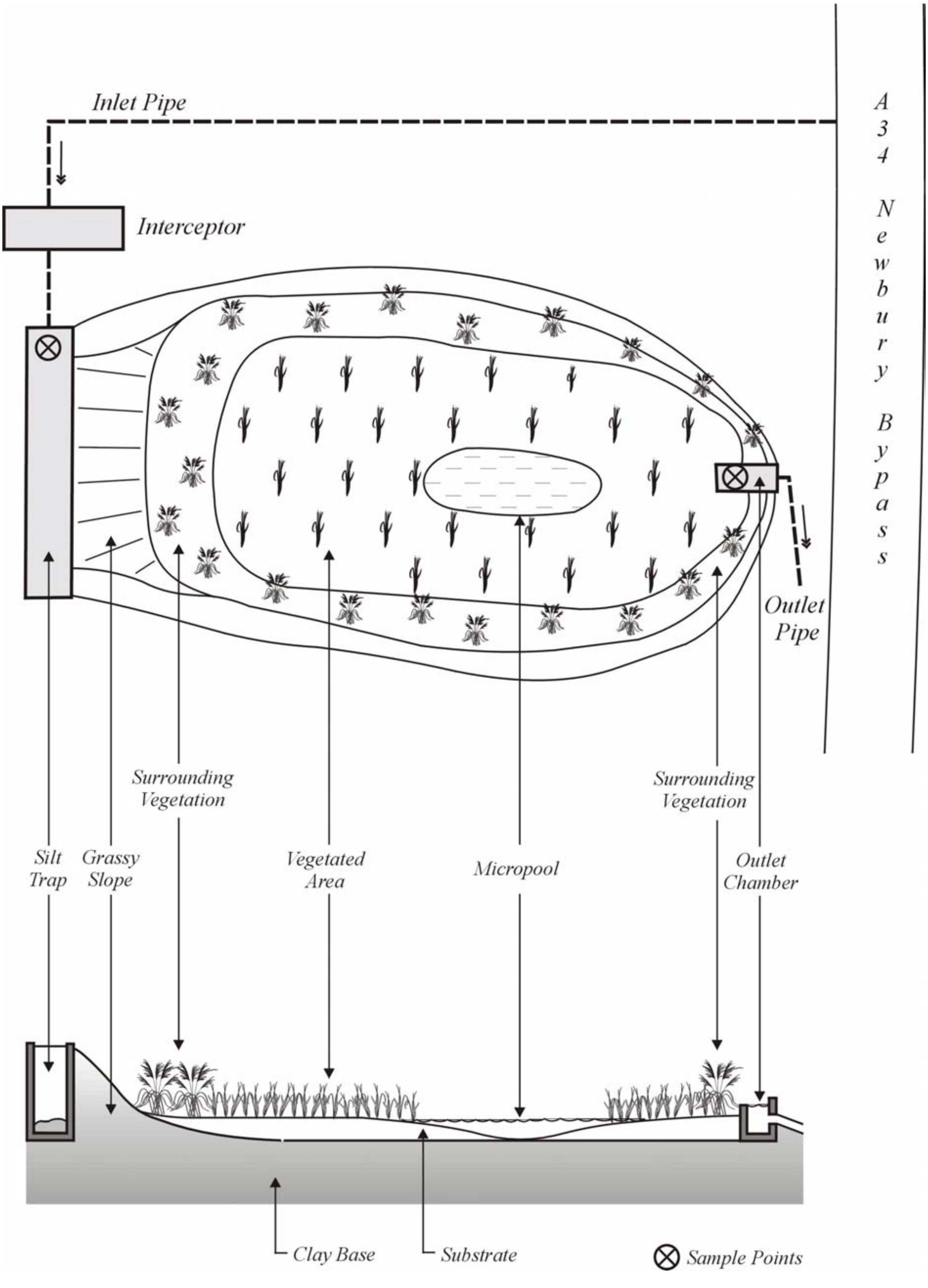


Figure 1.3. Location of transducer probe and trigger switch in silt trap at Pond F/G (with algal accumulation on straw bales in the background) in April 2001.

Figure 1.4. View of Pond F/G on 6th January 1999 looking towards the outlet and with the A34 in the background.

Figure 1.5. Overview of Pond B looking back towards the inlet in March 2001.

Figure 1.6. View of Pond B in May 2001 showing new Phragmites growth and overgrown feeder strip.

2. SAMPLING PROGRAMME

Four sampling sites were identified within the constructed wetland treatment system (Pond F/G; see Figure 1.1). These were:

- wetland inlet (water sample collected from the silt trap adjacent to the inflow pipe)
- the base of an aeration pipe in the *Typha* section of the subsurface flow bed (~5m from outlet end of bed)
- at a water height of 30cm in a different aeration pipe in the *Typha* section of the subsurface flow bed (~5m from outlet end of bed)
- the open wetland outlet pipe immediately before entering the receiving stream.

These sampling sites were used during both phases of the sampling programme except for that at the base of the aeration pipe in the *Typha* bed which was only sampled during phase 1.

The inlet and outlet sampling points were chosen to enable calculation of the pollutant attenuation/enhancement capability of the constructed wetland. However, it is important to note that for the routine monitoring samples, this calculation does not take account of the retention time of the measured pollutants within the pond. The purpose of the bed sampling points was to assess the water quality within the substrate at mid-depth and basal levels to determine the existence of any vertical attenuation of pollutant levels.

Two sampling sites were identified at the control pond (Pond B, see Figure 1.2). These were used throughout both phases of the sampling programme:-

- pond inlet (similar position as for the wetland inlet for Pond F/G); and
- pond outlet (adjacent to metal grill in outlet structure).

These sampling points are directly comparable to the inlet and outlet locations at Pond F/G and enable the estimation of pollutant behaviour during passage through the control pond.

The dates of the routine sampling visits are presented in Table 2.1 together with details of the types of samples collected on each of these dates. Sediment and plant samples were only collected from Pond F/G during Phase 1 of the sampling programme and the four selected occasions were chosen to allow the assessment of any seasonal variations. It should be noted that the samples collected in December 1998 and May 2001 corresponded to Pond F/G being flooded due to the presence of a raised outlet pipe/wooden plate across outlet pipe.

Table 2.1. Details of site visits (including routine sampling) during Phase 1 (December 1998 to December 1999) and Phase 2 (May 2000 to August 2001) of the overall monitoring period.

	Type of sample collected					
	Routine monitoring					
Sampling date	Water samples from Pond F/G	Water samples from Pond B	Sediment samples from Pond F/G	Plant samples from Pond F/G	Storm event water samples from Pond F/G	Site equipment installation and maintenance
04/12/98	✓	✓	✓	✓		
15/12/98	✓					
06/01/99	✓	✓				
29/01/99	✓					
09/02/99	✓	✓				
24/02/99	✓					
16/03/99	✓	✓	✓	✓		
26/04/99	✓	✓				
12/05/99	✓	✓				
02/06/99	✓	✓				
23/06/99	✓					
07/07/99	✓	✓	✓	✓		
27/07/99	✓					
04/08/99	✓	✓				
25/08/99	✓				✓ (25/08/99)	
07/09/99	✓	✓				
07/10/99	✓	✓	✓	✓		
25/10/99	✓					
11/11/99	✓	✓				
25/11/99	✓					
04/12/99					✓ (04/12/99)	
26/05/00	✓	✓				
18/07/00						✓
08/09/00	✓	✓				✓
31/10/00						✓
14/11/00						✓
29/11/99						✓
05/12/00						✓
02/02/01	✓	✓				✓
09/02/01						✓
22/02/01						✓
13/03/01					✓ (26/02/01)	✓
12/04/01						✓
30/05/01	✓	✓			✓ (22/04/01)	✓
17/07/01						✓
02/08/01					✓ (17/07/01)	✓

✓ indicates that samples were collected or that site equipment was attended to.
(--/--/--) = date of storm event (may not coincide exactly with site visit)

In addition to the routine monitoring, five storm events were sampled at Pond F/G. The storms of 25 August 1999 and 4 December 1999 occurred within Phase 1 and in each case, manual water samples were collected at the inlet over intervals of 15-30 minutes during the extent of the storm event. Coincident with this manual sampling, the depth of water over-topping the sill of the sedimentation tank at 3 metre intervals was measured together with the flow velocity using an Ott propeller meter. This enabled the flow rates and hence the inlet pollutant loadings to be calculated. The inlet flow rates for the Phase 2 storms (26 February 2001, 22 April 2001 and 17 July 2001) were calculated from continuously recorded water depths on a data logger using a pressure transducer probe to monitor water depth relative to a V-notch weir. A trigger switch positioned adjacent to the water depth probe in the silt trap controlled the operation of automatic samplers located at both the inlet and outlet positions of Pond F/G. The inlet sampler collected samples every 5 minutes for a period of 2 hours following the onset of the storm event. Outflow samples, during both phases of the monitoring programme, were collected automatically at 2 hour intervals following an initial delay after the storm event of 6 hours. A total of 24 automatic inlet and outlet samples were obtained for each storm event. On return to the laboratory these samples were time and flow selectively combined to produce a total of 8 inlet and 8 outlet samples. These were analysed to provide comprehensive coverage of both the 2 hour inlet flow and pollutant loading during the storm event and the outlet characteristics for the 54 hour period following the storm event.

An overall assessment of the performances of Ponds B and F/G with reference to each measured parameter is presented in this report and recommendations are made in connection with their design, operation and maintenance.

3. SAMPLE COLLECTION AND FIELD MEASUREMENT

3.1 Water Samples

Duplicate water samples were collected manually at each surface water sampling site in Ponds F/G and B using acid washed plastic bottles. The sub-surface sites in Pond F/G (Phase 1 only) were sampled by lowering stoppered plastic containers attached to a cane into identified ventilation pipes to the required depth and then releasing the stopper. On return to the laboratory the water samples were stored at 4°C prior to analysis.

The surface water sampling technique was used for the collection of manual samples at the inlet to Pond F/G during the 2 monitored storm events of Phase 1. The inlet samples during Phase 2 and the outlet samples for both phases, following a storm event, were collected automatically using an Epic 1011 Portable Wastewater Sampler.

3.2 Plant and Sediment Samples

Plant and sediment samples were collected on 4 occasions during Phase 1 (see Table 2.1) for metal and hydrocarbon analysis. The plant sampling involved the collection of a single plant of *Typha latifolia* and *Phragmites australis* from the boundary area between the *Typha* and *Phragmites* beds in the middle of Pond F/G. All plant species were carefully removed using a fork to ensure sufficient sections of the root systems were collected, and the plants were subsequently stored in large plastic bags. Sediment samples were collected using a plastic scoop from the root zone areas of the plants, and transferred to a plastic bag. Both plant and sediment samples were frozen when analysis could not be carried out immediately.

3.3 Other Parameters

Dissolved oxygen content (pHOX meter), temperature (pHOX meter), pH (pH meter) and conductivity (Electronic Switch gear, Model MC-1) were recorded at each water sampling site during the routine monitoring programme. Flow velocity (Ott propeller meter) was also measured at the outlet to Pond F/G, during routine monitoring visits, together with the water pipe cross-sectional parameters to enable the calculation of outlet flow rate (L/s).

During the two monitored storm events of Phase 1, the depths of water over-topping the sill of the sedimentation tank were measured at 3 metre intervals together with the coincident flow velocity using an Ott propeller meter. Prior to the commencement of Phase 2, a weir consisting of 133 V-notches was installed along the length of the outlet concrete sill to the silt trap at Pond F/G. Flow rates were calibrated against water depth over the weir which was continuously recorded using a combined pressure transducer probe/data logger (STS Instruments Model DL/N, V2.10; see Figure 1.3). Following initial instrumentation problems, inlet flow rates were continuously recorded from 31 October 2000 to 2 August 2001.

3.4 Pond Retention Times - Lithium Dosing Investigations

Lithium dosing was achieved by introducing a solution of lithium chloride (150g/l) into the flow at the inlet to each pond. An automatic sampler was set-up at the outlet of the system and programmed to collect water samples at regular intervals over a known period of time. The optimum sampling regime was established by "trial and error" and the automatic samplers at both ponds were pre-programmed to collect 24 consecutive samples at 3 hourly intervals commencing at the time of dosing. Lithium dosing was successfully carried out on a total of 4 occasions at Pond F/G (26 April, 12 May, 2 June and 7 July 1999) and on 3 occasions at Pond B (12 May, 2 June and 7 July 1999).

3.5 Observation of Plant Condition

The condition of the reeds *Typha latifolia* and *Phragmites australis* was carefully monitored throughout both phases of the overall monitoring period. Observations were made of leaf colour, ranging from green to yellow, which provides an indication of water stress and/or iron deficiency. Leaf senescense (or die-back) and leaf height were also recorded.

In pond F/G, the *Phragmites* bed remained healthy throughout the monitoring period except for the expected surface die-back during the winter months. In contrast, the condition of the lower *Typha* bed deteriorated during the monitoring programme and in May 2000 a profusion of unwanted weeds (grass, thistles and docks) was observed to be out-competing new *Typha* shoots in terms of growth potential. Subsequently, the decision was made to re-plant the lower half of the wetland system replacing *Typha* with *Phragmites*. The re-planting took place in early February 2001 and was accompanied by a raising of the water height within the sub-surface bed by placing a wooden plate across the outlet pipe to Pond F/G. This plate was eventually removed at the end of June 2001 thus restoring the holding capacity of the wetland to a level consistent with the most efficient sub-surface treatment potential. Unfortunately, the quality of re-planting was not of a high standard and by the date of the last site visit (August 2001), the new *Phragmites* bed was still struggling to establish itself in competition with other invasive species.

4. LABORATORY METHODOLOGY

The measurement of total heavy metal concentrations in water (µg/l), sediment (µg/g) and plants (µg/g) involved digestion of the sample with concentrated nitric acid, followed by analysis using either Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) or Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The specific procedures employed for acid digestion are described below.

