EFFECTS OF STORMWATER MANAGEMENT SYSTEMS ON GROUNDWATER QUALITY

FINAL REPORT

for

FDER Project WM190

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Submitted to:

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CHAPTER I

INTRODUCTION

It has long been recognized that nonpoint sources of pollution contribute significantly to receiving water loadings of both nutrients and toxic elements such as heavy metals (Harper, 1983; Sartor, et al., 1974). As a means of protecting Florida surface waters from the effects of nonpoint source pollution, the Florida Department of Environmental Regulation has established regulations which require new developments or projects to retain or detain specified volumes of runoff water on-site. In most cases runoff is collected in shallow ponds which infiltrate all or part of the retained or detained volumes into groundwaters.

When stormwater management facilities receive inputs of stormwater containing nutrients, heavy metals and other pollutants, processes such as precipitation, coagulation, settling and biological uptake deposit a large percentage of the input mass into the sediments. Recently, concern has been expressed that this continual accumulation of pollutants in the sediments of stormwater management ponds may begin to present a toxicity or pollution potential to underlying groundwaters. Specifically, do these pollutant accumulations cause physical and chemical changes to occur within the sediments of stormwater management facilities which mobilize certain pollutant species from the sediment phase into the water phase.

Previous Investigations

Until recently, the groundwater impacts of stormwater runoff discharged into stormwater management systems has received little attention by researchers. One of the earliest investigations into this problem within the State of Florida was conducted by Harper (1985) in a study on the effects of highway runoff on groundwater quality beneath a 1.3 hectare (3.2 acre) wet detention facility located at the Maitland Interchange on Interstate 4 north of the City of Orlando. The fate of nutrients and heavy metals in the detention basin were examined in a three-year study from 1981 to 1984 with particular emphasis on the stability of metal-sediment associations and potential for migration of metals into groundwaters. Analyses of 138 core samples were combined with the results of a sequential extraction procedure to examine the type of chemical associations and stability of metal species in sediments. The effects of changes in redox potential and pH on metal-sediment stability were investigated in an environmental test chamber which allowed incubation of sediments under varying conditions. Five multiport groundwater monitoring wells were also installed to monitor metal movement and accumulations under pond, swale and control areas.

Harper (1985) reported that total heavy metals in the sediments of the Maitland pond exhibited highest concentrations in the upper surface layer with a rapid decline in concentration with increasing depth. The rapid decline in concentration was found to observe an exponential decay relationship with values of R-square in most cases in excess of 0.90 when fitted to the model: ln (metal conc.) = K x ln (depth). All runoff related sediment accumulations of heavy metals were reduced in concentration by 90% in the first 10 cm or less with iron, zinc and cadmium reduced by 90% in the first 5 cm. After eight years of accumulations in the Maitland pond, most metals associated with sediments had remained in the top 10 cm of the sediment layer.

The results from the speciation and redox experiments combined with the analyses of the sediment metal concentrations presented evidence that under current conditions of redox potential and pH within the sediments of the Maitland pond, metal species, with the exceptions of cadmium and manganese, are stable within the sediments and exist in relatively immobile associations with Fe/Mn oxides and organic matter. The only exception to this conclusion appeared to be lead which is apparently held to a large degree in a strong exchangeable association.

Changes in redox potential from strongly oxidized to strongly reduced conditions did not appear to affect the release of metals from the sediments under current pH values of 7.5 to 8.5. The release of most metals, except cadmium and manganese, from the sediment phase to the water phase was substantially less than 1% of the total metal present even after several weeks of incubation. However, cadmium and manganese appear to be less tightly bound to sediments than other metals. The release of both cadmium and manganese into solution from the sediment phase during incubation was equal to approximately 5% of the total metal present.

In spite of the strong metal-sediment associations, mean concentrations of all heavy metals measured, except copper, were greater in shallow groundwaters beneath the pond than in surface water within the pond. The extent of significantly higher groundwater concentrations of lead extended to depths of 1-3 meters, while elevated levels of nickel, cadmium and chromium extended to a depth of 0.5 to 1.0 meter. In contrast, copper was found to be significantly higher in surface water within the pond than in groundwater. Average concentrations of zinc, manganese, aluminum and iron were found to be 4, 12, 8 and 50 times greater, respectively, in shallow groundwater immediately beneath the pond than in the pond water. Concentrations of cadmium and iron in groundwaters exceeded water quality criteria for Class III waters specified in Chapter 17-3 (1989) of the Florida Administrative Code.

During comparisons of detention and swale areas, it was found that concentrations of all heavy metals tested, with the exceptions of copper and nickel, were significantly higher beneath swale areas than beneath the detention pond. Increases in concentrations of manganese, aluminum, iron, lead and chromium beneath swale areas were more significant than for the remaining metals. It was suggested that the relatively rapid soil infiltration rates observed in the swale areas and the resulting short contact time with soil particles creates a lower pollutant trapping efficiency into the solid phase for swale areas than for retention ponds where diffusion and transport is very slow. These findings suggest that stormwater management facilities with rapid infiltration rates may be less efficient in retaining heavy metals in the soil or sediment phase than ponds with slow infiltration rates.

As a result of a very small hydraulic gradient, horizontal movement of groundwater in the Maitland area was calculated to be less than 10 m per year. Vertical groundwater fluctuations with changes in the seasonal water table may be more significant at this site than horizontal movement. As a result, Harper concluded that migration of the groundwater plume containing elevated levels of heavy metals is extremely limited, and groundwater contamination appears to be very localized.

Natural aging processes within stormwater management ponds, as well as lakes, result in the increased deposition of organic matter to the bottom sediments primarily as a result of the death and decay of both plant and animal matter. As these processes occur, it has often been observed that sediments become more reduced and decrease in pH value. Incubation experiments using sediments from the Maitland pond indicated that most metal species were stable and tightly bound to sediments under current conditions of redox potential and pH, but decreases in pH were found to increase the solubility of all heavy metals tested. Changes in redox potential produced no significant changes in release rates of metals in Maitland sediments.

The results of the Maitland experiments suggest that as the pond ages and accumulations of organic matter in the sediments begin to cause sediment pH values to decrease, mobilization of all metal species tested may increase and release of metal ions to groundwaters may occur. Although the solubility of all metals was found to increase with decreases in pH, the sediment release was, in general, only a small fraction of the total sediment metals present. For zinc, iron, aluminum, copper and chromium, the maximum release was less than 3% of the total metal present in the sediments, even at the most extreme pH value tested of 5.0. For nickel and lead, the release extended as high as 6% to 7% at a pH of 5.0. Manganese and cadmium were found to increase in solubility substantially as sediment pH decreases with almost total release of manganese and 25% to 30% release of cadmium at a pH of 5.0. Releases of this magnitude may produce measurable increases in groundwater concentrations beneath stormwater management facilities. The results further suggest that maintenance procedures may be necessary after a period of time to remove the accumulated sediment deposits which may cause conditions of low pH and release of metals.

Although the Maitland study constituted a detailed investigation of the current and future groundwater impacts from a wet detention facility receiving highway runoff, this study considered only a single stormwater management practice and a single land use type. Questions remain concerning potential groundwater impacts from stormwater management practices other than wet detention systems. In addition, the groundwater effects from different contributing land use categories, such as commercial and residential, should also be addressed.

Scope of Research Efforts Described in this Report

The research efforts described in this report present a detailed investigation of groundwater impacts from four common stormwater management practices, including a wet swale, dry swale, wet detention pond and dual pond systems, receiving stormwater runoff from interstate highway, residential and commercial land uses. Field investigations and laboratory studies began in October 1986 and continued through April 1988. In excess of 40,000 separate field and laboratory measurements were generated during the course of this project.

This report is divided into two separate volumes. This volume, Volume I, is titled "Effects of Stormwater Management Systems on Groundwater Quality" and consists of a presentation and discussion of the experimental data and conclusions. Volume II is titled "Effects of Stormwater Management Systems on Groundwater Quality -

Appendices" and contains the entire data set of laboratory measurements and selected portions of the field data set.

Units of Measurement

Research efforts described in this report were conducted almost exclusively with metric units of measurement. In general, all data, measurements and descriptions given in this report are presented in metric form with English equivalent units given in parentheses for measurements of length, area and volume. The only exception to this format is in the presentation of elevation data referenced to mean sea level (MSL) which is given in terms of English units (i.e., feet) only.

CHAPTER 2

FIELD AND LABORATORY PROCEDURES

Description of Study Sites

Field and laboratory investigations were conducted from October 1986 through June 1988 to evaluate and quantify potential groundwater impacts from common stormwater management systems and various contributing land use types typical of Central Florida. Five study sites were selected, including: (1) an interstate highway site which discharges to a roadside wet swale system; (2) an interstate highway site which discharges to a sandy, dry roadside swale system; (3) a dual pond system receiving residential runoff; (4) a shallow wet detention basin receiving runoff from a duplex residential area; and (5) a highly impervious commercial site discharging to a dual pond treatment system. Locations of the five study sites are indicated in Figure 2-1. A summary of general hydrologic characteristics for the five study sites is given in Table 2-1.

Site 1 - Wet Swale Site

The wet swale site is located adjacent to Interstate 4 (I-4) approximately 6.0 km (3.7 miles) north of downtown Orlando. A schematic of the study site is given in Figure 2-2. In the vicinity of the study site, I-4 consists of three traffic lanes plus an additional emergency lane in both eastbound and westbound directions, separated by a concrete

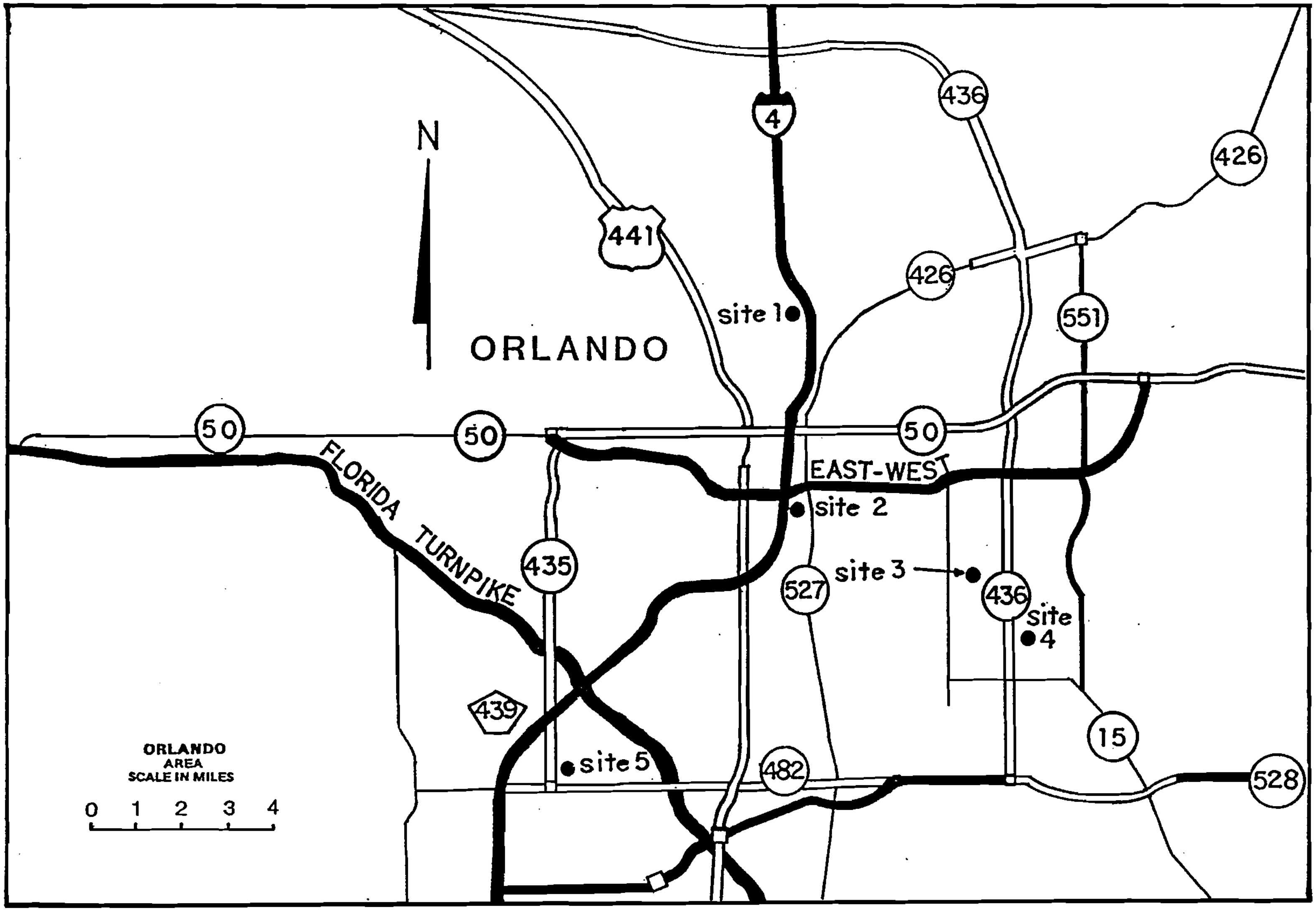


Figure 2-1. Locations of the Five Study Sites.

TABLE 2-1

GENERAL HYDROLOGIC CHARACTERISTICS OF THE FIVE STUDY SITES

WATERSHED PARAMETERS	STUDY SITE				
	1	2	3	4	5
Stormwater System	Wet Swale	Dry Swale	Dual Pond System	Wet Detention	Dual Pond System
Land Use	Interstate Highway	Interstate Highway	Single-Family Residential	Duplex Residential	Commercial
Drainage Area	0.47 ha 1.17 ac	0.53 ha 1.30 ac	2.99 ha 7.39 ac	10.17 ha 25.13 ac	0.88 ha 2.17 ac
Percent Impervious	100%	70%	65%	34%	100%
Directly Connected Impervious (%)	100%	13%	72%	69%	100%
Type of Impervious Area	Concrete	Concrete	Asphalt/Concrete	Asphalt/Concrete	Asphalt/Concrete
Average Watershed Slope (%)	1.83	0.722	0.337	0.247	0.187
Time of Concentration (min.)	6.0	45	9.8	14.8	5.5
Runoff Coefficient	0.95	0.63	0.66	0.44	0.90
Type of Conveyance	Curb/Stormsewer	Median/Stormsewer	Curb/Stormsewer	Curb/Stormsewer	Inlets/Stormsewer
Year Constructed	1965	1972	1986	1978	1985

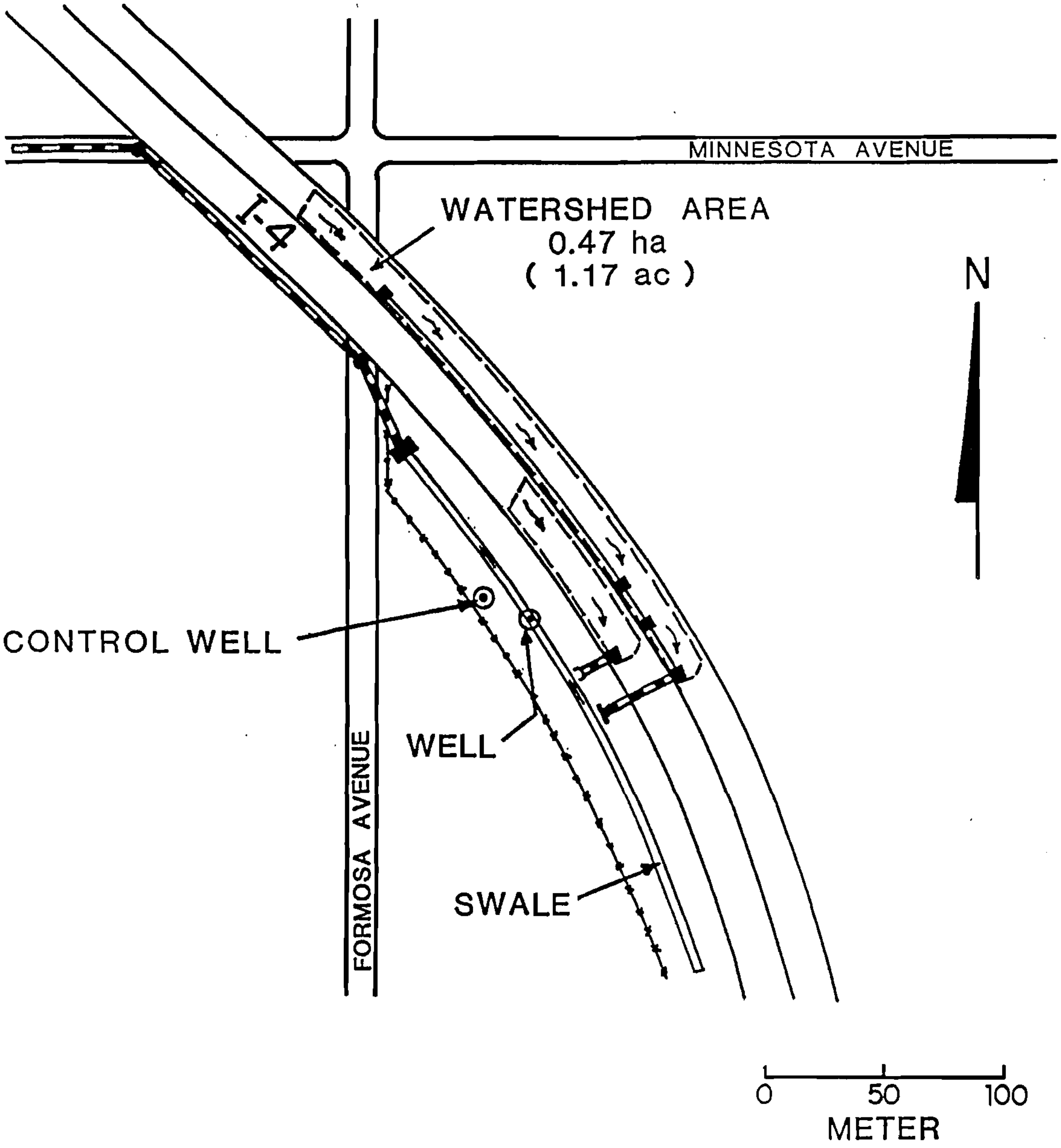


Figure 2-2. Schematic of the Wet Swale Study Site - Site 1.

median wall. All traffic lanes are constructed of concrete, while the emergency lanes located along the center median wall are asphalt coated. The total width of the three travel lanes and the emergency lane is approximately 15.5 m (50 ft) on both eastbound and westbound sides. Average daily traffic on I-4 near the study site during 1988 was approximately 64,800 vehicles per day in the eastbound direction and 62,300 vehicles per day in the westbound direction (Woods, 1989).

The swale area investigated during this research receives direct highway runoff from a 0.47 hectare (1.17 acres) drainage basin which is 100 percent impervious. The watershed consists of approximately 253 m (830 ft) of the eastbound travel lanes and 84 m (275 ft) of the westbound lanes. Both eastbound and westbound travel lanes are steeply sloped, with an average slope of 1.83 percent, as well as super-elevated due to the curve in the roadway. This combination of steep longitudinal and cross-sectional slopes results in a time of concentration of only 6.0 minutes.

As indicated in Figure 2-2, runoff from the eastbound and westbound lanes is collected in separate stormsewer systems which discharge into the swale area approximately 9 m (30 ft) apart. Large accumulations of depositional material such as sand, gravel and road debris are present near the outfall points for both stormsewer lines. Runoff flow can also enter the swale area from the steep grassed banks along the sides of the swale channel. However, these areas are densely vegetated with a thick grass cover which achieves virtually complete abstraction of rainfall for the majority of rain events.

The swale flow path consists of a well-defined parabolic shaped channel with a relatively uniform cross-sectional area. A typical swale cross-section is given in Figure

2-3. The average longitudinal slope for the swale area is approximately 0.23%. The center invert of the swale is cut slightly below the seasonal high groundwater elevation of the surrounding land, resulting in a continuous slow seepage of shallow groundwater into the swale channel during portions of the year. In spite of this continuous inflow into the swale, inter-event flow rates through the channel are extremely slow, and for all practical purposes, can be considered as stagnant conditions. Normal depth of flow at the center of the channel varied from 0.0 m (0.0 ft) to 0.60 m (2.0 ft) during the study period with slightly elevated flow depths during and immediately following storm events. Outflow from the swale is carried by underground stormsewer lines to a nearby wetland area.

The normal flow path for the swale is densely vegetated with wetland species such as pickerelweed, water pennywort and panic grass. Maintenance mowing of the roadside right-of-way is generally conducted to the edge of the wetland species.

Site 2 - Dry Swale Site

The dry swale site is located approximately 1.6 km (1.0 mile) south of downtown Orlando at the intersection of I-4 and the eastbound access ramps for the East-West Expressway. A schematic of the study site is given in Figure 2-4. The configuration of I-4 in the vicinity of the study site is similar to that described for Site 1, with three concrete travel lanes and an asphalt emergency lane in both eastbound and westbound directions. The center median, approximately 12 m (40 ft) wide, consists of both grassed and concrete lined channels used to collect and convey runoff from the westbound lanes. Average daily traffic on I-4 near the study site during 1988 was approximately 70,000

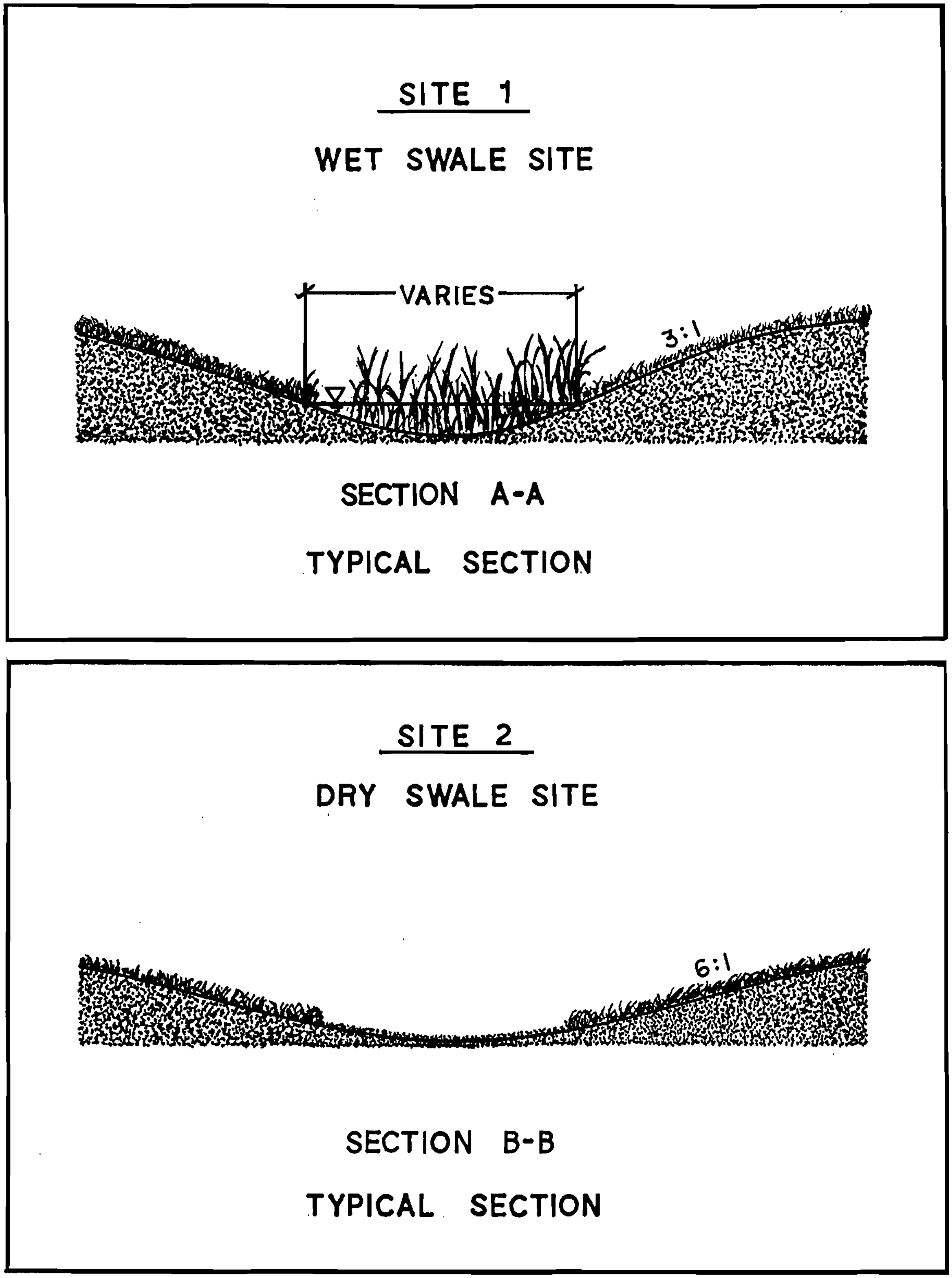


Figure 2-3. Typical Swale Cross-Sections for Study Sites 1 and 2.

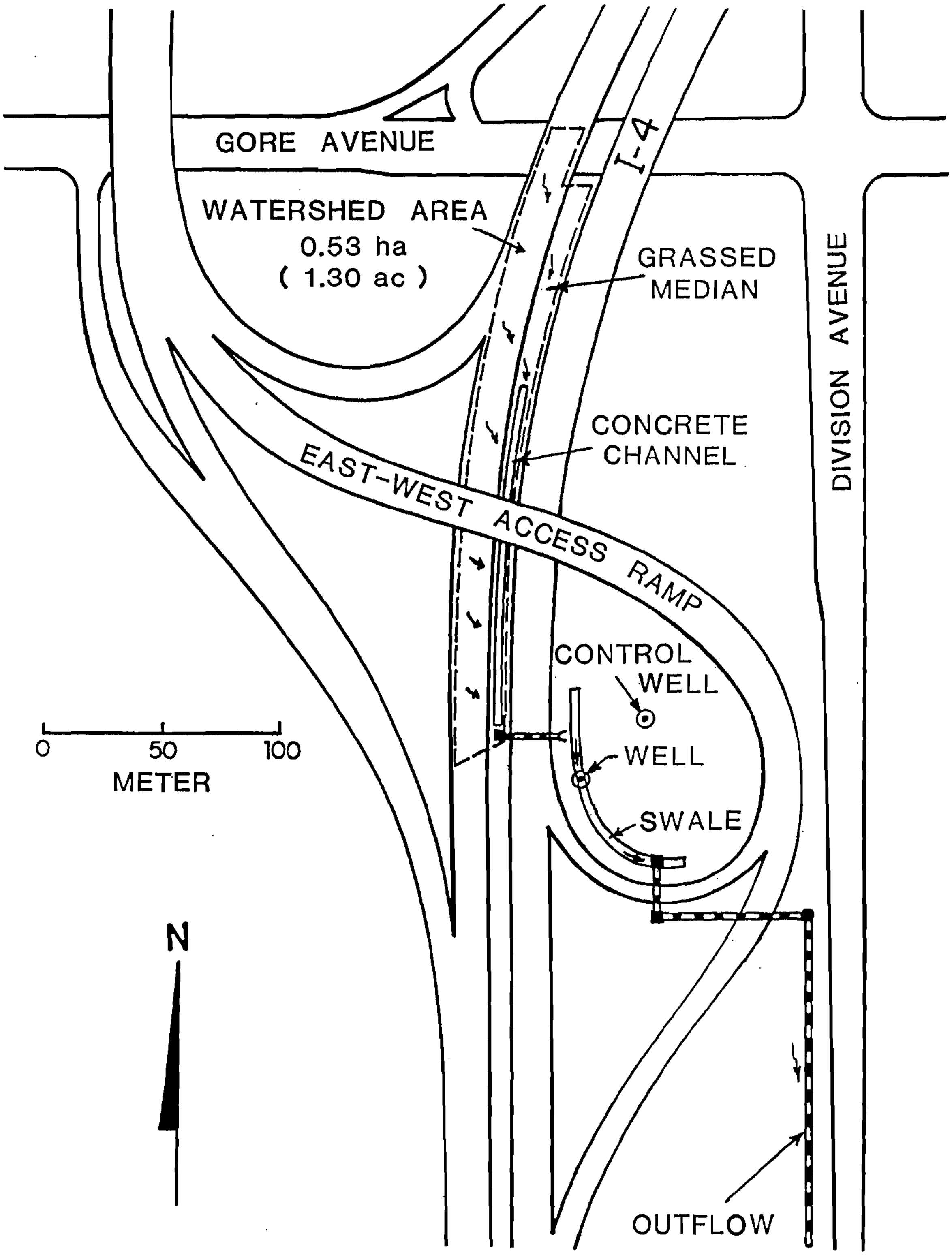


Figure 2-4. Schematic of the Dry Swale Study Site - Site 2.

vehicles per day in the eastbound direction and 68,000 vehicles per day in the westbound direction (Woods, 1989).

The swale area studied at this site receives highway runoff from a watershed of approximately 0.53 hectare (1.31 acres) which consists of 285 m (935 ft) of the westbound travel lanes including all three concrete traffic lanes and the asphalt emergency lane. The travel lanes have a moderate longitudinal slope of 0.722 percent in the direction of travel and a slight super-elevation sloping toward the center median. Due to the large amount of grassed area in the center median, the percent imperviousness of the total watershed is only 70 percent. The percentage of directly connected impervious area is only 13 percent since all highway runoff discharging into the center median must flow across grassed areas with a minimum width of 5.5 m (18 ft) before entering the center swale conveyance system, even in areas where the center channel is constructed of concrete. As seen in Table 2-1, the combination of moderate watershed slopes and flow through grassed areas produces a relatively long time of concentration of 45 minutes.

The swale flow path consists of a parabolic shaped channel with a highly variable cross-sectional area, depth and width, and a mild longitudinal slope of 0.45 percent. As seen in Figure 2-3, the flow area is shallow with mild 6:1 side slopes. The vegetative covering is sparse, consisting primarily of small annual weeds. The surface soils consist of coarse light-colored sand which is highly permeable and low in organic content. The seasonal high groundwater elevation is approximately 2 m (6.5 ft) below the center flow line of the swale.

Runoff inputs into the swale travel approximately 80 m (262 ft) before discharging into a drop inlet and entering a large stormsewer system which ultimately discharges into Lake of the Woods. However, much of the input runoff volume infiltrates into the porous soils during travel. Rain events of low intensity or low rainfall amounts were observed to be totally infiltrated into the swale with no discharge to the stormsewer system.

Site 3 - Residential Dual Pond System

The residential dual pond site is located in southeast Orlando approximately 0.3 km (0.5 mile) west of S.R. 436 (Figure 2-1). A schematic of the study site is given in Figure 2-5. The residential community, called Essex Pointe, consists of 90 upper middle class homes constructed using the zero lot line concept with a mean density of 6.6 dwelling units/acre. Roadways within the subdivision are constructed of asphalt with standard concrete Miami type curbs, while driveways and sidewalks are constructed of concrete. Home construction was begun in early 1985 and was completed in mid-1987. Prior to development, the site was occupied by an abandoned orange grove. According to the Orange County Soil Survey (U.S. Soil Conservation Service, 1957), on-site soils consist of Orlando Fine Sand (Hydrologic Soil Group A). Pre-development seasonal high groundwater elevations ranged from 0.3-0.9 m (1-3 ft) below ground surface.

The drainage system for Essex Pointe consists of concrete curbs and gutters which direct runoff into recessed curb inlets and an underground reinforced concrete pipe stormsewer system. The development is located entirely within the City of Orlando, which, at the time of design for this project, required construction of dual pond

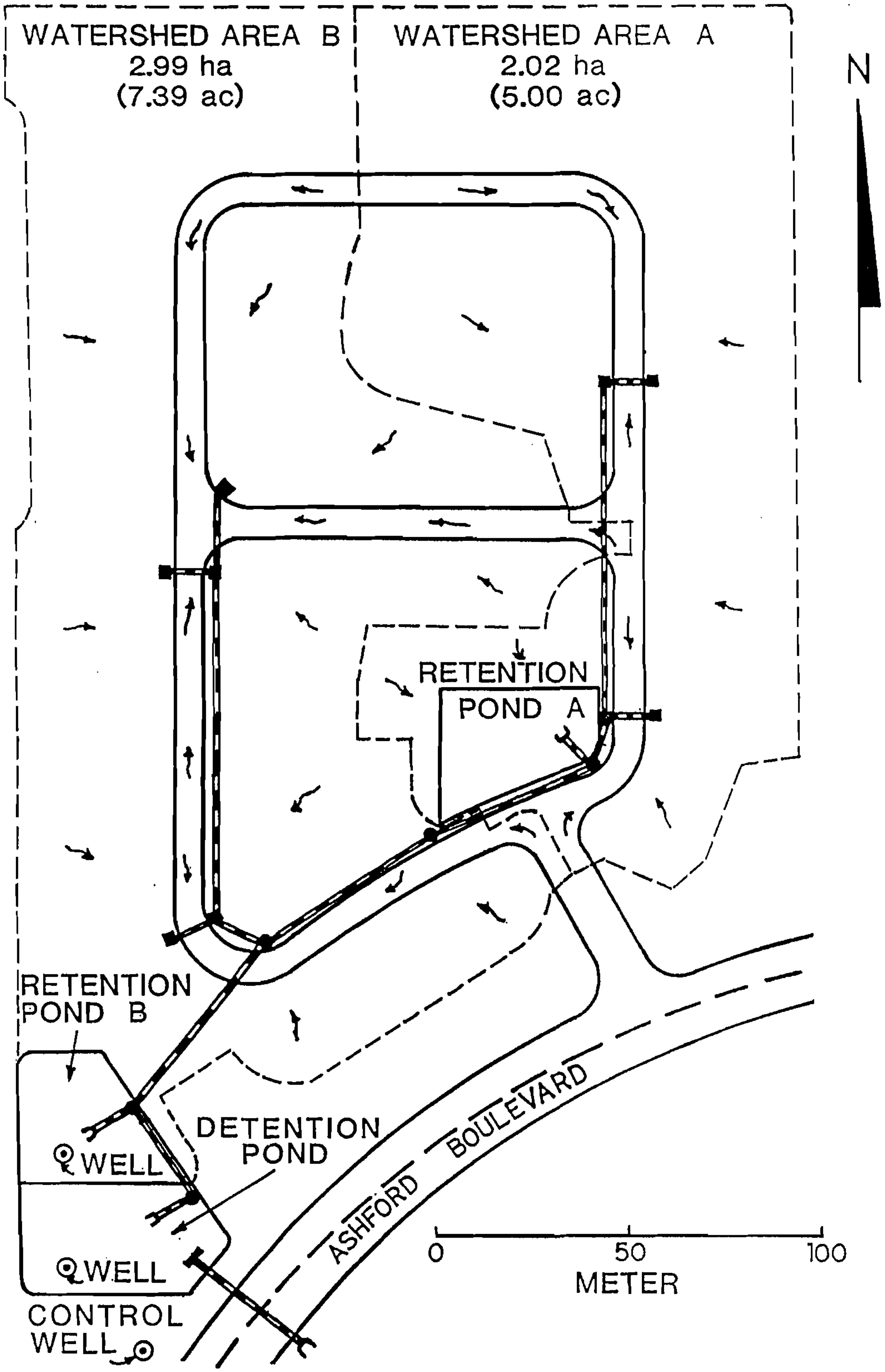


Figure 2-5. Schematic of the Residential Dual Pond Study Site - Site 3.

stormwater management systems. These systems consist of an off-line retention pond, designed to retain the runoff from the first 1.0 inch of rainfall, and a separate detention pond to attenuate post-development discharge flow rates to pre-development levels for a 25-year, 24-hour storm.

The Essex Pointe development is divided into two drainage sub-basins labeled as "Watershed A" and "Watershed B" in Figure 2-5. Each watershed has a separate off-line retention pond for pollution abatement. When the retention ponds reach the design storage volumes, the excess stormwater flows over a diversion weir into a common detention pond designed to attenuate peak flows for both areas. Field investigations conducted during this research considered only watershed area B, retention pond B and the detention pond located adjacent to retention pond B.

Retention pond B is constructed in a modified triangular shape with 5:1 side slopes and a flat bottom at an elevation of 102.5 feet. The bottom and side slopes consist of bare earth with no visible vegetation below elevation 105 feet. A diversion weir with an overflow elevation of 105.4 feet is located in a manhole adjacent to retention pond B and diverts first-flush runoff volumes into this pond. When the retention pond elevation reaches the weir elevation, stormwater inflow is diverted into the detention pond. Although the retention pond was designed as a dry bottom pond, infiltration into groundwater is slow, and the pond maintains a standing pool of water, ranging in depth from 0.3-0.9 m (1-3 ft), at all times.

The detention pond is constructed in an approximate rectangular shape with 5:1 side slopes and a flat sandy bottom at an elevation of 102.5 feet. The side slopes are well sodded with a sparse vegetative covering on the pond bottom. In general, the detention pond bottom remains dry with shallow pools of standing water observed for short periods after heavy rain events. Discharges from the pond are regulated by a narrow 7.6 cm (3 inch) wide rectangular weir with an invert elevation of 102.5 ft.

As seen in Table 2-1, the study area, consisting of Watershed B, occupies 2.99 ha (7.39 acres) and is approximately 65 percent impervious. All areas within the project site drain toward the streets, including rear yard areas. Approximately 72 percent of the impervious areas are directly connected. The only impervious areas which are not directly connected are rooftop areas which discharge into grassed backyards. In general, the watershed is relatively flat with an average slope of 0.337 percent. Because of the small watershed size, the time of concentration for runoff flow is 9.8 minutes.

Site 4 - Residential Wet Detention System

The residential wet detention site is located in southeast Orlando approximately 0.6 km (0.35 miles) east of S.R. 436 (Figure 2-1). A schematic of the study site is given in Figure 2-6. The residential community consists of 76 duplex units (152 homes), with an approximate size of 232 m^2 (2500 ft^2) per unit (1250 ft^2 per home), and a mean density of 7.47 duplex units/hectare (3.02 duplex units/acre). The subdivision is located entirely within the Orlando city limits.

Roadways within the subdivision are constructed of asphalt with standard concrete Miami curbs. Driveways and sidewalks are constructed of concrete. Subdivision construction began in 1976 and was completed in 1978. Prior to development, the site was vegetated with a natural pine flatwood community and a dense saw palmetto understory. According to the Orange County Soil Survey (U.S. Soil Conservation Service, 1957), on-site soils consist of Leon Fine Sand (Hydrologic Soil Group C).

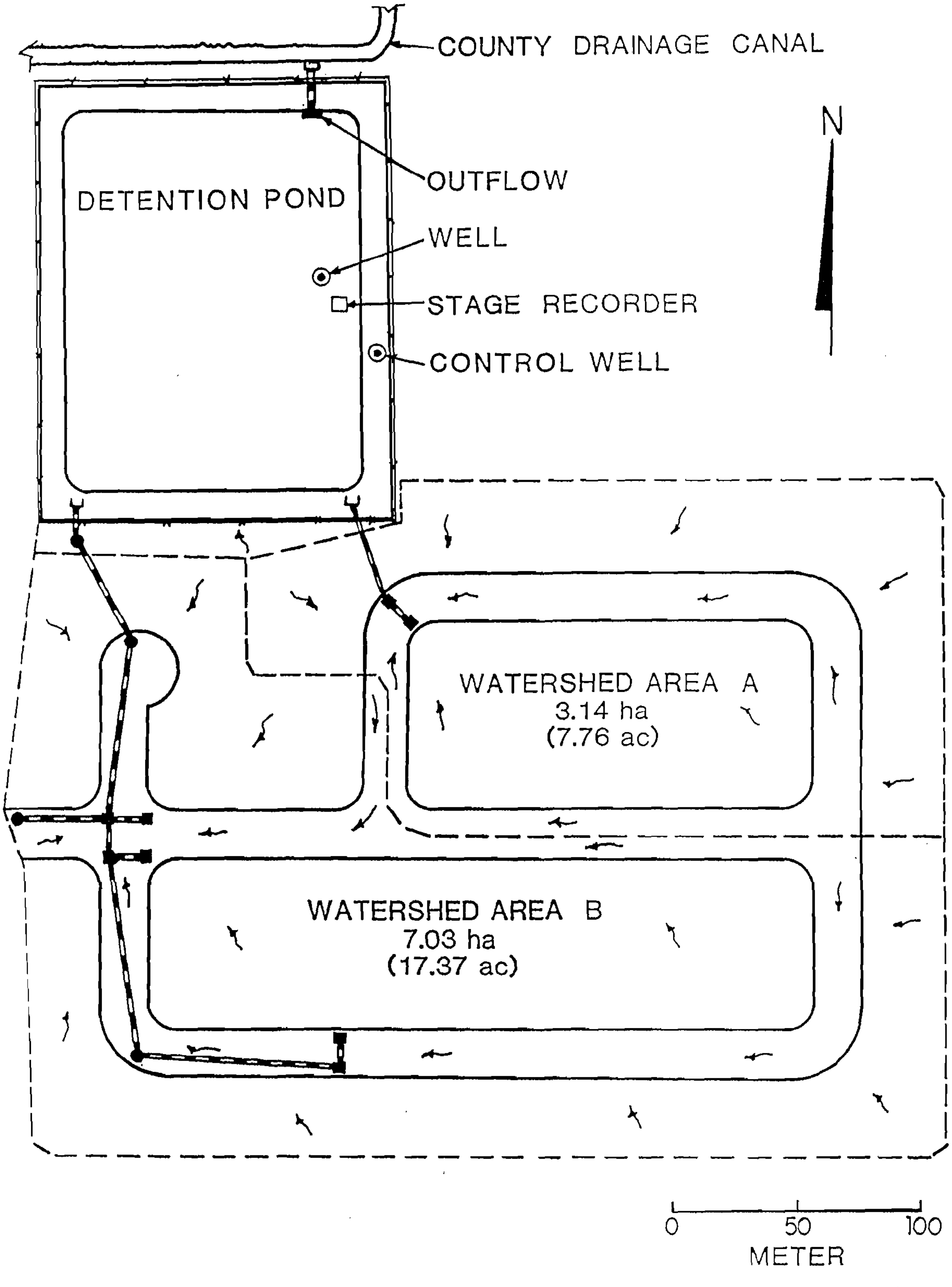


Figure 2-6. Schematic of the Residential Wet Detention Pond Study Site - Site 4.

The drainage system for the residential area consists of concrete curbs which collect and transport runoff to curb inlets and an underground reinforced concrete pipe stormsewer system. The development is divided into two drainage sub-basins labeled in Figure 2-6 as "Watershed Area A" with an area of 3.14 ha (7.76 ac) and "Watershed Area B" with an area of 7.03 ha (17.37 ac). Both sub-basins discharge runoff into a shallow 1.82 ha (4.50 ac) wet detention pond with a normal pool depth of approximately 0.8 m (2.6 ft). Discharges from the pond exit through a 91 cm (36 inch) RCP into an adjacent Orange County drainage canal. Information on design treatment volumes or drawdown times for this system could not be located in City of Orlando permit files.

The detention pond was constructed as a large rectangular basin with 3:1 side slopes and a flat bottom at an approximate elevation of 89.0 ft with the exception of pond areas subjected to erosion or deposition. In general, the pond bottom is heavily vegetated with a wide variety of submergent and emergent aquatic species which vary in diversity with fluctuations in water level. The pond is inhabited by large numbers of wading birds which feed in the early morning and late afternoon in the shallow pond areas.

As seen in Table 2-1, the watershed area is approximately 34 percent impervious. All areas within the project site drain toward the streets including rear yard areas. Approximately 69 percent of the impervious areas are directly connected. The only impervious areas which are not directly connected are rooftop areas which discharge into grassed backyards. In general, the watershed area is relatively flat with an average slope of 0.247 percent, typical of pine flatwood areas. The time of concentration is approximately 14.8 minutes.

Site 5 - Commercial Dual Pond System

The commercial dual pond site is located in southwest Orlando on International Drive approximately 0.1 km (0.06 mile) east of S.R. 435 (Figure 2-1). A schematic of the study site is given in Figure 2-7. The site, known as International Market Place, is one of many strip shopping centers located along International Drive which cater primarily to tourists. The single 2,974 m^2 (32,000 ft^2) concrete block building houses businesses which include retail outlets for gifts, clothes, shoes and jewelry, but no restaurants or other food vendors. Parking areas are located along the front and side of the main building with provisions for a total of 108 parking spaces including 73 full-size, 33 compact and 2 handicapped spaces. Vehicle activity within the parking area is virtually constant during business hours, with 50-75 percent of the parking spacers filled at any given time.

The drainage basin discharging to the dual pond system occupies an area of 0.88 ha (2.17 ac) which is 100 percent impervious and includes the building, rooftop, concrete sidewalks and the asphalt parking lot. Standard concrete curbs are located along the edges of all parking areas. Landscaped areas along the outer edges of the parking lot and in the southeast corner of the property are either self-contained for the majority of normal rain events or drain onto off-site areas. The drainage basin is extremely flat with an average slope of only 0.187 percent. Time of concentration for the drainage basin is approximately 5.5 minutes.

Stormwater runoff generated within the project site is collected in shallow depressed channels located in the center of each parking area or travel lane and transported to the nearest grate inlet and stormsewer system. All stormsewer lines are

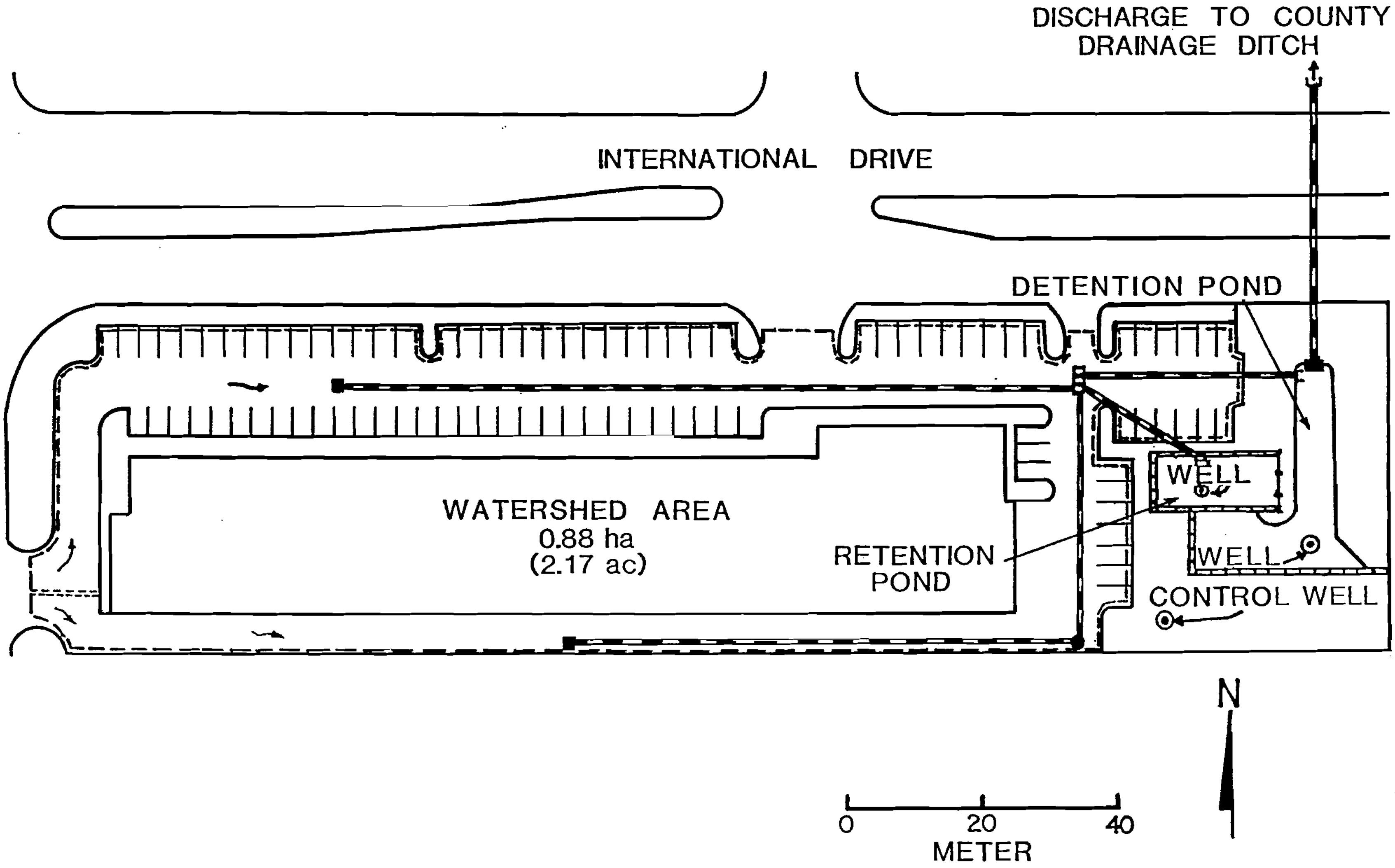


Figure 2-7. Schematic of the Commercial Dual Pond Study Site - Site 5.

connected to a single diversion box which uses an aluminum plate weir to divert first-flush waters into an off-line retention pond designed to retain the runoff from the first 1.0 inch of rainfall. When the retention pond achieves the design control elevation, runoff is diverted into a separate detention facility designed to attenuate post-development discharge flow rates to pre-development levels for a 25-year, 24-hour storm event. Discharges from the detention pond enter a large Orange County drainage canal.

The off-line retention pond is constructed as a rectangular basin with vertical concrete block retaining walls on the north and west sides. The east side is a sodded bank with 5:1 side slopes. The south side of the retention pond consists of two separate structures. A portion of the south side is constructed as a vertical block retaining wall similar to the north and west walls. The middle portion of the wall contains a structure described on the engineering site plans as a vertical filter box approximately 0.91 m (3 ft) wide, 6.1 m (20 ft) long and 1.4 m (4.67 ft) tall which is filled with No. 9 stone and capped with an 0.30 m (1 ft) deep layer of coarse sand. Approximately six 10 cm (4 in) PVC inlet pipes are present on the retention pond side of the filter, slightly above the pond bottom, which allow runoff inputs to enter the filter box. An equivalent number of PVC pipes are located on the detention side of the box which discharge water from the filter into the detention pond. All filtration appears to occur through the stone layer only. The presumed purpose of this structure is to drain the retention pond water into the detention pond to recover the required pollution abatement volume within the retention pond over a 24-hour period. No details were available in the City of Orlando permit files to describe the operation of this system.

The bottom sediments of the retention pond consists primarily of unconsolidated organic muck and fine sand. A dense community of cattails covers approximately 80 percent of the pond bottom. Infiltration losses to groundwater appear to be extremely slow resulting in a constant pool of standing water approximately 0.15-0.5 m (0.5-1.5 ft) deep within the basin.

The detention pond is constructed in an L-shape with vertical concrete block walls on the south and southwest sides as well as the common block wall which separates the retention and detention ponds. The remainder of the pond is constructed with sodded 6:1 side slopes. The detention pond bottom is primarily sand with sparse vegetative covering and a thin patch of cattails in the southwest corner. In general, standing water does not occur in the pond except for a period of 24-48 hours following rain events.

Site construction was begun in 1984 and completed in 1985. Prior to development, the site was occupied by a mixed community of pine flatwood and wetland species such as red maple and bay. According to the Orange County Soil Survey, on-site soils are poorly drained soils of the Leon and Rutledge series (Hydrologic Soil Groups C and D). Pre-development seasonal high groundwater elevations ranged from 0-0.3 m (0-1 ft) below ground surface.

Site Instrumentation

Field instrumentation was installed at each of the five study sites to monitor site hydrology for both surface and subsurface environments, collect surface water and stormwater runoff and collect groundwater samples from discrete points in the water table. Much of the instrumentation was common to all sites and will be discussed in general before presenting details for each individual site.

Hydrologic Monitoring

Continuous rainfall records were maintained at each of the five sites using a Texas Electronics Model 1014P Rainfall Recorder. These recorders work on the tipping bucket principle and create a permanent strip chart record of rainfall amount and intensity at five second intervals. Estimates of water surface evaporation were performed using a Qualimetrics Model 6811 Recording Evapograph which creates a permanent chart record of evaporation over a 24-hour or 7-day period. Each instrument was calibrated to a Class "A" pan evaporimeter on a periodic basis. Evaporimeters were placed at sites 3, 4 and 5 which contained open ponds as part of the stormwater management system. Evaporation was not recorded at the vegetated wet swale site, Site 1, since it was thought that evaporative losses from the swale would be minimal at this site. Records of evaporation were also not maintained at the dry swale site, Site 2, since standing water was present only during and immediately following rain events.

Instrumentation was also installed at each of the pond sites (Sites 3, 4 and 5) to monitor fluctuations in pond water level with time as well as following rain events. At Site 4, a Stevens Water Level Recorder was installed to provide a continuous record of water level fluctuations in the wet detention pond. However, because of aesthetic concerns by property owners as well as concerns over equipment security, staff gauges were used at Sites 3 and 5 rather than continuous recording equipment. Staff gauges were installed in both the retention and detention ponds at each site, and measurements were recorded on a daily basis throughout the study period.

Collection of Stormwater Runoff

Stormwater runoff was collected during rain events on a flow-weighted basis at each of the five study sites using two methods. Runoff collection at the pond sites (Sites 3, 4 and 5) was accomplished using ISCO Model 2700 Sequential Samplers and an ISCO Flowmeter programmed for the hydraulic characteristics of each inflow stormsewer line (pipe diameter, pipe material, slope, etc.).

Restrictions contained in the Florida Department of Transportation (FDOT) Utility Permit required for conducting activities within FDOT right-of-way at Sites 1 and 2 prohibited erection of structures for housing ISCO sequential samplers at these sites. After much deliberation, an alternative method of sample collection was developed for the swale systems at Sites 1 and 2. A schematic of the collection device is given in Figure 2-8.