4.1 Extraction Procedures for Heavy Metals

4.1.1 Water samples

Water samples (100ml), collected during Phases 1 and 2 of the monitoring programme, were placed in acid washed teflon beakers, to which 1ml of nitric acid was added, and then evaporated to dryness on a sand bath at 100°C. The residue was dissolved in 1% nitric acid, filtered through a Whatman No.42 filter paper and made up to a final volume of 100ml with 1% nitric acid. Duplicate samples were analysed for lead, copper, cadmium, chromium and nickel by GFAAS and for zinc by ICP-AES.

4.1.2 Sediment samples

Sediment samples, collected during Phase 1 of the monitoring programme, were dried in an oven at 100°C for 24 hours and sieved to the fraction size less than 250 µm. Sub-samples were digested by adding 25ml of aqua regia and then evaporated to dryness on a sand bath at 100°C. The residue was dissolved in 1% aqua regia, filtered through a Whatman No.42 filter paper and made up to a final volume of 100ml. Duplicate samples were analysed for lead, zinc, copper, cadmium, chromium, nickel, vanadium, molybdenum, platinum and palladium by ICP-AES.

4.1.3 Plant samples

Plant samples, collected during Phase 1 of the monitoring programme, were washed thoroughly with tap water to remove all attached sediment and separated into two components; one consisting of the roots and rhizomes, and the other of the leaves. These separate parts were oven dried at 100°C for 24 hours, ground in a mortar and pestle, and digested with 10ml of nitric acid. The residue was made up to a final volume of 100ml using the same procedure as for the water and sediment samples. Duplicate samples were analysed for lead, zinc, copper, cadmium, chromium, nickel, vanadium, and molybdenum by ICP-AES.

4.2 Extraction Procedures for Hydrocarbons

4.2.1 Water samples

Water samples (175ml), from Phases 1 and 2 of the monitoring programme, were progressively extracted (1 hour) by sonication with dichloromethane (DCM) (70ml; 35ml;35ml). Following separation from the water layer, the combined DCM extracts were dried using anhydrous calcium chloride and evaporated to dryness. The weight of total hydrocarbons in the water sample was recorded.

4.2.2 Sediment samples

Sediment samples (100g), from Phase 1 of the monitoring programme, were successively extracted (1 hour) by sonication with DCM (100ml; 50ml; 50ml). Following separation from the water layer, the combined DCM extracts were dried and then evaporated to complete. The weight of total hydrocarbons was compared to the dry weight of the original sediment sample, which was determined by drying a sediment sample in an oven at 100°C for 24 hours.

4.2.3 Plant samples

Plant samples, from Phase 1 of the monitoring programme, were washed thoroughly with tap water to remove all attached sediment and separated into a roots/rhizomes component and a leaves component. Known weights of these separate parts were successively extracted (1 hour) by sonication with DCM (100ml; 50ml; 50ml). Following separation from the water layer, the combined DCM extracts were dried and then evaporated to complete. The weight of total hydrocarbons was compared to the dry weight of the original plant sample, which was determined by drying a plant sample in an oven at 70°C for 24 hours.

4.3 Other Chemical and Physical Analytical Techniques

4.3.1 Chlorides, nitrates, phosphates and sulphates

The concentrations of chlorides (mg/l), nitrates (mg/l), phosphates (mg/l) and sulphates (mg/l) in water samples, collected in Phases 1 and 2 of the monitoring programme, were determined, following appropriate dilutions where necessary, using ion chromatography (Dionex DX-120 Ion Chromatograph).

4.3.2 Biochemical oxygen demand

To determine BOD_5 concentrations, water samples, collected in Phases 1 and 2 of the monitoring programme, were first diluted by a factor of 4 with dilution water (a nutrient solution saturated with oxygen) to ensure that excess dissolved oxygen was present during the experiment. The dissolved oxygen content was immediately measured using a Checkmate DO Meter (mg/l). Samples were incubated in the dark at 20°C and after 5 days the oxygen content was again measured. The difference between the initial and the final dissolved oxygen content represented the BOD_5 value of the sample following incorporation of the dilution factor. BOD_5 was not monitored for the storm events because it was not possible to refrigerate the automatically collected samples during the short time period between sampling and analysis.

4.3.3 Suspended solids

The concentrations of suspended solids in 500ml water samples were measured by vacuum filtration through pre-weighed and pre-washed filter papers (Whatman No.42). The filter papers were dried to constant weight at 100°C to determine the mass of suspended solids in the sample. Due to low collection volumes in some of the automatic samples obtained in Phase 2 of the monitoring programmes it has not been possible to report complete suspended solids concentrations for the 3 storm events and hence to calculate removal efficiencies.

4.4 Lithium Concentrations in Water Samples

Water samples collected from the pond outlets following dosing experiments were analysed directly for lithium in the laboratory using atomic absorption spectroscopy in emission mode (Model PU 9100X). The instrument was calibrated using known lithium concentrations in the range 0 to 0.2 mg/l.

4.5 Quality Control during Sampling and Analysis

During the monitoring programme every effort has been made to preserve the sample integrity during the collection and subsequent preservation stages and to ensure that quality control procedures have been maintained during laboratory analysis. The steps taken to comply with these requirements are described in the following sub-sections:

4.5.1 Field measurement

In-situ measurements (dissolved oxygen (DO), temperature and pH) have been employed where reliable techniques exist and where sample integrity following collection could not be guaranteed. The dissolved oxygen and pH probes were calibrated in the laboratory prior to field use but there were occasions when the DO probe behaved erratically and in these instances the field measurements are reported as ‘not detected’.

4.5.2 Sample collection

Water samples were collected manually in acid washed plastic bottles which represents the ideal conditions for obtaining samples for subsequent metal analysis. Plastic containers are not ideal when the collected water samples are to be analysed for organic components but for this project, metal analysis was considered to be the more important. Prior to collecting the water samples, the plastic containers were repeatedly and thoroughly rinsed with sample water in order to ensure that the acid wash did not influence any of the subsequently monitored parameters. During automatic water sampling, samples were also collected in acid-washed plastic containers but in this case they were thoroughly rinsed with distilled water before installing on site.

The collected plant species, in Phase 1 of the monitoring programme, were always from adjacent positions within the substrate of Pond F/G to enable realistic comparability of pollutant levels on a seasonal basis without any influence from location effects. Following removal of the individual plants, sediment was collected from the root zone area. Both sediment and plant samples were immediately placed in plastic bags for return to the laboratory.

4.5.3 Sample preservation

Sample preservation is a critical component of all monitoring programmes. In order to preserve sample integrity all manually collected samples were returned to the laboratory as rapidly as possible and either immediately analysed or stored at 4°C (water samples) or frozen (sediment and plant samples) to prevent the on-set of any biochemical processes. In the case of automatically collected water samples it was not possible to return these immediately to the laboratory, partly because of the 54 hour collection period. However, following the completion of the sample collection period every effort was made to return the water samples to the laboratory as soon as possible.

4.5.4 Laboratory analyses

All laboratory analyses were performed in duplicate and where the results indicated a mean value with a standard deviation exceeding ±10% of the mean value, further analyses were carried out until the required reproducibility was achieved. The main instrumental techniques used were Graphite Furnace Atomic Absorption Spectrophometry (GFAAS) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) (for metal analysis) and Ion Chromatography (for nutrient analysis). Prior to use, each instrument was fully calibrated within the required analytical range. In situations where analytes were more concentrated than the calibration range, appropriate dilutions were employed. The choice of instrumental technique for metal analysis depended on the environmental level with the more sensitive GFAAS being used for all analysed metals (lead, copper, cadmium, chromium and nickel) in the water samples except for zinc. This technique was too sensitive for the environmental zinc levels and therefore it was necessary to use ICP-AES for this metal. The higher metal concentrations in the extracts from the sediment and plant samples required the use of ICP-AES for analysis as opposed to the excessive dilution which would have been needed to conform to the calibration range of GFAAS. The four additional metals (vanadium, molybdenum, platinum, palladium) analysed in plant and sediment samples compared to water samples could only be analysed by ICP-AES because of equipment requirements.

The authenticity of the metal analytical procedures has been verified by applying them to the extraction and analysis of Standard Reference Materials (SRM's). The relevant certified reference materials were Surface Water (SPSW1) and Chinese Stream Sediment (GBW 07311), both of which were supplied by Promochem Ltd, Welwyn Garden City, Herts, England. These reference materials were selected as the quoted certified metal concentrations were within the range of values recorded in water and sediment samples collected at both sites during the monitoring programme. Table 4.1 gives the metal concentrations determined for each of the reference materials in comparison with the certified values.

The values determined for the surface water reference material using the routine method agreed well with the certified values except for lead where a comparison of the values indicated an extraction efficiency of only 58%. As the values for the other metals compared well, it was thought that this lower extraction efficiency for lead may be a due to a problem with the reference material. To test this hypothesis, the extraction procedure was repeated on a lead standard solution (5μg/l) which resulted in a lead extraction efficiency of 83%. Although this value is less than the extraction efficiencies reported for the other metals it is considerably greater than the extraction efficiency reported for the reference material, supporting the suggestion that the lower extraction value is associated with the reference material itself rather than with the extraction procedure.

Table 4.1 Mean metal concentrations determined in standard reference materials using routine extraction procedures in comparison to certified values (± standard deviation)

	Zn	Cd	Cr	Ni	Cu	Pb
Surface water sample (µg/l)						
determined values	19±2.8	0.5±0.0	1.8±0.28	9.9±1.9	21.4±2.3	2.9±0.17
certified values	20±1	0.5±0.01	2.0±0.01	10±0.1	20±1.0	5±0.1
Chinese Stream Sediment sample (µg/g)						
determined values	250±10.7	4.6±0.3	9±0.9	40.2±1.9	44±3	436±34
certified values	373±21	2.3±0.2	40±4	14.3±1.5	79±4	636±34

The values determined for the sediment reference material using the method vary markedly from the certified values (Table 4.1). The determined values are the mean of four separate samples; two of the samples involved the digestion of 5g of reference material, and two samples involved the digestion of 10g of reference material. The SDs associated with the mean values indicate that the concentrations determined were consistent for all four samples. The reference material originated from China, and although the UK supplier stated, in their brochure, that total dissolution techniques were used in the certification procedure, the company was not able to provide any further information on the extraction process. It is thought that possible differences in the extraction procedures employed are an explanation for the differences between the certified and determined values.

5. MONITORING RESULTS AND DISCUSSION

5.1 Pond Retention Times - Lithium Dosing Results

Lithium dosing experiments were carried out to determine the retention times of both ponds in April, May, June and July 1999 (Phase 1 of the monitoring programme). The incident rainfall intensities occurring immediately before the dosing and also during the measured dosing event were also obtained. Rainfall data was provided by the Environment Agency and was measured at Chieveley which is 7.5 km to the north of the project site. The results for Ponds B and F/G are shown in Table 5.1.

Table 5.1. Estimated retention times within Ponds B and F/G from lithium dosing experiments

Date	Antecedent conditions	Pond	Outlet flow rate (l/s) – Pond F/G only	Estimated retention time (hours)
April 1999	Steady rainfall (3.44mm; maximum intensity 0.6mm/hour)	F/G	2.59	~45
May 1999	No rainfall in preceding 12 hours. Intermittent rainfall (10.2 mm), 22-33 hours before dosing	F/G	0.8	~40
		B		n/a
June 1999	Heavy rainfall (35mm; maximum intensity 10.6mm/hour) prior to dosing	F/G	8.6	~30
		B		~48-60
July 1999	No rainfall	F/G	0.91	~85
		B		~90-120

n/a = not available from data obtained

5.2 Routine Monitoring

It is important to note that the samples obtained from the inlets and outlets of both ponds were taken almost simultaneously and therefore do not take account of the retention time within each pond. As such, comparison of the measured concentrations can only provide a guide and cannot be used to definitively predict pollutant removal efficiencies. The most accurate data regarding removal efficiencies are provided by the storm results (see Section 5.3) in which allowance is made for the pond retention time when comparing inlet and outlet loadings. However, the pollutant concentrations obtained during the routine monitoring exercise provide important information regarding trends as well as indicating changes relevant to the physico-chemical and biochemical processes within the ponds. These aspects are discussed in the following sections.

5.2.1 Field monitoring results

pH

The measured pH values throughout both phases of the monitoring period showed no significant deviations from neutrality, ranging from a minimum of 6.3 to a maximum of 8.8. Only three pH values greater than 8.0 were measured with the majority being in the 6.5 to 7.5 range. Inlet pH values for Pond F/G were generally higher than those for Pond B. It is known that the inlet of Pond F/G is influenced by a groundwater source which does not affect Pond B and this may be the reason for the differences. A tendency for pH values to increase slightly between the inlets and outlets of both ponds was observed. There is no evidence of acidic conditions which could result in the release of metals from the sediment to the aqueous phase. It is clear that the natural acidity of rainfall (pH ≤5.5) is being efficiently buffered within the catchment areas of both ponds and there is no need, at this stage, for any remedial action to raise the pH of the inlet waters in the silt trap.

Dissolved oxygen (DO)

As the ponds have become more established, there is clear evidence of a decrease in dissolved oxygen concentrations between the inlet and outlet of each pond. This can be explained by increased oxygen demand of the roots of the planted *Phragmites and Typha*, particularly during the spring and summer growing seasons, which out-competes oxygen production due to photosynthetic activity in the pond. The general occurrence of low dissolved oxygen levels at the pond outlets is of concern because of the potential stress which may be caused to aquatic species and the absence of dissolved oxygen at the outlet to Pond B in February 2001 is particularly worrying as it may indicate the onset of anaerobic conditions at this location. Dissolved oxygen concentrations at the pond inlets were often lower during the summer and autumn months due to depletion of oxygen in the surface runoff waters resulting from increased biodegradation during the warmer weather. This occurrence of low incoming dissolved oxygen levels can be partly attributed to increased oxygen demand from accumulated silt and algae and may indicate the need for a higher frequency of cleaning and de-gritting of the silt traps.

5.2.2 Conductivity, BOD_5, suspended solids and hydrocarbons

Conductivity

Conductivity values have generally remained below 1000 µS/cm at both inlets and outlets to the ponds although there have been occasional instances of relatively high conductivity (>2000µS/cm). These elevated values are mirrored by high concentrations of chloride clearly indicating that they are almost certainly a consequence of the use of de-icing salts on the road surfaces. The elevation of conductivity values by chloride ions emphasises the importance of planting macrophytes with a high tolerance of salinity in the ponds. *Phragmites australis* grows well in brackish waters and is therefore appropriate for planting at the inlet of Pond F/G, but *Typha latifolia* does not have the same range of salinity tolerance and could be susceptible to damage by elevated concentrations of chloride. There is some evidence of increases in conductivity levels through the ponds, which in spring and summer months can be explained by exudates produced due to the presence of abundant algal growth.

Biochemical Oxygen Demand (BOD_5)

The BOD_5 concentrations in the inlets and outlets of both ponds remained relatively low during the 33 month monitoring period except in May 2001 when high inlet (33.9-41.0 mg/l) and outlet (43.0-48.0 mg/l) levels were recorded for both ponds. These elevated BOD concentrations are difficult to explain by natural processes as increased levels of organic matter due to die-back of vegetation would not be expected at this time of the year. However, the associated observation of abundant algal growth may be a factor and the higher BOD levels in May 2001 are consistent with large decreases in dissolved oxygen monitored between inlet and outlet positions (11.5 to 3.0 mg/l in Pond F/G; 8.3 to 1.0 mg/l in Pond B). Therefore, the regular removal of decomposing algae and macrophytes from the final settlement ponds as well as the silt traps is essential to maintain low BOD values.

Considerable seasonal variation has been observed in the performances of both ponds during the overall monitoring programme with increasing outlet BOD values being attributable to seasonal decomposition of floating and submerged macrophyte tissue. During the summer, both ponds initially appeared to provide removal of BOD although removal trends were variable. However, this was not the case for Pond F/G during the final phase of the monitoring programme when a consistent increasing BOD trend between inlet and outlet positions was observed, with the spring/summer behaviour being explainable by visible accumulation of plant tissue at the outlet. In contrast, Pond B demonstrated BOD removal during the same period.

Suspended solids

The measured suspended solids concentrations at the inlets and outlets to both ponds remained low (below 30 mg/1) except for the results obtained during the May 2001 routine monitoring exercise. On this occasion there was also a notable increase between the inlet and outlet monitoring points in both ponds which is associated with the production of algal exudates (see also the discussion on Conductivity elsewhere in this report). This behaviour with respect to suspended solids is completely different to that a year earlier in May 2000 and identifies the possible variability in seasonal variations from year to year. The generally low inlet suspended solids concentrations in the early part of the monitoring programme reflect the successful development of vegetation and hence erosion control on the road verges and efficient sediment removal by the silt trap. The low suspended solids concentrations are believed to influence the removal efficiencies which are generally low and there is little evidence to suggest any substantial difference between surface and sub-surface flow systems for removal of suspended solids.

Hydrocarbons

The monitoring results do not enable any removal characteristics to be identified for either pond for aqueous hydrocarbons. Hydrocarbon concentrations were highly variable with samples collected at the beginning and end of the monitoring period having concentrations below the analytical detection limit. It is believed that the observed hydrocarbon concentrations during September to November 1999 are due to the resurfacing of the road which took place at this time.

5.2.3 Nutrient concentrations

Chloride

Chloride is considered to be a conservative parameter and, therefore, it is not surprising that neither pond demonstrated a consistent ability to remove it. Particularly high inlet chloride concentrations were occasionally observed which were almost certainly due to road salting having taken place. Where chloride concentrations increased between the inlets and outlets it is possible that chloride ions derived from previous road salting applications were being flushed out of the ponds. However, there are some instances where outlet chloride elevations (eg. Pond B in May 2001) cannot be easily explained. The observed trends in chloride concentrations always closely mirror those exhibited by conductivity and as mentioned earlier, this may have implications for the selection of reed species to ensure plants are sufficiently tolerant to the salinity ranges experienced. The measurement of chloride concentrations is also relevant as the levels of this ion can influence the mobility of certain metals and hence have implications for the metals leaving the ponds.

Nitrate

The inlet nitrate concentrations were initially higher than expected, particularly for Pond F/G (>50 mg/l) but after establishment of roadside vegetation these values have consistently decreased to levels below 10 mg/l. Comparison of the inlet nitrate concentrations to both ponds shows that these are higher for Pond F/G. An agricultural source resulting in contaminated spring water feeding into Pond F/G is considered to be a possible explanation for this. During the first few months of the monitoring programme there was no evidence for nitrate removal in Pond F/G whereas there was a consistent removal within Pond B for the same period. However, once the reeds had become established during the summer months of 1999, Pond F/G began to consistently exhibit removal of nitrate and this has been maintained. During the same period, nitrate was virtually eliminated by Pond B but this efficiency has fluctuated between positive and negative values in the final phase of the monitoring programme. The results demonstrate that the overall performance of the sub-surface system pond exhibits better removal of nitrate than the surface flow system indicating the importance of root/substrate based microbiological processes in the breakdown of nitrate ions.

Phosphate

Phosphate concentrations were only detected at the inlet to Pond F/G and only on 3 occasions during the first phase of the monitoring period. Phosphate was not detected in the inlet or outlet to Pond B. In all cases it was suspected that an agricultural source was responsible for the presence of phosphate in the inlet samples to Pond F/G. In all three instances, the phosphate was completely removed.

Sulphate

Sulphate concentrations (within the range 50-200 mg/l) were consistently higher at Pond B compared to Pond F/G with this trend being most exaggerated during the first six months of Phase 1 of the monitoring period. There were no distinct behavioural trends for sulphate within either pond across the full monitoring period although removal efficiencies of up to 77% have been observed for Pond B. Sulphate removal within the ponds may be dependent on the presence of sulphate reducing microorganisms and the performance, particularly of

Pond F/G, might have been expected to improve as the populations of relevant microorganisms increased in the sub-surface wetland substrate. The results have not demonstrated this to be the case.

5.2.4 Metal concentrations

The concentrations of metals analysed during the monitoring period represent total aqueous metal which includes both the soluble metal and that associated with fine suspended solids. The measured metal concentrations are all lower than those which would be expected in the runoff from a road with the traffic density associated with the Newbury Bypass (>35,000 vehicles per day). It is believed that this is due to the relative newness of the road surface which still retains the ability to preferentially adsorb metal ions rather than allowing them to be transported within drainage waters. The observed averages and ranges of the metal concentrations for both ponds are shown in Table 5.2. Similar low metal runoff concentrations have been reported by workers researching the performance of other balancing ponds associated with the Newbury Bypass (H Pontier, E May and JB Williams, Constructed wetlands for the treatment of runoff from the Newbury Bypass, *J Ch Instn Wat and Envir Mangt.*, 2001, **15**, 125-129; RJ Hares and NI Ward, Efficiency of wetland treatment ponds for removing chemicals (Heavy metals and cations/anions) from stormwater since the opening of a new bypass (A34) at Newbury, *Sci. Tot. Environ.*, (In Press)).

Table 5.2. Means (with standard deviations) and ranges of metal concentrations detected in Ponds B and F/G during the 33-month monitoring period.

	Average concentration(µg/l) with standard deviation	Range of concentrations (µg/l)
Copper	6.74 ± 5.20	nd - 25.6
Cadmium	0.66 ± 0.90	nd - 2.3
Chromium	3.65 ± 4.30	0.1- 27.6
Nickel	5.75 ± 3.78	nd - 14.3
Lead	1.41 ± 1.99	nd - 6.1
Zinc	21.61± 14.82	4.0 - 79.5

The low metal levels as well as their extreme variability are shown in Table 5.2. Within each pond there is a tendency for the removal of each metal to be more significant as the inlet metal concentration increases. However, based on consideration of the metal concentrations in grab samples collected at the inlet and outlet positions there is limited evidence for consistent removal efficiencies. The behaviours of specific metals are discussed in the following sections.

Copper

Plant and organic materials are known to have a high affinity for copper. Therefore, it might be expected that the concentrations of copper would be highest in autumn/winter due to the presence of decomposing plant tissue and that the removal performances within the ponds would be most efficient in spring/summer due to uptake by growing plants.

During the spring months it appears that for Pond B there was a net increase in copper due to the rate of release from decomposing plant tissue being higher than the rate of uptake by new plant growth. For Pond F/G, removal efficiencies of approximately 67% were consistently measured for this same period except during May 2001 when the maximum measured copper concentration of 25 µg/l was observed at the outlet to Pond F/G. There is evidence for an additional copper contribution from Pond F/G during storm events (see Sections 5.3.1 and 5.3.2) but this has not previously been recorded during routine monitoring and is not easily explainable. During the summer months both ponds demonstrated the ability to remove copper as could be predicted due to plant uptake of this essential micronutrient. Pond F/G appeared to function more efficiently when inlet copper concentrations were higher. From late August onwards, inlet copper concentrations to both ponds were low and there was no consistent pattern of removal within either pond. The overall results are inconclusive although there is some evidence that the sub-surface flow system performs more efficiently during the summer period.

Cadmium

Cadmium concentrations were consistently low throughout the 33 month monitoring period. This is in line with what would be expected for road runoff. The low concentrations make estimation of removal efficiencies difficult. Pond B exhibited up to 67% removal while pond F/G exhibited up to 83% removal. These results indicate a slight advantage in favour of the sub-surface pond with respect to cadmium removal.

Chromium

The measured total aqueous chromium concentrations were lower than would be expected for runoff from a road with the traffic density associated with the Newbury Bypass (see Table 5.2). Chromium concentrations were generally low in the inlet waters to both ponds. No discernible removal trend could be determined for Pond B except during Phase 2 when all four visits recorded concentration decreases between inlet and outlet. The reverse trend occurred for Pond F/G which exhibited a consistent ability to remove chromium (with removal rates of up to 60%) during Phase 1 but the Phase 2 performance was variable. The overall results indicate no preferential removal performance for chromium from either pond.

Nickel

Nickel concentrations in the runoff to both ponds were of similar magnitudes and consistent removal efficiencies were observed for both ponds throughout Phase 1 although a more random behaviour was noted during Phase 2. Removal efficiencies of up to 87% were observed dropping to 55% at higher flow rates through the ponds. There appears to be little overall difference in performance between the two ponds although the sub-surface flow system was more efficient during Phase 2.

Lead

Lead concentrations at the inlets and outlets of both ponds were often below the limit of detection and when detected the concentrations were consistently low. Up to 90% of the lead in road runoff is believed to be associated with particulate matter and the low levels observed may be indicative of the retention of lead containing particles within the new road structure material as mentioned earlier. Estimation of removal efficiencies is difficult due to the very limited data and by the relatively low monitored concentrations. The performance of Pond B improved during Phase 2 with removal efficiencies increasing to 45%. The maximum removal efficiency for Pond F/G was 73% but an overall comparison of the two ponds suggests little difference between them with respect to lead removal.

Zinc

Zinc concentrations were the highest of all the determined metal concentrations throughout the monitoring programme (Table 5.2). This is consistent with previous studies of the behaviour of this metal in highway runoff. Both ponds showed variable removal of zinc between inlet and outlet sampling points with removal efficiencies of up to 60% and 75% being observed for Ponds B and F/G, respectively. The performance of Pond F/G generally improved as the *Phragmites* bed became more established and there was evidence of efficient removal in the summer months which correlates with the expected metal uptake by plants at this time of year.

Both ponds have demonstrated the ability to remove zinc from highway runoff but the absence of a consistent trend between inlet and outlet positions is clearly evident from Figure 5.1, which shows the measured zinc levels for all samples collected during the 33 month monitoring period. For Pond F/G, there are 15 instances when zinc concentrations decreased between inlet and outlet positions, 7 instances when an increase in concentration occurred and 2 instances when identical concentrations were recorded. The comparable numbers for Pond B were 11, 4 and 1. Thus, the use of routine monitoring data indicates the existence of a random removal of zinc within both treatment systems.

5.2.5 Summary of inlet and outlet water sample data

The variability shown in Figure 5.1 for zinc was also demonstrated by the other pollutants measured during the routine monitoring. Therefore, the available evidence suggests that routine monitoring, in the form of analysed grab samples from the inlet and outlet positions, cannot be reliably used to determine treatment performance. This is not completely unexpected as the consecutive collection of samples does not take into account the residence time of pollutants within the system. The unreliability is further compounded by the collection of grab samples during both dry and wet weather conditions. During wet conditions the incoming pollutants will be strongly influenced by rainfall characteristics whereas outlet samples may relate to runoff which entered the pond under relatively dry conditions. Therefore, a more realistic comparison of inlet and outlet concentrations would be obtained by excluding the wet weather results obtained by grab sampling and only considering data collected when there was negligible rainfall during the 48 hours prior to sampling. Applying this approach reduces the usable data sets from 24 to 9 for Pond F/G and from 16 to 7 for Pond B. To investigate the environmental relevance of the resulting dry weather data sets, these have been analysed statistically.