The runoff collector was constructed of clear Lexan plastic with a length of 30 cm (12 inches) and a width of 30 cm (12 inches). Each collection was placed in the middle of the swale channel, approximately 3 m (10 ft) downstream from the stormsewer inflow, and anchored in place with spikes permanently attached to the collector bottom. Operation of the collector is based on the Manning equation for open channel flow which equates changes in the normal flow depth within the swale channel to changes in flow rate. Multi-level transfer tubes were inserted into the rear of the collector, leading to a buried 8-liter sample bottle. Runoff water flows into the collector and enters the multi-level transfer tubes at a rate proportional to the velocity of flow, depth of flow and the size of the transfer tubes. At low flow rates, runoff enters one transfer tube only at a rate proportional to the velocity of runoff flow. At higher flow depths, runoff is

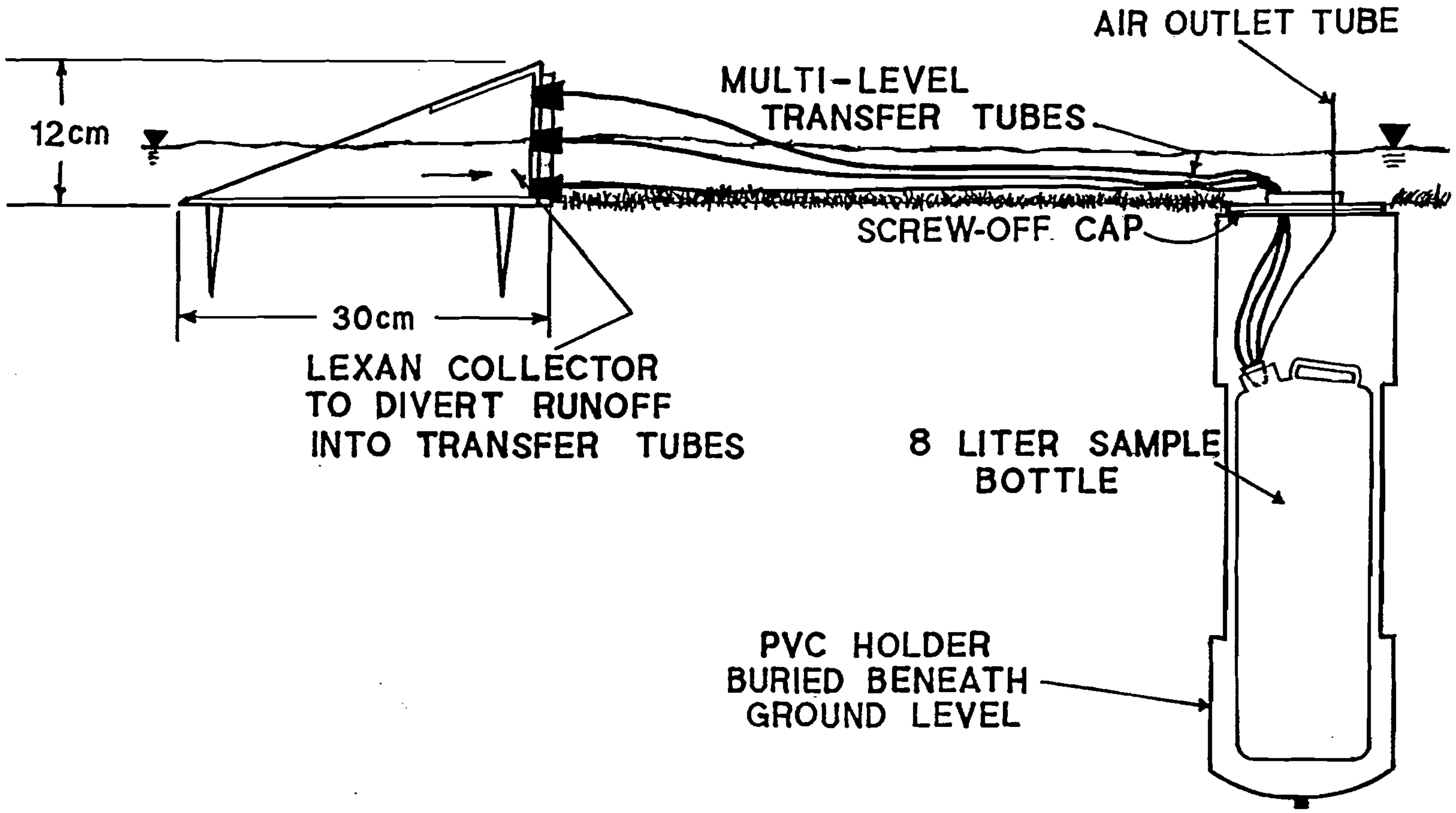


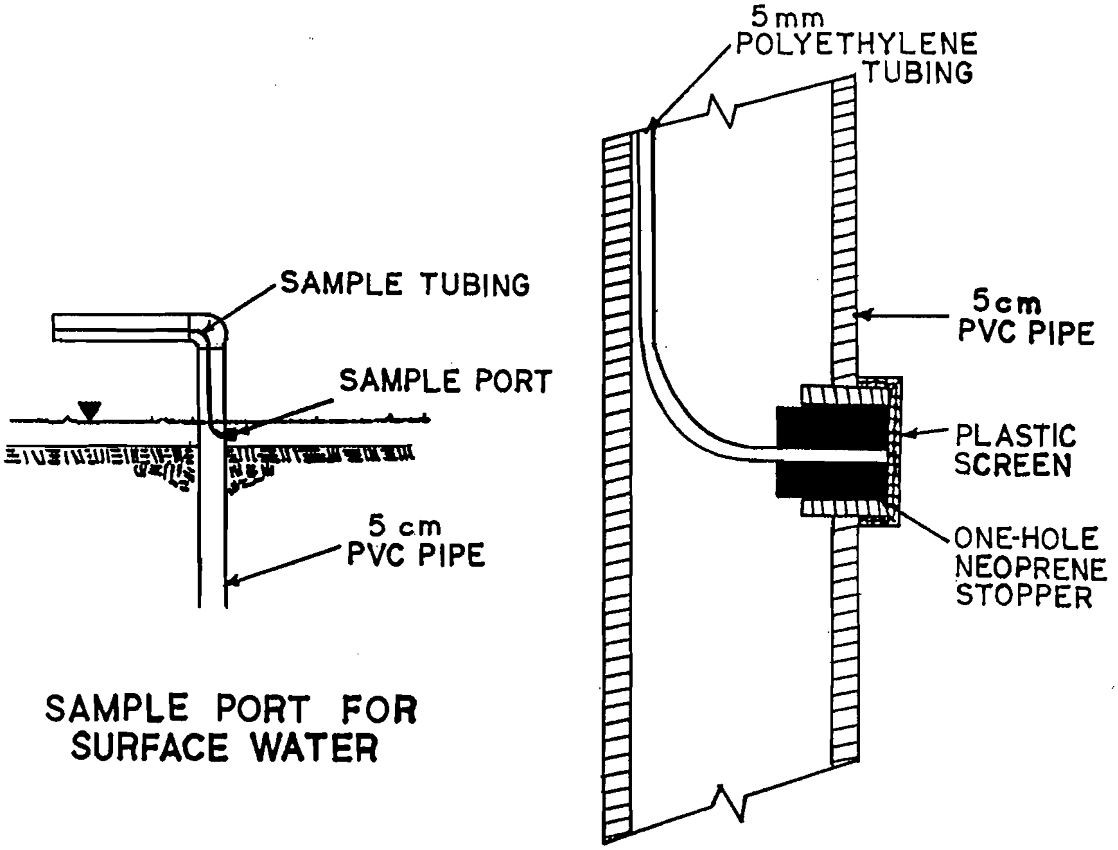
Figure 2-8. Sample Collector Used for Collection of Stormwater Runoff in Swale Channels at Sites 1 and 2.

transferred through multiple tubes. Numerous field experiments were conducted during testing of the collectors to find a combination of tube sizes and spacing which would simulate a flow-weighted collection process. After design optimization, a collector was capable of collecting a flow-weighted sample with an error of less than 10 percent. Very good relationships were observed between total rainfall volume and the quantity of sample collected within the sample bottle. In general, runoff samples were collected within 1-4 hours following a monitored rain event.

Collection of Surface Water

One of the primary field tasks conducted during this research involved biweekly field monitoring and collection of surface water samples from all study sites which contained standing pools of water. This process involved all sites except the dry swale site (Site 2). It was preferred that surface water samples be collected in the open water areas away from the pond edges. To eliminate the unavoidable disturbances to sediments and surface water caused by field personnel wading into open water, surface water samples were collected using surface water sample ports which were constructed and installed inside all wet ponds and the wet swale channel. A schematic of this device is given in Figure 2-9.

The sample surface water port consists of a length of 5 mm polyethylene tubing which is inserted into a one-hole neoprene stopper, fitted with a coarse mesh plastic screen and attached to a 5 cm (2 inch) PVC pipe. One pipe was installed permanently at each surface water site with the sample port located above the sediment surface. Sample tubing was extended to the shore inside a PVC pipe to prevent the growth of



SAMPLE PORT FOR
SURFACE WATER

CROSS SECTION OF
SAMPLING PORT
FOR SURFACE
WATER

Figure 2-9. Sample Port for Collection of Surface Water.

algae inside the tubing. Water samples were collected using a portable peristaltic pump with minimal disturbance of the water column. The coarse screen mesh allows collection of naturally occurring suspended solids but prevents entrance by insects or debris.

Field instrumentation was also installed for collection of groundwater samples and measurement of piezometric surfaces in test and control areas. Details of these techniques are given in a subsequent section.

Details of Instrumentation at the Five Study Sites

Site 1 - Wet Swale Site

A schematic of field instrumentation used at the wet swale site is given in Figure 2-10. Lexan plastic runoff collectors were installed along the flow channel as indicated. One collector was placed approximately 3 m (10 ft) downstream from the last incoming stormsewer line to monitor raw stormwater characteristics. This collector was placed flush with the bottom of the swale channel since standing water was not present in this part of the swale. A second collector was placed in the swale channel approximately 70 m (230 ft) downstream from the first collector to monitor changes in runoff characteristics resulting from flow through the vegetated channel. This sampler was installed slightly above the existing water surface elevation in the swale so that samples would only be collected as the depth of flow increased during storm events. A surface water sample port was also installed in the center of the swale channel as indicated in Figure 2-10.

Multi-port groundwater monitoring wells were installed as shown in Figure 2-10 with one well located in the center of the swale channel (Swale Well) and a second well

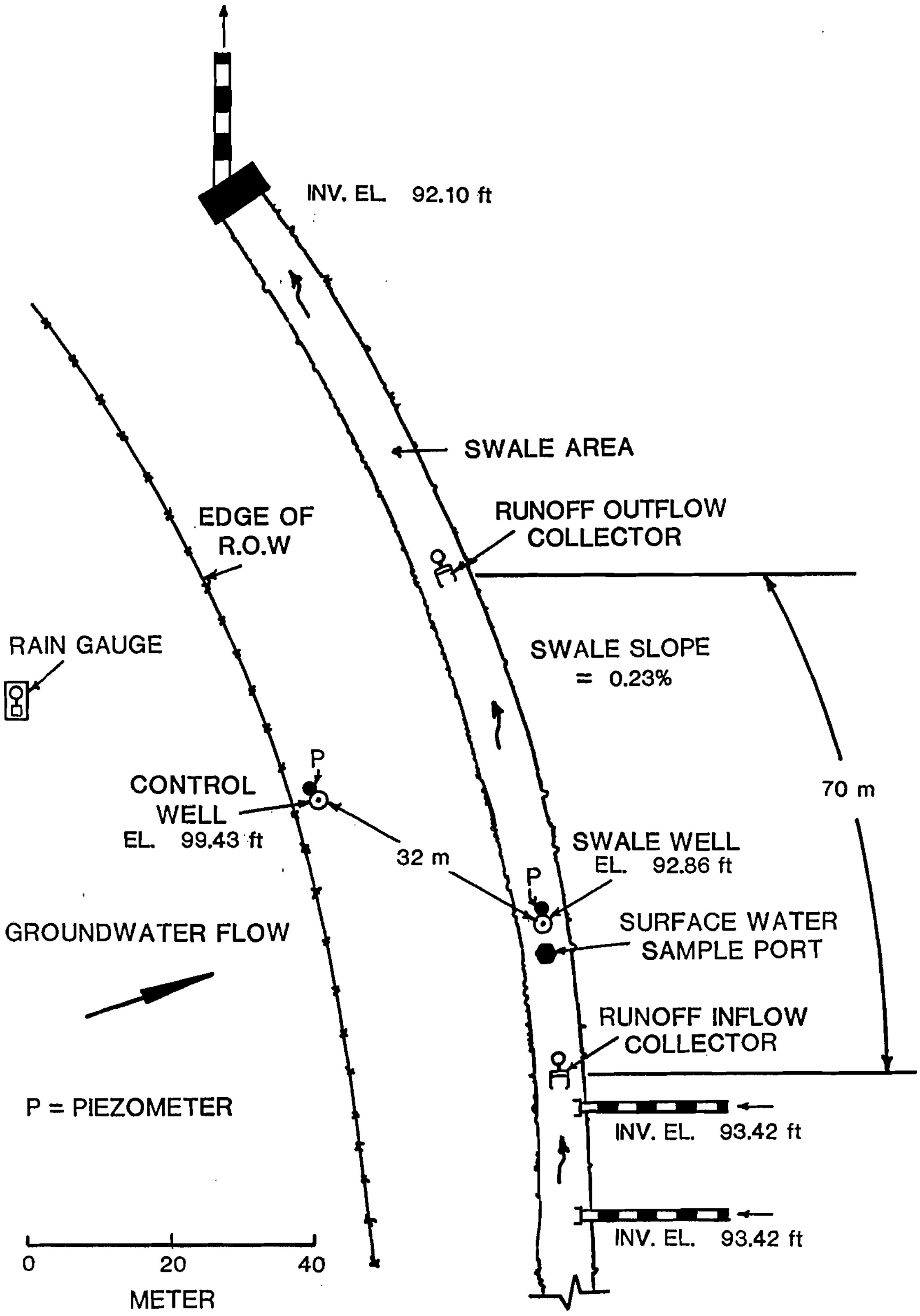


Figure 2-10. Field Instrumentation at the Wet Swale Site - Site 1.

(Control Well) located 32 m (105 ft) from the swale well in a high upland area at the edge of the FDOT right-of-way. Two piezometers were installed in each well bore hole with one at a depth of 1 m (3.3 ft) below the estimated seasonal high groundwater table elevation to monitor shallow piezometric levels and a second piezometer at a depth of 5 m (16 ft) to monitor deep piezometric levels. As indicated in Figure 2-10, the normal direction of local groundwater flow at this site is toward the east-northeast.

A recording rain gauge was installed at a private residence approximately 2 blocks from the site. Due to dense vegetative covering along the swale channel, evaporation was not measured at this site.

Site 2 - Dry Swale Site

A schematic of field instrumentation used at the dry swale site is given in Figure 2-11. Lexan plastic runoff collectors were installed along the swale channel as indicated. One collector was placed approximately 3 m (10 ft) downstream from the incoming stormsewer line to monitor raw stormwater characteristics. A second collector was placed in the center of the swale channel approximately 70 m (230 ft) downstream from the first collector to monitor changes in runoff characteristics resulting from flow through the dry swale channel. Both runoff collectors were installed flush with the swale bottom.

Multi-port groundwater monitoring wells were installed as shown in Figure 2-11 with one well located in the center of the swale channel (Swale Well) and a second well located 40 m (131 ft) from the swale well in an isolated upland area inside the cloverleaf of the East-West Expressway entrance ramp (Figure 2-4). One shallow and one deep piezometer was installed in each well bore hole at depths of 1 m and 5 m, respectively,

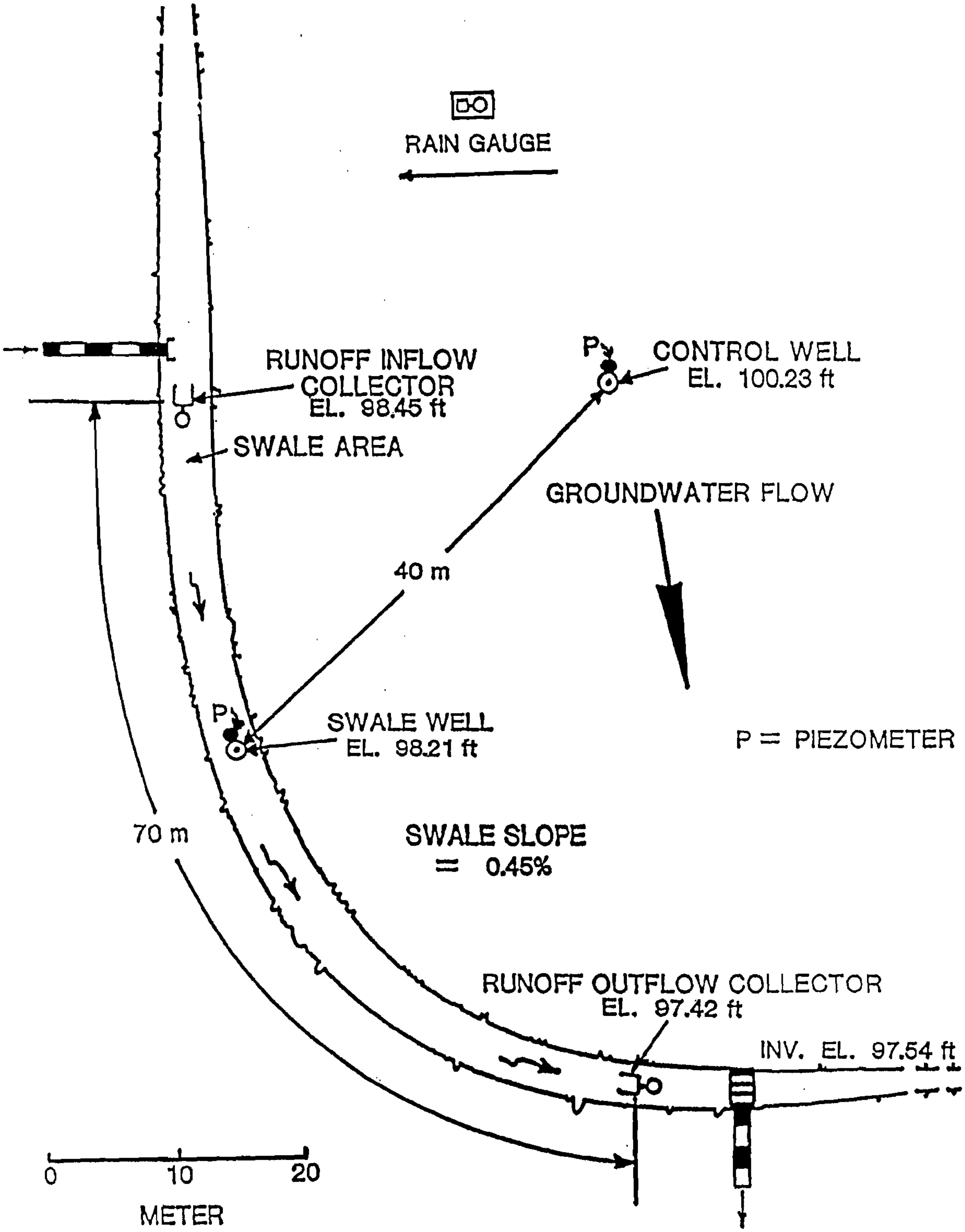


Figure 2-11. Field Instrumentation at the Dry Swale Site - Site 2.

below the estimated seasonal high groundwater table elevation. As indicated in Figure 2-11, the normal direction of local shallow groundwater flow at this site is to the south-southeast.

A recording rain gauge was installed on the roof of a City of Orlando office building approximately 3 blocks from the study site. Since standing water is only present at this site for short periods during rain events, an evaporimeter was not used at this location.

Site 3 - Residential Dual Pond Site

A schematic of field instrumentation used at the residential dual pond site is given in Figure 2-12. Stormwater runoff samples were collected with an ISCO sequential sampler placed inside the diversion manhole. The collector intake line was situated on the downstream side of the diversion wall to only sample inputs to the retention pond. Sequential samples collected during portions of rain events when flow was occurring over the diversion weir and discharging into the detention pond were not included in formation of composite samples to represent retention pond inflow.

Multi-port groundwater monitoring wells were installed at the locations indicated in Figure 2-12. One well was placed inside the retention pond (Retention Well), one inside the detention pond (Detention Well) and a control well was installed approximately 20 m (66 ft) upgradient from the detention pond well in an open grassed area. Shallow and deep piezometers were also installed in each well bore hole as described for previous sites. As indicated in Figure 2-12, the normal direction of local shallow groundwater flow at this site is to the northeast.

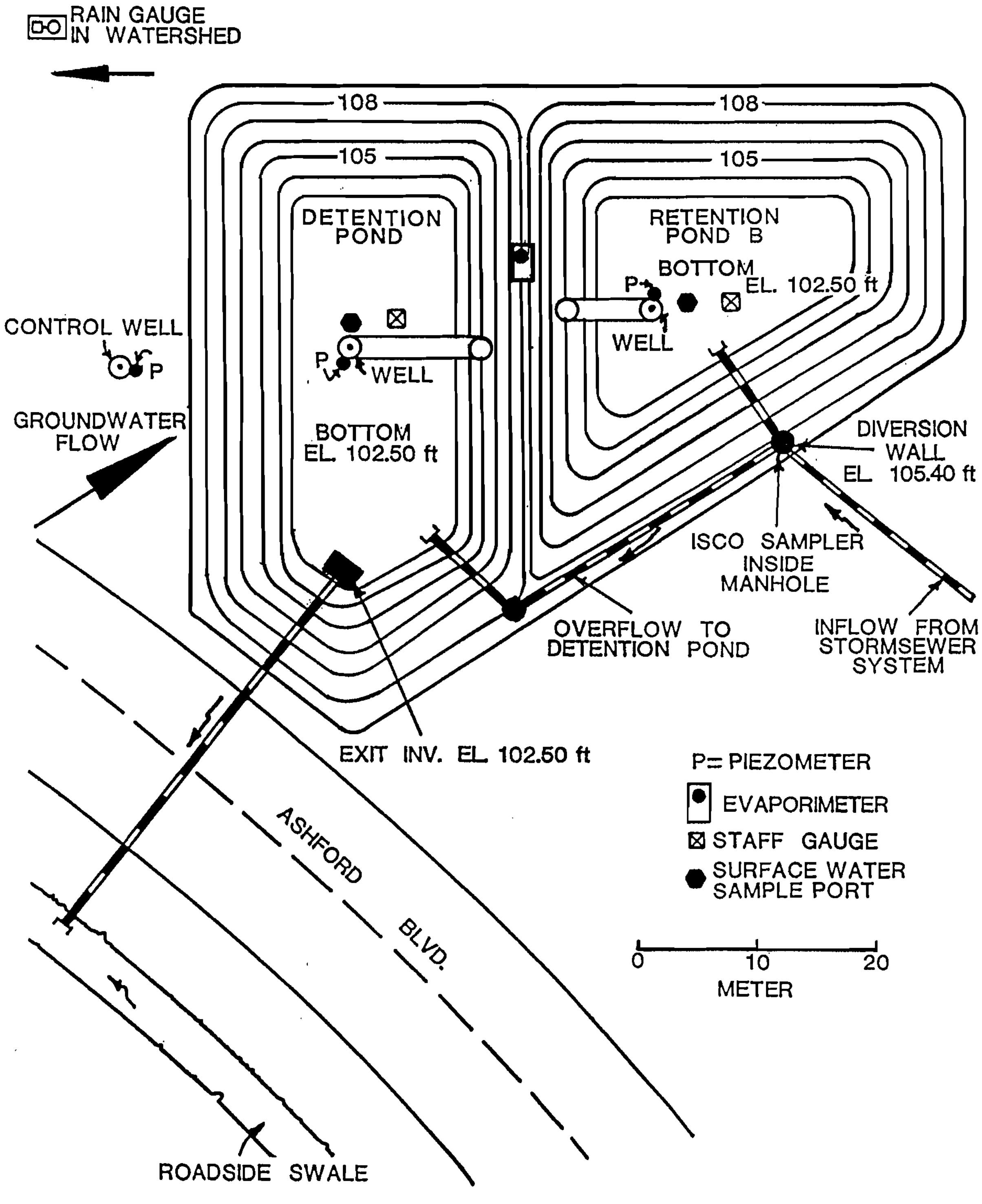


Figure 2-12. Field Instrumentation Used at the Residential Pond Site - Site 3.

A recording rain gauge was installed on the roof of a private residence inside the watershed boundary. An evaporimeter was placed on the earthen berm separating the two ponds. Chart records were retrieved on a daily or weekly basis depending on the rate of evaporation. Permanent staff gauges were installed in both retention and detention ponds and monitored on a daily basis. Surface water sample ports were installed in both retention and detention ponds as indicated in Figure 2-12.

Site 4 - Residential Wet Detention Pond Site

A schematic of field instrumentation used at the residential wet detention pond site is given in Figure 2-13. Runoff samples were collected from inflow stormsewer "A" at the point of discharge into the pond. An ISCO automatic sequential sampler with flowmeter attachment was placed inside a waterproof equipment shelter near the end of the outfall line. Sample collection tubing and flowmeter lines were extended from the sampler approximately 3 m (10 ft) into the stormsewer line. Runoff samples were collected on a flow-weighted basis. Runoff sampling was not conducted at inflow line "B" since this stormsewer pipe was either partially or fully submerged at all times.

Multi-port groundwater monitoring wells were installed at the locations indicated in Figure 2-13. One well was placed inside the detention pond, with a control well located approximately 37 m (121 ft) away in an upland area next to the perimeter fence. Shallow and deep piezometers were also installed in each well bore hole. The normal direction of shallow groundwater flow in the vicinity of the dual pond system is from east to west as indicated in Figure 2-13.

A recording rain gauge was installed on the roof of a nearby private residence within the watershed area. An evaporimeter was placed on the maintenance berm

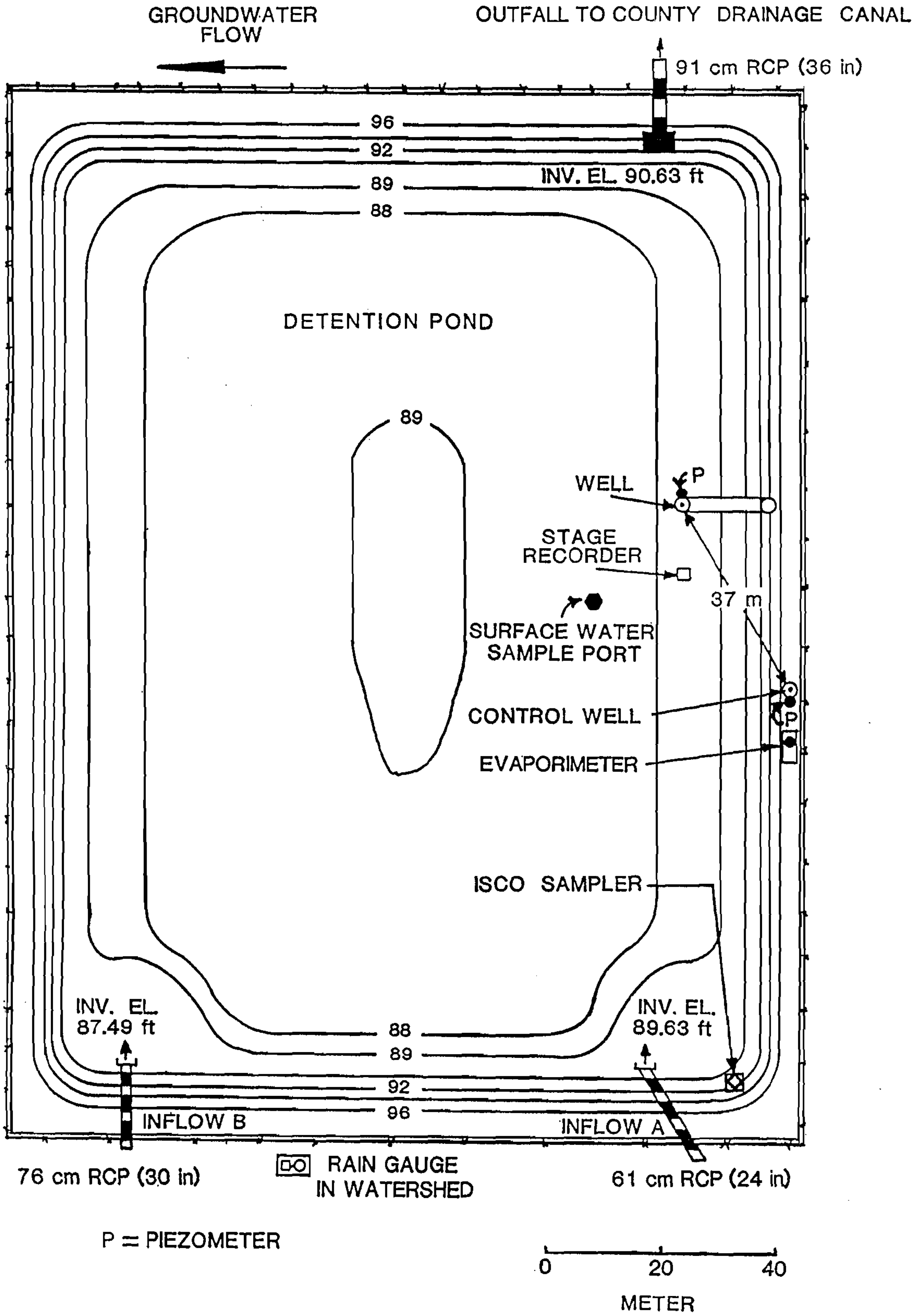


Figure 2-13. Field Instrumentation at the Residential Wet Detention Pond - Site 4.

surrounding the pond. Chart records were retrieved on a daily or weekly basis depending on the rate of evaporation. A Stevens Model A-71 stage recorder was installed inside the pond. The standpipe used to guide the float was installed with a clear travel path extending 0.5 m (1.6 ft) below the pond bottom to monitor the shallow piezometric surface in the event that the pond bottom should become dry. In addition, a surface water sample port was installed in the detention pond as indicated in Figure 2-13 with sample tubing extending to the nearby shore.

Site 5 - Commercial Dual Pond Site

A schematic of field instrumentation used at the commercial dual pond site is given in Figure 2-14. Runoff samples were collected from the stormsewer line entering the retention pond at the point of discharge into the pond. An ISCO automatic sequential sampler with flowmeter attachment was installed inside a waterproof equipment shelter located at the edge of the retention pond. Sample collection tubing and flowmeter lines were extended from the sampler approximately 3 m (10 ft) into the stormsewer line. Runoff sampling of the retention pond inflow was conducted on a flow-weighted basis.

A limited number of runoff samples were also collected from the stormwater flow diverted into the detention pond after the retention area reached the design storage elevation. Because of concerns over equipment security, these samples were collected manually rather than with automatic equipment. Discrete runoff samples and simultaneous flow measurements were collected over the runoff hydrograph by field personnel. Upon returning to the research lab, a flow-weighted composite sample was prepared based on the field flow measurements.

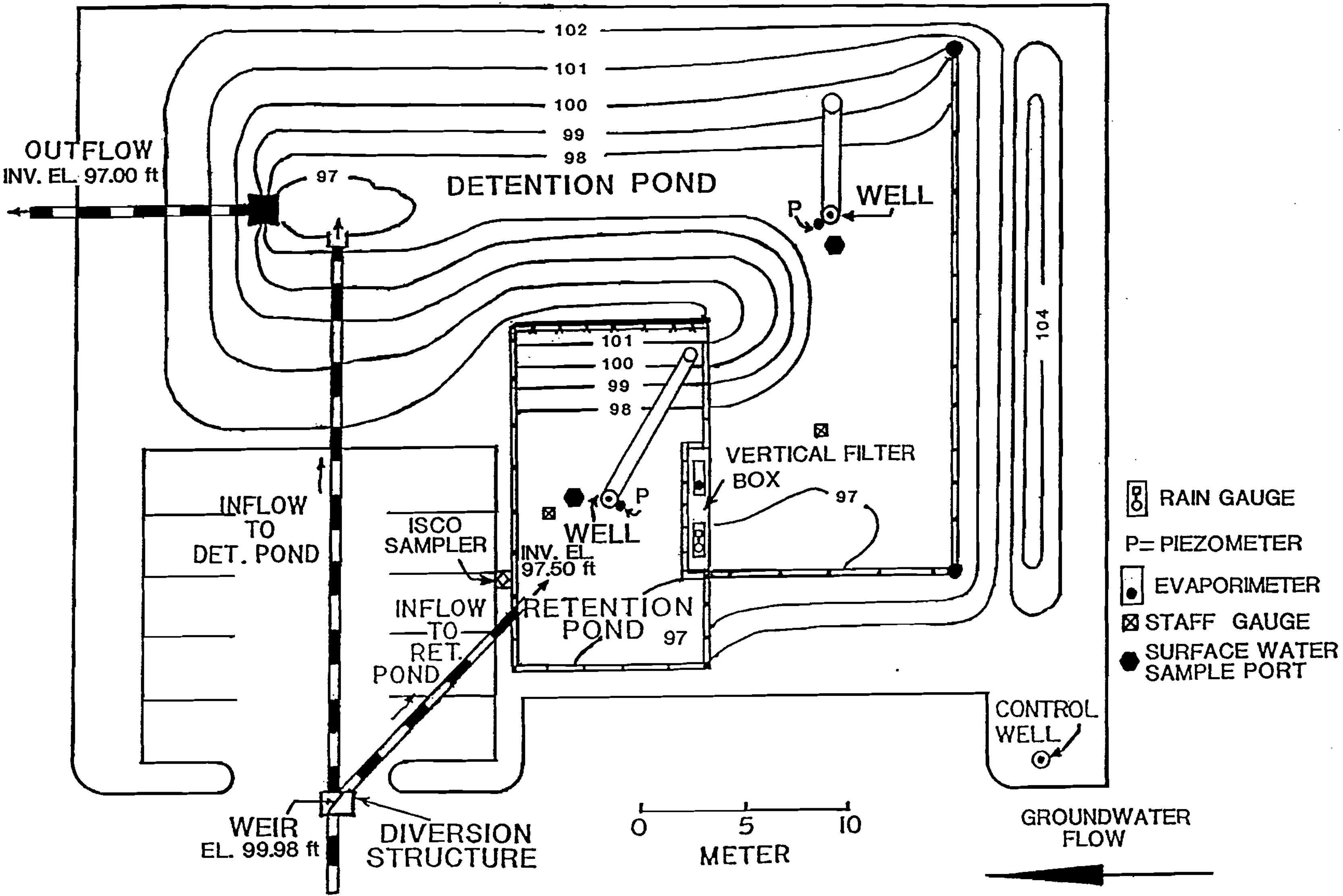


Figure 2-14. Field Instrumentation at the Commercial Dual Pond Site - Site 5.

Multi-port groundwater monitoring wells were installed at the locations indicated in Figure 2-14. One well was placed inside the retention pond (Retention Well), one was installed inside the detention pond (Detention Well) and a third well was installed in an upland grassed area (Control Well). Shallow and deep piezometers were also installed in each well bore hole. The normal direction of shallow groundwater flow in the vicinity of the dual pond system is from south to north.

A recording rain gauge and evaporimeter were placed on top of the vertical filter box. Staff gauges were installed inside both retention and detention ponds as indicated in Figure 2-14, with recordings taken on a daily basis. A surface water collection port was installed inside both retention and detention ponds with sample tubing extending to the nearby shore.

Monitoring Well Details

A total of 12 multi-port monitoring wells were installed at the five study sites. The multi-port design was such that all sample ports were housed in a single 5 cm (2 inch) PVC pipe. A schematic of a multi-port sampling device is shown in Figure 2-15. It was felt that this design would minimize soil disturbance and reduce groundwater recovery time for obtaining representative samples when compared to other monitoring well designs such as cluster wells installed at a variety of depths. Sample ports were constructed from one-hole neoprene stoppers with a 5 mm semi-rigid polyethylene tube inserted in the hole. The stopper was covered with a small mesh plastic screen to prevent soil particles from entering the tubing. The well casing was constructed of 5 cm

PVC pipe. Sample ports were inserted in the casing at depths of 0.1 m, 0.5 m, 1.0 m, 2.5 m and 5.0 m. Polyethylene tubing was extended from each sample port through the PVC casing to the surface where the ends were permanently marked for accurate identification of sample ports during sample collection.

Bore holes for the multi-port wells were formed by extending a 15 cm (6 inch) stainless steel casing into the ground in 1 m (3.3 ft) sections using a portable rotary cathead and a standard 64 kg (140 lb) hammer. No drilling fluids or lubricants of any kind were used during drilling. Once the drilling process was completed, the hole was backwashed with clean water until the wash water was clear and free of suspended solids. A portable well pump was then inserted into the casing, and any remaining wash water was pumped from the bore hole. The PVC monitoring well housing was inserted into the bore hole, and backfilling with clean silica sand (20-30 grade) was begun. After approximately 1.5 meters of backfill had been placed, the drill casing was gently raised and a 1 m (3.3 ft) section was removed. Bentonite seals, approximately 20 cm thick, in the form of 0.64 cm (0.25 inch) pellets, were placed mid-way between each of the sample ports as indicated in Figure 2-15. An additional seal was placed around the monitoring well casing at the ground surface to minimize seepage of water around the sides of the PVC pipe. A removable end cap cover was installed on each well to protect the sample tubes.

The depth of installation for monitoring wells was dictated by the type of stormwater management system at each of the study sites. At Site 1, the swale well was installed with the first sample port located 0.1 m below the swale channel. At Sites 3, 4 and 5, pond wells were installed with the first sample port located 0.1 m below the

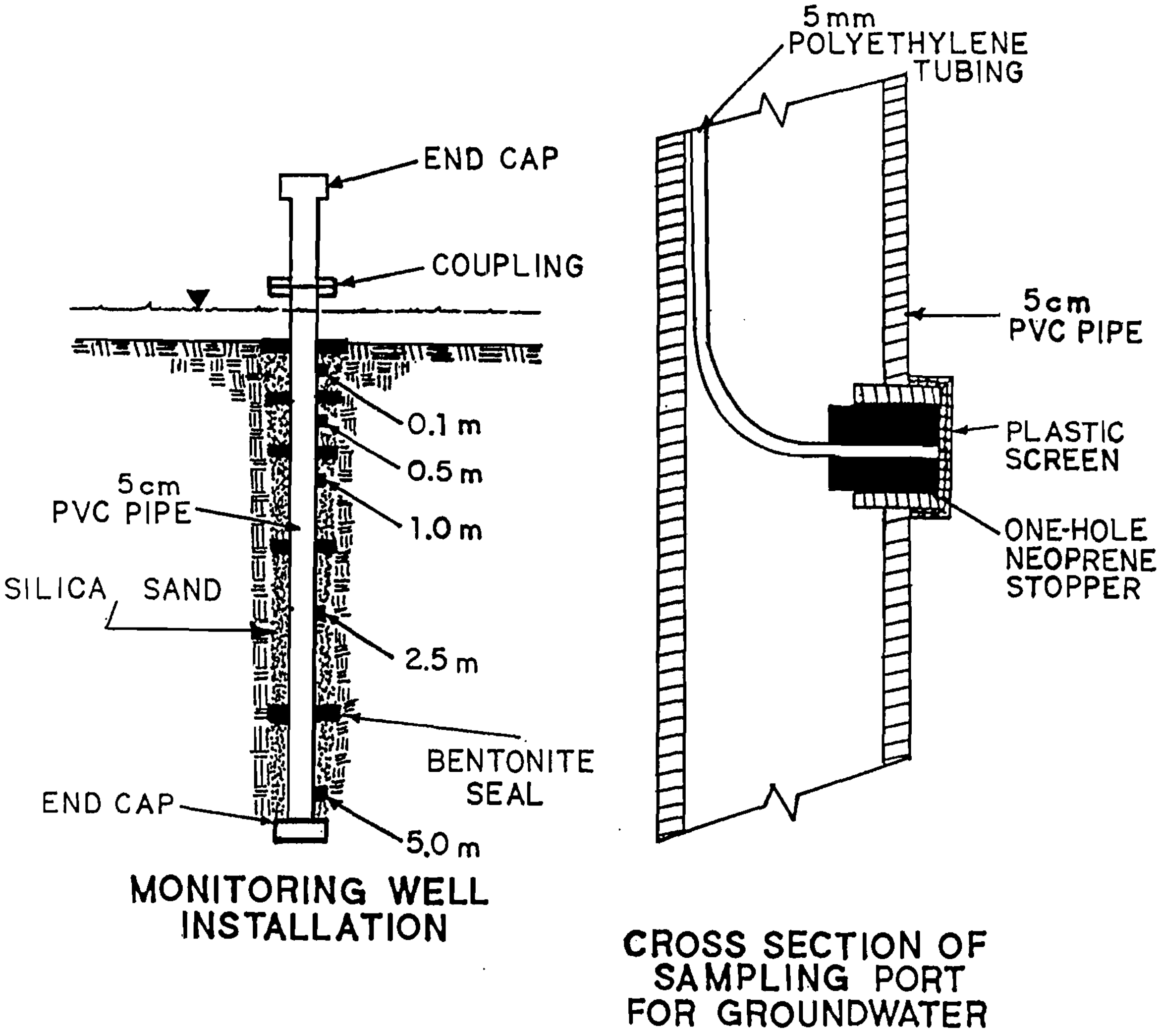


Figure 2-15. Schematic of the Multi-port Monitoring Wells.

pond bottom. At the dry swale site, Site 2, the swale well was installed with the first sample port located 0.1 m below the groundwater table estimated seasonal high which was found at a depth of approximately 3 m (10 ft) below the swale channel. All control wells at each site were installed with the sample ports at the same elevation as the other monitoring wells.

After construction was completed, sample collection was delayed for approximately 60 days to allow for groundwater disturbances created during the installation process to dissipate. In addition, during the first 60 days following construction, each port on each of the 12 wells was purged for 10 minutes on a weekly basis with a peristaltic pump to remove any remaining groundwater which may have been disturbed during construction. This process removed approximately 20 liters from each sample port on each weekly visit.

Sediment Core Collection

Numerous sediment core samples were collected at each of the five study sites to characterize the horizontal and vertical deposition of heavy metals and nutrients in stormwater management systems and in control areas. Sample cores were collected using a non-metallic split-spoon type core collection device. The collection device consisted of a 5 cm (2 inch) diameter split Schedule 40 PVC pipe, approximately 75 cm in length, with a beveled edge on one end for ease in sediment penetration. A schematic of the split-spoon sediment core sampler is given in Figure 2-16. A pair of hose clamps were used to hold the split-spoon sampler in place as it was inserted into the soil or sediments. In some locations the collection tube could be pushed into the sediments by hand, while

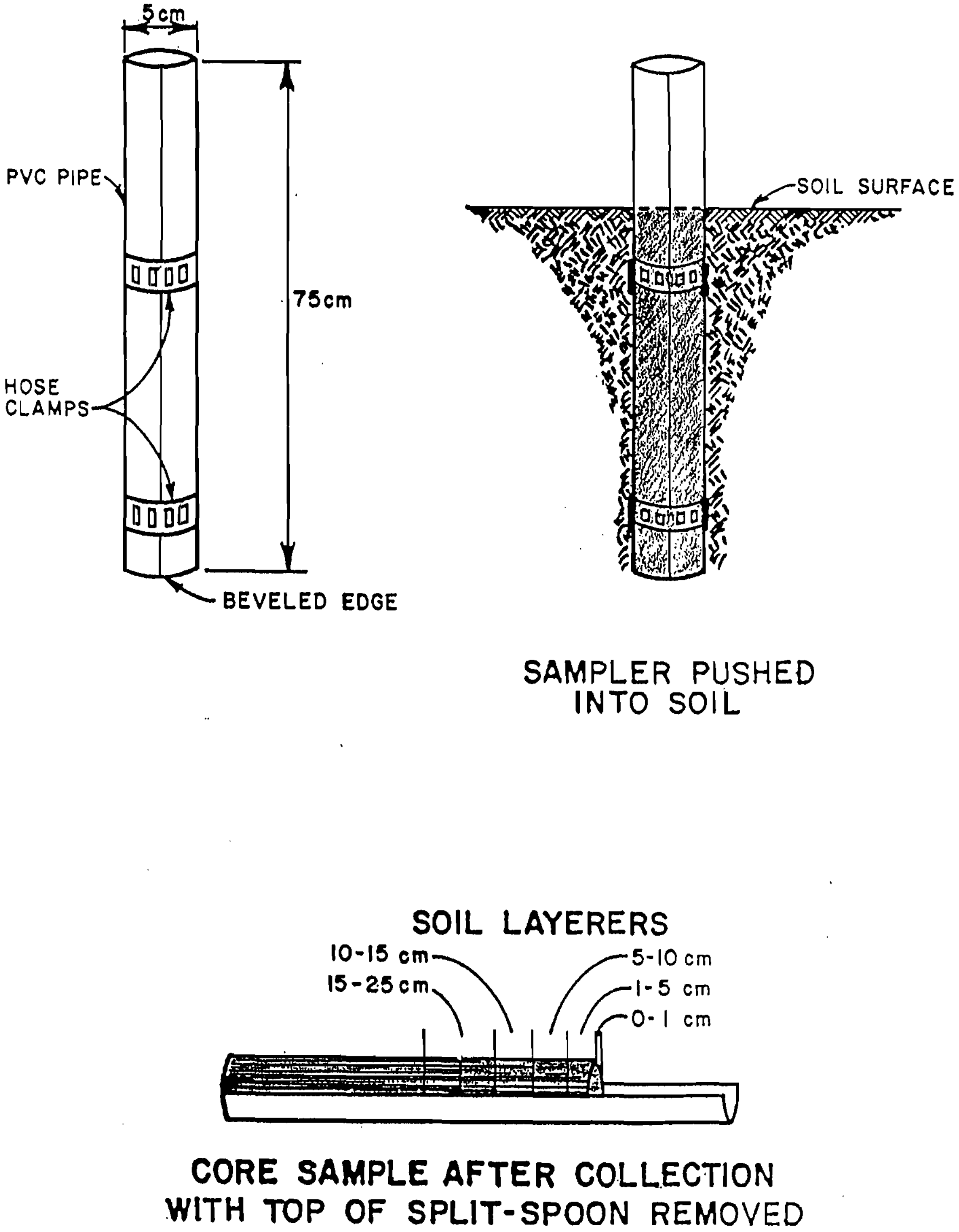


Figure 2-16. Schematic of the Sediment Core Collection Device.

at other locations a rubber hammer was used. The sediment removal technique consisted of inserting the sample collection device into the sediments to a depth of approximately 40 cm and then removing it using an upward twisting motion.

Upon removing the split-spoon sampler from the sediments, each core sample was immediately divided into the following layers: (1) 0-1 cm; (2) 1-5 cm; (3) 5-10 cm; (4) 10-15 cm; and (5) 15-25 cm. After separation of the sample into layers, each of the horizons were stored in separate polyethylene bottles and labeled appropriately. Three 5.0 cm diameter core samples were collected at each core sample site and combined to form a composite sample for each layer.

Locations for collection of sediment core samples at Sites 1 and 2 are indicated in Figures 2-17 and 2-18. Composite core samples were collected at each of the locations indicated. At both sites, core samples were collected along the center of the swale channel at distances of 2.5 m, 10 m, 25 m, 40 m and 70 m from the point of runoff inflow. The 0-1 cm layers from each sample were analyzed separately to characterize changes in sediment metal concentrations with distance along the swale flow path. The 1-5 cm, 5-10 cm, 10-15 cm and 15-25 cm layers from these samples were combined together by layer to form a single composite sample for each layer representative of general sediment characteristics beneath the swale area. A composite core sample was also collected from an area near the control well which is unaffected by runoff inputs. Samples at this location were analyzed separately for all five layers.

Locations for collection of composite sediment core samples at the two dual pond sites (Sites 3 and 5) are indicated in Figures 2-19 and 2-20. Composite core samples were collected from the retention pond, detention pond and control areas. The 0-1 cm

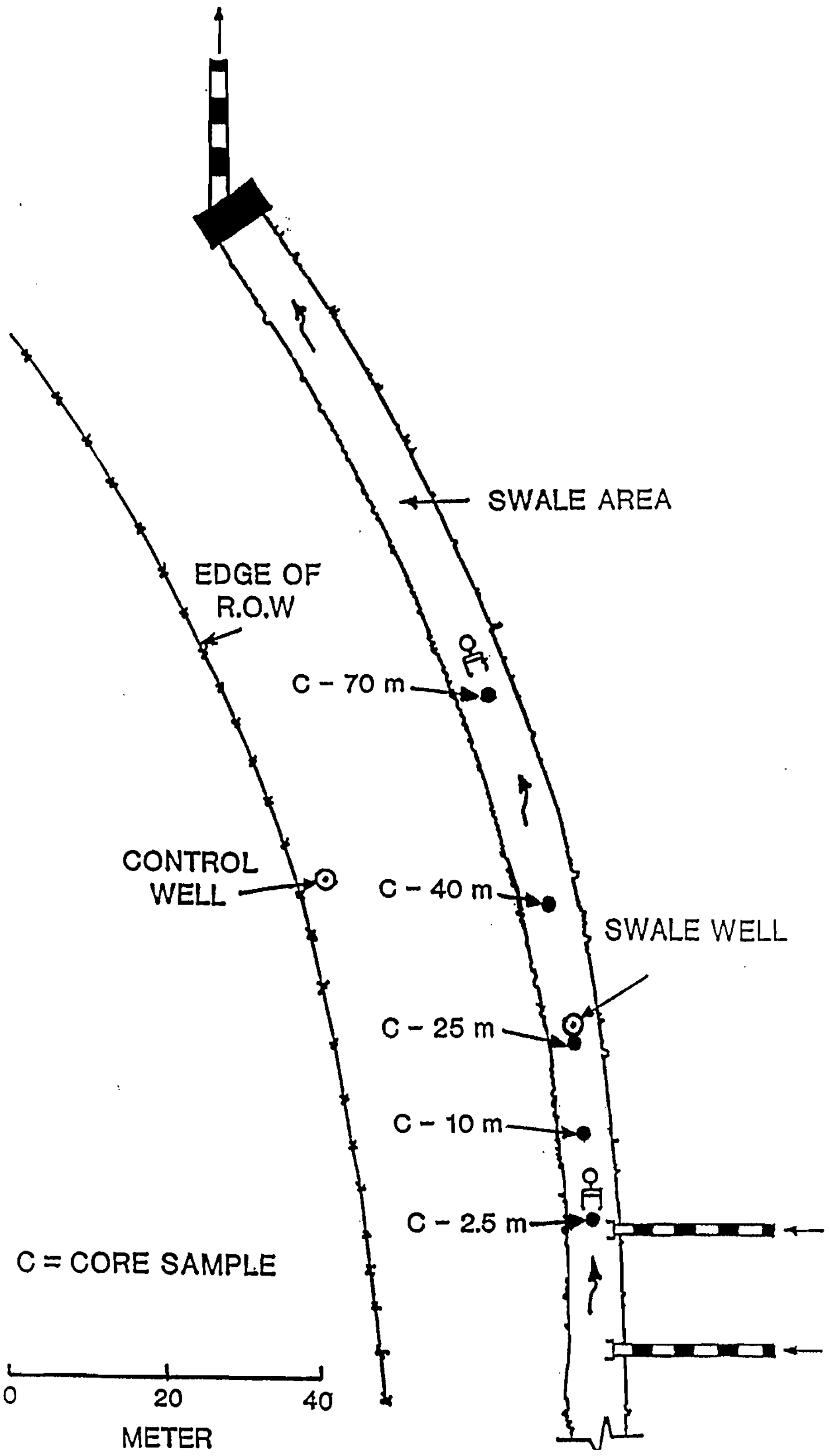


Figure 2-17. Sample Locations for Sediment Cores at the Wet Swale Site - Site 1.

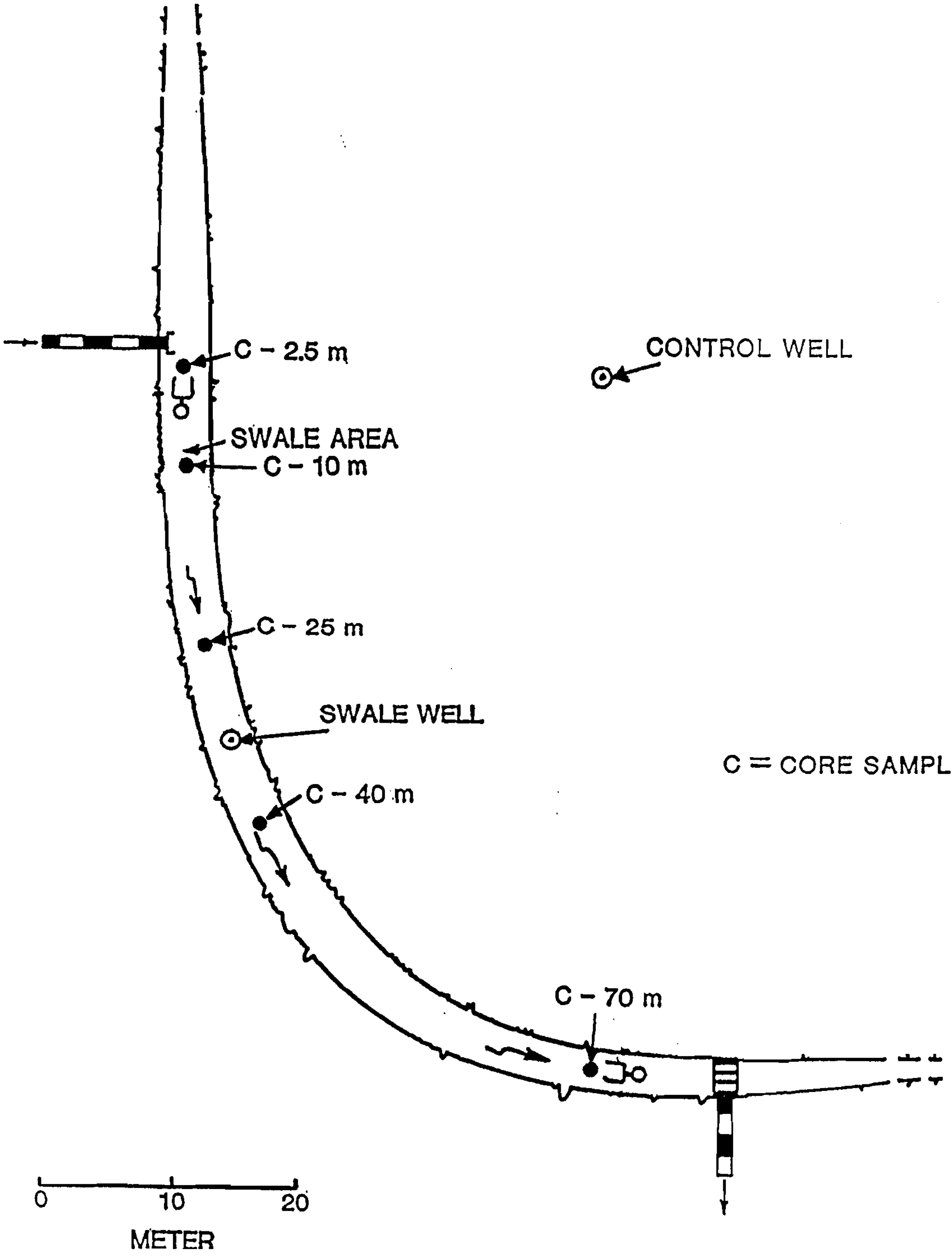


Figure 2-18. Sample Locations for Sediment Cores at the Dry Swale Site - Site 2.