The trends in the derived dry weather removal efficiencies are represented by box plots produced in MINITAB^{TM} (Figure 5.2). The continued variability of the dry weather only data is clearly demonstrated by consideration of the inter-quartile ranges (rectangular boxes) and the positions of the median values (horizontal lines within boxes) and mean values (solid dots). The extending vertical lines indicate upper and lower limits beyond the quartiles as ± 1.5 times the inter-quartile ranges. The greatest variability occurs for chromium in Pond B and the emphasis on negative removal can be explained by two high outlet chromium concentrations early in the monitoring period. In contrast, Pond F/G exhibited a consistent positive removal for chromium with little variability in values for the different sampling dates. The behaviour of nickel in Pond F/G is also characterised by consistently positive removal efficiencies with mean and median values between 60 and 75%. The other parameters showing predominantly positive removals are cadmium (in Pond F/G), nickel, sulphate and lead (in Pond B) and nitrate and zinc (in both ponds). However, the variability in each of these cases does not generate confidence regarding the validity of using periodic dry weather grab sampling to assess the performance of treatment ponds receiving highway runoff. The mean removal efficiencies of both suspended solids and BOD were indicated to be negative under dry weather conditions although the median value was positive for BOD in Pond F/G. The absence of suspended solids removal during low flow conditions is unexpected and is probably a function of the generally low inlet concentrations which were monitored.

Application of the Anderson-Darling normality test to the dry weather removal efficiency data sets provides evidence that all parameters are non-normally distributed for both ponds. Analysis of the data sets using the Wilcoxon Signed Rank Test shows that there is no significant overall difference between the removal efficiencies for Ponds B and F/G. The median removal efficiency for Pond F/G of 8.6% is significantly greater ($p<0.05$) than zero removal which was not the case for Pond B where the median removal efficiency was 5.6%. Therefore, both ponds exhibit low but positive overall removal efficiencies under dry weather conditions based on the analysis of grab samples collected simultaneously at the inlets and outlets. However, the large variability in the data raise questions concerning the validity of using instantaneous pollutant concentrations to determine removal efficiencies despite the cost effectiveness of this approach. This is particularly relevant when the monitored incoming water does not directly relate to that which is leaving the system. A more realistic approach would be to determine input and output pollutant loadings and to temporally match these by taking into account the retention time of the treatment system. This procedure has been attempted for Pond F/G during storm events (see Section 5.3) when the pollutant removal capability of runoff is at its most critical due to the presence of high inlet loadings and the increased possibility of resuspension within the treatment ponds.

Figure 5.1. Comparison of inlet and outlet concentrations of total aqueous zinc concentrations at Ponds F/G and B.

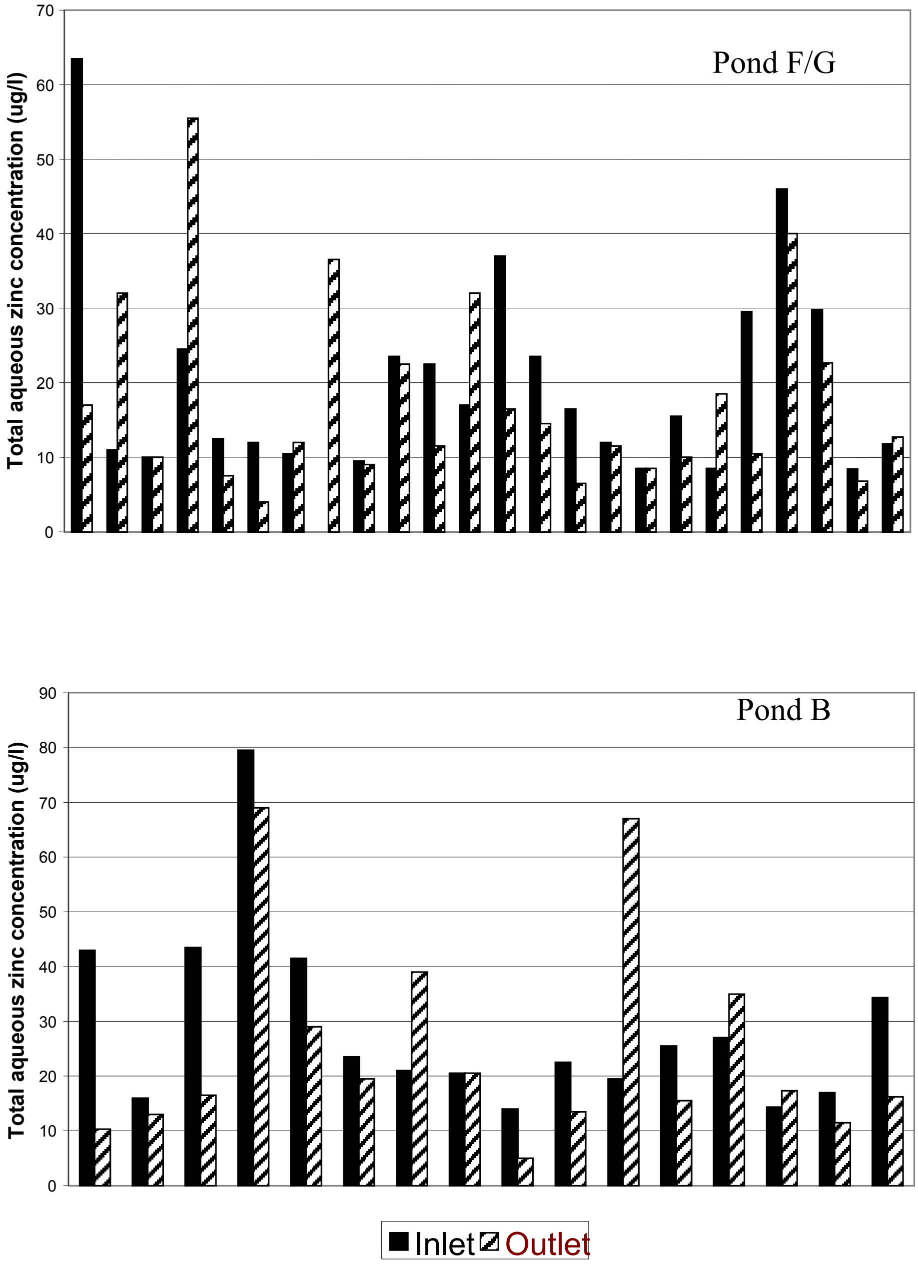
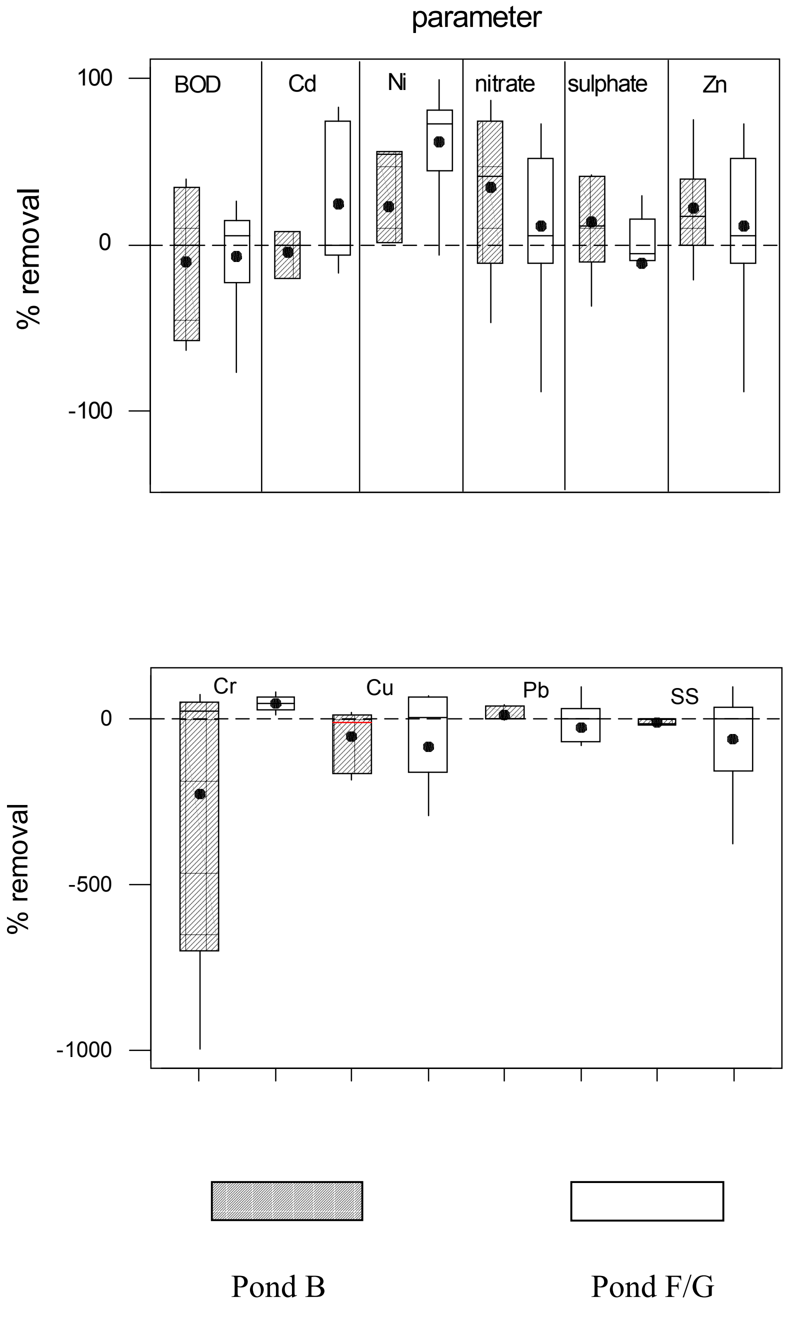


Figure 5.2. Statistical summary of removal efficiencies for Ponds B and F/G during dry weather conditions.



5.2.6 Metal and hydrocarbon levels in plant tissues and sediment

Plant tissue and sediment samples were collected from Pond F/G on only four seasonal occasions during Phase 1 of the monitoring programme and therefore the following interpretations are based on a restricted data set.

Metals in plant tissue

Total metal concentrations in the leaves and roots/rhizome of *Phragmites australis* and *Typha latifolia* collected from Pond F/G were examined in order to determine the levels of bioaccumulation in plant tissue. Many metals were only found in very low concentrations so, in the case of lead, molybdenum, chromium, platinum, cadmium and palladium no conclusions may be drawn on the preference for root/rhizome or leaf tissue.

During the spring there was a fall in *Phragmites* leaf metal concentrations for all metals except copper but increased concentrations of zinc, copper, nickel and vanadium in the root/rhizomes. This apparent preference for the root/rhizome continued during the summer particularly for copper. It should be noted that root and leaf concentrations may fall during spring and summer but that total metal loads will increase with increased biomass arising from spring and summer growth. During the autumn, zinc, copper and nickel continued to indicate a preference for the root/rhizomes, especially as leaf growth ceased.

Other than for zinc, vanadium and copper, there was no obvious affinity for the root/rhizome or leaves of *Typha* by any metals during winter. In the spring sample the concentrations of zinc, copper, nickel and vanadium increased in the leaves. Root concentrations for copper and nickel were reduced. During the summer, both root/rhizome and leaf concentrations were reduced, which may have been due to the poor condition of the plants at this time due to die-back caused by a reduced water intake as a consequence of a limited ability of the roots to reach the lowered water level.

Metals in sediment

Total metal concentrations in sediments collected from Pond F/G showed a general decrease over Phase 1 of the monitoring period particularly for chromium, copper, lead, nickel and zinc. The major contributing factors to the overall reduction in sediment metal levels were metal uptake by the two plant species and pre-treatment in the silt trap and grass filter zone. There was no evidence for significant uptake of platinum in either of the plant tissues but its presence in the sediment indicates the need for concern with regard to future environmental contamination by this metal.

Two of the monitored storm events (Storm 1, Section 5.3.1; Storm 2, Section 5.3.2) indicated a copper contribution by Pond F/G during wet conditions. To investigate if this was due to the presence of a copper rich environment, soil samples were collected from both the *Typha* and *Phragmites* beds in July 2000. The determined copper soil concentrations of 8.7 µg/g (*Typha* bed) and 7.0 µg/g (*Phragmites* bed) equate to the expected copper content of a typical natural unpolluted soil (~15 µg/g) and there is clearly no evidence for permanent copper contamination of the soil substrate in Pond F/G.

Hydrocarbons in plant tissue and sediment

Hydrocarbon sediment concentrations remained low in comparison to plant tissue samples throughout the first year of monitoring. The higher hydrocarbon concentrations in the plant tissues, and particularly the leaves, are almost certainly due to naturally occurring biosynthetic hydrocarbons. Highest hydrocarbon leaf concentrations were found in the summer samples of both *Typha* and *Phragmites* species when tissue growth was at a maximum.

5.3 Storm Event Monitoring

Five storm events have been monitored at the inlet and outlet to Pond F/G. During Phase 1 of the monitoring programme, inlet samples were manually collected whereas during Phase 2, both inlet and outlet samples were automatically collected on receipt of a signal from a trigger switch responding to the rising water level in the silt trap as a storm event commenced. The dates on which the 5 storms occurred, together with their future identification in this report are given in Table 5.3.

Table 5.3. Identification of the monitored storm events and their major hydrological characteristics.

	Date	Total runoff volume (m3)	Peak flow rate (l/s)	Storm duration (hour)
Storm 1	25 August 1999	112.5	37.5	1.5
Storm 2	8 December 1999	96.1	12.8	3.0
Storm 3	26 February 2001	211.2	32.0	4.0
Storm 4	22 April 2001	404.0	17.0	9.5
Storm 5	17 July 2001	494.8	57.0	4.0

5.3.1 Storm 1 (25 August 1999)

This storm event consisted of a short, intense rainfall event and resulted in a clearly defined and discrete flow peak. The total runoff volume generated (112.5 m^3) compares with a predicted value of 105 m^3 based on a 100% rainfall/runoff coefficient for 2.8 mm of rain falling on the impervious catchment area of 37,500 m^2. It is unlikely that such a high runoff coefficient will exist but the resulting reduction in runoff volume will be compensated by water flowing from the associated pervious surfaces (33,100 m^2). The equivalence between the measured and predicted flow volumes therefore gives confidence in the accuracy of the flow measurements.

The total amount of each monitored pollutant transported from the highway surface to Pond F/G during the storm event was estimated from the temporal loading curve with the individual loading rates having been calculated from metal concentrations and associated flow rates. Outlet loadings, corresponding to the pollutant load delivered by the incoming storm event, were determined using a retention time (derived from the lithium dosing experiments) of 24 to 54 hours for Pond F/G. The outlet flow rates were estimated from the retention time (30 hours) and the inlet storm flow volume (112.5 m^3). The resulting average outlet flow rate of 1.04 l/s was used to calculate loading rates and outlet loadings were derived from the outlet chemograph.

The calculated inlet and outlet loadings for each of the monitored pollutants are listed in Table 5.4 together with the corresponding removal efficiencies. The highest removal efficiencies are for lead and cadmium and there was significant removal of both zinc and suspended solids with removal efficiencies of 66.2 and 75.0%, respectively. In the case of copper, there is an apparent increase of 97.1% in the loading leaving the wetland during the storm monitoring period. The reason why Pond F/G appears to act as a source of copper during this storm event is not certain as copper is normally quite strongly bound to the organic content of soil particles. Analysis of sediment samples collected during July 2000 did not indicate an accumulation of copper which would be potentially available for release during subsequent storm events (see Section 5.2.6). The contribution of the pond to outflow copper loadings, which was observed during the storm event, is not reflected by measurements taken during dry weather conditions.

There is evidence for removal of nitrate and sulphate although this is generally at a lower removal efficiency than for the metals. The lower removal may be due to the high solubility of these ions which would also contribute to the observed fairly uniform outlet loading distribution. Phosphate was not detected entering Pond F/G during the storm but despite the known affinity of this ion for adsorption to particulate material, it was washed out of the wetland following Storm 1.

Table 5.4. Inlet and outlet loadings and pollutant removal efficiencies demonstrated by Pond F/G for Storm 1.

Parameter	Inlet load	Outlet load	Percentage removal efficiency
Suspended solids	11.3 kg	2.83 kg	75.0
Cadmium	0.114 g	0.014 g	90.3
Chromium	0.338 g	0.174 g	48.5
Copper	1.40 g	2.76 g	-97.1
Nickel	0.796 g	0.179 g	77.5
Lead	1.07 g	0.022 g	97.9
Zinc	4.79 g	1.2 g	66.2
Nitrate	3.42 kg	1.69 kg	50.6
Phosphate	0	0.175 g	-
Sulphate	8.67 kg	6.93 kg	20.1

Note: Negative values for removal efficiency indicate a net release from the pond

5.3.2 Storm 2 (8 December 1999)

Compared to Storm 1, Storm 2 involved a more prolonged rainfall volume (2.2 mm over a 3 hour period) and resulted in a broader storm hydrograph. The monitoring period for Storm 2 did not correspond to the full duration of the storm event as rainfall continued after the completion of the sample collection, and for this reason comparison of the inlet/outlet results may provide a less reliable interpretation of pollutant removal efficiencies. The total volume of runoff generated during Storm 2 (96.1 m^3) compares to a predicted runoff volume of 82.5 m^3 based on 2.2 mm of rainfall falling on the contributing impervious highway surface area.

The inlet and outlet loading rates for each pollutant were calculated from the measured concentrations and flow rates (average outlet flow rate estimated to be 0.89 l/s). The respective loadings were again derived from the plotted chemographs and are shown in Table 5.5. The total monitored input loading of suspended solids for Storm 2 (5.06 kg) is considerably less than for Storm 1 (11.3 kg). This is consistent with the lower rainfall intensities and an antecedent period in which rain fell on 5 of the preceding 7 days. It is also possible that some of the non-monitored storm event passed through the wetland within the 24 to 54 hour outlet monitoring period and, if so, this may partly account for the reduced suspended solids removal efficiency for Storm 2 (40.3%) compared to Storm 1 (75.0%).

Table 5.5. Inlet and outlet loadings and pollutant removal efficiencies demonstrated by Pond F/G for Storm 2.

Parameter	Inlet load	Outlet load	Percentage removal efficiency
Suspended solids	5.06 kg	3.02 kg	40.3
Cadmium	1.74 mg	0.01 mg	99.4
Chromium	0.120 g	0.091 g	24.2
Copper	0.888 g	1.67 g	-88.4
Nickel	0.656 g	0.100 g	84.8
Lead	4.12 g	0.097 g	97.6
Zinc	5.49 g	2.21 g	59.7
Nitrate	1.95 kg	1.31 kg	32.8
Phosphate	3.31 g	0 g	(100)
Sulphate	8.15 kg	13.65 kg	-67.5

Note: Negative values for removal efficiency indicate a net release from the pond

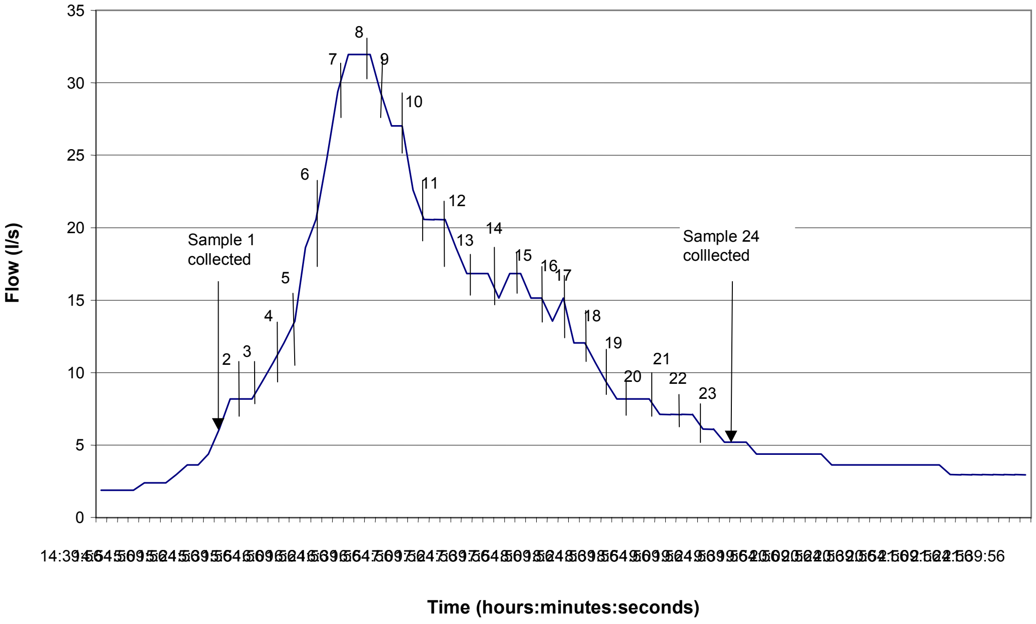
The removal efficiencies of zinc, nickel and chromium were 59.7%, 84.8% and 24.2%, respectively. Cadmium and lead both demonstrated very high removal efficiencies (99.4% and 97.6%) due to negligible outlet loadings although the presence of a loading peak between 38 and 54 hours was observed for lead. The results indicate a net release of copper from the pond during the storm event, similar to that observed during the monitoring of Storm 1. The reduced metal removal performance observed for Storm 2 could be due to elevated concentrations of chloride (up to 2196 mg/l) arising from winter road salting activities. The presence of chloride in runoff waters is known to have a mobilising effect on metals in terms of their solubilisation.

Nitrate and sulphate showed progressively increasing loadings throughout the 30 hour monitoring period. However, they result in different removal characteristics with nitrate being removed by Pond F/G (32.8%) whereas for sulphate there was a net increase (67.5). Phosphate was only detected in the last inlet sample collected and was not detected at all in any of the collected outlet samples. The results indicate a removal efficiency of 100% for phosphate but this may be misleading given the very low observed concentrations.

5.3.3 Storm 3 (26 February 2001)

The hydrograph for this storm is shown in Figure 5.3. Integration of the area under the hydrograph shows that a total flow volume of 211.2 m^3 passed through Pond F/G during Storm 3. Based on this the calculated average outlet flow rate is 1.086 l/s. The numbered vertical lines represent the times on the hydrograph at which each of the 24 inlet samples was collected. These were combined to produce 8 composite inlet samples representative of the different flow patterns during the storm. The measured inlet pollutant concentrations have been combined with the corresponding flow rates (from Figure 5.3) to obtain loading rates and these have been plotted against the relevant time of collection within the storm to produce the chemographs from which the inlet pollutant loadings have been obtained. The inlet chemograph for copper during Storm 3 is shown in Figure 5.4.

Figure 5.3 Hydrograph for Storm 3 occurring on 26 February 2001 at Pond F/G



The outlet concentrations have been combined with the average outlet flow (1.086 l/s) and the chemographs obtained by plotting the resulting loading rates against the time of sample collection in the 54 hour period following the commencement of the storm 1. The outlet chemograph for copper is shown in Figure 5.5. The outlet loadings are compared with the inlet loadings in Table 5.6 which also shows the removal efficiency for each pollutant.

Table 5.6. Inlet and outlet loadings and pollutant removal efficiencies demonstrated by Pond F/G for Storm 3.

Parameter	Inlet load	Outlet load	Percentage removal efficiency
Cadmium	886.5 mg	265.0 mg	70.1
Chromium	528.0 mg	317.4 mg	39.9
Copper	2.60 g	1.70 g	34.5
Nickel	240.6 mg	478.8 mg	-99.0
Lead	105.1 mg	188.4 mg	-79.3
Zinc	9.05 g	2.99 g	67.0
Nitrate	1250 g	430.5 g	65.6
Sulphate	12.65 kg	4.13 kg	67.4

Note: Negative values for removal efficiency indicate a net release from the pond

Figure 5.4. Inlet copper chemograph for Storm 3 on 26 February 2001 at Pond F/G

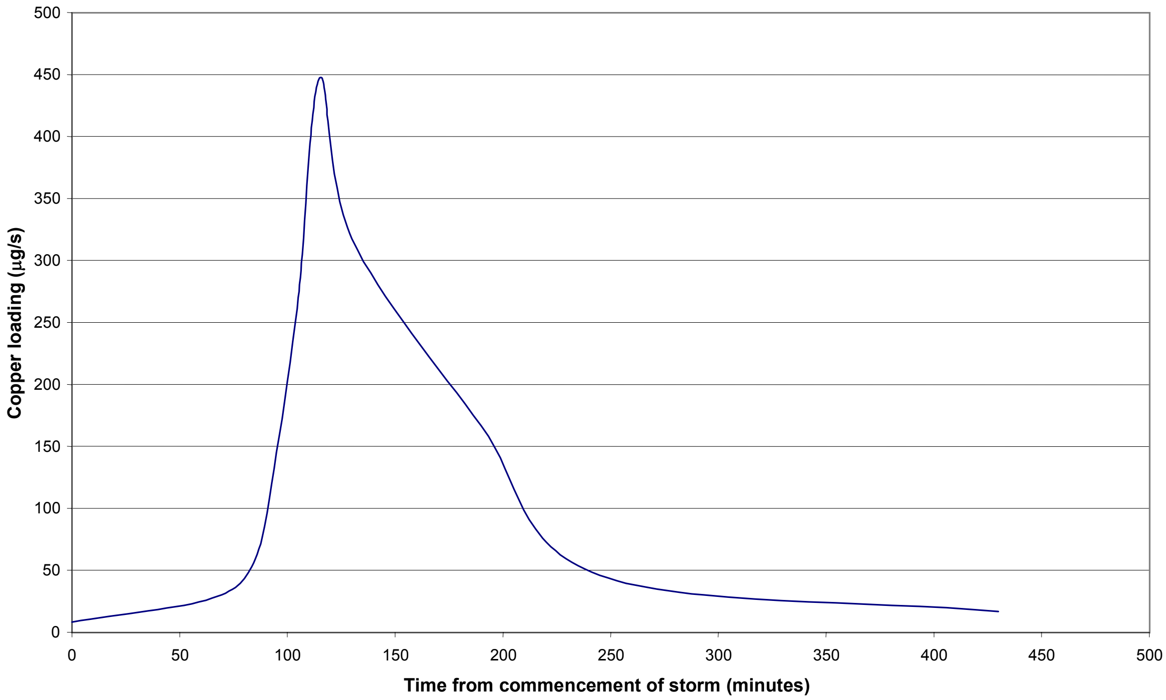
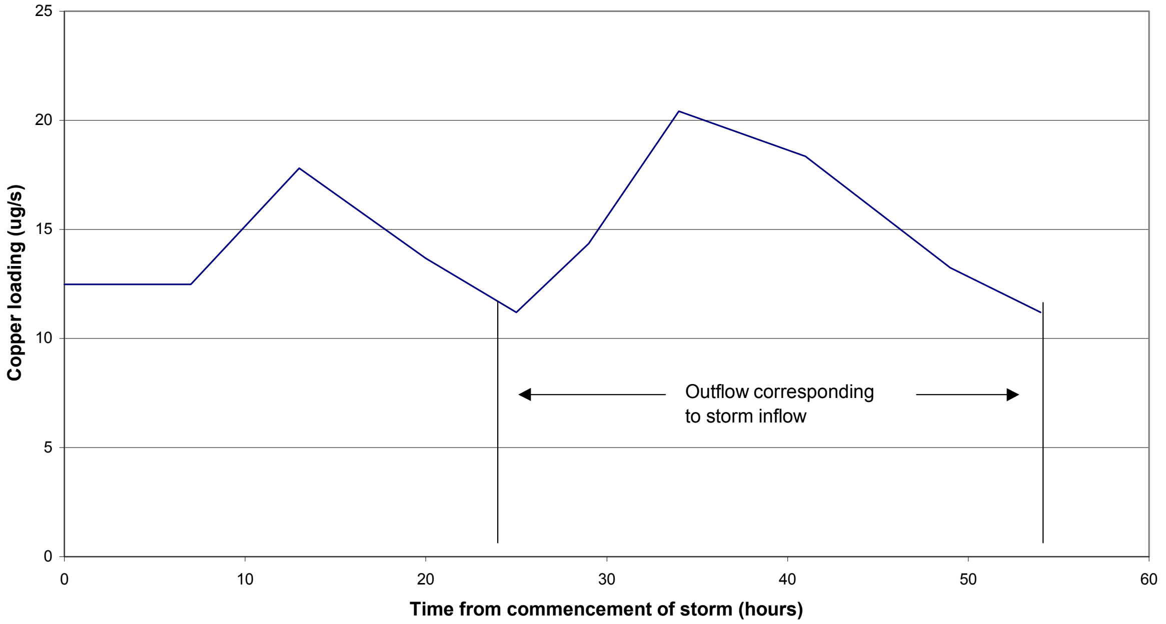


Figure 5.5. Outlet copper chemograph for Storm 3 on 26 February 2001 at Pond F/G



Storm 3 had a duration of approximately 4 hours and therefore was fully monitored in terms of outlet sample collection and hence outlet loadings. The inlet metal loadings are generally higher than those of Storm 2 and more comparable with the values observed in Storm 1. Exceptions are lead and nickel and the lower inlet loadings for these two metals result in overall negative removal efficiencies. Copper, which showed negative removal efficiencies for Storms 1 and 2, demonstrates improved performance (34.5% removal) during Storm 3. Phosphate was not detected in inlet or outlet samples but both nitrate and sulphate entered the pond in comparable amounts to the previous storms and showed good removal rates (65.6% and 67.4%, respectively). The mobilisation of lead and nickel as soluble chloro-complexes is unlikely as chloride concentrations did not exceed 230 mg/l and therefore the observed higher outlet loadings for these metals could be due to solubilisation by other non-monitored anions as well as being influenced by the reduced inlet loadings, particularly for lead.