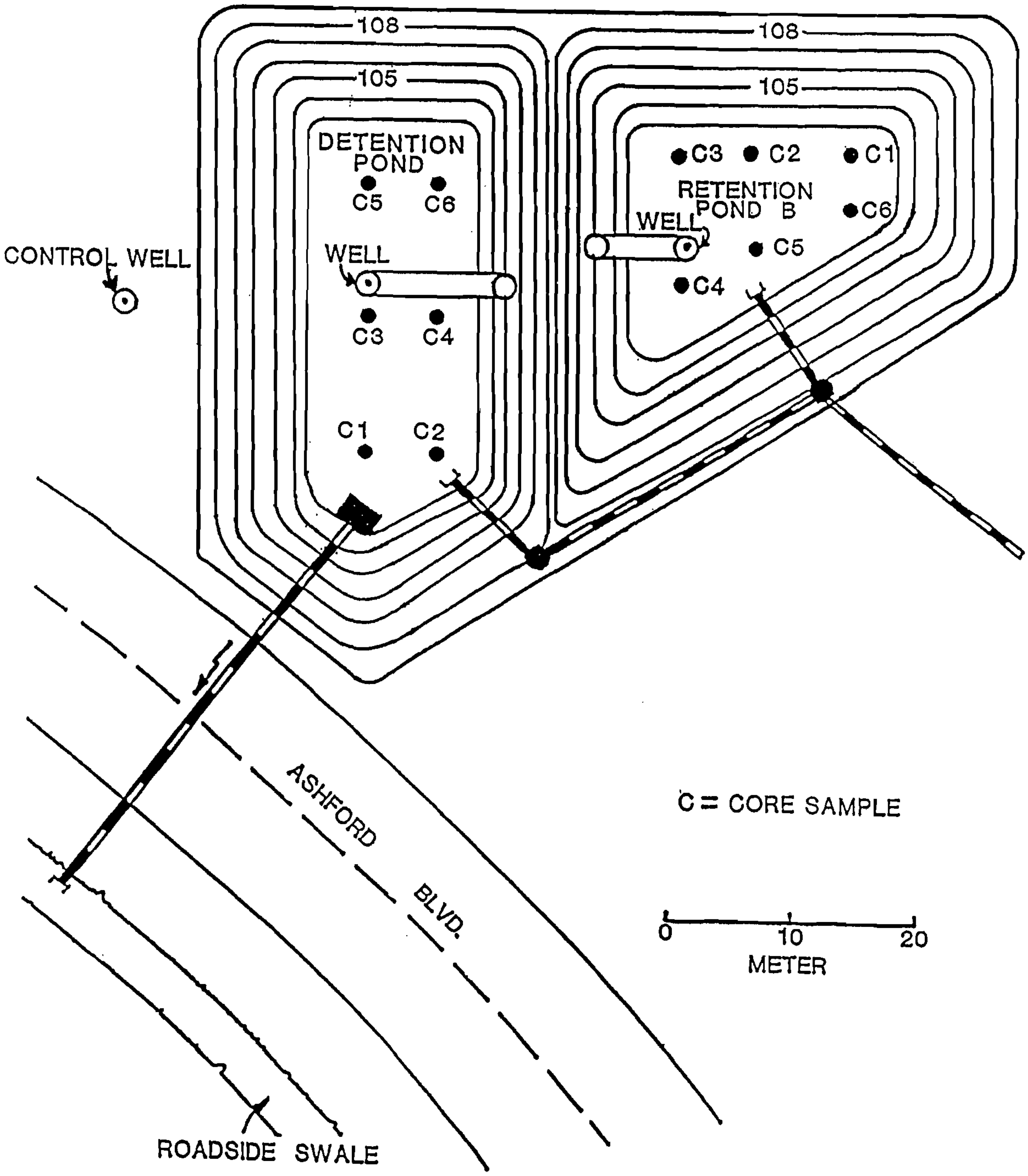


Figure 2-19. Sample Locations for Sediment Cores at the Residential Dual Pond Site - Site 3.

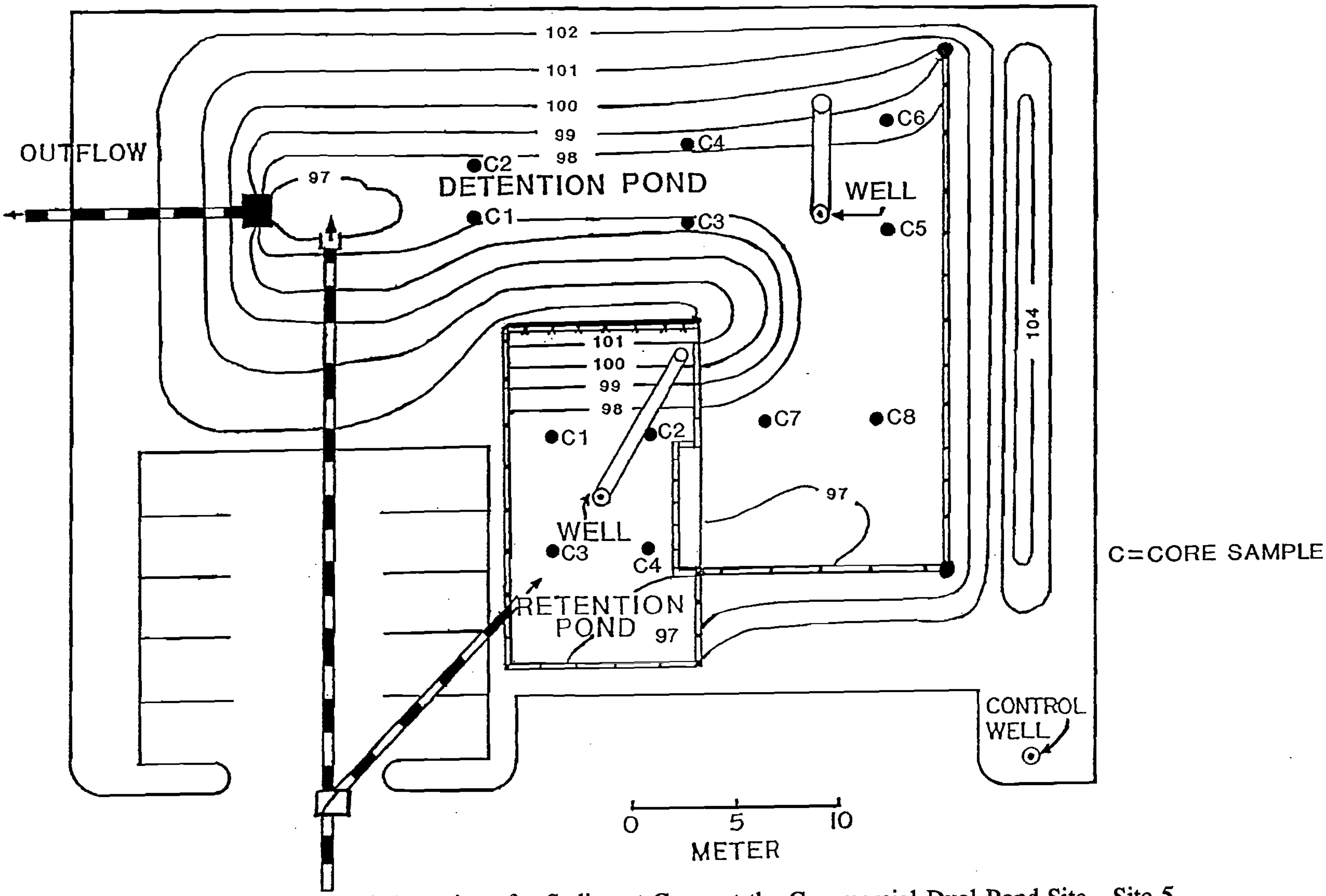


Figure 2-20. Sample Locations for Sediment Cores at the Commercial Dual Pond Site - Site 5.

layers were combined for each pond to form a composite sample of each depth layer in each pond. Core samples collected at the control area were analyzed for all five layers.

Locations for collection of composite sediment core samples at Site 4 are indicated in Figure 2-21. Composite core samples were collected in a grid pattern with relatively close spacing near the points of runoff inflow into the pond and more distant spacing near the pond outfall. This pattern was selected based on previous studies by ERD which indicated that heavy metals transported in stormwater runoff settle primarily near the point of inflow. The 0-1 cm layers from all samples were analyzed separately. The remaining samples were combined by layer to form a composite sample of each depth layer. Core samples collected at the control area were analyzed for all five layers.

Upon return to the ERD Research Lab, analyses were conducted for moisture content, organic content, total phosphorus, total nitrogen and heavy metals, including cadmium, zinc, manganese, copper, aluminum, iron, lead, nickel and chromium. Triplicate analyses were performed on all soil samples with the mean of these analyses used as the representative concentration for each parameter at a particular site.

Routine Field Procedures

Routine field monitoring and sample collection efforts for surface water, groundwater and stormwater were begun in January 1987 at each of the five study sites and continued for a period of 12 months. In general, field efforts were conducted in a uniform manner at all sites. Details of field procedures are given in the following sections. Detailed QA/QC information for field operations is contained in an approved Generic Quality Assurance Plan (No. 87322G).

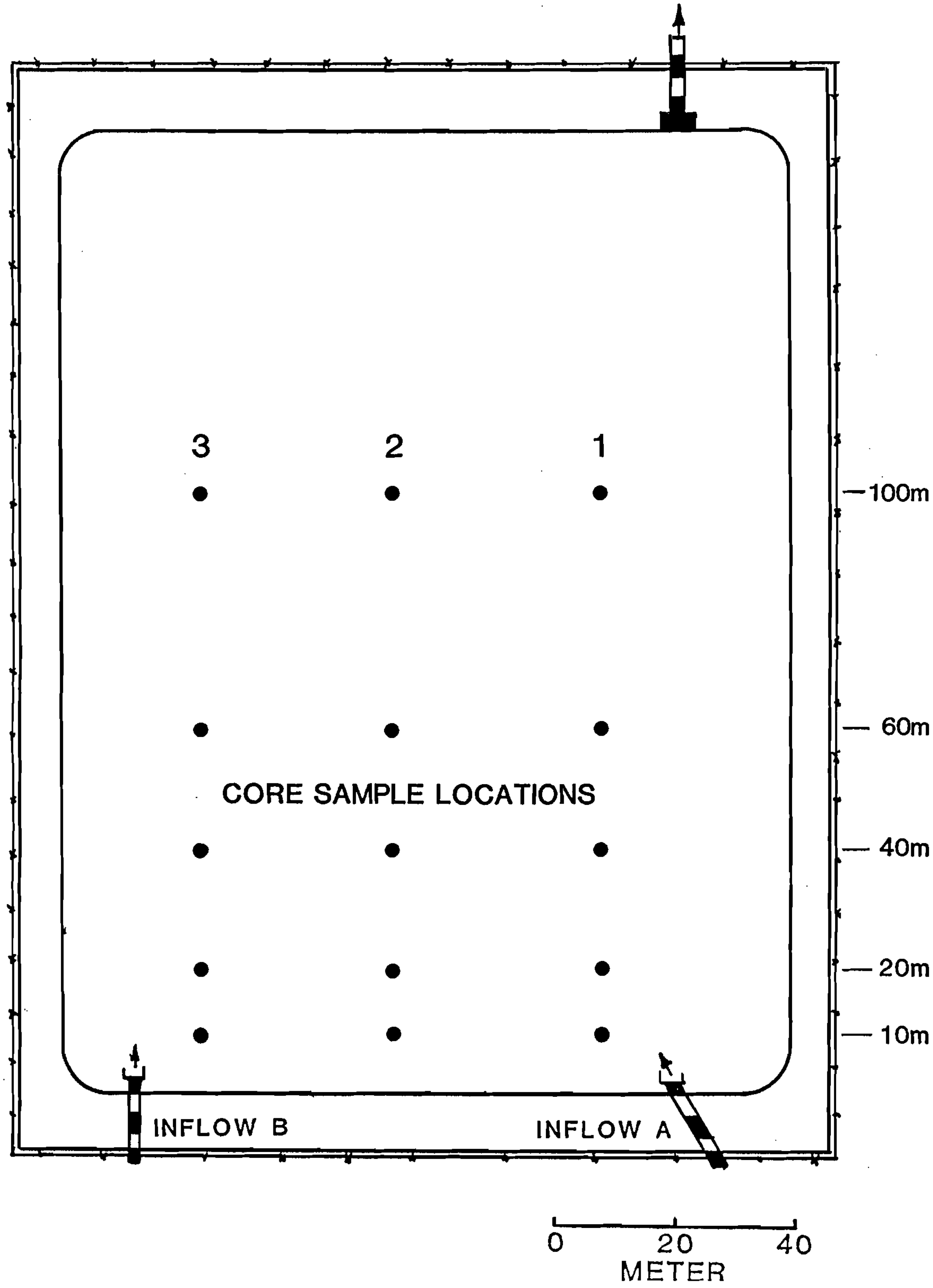


Figure 2-21. Sample Locations for Sediment Cores at the Residential Wet Detention Pond - Site 4.

Surface Water

Surface water samples were collected at Sites 1, 3, 4 and 5 on a biweekly basis from both swale and pond areas. All samples were collected using the permanent surface water sample ports as described in a previous section. A Masterflex portable battery powered peristaltic pump was connected to the end of the extended polyethylene tubing and used to slowly pump the surface water samples into collection bottles. Surface water was pumped at a rate of approximately 200 ml/minute to prevent disturbance of sediments near the sample port and to minimize turbulence in the sample tubing. Samples were collected in acid-washed polyethylene bottles which were rinsed in the field with approximately 100 ml of sample. All surface water samples were pumped directly into a flow-through cell connected to a Hydrolab Surveyor II Water Quality Monitor which was placed in line before the sample bottle. Field measurements of temperature, conductivity, pH, dissolved oxygen and redox potential were recorded as the sample was being collected. Field measurements collected in this manner are more accurate for certain parameters such as pH, dissolved oxygen and redox potential which are subject to rapid change during storage. Collected samples were stored on ice in the dark and returned to the ERD Research Lab for chemical analyses.

Groundwater

Groundwater samples and piezometric data were collected at each of the 12 monitoring wells on a monthly basis beginning in January 1987. The first field task conducted at each site was measurement of piezometric elevations in the two piezometers attached to each well. A Soiltest Model DR-760A water level indicator was used for all piezometric measurements.

Groundwater samples were collected from each of the five sample ports at all wells using a portable battery powered peristaltic pumps in a manner similar to that described for collection of surface water. Sample collection began at the 0.1 m sample port and progressed in order to the bottom 5 m sample port. After connecting the polyethylene sample tubing to the pump, groundwater was pumped through a flow cell connected to a Hydrolab Surveyor II Water Quality Monitor. Well pumping was continued until stable readings were obtained for temperature and conductivity. In most cases, this procedure required approximately 10 liters of groundwater. After reaching stable readings, field measurements of pH, temperature, dissolved oxygen, conductivity and redox potential were recorded. The discharge hose was removed from the flow cell and connected to an in-line 0.45 micron disposable sample filter for field filtration of samples. Samples were pumped at a rate of approximately 200 ml per minute. Each sample bottle was allowed to overflow 2-3 volumes. Pump and discharge tubing was rinsed with 1-liter of distilled water between sample ports. Collected samples were placed on ice and returned to the ERD Research Lab.

Stormwater Samples

Stormwater samples were collected using both Lexan plastic channel collectors and ISCO automatic samplers as described in previous sections. Field personnel closely monitored suspected rain activity, and in general, stormwater samples were collected within 2-4 hours after each rain event, but in no case was the waiting period more than 24 hours.

Stormwater collected using the channel collectors was retrieved from the field by removing the underground sample container and replacing it with a clean acid-washed container. The collected sample was then placed on ice and returned to the lab. Stormwater collected using ISCO samplers was retrieved by removing the bottom sample bottle holder from the sampler, capping the individual samples and returning the entire bottom unit to the lab. A new bottom unit containing cleaned sample bottles was reconnected to the main sampler unit. The center compartment of each field sampler was kept filled with ice while waiting for rain events.

Laboratory Analyses

Laboratory procedures during this research were divided into two primary tasks: (1) routine analyses of water and soil samples, and (2) extraction procedures for chemical speciation of heavy metals in sediment core samples. Each of these procedures is described in the following sections.

Routine Analyses for Water and Soils

A summary of routine water quality analyses for surface water, groundwater and stormwater is given in Table 2-2. Details of laboratory methods and quality control procedures are given in the approved Quality Assurance Plan.

Chemical Speciation of Sediment Cores

A chemical speciation procedure was conducted which identifies five fractions of heavy metal associations in sediments:

1. Soluble - metal ions contained in water which are trapped in interstitial pore spaces

TABLE 2-2

SUMMARY OF FIELD AND LABORATORY ANALYSES FOR WATER SAMPLES

PARAMETER	SCHEDULE OF ANALYSES		
	SURFACE WATER	GROUNDWATER	STORMWATER
pH (lab/field)	field	field	lab
Cond. (lab/field)	field	field	lab
Temperature (field)	field	field	-
Diss. Oxygen (field)	field	field	-
ORP (field)	field	field	-
Alkalinity	x	x	x
NH_3-N	x	x	x
NO_x-N	x	x	x
Dissolved Organic N	x	x	x
Particulate Organic N	x	-	x
Dissolved Ortho-P	x	x	x
Dissolved Organic P	x	-	x
Total P	x	x	x
Turbidity	x	-	x
Chloride	x	x	x
Sulfate	x	x	x
T.S.S.	x	-	x
V.S.S.	x	-	x
Color	x	x	x
BOD	x	x	x
T.D.S.	x	-	x
V.D.S.	x	-	x
Aluminum (Total/Diss.)	x	Diss.	x
Cadmium (Total/Diss.)	x	Diss.	x
Chromium (Total/Diss.)	x	Diss.	x
Copper (Total/Diss.)	x	Diss.	x
Iron (Total/Diss.)	x	Diss.	x
Lead (Total/Diss.)	x	Diss.	x
Manganese (Total/Diss.)	x	Diss.	x
Nickel (Total/Diss.)	x	Diss.	x
Zinc (Total/Diss.)	x	Diss.	x

x: indicates analyses conducted for parameter indicated

2. Exchangeable - metal ions which are specifically adsorbed and are ion exchangeable
3. Bound to Carbonates - metal ions which are associated with sediment carbonates as a precipitate or co-precipitate
4. Bound to Iron and Manganese Oxides - metal species attached or adsorbed onto iron and manganese oxides
5. Bound to Organic Matter - metals which are bound by adsorption or complexation to various forms of organic matter such as living organisms, detritus and coatings on mineral particles

After a critical evaluation of the available literature, a modification of the chemical extraction steps proposed by Tessler et al. (1979) was adopted. Details of the extraction steps are given in Harper (1985). All sediment samples were initially air dried and finely ground by passage through a 600-micron plastic mesh to remove extraneous material. A minimum of three finely ground 2-gram samples from each composite core layer were taken through the metal speciation steps. All extractions were conducted in 50-ml polypropylene centrifuge tubes to minimize losses of solid material.

Statistical Treatment of Data

A large number of statistical analyses were conducted during analysis of the experimental results from this research. All statistical procedures were performed using the Statistical Analysis System (SAS) and included PROC CORR for calculation of Pearson product-moment correlation coefficients; PROC PLOT to produce scatter diagrams of the values of one variable against the values of another variable for examination of relationships and functional forms; PROC MEANS to obtain simple univariate descriptive statistics such as means, standard deviation, minimum and maximum values; PROC ANOVA for analysis of variance procedures involving balanced designs and data sets; PROC GLM for analysis of variance procedures for unbalanced data sets; and PROC REG and PROC STEPWISE for regression analyses to provide least-square estimates to various linear regression models. All data sets were initially tested for normality of data distribution by examination of residuals. Most data sets required a log transformation to obtain a normally distributed probability distribution function. Subsequent statistical analyses were conducted using transformed data sets where appropriate.

Although most of the procedures listed above were reasonably straightforward, regression analyses involved a number of steps, and as a result, will be discussed in more detail. The purpose of the regression analyses was to determine the "best fit" least-square equation between various response and predictor variables. Since the objective in most cases was to determine the importance of significant predictor variables in regulating water quality characteristics, the "best fit" regression model was defined to be the model which included the largest number of predictor variables which were all significant at the 0.10 level or better. Regression analyses were conducted on stormwater, sediment and groundwater data sets to examine both predictive relationships between observed characteristics and various predictor variables.

The first step in a regression analysis was to examine the functional forms of the response and predictor variables. Plots of residuals and partial residuals versus each oaf the predictor variables were used to test for linearity or the presence of higher order effects. When functional forms were correctly specified, studentized residuals were used to detect outliers in the response variables, and values of Cook's D were used to detect outliers in the predictor variables. Observations with studentized residuals in excess of

2.5, or a value of Cook's D in excess of 0.400, were discarded as outliers. Most regression analyses resulted in the removal of very few data points as outliers. PROC REG was used to obtain values for the studentized residuals and Cook's D. Plots of raw residuals versus the predicted values of the response variables were examined as a test for homoscedasticity (equality of variances). A random scattering of the points with a slope of zero was used to indicate equality of variances.

In most analyses, the purpose of the regression procedures was for model specification and estimation of the regression coefficients. As a result, PROC REG was used with the full model to examine correlations and multicollinearities. The correlation matrix indicated predictor variables which were strongly correlated and unnecessary variables were removed from the model. The presence of multicollinearities was examined using eigenvalues and eigenvectors along with the variance inflation factor. In general, values of the variance inflation factor in excess of 10 were used to indicate the presence of multicollinearities. Variables which were strongly correlated or involved in multicollinearities were removed from the model. Variables not producing a significant test for B=0 at the 0.10 level or better were also discarded from the model.

Improvements in MSE (mean square error) and changes in the values of R-square were observed after removal of each variable. The model producing the best combination of a large value of R-square with a small value of MSE with no significant multicollinearities was chosen as the "best fit" model. A straight line on this plot indicated a normally distributed data set. A runs-test was also used to check for correlation of the error terms.

Two types of regression equations were calculated during this research. One equation was the least-squares "best fit" predictor equation. The other equation was the unit length standardized form of the "best fit" equation which has the form:

$$Y = u + B_1{*}W_1 + B_2{*}W_2 + \ldots + B_n{*}W_n$$

where u is the mean value of Y, B_1* is the standardized least-squares estimator and W_1 is the X_1 variable scaled to the unit length form with W equal to zero and a standard deviation equal to one. This type of standardized equation is more informative in determining the relative effects of the predictor variables since it is independent of units, and the magnitude of the standardized estimates is a direct reflection of their importance in predicting Y.

CHAPTER 3

RESULTS

Field monitoring, sample collection and laboratory analyses for surface water, groundwater, stormwater and sediments were conducted at each of the five study sites over a 12-month period from January to December 1987. Hydrologic monitoring of rainfall, evaporation, water surface elevations and piezometric levels was begun in January 1987 and continued for a period of 14 months through February 1988. A discussion of experimental results from these tasks is given in the following sections.

Site Hydrology

As previously discussed, a wide range of hydrologic information was collected at each of the five study sites. The purpose of this information was three-fold: (1) to provide hydrologic characteristics of rain events used for characterization of stormwater runoff; (2) to assist in evaluation of hydrologic budgets for selected sites; and (3) to evaluate the direction and rate of groundwater movement at swale and pond sites. In general, hydrologic information will be presented only as it relates to understanding and quantifying these three areas.

Site 1 - Wet Swale Site

Changes in piezometric surface elevations at the wet swale site during 1987 are shown in Figure 3-1. Piezometric levels are indicated for the shallow (1 m) and deep (5 m) piezometers in both the swale and control areas. Elevations indicated by the shallow (1 m) piezometer in the swale area closely reflect the actual water surface within the swale channel.

With the exception of only two monitoring dates during 1987, the wet swale area maintained a permanent pool of water which ranged in depth from 0.0 m (0.0 ft) to 0.6 m (2.0 ft) with an average depth of approximately 0.3 m (1.0 ft). In general, piezometric elevations in the control area were slightly higher than those measured in the swale channel, indicating a potential for migration of groundwaters from the control area toward the swale. A small base flow was observed in the swale channel on virtually all monitoring dates, presumably resulting from groundwater seepage into the swale. In addition, piezometric elevations in the deep (5 m) piezometer were generally found to be equal to or greater than shallow (1 m) piezometric elevations, indicating a potential for upward movement of groundwater.

A summary of vertical and horizontal hydraulic gradients at the wet swale site during 1987 is given in Figure 3-2. Vertical gradients were calculated within the swale channel as the difference between the 1 m and 5 m piezometric elevations divided by the distance separating the piezometers (4 m). Horizontal gradients were calculated using the 1 m piezometric elevations in the swale and control areas divided by the distance between the swale and control piezometers. A positive hydraulic gradient indicates that water is moving toward the swale, while a negative hydraulic gradient indicates that

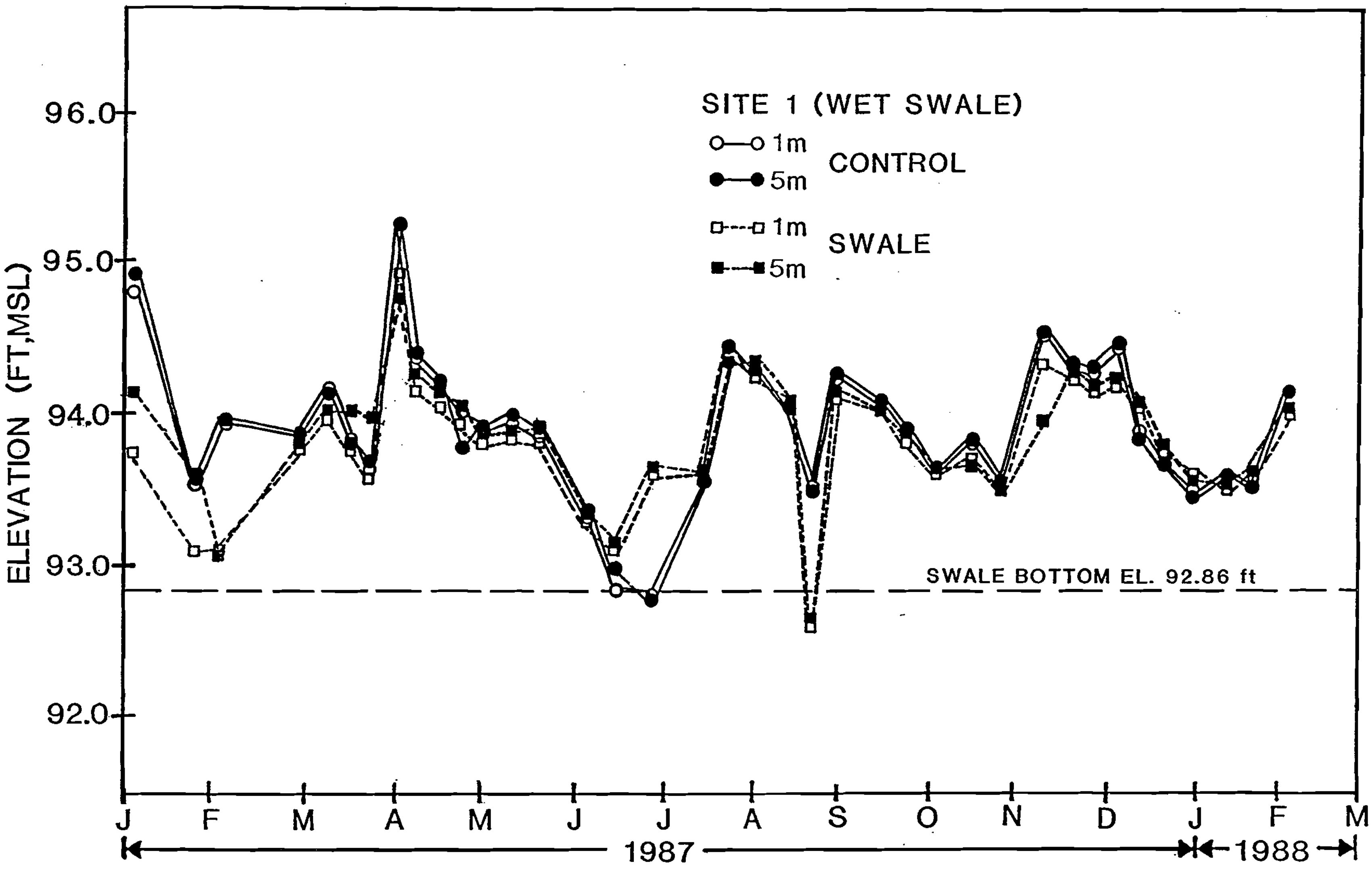


Figure 3-1. Fluctuations in Piezometric Elevations at the Wet Swale Site - Site 1.

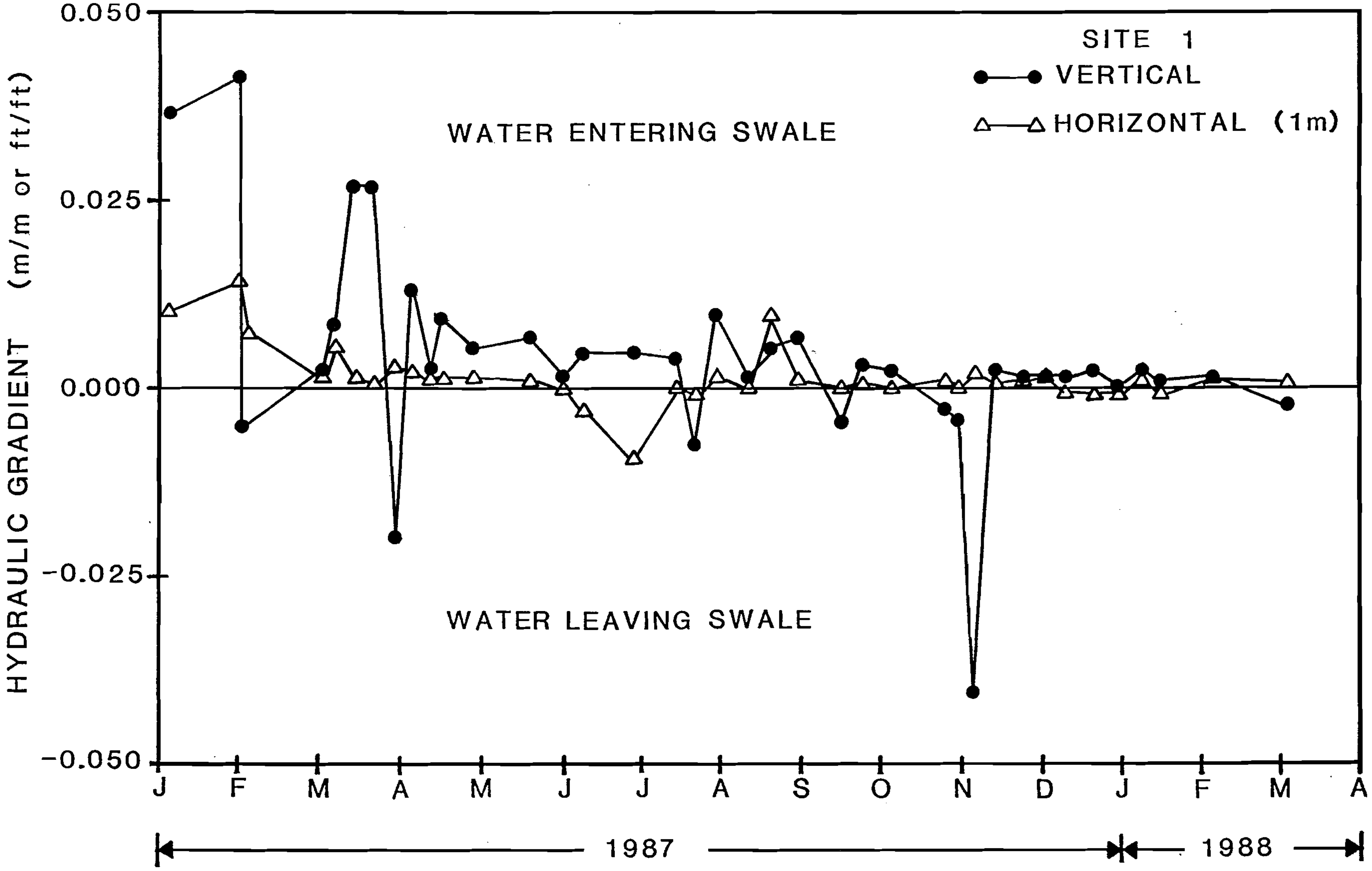


Figure 3-2. Horizontal and Vertical Hydraulic Gradients at the Swale Well in the Wet Swale Channel at Site 1 During 1987-88.

water is moving away from the swale. With only a few exceptions, most of which correlated with extreme rain events, the swale channel maintained a positive vertical hydraulic gradient throughout the study period. This trend suggests that vertical groundwater migration at this site is primarily in the upward direction although downward movement may occur for short periods as channel water elevations increase temporarily following extreme rain events. As seen in Figure 3-2, horizontal hydraulic gradients were also predominantly positive indicating a tendency for horizontal migration of groundwater into the swale channel. As a result, the primary direction of groundwater movement at this site appears to be toward and into the swale channel. Infiltration from the swale area into groundwaters is minimal, except following extreme rain events. Therefore, for any given rain event, the volume of runoff entering the swale channel closely approximates the volume of water discharging from the swale channel into the downstream stormsewer system.

Site 2 - Dry Swale Site

The dry swale channel is characterized by highly permeable sandy soils which infiltrate runoff water rapidly. Estimates of infiltration rates in the swale channel were performed on four occasions during the study period using a double-ring infiltrometer. A summary of field results is given in Table 3-1. Measurements of infiltration rates ranged from a low of 29.2 cm/hr (11.5 in/hr) in September near the end of the wet season to 38.6 cm/hr (15.2 in/hr) in March. Visual observations of swale performance during rain events indicated that virtually all runoff entering the swale channel infiltrated into the ground prior to reaching the outfall inlet. Discharges from the swale channel

TABLE 3-1

SUMMARY OF INFILTRATION RATE MEASUREMENTS IN THE DRY SWALE CHANNEL USING THE DOUBLE-RING INFILTROMETER METHOD

DATE	INFILTRATION RATE[1]	
	cm/hr	inches/hr
03/16/87	38.6	15.2
06/21/87	30.7	12.1
09/04/87	29.2	11.5
12/10/87	37.6	14.8

1. Steady-state values.

were observed only during periods of intense rainfall activity which would input large amounts of runoff into the swale in a short period of time. However, even during these extreme events, a large percentage of the stormwater inflow would infiltrate into the swale channel prior to reaching the outfall. Based on field observations during a number of rain events, it is conservatively estimated that approximately 80 percent of the general runoff inflow into the swale channel infiltrates into the soil on an annual basis.

Changes in piezometric surface elevations at the dry swale site during 1987 are indicated in Figure 3-3. In contrast to the mildly fluctuating piezometric profiles monitored at the wet swale site, piezometric elevations at the dry swale site were highly variable with a range of fluctuation of approximately 1.2 m (4 ft). Water table depths beneath the swale channel ranged from 1.47 m (4.82 ft) to 2.63 m (8.63 ft) during the study period.

Piezometric elevations at this site responded quickly to infiltration from large rain events. As seen in Figure 3-3, an extended rain event of approximately 20 cm (8.0 inches) over a 36-hour period on March 29-30 caused a rapid increase in groundwater elevation beneath the swale channel of approximately 1.02 m (3.35 ft) based on field measurements collected on March 31. This increase in piezometric elevation dissipated slowly over a period of approximately 60 days. Piezometric elevations beneath the swale channel were consistently greater than elevations measured beneath the control area. Groundwater beneath the swale appears to be exhibiting a small localized mounding effect.

Variations in vertical and horizontal hydraulic gradients at site 2 during 1987 are indicated in Figure 3-4. In general, both vertical and horizontal groundwater gradients

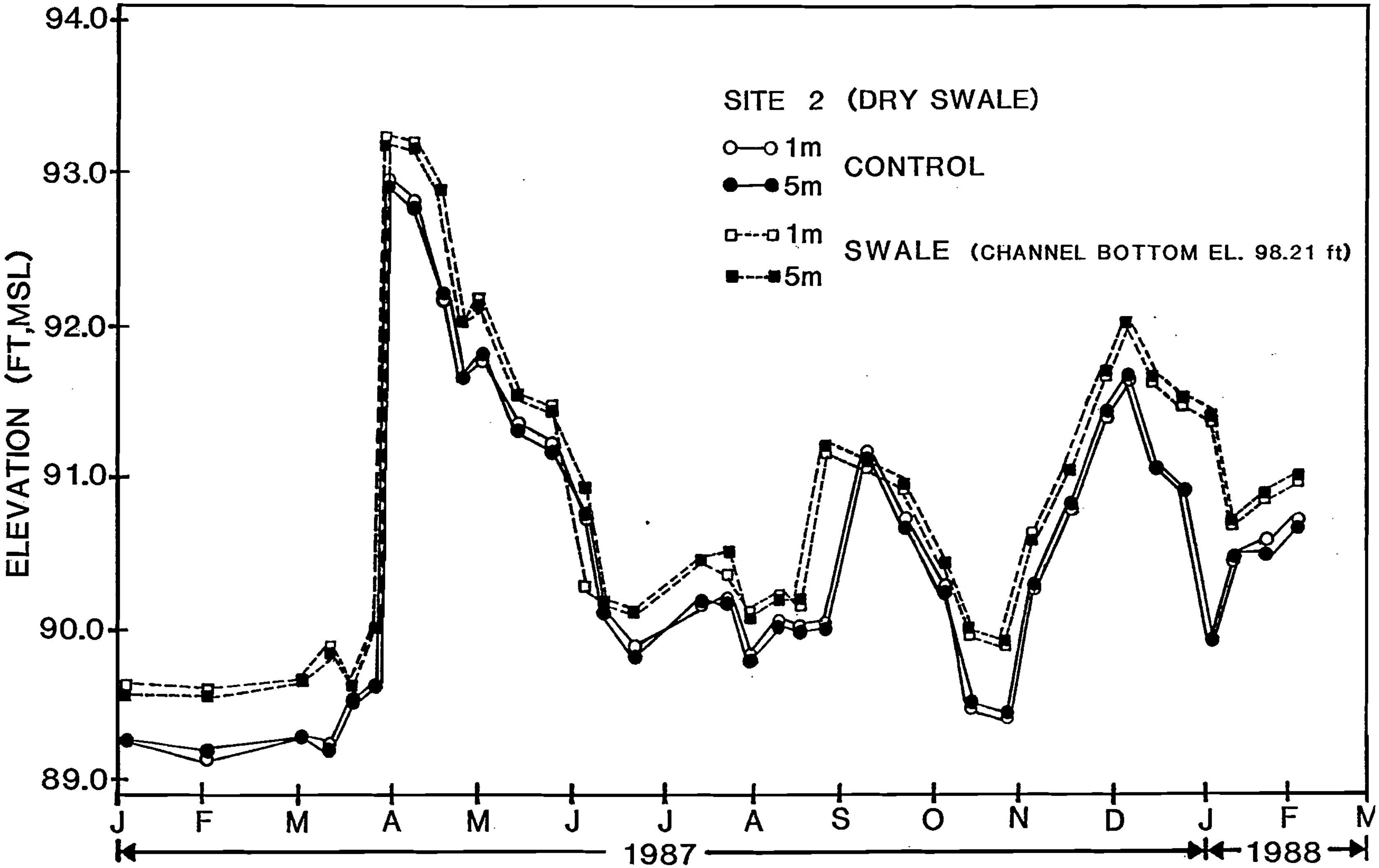


Figure 3-3. Fluctuations in Piezometric Elevations at the Dry Swale Site - Site 2.

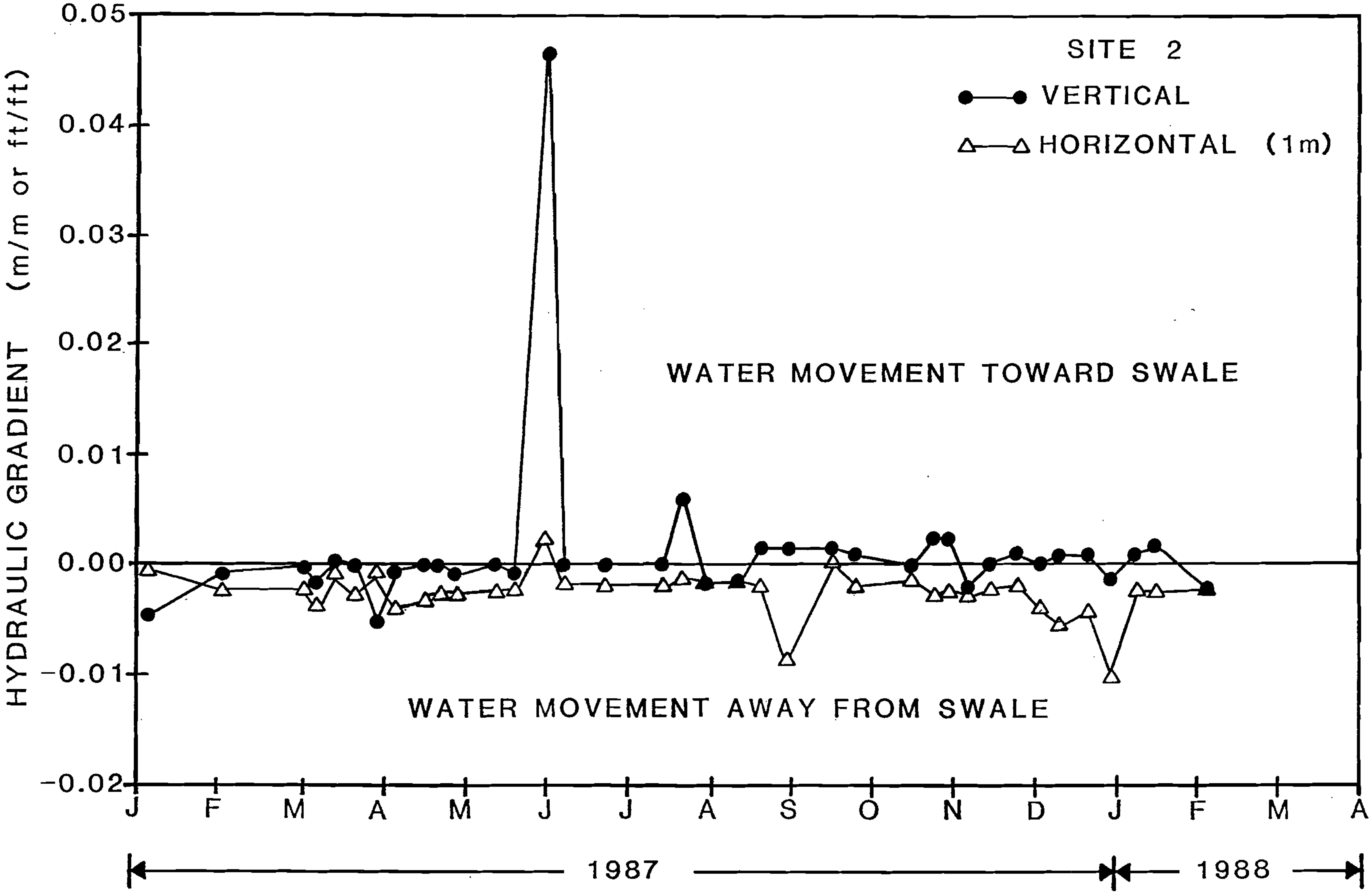


Figure 3-4. Horizontal and Vertical Hydraulic Gradients at the Swale Well in the Dry Swale Channel at Site 2 During 1987-88.

appear to be very small at this site. With only a few exceptions, vertical hydraulic gradients were found to be near zero throughout most of 1987. Horizontal groundwater gradients, although small in magnitude, indicate a net movement of groundwater away from the swale area for virtually all measurement dates in 1987. The tendency for horizontal gradients to remain very small in spite of a large infiltration of runoff along the swale channel is probably explained by the extremely porous nature of the soils found at this site which allow groundwater to migrate quickly away from the vicinity of the swale channel.

Site 3 - Dual Pond Residential Site

Changes in piezometric surface elevations at the dual pond residential site during 1987 are indicated in Figure 3-5. Piezometric elevations were highly variable at this site throughout 1987. Fluctuations in piezometric levels for pond and control areas exceeded 1.22 m (4.0 ft). In general, piezometric fluctuations indicated in Figure 3-5 correlate closely to inputs into the stormwater management system as a result of rain events. A rapid increase in piezometric elevation for both pond and control sites is noted in field measurements collected on March 31 after the extended rain event of approximately 20 cm (8.0 in) described previously.

As seen in Figure 3-5, piezometric elevations within the retention pond were consistently greater than piezometric elevations measured in either the detention or control areas. In general, piezometric elevations within the detention pond appear to be slightly greater than those measured in the control area although this trend was reversed on several dates during 1987. In addition, piezometric elevations in the shallow

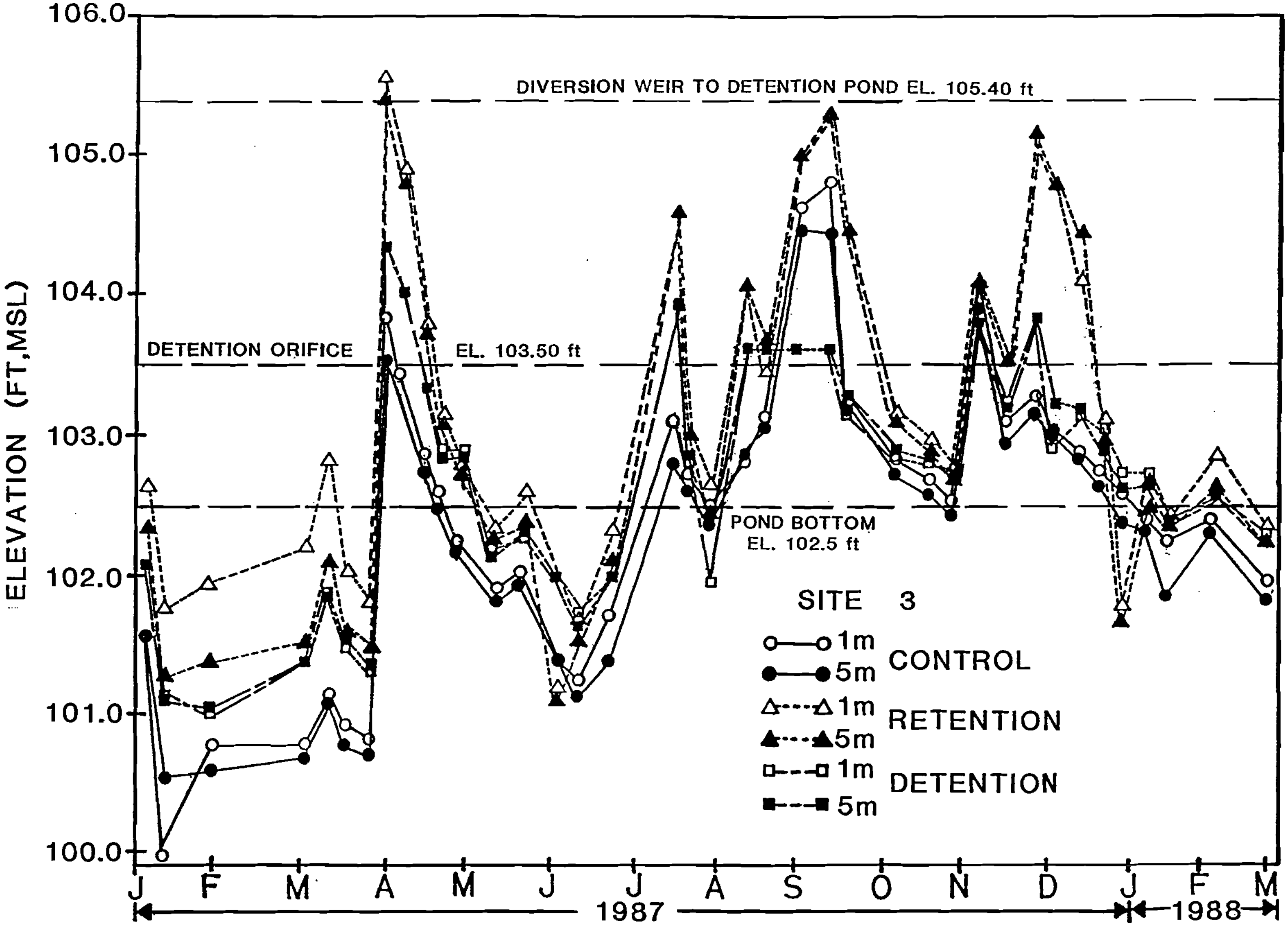


Figure 3-5. Fluctuations in Piezometric Elevations at the Residential Dual Pond Site - Site 3.

piezometers appear to be slightly greater than piezometric elevations measured in the deeper piezometers (5 m) for both pond and control areas. Piezometric elevations indicated by the shallow (1 m) piezometers for both the retention and detention ponds closely reflect the actual water surface within these ponds.

As seen in Figure 3-5, both retention and detention ponds exhibited periods with and without permanent pools of water. In general, with the exception of the period immediately following the extreme rain event which occurred at the end of March, both ponds were consistently dry during the typical dry season months from January through June and maintained a permanent pool of water during the typically wet season months from July through November. Water surface elevations within the retention pond approached the diversion weir elevation to the detention pond on only three recorded occasions during the study period. This suggests that direct discharges over the diversion weir into the detention pond were rare occurrences during 1987, and the majority of rain events were contained totally within the retention pond. As seen in Figure 3-5, the detention pond also rarely reached its exit orifice elevation, suggesting that the majority of inputs of runoff into the detention system were totally retained within that pond. Based on estimates of mass inputs into the pond systems and observations of system performance during actual rain events, it is estimated that approximately 80% to 90% of all runoff inputs into this dual pond system were retained within the system without discharges to off-site water bodies.

A summary of both vertical and horizontal groundwater hydraulic gradients in the retention pond at site 3 is given in Figure 3-6. Both vertical and horizontal gradients, with only a few exceptions, were found to be negative in value throughout the study

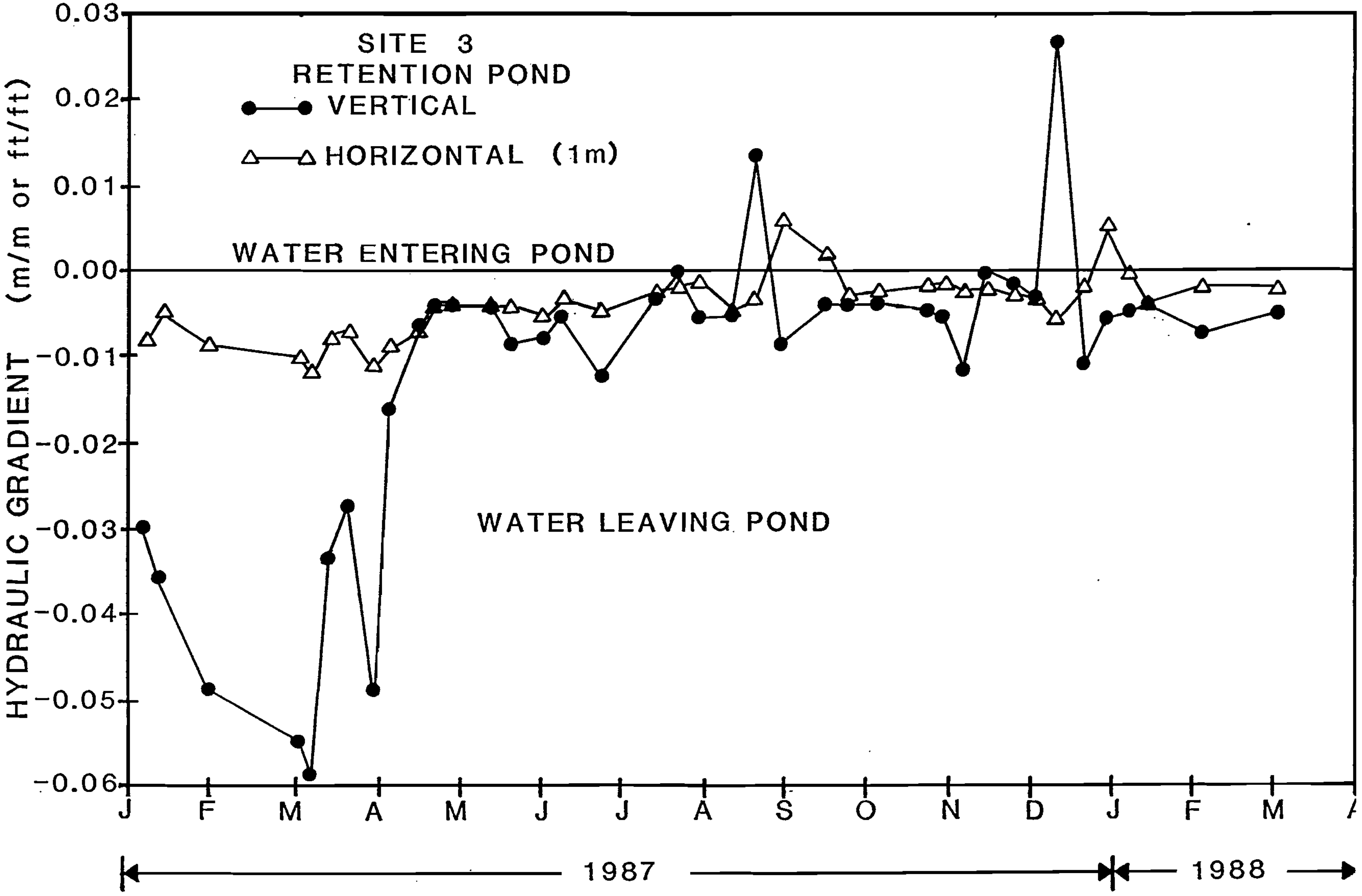


Figure 3-6. Horizontal and Vertical Hydraulic Gradients at the Retention Pond Well at the Residential Dual Pond Site (Site 3) During 1987-88.

period indicating a net migration of water away from the pond in both the vertical and horizontal directions. Vertical fluctuations in hydraulic gradient appear to be more variable than the horizontal gradients. During the first four months of 1987, downward vertical hydraulic gradients were relatively high within the retention pond. After April, vertical hydraulic gradients decreased and became similar in value to hydraulic gradients in the horizontal direction.

A summary of vertical and horizontal gradients for the detention pond at site 3 is given in Figure 3-7. Variability in both horizontal and vertical gradients is substantially greater in the detention pond than indicated in Figure 3-6 for the retention pond. Vertical and horizontal hydraulic gradients suggest periods when water is entering the detention pond as well as periods when water is migrating away from the detention pond. However, on an annual basis, the net movement of water in both the vertical and horizontal directions appears to be primarily away from the detention pond. Some of the variability in piezometric gradients measured beneath the detention pond may be a result of its close proximity to the retention pond and subsequent migration of groundwaters from the retention area toward the detention area.