5.3.4 Storm 4 (22 April 2001)

Storm 4 commenced at approximately 16.30 hours on 22 April 2001 and reached a peak flow rate of 17 l/s after 2 hours. This flow rate gradually declined over a period of nearly 5 hours to a value of 14 l/s before returning to baseflow level after a further 2 hour period. The prolonged duration of this storm means that sample collection was completed before the hydrograph returned to baseflow level. A total volume of 404.0 m^3 passed through Pond F/G during Storm 4. However, the water volume produced to the end of the sampling time was 223.5 m^3 which equates to an average outlet flow rate of 1.15 l/s. This flow rate has been used to calculate the outlet loadings for the measured parameters.

The inlet and outlet loading rates for each of the measured pollutants have been plotted against the time of sample collection to obtain the corresponding chemographs from which the loadings have been obtained. These are shown in Table 5.7 together with the derived removal efficiencies.

Table 5.7. Inlet and outlet loadings and pollutant removal efficiencies demonstrated by Pond F/G for Storm 4.

Parameter	Inlet load	Outlet load	Percentage removal efficiency
Cadmium	68.7 mg	23.3 mg	66.1
Chromium	479.0 mg	274.0 mg	42.8
Copper	685.0 mg	961.0 mg	-40.3
Nickel	740.0 mg	26.2 mg	96.5
Lead	96.8 mg	372.6 mg	-285
Zinc	0.839 g	1.629 g	-94.2
Nitrate	2.167 kg	0	(100)
Sulphate	8.795 kg	4.914 kg	44.1

Note: Negative values for removal efficiency indicate a net release from the pond

Storm 4 was the most prolonged of all the monitored storms, extending over a total time of around 9.5 hours. A consequence of this is the difficulty of accurately relating the samples collected during the 4 hour inlet monitoring period to the outlet samples. This may be one reason for the derived negative removal efficiencies obtained for three of the measured metals (copper, lead and zinc). An additional factor is the increasing chloride concentrations observed as the runoff passes through Pond F/G from ~190 mg/l to >2,900 mg/l. This can only be explained by the flushing of chloride out of the pond system and given this occurrence it is surprising that cadmium, chromium and nickel exhibited removal on passing through Pond F/G. Inlet nitrate loadings were comparable to the previous storms but the lack of detection of this anion in all monitored outlet samples produces what may be an exaggerated removal efficiency of 100%. The behaviour of sulphate, in terms of loadings and removal, was similar to that seen for Storms 1 and 3.

5.3.5 Storm 5 (17 July 2001)

Storm 5 commenced at approximately 16.00 hours on 17 July 2001 and reached a peak flow rate of 57 l/s after 2 hours. This flow rate declined rapidly over a 1 hour period before increasing again to 50l/s and remaining above 30 L/s for over 2 hours before returning to baseflow level after a further 2 hour period. The sample collection period of 4 hours effectively covers the time for which the stormflow was above 10 l/s. A total volume of 494.8 m^3 passed through Pond F/G during this storm, which would produce an average outlet flow rate of 2.54 l/s. This flow rate has been used to work out outlet loading rates for the measured parameters. The corresponding inlet loading rates were obtained from the measured pollutant concentrations and the relevant flow rates at the time of sample collection. The pollutant loadings obtained from the inlet and outlet chemographs are listed in Table 5.8 together with the removal efficiencies for Storm 5. No data are presented for lead because it was not detected in any of the analysed samples.

Table 5.8. Inlet and outlet loadings and pollutant removal efficiencies demonstrated by Pond F/G for Storm 5.

Parameter	Inlet load	Outlet load	Percentage removal efficiency
Cadmium	150.0 mg	23.0 mg	84.7
Chromium	422.0 mg	103.0 mg	75.6
Copper	3.61 g	1.66 g	54.0
Nickel	764.0 mg	193.0 mg	74.8
Zinc	13.88 g	2.51 g	81.9
Nitrate	3.45 kg	1.19 kg	65.5
Sulphate	29.11 kg	12.64 kg	56.6

Note: Negative values for removal efficiency indicate a net release from the pond

Storm 5 was the most efficient in terms of pollutant removal with all monitored parameters demonstrating reductions between inlet and outlet positions. The range of removal efficiencies (54.0% to 84.7%) indicate that Pond F/G was functioning according to its design criteria during this event, which being a summer storm did not exhibit any changes in chloride levels across the pond. The nitrate inlet loading and associated removal efficiency were similar to the other monitored summer storm event (Storm 1; 25 August 1999). The inlet load of sulphate (29.11 kg) was considerably higher than for the other storms but was subjected to a reduction of 56.6% on passing through the pond system.

5.3.6 Comparison of removal efficiencies for storm events

The removal efficiencies for each of the 5 monitored storm events are shown diagrammatically in Figure 5.6. The variability in the calculated values is clearly apparent particularly for copper and lead and, to a lesser extent, nickel, zinc and sulphate. In order to further understand the relevance of the removal efficiencies, the data set has been analysed statistically, producing the results shown in Figure 5.7 (in which the box plot representations have the same meaning as those shown in Figure 5.2).

The pollutants demonstrating consistent positive removal efficiencies for all storms and also limited variability about the mean and median values were cadmium, chromium, nitrate and suspended solids. Nickel, zinc and sulphate exhibited overall positive mean and median values although the variability indicated some inconsistency between storm events for these parameters. In the case of zinc, the removal efficiency distribution was strongly influenced by Storm 4 for which a value of -94.2% was recorded based on inlet and outlet loadings of 0.84 g and 1.63 g, respectively. A more exaggerated disparity was observed for lead for this storm with 96.8 mg entering the treatment system and 372.6 mg leaving it to give an increasing contribution by Pond F/G of 285%. There was also a contribution during this storm event for copper (-40.3%). The reason for this unusual behaviour by certain metals during this April storm event is believed to be associated with the elevated chloride concentrations (up to 2910 mg/l) and conductivity values (up to 7,200 μS cm^{-1}) which were monitored at the outlet. The ten-fold increase in both of these parameters between inlet and outlet strongly suggests that accumulated salts due to winter de-icing activities are being removed by the increased flows (up to 17 l/s) associated with this storm event. The ability of chloride ions to complex with certain metals and increase their solubility is well established and appears to be an important mechanism for lead, zinc and copper in this instance. The reason for the lack of impact by the increased conductivity/chloride levels on chromium, nickel and cadmium behaviour within Pond F/G is unclear although in the case of cadmium it may be related to the low input loading (68.7 mg) in comparison to the other metals.

The behaviour of copper in Pond F/G is unusual and unexpected in that for three out of the five monitored storms, negative removal efficiencies were recorded resulting in the overall negative mean and median values shown in Figure 5.7. Copper is known to have a strong affinity for organic materials and therefore the presence of increasing amounts at the outlet of a constructed wetland is difficult to explain. Although the macrophytes demonstrated some progressive plant tissue uptake, there was no evidence of copper accumulation on the substrate. Release of copper due to decay of macrophyte tissue and filamentous algae in open water areas would be expected during the winter months and although one winter storm exhibited increased outlet copper loadings, this process also occurred for a summer and a spring storm.

Figure 5.6. Comparison of the pollutant removal efficiencies for Storms 1, 2, 3, 4 and 5.

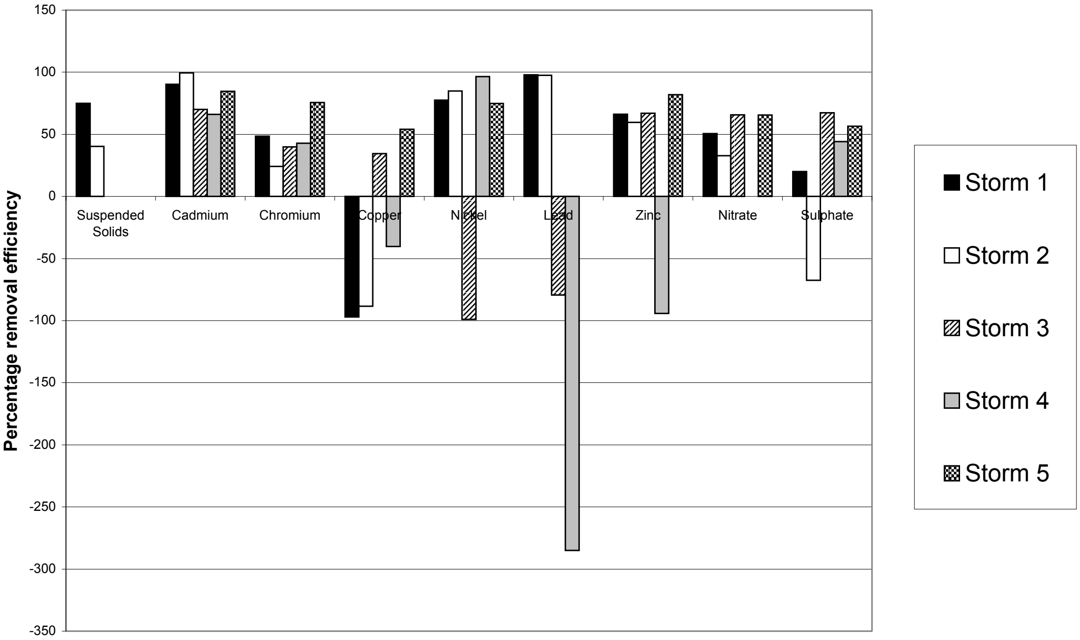
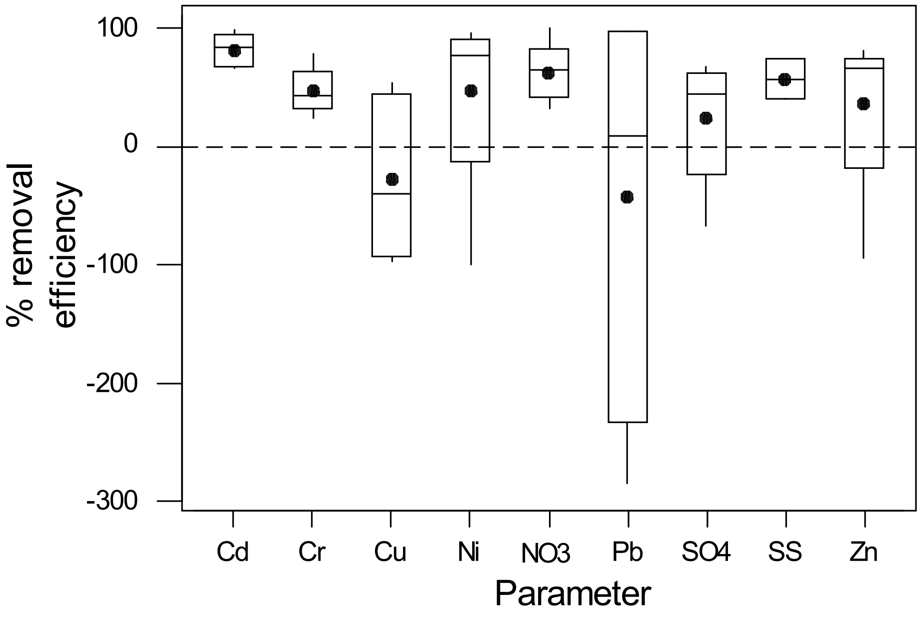


Figure 5.7. Statistical summary of the wet weather (storm event) removal efficiencies for Pond F/G



5.3.7 Comparison of dry and wet weather removal efficiencies.

The median removal efficiencies for Pond F/G during dry weather monitoring and in wet weather conditions (based on storm loadings) are shown in Table 5.9. Chromium (43-47%) and nickel (73-77%) are removed equally well whereas lead (0-9%) performs poorly during both types of weather conditions. In contrast, cadmium and nitrate demonstrate enhanced removal efficiencies during storm events and application of the Mann-Whitney test shows that the difference is statistically significant ($p<0.05$). There is a similar emphasis on more favourable removal under wet weather conditions for zinc, suspended solids and sulphate although in each of these cases the comparison with dry weather conditions is not significantly different. Only copper is predicted to have a higher removal during dry weather conditions and this is a consequence of the unexpected behaviour previously described for copper during storm event monitoring.

Table 5.9. Comparison of dry and wet weather removal efficiencies for Pond F/G.

Parameter	Median dry weather removal efficiency %	Median wet weather removal efficviency %
Cd*	0.0	84.7
Cr	47.2	42.8
Cu	4.0	-40.3
Ni	72.6	77.5
Pb	0.0	9.1
Zn	5.3	66.2
Suspended solids	9.7	57.7
NO3*	5.3	65.5
SO4	-5.4	44.1

* indicates that wet weather removal is significantly better than dry weather removal (Mann-Whitney test)

The considerations described above assume that the analysis of grab samples obtained simultaneously from inlet and outlet positions during dry weather conditions can be compared directly to storm event monitoring. Ideally, a series of time based inlet samples should have been collected and compared with similarly obtained outlet samples taking into account the residence time of Pond F/G under dry conditions. This would have provided a direct comparison between the performances during the two types of extreme weather conditions. In the absence of such a comparison an explanation of the results is not straightforward. Thus, the indicated preferable removal of the two monitored nutrients (nitrate and sulphate) during wet weather would not have been expected as more time for plant uptake would be available during dry conditions. Similarly, the settling out of suspended solids should be more efficient under quiescent conditions whereas a higher removal during storm events is predicted by the results. However, this phenomenon is partly a function of the inlet suspended solids concentrations which did not exceed 20 mg/l for routine monitoring but regularly approached 100 mg/l during storm runoff conditions. Lead is commonly found to be strongly associated with particulate material but the absence of a marked inlet concentration difference between dry (maximum 4.5 μg/l) and wet (maximum 10.1 μg/l) weather conditions results in a median removal efficiency value (9.1%) for the latter conditions which is only slightly higher than the dry weather value (0.0%). Cadmium is the most effectively removed metal during storm events and is the most significantly different from the dry weather results ($p<0.05$; Mann-Whitney test). This finding is again unexpected given the predicted high solubility of cadmium in highway and urban runoff. Metal removal by a constructed wetland receiving highway runoff can generally be seen to be efficient during carefully designed storm event monitoring conditions (Table 2) with only copper showing an aberrant behaviour and lead demonstrating a small positive removal.

5.4 Environmental Significance of Drainage Pond Discharge

The following paragraphs make a brief comparison of the measured values in the outlet from the drainage ponds with a variety of standards for environmental pollution. This comparison is solely for the purpose of putting the measured results into context and is not intended to be a general statement on the environmental significance of runoff from highway treatment ponds.

5.4.1 Metals

The concentrations of heavy metals monitored at the inlets to both ponds have been lower than expected and the cadmium and lead levels were often below the relevant detection limits. Because of the generally low metal concentrations, the original intention of determining both soluble and particulate associated metals was not proceeded with and all reported concentrations are for total metals. The measured concentrations of all metals were below the numerical Environmental Quality Standard (EQS) values specified in the Dangerous Substance Directive (76/464/EEC) with the exception of copper which had occasional values in excess of the EQS value. However, for all metals, including copper, the annual average concentrations (which are the basis for the EQS) were substantially lower than the limits specified in the Directive.

5.4.2 BOD, dissolved oxygen and pH

Several other parameters may be compared to the criteria set out in the General Quality Assessment Classification Scheme for rivers. Dissolved oxygen values are above the value specified for class RE 4 for 67% of measured values while values for BOD are better than the value specified for this class for 53% of measured values. Subsequent aeration and/or dilution in the receiving water would ameliorate any problems which might occur due to these inputs. Values for pH are within the range specified for all measured values. (RE is River Ecosystem class).

5.4.3 Suspended solids

Suspended solids concentrations were below the values specified in the EC Freshwater Fish Directive (78/659/EEC) for both Salmonids and Cyprinids for all measured values.

5.4.4 Chloride, nitrate, phosphate and sulphate

Values for chloride, nitrate, phosphate and sulphate are specified in the Surface Water for Drinking Directive (75/440/EEC). Chloride values are generally within the limit specified in the Directive although concentrations exceed the permitted value at times, particularly during the winter period. Nitrate values are generally within the limit specified in the Directive although concentrations occasionally slightly exceed the permitted value. Phosphates were rarely detected. Sulphate values were below the guideline values specified in the Directive for the majority of the time and were always below the mandatory values specified.

In summary, the quality of the water discharged from both ponds appeared to be relatively high and in most cases would be unlikely to give rise to any environmental concerns. Of greatest concern perhaps is the occasional very high chloride concentrations though these would undoubtedly be diluted on discharge to the receiving water and would only occur when road salting was necessary.

6. CONCLUSIONS

6.1 Sampling Programme

The planned sampling programme, which involved routine and storm monitoring in two phases over a 33 month period, has been successfully completed. During Phase 1 (December 1998 to December 1999), four samples (inlet, outlet and two sub-surface samples) were collected from Pond F/G on 20 occasions and two samples (inlet and outlet) were collected from Pond B on 12 visits. Two storm events, in August 1999 and December 1999, were fully monitored at Pond F/G. The routine monitoring during Phase 2 (May 2000 to August 2001) was reduced to two samples (inlet and outlet) from both ponds on 4 occasions and, in addition three storm events were fully monitored at Pond F/G. These storm events involved fully automated sample collection at inlet and outlet positions and the continuous recording of inlet flow rates.

The retention times of both ponds have been determined by lithium dosing experiments and found to exceed 30 hours for Pond F/G and 48 hours for Pond B for the different rainfall conditions during and prior to the dosing exercise. The measured retention times indicate that the overall designs of both ponds are satisfactory for the provision of optimum pollutant treatment.

6.2 Pond Performance

The results of the routine monitoring suggest that there is little difference between the performances of both ponds with respect to pollutant removal. There are instances under which Pond F/G is more efficient such as with regard to the removal of nickel and nitrate after becoming fully established and an improved zinc removal in summer, possibly due to more efficient plant uptake. However, it has been shown that there are limitations with utilising analysed grab samples as the basis for estimating pollutant removal efficiencies between the inlet and outlet of a water treatment system. This is particularly true in wet weather conditions and therefore the dry weather only routine monitoring data have been analysed separately. A statistical interpretation of the reduced data set shows no overall difference between Ponds F/G and B although the median removal efficiency for Pond F/G (8.6%) is significantly greater ($p<0.05$) than zero removal which is not the case for Pond B where the median removal efficiency is 5.6%. In terms of specific pollutant behaviour, those showing a predicted positive removal were cadmium and chromium (Pond F/G), nickel, zinc and nitrate (both ponds), and lead and sulphate (Pond B).

Carefully planned storm event sampling can provide reliable removal efficiencies calculated from inlet and outlet loadings. Five storms have been monitored at Pond F/G and the results show some similarities between storms collected at similar times of the year eg. Storms 1 and 5 which were both summer storms. Statistical analysis of the storm data has indicated that the largest variability in removal efficiencies are for copper and lead which may be due to the increased chloride contributions from the wetland during two of the storm events. The perceived process of metal mobilisation due to chloride interactions may also be responsible for increased zinc loads leaving the treatment system during Storm 4. Cadmium, chromium, nitrate and suspended solids exhibited consistent positive removal efficiencies about the mean and median values and, in general, the unexplainable variability of the measured pollutants was less during storm events than for the dry weather routine monitoring.

Data obtained for the constructed wetland show evidence of increased or equivalent removal of several pollutants during storm events in comparison to dry weather conditions. Application of the Mann-Whitney test has shown that cadmium and nitrate are removed significantly more efficiently ($p<0.05$) during storm events and there is a similar, although not statistically significant predominant removal for zinc, suspended solids and sulphate. These findings are difficult to explain scientifically and it is necessary to note that direct comparisons assume that the grab samples obtained from the inlet and outlet positions during dry weather take into account the retention time within the pond, which is not necessarily the case. Ideally, a series of time based inlet samples should have been collected and compared with similarly obtained outlet samples after allowing for the residence time of Pond F/G under dry conditions. This would have provided a direct comparison between the performances during the two types of extreme weather conditions.

6.3 Environmental Significance of Pond Discharge

A broad comparison has been made between the concentrations of the parameters measured in the discharge from the monitored ponds with a variety of Directives which set standards for environmental discharges for the purposes of putting the current results into context. In summary, the quality of the water discharged from the ponds appears to be relatively high and in most cases would be unlikely to give rise to any environmental concerns. Of greatest concern perhaps is the occasional existence of anoxic conditions in outlet waters and also very high chloride concentrations. The impact of both these occurrences would be expected to be reduced on discharge to the receiving water.

6.4 Sediment and Biomass

The results indicate that there is an accumulation of metals in the reed biomass, in particular in the root rhizomes. There is no clear evidence for loss of bio-accumulated metals, although there is some metal release, particularly of copper, from Pond F/G during storm conditions. The current results cover too short a time period to determine the long term management implications of this bio-accumulation. However, it is clear that a time will come when either the concentration of accumulated metals is such that the reeds will die or that they would become ineffective in removing further metal from the water. At, or preferably before this time, it would be necessary to remove the reeds including roots and rhizomes. Suitable disposal for this waste material would need to be identified based on analysis of the material at that time.

Sediment is trapped in the silt traps and settlement ponds at the inlet end of the ponds. Although not analysed as part of this project, the collected sediment will contain heavy metals which could over time leach back into the water entering the ponds. It would appear prudent to undertake a regular programme of sediment removal from the silt traps and settlement ponds to minimise the risks of metals leaching into the influent from accumulated sediment.

7. RECOMMENDATIONS

7.1 Design

7.1.1 Substrate

In the design of pond F/G the top l50mm of the substrate consisted of topsoil over a bed of gravel. This was placed to provide a source of nutrients for the growing wetlands as it was perceived that the incoming highway runoff would contain insufficient nutrients to sustain growth. However, the use of topsoil was found to encourage the growth of invasive weed species in competition to the planted reeds. It is recommended that in future designs of sub-surface flow systems for highway runoff treatment, the top 150mm of substrate should not be pure topsoil but should be either a mixture of gravel and sand/topsoil or preferably, gravel only. These options would increase the hydraulic conductivity and assist in reducing the possibility of an additional surface build-up of sediment. It may be necessary, especially when using a gravel only substrate, to dose with a slow release fertiliser, perhaps also including the trace elements iron and manganese, although this should be decided on a case by case basis following consultation with the contractor engaged to construct the wetland.

7.1.2 Control of water level

It is recommended that an appropriate hydraulic control be inserted at the outlet to the ponds to enable the easy regulation of the water level within the system. The growth of weeds should be controllable through flooding of the ponds and in the case of Pond F/G, it is probable that the use of such actions could have prevented the invasive growth of *Agrostis stolonifera* early in the development of the *Typha* bed.

During Phase 1 of the monitoring programme, an elbow joint was fitted to the pond outlet which placed the discharge point at a higher elevation allowing a certain degree of flooding to be achieved. Similarly, in Phase 2, after the replanting of the lower bed in Pond F/G, a wooden plate was placed across the outlet to raise the water level. Neither of these systems provided a useful degree of control and required fairly complex engineering practices to put them in place and subsequently to remove them.

As flooding will use up some of the pond's retention capacity this procedure is not desirable in the long term. Furthermore, a continuously flooded system would not be conducive to deep root growth. A simple system which allows a PVC elbow, flexible pipe or a weir to be manually raised or lowered to easily allow control of the level should be incorporated into the pond outlet. Alternatively, two outlet orifices could be constructed. The lower orifice would be the "normal" outlet for the pond. If flooding were desired this lower orifice could be blanked off and discharge would be through the higher orifice, thus raising water levels in the pond.

7.1.3 Inlet settlement pond

When designing a sub-surface flow system careful consideration should be given to the size of the inlet settlement pond. In Pond F/G the size of the inlet pond was determined by the available space afforded by the pre-existing pond structure into which the sub-surface flow system was retro-fitted. It is believed that a minimum retention time of 30 minutes would be achieved in the inlet settlement pond within the volume which would permit sub-surface flow conditions to be maintained (ie the level between the lower water level and the overtopping level of the gabion).

In the case of Pond F/G the area available for settlement is 174m^2 and the depth within which sub-surface flow would be maintained is 0.3m. This equates to a total retention capacity of 52m^3. This is approximately 41% of the indicated volume for a 1 in 1 year return period storm, 31% of the indicated volume for a 1 in 5 year return period storm and 28% of the indicated volume for a 1 in 10 year return period storm. This would indicate an area for the inlet settlement pond of some 620m^2 for a design based on a 1 in 10 year return period storm.

Alternatively, to achieve, for a 1 in 10 year return period storm, inlet velocities of between 0.3 and 0.5 m/s, which are quoted as the velocity range required to achieve effective sedimentation in a previous report ("Treatment of Highway Runoff Using Constructed Wetlands - An Interim Manual"), would require that the area of the inlet settlement pond was between 370 and 617m^2, respectively [1]. This is between 213% and 357% of the actual size (area) of the inlet settlement pond provided for Pond F/G.

Notwithstanding the apparent reduced size of the inlet settlement pond in Pond F/G it would appear that, in practice, it adequately performed its intended function. There has been no significant evidence of silting up of the interstices of the gabion wall and visual inspection of the substrate in the second part of the reed bed did not yield any visual evidence of sediment accumulation. Indeed, the efficient build-up of silt within the inlet settlement pond and the requirement for regular de-silting indicate that, under the conditions encountered, velocities were sufficiently low to allow deposition of incoming suspended solids.

Having a large settlement pond followed by the sub-surface flow system for polishing and metals removal is an ideal, which would, in reality, be limited by land availability and/or cost constraints.