As discussed in Chapter 2, attempts were made at both sites 3 and 4 to construct a detailed hydrologic budget which would allow estimates of actual seepage rates into groundwaters for stormwater treatment ponds at these sites. These estimates were based upon measured decreases in water surface for the retention pond at site 3 and the detention pond at site 4 during periods which were unaffected by rainfall activity. Estimates of losses due to evaporation were measured at each of these sites and subtracted from decreases in water surface elevations to obtain estimates of seepage rates

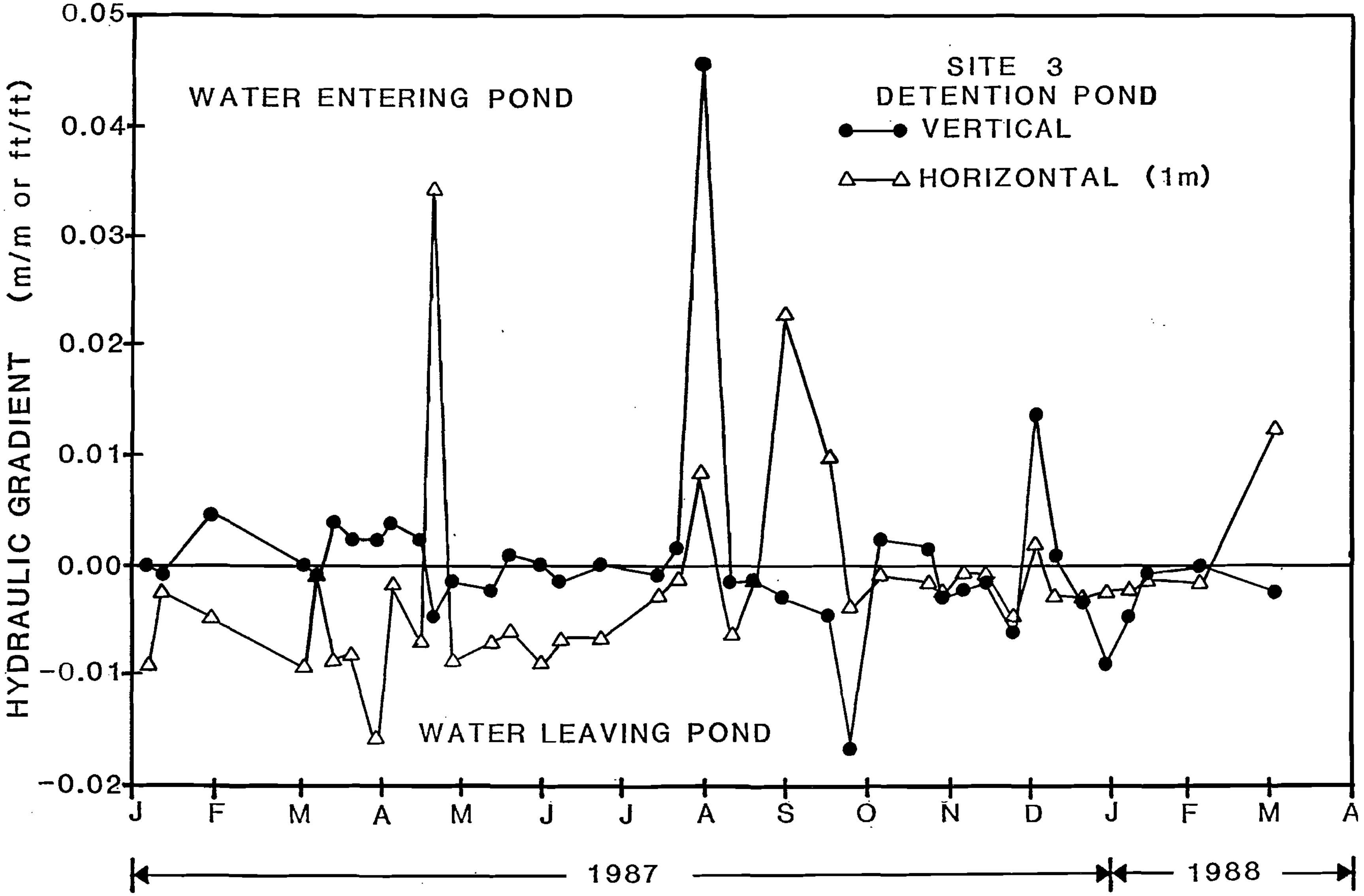


Figure 3-7. Horizontal and Vertical Hydraulic Gradients at the Detention Pond Well at the Residential Dual Pond Site (Site 3) During 1987-88.

into groundwaters. Estimates of losses due to evaporation were conducted at both sites 3 and 4 and then averaged together to produce final estimates for use in calculation of seepage rates. Measured evaporative losses at sites 3 and 4 during 1987 are presented in Figure 3-8.

Estimated seepage rates for the retention pond at site 3 and the detention pond at site 4 are given in Figure 3-9. Infiltration or seepage rates appear to be somewhat related to piezometric elevations as well as the influence of rain events. Infiltration rates at both sites increased during the first six months of 1987, reaching a peak of approximately 4.4 cm/day at site 3 and 7.5 cm/day at site 4. Seepage rates appear to decrease substantially after the onset of the rainy season, presumably due to increasing groundwater elevations in areas surrounding the ponds and corresponding decreases in hydraulic gradients. Slight increases in seepage rates are observed at both sites beginning in September or October after the end of the rainy season.

Site 4 - Residential Wet Detention Pond

Fluctuations in piezometric elevations at the residential wet detention pond during 1987 are indicated in Figure 3-10 for both control and detention areas. In addition, water surface elevations within the detention pond are also indicated on this figure. In general, piezometric elevations exhibited a relatively wide range of fluctuations, with a range in values of approximately 1.5 m (5.0 ft) during the study period. Piezometric elevations during the first three months of 1987 were relatively constant. A large increase in elevation was observed for both the detention pond and the control area immediately following the extreme rain event which occurred near the end of March

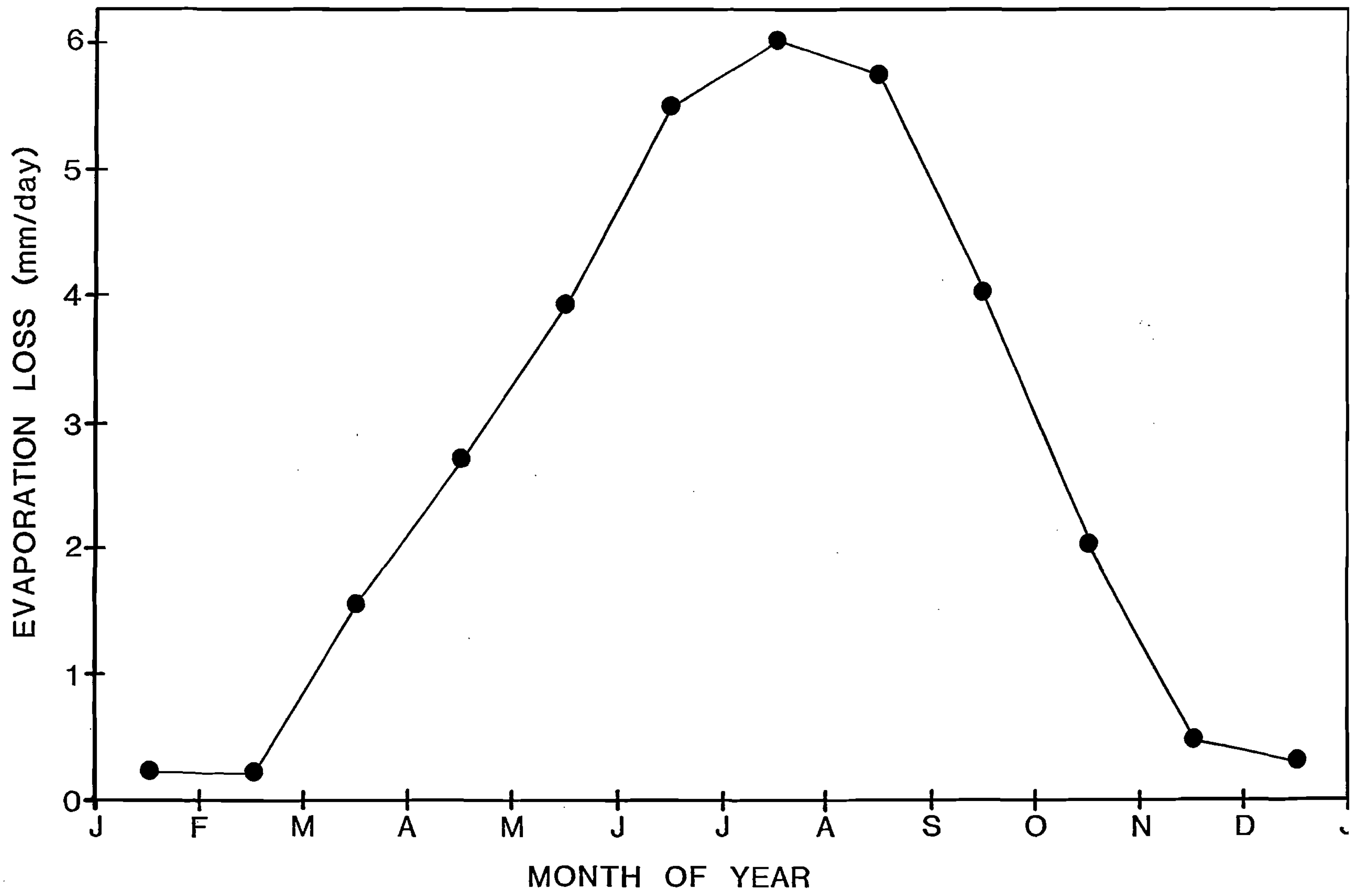


Figure 3-8. Measured Evaporative Losses at Sites 3 and 4 During 1987.

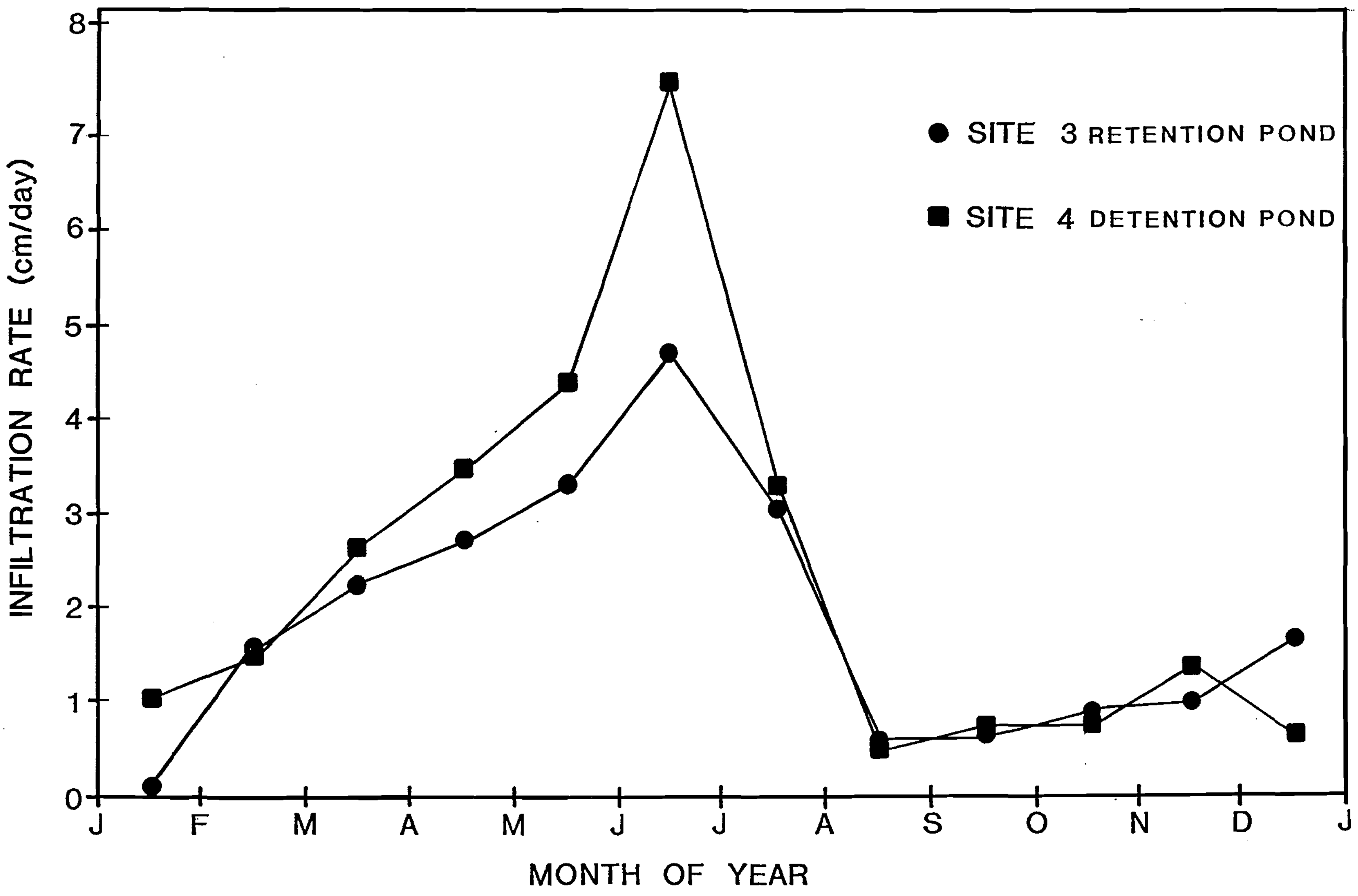


Figure 3-9. Estimates of Infiltration Rates in Stormwater Ponds at Sites 3 and 4.

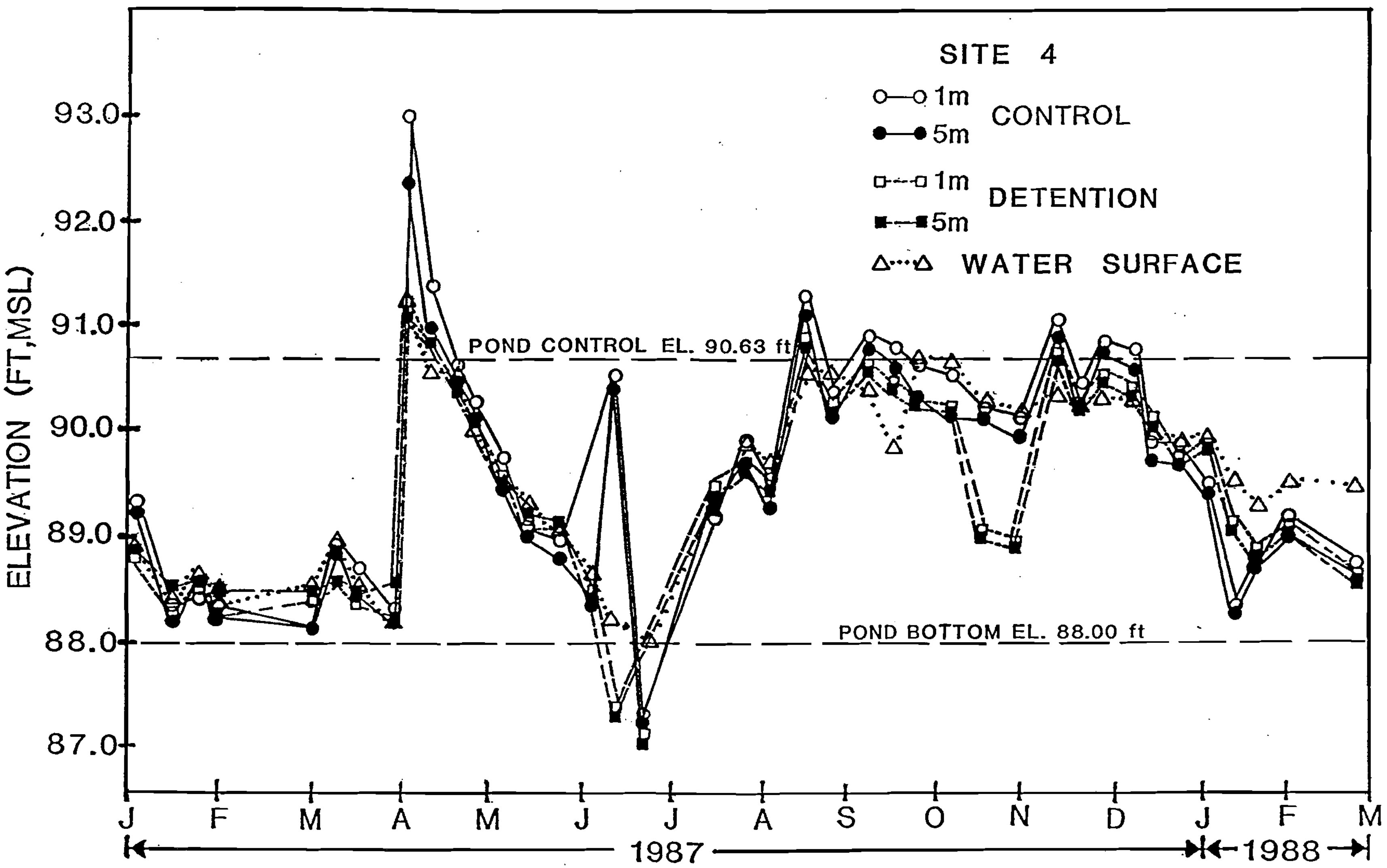


Figure 3-10. Fluctuations in Piezometric Elevations at the Residential Wet Detention Pond - Site 4.

1987. Piezometric elevations exhibited a slow but continuous decline following this event until approximately the beginning of July when elevations began to increase again as a result of onset of the wet season. Piezometric elevations remained fairly constant up through November with a gradual but steady decline for the next 60-90 days.

With only a few exceptions, water surface elevations within the detention pond remained below the pond control elevation at all times during the study period. Discharges from the detention pond were extremely rare during 1987 with observed outflow occurring on only three occasions: one after the extreme event at the end of March, and on two occasions during the rainy summer period. It is conservatively estimated that more than 80-90% of all hydraulic inputs into the detention pond were totally retained within the system with the primary removal and drawdown mechanisms being evaporation from the water surface and infiltration of pond water into the ground. As indicated in Figure 3-9, infiltration rates through the pond bottom were effected by both season and rainfall amounts with a maximum infiltration rate of approximately 7.5 cm/day during July.

A summary of vertical and horizontal groundwater hydraulic gradients for the detention pond at site 4 is given in Figure 3-11. Considerable variability is evident in both vertical and horizontal hydraulic gradients particularly during the first six months of 1987. In general, vertical hydraulic gradients suggest a potential for movement of water downward out of the pond during the first 4-5 months of 1987, and then a switch to a small upward gradient for migration of water into the pond for the remainder of the study period. Horizontal gradients, on the other hand, suggest a constant tendency for migration of waters out of the pond in a lateral direction. Therefore, the primary

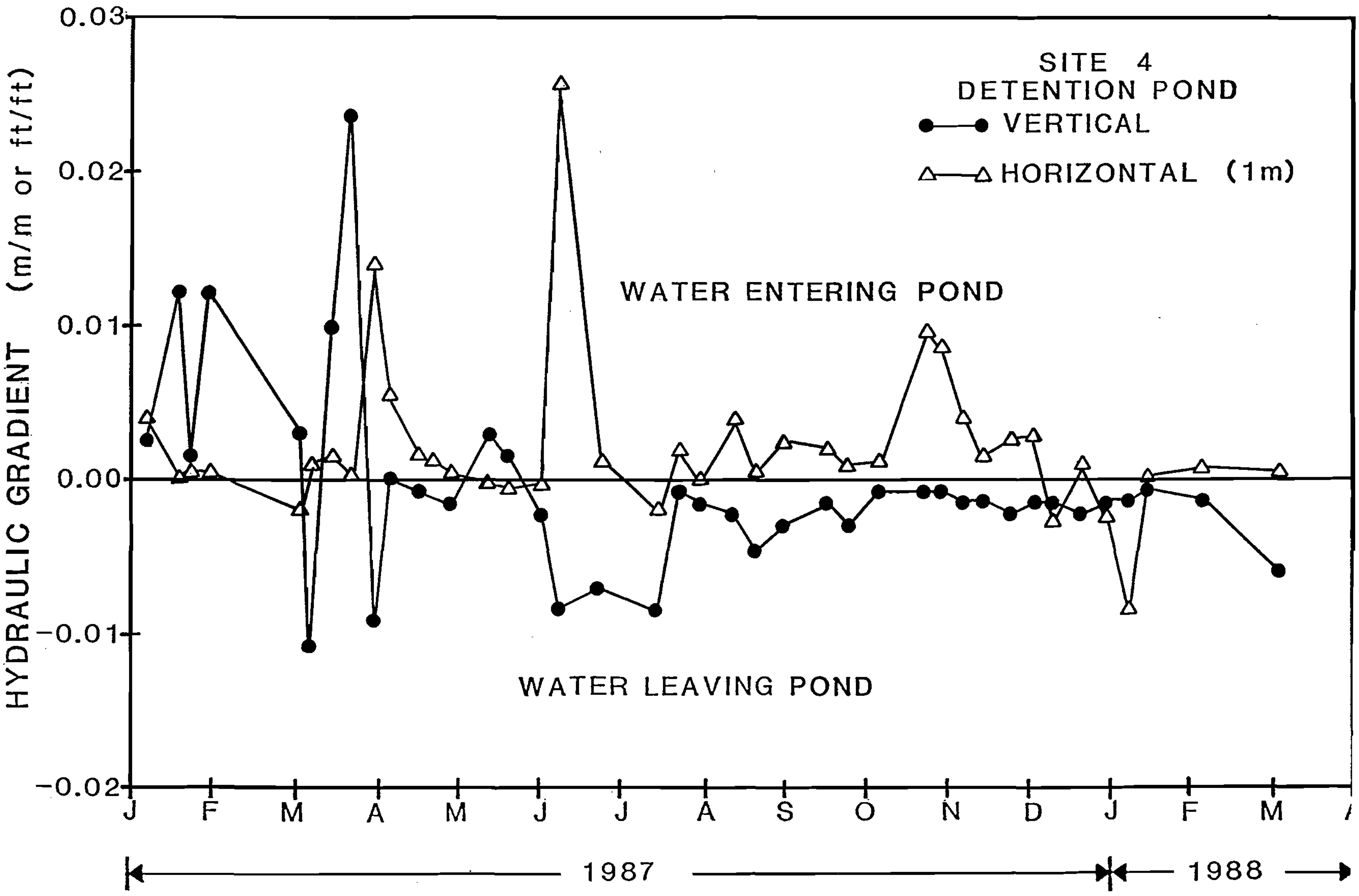


Figure 3-11. Horizontal and Vertical Hydraulic Gradients at the Detention Pond Well in the Wet Detention Pond (Site 4) During 1987-88.

mechanism for exfiltration of pond water into the ground at this site appears to be a lateral migration rather than a direct vertical movement.

Site 5 - Commercial Dual Pond Site

Fluctuations in piezometric elevations for the control area, retention pond and detention pond at Site 5 are indicated in Figure 3-12. In general, piezometric elevations in the control area were greater than those measured in either pond, while the retention pond elevations exceeded those measured in the detention pond. Piezometric elevations also appeared to be slightly greater in shallow (1 m) groundwaters than in deep (5 m) groundwaters for all wells, suggesting a small downward vertical gradient. However, the dominant movement of groundwaters at this site appears to be in the horizontal direction.

Water surface elevations in both the retention and detention ponds closely followed the piezometric levels indicated in the shallow piezometers in each pond. In general, water surface elevations for both ponds appeared to fluctuate over a relatively narrow range. In spite of several extreme rain events, including the 20 cm (8.0 inches) rain event on March 29-30, the water level elevation inside the retention pond was never observed to exceed the overflow weir elevation of 99.98 ft for diversion of flow directly into the detention pond. The most likely explanation for this phenomenon is that runoff inputs into the retention pond were rapidly discharged through the vertical filter box into the detention pond at a rate which minimized drastic changes in stage within the retention pond and which prevented the retention pond from exceeding the weir overflow elevation. However, the inability to accurately measure flow rates either into or out of the filter box made it impossible to accurately construct a hydrologic balance for this site.

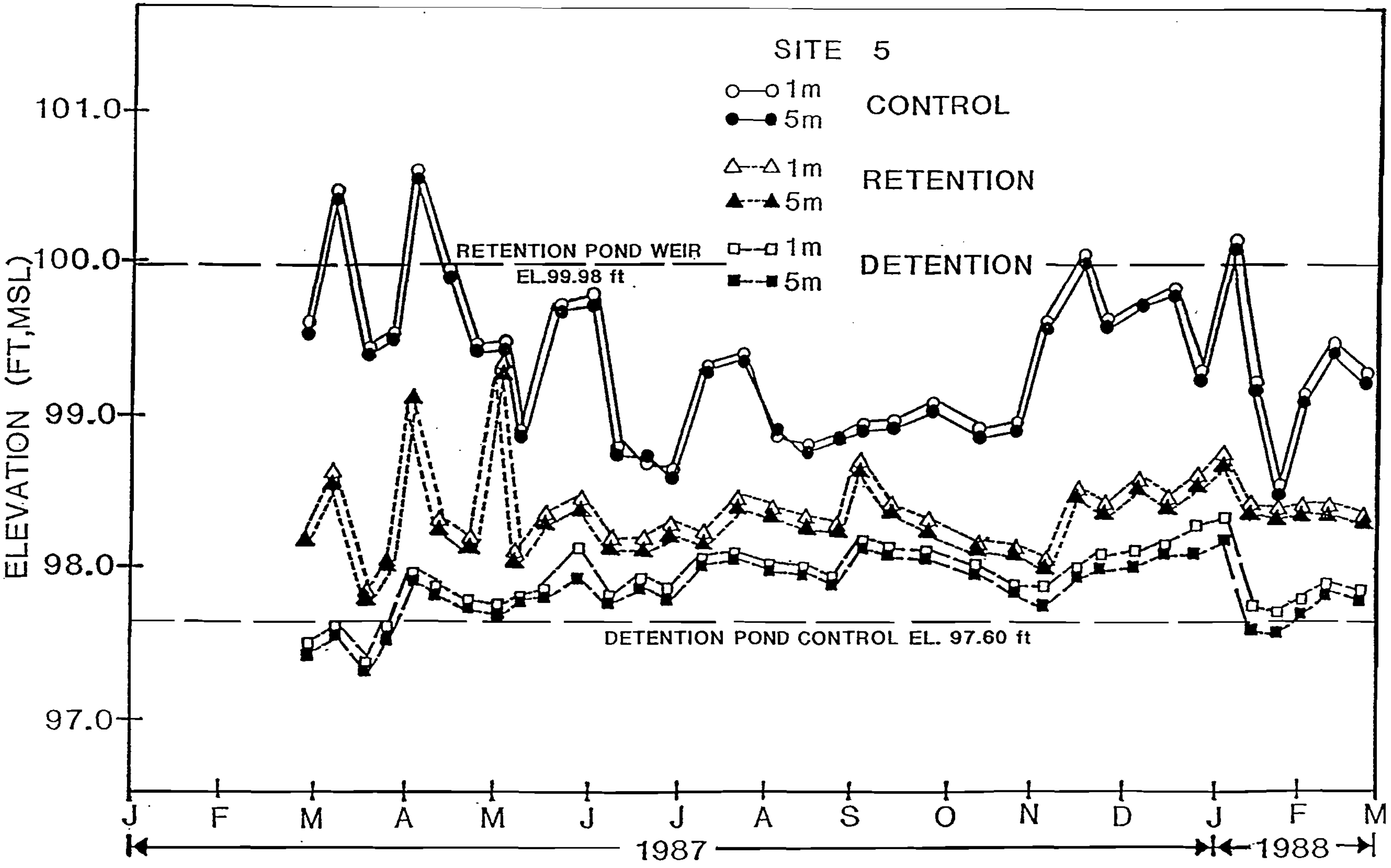


Figure 3-12. Fluctuations in Piezometric Elevations at the Commercial Dual Pond Facility - Site 5.

A summary of vertical and horizontal hydraulic groundwater gradients for the retention pond at site 5 is given in Figure 3-13. Substantial variations are apparent in horizontal groundwater gradients while the vertical gradients appear to be more stable and consistent in value. Vertical groundwater gradients, although low in value, exhibited a consistent potential for upward migration of groundwater into the pond. On the other hand, horizontal gradients were often much larger in value and exhibited a consistent tendency for migration of waters out of the pond in a lateral direction. Clearly, the dominant mechanism for groundwater migration in the retention pond area at this site is lateral movement away from the pond rather than a downward vertical migration.

A summary of vertical and horizontal groundwater hydraulic gradients in the detention pond at site 5 is given in Figure 3-14. Hydraulic gradients indicated in this figure are very similar to those previously discussed for the retention area. Vertical gradients consistently indicated a tendency for upward migration of groundwaters into the detention pond. However, horizontal groundwater gradients suggest a consistent and much stronger tendency for groundwaters to migrate laterally away from the detention pond. As observed for the retention pond, the primary mechanism for removal of infiltrated runoff in the detention pond is lateral migration rather than vertical movement downward.

Characteristics of Stormwater Runoff Collected at the Five Study Sites

As described in Chapter 2, flow-weighted stormwater runoff samples were collected at each of the five study sites on various occasions during 1987. A summary of storm event characteristics, including event date, total rainfall, event duration and

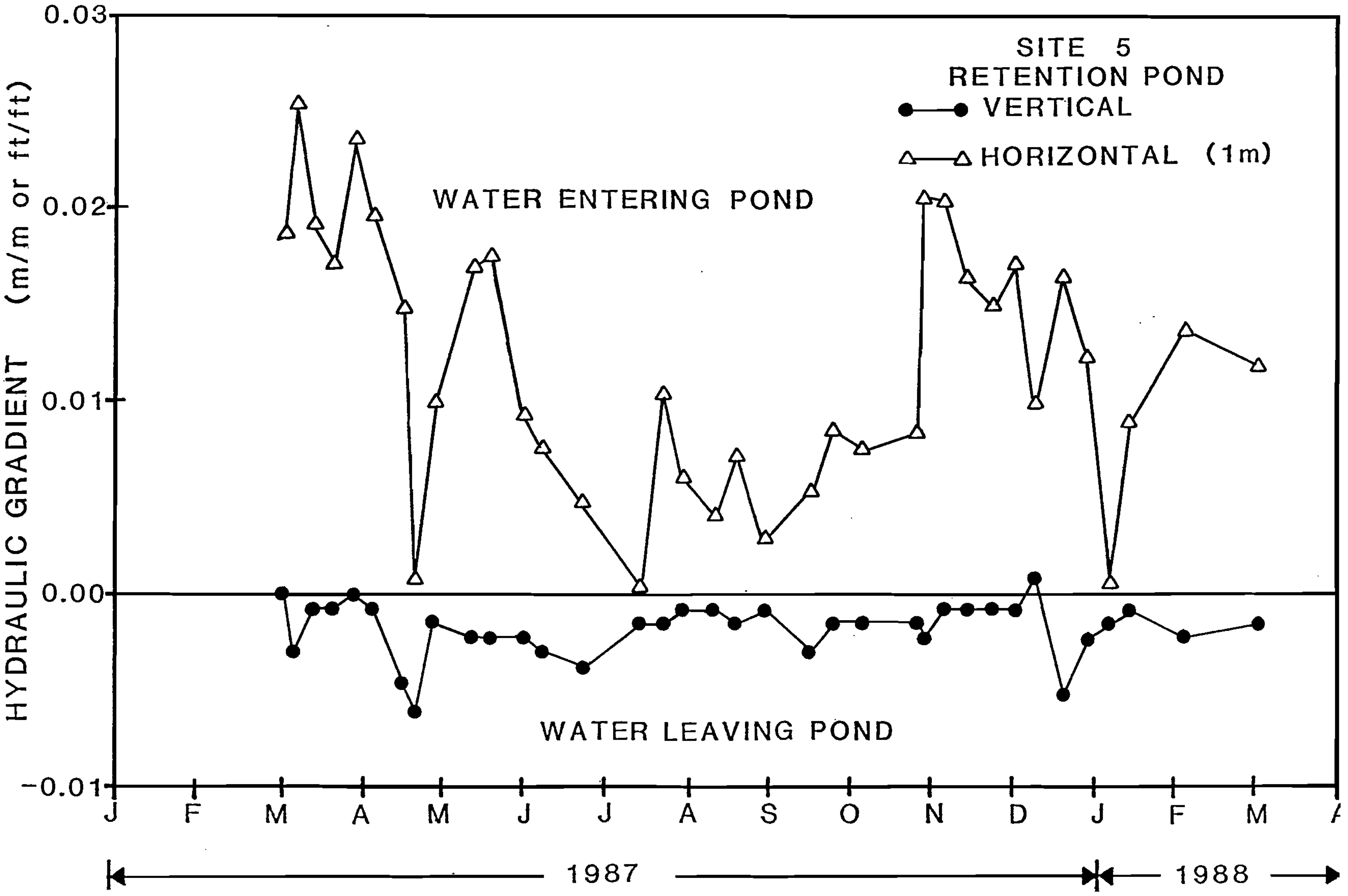


Figure 3-13. Horizontal and Vertical Hydraulic Gradients at the Retention Pond Well at the Commercial Dual Pond Site (Site 5) During 1987-88.

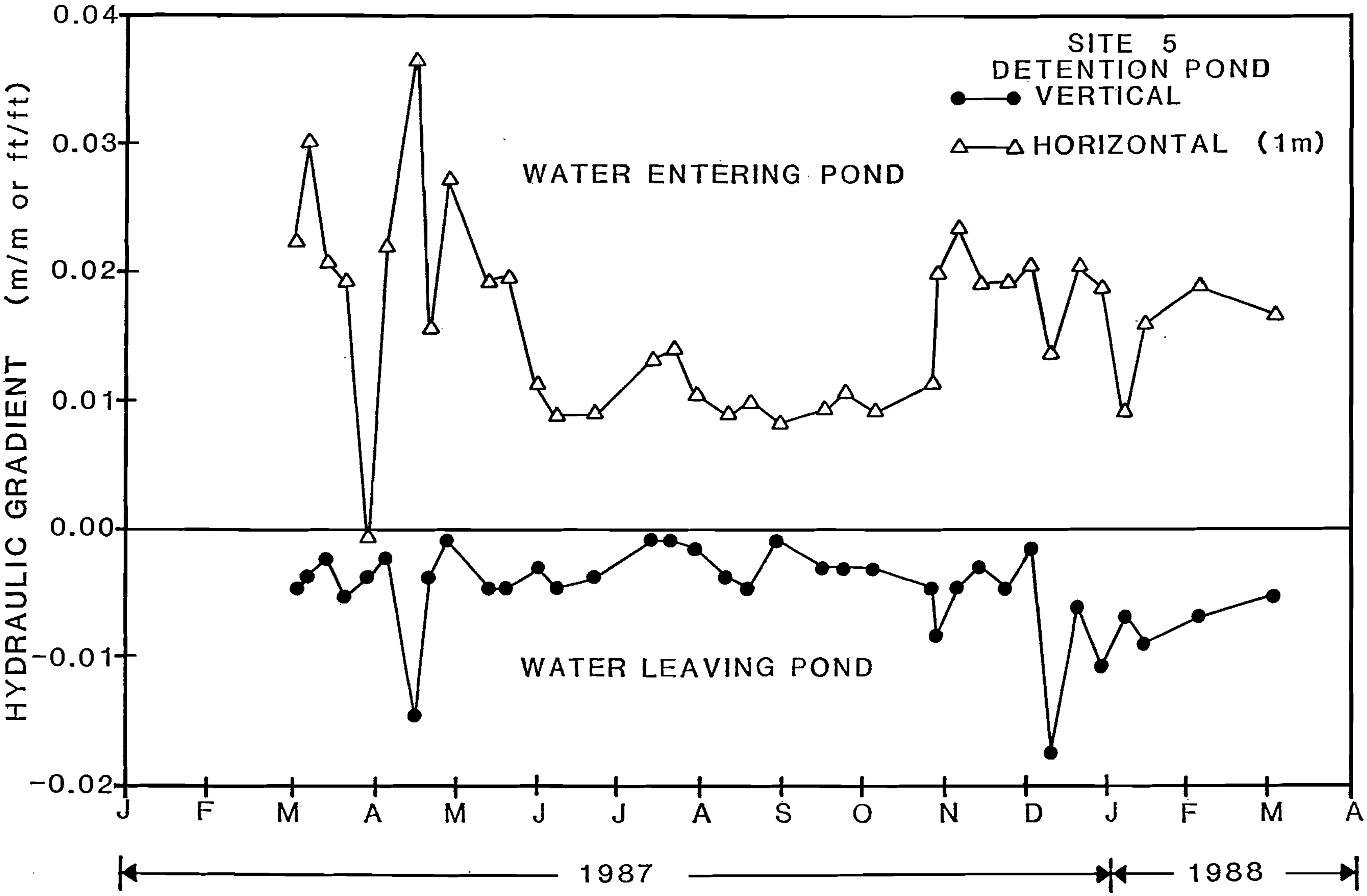


Figure 3-14. Horizontal and Vertical Hydraulic Gradients at the Detention Pond Well at the Commercial Dual Pond Site (Site 5) During 1987-88.

antecedent dry period for all monitored events is given in Table 3-2. In general, monitored storm events covered a wide range of rainfall amounts, duration and antecedent dry periods. A discussion of chemical characteristics of runoff samples is given in the following sections.

Site 1 - Highway Runoff

A summary of chemical characteristics of stormwater runoff from the inflow and outflow at the wet swale site is given in Table 3-3. As indicated in Figure 2-10, the runoff inflow collector was located approximately 3 m downstream from the point at which the runoff entered the swale channel. The outflow runoff collector was located a distance of approximately 70 m along the swale flow path to monitor changes in chemical characteristics of the runoff inputs during travel through the swale channel. A total of 11 storm events were monitored at this site for both inflow and outflow characteristics. Rainfall amounts in monitored events ranged from 0.20-5.56 cm (0.08-2.19 in) with event durations ranging from 1.0-36.0 hours and antecedent dry periods of 0.66-19.4 days.

As seen in Table 3-3, highway runoff entering the swale channel was slightly acidic, with a mean pH value of approximately 6.51, and poorly buffered, with a mean alkalinity of only 42 mg/l. The dominant inorganic nitrogen species was nitrate with a mean value of approximately 400 μg/l. Concentrations of dissolved and particulate organic nitrogen were approximately equal. The mean total nitrogen concentration was 1601 μg/l. The mean total phosphorus concentration in highway runoff measured at this site was 229 μg/l, with approximately 28% as dissolved orthophosphorus, 15% as dissolved organic phosphorus, and 57% as particulate phosphorus.

TABLE 3-2

SUMMARY OF STORM EVENT CHARACTERISTICS FOR MONITORED STORM EVENTS AT THE FIVE STUDY SITES

SITE	STORM EVENT CHARACTERISTICS			
	DATE	TOTAL RAINFALL (inches)	EVENT DURATION (hours)	ANTECEDENT DRY PERIOD (days)
Site 1 Highway Runoff	01/24/87	0.47	4.25	2.65
	02/06/87	0.66	6.83	3.02
	04/15/87	0.36	1.30	0.66
	05/19/87	0.25	1.25	6.00
	07/15/87	0.15	1.50	1.76
	08/10/87	1.26	1.25	6.00
	10/11/87	2.19	36.6	10.4
	11/19/87	0.91	3.83	1.62
	12/15/87	0.08	1.00	19.4
	01/21/88	0.16	5.00	3.72
Site 2 Highway Runoff	01/21/87	0.16	5.00	4.25
	03/24/87	0.47	3.72	2.65
	05/19/87	0.04	0.75	1.11
	07/15/87	0.83	1.33	1.75
	07/20/87	0.22	1.08	1.01
	08/04/87	0.48	0.66	14.1
	08/10/87	1.71	2.09	3.73
	08/20/87	2.77	3.09	6.01
	09/04/87	0.09	2.25	0.09
	09/11/87	0.45	1.17	1.82
	11/18/87	0.20	4.42	1.67
	11/25/87	0.34	17.92	6.87
	12/15/87	0.08	16.40	19.37
Site 3 Residential Runoff	01/21/87	0.19	3.33	3.72
	03/24/87	0.47	4.25	2.65
	04/06/87	0.08	4.25	11.97
	06/26/87	0.14	1.09	3.57
	07/06/87	0.22	0.58	0.97
	07/15/87	0.73	1.58	1.73
	08/12/87	0.17	1.00	1.03
	10/12/87	0.14	0.33	10.14
	11/03/87	0.07	0.33	1.96
	11/16/87	1.04	2.17	7.01

TABLE 3-2 -- CONTINUED

SITE	STORM EVENT CHARACTERISTICS			
	DATE	TOTAL RAINFALL (inches)	EVENT DURATION (hours)	ANTECEDENT DRY PERIOD (days)
Site 4 Residential Runoff	02/07/87	0.04	0.17	12.7
	03/11/87	0.08	0.91	0.72
	05/18/87	0.03	2.60	6.69
	05/19/87	0.31	0.67	0.86
	06/20/87	0.07	0.50	14.2
	07/17/87	0.70	3.74	0.92
	08/02/87	1.08	1.08	1.18
	09/05/87	0.88	2.00	0.90
	11/25/87	0.24	10.17	6.87
Site 5 Commercial Runoff	01/10/87	0.22	2.42	0.98
	02/19/87	0.16	5.00	3.72
	03/11/87	0.08	0.91	3.06
	05/15/87	0.73	1.58	1.73
	06/28/87	0.90	3.00	2.60
	07/16/87	0.33	1.00	1.15
	08/13/87	0.17	1.00	1.03
	11/02/87	0.22	5.17	0.16

TABLE 3-3

SUMMARY OF CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF FROM INFLOW AND OUTFLOW AT THE WET SWALE SITE (SITE 1)

PARAMETER	UNITS	RUNOFF INFLOW TO WET SWALE[1]			RUNOFF OUTFLOW FROM WET SWALE[1]		
		MEAN	RANGE	C.V.[2]	MEAN	RANGE	C.V.[2]
pH	--	6.51	5.82-7.29	6	6.55	6.29-7.00	3
Spec. Cond.	μmhos/cm	150	50-367	73	158	41-292	50
Rainfall	inches	0.73	0.08-2.19	93	--	--	--
Duration	hours	7.11	1.00-36.00	149	--	--	--
Ant. Dry Period	days	5.12	0.66-19.40	107	--	--	--
Alkalinity	mg/l	41.9	14.7-100.0	59	36.9	17.8-53.4	32
NH_3-N	μg/l	88	<10-234	95	98	<10-235	77
NO_2 + NO_3-N	μg/l	400	<10-1240	110	192	<10-791	131
Diss. Organic N	μg/l	543	251-1802	81	471	294-767	31
Part. Organic N	μg/l	570	<10-2097	100	203	<10-588	91
Total N	μg/l	1601	465-5118	83	964	433-2015	49
Diss. Ortho-P	μg/l	64	8-159	81	83	27-176	63
Diss. Organic P	μg/l	34	2-57	57	28	10-60	51
Total P	μg/l	229	89-539	59	190	67-361	54
Chlorides	mg/l	10	2-26	69	21	4-456	57
Sulfates	mg/l	21.0	2.4-87.1	120	22.1	9.1-41.0	48
BOD	mg/l	6.9	1.9-14.7	57	3.6	1.0-7.3	56
Color	Pt-Co Units	56	13-180	88	50	17-136	64
T.D.S.	mg/l	117	33-296	86	114	52-180	37
V.D.S.	mg/l	43	1-131	86	39	2-93	70
Turbidity	NTU	21.8	3.8-50.6	67	9.3	1.9-33.7	109
S.S.	mg/l	34.0	4.9-123.0	99	6.4	0.4-18.4	83
V.S.S.	mg/l	20.9	2.2-74.5	97	4.6	0.3-13.0	83

1. Number of Samples = 11
2. Coefficient of Variation

Highway runoff entering the swale channel carried high loads of suspended solids. As seen in Table 3-3, the mean suspended solids concentration in highway runoff was 34 mg/l, of which approximately 61% was organic in nature. Runoff samples were also characterized by high levels of turbidity, with a mean value of approximately 22 NTU.

In general, runoff inflow to the wet swale channel was highly variable in terms of its physical and chemical characteristics. This variability is indicated by both the large range of values indicated in Table 3-3 as well as the relatively large coefficient of variation calculated for each of the measured parameters. Of the measured parameters, the most variable were nitrate, organic nitrogen, sulfates and suspended solids. Many of these parameters exhibited measured concentrations which covered several orders of magnitude.

Chemical characteristics of stormwater runoff leaving the swale channel are also shown in Table 3-3. In general, measured concentrations of chemical constituents in the outflow from the swale channel are lower in concentration and also less variable than measured runoff inputs to the swale channel. This reduced variability is particularly evident for constituents such as specific conductivity, alkalinity, total nitrogen, sulfates, total dissolved solids, and to a lesser extent, suspended solids.

Changes in chemical characteristics of runoff inputs during flow through the wet swale channel are indicated in Table 3-4. The majority of measured parameters exhibited decreases in concentration during flow through the swale channel. Concentrations of total nitrogen decreased by an average of 40% during flow through the channel, primarily resulting from decreases in nitrate and particulate organic nitrogen. Total phosphorus decreased by an average of 17% although concentrations of orthophosphorus

TABLE 3-4

CHANGES IN CHEMICAL CHARACTERISTICS OF RUNOFF INPUTS DURING FLOW THROUGH THE WET SWALE SYSTEM (SITE 1)

PARAMETER	UNITS	MEAN INFLOW TO SWALE[1]	MEAN OUTFLOW FROM SWALE[1]	PERCENT CHANGE (%)
pH	--	6.51	6.55	+ 1
Spec. Cond.	μmhos/cm	150	158	+ 5
Alkalinity	mg/l	41.9	36.9	- 11
NH_3-N	μg/l	88	98	+ 11
NO_2 + NO_3-N	μg/l	400	192	- 52
Diss. Organic N	μg/l	543	471	- 13
Part. Organic N	μg/l	570	203	- 64
Total N	μg/l	1601	964	- 40
Diss. Ortho-P	μg/l	64	83	+ 30
Diss. Organic P	μg/l	34	28	- 18
Total P	μg/l	229	190	- 17
Chlorides	mg/l	10	21	+ 110
Sulfates	mg/l	21.0	22.1	+ 5
BOD	mg/l	6.9	3.6	- 48
Color	Pt-Co Units	56	50	- 11
T.D.S.	mg/l	117	114	- 3
V.D.S.	mg/l	43	39	- 9
S.S.	mg/l	21.8	9.3	- 57
V.S.S.	mg/l	34.0	6.4	- 82
Turbidity	NTU	20.9	4.6	- 78

1. Number of Samples = 11

were found to increase slightly. A relatively large percentage increase was observed for chlorides, although both inflow and outflow values were relatively small. Measured concentrations of BOD were reduced by approximately 48%, turbidity by 57%, and suspended solids by approximately 81%. It appears that the wet swale channel was very effective in removing the species which are primarily particulate in form, while exhibiting poor removal efficiencies for many species which are primarily in a dissolved form.

A summary of heavy metal concentrations in runoff inflow and outflow from the swale channel is given in Table 3-5. With the exceptions of aluminum and iron, the dominant heavy metals measured in highway runoff entering the swale channel were zinc (with a mean concentration of 170 μg/l), copper (with a mean concentration of 50 μg/l), and lead (with a mean concentration of 224 μg/l). Relatively high levels of cadmium and especially nickel were also observed at this site, while concentrations of total manganese and total chromium were relatively low. In general, heavy metal inputs were much less variable than the general chemical parameters. The most variable heavy metals measured were copper, aluminum and iron. Variations in the remaining heavy metals were approximately equal.

Heavy metal concentrations in runoff measured at the end of the swale channel are also given in Table 3-5. In general, concentrations of most heavy metals were reduced during travel through the swale channel. Heavy metal concentrations measured at the outflow are also somewhat less variable than those measured in the runoff inflow, although the reductions in variability in many cases are relatively small.

Changes in concentrations of heavy metals during flow through the wet swale channel are indicated in Table 3-6. With the exception of dissolved iron, concentrations

TABLE 3-5

SUMMARY OF INFLOW AND OUTFLOW CONCENTRATIONS OF HEAVY METALS AT THE WET SWALE SITE (SITE 1)

(All concentrations in $\mu g/l$)

PARAMETER		RUNOFF INFLOW TO WET SWALE[1]			RUNOFF OUTFLOW FROM WET SWALE[1]		
		MEAN	RANGE	C.V.[2]	MEAN	RANGE	C.V.[2]
Cd -	Diss.	5.99	1.3-10	50	3.82	2.2-7.4	41
	Total	8.45	3.7-16	40	4.98	3.2-8.2	35
Zn -	Diss.	83.7	28-174	55	44.3	20-71	43
	Total	170	83-481	66	52.8	22-97	49
Mn -	Diss.	16.9	8-34	58	10.6	3-23	63
	Total	31.3	14-88	64	22.5	9-52	58
Cu -	Diss.	25.1	8-59	62	17.7	3-40	59
	Total	49.8	16-166	85	21.8	10-43	49
Al -	Diss.	133	31-886	188	95.8	21-139	33
	Total	974	158-2590	71	244	104-474	52
Fe -	Diss.	105	28-347	86	171	15-594	111
	Total	1120	156-2740	59	679	102-2280	91
Pb -	Diss.	129	48-253	43	93.6	30-139	39
	Total	224	110-449	44	112	38-160	33
Ni -	Diss.	42.0	14-91	50	27.6	10-43	40
	Total	46.0	8.7-103	56	31.6	10-44	35
Cr -	Diss.	8.71	3.1-15	37	6.85	2.8-9.5	31
	Total	13.1	5.8-29	46	8.23	3.2-11	33

1. Number of Samples = 11

2. Coefficient of Variation

TABLE 3-6

CHANGES IN CONCENTRATIONS OF HEAVY METALS IN RUNOFF DURING FLOW THROUGH THE WET SWALE SYSTEM (SITE 1)

(All concentrations in μg/l)

PARAMETER		MEAN INFLOW TO SWALE	MEAN OUTFLOW FROM SWALE	PERCENT REMOVED (%)
Cd-	Diss.	5.99	3.82	- 36
	Total	8.45	4.98	- 41
Zn -	Diss.	83.7	44.3	- 47
	Total	170	52.8	- 69
Mn -	Diss.	16.9	10.6	- 37
	Total	31.3	22.5	- 28
Cu -	Diss.	25.1	17.7	- 30
	Total	49.8	21.8	- 56
Al -	Diss.	133	95.8	- 28
	Total	974	244	- 75
Fe -	Diss.	105	171	+ 63
	Total	1120	679	- 39
Pb -	Diss.	129	93.6	- 27
	Total	224	112	- 50
Ni -	Diss.	42.0	27.6	- 34
	Total	46.0	31.6	- 31
Cr -	Diss.	8.71	6.85	- 21
	Total	13.1	8.23	- 37

of all heavy metals were reduced during travel through the swale channel. The most significant reductions were observed for zinc (which decreased by 69%), aluminum (which decreased by 75%), and lead (which decreased by 50%) during flow through the swale channel. Removal efficiencies for the remaining metals ranged from approximately 30% to 40% for total metal species.

Site 2 - Highway Runoff

A summary of chemical characteristics of stormwater runoff measured at the inflow to the dry swale channel is given in Table 3-7. A total of 16 storm events were monitored for chemical characteristics of the inflow and 15 events monitored for characteristics of outflow. Total rainfall of monitored events ranged from 0.10-9.78 cm (0.04-3.85 in) with event durations of 0.66-36.6 hours and antecedent dry periods of 0.09-19.37 days.

As observed at the previous site, highway runoff was found to be slightly acidic, with a mean pH value of 6.78, and also relatively poorly buffered with a mean alkalinity of 42 mg/l. The pH values of monitored events covered a range of 4 pH units with a mean pH value of 3.20 for stormwater runoff during one event. After travel over the swale channel, the pH of runoff for this event was reduced even further to a value of 2.19. However, these pH values clearly reflected an extreme event since no other runoff events had measured pH values less than 6.40.

Concentrations of total nitrogen averaged 2152 μg/l which consisted primarily of nitrate and both dissolved and particulate organic nitrogen. Measured concentrations of ammonia comprised on the average only 6% of the total nitrogen found. Mean

TABLE 3-7

SUMMARY OF CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF FROM INFLOW AND OUTFLOW AT THE DRY SWALE SITE (SITE 2)

PARAMETER	UNITS	RUNOFF INFLOW TO DRY SWALE[1]			RUNOFF OUTFLOW FROM DRY SWALE[2]		
		MEAN	RANGE	C.V.[3]	MEAN	RANGE	C.V.[3]
pH	–	6.78	3.20-7.04	14	5.50	2.19-7.22	19
Spec. Cond.	μmhos/cm	111	56-201	41	358	51-4120	291
Rainfall	inches	0.90	0.04-3.85	125	--	--	–
Duration	hours	6.82	0.66-36.60	141	--	–	–
Ant. Dry Period	days	4.76	0.09-19.37	116	--	–	–
Alkalinity	mg/l	41.9	0.0-106.0	55	30.0	0.0-64.6	47
NH_3-N	μg/l	131	<10-439	88	142	<10-549	97
NO_2 + NO_3-N	μg/l	542	25-1412	76	532	22-1230	77
Diss. Organic N	μg/l	807	93-3066	120	681	<10-2312	103
Part. Organic N	μg/l	672	<10-2935	108	353	<10-926	78
Total N	μg/l	2152	594-6405	72	1707	657-3707	63
Diss. Ortho-P	μg/l	159	12-313	66	235	5-966	107
Diss. Organic P	μg/l	126	7-373	93	132	20-296	73
Total P	μg/l	550	165-2103	84	481	112-1182	66
Chlorides	mg/l	8	1-22	65	8	3-18	63
Sulfates	mg/l	8.6	1.0-22.6	76	43.3	2.0-540.0	318
BOD	mg/l	4.2	0.6-9.3	59	6.5	0.9-37.0	137
Color	Pt-Co Units	50	<1-144	87	60	<1-152	73
T.D.S.	mg/l	88	33-219	59	91	17-301	90
V.D.S.	mg/l	34	3-65	49	39	3-166	103
Turbidity	NTU	29.2	5.8-86.2	75	19.4	2.5-56.9	91
S.S.	mg/l	66.5	11.8-213.0	79	27.5	1.4-81.4	89
V.S.S.	mg/l	32.6	5.3-98.4	80	16.1	1.2-64.4	108

1. Number of Samples = 16
2. Number of Samples = 15
3. Coefficient of Variation

concentration of total phosphorus was found to be 550 μg/l of which 29% was dissolved orthophosphorus, 23% was dissolved organic phosphorus, and 48% was particulate phosphorus. Concentrations of chlorides and sulfates were both relatively low.

Highway runoff at this site was also characterized by a high loading of suspended solids. The mean suspended solids concentration was approximately 67 mg/l, with a range of measured values from 12 to 213 mg/l. Measured concentrations of turbidity were also relatively high with a mean value of 29.2 NTU. Of the measured suspended solids, approximately 50% was organic in nature and 50% inert.