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[1] It has been simplistically assumed that there will only be a vertical element to the velocity and that horizontal velocities will have minimal impact. This may not be the case in reality. Using this simplistic approach the estimated storm volumes are divided by the velocity to give the required pond area.

7.1.4 Design as a system

Each treatment system consists of a number of separate treatment components and to achieve maximum pollutant removal efficiency it is important that each one operates efficiently. In the reported study, both ponds were fitted with front-end oil separators and silt traps to deliver the incoming highway runoff to the main treatment system via a vegetated feeder strip. No evidence of oil pollution was detected in either system suggesting that the oil separators functioned efficiently throughout the monitoring period. The operational performances of the silt traps (Section 7.3.1) and the feeder strip (Section 7.3.3) are commented on elsewhere in this report. A difference in the design of the treatment systems was the existence of two settlement ponds in Pond F/G, one after the vegetated feeder strip and the other immediately before the outlet pipe. The former was under-designed (see Section 7.1.3) but nevertheless demonstrated an important sediment trapping role. The purpose of the outlet settlement was to provide a final polishing mechanism with regard to fine suspended sediment removal.

The differences in performance of the sub-surface wetland and the surface flow vegetated pond have been extensively discussed in this report (see Chapter 5) for a range of pollutants and for extremes of weather conditions. There appears to be no statistically significant difference in performance between Pond B and Pond F/G, especially under dry weather conditions. However there is evidence of some improved performance of Pond F/G, especially when wet weather conditions are included in the analysis. Unfortunately Pond B was not monitored for storm events and therefore it is not possible to make a direct comparison with Pond F/G under these conditions. The performance of the sub-surface system showed a clear improvement under the more controlled monitoring conditions which were applied during storm events. It is important to note that all monitoring was carried out in the early development stage of both planted systems and it is probable that in both cases the performances would improve as the systems mature.

Although Pond F/G was designed as a sub-surface flow system, the capacity was such that under high flows it became a surface flow system and under such conditions would function similarly to Pond B. The major differences in pollutant removal mechanisms between the ponds under design operating conditions are the filtering and adsorption processes provided by the presence of the gravel substrate in Pond F/G. In selecting an appropriate treatment system it should be borne in mind that sub-surface flow constructed wetlands are able to provide at least the same level of treatment as surface flow systems but in a smaller land space and over shorter periods of time. This will obviously be at the expense of incorporating an equivalent storage capacity. Ideally sub-surface flow systems should be designed to be able to treat all runoff through horizontal flow within the gravel substrate. Where this is not possible, the sub-surface system should be designed to provide full treatment of the initial highly contaminated highway runoff with the subsequent higher flows (containing , in most instances, lower pollutant concentrations) receiving both sub-surface and surface flow treatment.

Design of the entire system including the embankment, grass apron and reed bed must be such as to prevent creation, even temporarily, of uneven distributions of flow. This is especially important where construction of the wetland and the highway is likely to occur over several phases and more so when construction of the wetland occurs in the earlier phases.

7.2 Construction

7.2.1 Level of outlet sill in silt trap

The outlet sill of the silt trap needs to be built in such a way that there is a constant overflow height feeding the vegetated strip to the ponds. Measurements have shown differences of 1 to 2 cm in water height from the inlet pipe end along the 15 m length of the sill. This may be partly due to the hydraulic head caused by the incoming water and this should be allowed for. This problem was rectified at Pond F/G with the installation in July 2000, prior to the commencement of Phase 2 storm event monitoring, of a weir structure to enable automatic inlet flow monitoring during storm events.

7.2.2 Control of sediment ingress during construction

During the construction phase it is important that steps are taken to ensure that minimal amounts of sediment are allowed to enter the wetland system. Therefore, ideally the constructed wetland should be built as late as possible in the highway construction programme and the surrounding banks should be vegetated as early as possible to prevent the in-wash of both sediments and nutrients. Nitrate levels were enhanced in Pond F/G early in Phase 1 of the monitoring programme before the bank-side vegetation became established and could provide uptake of nutrients.

Sediment build-up was particularly significant in the inlet settlement pond to Pond F/G and on the upper surface of the substrate. This was noticed early in the monitoring programme and in March 1999 the depth of soil and clay above the gravel substrate was found to vary in depth between 0 and 28 cm across the entire bed surface with an average depth of 16 cm. This was not part of the original design and it is most probable that the growth of an invasive grass species, *Agrostis stolonifera*, was encouraged as a consequence of this sediment build-up. This grass growth impeded the development of the planted reeds, particularly in the *Typha* bed, and in February 1999 it was necessary to perform a herbicide (glyphosate) treatment. Similar problems with regard to weed infestations were observed in the lower bed in Pond F/G after it was replanted in February 2001. It is essential, therefore, that careful staged inspections are carried out both during the construction process and in the immediate post construction phase when the reeds are becoming established.

7.2.3 Avoidance of short circuiting

Constructed wetlands require careful monitoring for evidence of short-circuiting. In June 1999, it was observed that there seemed to be some short-circuiting of flow down one side of Pond F/G. This arose because the gabions did not extend to the full width of the wetland. This was rectified in November 1999. It is important that during all construction activities, either pre- or post-operation, very careful monitoring is carried out and that all agencies communicate fully with each other.

7.3 Operation and Maintenance

7.3.1 Removal of sediment

It is essential that there is regular removal of sediment from the inlet settlement ponds if these are to maintain their function as a sedimentation device. During the first 12 months of operation there was excessive sediment build-up which continued in the later stages although at a lower rate. The initial rapid sediment input occurred during the highway construction. However, the rate of sedimentation during normal operation has been shown to be substantial and it is strongly recommended that both the sedimentation ponds and the silt traps adjacent to the inlets should be cleaned twice yearly, preferably in spring and autumn. Problems associated with excessive silt accumulation in the inlet settlement pond include invasion and subsequent colonisation of this area by Phragmites runners. This has been repeatedly observed at Pond F/G and a future impact is expected to be silting-up of the inlet gabion retaining the reed substrate resulting in reduced flows through the system and entailing an expensive cleaning regime using high pressure jetting. The presence of sediment build-up in the silt traps can lead to an increased oxygen demand in the inlet waters entering the wetland treatment system and to elevated suspended solids levels under the turbulent inlet conditions which may be associated with intense rainfall events.

7.3.2 Removal of substrate and root rhizomes

In sub-surface systems, after a period of time, as yet undeterminable but probably of the order of 15 to 20 years, it will be necessary to remove the substrate and the root rhizomes. This is because after this time the threshold for metal removal will have been reached. The material which is removed would need to be tested and agreement would need to be sought from waste management companies and waste regulators on whether the material would be classified as a hazardous waste and what disposal options would be appropriate. Constructed wetlands for treatment of contaminated land have been known to die due to metal poisoning and this needs to be avoided.

7.3.3 Maintenance of vegetated feeder strip

The inlet vegetated feeder strips are designed to reduce the velocities of the influents before they enter the initial sedimentation pond. The vegetated feeders require regular maintenance to ensure that an even flow distribution is maintained with no short-circuiting or channelling. In practice, this maintenance involves mowing to keep vegetation heights low. The intermittent mowing which was carried out at Ponds B and F/G was not sufficient to prevent the growth of unwanted macrophytes, such as *Juncus* species, and terrestrial plants, such as buttercup, willow herb and other weeds. It is advocated that regular maintenance (mainly mowing) with, at least, a monthly frequency (in summer) is required to preserve a viable vegetated feeder zone.

7.3.4 Control of algae

During the summer months, algal growth was observed in the initial and final settlement ponds at Pond F/G and in the silt traps of both ponds. Barley straw bags have been introduced in the hope that they will serve to reduce algal growth in future years but their function and efficiency is not yet proven. A major concern with algal growth is that if it is not removed before winter there is the possibility of a high oxygen demand and increasing suspended solids levels as the algae decompose. Additionally, the exudates released by the algae can contribute to increased levels of conductivity. All these problems have been observed as part of the routine monitoring programme and it is recommended that accumulated sediment and algae should be removed at six monthly intervals. However, when flow monitoring is ongoing via the weir on the sill of the silt trap at Pond F/G then more frequent cleaning will be required to prevent the V-notches being fouled by retained algal strands.

7.3.5 Management of trash screens

There has been a tendency for the metal grills at the outlets to Ponds B and F/G to become partially blocked with waste material and there is a need to introduce a maintenance programme which ensures cleaning of the grills on, at least, a 2 monthly basis.

7.3.6 Choice of reeds

Management of *Phragmites australis*

Phragmites australis has shown good growth in both ponds throughout the monitoring period. There is a danger in Pond B that the expansive growth of this species may pose a future threat for the area of open water which is designed to exist in the centre of the pond for wildlife and aesthetic purposes. If it is considered important to preserve a reed-free micro pool of water an appropriate management strategy needs to be introduced involving removal (by up-rooting) of vegetation in this area.

The growth of *Phragmites* in the front bed of Pond F/G has been less vigorous than in Pond B in terms of reed height but a good reedbed system has been established. *Phragmites* grows well in brackish waters and therefore is suited to being located at the front end of Pond F/G. The new *Phragmites* bed in the lower bed of Pond F/G was less successful in becoming established after the planting in February 2001 and this highlights the requirement for a proper and thorough preparation of the surface prior to planting.

Management of *Typha latifolia*

The initial *Typha latifolia* bed at Pond F/G was considerably less successful than the adjacent *Phragmites* bed with a less dense growth and evidence of recolonisation of the area by grasses and other weeds, including thistles, during the first year of the monitoring period. A distinct deterioration in the condition of the *Typha* was observed from August 1999 onwards due to a yellowing of the leaves and fruit bearing stems. The main explanation for this early die-back is believed to be a consequence of the prevailing hot and dry conditions and the inability of the *Typha* root systems to reach down to the lower level of water during these conditions. The deeper root system of *Phragmites* meant these plants did not suffer in the same way. As a consequence of the continued deterioration of the *Typha* bed the decision was made in July 2000 to replant the *Typha* section using *Phragmites*. This was carried out in February 2001 as described above. A contributing factor to the demise of the *Typha* bed could have been the existence of an iron deficiency due to a limited source of this trace element in the wetland substrate, which is dominated by gravel. In the event that this could be shown to be occurring, the recommended treatment would be to spray the leaves with a 2.5% ferrous sulphate solution.

The experience from these studies suggests that *Phragmites* is a more resilient species than *Typha* for the treatment of highway runoff. However, it is important that the characteristics of the chosen reed species are fully researched prior to planting and that they are consistent with all the design aspects of the treatment system. *Typha* has been extensively and successfully used in reedbeds for the treatment of urban runoff and the problems encountered in this study arose due to the inability of the young *Typha* root systems to reach down to the existing water level (at a depth of 300mm) during prolonged dry weather conditions. Where several reed species can be shown to be adaptable to predicted prevailing conditions, there are ecological and aesthetic advantages to be gained by adopting such a mixed system.

7.4 Future Monitoring

7.4.1 Monitoring of plant condition

It is essential that seasonal plant inspections are carried out for evidence of chlorosis, tip curl or early die-back. If serious deteriorating plant conditions are observed an appropriate maintenance/management strategy should be developed, such as that described in Section 7.3.6 to deal with the *Typha* bed at Pond F/G. The overall growth performance of *Typha* was disappointing during Year 1 and at the end of the monitoring period (August 2001) the condition of the *Phragmites*, in the replanted downstream part of the reedbed was still unsatisfactory.

7.4.2 Performance of barley straw in controlling algal growth

The performance of the barley straw bags with respect to controlling algal growth at the inlets and outlets to both ponds should be carefully monitored. The mode of operation of barley straw in controlling algae is not known. If the placement of barley straw bags does not provide control of algae then alternative algae control measures need to be used.

7.4.3 Need for long term monitoring

It is recommended that a longer term (up to 10 years) routine monitoring programme should be undertaken based on seasonal sample collection to assess the behaviour of the reedbed as it continues to develop and to estimate when pollutant saturation levels might be reached. Initial road runoff results have indicated the occurrence of low metal concentrations which may be a function of the porous road surface of the A34 Newbury bypass. A longer term investigation is required to assess the ability of the road surface to continue to retain pollutants as it ages. Furthermore, the wetland plants, especially the *Phragmites* in the replanted part of Pond F/G are at an early stage of their establishment and as such are unlikely to be operating at their maximum pollutant removal potential. It would be desirable to monitor pond performance once it has fully reached a mature stage of development. A ten year monitoring programme would provide a solid body of results on performance in addition to more considered indications of the needs for long term operation and maintenance.

The installation of the facility for automatic collection of storm event samples as well as the continuous recording of inlet flow rates at Pond F/G should be utilised to monitor more storm events to extend the current database which incorporates results from 5 storms. This report has highlighted the problems associated with routine monitoring where the retention time of the treatment system is not taken into account. The routine monitoring should be arranged, where possible, to take place during dry weather conditions with inlet and outlet samples collected with a time interval corresponding to the estimated retention time under the prevailing conditions. This would enable a realistic comparison to be made between the performance of the treatment system during both dry and wet weather conditions and hence contribute to the design of constructed wetlands for the control of highway derived pollutants under extreme types of weather condition.

It is recognised that the costs of such a proposed monitoring strategy may require its restriction in terms of scope of pollutants to be monitored. Therefore, it is proposed that one metal and one nutrient should be measured as indicators of the overall performance. The results described in this report indicate that chromium and nitrate have shown the most consistent behaviours, particularly during storm events. These pollutants are therefore recommended as suitable indicators of the overall behaviour of highway runoff treatment ponds during a long term monitoring regime.

7.4.4 Design manual for reed bed treatment of highway runoff

The recommendations made in this report as the result of a 33 month monitoring programme of two different designs of treatment system for highway runoff are incorporated into the Guidance Manual for Constructed Wetlands, R&D Technical Report P2-159/TR2. This provides guidance in best practice for design, construction, operation and maintenance of reed bed systems for highway runoff.