Chemical characteristics of stormwater runoff leaving the dry swale channel are also given in Table 3-7. In general, chemical parameters associated with particulate matter were found to decrease in concentration during flow through the swale as observed for particulate organic nitrogen, total phosphorus, turbidity and suspended solids. However, many of the dissolved pollutants were found to increase or remain unchanged during flow through the swale channel. This phenomenon is particularly evident for conductivity, ammonia, dissolved orthophosphorus, sulfates, color and dissolved solids.

Unlike trends observed in the wet swale channel, travel through the dry swale channel did not improve the variability of runoff inputs measured at the outflow. As seen in Table 3-7, the variability in chemical characteristics of the runoff inflow is very similar to the variability measured in the runoff outflow. For certain parameters like orthophosphorus, sulfates, BOD and dissolved solids, variability was observed to increase as a result of flow through the dry swale channel.

Changes in chemical characteristics of runoff inputs during flow through the dry swale system are indicated in Table 3-8. As indicated previously, significant removal

TABLE 3-8

CHANGES IN CHEMICAL CHARACTERISTICS OF RUNOFF INPUTS DURING FLOW THROUGH THE DRY SWALE SYSTEM (SITE 2)

PARAMETER	UNITS	MEAN INFLOW TO SWALE[1]	MEAN OUTFLOW FROM SWALE[2]	PERCENT CHANGE (%)
pH	--	6.78	5.50	- 19
Spec. Cond.	μmhos/cm	111	358	+ 223
Alkalinity	mg/l	41.9	30.0	- 28
NH_3-N	μg/l	131	142	+ 8
NO_2 + NO_3-N	μg/l	542	532	- 2
Diss. Organic N	μg/l	807	681	- 16
Part. Organic N	μg/l	672	352	- 47
Total N	μg/l	2152	1707	- 21
Diss. Ortho-P	μg/l	159	235	+ 48
Diss. Organic P	μg/l	126	132	+ 5
Total P	μg/l	550	481	- 13
Chlorides	mg/l	8	8	0
Sulfates	mg/l	8.6	43.3	+ 403
BOD	mg/l	4.2	6.5	+ 55
Color	Pt-Co Units	50	60	+ 20
T.D.S.	mg/l	88	91	+ 3
V.D.S.	mg/l	34	39	+ 15
S.S.	mg/l	29.2	19.4	- 34
V.S.S.	mg/l	66.5	27.5	- 59
Turbidity	NTU	32.6	16.1	- 51

1. Number of Samples = 16
2. Number of Samples = 15

efficiencies are observed for only those parameters which are primarily particulate in nature, such as particulate organic nitrogen, total phosphorus, turbidity and suspended solids. Small removal efficiencies were observed for dissolved organic nitrogen and alkalinity. However, the majority of measured parameters which exist primarily in a dissolved form showed increases during flow through the swale channel. These increases are most evident for conductivity (which increased by more than 200%), orthophosphorus (which increased by 48%), sulfates (which increased by more than 400%), and BOD (which increased by approximately 55%).

Inflow and outflow concentrations of heavy metals at the dry swale site are given in Table 3-9. As observed at site 1 (with the exceptions of aluminum and iron), zinc, copper and lead were the most abundant heavy metals measured in highway runoff entering the dry swale channel. However, mean concentrations of each of these heavy metals measured at the dry swale site were much higher than those measured at the previous highway site. The mean concentration of total zinc measured at this site was 272 μg/l compared with 170 μg/l measured at site 1, total copper averaged 67 μg/l compared with 50 μg/l measured at site 1, and total lead averaged 343 μg/l compared with 242 μg/l measured at site 1. Measured concentrations of cadmium and chromium were similar at both sites. Total nickel was found to be much lower at this site than the relatively high values measured at site 1.

As seen in Table 3-9, several of the measured heavy metals such as cadmium, nickel and chromium, exhibited a relatively small variability in measured concentrations between rain events. Other heavy metals such as zinc, manganese, copper, iron and lead were found to have a large variability in event mean concentrations.

TABLE 3-9

SUMMARY OF INFLOW AND OUTFLOW CONCENTRATIONS OF HEAVY METALS AT THE DRY SWALE SITE (SITE 2)

(All concentrations in $\mu g/l$)

PARAMETER		RUNOFF INFLOW TO DRY SWALE[1]			RUNOFF OUTFLOW FROM DRY SWALE[2]		
		MEAN	RANGE	C.V.[3]	MEAN	RANGE	C.V.[3]
Cd -	Diss.	5.55	3.7-8.9	28	2.50	<0.5-4.8	54
	Total	8.35	5.3-12	22	4.27	2.0-6.9	32
Zn -	Diss.	107	37-475	102	81.4	25-270	75
	Total	272	61-838	87	140	51-300	60
Mn -	Diss.	8.37	<1-22	75	7.00	2-24	85
	Total	31.5	4-82	78	16.1	3-37	58
Cu -	Diss.	25.4	5-68	69	22.9	6-45	48
	Total	66.9	5-334	117	36.2	6-75	53
Al -	Diss.	99.1	37-281	73	115	30-313	70
	Total	2160	167-6150	81	1070	34-2790	83
Fe -	Diss.	95.4	17-384	126	97.5	25-604	151
	Total	1450	129-4710	96	705	61-2020	88
Pb -	Diss.	74.6	3-302	91	65.1	29-242	78
	Total	343	48-1250	109	167	29-539	82
Ni -	Diss.	14.9	5.9-23	36	10.3	4.6-19	41
	Total	19.7	8.2-33	35	11.8	4.6-19	36
Cr -	Diss.	5.35	1.7-11	38	4.91	2.4-7.9	34
	Total	13.6	3.7-31	60	8.17	2.4-14	47

1. Number of Samples = 16

2. Number of Samples = 15

3. Coefficient of Variation

Concentrations of heavy metals in runoff leaving the dry swale channel were found to be significantly lower than input concentrations for all heavy metals measured. These large reductions in concentrations were observed for total metal concentrations, while dissolved concentrations for most metals changed very little. This behavior suggests that the swale channel is effective in removing particulate bound metal species, but is much less effective in removing dissolved metal ions. Metal species such as zinc, manganese, copper, lead and chromium exhibited less variability in measured concentrations after flowing through the swale channel than was observed in the raw runoff water. However, the variability in concentrations for some metals such as cadmium and iron was increased after flow through the dry swale channel.

Changes in concentrations of heavy metals during flow through the dry swale channel are indicated in Table 3-10. Total concentrations of all of the measured heavy metals were reduced from 40% to 50% during flow through the 70 m long dry swale channel. However, reductions in dissolved metal concentrations were generally much less. The best reductions in dissolved metal concentrations were observed for cadmium, zinc and nickel which were reduced in concentration by 55%, 24% and 31%, respectively. Dissolved concentrations for other metal species were reduced by less than 20%. Dissolved concentrations of aluminum actually increased slightly during flow through the dry swale channel.

Site 3 - Residential Runoff

A summary of chemical characteristics of residential runoff collected at the dual pond site is given in Table 3-11. A total of 10 storm events were monitored at this site

TABLE 3-10

CHANGES IN CONCENTRATIONS OF HEAVY METALS IN RUNOFF DURING FLOW THROUGH THE DRY SWALE SYSTEM (SITE 2)
(All concentrations in μg/l)

PARAMETER		MEAN INFLOW TO SWALE	MEAN OUTFLOW FROM SWALE	PERCENT REMOVED (%)
Cd-	Diss.	5.55	2.50	- 55
	Total	8.35	4.27	- 49
Zn -	Diss.	107	81.4	- 24
	Total	272	140	- 49
Mn -	Diss.	8.37	7.00	- 16
	Total	31.5	16.1	- 49
Cu -	Diss.	25.4	22.9	- 10
	Total	66.9	36.2	- 46
Al -	Diss.	99.1	115	+ 16
	Total	2160	1070	- 51
Fe -	Diss.	95.4	97.5	- 2
	Total	1450	705	- 51
Pb -	Diss.	74.6	65.1	- 13
	Total	343	167	- 51
Ni -	Diss.	14.9	10.3	- 31
	Total	19.7	11.8	- 40
Cr -	Diss.	5.35	4.91	- 8
	Total	13.6	8.17	- 40

TABLE 3-11

SUMMARY OF CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN VALUE[1]	RANGE	C.V.[2]
pH	--	7.15	6.76 - 7.75	2
Spec. Cond.	µmhos/cm	83	29 - 160	53
Rainfall	inches	0.33	0.07 - 1.04	100
Duration	hours	1.89	0.33 - 4.25	82
Ant. Dry Period	days	4.48	0.97 - 11.97	87
Alkalinity	mg/l	50.1	15.7 - 110.0	66
NH_3-N	µg/l	34	< 10 - 83	74
NO_2 + NO_3-N	µg/l	628	100 - 1672	99
Diss. Organic N	µg/l	841	232 - 2185	67
Part. Organic N	µg/l	342	106 - 1078	88
Total N	µg/l	1845	516 - 4342	68
Diss. Ortho-P	µg/l	49	9 - 244	142
Diss. Organic P	µg/l	59	4 - 297	150
Total P	µg/l	198	34 - 641	90
Chlorides	mg/l	11	3 - 34	93
Sulfates	mg/l	11.5	0.1 - 45.7	123
BOD	mg/l	6.5	2.4 - 20.6	84
Color	Pt-Co Units	39	9 - 94	68
T.D.S.	mg/l	85	10 - 201	76
V.D.S.	mg/l	29	6 - 63	80
Turbidity	NTU	9.6	2.4 - 35.2	99
S.S.	mg/l	30.1	2.7 - 81.0	104
V.S.S.	mg/l	14.0	2.2 - 58.0	120

1. Number of Samples = 10

2. Coefficient of Variation

with a range of total rainfall amounts from 0.18-2.64 cm (0.07-1.04 in), event durations from 0.33-4.25 hours and antecedent dry periods from 0.97-11.97 days. Runoff collected at this site was approximately neutral in pH, with an alkalinity of 15 mg/l. The mean total nitrogen concentration measured in this residential runoff was 1845 μg/l which was comprised primarily from nitrate and organic nitrogen. Ammonia ions contributed only 2% of the total nitrogen measured in runoff at this site. The mean concentration of total phosphorus measured in this residential runoff was 198 μg/l, which was approximately 25% dissolved orthophosphorus, 30% dissolved organic phosphorus and 45% particulate phosphorus. Concentrations of chlorides and sulfates were relatively low at this site.

In general, residential runoff measured at this site exhibited a lower loading of suspended solids than runoff measured at the two highway sites, with a mean suspended solids concentration of approximately 30 mg/l and a mean turbidity of 9.6 NTU. Dissolved solids were also relatively low in runoff measured at this site. The mean BOD value of 6.5 mg/l was similar to values found at the highway sites.

Similar to patterns observed at the highway sites, runoff characteristics measured in the residential runoff exhibited extreme variability for certain parameters. The most variable parameters included nitrate, orthophosphorus, dissolved organic phosphorus, sulfates, turbidity and suspended solids. The least variable parameters included conductivity, ammonia, total nitrogen and color. Many of the measured chemical parameters which exhibited high variability were found to have event mean concentrations which extended over several orders of magnitude.

A summary of concentration-based removal efficiencies for stormwater pollutants in the residential dual pond system is given in Table 3-12. Removal efficiencies were

TABLE 3-12

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR STORMWATER POLLUTANTS IN THE RESIDENTIAL DUAL POND SYSTEM (SITE 3)

PARAMETER	UNITS	MEAN RUNOFF CONC.	MEAN REMOVAL IN RETENTION POND		TOTAL REMOVAL THROUGH DETENTION POND	
			MEAN POND CONC.	REMOVAL (%)	MEAN POND CONC.	REMOVAL (%)
pH	--	7.15	8.22	+ 15	8.19	+ 15
Spec. Cond.	μmhos/cm	83	196	+ 136	260	+ 213
Alkalinity	mg/l	50.1	63.4	+ 27	56.0	+ 12
NH_3-N	μg/l	34	42	+ 24	39	+ 15
$NO_2 + NO_3$-N	μg/l	628	42	- 93	382	- 39
Diss. Organic N	μg/l	841	414	- 51	720	- 14
Part. Organic N	μg/l	342	210	- 39	247	- 28
Total N	μg/l	1845	708	- 62	1388	- 25
Diss. Ortho-P	μg/l	49	59	+ 20	11	- 78
Diss. Organic P	μg/l	59	36	- 39	25	- 58
Total P	μg/l	198	141	- 29	82	- 59
Chlorides	mg/l	11	30	+ 173	32	+ 191
Sulfates	mg/l	11.5	19.9	+ 73	32.1	+ 179
BOD	mg/l	6.5	5.2	- 20	3.4	- 48
Color	Pt-Co Units	39	39	0	33	- 15
T.D.S.	mg/l	85	133	+ 57	173	+ 104
V.D.S.	mg/l	29	35	+ 21	63	+ 117
S.S.	mg/l	30.1	7.1	- 76	6.9	- 77
V.S.S.	mg/l	14.0	5.6	- 60	4.7	- 66
Turbidity	NTU	9.6	4.4	- 54	4.0	- 58

calculated based upon the mean runoff concentration entering the pond system and mean chemical characteristics of surface waters measured in the retention and detention ponds. Removal efficiencies were calculated based upon changes in concentrations between the mean runoff value and mean surface water characteristics measured in the retention and detention ponds.

As seen in Table 3-12, the dual pond system was relatively effective in reducing inputs of total nitrogen, with a mean removal efficiency of 62%. This removal is primarily due to reductions in concentrations of nitrate and to a lesser degree, organic nitrogen. Ammonia actually increased in concentration within the retention pond compared to the mean runoff value. Reductions in total phosphorus, however, were much less than those observed for total nitrogen, averaging only 29% within the retention pond itself. Concentrations of chlorides and sulfates also increased in the retention pond over values measured in the runoff flow. A slight reduction in concentration was observed for BOD.

As would be expected, the pond provided relatively good removal efficiencies for particulate runoff species. Concentrations of suspended solids were reduced by 76% and turbidity was reduced by 54% compared with initial runoff values.

Since final discharges from the stormwater treatment system occur through the detention pond, overall system removal efficiencies were also calculated by comparing initial runoff concentrations with mean water quality characteristics measured within the detention pond. When the final detention pond was considered, the removal efficiency for total nitrogen decreased substantially from the 62% removal achieved in the retention pond to a final removal of only 25% in concentration for discharges leaving the detention pond. On the other hand, the removal of total phosphorus was improved by the addition of this final pond from an efficiency of 29% in the retention pond alone to a final efficiency of 59% for discharges from the detention pond. Chlorides and sulfates continued to increase in the detention pond compared with the mean values measured in runoff inputs.

Concentration-based removal efficiencies for BOD and color improved after reaching the final detention pond. Removal efficiencies for suspended solids and turbidity also improved slightly. However, concentrations of dissolved solids continued to increase from the retention pond to the detention pond, with a total increase of more than 100% when compared to mean runoff input values.

A summary of heavy metal concentrations in stormwater runoff collected at the residential dual pond site is given in Table 3-13. In general, measured concentrations of heavy metals in the residential runoff were substantially less than those measured in the highway runoff at sites 1 and 2. With the exceptions of aluminum and iron, zinc and lead were the most common stormwater-related heavy metals found at this site, followed by nickel, copper, manganese and chromium. Event mean concentrations of cadmium were relatively low in this residential runoff.

Similar to the trends previously observed for sites 1 and 2, concentrations of heavy metals exhibited much less variability than concentrations of general chemical parameters. The most variable heavy metal measured at this site was cadmium which exhibited a range of values covering approximately one order of magnitude. Variabilities for other heavy metals appear to be much less.

Removal efficiencies for heavy metals in the residential dual pond system are presented in Table 3-14. Removal efficiencies are presented for both the retention pond

TABLE 3-13

SUMMARY OF HEAVY METAL CONCENTRATIONS IN STORMWATER RUNOFF COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

(All concentrations in $\mu g/l$)

PARAMETER		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]
Cd-	Diss.	1.86	< 0.5 - 4.7	100
	Total	2.17	< 0.5 - 5.6	96
Zn -	Diss.	19.2	9 - 38	49
	Total	44.9	22 - 92	63
Mn -	Diss.	11.1	2 - 17	44
	Total	23.1	8 - 37	44
Cu -	Diss.	21.8	13 - 31	31
	Total	27.4	19 - 36	21
Al -	Diss.	115	24 - 238	54
	Total	537	181 - 1010	53
Fe -	Diss.	55.8	26 - 140	65
	Total	420	177 - 848	49
Pb -	Diss.	93.1	40 - 188	52
	Total	132	53 - 211	39
Ni -	Diss.	21.1	13 - 43	43
	Total	29.2	18 - 47	32
Cr -	Diss.	11.7	5.2 - 23	49
	Total	16.5	10 - 25	33

1. Number of Samples = 10

2. Coefficient of Variation

TABLE 3-14

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR HEAVY METALS IN THE RESIDENTIAL DUAL POND SYSTEM (SITE 3)

PARAMETER		MEAN RUNOFF CONC.	POLLUTANT REMOVAL IN RETENTION POND		TOTAL REMOVAL THROUGH DETENTION POND	
			MEAN POND CONC.	REMOVAL (%)	MEAN POND CONC.	FINAL REMOVAL (%)
Cd -	Diss.	1.86	4.80	+ 158	5.51	+ 196
	Total	2.17	6.19	+ 185	7.16	+ 230
Zn -	Diss.	19.2	14.2	- 26	15.4	- 20
	Total	44.9	18.6	- 59	20.1	- 55
Mn -	Diss.	11.1	17.4	+ 57	29.9	+ 169
	Total	23.1	24.7	+ 7	39.7	+ 72
Cu -	Diss.	21.8	18.2	- 17	16.5	- 24
	Total	27.4	21.0	- 23	20.8	- 24
Al -	Diss.	115	551	+ 379	569.3	+ 395
	Total	537	693	+ 29	853	+ 59
Fe -	Diss.	55.8	77.7	+ 39	54.4	- 3
	Total	420	119	- 72	148	- 65
Pb -	Diss.	93.1	162	+ 74	186	+ 100
	Total	132	177	+ 34	194	+ 47
Ni -	Diss.	21.1	29.5	+ 40	31.1	+ 47
	Total	29.2	32.3	+ 11	32.5	+ 11
Cr -	Diss.	11.7	18.6	+ 59	20.5	+ 75
	Total	16.5	20.1	+ 22	21.1	+ 28

and the final detention pond prior to discharge from the stormwater system. Removal efficiencies for heavy metals in the retention pond were extremely poor. Only zinc, copper and iron were found to decrease in concentration inside the retention pond. Concentrations of all other heavy metals increased in the retention pond water when compared to mean runoff characteristics. For some metals, increases in the retention pond were quite substantial. For example, concentrations of both total and dissolved cadmium increased by more than 150% in the retention pond. Concentrations of dissolved aluminum increased by almost 400% in the retention pond, with total lead, total nickel and total chromium exhibiting increases from 10% to 35%.

Movement of runoff flow through the final detention pond did not improve removal efficiencies for heavy metals when compared to pollutant removals already obtained in the initial retention pond. With the exception of copper, measured concentrations of all heavy metals were actually higher in the detention pond than those measured in the retention pond. Only three heavy metals (including zinc, copper and iron) were found in lower concentrations in the final detention pond water than in the initial runoff flow with a total removal efficiency of 55% for zinc, 24% for copper and 65% for total iron.

Site 4 - Residential Runoff

A summary of chemical characteristics of residential runoff collected at site 4 is given in Table 3-15. A total of nine storm events were monitored at this site with rainfall amounts ranging from 0.08-2.74 cm (0.03-1.08 in), event durations ranging from 0.17-10.17 hours and antecedent dry periods ranging from 0.72-14.2 days.

TABLE 3-15

SUMMARY OF CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF COLLECTED AT THE RESIDENTIAL DETENTION FACILITY (SITE 4)

PARAMETER	UNITS	MEAN VALUE[1]	RANGE	C.V.[2]
pH	--	7.22	6.71 - 8.12	6
Spec. Cond.	μmhos/cm	109	48 - 188	38
Rainfall	inches	0.38	0.03 - 1.08	105
Duration	hours	2.43	0.17 - 10.17	128
Ant. Dry Period	days	5.00	0.72 - 14.20	108
Alkalinity	mg/l	57.9	24.1 - 82.1	30
NH_3-N	μg/l	202	< 10 - 1274	207
NO_2 + NO_3-N	μg/l	262	99 - 400	44
Diss. Organic N	μg/l	2880	95 - 10,420	129
Part. Organic N	μg/l	1281	147 - 2723	77
Total N	μg/l	4624	619 - 12,636	96
Diss. Ortho-P	μg/l	106	40 - 236	56
Diss. Organic P	μg/l	822	56 - 3229	134
Total P	μg/l	1698	87 - 4950	109
Chlorides	mg/l	20	8 - 38	54
Sulfates	mg/l	5.2	1.0 - 12.2	70
BOD	mg/l	9.5	3.8 - 14.1	38
Color	Pt-Co Units	53	4 - 106	65
T.D.S.	mg/l	125	26 - 371	83
V.D.S.	mg/l	56	15 - 200	102
Turbidity	NTU	13.1	2.3 - 37.4	88
S.S.	mg/l	63.2	3.9 - 138.0	67
V.S.S.	mg/l	28.3	2.8 - 65.8	56

1. Number of Samples = 9

2. Coefficient of Variation

Residential runoff collected at this site was found to have a near-neutral pH of 7.22 with an alkalinity of approximately 58 mg/l. Measured concentrations of total nitrogen at this site were found to be relatively high with a mean total nitrogen value of 4624 μg/l. Total nitrogen was comprised primarily of organic species with relatively small contributions from inorganic ions of ammonia and nitrate. Concentrations of total phosphorus were also extremely high at this site. Total phosphorus was primarily found as dissolved organic phosphorus and as particulate phosphorus with dissolved orthophosphorus comprising only 6% of the total phosphorus found. Concentrations of chlorides and sulfates in the runoff flow were relatively small. The residential runoff was also found to have a relatively high BOD value with a mean of 9.5 mg/l.

Residential runoff measured at site 4 was characterized by a high loading of suspended matter. The mean suspended solids concentrations of 63.2 mg/l is much greater than suspended solids measured in the residential runoff at site 3 and is similar to concentrations measured in highway runoff at site 2. This suspended matter was approximately 45% organic and 55% inert in nature. Although the suspended solids concentration was relatively high, measured values of turbidity appeared to be relatively low with a mean of 13.1 NTU.

Similar to trends observed at the previous sites, stormwater characteristics monitored at site 4 were extremely variable, particularly for ammonia, dissolved organic nitrogen, dissolved organic phosphorus, total phosphorus and dissolved solids. Measured event mean concentrations for ammonia and organic nitrogen covered more than two orders of magnitude in range.

A summary of concentration-based removal efficiencies for general stormwater pollutants in the residential wet detention pond is given in Table 3-16. Pollutant

TABLE 3-16

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR STORMWATER POLLUTANTS IN THE RESIDENTIAL WET DETENTION POND (SITE 4)

PARAMETER	UNITS	MEAN RUNOFF CONC.	MEAN POND CONC.	PERCENT REMOVED (%)
pH	--	7.22	8.53	+ 18
Spec. Cond.	μmhos/cm	109	95	- 13
Alkalinity	mg/l	57.9	44.1	- 24
NH_3-N	μg/l	202	13	- 94
NO_2 + NO_3-N	μg/l	262	14	- 95
Diss. Organic N	μg/l	2880	641	- 78
Part. Organic N	μg/l	1281	192	- 85
Total N	μg/l	4624	860	- 81
Diss. Ortho-P	μg/l	106	17	- 84
Diss. Organic P	μg/l	822	50	- 94
Total P	μg/l	1698	147	- 91
Chlorides	mg/l	20	10	- 50
Sulfates	mg/l	5.2	3.0	- 42
BOD	mg/l	9.5	3.8	- 60
Color	Pt-Co Units	53	31	- 42
T.D.S.	mg/l	125	75	- 40
V.D.S.	mg/l	56	36	- 36
S.S.	mg/l	63.2	11.4	- 82
V.S.S.	mg/l	28.3	5.4	- 94
Turbidity	NTU	13.1	6.6	- 50

attenuation in this wet detention facility was far superior to removal efficiencies observed at the previous study sites. With the exception of pH, all measured parameters exhibited significant reductions in concentration after entering the wet detention facility. Concentrations of total nitrogen were reduced by approximately 81%. Unlike trends observed at the previous sites, all nitrogen species were removed effectively within the wet detention pond with removals in excess of 90% for ammonia and nitrate, and a removal of approximately 80% for organic nitrogen. Total phosphorus was also removed very effectively within the wet detention facility, with an ultimate removal of 91%. Both orthophosphorus and dissolved organic phosphorus were removed extremely well in this facility. This facility was also effective in reducing concentrations of chlorides and sulfates by 40% to 50% and BOD by approximately 60%. Suspended solids were reduced in excess of 80% in this facility with turbidity reductions of approximately 50%.

A summary of heavy metal concentrations in residential runoff collected at site 4 is given in Table 3-17. Mean concentrations for heavy metals presented in Table 3-17 appear to be relatively high. With the exceptions of nickel and chromium, concentrations of heavy metals measured in the residential runoff at site 4 exceed heavy metal concentrations measured in residential runoff at site 3. As observed previously, with the exceptions of iron and aluminum, lead, zinc and copper are the most prominent stormwater-related heavy metals.

As indicated by the listed range of values and the calculated coefficient of variation for each of the heavy metals presented in Table 3-17, measured event mean concentrations of heavy metals appeared to be much less variable than concentrations of general chemical parameters. The most variable heavy metals appeared to be cadmium,

TABLE 3-17

SUMMARY OF HEAVY METAL CONCENTRATIONS IN STORMWATER RUNOFF COLLECTED AT THE RESIDENTIAL DETENTION POND (SITE 4)

(All concentrations in μg/l)

PARAMETER		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]
Cd-	Diss.	3.06	1.3 - 5.8	50
	Total	5.02	2.8 - 11	48
Zn -	Diss.	29.9	10 - 60	49
	Total	88.9	28 - 185	59
Mn -	Diss.	9.78	3 - 31	85
	Total	28.4	13 - 52	50
Cu -	Diss.	22.1	14 - 39	33
	Total	32.9	14 - 48	36
Al -	Diss.	156	105 - 291	37
	Total	1800	181 - 4030	69
Fe -	Diss.	31.8	12 - 84	67
	Total	464	30 - 924	69
Pb -	Diss.	100	59 - 166	32
	Total	158	63 - 259	39
Ni -	Diss.	14.4	8.5 - 26	35
	Total	19.7	12 - 37	37
Cr -	Diss.	9.00	6 - 15	29
	Total	15.3	7.8 - 25	33

1. Number of Samples = 9

2. Coefficient of Variation

zinc, aluminum and iron, while copper, lead, nickel and chromium exhibited mean concentrations within a relatively narrow range of values. With the exceptions of aluminum and iron, none of the measured heavy metals exhibited a range which exceeded one order of magnitude.

Concentration-based removal efficiencies for heavy metals in the residential wet detention facility are given in Table 3-18. With the exception of cadmium, concentrations of all heavy metals were reduced after entering the wet detention facility. Total concentrations of five heavy metals (including zinc, manganese, copper, iron and lead) were reduced by approximately 50% or more within the wet detention facility. Removal efficiencies for total nickel and chromium ranged between 30% and 40%. Concentrations of total aluminum were reduced by approximately 15% within the wet detention facility in spite of a large increase in dissolved aluminum ions. Concentrations of total cadmium were not reduced within the wet detention facility.

Site 5 - Commercial Runoff

A summary of chemical characteristics of commercial runoff collected at the dual pond facility at site 5 is given in Table 3-19. A total of eight storm events were monitored for runoff stormwater characteristics flowing into the retention pond facility. Total rainfall in monitored storm events ranged from 0.20 to 2.29 cm (0.08 to 0.90 inches), with event durations ranging from 0.91 to 5.17 hours and antecedent dry periods from 0.16 to 3.72 days.

Commercial runoff monitored at site 5 was found to be approximately neutral in pH with a mean alkalinity of 69 mg/l. In general, nutrient concentrations measured in

TABLE 3-18

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR HEAVY METALS IN THE RESIDENTIAL WET DETENTION FACILITY (SITE 4)
(All concentrations in μg/l)

PARAMETER		MEAN RUNOFF CONC.	MEAN POND. CONC.	PERCENT REMOVED (%)
Cd-	Diss.	3.06	4.52	+ 48
	Total	5.02	5.30	+ 6
Zn -	Diss.	29.9	13.4	- 55
	Total	88.9	16.4	- 82
Mn -	Diss.	9.78	6.09	- 38
	Total	28.4	9.48	- 67
Cu -	Diss.	22.1	11.1	- 50
	Total	32.9	15.7	- 52
Al -	Diss.	156	692	+ 344
	Total	1800	1526	- 15
Fe -	Diss.	31.8	70.3	+ 121
	Total	464	175	- 62
Pb -	Diss.	100	69.5	- 31
	Total	158	79.9	- 49
Ni -	Diss.	14.4	11.2	- 22
	Total	19.7	13.4	- 32
Cr -	Diss.	9.00	7.31	- 19
	Total	15.3	8.84	- 42

TABLE 3-19

SUMMARY OF CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF COLLECTED AT THE COMMERCIAL RETENTION FACILITY (SITE 5)

PARAMETER	UNITS	MEAN VALUE[1]	RANGE	C.V.[2]
pH	--	6.96	6.22 - 8.41	9
Spec. Cond.	μmhos/cm	131	40 - 359	79
Rainfall	inches	0.35	0.08 - 0.90	85
Duration	hours	2.51	0.91 - 5.17	70
Ant. Dry Period	days	1.80	0.16 - 3.72	67
Alkalinity	mg/l	69.3	28.3 - 148.0	60
NH_3-N	μg/l	90	< 10 - 233	82
$NO_2 + NO_3$-N	μg/l	484	28 - 1827	136
Diss. Organic N	μg/l	639	29 - 1613	96
Part. Organic N	μg/l	314	26 - 863	109
Total N	μg/l	1527	220 - 3769	80
Diss. Ortho-P	μg/l	18	< 1 - 46	88
Diss. Organic P	μg/l	28	< 1 - 86	96
Total P	μg/l	189	68 - 321	50
Chlorides	mg/l	16	2 - 86	96
Sulfates	mg/l	13.1	0.1 - 32.1	105
BOD	mg/l	11.6	3.0 - 22.1	61
Color	Pt-Co Units	27	9 - 47	51
T.D.S.	mg/l	180	38 - 409	69
V.D.S.	mg/l	52	2 - 159	99
Turbidity	NTU	30.3	4.0 - 80.0	84
S.S.	mg/l	111.4	9.9 - 282.0	101
V.S.S.	mg/l	36.6	4.4 - 86.2	89

1. Number of Samples = 8
2. Coefficient of Variation

commercial runoff were much lower than nutrient concentrations measured in the other runoff sites. The mean concentration of total nitrogen was 1527 μg/l, comprised primarily of nitrate and organic nitrogen. Ammonia constituted less than 6% of the total nitrogen found. The mean concentration of total phosphorus was 189 μg/l, comprised primarily of particulate phosphorus. Dissolved orthophosphorus and dissolved organic phosphorus represented less than 25% of the total phosphorus present. Concentrations of chlorides and sulfates were relatively low and similar in value to concentrations reported at the other study sites. The mean BOD concentration of 11.6 mg/l was the largest mean BOD value found at any of the five study sites.

Stormwater runoff collected at the commercial site was characterized by a high loading of suspended matter. The mean suspended solids concentration of approximately 111 mg/l was higher than mean values found at any of the other sites. Based upon measurements of volatile suspended solids, suspended solids collected at the commercial site consisted of approximately 33% organic matter and 67% inert material. Measured values of turbidity were also relatively high with a mean of 30 NTU. This value is also the highest value measured at any of the study sites.

As observed for each of the other study sites, event mean concentrations of chemical parameters measured at the commercial site were extremely variable. This variability was particularly evident for constituents such as ammonia, nitrate, organic nitrogen, dissolved phosphorus, chlorides, sulfates and suspended solids.

A summary of concentration-based removal efficiencies for stormwater pollutants in the commercial dual pond system is given in Table 3-20. Removal efficiencies are calculated for both the retention pond and the final detention pond by comparing mean

TABLE 3-20

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR STORMWATER POLLUTANTS IN THE COMMERCIAL DUAL POND SYSTEM (SITE 5)

PARAMETER	UNITS	MEAN RUNOFF CONC.	MEAN REMOVAL IN RETENTION POND		TOTAL REMOVAL THROUGH DETENTION POND	
			MEAN POND CONC.	REMOVAL (%)	MEAN POND CONC.	REMOVAL (%)
pH	--	6.96	6.58	- 6	7.49	+ 8
Spec. Cond.	μmhos/cm	131	300	+ 129	305	+ 133
Alkalinity	mg/l	69.3	135	+ 95	149.3	+ 115
NH_3-N	μg/l	90	392	+ 336	81	- 10
NO_2 + NO_3-N	μg/l	484	24	- 95	25	- 95
Diss. Organic N	μg/l	639	569	- 11	723	+ 13
Part. Organic N	μg/l	314	245	- 22	250	- 20
Total N	μg/l	1527	1230	- 19	1079	- 29
Diss. Ortho-P	μg/l	18	10	- 44	7	- 61
Diss. Organic P	μg/l	28	19	- 32	16	- 43
Total P	μg/l	189	51	- 73	46	- 76
Chlorides	mg/l	16	17	+ 6	17	+ 6
Sulfates	mg/l	13.1	1.9	- 86	2.4	- 82
BOD	mg/l	11.6	4.6	- 60	4.2	- 64
Color	Pt-Co Units	27	96	+ 256	70	+ 159
T.D.S.	mg/l	180	204	+ 13	198	+ 10
V.D.S.	mg/l	52	76	+ 46	65	+ 25
S.S.	mg/l	111.4	7.4	- 93	12.8	- 89
V.S.S.	mg/l	36.6	8.0	- 78	9.0	- 75
Turbidity	NTU	30.3	7.8	- 74	8.5	- 72

surface water characteristics in each of the two ponds with mean runoff characteristics. As seen in Table 3-20, the retention pond was effective in removing many of the measured stormwater pollutants. Total nitrogen was reduced by approximately 19% within the retention pond. This removal was achieved primarily as a result of reductions in concentrations of nitrate and, to a lesser degree, reductions in concentrations of organic nitrogen. However, ammonia was found to increase substantially in the retention pond as compared to mean runoff input values. Total phosphorus was removed by approximately 73% within the retention pond with removals for dissolved orthophosphorus and dissolved organic phosphorus ranging from 30% to 45%.

As seen in Table 3-20, the retention pond was very effective in removal of sulfates and BOD from the runoff flow, with removal efficiencies of 86% and 60%, respectively. Significant removals of suspended solids and turbidity were also achieved within the retention pond system. However, the retention pond did not reduce concentrations of chlorides and actually increased concentrations of color and total dissolved solids.

Migration of water through the detention pond provided very little improvement in water quality for runoff inputs. Although removal of total nitrogen increased from only 19% in the retention pond to 29% in the detention pond, removal efficiencies for other parameters such as total phosphorus, chlorides, sulfates, BOD, dissolved solids, suspended solids and turbidity remained essentially the same as those initially achieved in the retention pond.

A summary of heavy metal concentrations in commercial runoff collected at site 5 is given in Table 3-21. Concentrations of manganese, copper, lead, nickel and

TABLE 3-21

SUMMARY OF HEAVY METAL CONCENTRATIONS IN STORMWATER RUNOFF COLLECTED AT THE COMMERCIAL DUEL POND SITE (SITE 5)

(All concentrations in μg/l)

PARAMETER		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]
Cd-	Diss.	4.49	< 0.5 - 14	95
	Total	8.15	3.2 - 20	68
Zn -	Diss.	46.9	10 - 104	72
	Total	168	23 - 478	89
Mn -	Diss.	10.5	1 - 31	99
	Total	30	7 - 58	63
Cu -	Diss.	18.4	2 - 38	73
	Total	31	6 - 64	74
Al -	Diss.	93.3	44 - 165	42
	Total	1270	229 - 4240	121
Fe -	Diss.	115	16 - 364	117
	Total	1100	149 - 1920	61
Pb -	Diss.	62.1	18 - 103	47
	Total	136	64 - 261	55
Ni -	Diss.	18.9	3.7 - 42	70
	Total	27.6	12 - 52	57
Cr -	Diss.	5.55	1.5 - 9.6	55
	Total	13.0	2.9 - 31	79

1. Number of Samples = 9

2. Coefficient of Variation

chromium are all similar to those measured in residential runoff at site 4. On the other hand, elevated levels of total cadmium and total zinc were found in the commercial runoff collected at site 5. The mean concentration of 8.15 μg/l for total cadmium is similar to that found in highway runoff measured at sites 1 and 2. The mean total zinc concentration of 168 μg/l is similar to the mean value measured in highway runoff collected at site 1.

In general, measured event mean concentrations for heavy metals at the commercial site appeared to be somewhat more variable than concentrations measured at the other study sites. The measured concentrations for cadmium, zinc, aluminum, iron, nickel and chromium covered a wide range of values which spanned two orders of magnitude in many cases.

A summary of concentration-based removal efficiencies for heavy metals in the commercial dual pond system is given in Table 3-22. The retention pond reduced input concentrations of total zinc and total aluminum by approximately 75% to 85%, total copper by approximately 25%, and total chromium by approximately 11%. However, the retention pond did not provide reductions in concentrations for cadmium, manganese, iron, lead or nickel. In fact, concentrations of each of these metals (except lead) increased substantially in the retention pond compared with measured concentrations in the stormwater flow.

Migration of stormwater pollutants through the final detention pond appeared to have little effect on attenuation of heavy metals. Final removal efficiencies achieved within the detention pond were similar to those achieved in the retention pond. Only zinc, copper, and aluminum exhibited reductions in concentrations in the final detention

TABLE 3-22

REMOVAL EFFICIENCIES FOR HEAVY METALS IN THE COMMERCIAL DUAL POND SYSTEM (SITE 5)

(All concentrations in $\mu g/l$)

PARAMETER		MEAN RUNOFF CONC.	POLLUTANT REMOVAL IN RETENTION POND		TOTAL REMOVAL THROUGH DETENTION POND	
			MEAN POND CONC.	REMOVAL (%)	MEAN POND CONC.	FINAL REMOVAL (%)
Cd -	Diss.	4.49	11.5	+ 156	11.0	+ 145
	Total	8.15	15.7	+ 93	14.8	+ 82
Zn -	Diss.	46.9	25.2	- 46	24.2	- 48
	Total	168	38.5	- 77	31.5	- 81
Mn -	Diss.	10.5	41.4	+ 294	22.7	+ 116
	Total	29.9	55.0	+ 84	39.8	+ 33
Cu -	Diss.	18.4	17.5	- 5	21.1	+ 15
	Total	31.3	23.5	- 25	26.1	- 17
Al -	Diss.	93.3	165	+ 77	167	+ 79
	Total	1270	264	- 79	340	- 73
Fe -	Diss.	115	2124	+ 1747	801	+ 597
	Total	1100	3909	+ 255	1933	+ 76
Pb -	Diss.	62.1	121	+ 95	144	+ 132
	Total	136	135	- 1	161	+ 18
Ni -	Diss.	18.9	30.7	+ 62	33.6	+ 78
	Total	27.6	34.8	+ 26	42.3	+ 53
Cr -	Diss.	5.55	8.92	+ 61	10.2	+ 84
	Total	13.0	11.6	- 11	12.8	- 2

facility compared with initial runoff values. The remaining heavy metals remained unchanged or exhibited increases from the initial runoff values within the detention pond waters.

One of the primary objectives of the dual pond stormwater facilities required by the City of Orlando for new development is to divert the pollutant-laden first-flush waters into an off-line retention facility until the design pollution abatement volume is met. Runoff flow which occurs after the retention volume has been filled bypasses the retention facility and enters the detention pond directly. In many cases, inputs into the detention facilities are allowed to discharge immediately at a controlled rate. The first-flush concept assumes that runoff flow entering the detention facility after the retention storage volume has been filled should be relatively free of pollutant loadings and should not pose a threat to off-site water bodies.

The effectiveness of the commercial dual pond facility in meeting these objectives was examined during two storm events which occurred on June 28 and July 16, 1987. During each of these events, runoff flow was sufficient to fill the available retention pond storage volume, and the remaining flow was diverted directly into the detention pond. Flow weighted samples were collected during each of these events for inputs into both the retention and detention ponds to examine differences in chemical characteristics for inputs into these systems.

A comparison of stormwater inflow characteristics to the retention and detention ponds for the selected storm events is given in Table 3-23. Measured rainfall events for these two events ranged from .84 to 2.29 cm (0.33 to 0.90 in), with event durations of 1.0 and 3.0 hours and antecedent dry periods from 1.2 to 2.6 days.

TABLE 3-23

COMPARISON OF STORMWATER INFLOW CHARACTERISTICS TO THE RETENTION AND DETENTION PONDS AT THE COMMERCIAL DUAL POND FACILITY FOR STORM EVENTS ON 6/28/87 AND 7/16/87

PARAMETER	UNITS	INFLOW TO RETENTION POND		INFLOW TO DETENTION POND		PERCENT CHANGE
		MEAN	RANGE	MEAN	RANGE	
pH	--	6.43	5.22-7.63	7.10	6.85-7.65	+ 10
Spec. Cond.	μmhos/cm	95	72-117	43	36-49	- 55
Rainfall	inches	0.62	0.33-0.90	0.62	0.33-0.90	--
Duration	hours	2.00	1.00-3.00	2.00	1.00-3.00	--
Ant. Dry	days	1.88	1.15-2.60	1.87	1.15-2.60	--
Alkalinity	mg/l	29.4	28.3-30.4	27.3	26.2-28.3	- 7
NH_3-N	μg/l	109	96-121	54	43-65	- 50
NO_2 + NO_3-N	μg/l	169	69-268	178	159-196	+ 5
Diss. Organic N	μg/l	407	29-785	440	245-635	+ 8
Part. Organic N	μg/l	208	26-390	36	12-59	- 83
Total N	μg/l	892	220-1564	707	481-933	- 21
Dissolved Ortho-P	μg/l	28	9-46	21	11-31	- 25
Diss. Organic P	μg/l	208	26-390	56	5-106	- 73
Total P	μg/l	281	266-296	116	108-123	- 59
Chlorides	mg/l	7	6-8	5	4-6	- 29
Sulfates	mg/l	5.4	1.9-8.8	2.6	0.8-4.3	- 52
BOD	mg/l	9.7	3.0-16.3	4.8	3.8-5.8	- 51
Color	Pt-Co Units	33	29-37	14	11-16	- 58
T.D.S.	mg/l	143	99-186	76	63-88	- 47
V.D.S.	mg/l	40	17-63	16	11-21	- 60
Turbidity	NTU	43.1	6.1-80.0	11.9	4.0-19.8	- 72
S.S.	mg/l	72.8	15.5-130.0	25.5	8.0-43.0	- 65
V.S.S.	mg/l	28.6	7.1-50.0	18.5	6.0-31.0	- 35

As seen in Table 3-23, mean concentrations for most measured parameters were substantially lower in runoff inflow entering the detention pond compared to runoff entering the retention pond. Concentration reductions in excess of 50% were observed for conductivity, ammonia, particulate organic nitrogen, dissolved organic phosphorus, total phosphorus, sulfates, BOD, color, dissolved solids, turbidity and suspended solids. Based upon this limited database, it appears as though this dual pond facility is achieving the intended design goals of diverting and retaining the pollutant-laden first-flush waters in the retention area.

Correlations Between Storm Event Characteristics and Runoff Water Quality

Regression and correlation procedures were used to evaluate relationships between rainfall event characteristics such as total rainfall, event duration, average intensity and antecedent dry period with chemical characteristics of the runoff flow. In these analyses, correlations were conducted between each of the calculated rainfall characteristics and event mean concentrations for each of the measured parameters. A separate analysis was conducted for each site and runoff land use type. A summary of the results of these analyses is given in Table 3-24. Only those parameters which exhibited significant correlations at the 0.05 level of significance are included in this table.

As seen in Table 3-24, total rainfall, event duration and antecedent dry period produced the most common correlations with chemical characteristics of stormwater runoff. Alkalinity was found to exhibit a positive correlation with total event duration for each of the two highway runoff sites, but this correlation was not observed for any

TABLE 3-24

CORRELATIONS BETWEEN STORMWATER RUNOFF QUALITY AND STORM EVENT CHARACTERISTICS

SITE	PARAMETER	SIGNIFICANT CORRELATION		
		RAINFALL CHARACTERISTIC	CORRELATION COEFFICIENT	VALUE OF R-SQUARE
1. Interstate Highway	Alkalinity	Event Duration	0.708	0.501
	Part. Org. N	Total Rainfall	-0.600	0.360
	Diss. Org. P	Total Rainfall	-0.699	0.489
	Diss. Al	Total Rainfall	0.693	0.481
		Event Duration	0.920	0.846
2. Interstate Highway	Alkalinity	Event Duration	0.690	0.476
	Ammonia	Ant. Dry Period	0.566	0.321
	BOD	Ant. Dry Period	0.787	0.620
3. Residential	Conductivity	Avg. Intensity	-0.790	0.624
	Diss. Org. N	Ant. Dry Period	0.644	0.414
	Sulfate	Event Duration	0.768	0.589
	V.D.S.	Event Duration	0.707	0.500
	Turbidity	Ant. Dry Period	0.764	0.584
	Diss. Mn	Event Duration	0.647	0.419
4. Residential	Part. Org. N	Total Rainfall	-0.771	0.595
	Total P	Total Rainfall	-0.666	0.444
	BOD	Total Rainfall	-0.719	0.517
	Total Zn	Ant. Dry Period	0.708	0.501
	Total Mn	Ant. Dry Period	0.701	0.491
	Total Al	Ant. Dry Period	0.702	0.492
	Total Fe	Ant. Dry Period	0.696	0.485
	Total Pb	Ant. Dry Period	0.637	0.406
	Total Ni	Ant. Dry Period	0.608	0.370
	Total Cr	Ant. Dry Period	0.664	0.441
5. Commercial	Ammonia	Ant. Dry Period	0.685	0.469
	Diss. Org. P	Avg. Intensity	0.897	0.805
	Diss. Fe	Total Rainfall	0.966	0.933
	Diss. Ni	Event Duration	-0.700	0.490
	Diss. Cr	Event Duration	-0.689	0.474
	Total Ni	Event Duration	-0.702	0.497

of the other runoff types. This behavior suggests that acidic particles may accumulate on roadways between rain events but are mobilized from the roadway surface during the early portions of a rain event. As the rain event continues, the acidity of the runoff flow decreases and alkalinity increases.

Negative correlations were found between total rainfall and particulate organic nitrogen as well as dissolved organic phosphorus at highway runoff site 1. This trend of decreasing concentration with increasing rainfall amounts is presumably related to the first-flush phenomenon. Both ammonia and BOD were found to be positively correlated with antecedent dry period at highway runoff site 2, suggesting that these constituents accumulate on roadway surfacers between rain events. A strong positive correlation was found between dissolved aluminum and both total rainfall and event duration, indicating that concentrations of aluminum increased with increases in rainfall and increases in rain event duration. This phenomenon was not observed for any other metal ions and suggests that aluminum may be bound more tightly to the roadway surface than that which occurs for other metal species. This stronger bonding results in a slower dissolution of dissolved aluminum into the runoff flow during rain events.

Antecedent dry period was also found to be correlated with runoff characteristics at each of the residential sites. Strong correlations were found between antecedent dry period and dissolved organic nitrogen as well as turbidity at site 3 and with total concentrations of zinc, manganese, aluminum, iron, lead, nickel and chromium at site 4. Strong negative correlations were observed at site 4 between total rainfall and particulate organic nitrogen, total phosphorus and BOD, again presumably associated with first-flush effects.

Strong positive correlations were observed between event duration and concentrations of sulfate, volatile dissolved solids and dissolved manganese at site 3. This type of positive correlation suggests that these parameters may require longer time periods to become mobilized in the runoff flow, possibly as a result of either limited solubility or slow dissolution of the depositional forms for these constituents within the watershed. Conductivity was also found to exhibit a strong positive correlation with average rainfall intensity, suggesting that the release of dissolved ions into the stormwater flow increases as the force of the rain on the watershed surface increases.

At the commercial site, ammonia was found to exhibit a strong positive correlation with antecedent dry period, and dissolved organic phosphorus was also found to exhibit a strong positive correlation with average rainfall intensity. Dissolved concentrations of nickel and chromium and total nickel were found to be negatively correlated with event duration, again presumably related to first-flush effects.

Characteristics of Surface Water at the Five Study Sites

Surface water samples were collected at sites 1, 3, 4 and 5 from January to December 1987 on a biweekly basis from swale and pond areas. All surface water samples were collected using the permanent surface water sample points as described in Chapter 2. Samples were analyzed for general water quality characteristics as well as heavy metals. A complete listing of chemical analyses for all parameters measured in surface water samples is given in the Appendices to this report.

Site 1 - Wet Swale Site

A summary of general water quality characteristics in surface water samples collected at the wet swale site is given in Table 3-25. Surface water samples collected from the swale channel were found to be slightly acidic with a range of pH values from 5.36 to 6.57 and a mean pH value of 5.92. Dissolved oxygen concentrations in the surface water were generally quite low with a range of .2 mg/l to 6.6 mg/l and a mean value of only 1.5 mg/l. Low concentrations of dissolved oxygen in the surface water created a reduced condition in the water column as indicated by the mean redox potential of -39 mv.

Concentrations of total nitrogen in the wet swale surface water averaged 884 μg/l, with 27% of the total nitrogen contributed by ammonia, 1% contributed by nitrate, 53% contributed by dissolved organic nitrogen, and 19% contributed by particulate organic nitrogen. The mean value for total phosphorus was 217 μg/l, with 71% as dissolved orthophosphorus, 12% as dissolved organic phosphorus and 17% as particulate phosphorus.

Measured concentrations of chloride, sulfate and BOD in the swale channel were all relatively low, although each parameter exhibited a wide fluctuation in values throughout the test period. The swale surface water exhibited a moderate color with a mean value of 88 Pt-Co units. In general, concentrations of suspended material was found to be generally low within the water column as evidenced by relatively low values for turbidity and suspended solids.

A summary of heavy metal concentrations in surface water samples collected from the swale area at site 1 is given in Table 3-26. With the exceptions of cadmium, iron,

TABLE 3-25

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN SURFACE WATER SAMPLES COLLECTED FROM THE WET SWALE SITE (SITE 1) DURING 1987

PARAMETER	UNITS	MEAN VALUE[1]	RANGE	C.V.[2]
pH	--	5.92	5.36 - 6.57	6
Spec. Cond.	μmhos/cm	211	136 - 267	13
Temperature	°C	22.31	12.05 - 30.40	22
Dissolved O_2	mg/l	1.5	0.2 - 6.6	107
ORP	mv	- 39	-127 - 62	147
Alkalinity	mg/l	68.2	40.8 - 173.0	39
NH_3-N	μg/l	236	< 10 - 860	89
$NO_2 + NO_3$-N	μg/l	12	< 10 - 61	112
Diss. Organic N	μg/l	470	96 - 907	47
Part. Organic N	μg/l	163	14 - 535	78
Total N	μg/l	884	334 - 1710	39
Diss. Ortho-P	μg/l	155	26 - 592	83
Diss. Organic P	μg/l	25	< 1 - 74	89
Total P	μg/l	217	39 - 649	63
Chloride	mg/l	33	12 - 55	40
Sulfate	mg/l	9.5	0.5 - 34.0	82
BOD	mg/l	5.0	0.8 - 11.3	66
Color	Pt-Co Units	88	25 - 188	49
T.D.S.	mg/l	139	78 - 209	22
V.D.S.	mg/l	53	20 - 118	44
Turbidity	NTU	5.4	1.4 - 14.0	56
S.S.	mg/l	4.0	0.6 - 24.0	140
V.S.S.	mg/l	3.2	0.1 - 16.6	134

1. Number of Samples = 24

2. Coefficient of Variation

TABLE 3-26

SUMMARY OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER SAMPLES COLLECTED FROM THE SWALE AREA AT THE WET SWALE SITE (SITE 1)

(All concentrations in μg/l)

PARAMETER		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]
Cd-	Diss.	3.60	< 0.5 - 6.2	41
	Total	5.33	1.5 - 9.7	39
Zn -	Diss.	10.2	< 1 - 26	71
	Total	17.1	< 1 - 60	80
Mn -	Diss.	26.0	5 - 57	54
	Total	34.5	10 - 84	52
Cu -	Diss.	11.4	3 - 41	75
	Total	16.6	4 - 54	77
Al -	Diss.	101	40 - 222	37
	Total	234	50 - 659	65
Fe -	Diss.	1258	63 - 3680	90
	Total	1931	205 - 4760	73
Pb -	Diss.	93.4	18 - 151	36
	Total	114	39 - 197	33
Ni -	Diss.	30.3	7.4 - 52	41
	Total	36.0	8.3 - 73	44
Cr -	Diss.	6.64	1.8 - 11	41
	Total	7.56	2 - 13	39

1. Number of Samples = 24

2. Coefficient of Variation

lead and nickel, measured concentrations of heavy metals in surface waters were found to be relatively low. However, even in spite of elevated levels exhibited by the previously mentioned heavy metals, concentrations of all heavy metals in surface water samples (with the exception of iron) were lower than those measured in the runoff flow entering the wet swale channel. The majority of heavy metal species were found in the dissolved form with dissolved percentages of 68% for cadmium, 60% for zinc, 75% for manganese, 69% for copper, 43% for aluminum, 65% for iron, 82% for lead, 84% for nickel and 88% for chromium.

Site 3 - Residential Dual Pond Site

A summary of general water quality characteristics in surface water from the retention and detention ponds at the residential dual pond facility is given in Table 3-27. Ambient pH levels in both ponds were found to be slightly alkaline with a mean value of approximately 8.2 for both ponds. Both ponds were also found to be well oxygenated on most occasions with a mean dissolved oxygen value of 8.2 mg/l for the retention pond and 10.8 mg/l for the detention pond. However, as seen in Table 3-27, fluctuations in dissolved oxygen levels within the retention pond were much more severe than those observed within the detention pond.

The mean value of total nitrogen measured in the retention pond was 708 μg/l, with 12% contributed by inorganic nitrogen ions and 88% contributed by organic nitrogen species. The mean total nitrogen concentration of 1385 μg/l for the detention pond was much greater than that found in the retention pond. Total nitrogen in the detention pond was contributed approximately 3% by ammonia, 28% by nitrate, 52% by

TABLE 3-27

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN SURFACE WATER SAMPLES COLLECTED FROM THE RETENTION AND DETENTION PONDS FOR THE RESIDENTIAL DUAL POND FACILITY (SITE 3) DURING 1987

PARAMETER	UNITS	RETENTION POND[1]			DETENTION POND[2]		
		MEAN VALUE	RANGE	C.V.[3]	MEAN VALUE	RANGE	C.V.[3]
pH	--	8.22	7.11-9.45	9	8.19	6.08-10.76	14
Spec. Cond.	µmhos/cm	196	68-524	57	260	44-411	33
Temperature	°C	25.28	12.57-33.05	23	26.50	12.22-36.29	25
Dissolved O_2	mg/l	8.2	1.9-15.2	38	10.8	6.0-16.0	31
ORP	mv	365	66-723	36	308	193-443	21
Alkalinity	mg/l	63.4	19.9-124	43	55.9	18.8-95.3	34
NH_3-N	µg/l	42	<10-232	138	39	<10-166	94
$NO_2 + NO_3$-N	µg/l	42	<10-322	164	382	<10-3650	272
Diss. Organic N	µg/l	414	106-1126	57	720	116-1755	64
Part. Organic N	µg/l	210	<10-863	104	247	<10-947	94
Total N	µg/l	708	200-1528	63	1385	364-5895	105
Diss. Ortho-P	µg/l	59	2-152	61	11	1-36	85
Diss. Organic P	µg/l	36	2-192	108	24	8-68	69
Total P	µg/l	141	66-407	54	82	18-301	83
Chlorides	mg/l	29	5-107	95	32	10-53	39
Sulfates	mg/l	19.9	0.3-202	208	32.1	2.4-55.6	53
BOD	mg/l	5.2	1.8-10.3	50	3.3	0.5-6.8	53
Color	Pt-Co Units	39	<1-192	110	33	<1-93	88
T.D.S.	mg/l	133	42-305	52	173	34-312	37
V.D.S.	mg/l	35	7-123	73	63	21-149	57
Turbidity	NTU	4.4	0.8-20.0	87	4.0	0.9-12.7	83
S.S.	mg/l	7.1	0.1-34.0	119	6.9	0.7-4.0	117
V.S.S.	mg/l	5.5	0.1-29.0	134	4.7	0.7-16.2	91

1. Number of Samples = 24

2. Number of Samples = 22

3. Coefficient of Variation

dissolved organic nitrogen and 17% by particulate organic nitrogen. The total phosphorus concentration in the retention pond averaged 141 μg/l, with 32% as orthophosphorus, 26% as dissolved organic phosphorus and 42% as particulate phosphorus. Phosphorus concentrations in the detention pond were found to be much lower with an average of 82 μg/l, with 13% as orthophosphorus, 29% as dissolved organic phosphorus and 58% as particulate phosphorus.

Mean concentrations of chloride, color, turbidity and suspended solids were very similar between the two ponds. However, concentrations of sulfate were found to be substantially higher in the detention pond than those measured in the retention pond, while BOD was found to be higher in the retention pond. Both concentrations of dissolved solids and volatile dissolved solids were substantially higher in the detention pond.

A summary of heavy metal concentrations in surface water from the retention and detention ponds is given in Table 3-28. With the exceptions of cadmium, lead and nickel, concentrations of heavy metals in both ponds were found to be relatively low. In general, concentrations of all heavy metals were found to be higher in surface waters within the detention pond than in surface waters within the retention pond. As observed at the wet swale site, the majority of heavy metal species were found to be in a dissolved form.

Site 4 - Residential Wet Detention Facility

A summary of general water quality characteristics in surface water samples collected from the residential wet detention facility is given in Table 3-29. Surface

TABLE 3-28

SUMMARY OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER SAMPLES COLLECTED FROM THE DETENTION AND RETENTION PONDS AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

(All concentrations in μg/l)

PARAMETER		RETENTION POND			DETENTION POND		
		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]	MEAN VALUE[3]	RANGE OF VALUES	C.V.[2]
Cd -	Diss.	4.80	<0.5-14	72	5.51	1.7-12	56
	Total	6.19	<0.5-18	74	7.16	1.9-17	55
Zn -	Diss.	14.1	3-32	50	15.4	3-39	60
	Total	18.6	6-39	54	20.1	6-41	44
Mn -	Diss.	17.4	5-28	34	29.9	9-181	118
	Total	24.7	6-62	56	39.7	9-190	96
Cu -	Diss.	18.2	7-41	48	16.5	3-35	48
	Total	21.0	4-41	46	20.8	3-43	45
Al -	Diss.	551	80-1620	62	569	113-2580	92
	Total	693	129-2660	73	853	121-2920	90
Fe -	Diss.	77.8	9-540	166	54.4	22-183	61
	Total	119	13-542	111	148	25-437	84
Pb -	Diss.	162	68-270	30	186	97-277	26
	Total	177	68-263	29	194	97-281	25
Ni -	Diss.	29.5	5.2-60	42	31.1	15-41	25
	Total	32.0	6.2-66	42	32.5	15-43	23
Cr -	Diss.	18.6	7.5-30	34	20.5	11-31	24
	Total	20.1	8-30	35	21.1	11-31	24

1. Number of Samples = 24

2. Coefficient of Variation

3. Number of Samples = 21

TABLE 3-29

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN SURFACE WATER SAMPLES COLLECTED FROM THE RESIDENTIAL DETENTION FACILITY (SITE 4) DURING 1987

PARAMETER	UNITS	MEAN VALUE[1]	RANGE	C.V.[2]
pH	--	8.53	6.70 - 9.62	9
Spec. Cond.	µmhos/cm	95	71 - 129	19
Temperature	°C	25.70	13.89 - 34.49	20
Dissolved O_2	mg/l	9.4	5.5 - 15.6	25
ORP	mv	328	153 - 477	21
Alkalinity	mg/l	44.1	27.2 - 68.1	27
NH_3-N	µg/l	13	< 10 - 53	101
$NO_2 + NO_3$-N	µg/l	14	< 10 - 67	110
Diss. Organic N	µg/l	641	227 - 1376	37
Part. Organic N	µg/l	192	10 - 492	79
Total N	µg/l	859	336 - 1458	37
Diss. Ortho-P	µg/l	17	1 - 61	78
Diss. Organic P	µg/l	50	7 - 156	70
Total P	µg/l	147	25 - 753	112
Chloride	mg/l	10	3 - 22	57
Sulfate	mg/l	3.0	0.2 - 7.2	60
BOD	mg/l	3.8	0.6 - 8.0	60
Color	Pt-Co Units	31	< 1 - 798	55
T.D.S.	mg/l	75	42 - 154	33
V.D.S.	mg/l	36	7 - 69	53
Turbidity	NTU	6.6	0.9 - 22.0	91
S.S.	mg/l	11.4	0.5 - 51.7	109
V.S.S.	mg/l	5.4	0.4 - 27.9	119

1. Number of Samples = 23

2. Coefficient of Variation

waters collected at this site were found to be slightly alkaline with a mean pH value of 8.53. Surface waters were also found to be well oxygenated with a mean dissolved oxygen concentration of 9.4 mg/l and a minimum measured value of 5.5 mg/l.

The mean surface water concentration for total nitrogen at this site was 859 μg/l. Total nitrogen was comprised almost exclusively of organic nitrogen species with a contribution of only 3% from inorganic nitrogen species. Dissolved organic nitrogen contributed the primary share of the organic nitrogen. The mean surface water concentration for total phosphorus of 147 μg/l was contributed 12% from orthophosphorus, 34% from dissolved organic phosphorus and 54% from particulate phosphorus.

Concentrations of chloride, sulfate, BOD and color were all found to be relatively low in surface waters from the wet detention pond. In addition, measured individual values for each of these parameters exhibited a relatively narrow range. On the other hand, concentrations of particulate matter appeared to be somewhat elevated, as exhibited by a mean turbidity of 6.6 NTU and a mean suspended solids concentration of 11.4 mg/l. These parameters also exhibited a very wide range of measured concentrations.

A summary of heavy metals concentrations in surface water samples collected from the detention pond is given in Table 3-30. With the exception of aluminum, concentrations of all heavy metals measured in surface waters were found to be very low. Concentrations of heavy metals measured at this site were generally lower than concentrations measured in surface waters at any of the other study sites. As observed in surface waters collected from the other sites, the majority of metal species were found

TABLE 3-30

SUMMARY OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER SAMPLES COLLECTED FROM THE DETENTION POND AT THE RESIDENTIAL WET DETENTION SITE (SITE 4)

(All concentrations in μg/l)

PARAMETER		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]
Cd-	Diss.	4.52	0.9 - 23	96
	Total	5.30	2.4 - 8.3	34
Zn -	Diss.	13.4	< 1 - 53	91
	Total	16.4	2 - 39	57
Mn -	Diss.	6.09	1 - 12	42
	Total	9.48	1 - 24	51
Cu -	Diss.	11.1	2 - 26	56
	Total	15.7	5 - 32	44
Al -	Diss.	692	40 - 2500	93
	Total	1526	228 - 8530	131
Fe -	Diss.	70.4	6 - 528	178
	Total	175	18 - 723	106
Pb -	Diss.	69.5	29 - 102	24
	Total	79.9	55 - 104	18
Ni -	Diss.	11.2	5 - 28	46
	Total	13.4	6 - 30	45
Cr -	Diss.	7.31	2.4 - 15	32
	Total	8.84	5.6 - 16	30

1. Number of Samples = 23

2. Coefficient of Variation

to be in a dissolved form with most heavy metals exhibiting dissolved fractions of 80% or more.

Site 5 - Commercial Dual Pond Facility

A summary of general chemical characteristics of surface water samples collected from the retention and detention ponds at the commercial dual pond facility is given in Table 3-31. Surface water within the retention pond was found to be slightly acidic with a mean pH value of 6.58, while surface water within the detention pond was found to be slightly alkaline with a mean pH value of 7.49.

However, substantial differences were observed between the two ponds for mean values of temperature, dissolved oxygen and redox potential. As described in Chapter 2, the retention pond at this site was heavily overgrown with a dense community of cattails that covered the entire pond area, while the detention pond consisted primarily of open water. Apparently, the dense cattail community intercepted much of the solar radiation that normally would have reached the water surface and created conditions of lower water temperature. This reduction in solar energy may have also caused a reduction in photosynthetic activity in the surface water column contributing to conditions of dissolved oxygen and redox potential. However, it is also likely that the dense cattail stand may have also physically limited the aeration processes from the atmosphere into the water column causing further reductions in dissolved oxygen concentrations. As seen in Table 3-31, the maximum dissolved oxygen value measured in the retention pond surface water was 3.6 mg/l, while the minimum level measured in the detention pond was 5.5 mg/l.

TABLE 3-31

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN SURFACE WATER SAMPLES COLLECTED FROM THE RETENTION AND DETENTION PONDS FOR THE COMMERCIAL DUAL POND FACILITY (SITE 5) DURING 1987

PARAMETER	UNITS	RETENTION POND[1]			DETENTION POND[2]		
		MEAN VALUE	RANGE	C.V.[3]	MEAN VALUE	RANGE	C.V.[3]
pH	--	6.58	6.06-7.38	5	7.49	6.60-8.23	6
Spec. Cond.	µmhos/cm	300	140-405	22	305	173-418	26
Temperature	°C	21.47	11.41-28.16	24	26.12	15.96-36.55	27
Dissolved O_2	mg/l	1.1	0.1-3.6	92	9.5	5.5-22.3	41
ORP	mv	72	- 50-448	152	342	243-553	26
Alkalinity	mg/l	135	56.5-324	38	149	79-370	40
NH_3-N	µg/l	392	18-2423	174	81	<10-557	186
NO_2 + NO_3-N	µg/l	24	<10-241	197	25	<10-232	202
Diss. Organic N	µg/l	569	135-1016	46	723	313-1120	36
Part. Organic N	µg/l	245	41-1100	103	250	<10-899	97
Total N	µg/l	1234	260-3243	66	1079	592-1921	37
Diss. Ortho-P	µg/l	10	<1-50	100	7	<1-34	113
Diss. Organic P	µg/l	19	1-54	65	16	<1-36.0	63
Total P	µg/l	51	10-107	47	46	13-145	69
Chlorides	mg/l	17	7-83	78	17	2-36	52
Sulfates	mg/l	1.8	0.1-7.7	101	2.4	0.5-9.6	94
BOD	mg/l	4.6	1.3-17.5	73	4.2	0.1-10.2	64
Color	Pt-Co Units	95	4-220	54	70	15-160	53
T.D.S.	mg/l	204	42-316	37	198	113-292	26
V.D.S.	mg/l	76	17-190	59	65	9-134	44
Turbidity	NTU	7.8	1.4-29.0	68	8.5	2.9-38.3	90
S.S.	mg/l	7.4	0.2-17.1	56	12.7	1.6-45.8	100
V.S.S.	mg/l	8.0	0.1-81.0	198	8.9	1.2-40.8	114

1. Number of Samples = 24

2. Coefficient of Variation

The mean total nitrogen concentration of 1234 μg/l in the retention pond is slightly greater than the mean total nitrogen value of 1079 μg/l for the detention pond. Total nitrogen within both ponds was found to be primarily associated with dissolved organic nitrogen. In the detention pond, total nitrogen consisted of 32% ammonia, 2% nitrate, 46% dissolved organic nitrogen and 20% particulate organic nitrogen, while total nitrogen in the detention pond consisted of 8% ammonia, 2% nitrate, 67% dissolved organic nitrogen and 23% particulate organic nitrogen. Mean concentrations of total phosphorus were similar between the two ponds with a value of 51 μg/l for the retention pond and 46 μg/l for the detention pond. Total phosphorus in the retention pond consisted of 20% orthophosphorus, 37% dissolved organic phosphorus and 43% particulate phosphorus, while total phosphorus in the detention pond was comprised of 15% orthophosphorus, 36% dissolved organic phosphorus and 49% particulate phosphorus.

Mean concentrations for chloride, sulfate and BOD were generally low in value and similar between the two ponds. The retention pond water contained more color than the detention pond water with a mean value of 95 units for the retention pond compared with 70 units for the detention pond. Measurements of turbidity were similar and low in value for both ponds. However, suspended solids concentrations appear to be somewhat elevated in both ponds with higher concentrations of both suspended solids and volatile suspended solids found in the detention pond.

A summary of mean heavy metal concentrations in surface water samples collected from the retention and detention ponds is given in Table 3-32. In general, concentrations of heavy metals appear to be somewhat elevated in both the retention and

TABLE 3-32

SUMMARY OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER SAMPLES COLLECTED FROM THE DETENTION AND RETENTION PONDS AT THE COMMERCIAL DUAL POND SITE (SITE 5)

(All concentrations in μg/l)

PARAMETER		RETENTION POND			DETENTION POND		
		MEAN VALUE[1]	RANGE OF VALUES	C.V.[2]	MEAN VALUE[3]	RANGE OF VALUES	C.V.[2]
Cd -	Diss.	11.5	2.4-23	48	11.0	3-19	39
	Total	15.7	8.4-33	37	14.9	3-26	36
Zn -	Diss.	25.2	4-85	83	24.2	5-61	63
	Total	38.5	5-107	83	31.5	13-74	54
Mn -	Diss.	41.4	6-101	63	22.7	9-54	152
	Total	55.0	7-120	58	39.8	9-73	42
Cu -	Diss.	17.5	5-57	70	21.1	6-77	70
	Total	23.5	7-107	93	26.1	9-94	67
Al -	Diss.	165	32-488	67	167	105-317	31
	Total	264	77-669	72	340	118-895	52
Fe -	Diss.	2124	14-6880	74	801	138-1840	66
	Total	3909	276-10,270	55	1933	702-4470	59
Pb -	Diss.	121	77-193	23	144	77-236	30
	Total	135	93-217	25	161	87-278	31
Ni -	Diss.	30.7	15-74	41	33.6	21-54	27
	Total	34.8	21-81	43	42.3	24-98	37
Cr -	Diss.	8.92	3.9-15	29	10.2	6.6-18	25
	Total	11.7	6.5-33	62	12.8	7.5-23	39

1. Number of Samples = 23

2. Coefficient of Variation

3. Number of Samples = 10

detention ponds. Elevated concentrations are particularly evident in both ponds for cadmium, zinc, iron, lead and nickel. Concentrations of most heavy metals were quite variable in both ponds with most metal species exhibiting a range of concentrations which spanned one order of magnitude. Variability in concentration is particularly evident for cadmium, copper and iron.

Concentrations of cadmium, zinc, manganese, and iron were found to be higher within the retention pond while concentrations of copper, aluminum, lead, nickel and chromium were higher in surface water within the detention pond. Mean concentrations of many heavy metals measured in surface waters within these ponds exceeded heavy metal concentrations in runoff inputs into the ponds. For example, surface water concentrations of cadmium, manganese, lead and chromium are higher in surface waters for both ponds than in stormwater runoff. Similar to the trend observed at the other study sites, the majority of heavy metal species appeared to be present in a dissolved form within the surface water.

Characteristics of Sediments at the Five Study Sites

Physical and chemical characteristics of sediments in swale, pond and control areas at each of the five study sites were evaluated by collection and analysis of multiple core samples at each site. A discussion of sediment collection procedures and exact locations used for collection of sediment cores at each site was provided in Chapter 2. After collection, sediment cores were divided into the following layers: 0-1 cm, 1-5 cm, 5-10 cm, 10-15 cm and 15-25 cm. In general, each sediment layer was analyzed for grain size distribution, nutrient and organic content, heavy metals and sediment speciation for heavy metals and phosphorus. A complete listing of physical and chemical sediment characteristics measured at each of the five study sites is given in the Appendices to this report contained in a separate document.

Physical Characteristics of Soils and Sediments at the Five Study Sites

A summary of grain size distributions in soil samples from pond and swale areas at the five study sites is given in Table 3-33. Standard sieve analyses were conducted for each of the five depth layers on composite soil samples collected from swale and pond areas at each site.

Several interesting trends are apparent in the data presented in Table 3-33. First, grain size distributions of soils and sediments in stormwater management systems appear to be affected significantly by continuous inputs of stormwater runoff over long periods of time. For example, pond systems at study sites 3 and 5 were constructed approximately one to two years prior to the start of field operations for this research. As seen in Table 3-33, grain size distributions in each of the soil layers for both retention and detention ponds at these sites appear to be relatively uniform. In addition, mean particle sizes appear to be relatively uniform from layer to layer in these ponds. On the other hand, grain size distributions in the top 5 cm of soils collected from stormwater management systems that have been in operation for a number of years appear to be significantly different than sediment characteristics in layers deeper than 5 cm.

TABLE 3-33

GRAIN SIZE DISTRIBUTIONS IN SOIL LAYERS AT THE FIVE STUDY SITES

SITE/ LOCATION	GRAIN SIZE DISTRIBUTION IN EACH SOIL LAYER (%)							MEAN PARTICLE SIZE (mm)
	COARSE SAND	MEDIUM SAND		FINE SAND			SILT	
	> 2 mm	2.00-0.85 mm	0.850-0.425 mm	0.425-0.180 mm	0.180-0.125 mm	0.125-0.075 mm	< 0.075 mm	
<u>1-Swale Area</u>								
0-1 cm	0.6	2.3	5.9	33.9	35.2	17.9	4.2	0.260
1-5 cm	0.5	1.1	3.2	32.6	40.1	18.4	4.1	0.228
5-10 cm	0.1	0.7	2.3	30.0	41.6	19.6	5.7	0.205
10-15 cm	0.2	0.5	1.9	33.8	41.6	17.2	4.8	0.213
15-25 cm	0.1	0.3	1.3	34.1	43.1	17.4	3.7	0.204
Weighted Ave.	0.2	0.6	2.1	33.0	41.7	18.0	4.4	0.211
<u>2-Swale Area</u>								
0-1 cm	2.2	4.4	8.8	34.4	26.2	14.5	9.5	0.329
1-5 cm	2.5	3.3	6.3	33.6	31.5	16.0	6.8	0.308
5-10 cm	0.5	1.3	3.7	33.3	34.9	20.6	5.7	0.231
10-15 cm	0.3	1.0	2.8	29.8	37.7	22.3	6.1	0.213
15-25 cm	1.2	1.3	2.7	31.8	38.6	20.2	4.2	0.239
Weighted Ave.	1.2	1.7	3.7	32.1	36.0	19.8	5.5	0.248
<u>3-Retention</u>								
0-1 cm	0.4	0.6	2.8	52.6	32.8	7.8	3.0	0.254
1-5 cm	0.1	0.3	2.7	57.9	32.1	5.6	1.3	0.255
5-10 cm	0.0	0.7	2.8	55.5	33.6	5.5	1.8	0.254
10-15 cm	0.0	0.6	2.7	55.4	34.0	5.8	1.5	0.253
15-25 cm	0.0	0.9	3.5	56.8	32.0	5.0	1.8	0.263
Weighted Ave.	0.0	0.7	3.0	56.3	32.8	5.5	1.7	0.257

TABLE 3-33 -- CONTINUED

SITE/ LOCATION	GRAIN SIZE DISTRIBUTION IN EACH SOIL LAYER (%)							MEAN PARTICLE SIZE (mm)
	COARSE SAND	MEDIUM SAND		FINE SAND			SILT	
	> 2 mm	2.00-0.85 mm	0.850-0.425 mm	0.425-0.180 mm	0.180-0.125 mm	0.125-0.075 mm	< 0.075 mm	
3-Detention								
0-1 cm	0.0	0.6	4.9	59.2	29.3	4.7	1.3	0.270
1-5 cm	0.0	0.5	3.8	51.0	34.9	6.5	3.3	0.248
5-10 cm	0.0	0.6	4.5	52.2	34.2	5.3	3.2	0.255
10-15 cm	0.0	0.7	4.9	53.0	34.6	4.7	2.1	0.261
15-25 cm	0.0	0.8	4.0	49.6	36.9	4.9	3.8	0.251
Weighted Ave.	0.0	0.7	4.3	51.4	35.2	5.2	3.2	0.255
4-Detention								
0-1 cm	5.8	13.0	17.0	36.6	14.2	7.2	6.2	0.554
1-5 cm	1.9	7.4	18.3	48.0	13.0	5.7	5.6	0.435
5-10 cm	0.5	5.8	18.3	52.3	13.3	5.0	4.8	0.397
10-15 cm	0.3	4.4	17.4	52.8	14.4	5.4	5.3	0.371
15-25 cm	0.5	5.1	19.0	52.5	13.2	5.0	4.7	0.392
Weighted Ave.	0.9	5.8	18.3	51.2	13.5	5.3	5.0	0.402
5-Retention								
0-1 cm	0.1	0.5	2.3	20.5	39.4	31.9	5.3	0.182
1-5 cm	0.2	0.9	3.0	20.3	37.1	31.3	7.2	0.191
5-10 cm	2.9	1.2	3.6	21.8	36.8	29.1	4.6	0.253
10-15 cm	0.3	1.2	1.8	20.7	42.7	28.2	5.1	0.195
15-25 cm	1.0	2.8	2.4	21.2	42.6	23.5	6.5	0.233
Weighted Ave.	1.1	1.8	2.6	21.0	40.5	27.1	5.9	0.221
5-Detention								
0-1 cm	0.1	0.9	1.8	14.9	35.2	38.5	8.6	0.170
1-5 cm	0.2	0.8	1.1	17.4	40.4	34.7	5.4	0.176
5-10 cm	0.6	0.2	0.8	19.0	42.1	32.4	4.9	0.178
10-15 cm	0.0	0.1	0.6	18.6	43.5	31.8	5.4	0.164
15-25 cm	0.0	0.2	0.6	22.8	40.0	32.8	3.6	0.172
Weighted Ave.	0.2	0.3	0.8	20.0	41.0	33.0	4.7	0.173

For example, the wet detention facility at site 4 has been in operation for approximately 10 years, while the roadside swale areas at sites 1 and 2 have been receiving stormwater runoff for 22 and 15 years, respectively. As seen in Table 3-33, the top 5 cm of the soil column at each of these sites has accumulated elevated amounts of both coarse grain and fine grain particles when compared to soil characteristics at depths below 5 cm. The percentages of coarse and medium sand in the top 5 cm of the wet detention pond at site 4 and the swale areas at sites 1 and 2 are several times larger than percentages of the same particle sizes in sediments collected at depths below 5 cm. This trend was not observed to any significant degree in the newly constructed stormwater ponds at sites 3 and 5. Increases in percentages of silt sized particles are also apparent, particularly at sites 2 and 4, while this trend was not observed in the newly constructed ponds. These differences in sediment characteristics between the upper 5 cm and soils below that depth are presumably due to the settling and accumulation of both coarse and fine grain materials in stormwater management systems with time.

The second important conclusion suggested by the data contained in Table 3-33 is that groundwater elevations and local hydrology were more important in determining the infiltration characteristics of the stormwater management systems studied during this research than the grain size distribution of the soil within the swale or pond area. For example, mean particle sizes within the top 25 cm of the swale area at site 2 and both the retention and detention ponds at site 3 are numerically very similar. However, infiltration in the swale area was extremely rapid due to a very low water table condition, while infiltration rates at the retention and detention ponds at site 3 were relatively slow due to high groundwater conditions. Given similar groundwater conditions, infiltration rates are apparently affected by the physical characteristics of the soils to a substantial degree. Subsurface groundwater conditions were very similar for the retention pond at site 3 and the detention pond at site 4, yet as indicated in Figure 3-9, infiltration rates at site 4 were slightly greater than those measured in the retention pond at site 3. As seen in Table 3-33, mean particle sizes for each of the five sediment layers were found to be considerably larger at site 4 than in soil samples collected in the retention pond at site 3. The larger diameter soils in the detention pond at site 4 may be at least partially responsible for the higher infiltration rates measured at this site compared to those found at site 3.

Horizontal Distributions of Heavy Metals in Swale and Pond Areas at the Five Study Sites

An analysis of the horizontal distributions of heavy metals in the sediments of stormwater management systems at the five sites was conducted to characterize the settling patterns of various heavy metals upon entering the respective stormwater management systems. Heavy metal concentrations in the 0-1 cm layer were used to characterize horizontal metal distributions.

Site 1 - Wet Swale Site

A summary of sediment concentrations of heavy metals, nutrients and organic content in the 0-1 cm layer in sediment core samples collected at the wet swale site is given in Table 3-34. Aluminum and iron were the most abundant heavy metals found in sediments along the swale channel. Sediment concentrations of iron increased steadily during movement along the swale channel, reached a maximum concentration at the 25

TABLE 3-34

CHEMICAL CHARACTERISTICS OF THE 0-1 cm LAYER IN SEDIMENT CORE SAMPLES COLLECTED AT THE WET SWALE SITE (SITE 1)

PARAMETER	SEDIMENT CONCENTRATION (μg/g dry weight)					
	2.5 m	10 m	25 m	40 m	70 m	CONTROL
Cd	0.1	0.4	3.9	0.6	0.9	1.7
Zn	147	118	182	118	222	60
Mn	3	3	16	3	6	14
Cu	23	21	26	16	26	8
Al	7620	4330	2240	5630	7440	8450
Fe	1210	1290	3310	2630	1320	838
Pb	348	269	611	207	199	91
Ni	4	3	9	3	5	9
Cr	9	7	10	7	7	11
P	650	396	398	462	947	362
N	1245	1091	1547	1771	4202	275
Organic (%)	5.0	6.8	4.1	11.6	8.3	4.1

m point and then declined steadily through the 40 m and 70 m locations. All measured concentrations of iron along the swale channel exceeded values measured in the control area. Sediment concentrations of aluminum decreased steadily with distance along the swale channel, with a minimum concentration at the 25 m location and steady increases in sediment concentration at downstream locations. The measured value of aluminum in soils from the control area exceeded all values of aluminum measured along the swale channel.

Horizontal distributions of cadmium, zinc, copper, chromium, lead and nickel with distance along the swale channel are indicated in Figure 3-15. With the exceptions of aluminum and iron, lead was the most abundant heavy metal found in the sediments along the swale channel. Sediment concentrations of lead reached a peak at the 25 m location, with rapid decreases in concentration both upstream and downstream at this point. Sediment concentrations of zinc appear to be more uniform in value along the swale channel and did not exhibit the sharp peak concentration observed for lead.

Sediment concentrations of copper, cadmium, chromium and nickel exhibited similar horizontal distributions along the swale channel. Each of these metals reached a peak sediment concentration at a distance of 25 m along the swale channel. However, in most cases, the peak concentrations for these metals reached along the swale were similar to sediment concentrations measured within the control area.

As seen in Table 3-34, sediment concentrations of both phosphorus and nitrogen were extremely variable along the swale channel. Neither of these elements exhibited a pronounced trend for either increasing or decreasing concentrations with distance along the channel, although both elements exhibited highest sediment concentrations at the 70

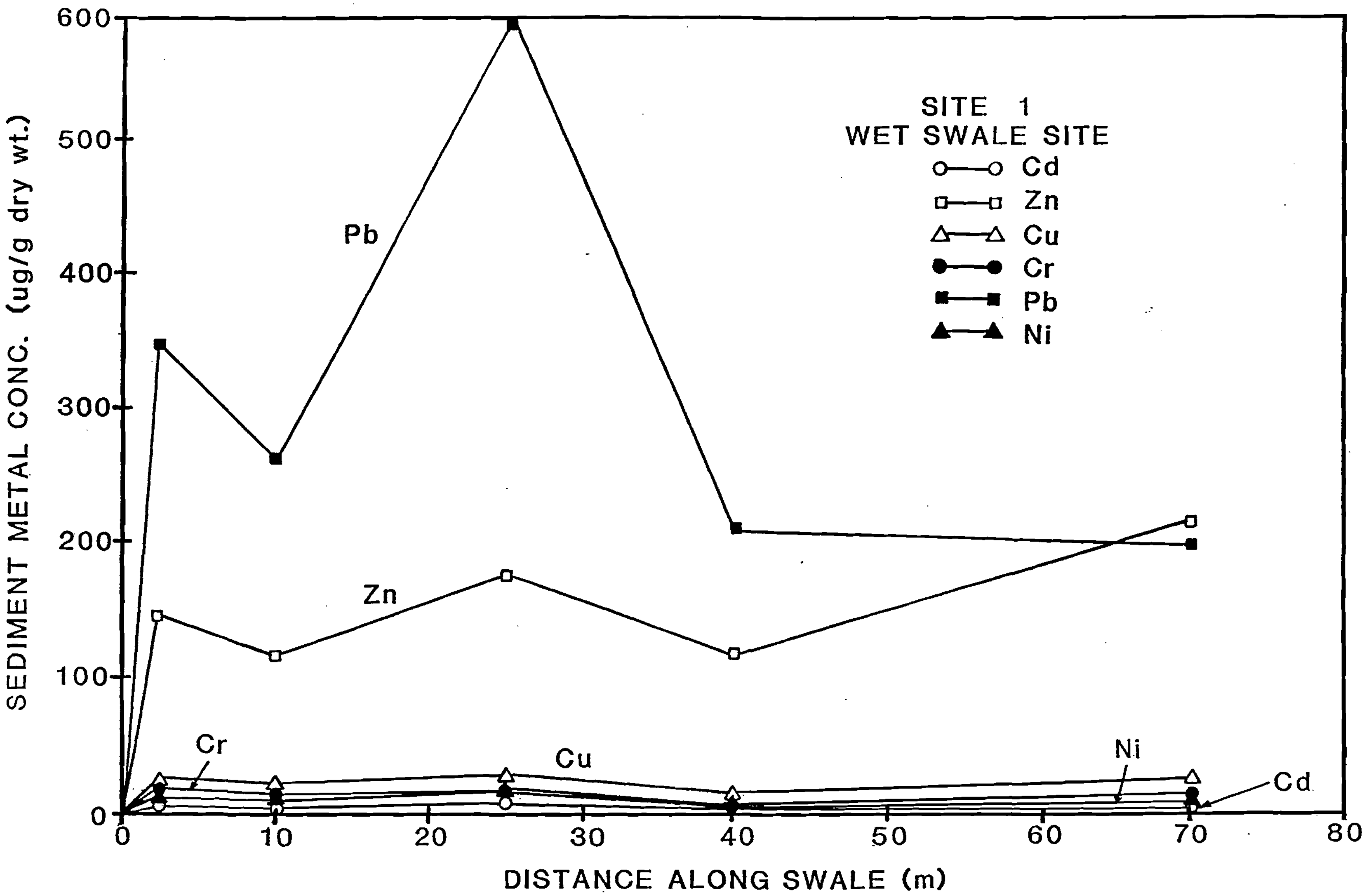


Figure 3-15. Sediment Concentrations of Selected Heavy Metals in the 0-1 cm Layer of the Wet Swale Channel at Site 1.

m location. A similar trend was observed for organic content which reached a peak concentration at the 40 m location. Sediment concentrations of phosphorus, nitrogen and organic content along the swale channel were all greater than values measured in the control area.

Site 2 - Dry Swale Site

A summary of chemical characteristics of the 0-1 cm layer in sediment core samples collected along the dry swale channel is given in Table 3-35. As observed for site 1, aluminum and iron were the most abundant metals found in the sediments along the swale channel. Sediment concentrations of each metal increased steadily with distance along the swale channel reaching a peak concentration at a distance of 70 m for aluminum and at a distance of 40 m for iron. Peak sediment concentrations measured in the swale channel for both metals were much greater than sediment concentrations measured in the control area.

Horizontal distributions for cadmium, zinc, copper, chromium, lead and nickel in the 0-1 cm layer of sediments along the dry swale channel are given in Figure 3-16. With the exceptions of aluminum and iron, lead is clearly the most abundant heavy metal found in the sediments at this site. Sediment concentrations of lead increase rapidly with distance along the swale channel, reaching a peak concentration of approximately 2100 μg/g at the 40 m location. Sediment concentrations of lead measured at this site are more than three times greater than sediment lead concentrations measured at the wet swale site in spite of the fact that the wet swale site has been receiving highway runoff since 1965 while the dry swale channel has been receiving highway runoff since only

TABLE 3-35

CHEMICAL CHARACTERISTICS OF THE 0-1 cm LAYER IN SEDIMENT CORE SAMPLES COLLECTED AT THE DRY SWALE SITE (SITE 2)

PARAMETER	SEDIMENT CONCENTRATION (μg/g dry weight)					
	2.5 m	10 m	25 m	40 m	70 m	CONTROL
Cd	13	8.6	10	12	12	2.6
Zn	193	266	720	1180	1040	53
Mn	50	37	81	140	139	16
Cu	85	26	66	107	93	5
Al	5710	4890	6920	24,100	27,100	10,300
Fe	6230	3070	5210	11,700	10,900	1110
Pb	444	719	1700	2100	1930	139
Ni	22	16	21	33	30	5
Cr	78	36	44	60	60	9
P	233	492	556	1368	1091	1351
N	298	1141	1086	2466	2627	2832
Organic (%)	2.9	6.2	5.9	31.3	27.5	24.8

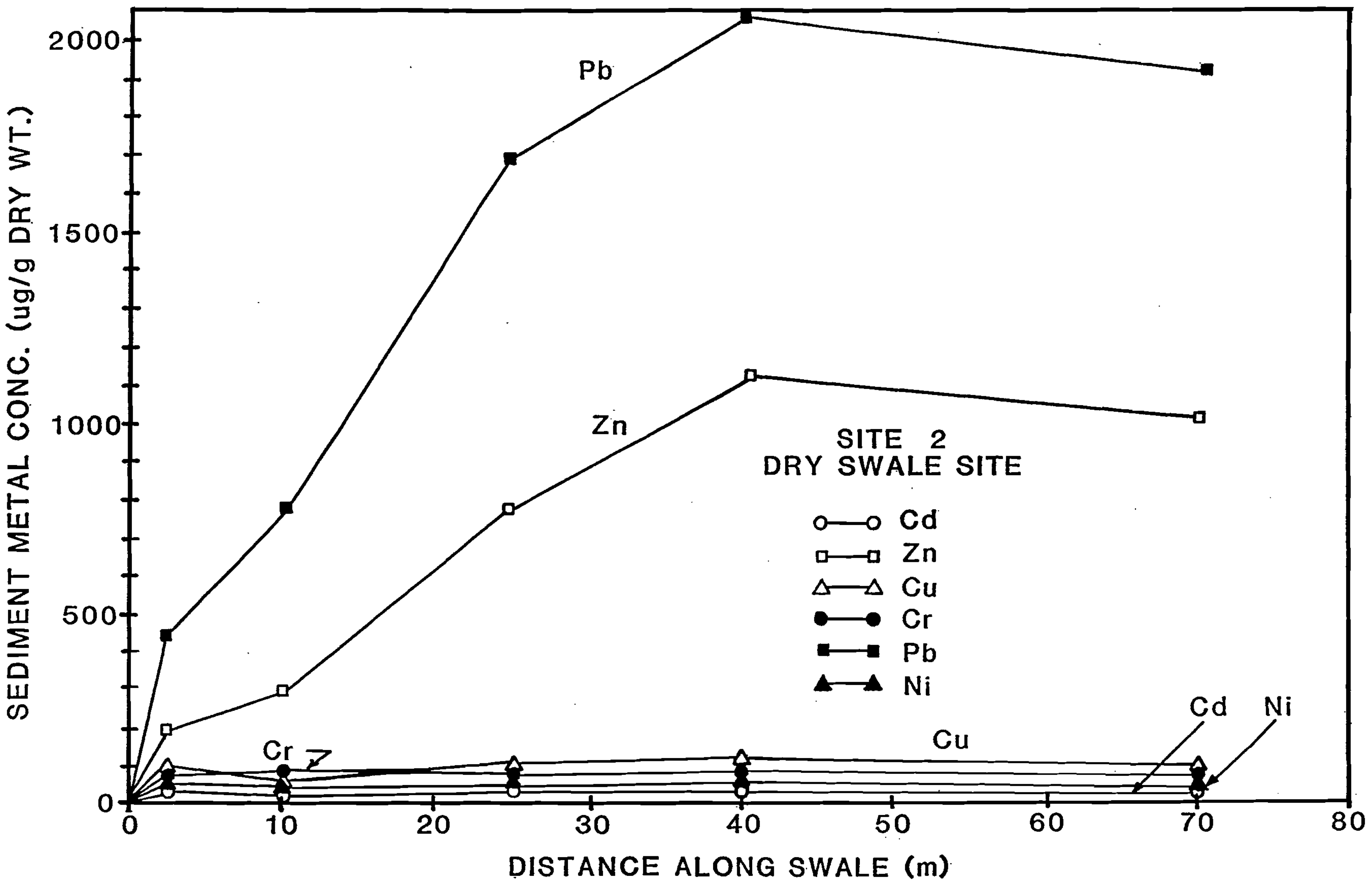


Figure 3-16. Sediment Concentrations of Selected Heavy Metals in the 0-1 cm Layer of the Dry Swale Channel at Site 2.

1972. As seen in Figure 3-16, sediment concentrations of zinc follow a pattern very similar to that exhibited by lead with a peak sediment concentration occurring at the 40 m location. The peak sediment zinc concentration of 1180 μg/g along the dry swale channel is more than five times the peak sediment concentration of 222 μg/g for zinc measured in the wet swale channel.

Attenuation patterns for cadmium, copper, nickel and chromium were less pronounced than those exhibited by lead and zinc. Maximum sediment concentrations of cadmium and chromium were found at the 2.5 m location while peak concentrations of copper and nickel occurred at the 40 m location. Sediment concentrations for each of these metals found along the swale channel far exceeded sediment concentrations measured in the control area.

As seen in Table 3-35, sediment concentrations in the 0-1 cm layer for phosphorus, nitrogen and organic content exhibited patterns similar to that found for heavy metals. Each of these parameters increased in concentration with distance along the swale channel. Maximum sediment concentrations of phosphorus and organic content were found at the 40 m location with maximum concentrations of nitrogen occurring at the 70 m location. However, contrary to the trend observed for heavy metals, sediment concentrations of phosphorus and nitrogen in the control area were equal to or greater than concentrations measured along the swale channel.

<u>Site 3 - Residential Dual Pond Site</u>

A summary of chemical characteristics of the 0-1 cm layer in sediment core samples collected from the retention pond, detention pond and control area at the residential dual pond site is given in Table 3-36. With the exception of aluminum, sediment concentrations of all heavy metals, nitrogen, phosphorus and organic content were much lower than values measured in sediments at the swale sites. This apparent lack of accumulation within the pond sediments at this site is probably due to differences in the pollutant loading characteristics of the residential land use along with the fact that these ponds have only been receiving stormwater runoff since 1986.

Because of the relatively small size of both the retention and detention ponds at this site, it is likely that the turbulence and movement of runoff inputs into these ponds during storm events causes a well mixed condition to exist within each pond. As a result, the accumulation of heavy metals and nutrients within the pond sediments would be expected to be relatively uniform throughout the pond area. This type of uniformity is somewhat apparent in the sediment concentrations given in Table 3-36.

However, in spite of these well mixed conditions, many parameters appear to exhibit slightly elevated sediment concentrations in areas located along the direct flow path for runoff inputs into each pond. For example, sediment core locations 3, 4 and 5 within the retention pond appear to be in areas which would be most affected by runoff flow entering the pond, while locations 1, 2 and 6 would be least affected. A comparison of mean sediment characteristics for stations 3, 4 and 5 combined and stations 1, 2 and 6 combined for the retention pond is given in the bottom of Table 3-36. Mean sediment concentrations at sites 3, 4 and 5 which are directly affected by runoff inputs are greater for every parameter measured than for locations 1, 2 and 6 which are less affected by runoff inputs. A similar trend is observed in the detention pond where sediment core sites 2 and 3 appear to be located along the direct flow path for runoff

TABLE 3-36

CHEMICAL CHARACTERISTICS OF THE 0-1 cm LAYER IN SEDIMENT CORE SAMPLES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

SAMPLE	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
		Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Ret. Pond												
Ret.-1	2.2	1.5	17	9	13	4680	680	15	3	6	591	781
Ret.-2	1.4	1.4	18	6	14	5630	534	15	3	8	503	259
Ret.-3	2.4	1.8	13	7	12	8260	628	15	3	8	619	615
Ret.-4	3.4	1.6	31	11	16	7450	914	21	4	11	801	899
Ret.-5	2.1	1.2	24	9	11	7080	729	16	4	9	559	616
Ret.-6	2.0	1.3	16	5	7	3590	560	11	2	5	343	298
Det. Pond												
Det.-1	1.5	0.8	4	9	3	2050	433	7	1	2	224	414
Det.-2	2.2	1.4	12	9	8	6160	675	12	3	6	716	583
Det.-3	1.8	1.5	8	9	6	4120	581	10	2	6	563	1113
Det.-4	1.6	1.6	4	13	5	7980	455	12	3	7	722	827
Det.-5	1.5	1.7	5	5	5	5560	445	10	2	5	4828	3511
Det.-6	1.5	1.0	5	7	5	2690	348	8	1	3	3133	3882
Control Area	3.1	2.1	25	45	45	6800	680	24	4	18	6777	19,630
Mean Value:												
Retention												
3, 4, 5	2.6	1.5	23	9	13	7597	757	17	4	9	660	710
1, 2, 6	1.9	1.4	17	7	11	4633	591	14	3	6	479	446
Detention												
2, 3	2.0	1.5	10	9	7	5140	628	11	3	6	640	848
1, 4, 5, 6	1.5	1.3	5	9	5	4570	420	9	2	4	2227	2159

inputs while core locations 1, 4, 5 and 6 appear to be less affected. Sediment concentrations of all heavy metals are greater at sites 2 and 3 than at the remaining sites. However, this trend is not observed for nutrients which were found to be in greater concentration at core sites 1, 4, 5 and 6 than at sites 2 and 3.

It should be noted that sediment characteristics for all parameters measured within the control area appear to be substantially higher in concentration than found in sediments within the retention and detention ponds. Although this situation is somewhat unusual, it is most likely due to the type of construction used for the stormwater management facility at this site. The stormwater management ponds were dug as small pits into the existing land surface with the spoils material transported to another location. Chemical characteristics measured in the control area represent, for the most part, unaffected soil characteristics of the general area and presumably reflected surface soil characteristics in the areas now occupied by the retention and detention ponds before they were constructed. Upon construction of these ponds, the pond bottoms were formed from deep soil layers which contained relatively low concentrations of heavy metals and nutrients.

Site 4 - Residential Wet Detention Facility

Chemical characteristics of the 0-1 cm layer in sediment core samples collected at the residential wet detention site are given in Table 3-37. As indicated in Figure 2-21, sediment core samples were collected within the wet detention pond along a grid pattern established at distances of 10, 20, 40, 60 and 100 m from the stormwater inflows into

TABLE 3-37

CHEMICAL CHARACTERISTICS OF THE 0-1 cm LAYER IN SEDIMENT CORE SAMPLES COLLECTED AT THE RESIDENTIAL WET DETENTION SITE (SITE 4)

SAMPLE	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
		Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
<u>Pond Area</u>												
10M-1	12.2	3.3	82	16	11	64,300	6140	91	17	48	1861	3104
10M-2	6.2	3.0	58	17	5	73,100	6450	95	18	54	1242	242
10M-3	4.7	2.3	38	11	4	29,900	2830	39	8	21	940	1869
20M-1	9.6	2.9	64	15	6	71,300	6420	86	18	51	1575	2251
20M-2	3.0	1.9	31	10	5	53,200	4400	50	13	35	699	1177
20M-3	3.5	1.1	27	8	4	35,400	2960	34	9	23	517	1333
40M-1	8.4	2.3	50	16	5	60,700	5480	96	14	48	881	2063
40M-2	1.4	0.8	9	3	3	17,100	1280	17	4	10	286	605
40M-3	7.7	2.9	100	18	6	66,100	6100	84	18	46	695	1687
60M-1	4.8	3.0	35	12	3	44,100	3630	65	11	37	588	1469
60M-2	0.8	1.5	6	2	2	4,990	482	10	2	4	245	494
60M-3	6.3	2.8	65	1	5	55,300	5220	83	15	42	1058	2637
100M-1	8.8	3.1	45	16	4	64,200	5520	93	15	52	945	1280
100M-2	1.5	1.1	11	4	3	17,000	1370	28	4	13	264	562
100M-3	9.2	2.2	40	13	6	51,000	4830	66	13	39	1088	3005
Control Area	9.1	1.7	19	3	8	12,700	2720	8	6	4	5740	8388

the pond. Three core sample locations were selected approximately equidistant along each of these transects.

In general, sediment concentrations of heavy metals in the 0-1 cm layer of the wet detention pond were greater than sediment concentrations measured in the top layer in the control area. For metals such as zinc, aluminum, lead and chromium, sediment concentrations within the detention pond were approximately four to five times greater than concentrations found in the control area. However, sediment concentrations of phosphorus and nitrogen within the wet detention sediments were substantially lower than concentrations measured within the control area.

Depositional patterns for heavy metal inputs into the wet detention pond were evaluated for the most common heavy metal parameters, including zinc, lead, nickel and chromium. Estimates of sediment concentration isopleths were prepared for each of these heavy metals based upon sediment concentrations given in Table 3-37 which were measured at each of the grid points indicated in Figure 2-21.

Horizontal depositional patterns of zinc in the 0-1 cm layer of the wet detention pond are given in Figure 3-17. The deposition of zinc upon entering the wet detention pond appears to be rapid for both Inflow A and Inflow B. As seen in Figure 3-17, depositional patterns are clearly affected by the raised area located along the center of the pond. The primary depositional areas for Inflow A occur along the east side of the raised area, while the deposition of zinc from Inflow B occurs primarily along the west side of this area. Peak sediment concentrations of zinc appear to occur within the first 20-30 m of the detention pond. At a distance of approximately 80-100 m into the

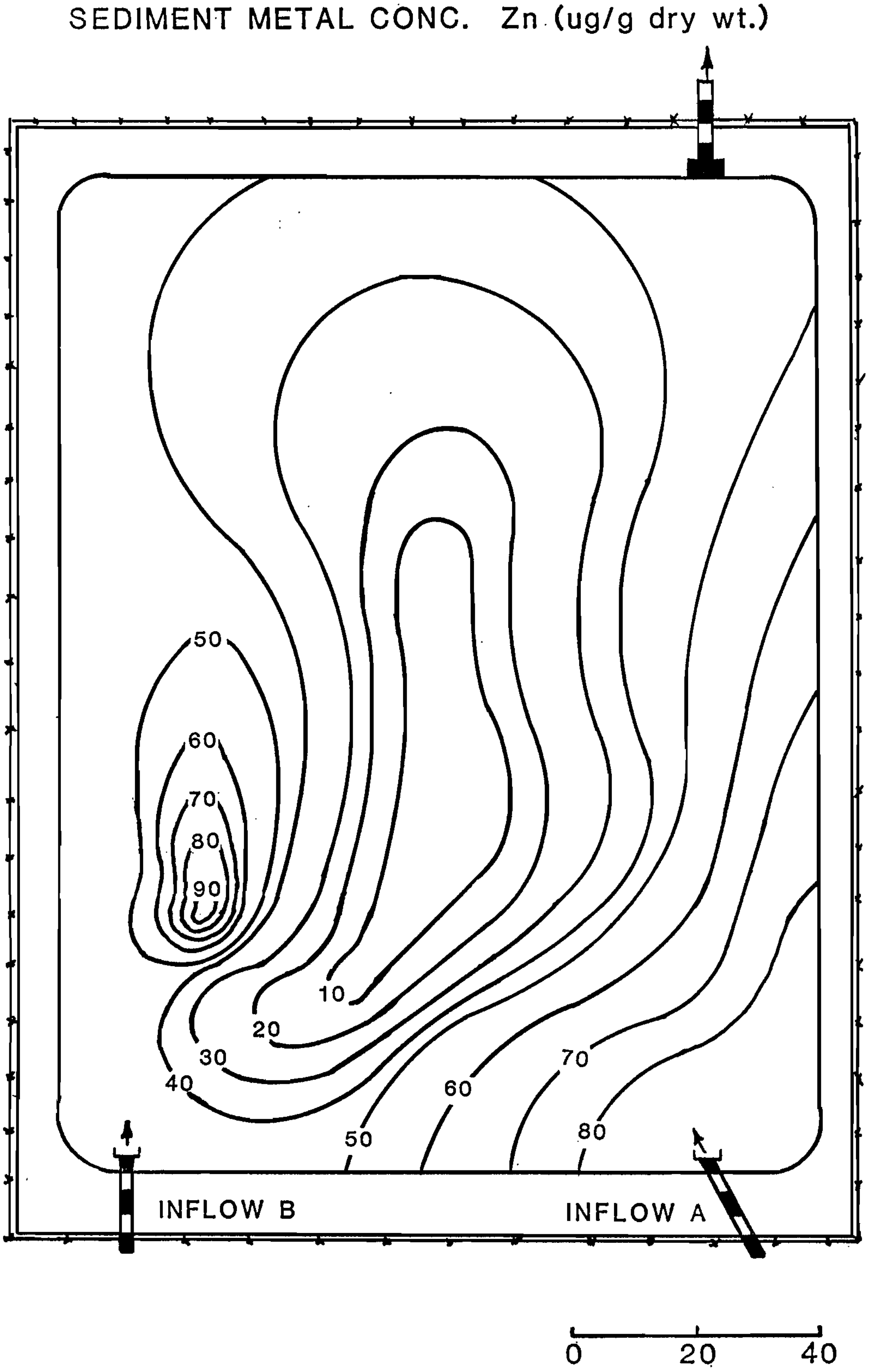


Figure 3-17. Horizontal Distribution of Zinc in the 0-1 cm Layer of Sediments at the Residential Wet Detention Pond (Site 4).

detention pond, sediment concentrations of zinc are approximately 40-50% of the maximum concentrations measured near the two inflow points.

Horizontal distributions of lead in the 0-1 cm layer at the wet detention pond are given in Figure 3-18. In general, the attenuation of lead upon entering the wet detention pond appears to be less pronounced than that observed for zinc. Depositional patterns for both Inflow A and Inflow B extend over much larger areas of the pond bottom than was observed for zinc. Sediment concentrations of lead along the flow path for Inflow A exceeded 90 μg/g at distances greater than 100 m into the pond.

Horizontal distributions of nickel in sediments of the residential wet detention pond are given in Figure 3-19. In general, depositional patterns for nickel appear to be less pronounced than those observed for lead or zinc. Nickel appears to be somewhat mobile upon entering the wet detention pond, and distinct areas of concentrated deposition were not detected for nickel.

Horizontal depositional patterns for chromium in the wet detention pond are given in Figure 3-20. Similar to patterns observed for nickel, the deposition of chromium appears to extend over much of the detention pond. Distinct areas of sediment accumulations were not detected for chromium.

<u>Site 5 - Commercial Dual Pond Facility</u>

Chemical characteristics of the 0-1 cm layer in sediment core samples collected from the retention pond, detention pond and control area at the commercial dual pond site are given in Table 3-38. The retention pond at this site is a relatively small facility similar to that described previously for site 3. Because of its small size, water within

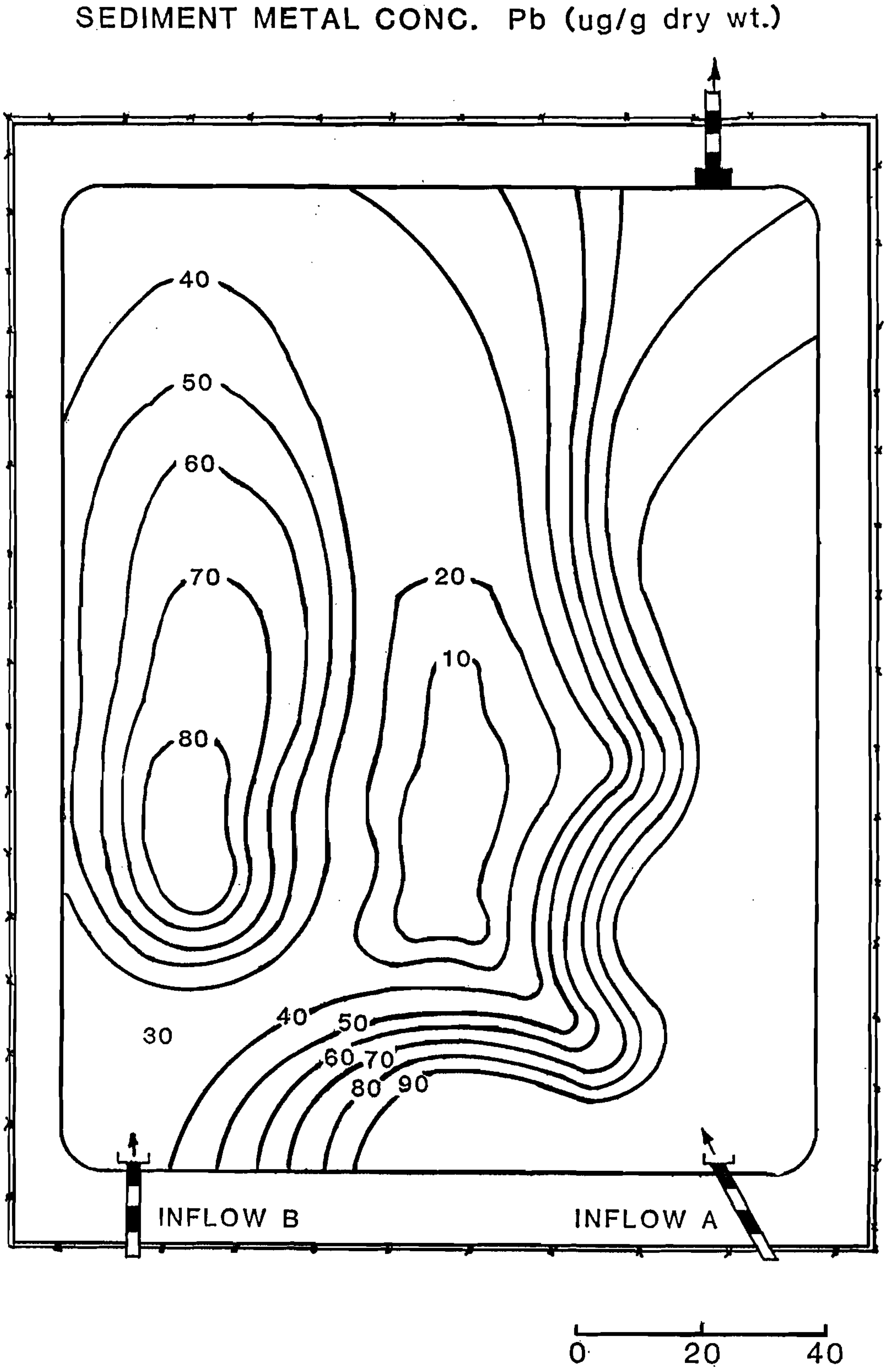


Figure 3-18. Horizontal Distribution of Lead in the 0-1 cm Layer of Sediments at the Residential Wet Detention Pond (Site 4).

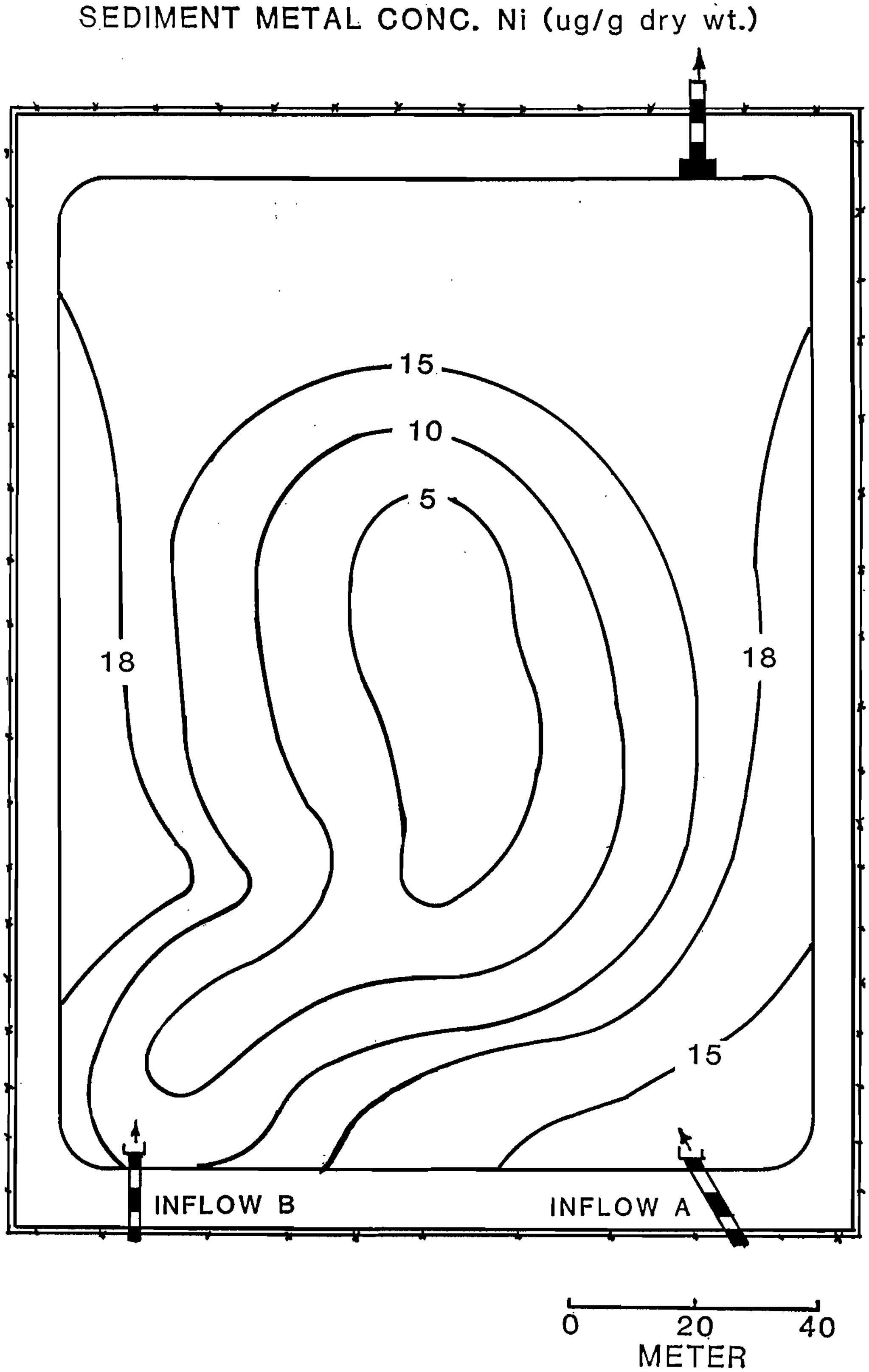


Figure 3-19. Horizontal Distribution of Nickel in the 0-1 cm Layer of Sediments at the Residential Wet Detention Pond (Site 4).

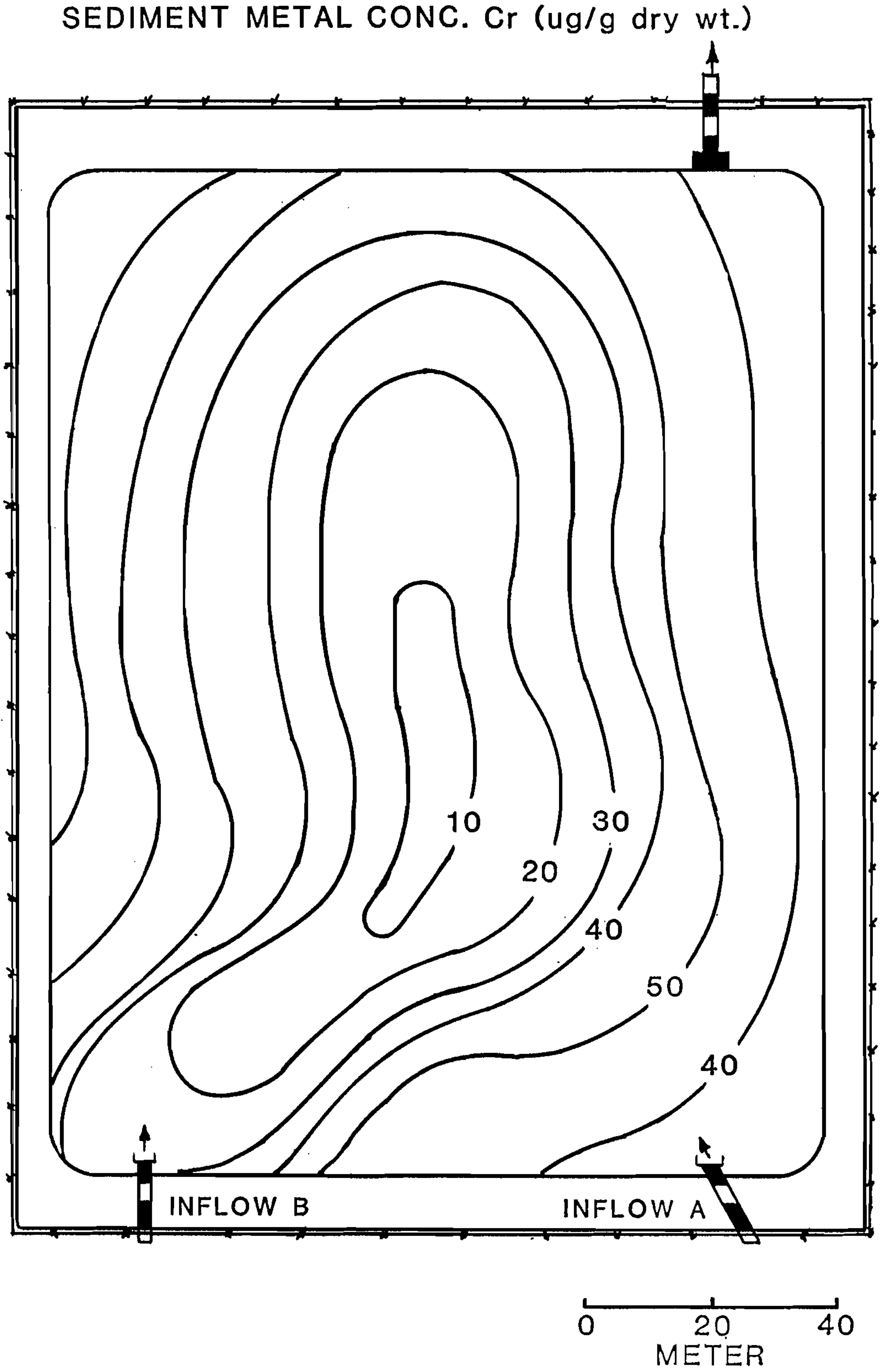


Figure 3-20. Horizontal Distribution of Chromium in the 0-1 cm Layer of Sediments at the Residential Wet Detention Pond (Site 4).

TABLE 3-38

CHEMICAL CHARACTERISTICS OF THE 0-1 cm LAYER IN SEDIMENT CORE SAMPLES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

SAMPLE	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (µg/g dry weight)										
		Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
<u>Ret. Pond</u>												
Ret.-1	7.0	2.4	308	6	11	5,770	2,600	55	7	10	3179	15,346
Ret.-2	2.9	4.0	156	6	5	1,800	1,670	52	7	7	5838	23,507
Ret.-3	3.6	3.7	224	8	9	4,380	2,650	62	8	12	2078	6,349
Ret.-4	3.1	2.5	116	7	5	2,760	1,510	39	5	7	1122	2,999
<u>Det. Pond</u>												
Det.-1	27.5	4.3	288	26	24	4,960	30,600	91	9	14	2139	21,722
Det.-2	11.1	1.1	208	17	9	2,720	10,200	41	5	8	2689	21,122
Det.-3	6.1	2.0	69	9	6	11,700	5,120	40	7	11	3199	7,735
Det.-4	2.6	0.2	37	4	3	2,190	1,630	15	2	4	969	4,516
Det.-5	1.8	0.6	21	5	2	4,810	1,390	15	3	4	1728	2,783
Det.-6	2.7	1.1	29	6	2	3,550	2,920	16	3	5	3870	5,195
Det.-7	0.8	0.8	11	2	2	4,730	665	7	2	3	890	2,309
Det.-8	1.7	1.3	23	3	2	7,060	1,470	12	4	5	1524	2,722
Control Area	7.3	4.1	35	14	4	6,300	1,530	52	7	11	3178	29,111

the retention basin becomes relatively well mixed by inputs of stormwater runoff during rain events. For this reason, distinct accumulation patterns for heavy metals in the upper sediment layers of this pond may be difficult to detect.

As seen in Table 3-38, sediment concentrations for many of the heavy metals measured at the four core locations within the retention pond appear to be relatively similar in value. Sediment concentrations for many parameters given in Table 3-38 appear to be greater in value for the core samples collected along the flow path for stormwater inputs compared with core samples collected in areas away from the dominant flow path. As seen in Figure 2-20, sediment core locations 1 and 3 appear to be along the flow path while sediment core locations 2 and 4 appear to be away from the dominant flow path. Patterns of stormwater inflow within the retention pond are also influenced to a large extent by the very dense growth of cattails which exists in the pond, particularly along the center of the pond. This growth physically separates pond areas indicated by core sites 1 and 3 from those in the areas of core sites 2 and 4. As seen in Table 3-38, measured values for virtually all parameters except nitrogen and phosphorus appear to be higher at locations 1 and 3 than at locations 2 and 4.

Flow patterns within the detention pond are quite different than those which occur within the retention pond. Due to the unusual shape of the detention pond, well mixed conditions are not expected to occur, and increased sediment concentrations of heavy metals would be expected in sediment core samples located nearest the point of inflow into the pond. As seen in Figure 2-20, sediment core locations located near the point of inflow to the pond and along the primary flow path to the pond would include locations 1, 2 and 3. Sediment concentrations of virtually every parameter listed in Table 3-38 are substantially greater at these three locations than at the remaining five locations throughout the pond. These elevated concentrations are particularly evident for organic content, cadmium, zinc, manganese, copper, iron, lead, nickel, chromium and nitrogen. As seen in Table 3-38, there appears to be very little difference in sediment concentrations measured at the remaining five sites. The primary accumulation area for heavy metals within the detention pond appears to extend over a distance of approximately 20-25 m. It is also interesting to note that maximum sediment concentrations for many parameters in Table 3-38 appear to be greater within detention pond sediments than in the sediments of the retention pond. This is particularly apparent for organic content, manganese, copper, aluminum, iron and lead.

Vertical Attenuation of Heavy Metals and Nutrients in Soils and Sediments at the Five Study Sites

Site 1 - Wet Swale Site

A summary of chemical characteristics of the top 25 cm in sediment core samples collected in swale and control areas at the wet swale site is given in Table 3-39. Aluminum was the most abundant metal present in both swale and control areas in all depth layers, with average aluminum concentrations several orders of magnitude larger than most of the other heavy metals. The second most abundant metal present was iron, with average concentrations at all depths approximately one order of magnitude larger than other heavy metals. Lead was the third most abundant heavy metal present, followed by zinc, copper, manganese, chromium, nickel and cadmium. In general,

TABLE 3-39

CHEMICAL CHARACTERISTICS OF THE TOP 25 cm IN SEDIMENT CORE SAMPLES COLLECTED AT THE WET SWALE SITE (SITE 1)

SAMPLE	DEPTH LAYER (cm)	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
			Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Swale Composite	0-1	4.0	2.4	118	15	17	7,060	2970	441	6	9	571	1971
	1-5	3.2	1.0	109	7	13	3,430	2690	437	6	8	268	789
	5-10	2.5	0.8	95	5	6	7,820	1897	273	5	7	258	729
	10-15	1.5	0.7	63	3	6	5,760	1160	140	3	7	221	415
	15-25	0.7	0.3	3	2	1	11,500	1020	9	2	7	123	181
Control Area	0-1	4.1	1.7	60	14	8	8,450	838	91	9	11	362	275
	1-5	3.1	1.6	34	9	6	6,320	715	84	5	7	278	935
	5-10	1.9	1.4	25	7	5	5,610	679	39	4	7	274	804
	10-15	1.8	1.	23	4	4	3,460	348	29	2	3	224	383
	15-25	0.8	0.1	6	2	2	2,360	184	6	1	2	240	598

sediment concentrations of nickel, chromium and cadmium were very low in both swale and control areas.

As seen in Table 3-39, concentrations of all heavy metals (with the exception of aluminum) were highest in the surface layer with a decreasing concentration with increasing depth. This same general trend was also observed for organic content, phosphorus, and to a lesser extent, nitrogen. The attenuation of zinc, copper, iron and lead in sediments of both swale and control areas is shown in Figure 3-21. Sediment concentrations of iron and lead appear to be attenuated very rapidly with increasing depth in the swale area. Sediment concentrations of zinc and copper, although decreasing with increasing depth, do not exhibit the rapid attenuation shown by lead and iron. With the exception of iron, sediment concentrations for the remaining heavy metals appear to be very similar in both swale and control areas in the final 15-25 cm sediment layer.

Vertical distributions of cadmium, manganese, nickel and chromium in the swale and control areas are indicated in Figure 3-22. In general, sediment concentrations of each of these heavy metals are extremely low in both swale and control areas. There appears to be little difference between sediment accumulations of cadmium, manganese and nickel in swale and control areas. Chromium, however, exhibits higher concentrations at all depths in the swale channel than in sediments beneath the control area.

The attenuation of heavy metals in swale and control areas with increasing depth was modeled using a semi-log relationship of the form: $\ln (C/C_o) = K \times (\text{Depth})$, where K represents the slope of the semi-log regression line and is an indication of the rate of attenuation of sediment concentration with increasing sediment depth. Larger absolute

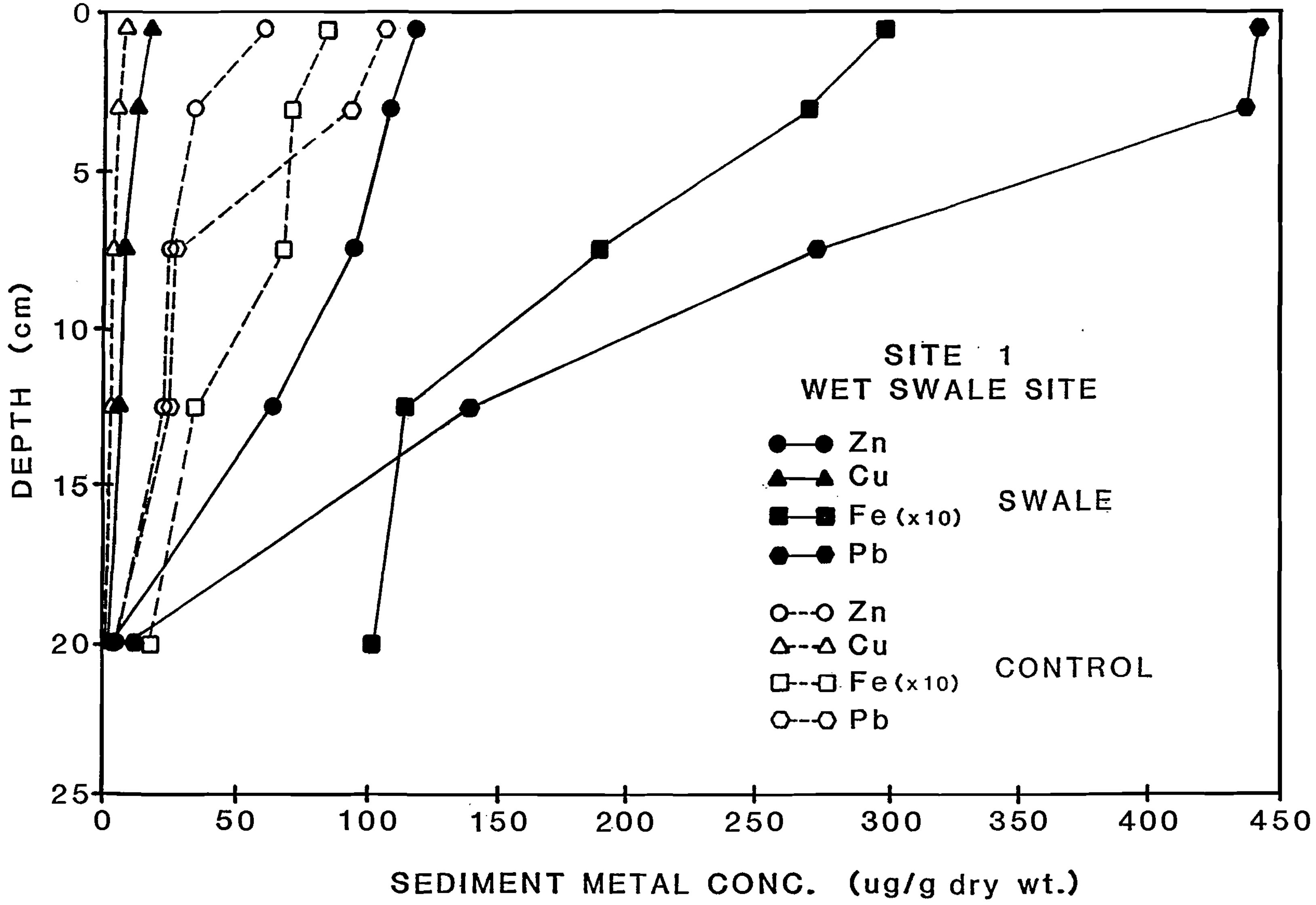


Figure 3-21. Vertical Distribution of Zinc, Copper, Iron and Lead in the Top 25 cm of the Swale and Control Areas at the Wet Swale Site - Site 1.

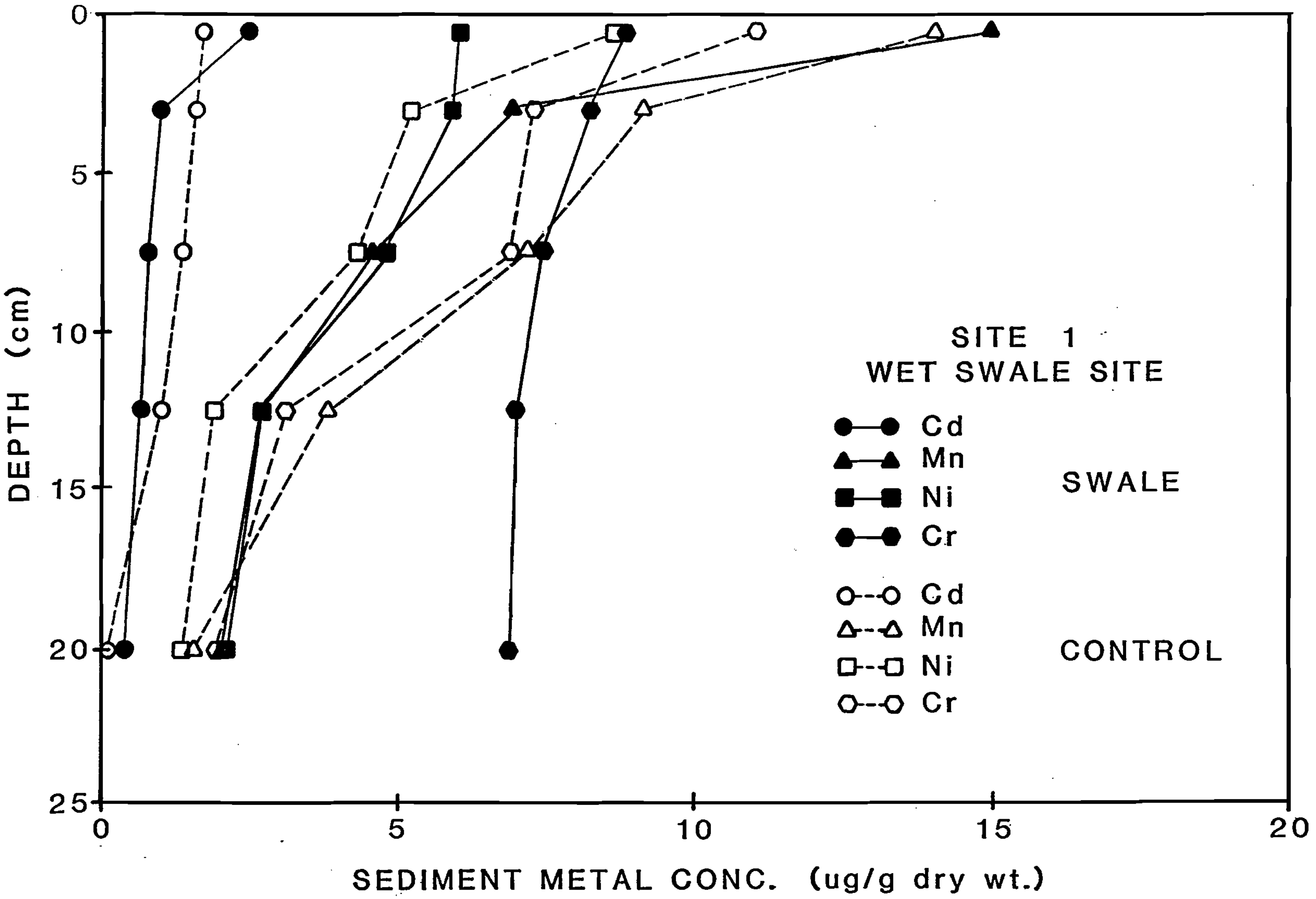


Figure 3-22. Vertical Distribution of Cadmium, Manganese, Nickel and Chromium in the Top 25 cm of the Swale and Control Areas at the Wet Swale Site - Site 1.

values of K indicate rapid attenuation of concentration with increasing depth while small absolute values of K indicate little attenuation or perhaps a linear decline in concentration with increasing sediment depth. A summary of the results of these models is given in Table 3-40. The semi-log relationship appeared to fit the data points extremely well for most metal species. With few exceptions, the calculated values of R-square were generally in excess of 0.90 for each heavy metal. Using the values of K as a measure of the rate of attenuation for heavy metals during travel through sediment layers, it appears that lead was attenuated at the fastest rate followed by zinc, manganese, copper, cadmium, iron, nickel and chromium. Concentrations of aluminum actually increased with increasing depth.

Site 2 - Dry Swale Site

A summary of chemical characteristics of the top 25 cm in sediment core samples collected in swale and control areas at the dry swale site is given in Table 3-41. As observed in sediments at the wet swale site, aluminum and iron were the most common metal species found in sediments at the dry swale site, followed by lead, zinc, manganese, copper, chromium, nickel and cadmium. However, concentrations of all metal species measured in the sediments at the dry swale site were approximately five to ten times greater than metal concentrations measured at the wet swale site, in spite of the fact that the wet swale channel has been receiving highway runoff since 1965 while the dry swale channel has been receiving highway runoff since only 1972. These differences in sediment metal concentrations cannot be explained by substantial differences in the heavy metal content of runoff inputs to these systems since the heavy

TABLE 3-40

ATTENUATION OF HEAVY METALS IN SEDIMENT CORES COLLECTED AT THE WET SWALE SITE (SITE 1)

HEAVY METAL	VALUE OF K FOR "BEST FIT" EQUATION OF THE FORM: $\ln (C/C_o) = K (\text{Depth})$	
	SWALE AREA	CONTROL AREA
Cd	-0.1065	-0.2293
Zn	-0.1349	-0.1091
Mn	-0.1169	-0.1172
Cu	-0.1165	-0.0750
Al	0.0094	-0.0732
Fe	-0.0592	-0.0907
Pb	-0.1538	-0.1537
Ni	-0.0526	-0.0899
Cr	-0.0126	-0.0919

TABLE 3-41

CHEMICAL CHARACTERISTICS OF THE TOP 25 cm IN SEDIMENT CORE SAMPLES COLLECTED AT THE DRY SWALE SITE (SITE 2)

SAMPLE	DEPTH LAYER (cm)	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
			Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Swale Composite	0-1	14.2	16	1480	191	142	32,200	15,600	2740	44	81	748	1524
	1-5	7.1	15	1250	162	111	15,100	10,500	2590	30	61	522	1328
	5-10	3.7	3.9	247	95	27	7,040	2,880	996	9	13	429	1317
	10-15	4.5	3.8	235	26	22	6,280	2,450	501	8	12	419	1254
	15-25	2.2	0.6	93	12	11	6,150	1,200	195	4	8	304	790
Control Area	0-1	7.2	2.6	53	16	5	10,300	1,110	139	5	9	1351	2832
	1-5	5.0	2.5	37	16	4	7,930	1,090	71	5	8	499	1598
	5-10	2.1	2.0	32	15	4	6,460	816	62	4	7	466	630
	10-15	1.9	1.9	25	14	3	5,690	633	44	4	5	311	268
	15-25	1.2	1.7	12	11	2	5,320	373	26	4	4	437	471

metal concentrations in stormwater runoff at these sites, listed in Tables 3-4 and 3-8, appear to be similar. It appears, therefore, that the dry swale system was much more effective in retaining heavy metal inputs within the swale channel than observed for the wet swale channel.

Vertical attenuation of zinc, copper, iron and lead in sediments of the swale and control areas is shown in Figure 3-23. Sediment concentrations of all four heavy metals were substantially greater in the swale area than in sediments collected within the control area. Sediment metal concentrations beneath the swale area began to approach those measured in the control area in the final 15-25 cm depth layer, although swale concentrations of the four heavy metals still exceed those measured in the control area even at this layer.

The attenuation of cadmium, manganese, nickel and chromium in sediments along the swale and control areas is indicated in Figure 3-24. Sediment concentrations of each of these heavy metals are also substantially greater along the swale channel than in the control area. However, metal concentrations in the swale area begin to closely approximate those measured in the control area in the final 15-25 cm layer.

The results of a semi-log regression analysis for attenuation of heavy metals in sediment core samples are given in Table 3-42. As described for site 1, the rate of attenuation of heavy metal species is quantified by calculation of the slope, K, of the semi-log regression line for sediment concentrations as a function of depth. As seen in Table 3-42, sediment metal concentrations were attenuated very rapidly within the swale area when compared with values measured within the control area. Within the swale channel, cadmium was attenuated at the most rapid rate, followed by zinc, iron, copper,

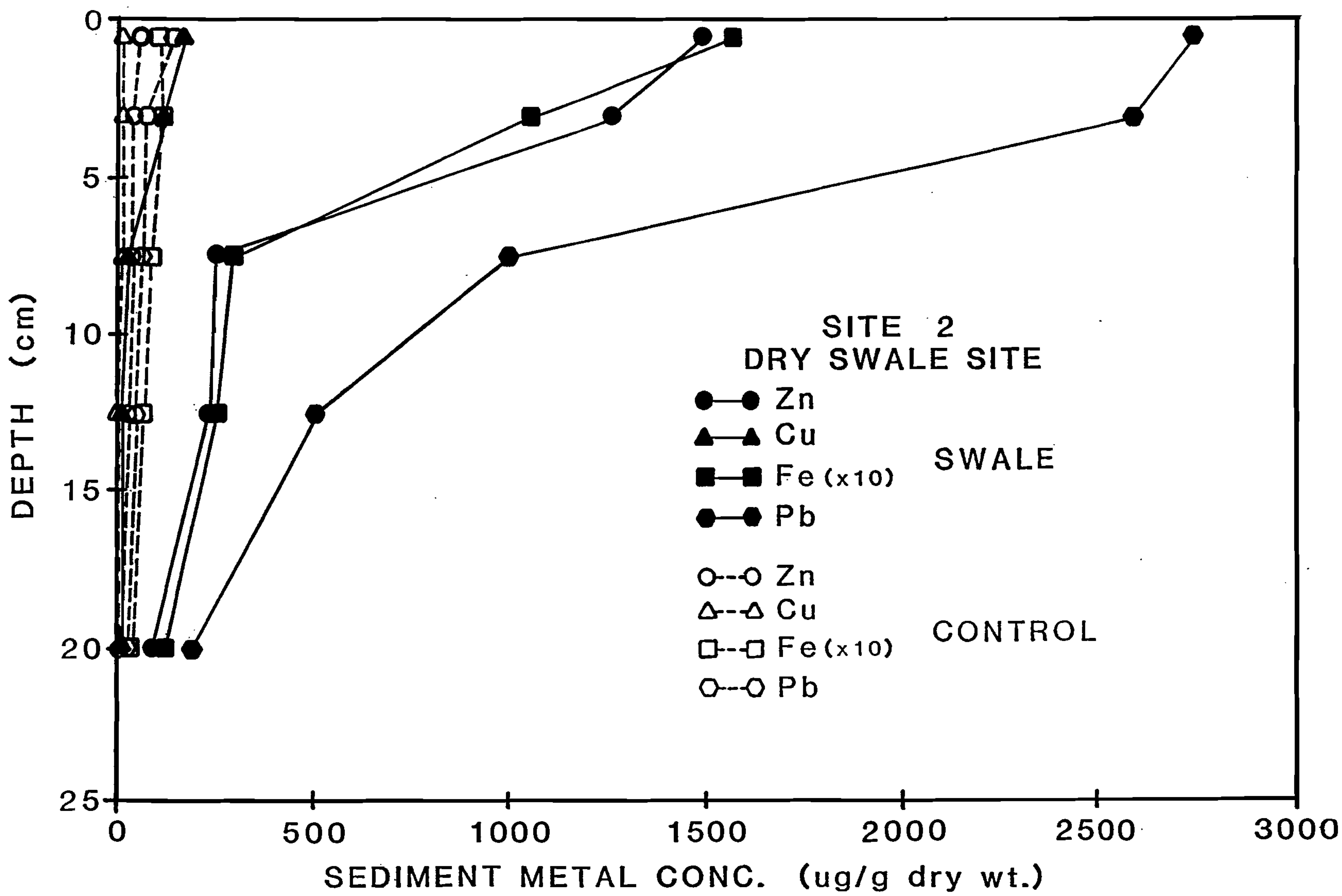


Figure 3-23. Vertical Distribution of Zinc, Copper, Iron and Lead in the Top 25 cm of the Swale and Control Areas at the Dry Swale Site - Site 2.

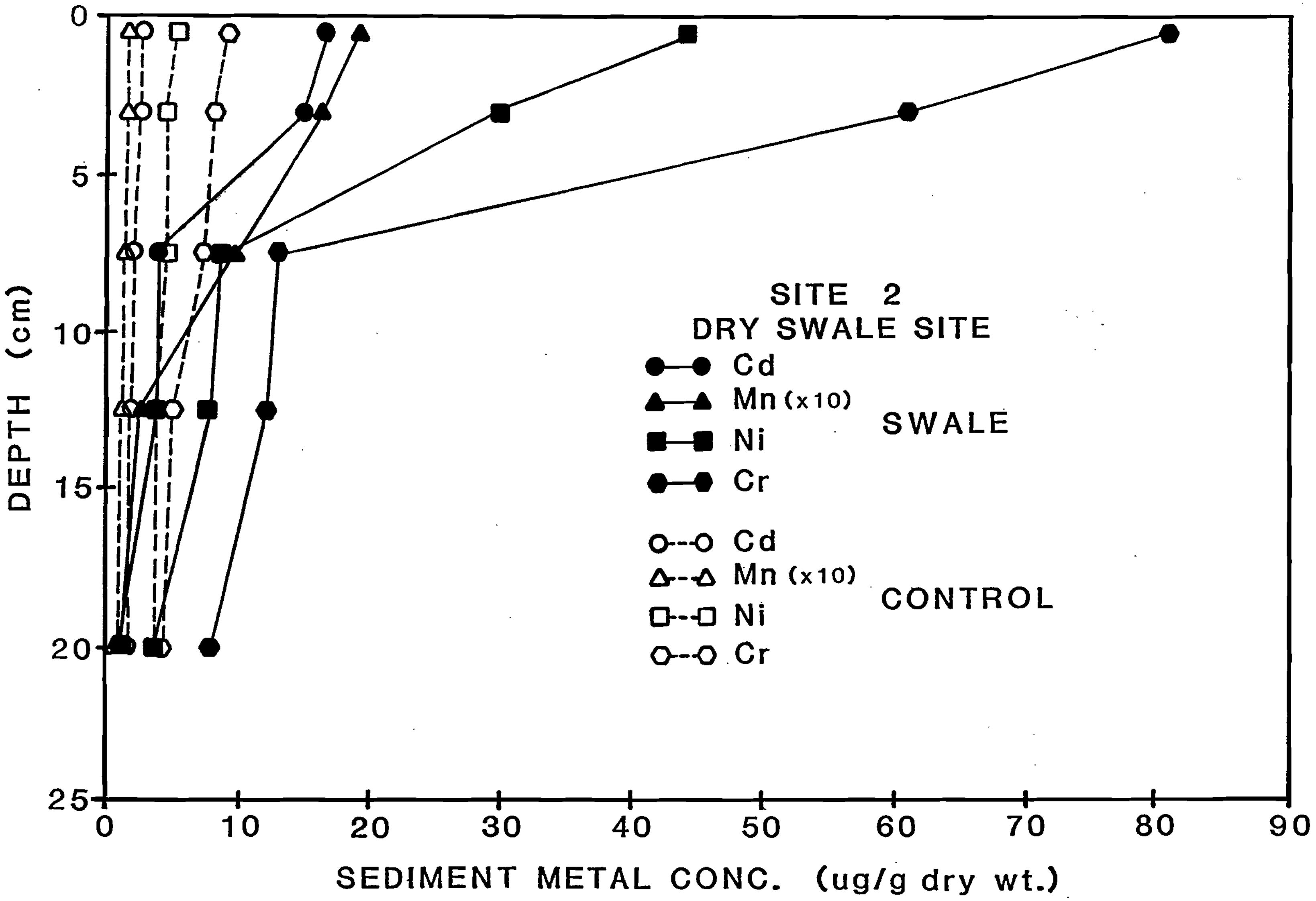


Figure 3-24. Vertical Distribution of Cadmium, Manganese, Nickel and Chromium in the Top 25 cm of the Swale and Control Areas at the Dry Swale Site - Site 2.

TABLE 3-42

ATTENUATION OF HEAVY METALS IN SEDIMENT CORES COLLECTED AT THE DRY SWALE SITE (SITE 2)

HEAVY METAL	VALUE OF K FOR "BEST FIT" EQUATION OF THE FORM: ln $(C/C_o) = K$ (Depth)	
	SWALE AREA	CONTROL AREA
Cd	-0.1524	0.0237
Zn	-0.1485	-0.0688
Mn	-0.1384	-0.0125
Cu	-0.1410	-0.0355
Al	-0.1081	-0.0359
Fe	-0.1421	-0.0330
Pb	-0.1317	-0.0345
Ni	-0.1319	-0.0043
Cr	-0.1368	-0.0345

manganese, chromium, nickel, lead and aluminum. These rapid attenuation patterns suggest that heavy metals within the swale channel are being retained primarily in the surface soil layers with very little tendency for downward migration of sediment-bound metal species. The attenuation of heavy metals within the dry swale channel is much greater than values listed for the wet swale channel listed in Table 3-40. This difference again suggests that the dry swale channel is more effective in retaining heavy metals within the sediments than observed at the wet swale site.

It is interesting to note that the large differences in sediment concentrations observed for heavy metal species between swale and control areas were not observed for nitrogen and phosphorus. In fact, surface concentrations of both nitrogen and phosphorus were higher within the control area than in sediments along the swale. The swale channel appears to be much less effective in retaining nutrient inputs within the sediments than in retaining metal inputs into the channel.

Site 3 - Residential Dual Pond Site

A summary of chemical characteristics of the top 25 cm in sediment core samples collected from the retention, detention and control areas at the residential dual pond site is given in Table 3-43. As observed at both sites 1 and 2, aluminum and iron are the most common metal species found in the sediments at this site. However, compared with sediment metal concentrations measured in the swale areas at sites 1 and 2, sediment metal concentrations at the residential dual pond site were extremely low for all measured heavy metals. With the exceptions of aluminum and iron, lead was the most abundant

TABLE 3-43

CHEMICAL CHARACTERISTICS OF THE TOP 25 cm IN SEDIMENT CORE SAMPLES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

SAMPLE	DEPTH LAYER (cm)	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
			Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Detention Composite	0-1	2.3	1.9	8	1	12	6,070	609	16	2	10	3698	1,722
	1-5	2.2	1.0	7	9	9	11,100	720	15	3	10	3512	1,388
	5-10	1.7	0.9	6	7	8	11,100	608	14	2	10	3076	758
	10-15	1.5	0.6	5	3	8	10,600	411	14	2	9	2915	387
	15-25	1.8	0.3	3	3	7	13,400	420	12	2	12	2600	380
Control Area	0-1	3.1	2.1	25	45	45	6,800	680	24	4	18	6777	19,630
	1-5	4.0	1.8	15	24	33	5,960	601	14	2	10	6565	17,534
	5-10	8.0	1.5	14	33	27	5,350	698	11	2	9	8857	14,300
	10-15	3.2	0.8	14	21	22	5,450	575	11	1	9	8457	6,776
	15-25	4.2	0.6	11	23	16	3,100	386	12	1	10	9983	7,208
Retention Composite	0-1	2.6	1.7	20	8	12	7,060	713	18	3	9	569	578
	1-5	1.1	1.5	6	5	7	7,260	534	11	3	6	389	256
	5-10	1.2	1.4	5	4	7	6,710	510	10	2	5	366	193
	10-15	1.0	1.6	5	5	7	5,260	470	9	2	5	362	171
	15-25	1.4	1.6	4	5	7	4,440	431	8	1	4	400	205

heavy metal measured, followed by approximately equal sediment concentrations of zinc, manganese, copper and chromium.

Vertical distributions of zinc, copper and lead in sediments of the retention and detention ponds at site 3 are indicated in Figure 3-25. With the exceptions of slightly elevated concentrations of zinc and lead in the 0-1 cm layer within the retention pond, there appears to be little difference in sediment concentrations for each of the three heavy metals between the retention and detention ponds. The rapid attenuation of sediment concentration with increasing depth observed in the swale channels is not apparent at this site for zinc, copper or lead. In fact, as indicated in Table 3-43, sediment concentrations for each of these metals appears to be higher in the control area than in the sediments of either the detention or retention ponds.

Vertical attenuation of cadmium, manganese, nickel and chromium in retention and detention pond sediments is shown in Figure 3-26. In general, sediment concentrations of each of these metals are extremely low in the sediments of both ponds. Patterns of increased surface concentrations and rapid attenuation in concentration with increasing depth are not apparent for these metals in either pond, and there appears to be little difference in sediment concentrations for any of these metals between the two pond sediments. However, as discussed previously, the stormwater management system at this site had been in operation for less than two years at the time of this study. In addition, these ponds receive residential runoff which is normally not associated with large inputs of heavy metals.

The results of regression analyses for semi-log relationships of heavy metal concentrations with increasing depth are given in Table 3-44. Attenuation coefficients

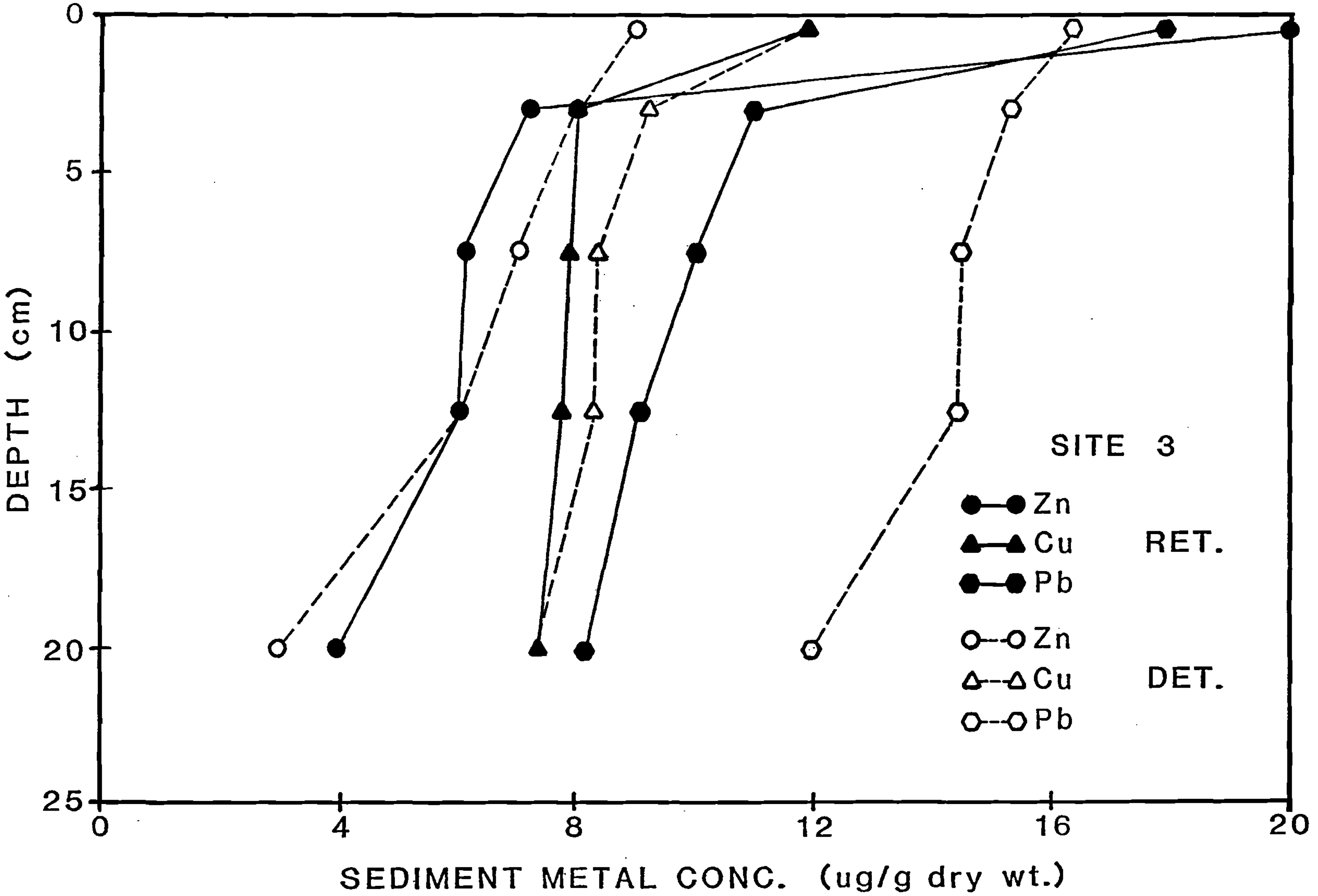


Figure 3-25. Vertical Distribution of Zinc, Copper and Lead in the Top 25 cm of the Retention and Detention Ponds at the Residential Dual Pond Facility - Site 3.

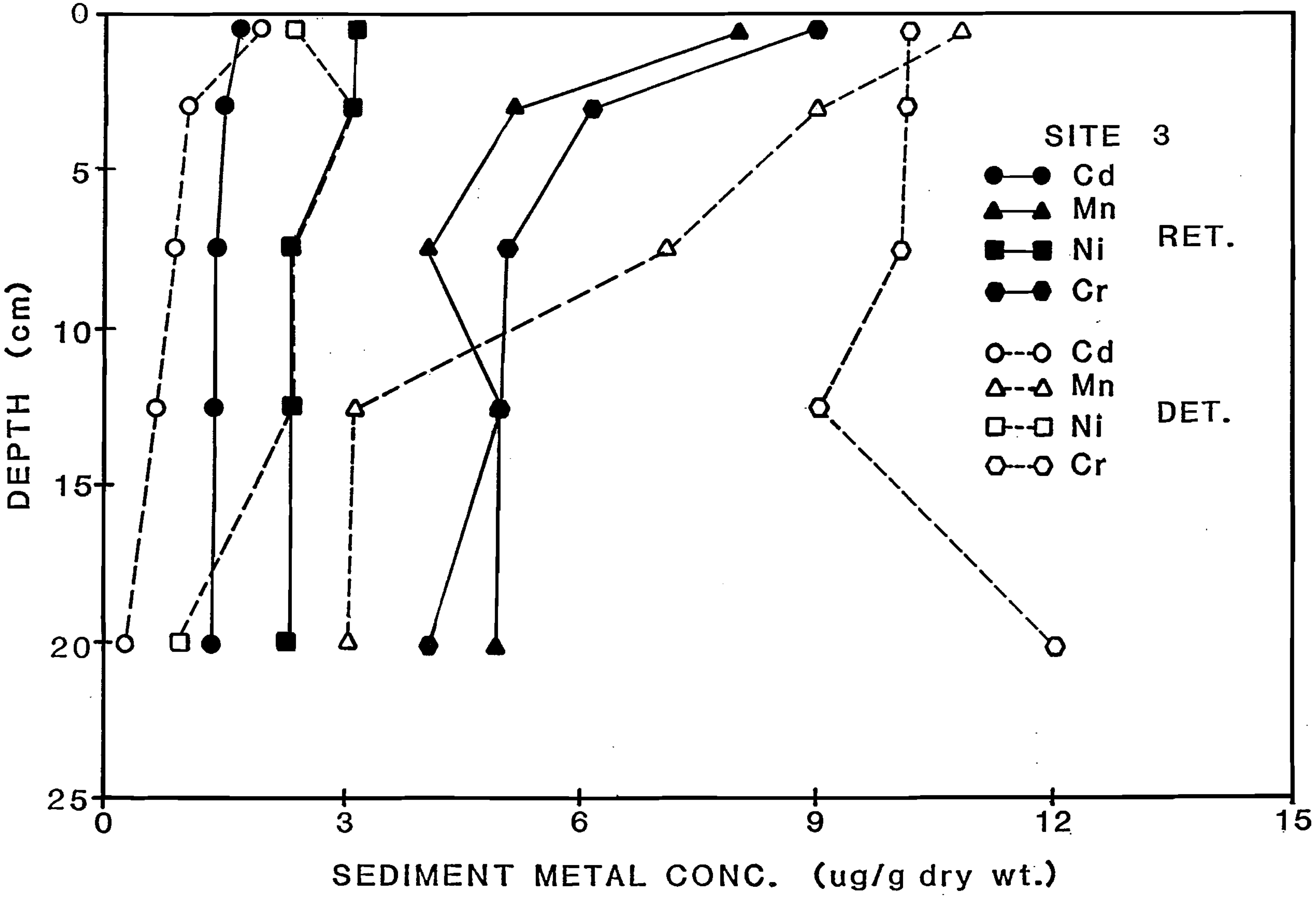


Figure 3-26. Vertical Distribution of Cadmium, Manganese, Nickel and Chromium in the Top 25 cm of the Retention and Detention Ponds at the Residential Dual Pond Facility - Site 3.

TABLE 3-44

ATTENUATION OF HEAVY METALS IN SEDIMENT CORES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METAL	VALUE OF K FOR "BEST FIT" EQUATION OF THE FORM: ln $(C/C_o) = K$ (Depth)		
	RETENTION POND	DETENTION POND	CONTROL AREA
Cd	-0.0056	-0.0474	-0.0644
Zn	-0.0927	-0.0325	-0.0475
Mn	-0.0285	-0.0778	-0.0443
Cu	-0.0295	-0.0338	-0.0664
Al	-0.0007	-0.0469	-0.0333
Fe	-0.0178	-0.0191	-0.0219
Pb	-0.0362	0.0148	-0.0500
Ni	-0.0196	-0.0089	-0.0672
Cr	-0.0225	-0.1310	-0.0496

for each of the heavy metals in retention, detention and control areas are extremely small, particularly compared with values measured at the previous swale sites. These small attenuation coefficients provide additional indication that accumulation of heavy metals within pond sediments at this site has not yet occurred to a significant degree.

Site 4 - Residential Wet Detention Facility

A summary of chemical characteristics of the top 25 cm in sediment core samples collected from pond and control areas at the residential wet detention facility is given in Table 3-45. As observed at the previous sites, aluminum and iron are the most abundant metal species measured in the soils and sediments at this site. The third most abundant metal measured was lead, followed by zinc, chromium, nickel, manganese, copper and cadmium. In general, sediment metal concentrations for all heavy metals appear to be substantially greater than those measured at site 3 although less than concentrations measured along the two swale sites. All heavy metals indicated in Table 3-45 appear to have elevated concentrations in the surface layer with a rapid decline in concentration with increasing sediment depth.

The vertical attenuation of zinc, copper, lead and iron in pond and control sediments is indicated in Figure 3-27. In general, sediment concentrations of zinc, iron and lead are substantially higher within the top 20 cm of the sediments of the detention pond than within the control area. After a depth of 5 cm, sediment concentrations for these metals began to be relatively similar between the two areas. Sediment concentrations of copper were extremely low in both areas with slightly higher concentrations found within the control area. It appears that accumulations of zinc, iron

TABLE 3-45

CHEMICAL CHARACTERISTICS OF THE TOP 25 cm IN SEDIMENT CORE SAMPLES COLLECTED AT THE RESIDENTIAL WET DETENTION FACILITY (SITE 4)

SAMPLE	DEPTH LAYER (cm)	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS (μg/g dry weight)										
			Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Pond Composite	0-1	8.0	2.2	39	11	5	47,500	4170	62	12	35	859	1585
	1-5	6.4	0.6	11	3	2	21,300	1780	12	4	12	619	624
	5-10	2.0	0.1	10	1	1	4,060	619	6	2	3	569	194
	10-15	1.8	0.1	9	1	1	3,160	420	5	2	3	556	140
	15-25	1.3	< 0.01	6	1	1	2,730	318	4	1	2	548	139
Control Area	0-1	2.6	1.7	19	3	8	12,700	2720	8	6	4	5740	8388
	1-5	4.5	0.4	13	2	3	8,420	2900	4	4	2	6564	3929
	5-10	0.6	0.7	8	3	3	12,700	1010	1	2	1	5500	1857
	10-15	0.3	0.5	6	2	2	11,800	922	1	1	1	5597	2132
	15-25	0.4	< 0.01	4	1	2	9,210	640	1	1	1	3360	1033

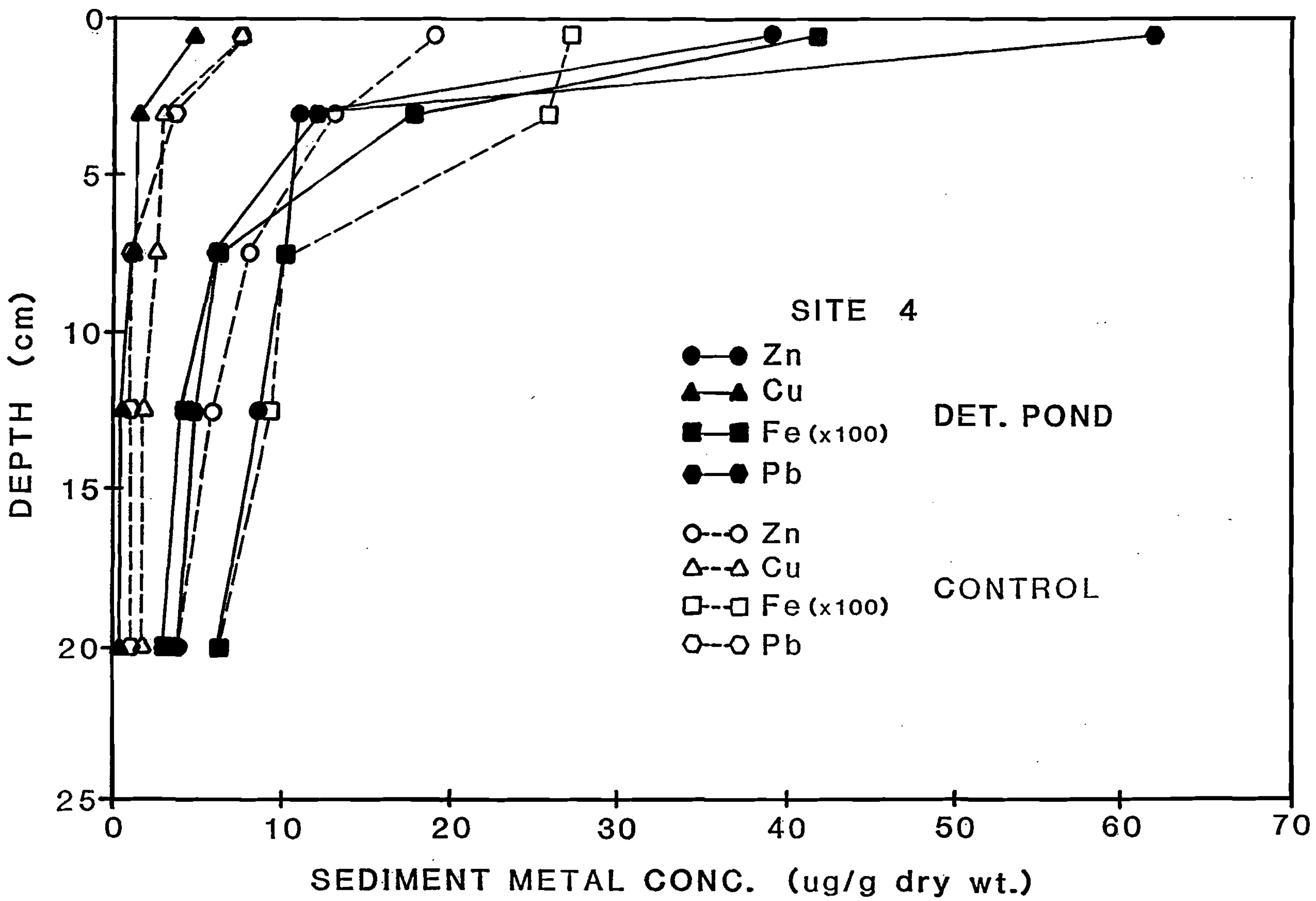


Figure 3-27. Vertical Distribution of Zinc, Copper, Lead and Iron in the Top 25 cm of the Pond and Control Areas at the Residential Wet Detention Facility - Site 4.

and lead have occurred within the top 5 cm of the pond sediments while copper has not accumulated to any apparent degree.

Vertical attenuation of cadmium, manganese, nickel and chromium in pond and control sediments is indicated in Figure 3-28. Elevated concentrations of manganese and nickel appeared to exist within the top 1 cm of the pond sediments, while elevated concentrations of chromium apparently extended down to a depth of 5 cm within the pond sediments. Below these depths there appeared to be little difference between sediment concentrations in pond or control areas. Pond concentrations of cadmium within the 0-1 cm layer were only slightly greater than those found within the control area. It appeared that each of these four heavy metals is capable of accumulating within the pond sediments although accumulations at this time appear to be relatively small. It should be noted that the relatively large area of the pond may be largely responsible for the low accumulations found for all heavy metals at this site.

Regression coefficients for the attenuation of heavy metals in pond and control areas are presented in Table 3-46 for a semi-log relationship. Attenuation coefficients for heavy metals are substantially greater than those measured at site 3 and appear to be similar to the large coefficients found at the dry swale site. Within the sediments of the detention pond, the most rapid attenuation was observed for cadmium, followed by aluminum, lead, chromium, manganese, iron, nickel, copper and zinc. Relatively large attenuation coefficients were also found for control area soils as well. The large attenuation coefficients for the detention pond provide further evidence that the sediments of this pond are capable of retaining heavy metal inputs within the top sediment layers.

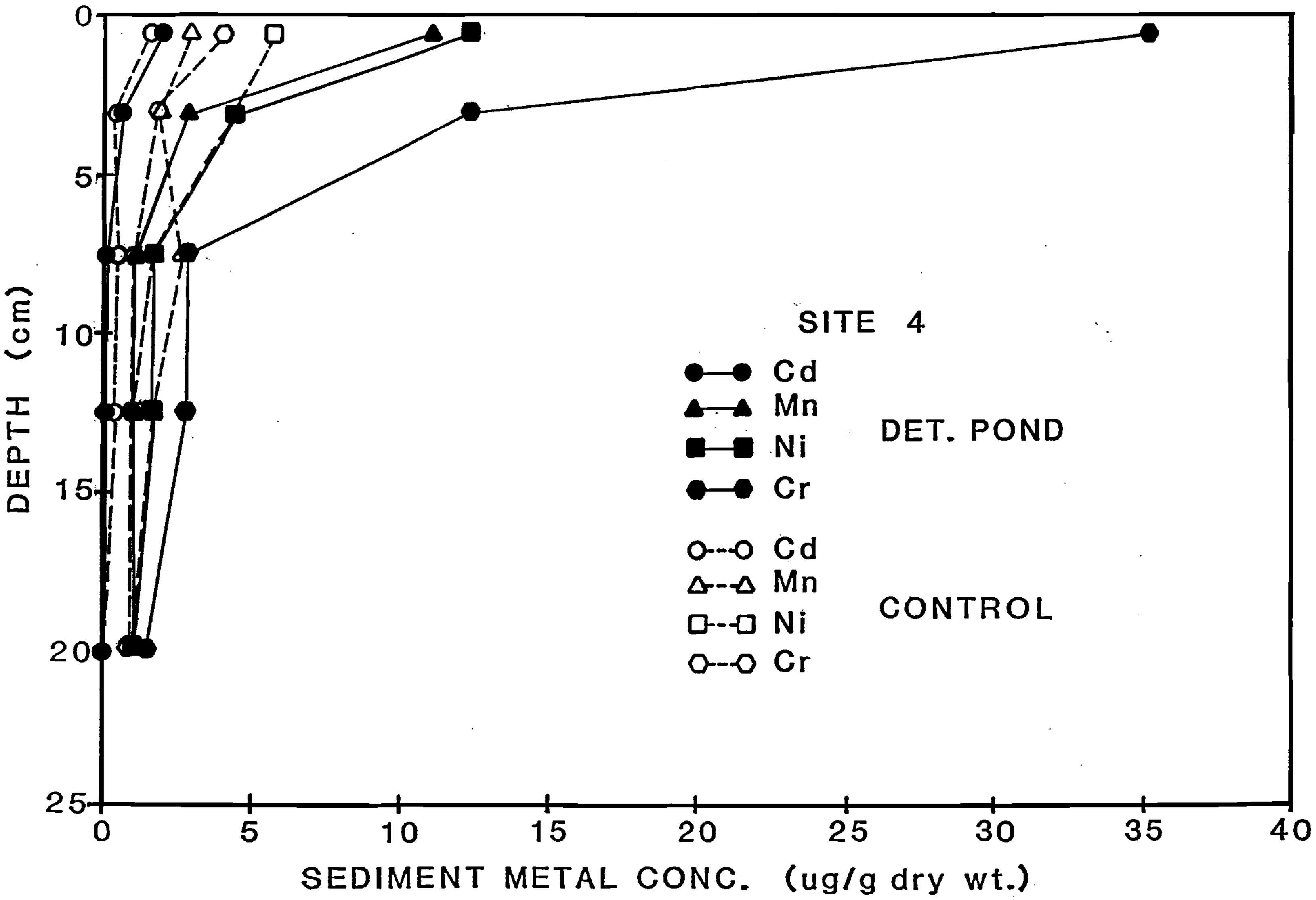


Figure 3-28. Vertical Distribution of Cadmium, Manganese, Nickel and Chromium in the Top 25 cm of the Pond and Control Areas at the Residential Wet Detention Facility - Site 4.

TABLE 3-46

ATTENUATION OF HEAVY METALS IN SEDIMENT CORES COLLECTED AT THE RESIDENTIAL WET DETENTION POND (SITE 4)

HEAVY METAL	VALUE OF K FOR "BEST FIT" EQUATION OF THE FORM: ln $(C/C_o) = K$ (Depth)	
	DETENTION POND	CONTROL AREA
Cd	-0.3038	-0.3789
Zn	-0.1116	-0.2358
Mn	-0.1583	-0.1639
Cu	-0.1287	-0.2393
Al	-0.1800	-0.0138
Fe	-0.1561	-0.0800
Pb	-0.1750	-0.1232
Ni	-0.1325	-0.0981
Cr	-0.1712	-0.1088

Site 5 - Commercial Dual Pond Facility

Chemical characteristics of the top 25 cm in sediment core samples collected from retention, detention and control areas at the commercial dual pond facility are indicated in Table 3-47. As observed at each of the previous sites, aluminum and iron were the most abundant metal species measured in sediments at this site. In the sediments of the retention pond, the next most abundant heavy metal was zinc, followed by lead, chromium and approximately equal concentrations of nickel, copper and manganese. However, within the sediments of the detention pond, lead was the most abundant heavy metal measured, followed by zinc, copper, chromium, nickel and manganese.

Vertical attenuation of zinc, copper and lead in sediments of the retention and detention ponds is indicated in Figure 3-29. In general, sediment concentrations in the 0-1 cm layer of zinc, copper and lead were substantially greater in sediments within the detention pond than in sediments within the retention pond. Sediment concentrations for each of these metals within the detention pond appear to peak in the 0-1 cm layer and decline rapidly with increasing sediment depth. Sediment concentrations within the retention pond exhibited a much less gradual decline in concentration with increasing sediment depth. Sediment concentrations within the retention pond generally exceeded those measured in the detention pond at depths greater than 1 cm. It appears that both ponds are able to attenuate and retain heavy metal inputs within the sediments, although metal concentrations appear to migrate to lower depths within the retention pond than within the detention pond.

The vertical attenuation of cadmium, copper, manganese, nickel and chromium in retention and detention pond sediments is indicated in Figure 3-30. In general, the

TABLE 3-47

CHEMICAL CHARACTERISTICS OF THE TOP 25 cm IN SEDIMENT CORE SAMPLES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

SAMPLE	DEPTH LAYER (cm)	ORGANIC CONTENT (%)	SEDIMENT METAL CONCENTRATIONS ($\mu g/g$ dry weight)										
			Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr	P	N
Retention Composite	0-1	4.7	3.2	163	7	8	3,720	1680	52	7	14	3054	12,050
	1-5	4.1	2.7	103	7	6	11,300	2630	42	6	11	1936	5,206
	5-10	1.7	0.7	22	4	3	7,550	1160	19	4	11	1558	2,216
	10-15	1.9	0.5	5	4	2	20,300	2720	15	7	7	1354	1,491
	15-25	1.9	0.5	5	3	2	22,600	2950	13	8	6	811	1,524
Detention Composite	0-1	6.7	3.1	260	11	21	5,500	2910	614	8	11	2126	8,519
	1-5	0.9	1.0	11	5	3	3,000	2390	25	8	10	1198	1,463
	5-10	0.9	0.7	3	2	1	3,990	1620	9	2	3	954	674
	10-15	0.6	0.3	2	1	0.8	6,560	829	7	3	3	966	661
	15-25	1.1	0.3	6	0.7	0.2	5,800	1320	5	2	2	873	616
Control Area	0-1	7.3	4.1	35	14	4	6,300	1530	52	7	11	3178	29,111
	1-5	5.4	2.3	11	9	3	5,970	548	33	4	6	2944	18,949
	5-10	1.2	2.1	6.2	7	2	4,130	450	65	4	5	1213	4,539
	10-15	1.4	1.4	3.6	3	2	3,500	443	17	3	4	633	4,541
	15-25	0.7	0.2	1.4	1	0.7	1,310	187	7	1	2	303	5,795

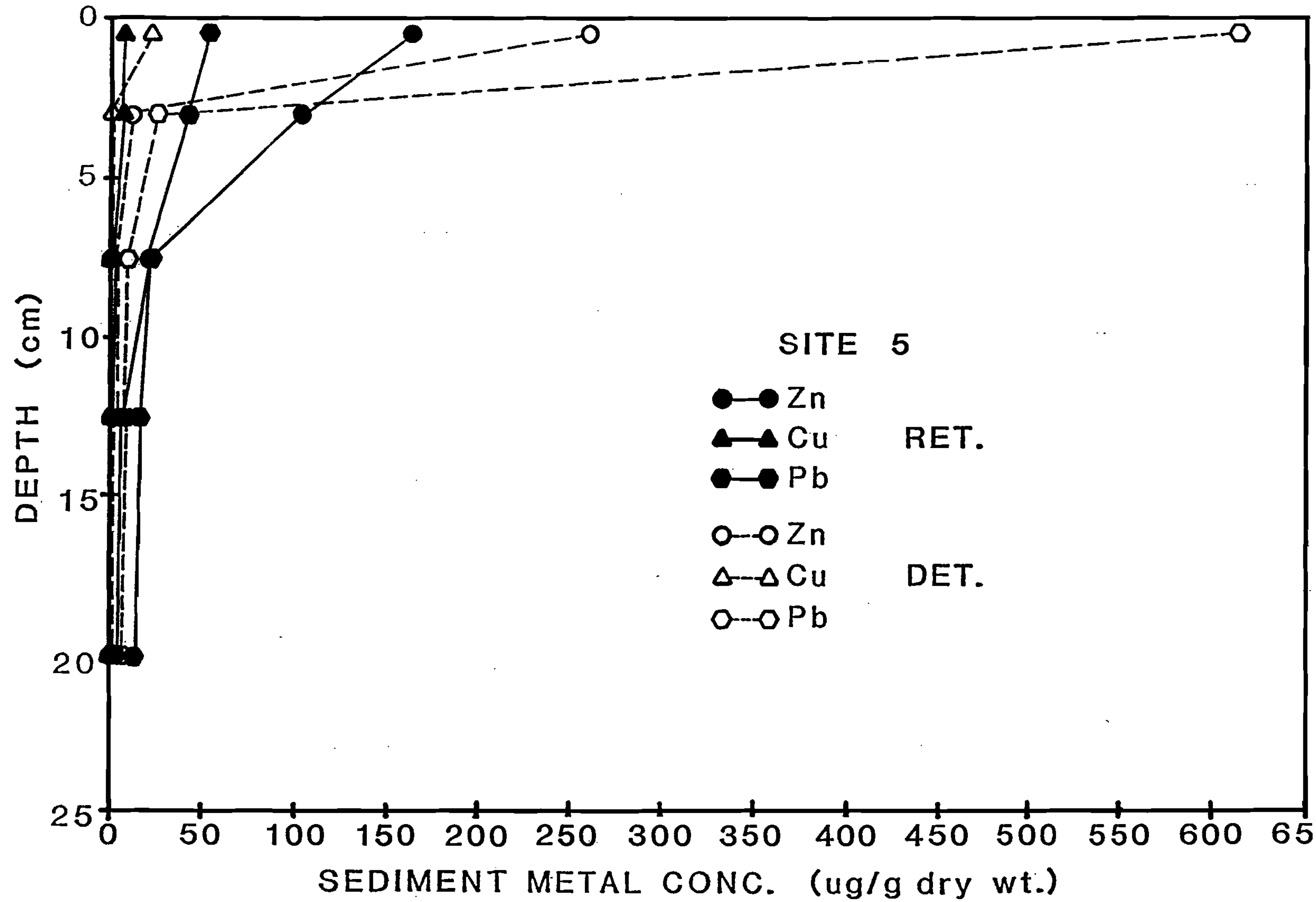


Figure 3-29. Vertical Distribution of Zinc, Copper and Lead in the Top 25 cm of the Retention and Detention Ponds at the Commercial Dual Pond Facility - Site 5.

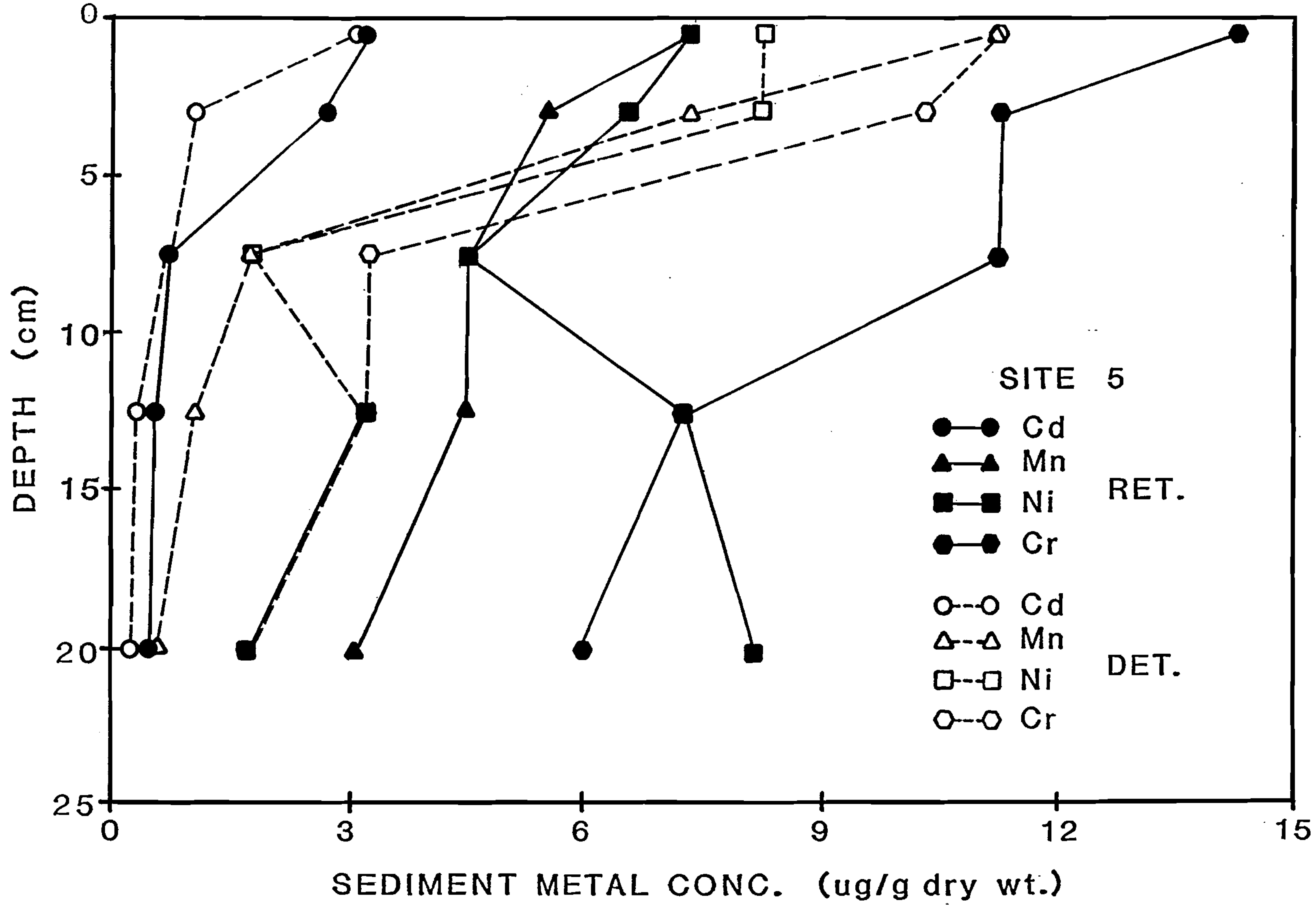


Figure 3-30. Vertical Distribution of Cadmium, Manganese, Nickel and Chromium in the Top 25 cm of the Retention and Detention Ponds at the Commercial Dual Pond Site - Site 5.

accumulation of each of these metals within pond sediments appeared to be relatively low. However, each of these metals exhibited elevated concentrations within the top 5 cm in both ponds, indicating an ability of these metal species to accumulate and be retained within this sediment layer even at the relatively low concentrations measured.

Regression coefficients for the attenuation of heavy metals in sediment cores of the retention, detention and control area is indicated in Table 3-48. Zinc was attenuated at the most rapid rate within the retention pond, followed by cadmium, lead, copper and manganese. Zinc was also attenuated at the most rapid rate within the detention pond, followed by lead, copper, manganese and cadmium.

Relationship Between Sediment Grain Size and Heavy Metal Content

Correlation analyses were conducted to investigate relationships between sediment grain size distributions and heavy metal concentrations in soil layers at the five study sites. Grain size distributions previously given in Table 3-33 for soil layers at the five study sites were regressed against sediment heavy metal concentrations for each of the soil layers. The results of these analyses are given in Table 3-49. In this table, correlation coefficients, indicating the strength of the relationship between a particular heavy metal and a soil grain size particle, are given on the first line of each data entry. The probability of a significant correlation between grain size and metal content is listed on the line below the correlation coefficient, in percent.

As seen in Table 3-49, significant correlations with a probability in excess of 99% were found between all of the heavy metals measured and sediment organic content. As

TABLE 3-48

ATTENUATION OF HEAVY METALS IN SEDIMENT CORES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METAL	VALUE OF K FOR "BEST FIT" EQUATION OF THE FORM: ln (C/C_o) = K (Depth)		
	RETENTION POND	DETENTION POND	CONTROL AREA
Cd	-0.1131	-0.1027	-0.1250
Zn	-0.2103	-0.2883	-0.1756
Mn	-0.0467	-0.1129	-0.1227
Cu	-0.0808	-0.2020	-0.0778
Al	0.1061	0.0418	-0.0678
Fe	0.0255	-0.0587	-0.1120
Pb	-0.0828	-0.2758	-0.0865
Ni	-0.0013	-0.0594	-0.0800
Cr	-0.0311	-0.0337	-0.0884

TABLE 3-49

CORRELATIONS BETWEEN SEDIMENT GRAIN SIZE AND HEAVY METAL CONTENT FOR THE FIVE STUDY SITES

SEDIMENT PARAMETER/ GRAIN SIZE	CORRELATION COEFFICIENT/PROB. OF SIGNIFICANT CORRELATION								
	Cd	Zn	Mn	Cu	Al	Fe	Pb	Ni	Cr
Organic Content	0.795 99.9	0.792 99.9	0.735 99.9	0.777 99.9	0.510 99.8	0.853 99.9	0.760 99.9	0.850 99.9	0.685 99.9
> 2 mm	0.349 96.0	0.342 95.6	0.344 95.7	0.321 94.0	0.670 99.9	0.478 99.6	0.329 94.7	0.480 99.7	0.416 98.7
2.0- 0.85 mm	0.153 62.0	0.160 64.3	0.164 65.4	0.138 57.1	0.600 99.9	0.294 91.5	0.145 59.5	0.294 91.4	0.266 87.8
0.85- 0.425 mm	0.031 14.0	0.066 29.3	0.071 31.6	0.049 22.2	0.218 79.2	0.093 40.7	0.049 22.0	0.097 42.0	0.119 50.2
0.425- 0.018 mm	-0.099 42.9	-0.141 58.1	-0.072 32.0	-0.055 24.5	-0.197 74.3	-0.261 87.0	-0.140 57.9	-0.231 81.8	0.037 16.6
0.018- 0.125 mm	-0.077 33.9	-0.076 33.4	-0.095 41.3	-0.079 34.7	-0.205 76.3	-0.073 32.3	-0.054 24.3	-0.095 41.3	-0.178 69.2
0.125- 0.075 mm	0.047 21.0	0.080 35.2	-0.010 4.5	-0.001 0.7	0.010 4.6	0.159 63.7	0.079 34.8	0.133 55.5	-0.106 45.4
< 0.075 mm	0.503 99.8	0.567 99.9	0.491 99.7	0.489 99.7	0.374 97.3	0.657 99.9	0.552 99.9	0.635 99.9	0.304 92.4

indicated by the magnitude of the correlation coefficients, metal associations with organic content were particularly strong for iron and nickel. Sediment metal content was also strongly correlated with particle sizes greater than 2 mm in diameter, with all probabilities in excess of 94%. Correlations between metal content and particles greater than 2 mm were particularly strong for aluminum, iron and nickel. These associations presumably represent heavy metals bound to large organic particles such as leaves or other organic debris.

Particle sizes less than 2 mm but greater than 0.425 mm in size are included in the category of medium sand. Within this category, only aluminum exhibited a significant correlation between particle size and sediment concentration at the 0.05 level or better. Aluminum was found to be significantly correlated with particle sizes ranging from 0.85-2.0 mm in diameter. Particle sizes smaller than 0.425 mm but greater than 0.075 mm are included in the category of fine sand. None of the heavy metals exhibited significant relationships between sediment concentrations and particle sizes in this range.

Particle sizes smaller than 0.075 mm in diameter are generally classified as silt. With the exception of chromium, all of the heavy metals exhibited strong correlations at the 0.05 level or better between sediment metal concentrations and silt particles, with the strongest correlations exhibited by iron and nickel. It appears, therefore, that heavy metals within the sediments of the five study sites were primarily associated with particles greater than 2 mm in diameter and also with silt particles less than 0.075 mm in diameter, but were poorly correlated with medium or fine sand particles.

Speciation of Heavy Metals and Phosphorus in Sediments at the Five Study Sites

Composite sediment samples collected from swale, pond and control areas at each of the five study sites were processed through a series of chemical extraction steps to identify and quantify sediment-metal associations with the following five fractions: soluble metal ions in the interstitial spaces between soil particles, metals bound to sediments through exchange reactions, bound with precipitates of iron and manganese oxides, bound as precipitates with carbonates and bound in associations with organic matter. It is generally believed that the stability of metal-soil associations increases in the following order: soluble < exchangeable < bound to carbonates < bound to iron and manganese oxides < bound to organic matter.

Soluble sediment metal associations for each depth layer at the five study sites are indicated in Table 3-50. Concentrations of metals and phosphorus are presented in terms of the mass of each species released from the sediments in terms of μg/g of dry sediment during each extraction procedure. In general, only a small portion of the total metals present in the sediments were extracted as soluble fractions. With only a few exceptions, sediment metal release was generally less than 1 μg/g. Soluble fractions of zinc were highest in the swale area at the wet swale site with virtually no soluble sediment associations of zinc at any of the other sites. Soluble phosphorus was also most abundant in sediments at the wet swale site and in the detention pond at site 4 with very little soluble phosphorus in sediments at the other sites. The only remaining metals which exhibited measurable release at any of the sites were aluminum and iron. The largest soluble fractions of both aluminum and iron were found in the retention and detention

TABLE 3-50

SOLUBLE SEDIMENT METAL ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	0-1	0.2	3.3	0.8	0.3	0.3	3	2	1.0	0.1	0.04
	1-5	< 0.01	2.0	0.7	0.1	0.2	4	1	< 0.1	< 0.01	< 0.01
	5-10	0.02	7.5	1.2	0.1	0.1	6	4	1.0	0.2	0.02
	10-15	< 0.01	1.5	0.2	0.1	0.1	3	1	1.0	< 0.01	< 0.01
	15-25	< 0.01	0.7	< 0.1	< 0.1	0.1	3	2	< 0.1	< 0.01	< 0.01
1 Control Area	0-1	< 0.01	< 0.1	1.6	< 0.1	0.1	4	< 1	< 0.1	< 0.01	< 0.01
	1-5	< 0.01	0.2	1.5	0.1	0.2	3	< 1	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	< 0.1	0.4	< 0.1	0.1	5	< 1	< 0.1	< 0.01	< 0.01
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	13	< 1	< 0.1	0.1	0.02
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	14	< 1	< 0.1	0.1	< 0.01
2 Swale Area	0-1	0.03	0.7	0.6	0.2	0.3	< 1	1	1.0	0.1	0.01
	1-5	< 0.01	0.6	0.5	0.1	0.2	6	2	1.0	0.1	0.03
	5-10	< 0.01	0.4	0.8	< 0.1	0.1	7	2	1.0	< 0.01	0.01
	10-15	< 0.01	0.4	< 0.1	< 0.1	0.2	8	1	1.0	< 0.01	< 0.01
	15-25	< 0.01	0.4	< 0.1	< 0.1	0.1	36	4	< 0.1	< 0.01	< 0.01
2 Control Area	0-1	0.06	0.1	< 0.1	0.4	< 0.1	2	< 1	1.0	0.2	0.06
	1-5	< 0.01	0.4	< 0.1	< 0.1	< 0.1	1	< 1	1.0	0.1	0.03
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	0.2	6	1	< 0.1	< 0.01	< 0.01
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	11	1	< 0.1	< 0.01	< 0.01
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	13	< 1	< 0.1	< 0.01	< 0.01

TABLE 3-50 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	0-1	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	5	< 1	< 0.1	< 0.01	0.01
	1-5	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	1	< 1	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	17	< 1	< 0.1	< 0.01	< 0.01
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
3 Detention Pond	0-1	< 0.01	< 0.1	< 0.1	0.3	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
	1-5	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
3 Control Area	0-1	0.01	0.1	3.2	0.2	0.1	2	< 1	< 0.1	< 0.01	< 0.01
	1-5	0.08	0.1	2.8	0.1	0.2	4	1	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	0.1	1.6	0.1	0.4	5	1	< 0.1	< 0.01	< 0.01
	10-15	0.02	< 0.1	1.7	< 0.1	0.3	1	< 1	< 0.1	< 0.01	< 0.01
	15-25	< 0.01	0.1	1.8	< 0.1	0.1	< 1	< 1	< 0.1	< 0.01	< 0.01
4 Detention Pond	0-1	< 0.01	< 0.1	6.4	< 0.1	0.1	11	1	< 0.1	< 0.01	< 0.01
	1-5	0.08	< 0.1	3.2	< 0.1	< 0.1	26	3	< 0.1	< 0.01	0.03
	5-10	0.01	0.1	2.3	< 0.1	< 0.1	24	1	< 0.1	< 0.01	< 0.01
	10-15	0.03	0.1	1.2	0.1	0.1	18	2	< 0.1	0.1	0.06
	15-25	0.03	< 0.1	1.6	< 0.1	< 0.1	5	1	< 0.1	< 0.01	0.03

TABLE 3-50 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	0-1	0.06	0.2	2.4	0.1	0.1	7	2	< 0.1	0.1	0.04
	1-5	0.05	0.1	2.9	< 0.1	0.1	7	3	< 0.1	< 0.01	0.02
	5-10	0.03	0.1	3.6	< 0.1	< 0.1	11	2	< 0.1	0.1	0.02
	10-15	< 0.01	< 0.1	0.1	< 0.1	< 0.1	4	< 1	< 0.1	< 0.01	< 0.01
	15-25	0.03	< 0.1	0.2	< 0.1	0.1	17	1	< 0.1	< 0.01	0.03
5 Retention Pond	0-1	0.11	0.1	< 0.1	< 0.1	< 0.1	4	2	0.8	0.02	0.05
	1-5	< 0.01	0.1	< 0.1	< 0.1	0.1	14	3	0.7	0.10	0.06
	5-10	0.01	< 0.1	< 0.1	< 0.1	< 0.1	22	5	0.8	0.06	0.08
	10-15	0.06	0.1	< 0.1	0.1	0.1	55	13	0.9	0.09	0.12
	15-25	0.02	0.1	5.8	0.2	0.1	513	123	1.1	0.34	0.51
5 Detention Pond	0-1	< 0.01	< 0.1	< 0.1	< 0.1	0.1	16	4	1.0	0.09	0.10
	1-5	0.05	0.4	0.4	0.1	0.1	41	9	1.0	0.11	0.12
	5-10	0.05	< 0.1	2.3	0.1	0.3	100	17	1.5	0.12	0.23
	10-15	< 0.01	< 0.1	< 0.1	0.1	0.1	20	5	0.7	0.06	0.09
	15-25	0.07	< 0.1	< 0.1	0.1	0.2	42	9	0.8	0.20	0.13
5 Control Area	0-1	< 0.01	< 0.1	12.7	< 0.1	0.3	5	1	1.3	0.07	0.11
	1-5	< 0.01	< 0.1	6.2	< 0.1	0.3	12	4	1.0	0.07	0.12
	5-10	< 0.01	< 0.1	20.5	< 0.1	0.3	39	6	0.9	0.09	0.15
	10-15	0.02	< 0.1	< 0.1	0.1	0.1	31	4	1.2	0.12	0.15
	15-25	< 0.01	< 0.1	< 0.1	0.1	0.4	14	2	1.1	0.08	0.10

ponds at site 5, although an elevated release of soluble aluminum was also measured at site 4 as well.

Exchangeable sediment metal associations by depth layer in the five study sites are presented in Table 3-51. In general, release of heavy metals in phosphorus from exchangeable associations is significantly higher than that observed for soluble metal associations. Although there are several exceptions, it appears that exchangeable sediment associations are highest in the surface sediment layers and decrease with increasing sediment depth. Relatively large exchangeable sediment associations are present for cadmium, zinc, lead and nickel in sediments along the wet swale channel, with relatively small exchangeable fractions for each of these metal species at the other study sites.

Sediment associations with carbonates in depth layers at the five study sites are indicated in Table 3-52. In general, metal associations with carbonates are substantially less than those observed for exchangeable or Fe/Mn bonds. For most metals measured, carbonate metal associations are similar to those exhibited for soluble fractions. A distinct tendency for increasing or decreasing carbonate sediment-metal associations with increasing sediment depth is not obvious in Table 3-52 since carbonate associations for many metal species increase with increasing depth.

Sediment associations with iron and manganese oxides are presented in Table 3-53. Strong sediment associations with iron and manganese oxides are found at all sites for zinc, phosphorus, aluminum, iron and chromium. Sediment metal release with the Fe/Mn fraction was substantially larger for these metals than was observed for the exchangeable and soluble fractions. Only cadmium, manganese and nickel exhibited

TABLE 3-51

EXCHANGEABLE SEDIMENT METAL ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	0-1	1.06	37	5.7	2.1	0.4	15	15	110	1.53	0.11
	1-5	0.79	32	4.3	1.3	< 0.1	15	17	148	1.27	0.08
	5-10	0.58	17	3.1	0.8	0.3	226	23	142	1.01	0.05
	10-15	0.52	9.0	3.2	0.7	0.1	202	19	143	1.04	0.04
	15-25	0.50	1.6	3.0	0.7	0.1	345	16	85	0.79	0.04
1 Control Area	0-1	0.55	1.8	4.4	0.9	0.1	330	17	62	0.81	0.08
	1-5	0.36	13	< 0.1	5.0	0.4	< 1	1	< 0.1	0.87	0.06
	5-10	0.41	1.4	3.0	< 0.1	4.0	< 1	< 1	< 0.1	0.93	0.09
	10-15	0.36	0.3	1.3	0.9	< 0.1	9	< 1	< 0.1	0.93	0.10
	15-25	< 0.01	0.1	1.4	0.7	< 0.1	11	< 1	< 0.1	0.89	0.10
2 Swale Area	0-1	0.81	15	2.1	7.0	< 0.1	< 1	< 1	< 0.1	1.03	0.16
	1-5	1.36	28	6.7	14	0.7	< 1	3	1.5	1.06	0.13
	5-10	1.13	15	5.6	6.1	0.2	< 1	< 1	1.7	0.91	0.10
	10-15	1.02	17	4.2	6.2	0.3	< 1	< 1	1.2	0.80	0.08
	15-25	0.95	19	3.1	6.9	0.4	< 1	< 1	0.7	0.82	0.06
2 Control Area	0-1	0.77	4.7	29	12	< 0.1	4	2	< 0.1	0.99	0.21
	1-5	0.63	0.8	20	3.6	< 0.1	5	< 1	< 0.1	0.99	0.18
	5-10	0.39	0.4	12	0.7	< 0.1	11	< 1	< 0.1	0.83	0.13
	10-15	0.33	0.1	10	1.2	< 0.1	7	< 1	< 0.1	0.71	0.10
	15-25	0.38	0.0	9.5	0.9	< 0.1	18	< 1	< 0.1	0.64	0.11

TABLE 3-51 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	0-1	0.36	0.3	1.3	0.8	< 0.1	< 1	< 1	< 0.1	0.53	0.07
	1-5	0.13	0.7	1.1	2.0	0.2	< 1	< 1	< 0.1	0.46	0.01
	5-10	0.06	1.0	0.3	2.1	0.2	< 1	< 1	< 0.1	0.45	< 0.01
	10-15	0.19	1.0	1.2	2.5	0.1	< 1	< 1	< 0.1	0.43	< 0.01
	15-25	0.08	0.6	0.5	2.1	< 0.1	< 1	< 1	< 0.1	0.29	< 0.01
3 Detention Pond	0-1	0.06	1.7	0.1	9.6	0.1	< 1	< 1	< 0.1	0.37	0.02
	1-5	< 0.01	1.3	< 0.1	4.8	0.3	< 1	< 1	< 0.1	0.30	0.01
	5-10	< 0.01	0.8	< 0.1	3.5	0.2	< 1	< 1	< 0.1	0.20	< 0.01
	10-15	< 0.01	0.4	0.2	1.5	< 0.1	< 1	< 1	< 0.1	0.15	< 0.01
	15-25	0.10	1.1	0.8	3.6	0.2	7	< 1	< 0.1	0.26	0.03
3 Control Area	0-1	0.29	7.1	8.3	38	< 0.1	5	1	< 0.1	0.38	0.05
	1-5	0.07	6.3	3.4	24	0.2	12	2	< 0.1	0.32	0.04
	5-10	0.29	3.5	4.5	11	0.7	4	< 1	< 0.1	0.46	0.07
	10-15	0.36	3.2	6.0	10	0.8	5	< 1	< 0.1	0.39	0.09
	15-25	< 0.01	1.1	1.8	2.2	0.4	< 1	< 1	< 0.1	0.07	< 0.01
4 Detention Pond	0-1	0.61	1.7	4.2	5.8	< 0.1	10	< 1	0.3	0.60	0.18
	1-5	0.26	1.2	1.4	1.4	< 0.1	13	1	0.5	0.53	0.11
	5-10	0.06	0.7	5.9	3.6	< 0.1	172	9	2.0	0.60	0.10
	10-15	< 0.01	0.2	2.3	3.2	< 0.1	309	4	< 0.1	0.39	0.05
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	83	< 1	< 0.1	< 0.01	< 0.01

TABLE 3-51 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (µg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	0-1	1.60	21	6.1	5.7	0.1	11	2	1.6	0.32	0.10
	1-5	2.71	7.9	6.3	1.1	0.3	15	3	5.6	0.36	0.10
	5-10	2.26	6.4	4.2	6.5	0.2	7	< 1	< 0.1	0.23	0.09
	10-15	0.43	1.4	2.4	3.4	< 0.1	28	2	3.6	0.19	0.09
	15-25	< 0.01	0.1	0.5	< 0.1	< 0.1	318	2	< 0.1	< 0.01	0.03
5 Retention Pond	0-1	0.22	3.4	2.3	3.4	< 0.1	14	1	4.1	0.40	0.11
	1-5	< 0.1	0.8	< 0.1	1.3	< 0.1	25	< 1	< 0.1	< 0.01	0.02
	5-10	0.14	0.4	1.3	3.2	0.1	24	< 1	< 0.1	0.21	0.09
	10-15	0.23	0.2	1.0	0.5	< 0.1	24	3	< 0.1	0.14	0.09
	15-25	< 0.01	0.4	< 0.1	5.6	< 0.1	8	6	< 0.1	< 0.01	0.05
5 Detention Pond	0-1	0.28	1.0	1.5	6.6	0.1	10	< 1	< 0.1	0.34	0.11
	1-5	0.16	0.1	0.2	0.5	< 0.1	15	3	8.0	0.29	0.07
	5-10	0.98	0.3	6.8	1.4	0.3	48	20	9.4	1.34	0.18
	10-15	0.11	< 0.1	< 0.1	0.2	0.2	6	1	4.1	0.19	0.04
	15-25	< 0.01	0.1	< 0.1	0.1	< 0.1	7	3	< 0.1	< 0.01	0.01
5 Control Area	0-1	0.61	0.8	24	4.6	0.2	9	2	10	0.66	0.20
	1-5	0.49	0.5	10	2.7	0.2	7	1	9.2	0.33	0.15
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 0.1	< 0.01	0.01
	10-15	0.17	< 0.1	1.4	0.2	< 0.1	26	2	4.6	0.27	0.09
	15-25	< 0.01	0.1	0.5	< 0.1	< 0.1	13	< 1	< 0.1	0.05	0.04

TABLE 3-52

CARBONATE SEDIMENT METAL ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	0-1	0.17	0.18	2.6	0.3	0.4	21	2	12	0.38	0.12
	1-5	0.05	0.3	< 0.1	0.1	0.1	13	< 1	9.8	0.22	0.09
	5-10	< 0.01	0.3	< 0.1	< 0.1	< 0.1	7	1	9.1	0.16	0.07
	10-15	< 0.01	0.9	< 0.1	< 0.1	< 0.1	9	1	7.7	0.06	0.05
	15-25	< 0.01	1.9	11	< 0.1	0.1	12	< 1	6.0	0.12	0.08
1 Control Area	0-1	0.15	7.5	3.6	0.3	< 0.1	3	78	< 0.1	< 0.01	< 0.01
	1-5	0.09	7.7	5.3	1.1	0.2	54	2	7.1	< 0.01	0.05
	5-10	1.13	7.2	12	4.6	0.3	30	11	38	1.27	0.47
	10-15	1.27	2.6	7.9	11	0.3	38	7	31	1.71	0.66
	15-25	1.03	1.7	7.3	2.7	0.3	65	5	25	1.32	0.46
2 Swale Area	0-1	2.20	124	25	20	0.6	40	15	176	2.57	0.89
	1-5	1.79	70	23	17	0.4	29	12	156	2.35	0.77
	5-10	1.91	85	18	16	0.5	29	10	212	2.51	0.79
	10-15	1.93	99	20	20	0.8	29	16	223	2.56	0.76
	15-25	1.61	76	17	16	0.8	23	9	209	2.00	0.49
2 Control Area	0-1	0.88	14	70	7.8	0.1	23	5	24	0.77	0.19
	1-5	1.83	37	31	13	0.3	32	12	103	2.47	0.78
	5-10	1.54	3.5	20	4.9	0.1	35	9	135	2.01	0.58
	10-15	1.51	4.4	19	9.6	0.2	38	10	37	2.22	0.68
	15-25	0.93	2.2	12	4.6	< 0.1	35	7	20	1.27	0.36

TABLE 3-52 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	0-1	0.51	5.6	11	5.3	0.3	31	7	8.8	0.73	0.18
	1-5	0.18	1.1	11	2.3	0.5	171	6	1.9	0.32	0.12
	5-10	0.12	0.6	9.0	2.1	0.5	229	8	1.8	0.27	0.12
	10-15	0.21	0.6	9.8	2.4	0.6	223	10	1.9	0.23	0.12
	15-25	0.14	0.7	8.8	3.0	0.7	261	11	1.8	0.24	0.12
3 Detention Pond	0-1	0.26	1.3	11	4.2	0.3	206	11	1.7	0.34	0.15
	1-5	0.17	1.0	9.5	2.3	0.6	341	7	2.5	0.33	0.18
	5-10	0.21	0.8	12	3.1	0.8	442	10	2.2	0.31	0.19
	10-15	0.20	0.3	6.7	1.1	< 0.1	453	5	1.2	0.19	0.17
	15-25	0.14	0.2	7.0	0.6	< 0.1	709	3	1.1	0.22	0.26
3 Control Area	0-1	0.13	2.5	30	8.5	< 0.1	52	3	2.3	0.16	0.06
	1-5	0.17	2.2	27	7.9	0.8	91	3	3.0	0.15	0.10
	5-10	0.12	4.6	20	7.8	3.0	203	2	3.5	0.25	0.15
	10-15	0.11	9.4	29	14	4.7	139	2	4.5	0.67	0.20
	15-25	0.09	4.0	21	6.4	3.0	213	2	3.1	0.07	0.15
4 Detention Pond	0-1	0.02	0.7	7.9	1.9	< 0.1	231	12	5.4	0.09	0.31
	1-5	0.11	0.2	6.9	0.6	< 0.1	388	7	3.2	0.37	0.27
	5-10	0.01	< 0.1	8.6	0.3	< 0.1	623	3	0.9	0.18	0.23
	10-15	0.05	< 0.1	8.9	0.2	< 0.1	672	2	0.8	< 0.01	0.25
	15-25	0.01	0.1	9.0	0.3	< 0.1	690	2	0.3	0.05	0.23

TABLE 3-52 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	0-1	0.22	13	36	3.3	0.2	67	3	4.4	0.15	0.12
	1-5	0.45	9.6	25	2.7	0.3	85	4	3.8	< 0.01	0.17
	5-10	0.51	9.0	19	4.4	0.3	69	3	5.7	< 0.01	0.17
	10-15	< 0.01	0.4	3.6	0.3	< 0.1	179	1	< 0.1	< 0.01	0.11
	15-25	< 0.01	< 0.1	9.0	< 0.1	< 0.1	707	4	< 0.1	< 0.01	0.25
5 Retention Pond	0-1	0.77	117	8.3	3.4	0.1	97	82	32	1.9	0.90
	1-5	0.63	73	6.6	3.1	0.1	160	117	29	1.67	1.02
	5-10	0.07	8.3	< 0.1	1.2	< 0.1	236	36	16	0.44	0.54
	10-15	< 0.01	1.3	< 0.1	0.2	< 0.1	149	32	5.0	< 0.01	0.23
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	121	26	< 0.1	< 0.01	0.06
5 Detention Pond	0-1	0.17	22	1.0	2.4	< 0.1	53	62	8.6	0.19	0.23
	1-5	0.08	1.1	1.3	0.4	< 0.1	84	35	7.0	0.05	0.20
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	237	30	2.9	< 0.01	0.14
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	456	29	2.3	< 0.01	0.14
	15-25	< 0.01	0.3	0.8	< 0.1	< 0.1	373	25	0.2	< 0.01	0.08
5 Control Area	0-1	1.06	7.6	28	3.2	< 0.1	16	6	25	1.45	0.53
	1-5	1.11	5.0	18	4.1	0.2	24	7	33	2.25	0.81
	5-10	1.91	1.2	13	6.8	0.5	51	15	72	5.83	3.09
	10-15	0.40	0.2	5.5	1.5	< 0.1	108	8	9.9	0.61	0.22
	15-25	0.45	0.1	4.9	0.5	0.1	141	10	13	0.72	0.28

TABLE 3-53

IRON/MANGANESE OXIDE SEDIMENT METAL ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE ($\mu g/g$ dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	0-1	0.76	61	63	2.3	0.9	1130	515	173	2.10	1.08
	1-5	0.24	31	42	0.7	0.4	889	218	105	0.87	0.77
	5-10	0.11	15	46	0.1	0.2	1290	156	41	0.33	0.49
	10-15	0.13	12	28	0.1	0.2	1660	160	44	0.39	0.63
	15-25	0.09	2.2	16	< 0.1	0.1	1540	71	12	0.16	0.49
1 Control Area	0-1	< 0.01	2.9	35	0.4	< 0.1	607	26	0.5	0.12	0.18
	1-5	0.04	18	52	0.6	< 0.1	778	83	6.2	0.21	0.18
	5-10	< 0.01	19	42	0.8	0.1	532	116	14	0.50	0.31
	10-15	0.04	11	44	1.8	0.3	843	96	5.1	0.47	0.36
	15-25	0.01	12	44	2.0	0.6	1220	144	4.5	0.56	0.44
2 Swale Area	0-1	1.98	335	164	33	3.3	630	797	341	7.05	4.34
	1-5	1.54	202	124	16	2.6	490	626	289	5.25	3.09
	5-10	0.69	158	120	12	2.8	728	635	226	2.88	1.92
	10-15	0.52	165	100	12	3.5	628	715	231	2.55	1.42
	15-25	0.32	96	68	6.5	3.3	675	524	158	1.95	1.15
2 Control Area	0-1	0.12	50	270	9.7	0.2	1650	302	25	0.53	0.47
	1-5	0.24	24	103	11	0.1	855	383	28	1.06	0.65
	5-10	0.13	16	107	15	0.8	1170	398	130	0.71	0.89
	10-15	0.16	15	114	8.2	0.1	1270	359	11	0.70	0.59
	15-25	0.08	6.4	132	7.2	0.4	1450	303	5.6	0.69	1.87

TABLE 3-53 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	0-1	0.10	14	183	3.1	2.2	1890	249	2.7	0.76	1.33
	1-5	0.04	2.3	92	0.6	1.3	1200	112	< 0.1	0.32	0.56
	5-10	< 0.01	1.2	102	0.7	1.2	1280	117	< 0.1	0.23	0.52
	10-15	0.03	1.6	96	0.9	1.5	1320	123	< 0.1	0.28	0.61
	15-25	< 0.01	2.0	111	1.5	1.8	1650	180	< 0.1	0.45	0.74
3 Detention Pond	0-1	< 0.01	< 0.1	74.1	2.7	0.5	968	127	< 0.1	0.18	0.46
	1-5	< 0.01	1.7	169	1.0	1.4	2030	112	< 0.1	0.14	0.90
	5-10	< 0.01	1.0	195	1.3	1.4	2460	143	< 0.1	0.18	1.16
	10-15	< 0.01	0.1	222	0.6	0.4	2890	72	0.2	0.12	1.25
	15-25	< 0.01	< 0.1	251	0.2	0.1	3940	53	0.1	0.12	1.85
3 Control Area	0-1	< 0.01	2.9	118	7.5	< 0.1	289	170	0.8	0.08	0.27
	1-5	< 0.01	4.0	169	9.5	1.8	908	156	1.8	0.10	0.83
	5-10	< 0.01	8.8	292	25	7.9	1710	273	1.9	0.44	1.54
	10-15	0.17	16	406	39	14	1630	287	5.1	0.57	2.53
	15-25	0.05	6.9	307	15	7.4	1700	251	1.8	0.42	1.18
4 Detention Pond	0-1	0.14	21	79	1.6	0.2	3860	373	0.2	1.83	1.61
	1-5	0.04	6.0	92	0.5	0.1	2770	136	0.3	1.57	0.97
	5-10	0.07	1.3	73	0.1	< 0.1	1730	50	< 0.1	0.54	0.58
	10-15	0.01	0.3	63	< 0.1	0.1	1500	26	< 0.1	0.31	0.47
	15-25	< 0.01	0.1	51	< 0.1	< 0.1	1230	20	< 0.1	0.28	0.39

TABLE 3-53 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	0-1	0.32	38	195	3.7	0.8	1520	294	4.1	0.56	0.75
	1-5	0.70	32	270	3.9	2.8	1750	363	4.7	0.87	1.25
	5-10	0.69	34	218	9.0	2.4	1540	1140	8.3	1.03	1.27
	10-15	0.03	5.7	102	0.6	0.7	1700	83	0.3	0.27	0.64
	15-25	< 0.01	1.1	70	0.1	< 0.1	1680	64	< 0.1	0.32	0.60
5 Retention Pond	0-1	0.17	53	51	0.9	0.9	569	950	5.3	0.80	0.51
	1-5	0.06	45	24	1.0	0.6	680	852	1.1	0.58	0.34
	5-10	0.03	9.4	9.5	0.5	0.1	732	317	< 0.1	0.46	0.32
	10-15	0.11	6.2	4.3	0.2	0.6	1240	385	< 0.1	0.51	0.50
	15-25	0.01	0.8	2.2	0.2	< 0.1	1460	859	< 0.1	0.63	0.70
5 Detention Pond	0-1	0.19	17.1	49.3	1.3	0.1	531	1560	0.8	0.51	0.26
	1-5	< 0.01	2.0	8.4	0.2	0.2	302	409	< 0.1	0.17	0.08
	5-10	< 0.01	0.7	2.0	< 0.1	0.1	491	181	< 0.1	0.20	0.11
	10-15	0.02	0.3	5.1	0.1	< 0.1	597	117	0.6	0.31	0.15
	15-25	0.03	0.2	2.0	0.1	< 0.1	425	83	< 0.1	0.21	0.11
5 Control Area	0-1	0.19	7.3	34	0.9	0.4	307	196	3.7	0.34	0.18
	1-5	0.19	3.4	46	0.6	0.1	231	148	3.9	0.20	0.20
	5-10	0.41	1.3	29	0.8	0.1	393	213	7.9	0.65	0.58
	10-15	0.11	0.9	7.3	0.2	0.1	425	94	1.5	0.11	0.12
	15-25	0.16	0.9	3.0	< 0.1	< 0.1	226	39	2.0	0.10	0.06

stronger associations with exchangeable or soluble fractions than with iron and manganese oxides. In general, it appears that the importance of Fe/Mn oxide sediment associations decreases with increasing sediment depth, although there are many exceptions to this generality in Table 3-53.

Organic sediment metal associations in depth layers at the five study sites are given in Table 3-54. In general, organic sediment associations were relatively large for each of the heavy metals measured. Elements such as phosphorus, copper and chromium exhibited a larger organic sediment association than with any other sediment bond. Strong organic associations were also found for cadmium, aluminum, iron and nickel although this was not the dominant bonding mechanism for these metals in sediments. For most metals, it appeared that organic sediment associations decreased with increasing sediment depth. The primary exception to this generality is aluminum which exhibited both decreases and increases in organic associations with increasing sediment depth.

An overall summary of metal sediment associations in depth layers at the five study sites is given in Table 3-55. Sediment associations are given in terms of the percent of total metal release for each fraction in the top 0-25 cm layer combined. A discussion of sediment bonding mechanisms at each of the five study sites is given in the following sections.

Site 1 - Wet Swale Channel

Bonding mechanisms for heavy metals in swale and control areas at the wet swale site (site 1) appear to vary considerably between the measured metal species. Heavy metals such as cadmium, zinc, manganese, lead and nickel in sediments along the swale

TABLE 3-54

ORGANIC BOUND METAL SEDIMENT ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (μg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	0-1	0.23	8.3	140	0.6	12	517	245	47	0.65	1.78
	1-5	0.20	5.8	61	0.4	6.2	306	187	27	0.45	1.38
	5-10	0.14	2.6	63	0.4	3.8	433	140	15	0.36	0.87
	10-15	0.10	2.2	35	0.3	2.2	396	135	13	0.25	0.57
	15-25	0.06	0.9	18	0.3	1.2	245	16	4.2	0.22	0.32
1 Control Area	0-1	0.05	0.6	16	0.3	0.2	74	2	1.0	0.30	0.16
	1-5	< 0.01	3.3	70	0.4	1.4	358	27	< 0.1	0.71	0.46
	5-10	< 0.01	2.6	52	0.1	1.8	411	28	4.8	0.52	0.38
	10-15	< 0.01	2.5	35	0.2	1.4	400	20	< 0.1	0.41	0.41
	15-25	< 0.01	3.0	41	0.3	2.1	617	21	0.1	0.55	0.55
2 Swale Area	0-1	0.38	47	231	2.1	28	1100	321	138	2.03	3.26
	1-5	0.20	21	255	1.8	23	1300	282	103	2.04	3.24
	5-10	< 0.01	5.5	50	0.1	6.5	389	52	32	0.11	0.92
	10-15	0.16	9.6	119	0.8	15	785	127	62	0.58	1.77
	15-25	< 0.01	7.5	92	0.6	8.0	761	60	31	0.62	1.06
2 Control Area	0-1	0.19	5.9	964	0.7	5.2	2440	127	4.7	0.82	1.63
	1-5	< 0.01	2.8	148	0.3	2.4	930	83	< 0.1	< 0.01	0.65
	5-10	< 0.01	12	80	0.2	1.2	623	31	8.5	< 0.01	0.72
	10-15	< 0.01	1.8	151	0.1	1.5	734	42	< 0.1	< 0.01	0.49
	15-25	< 0.01	0.9	88	< 0.1	1.2	640	28	1.0	< 0.01	1.01

TABLE 3-54 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE ($\mu g/g$ dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	0-1	< 0.01	1.0	149	0.2	6.1	1070	40	< 0.1	< 0.01	0.84
	1-5	< 0.01	< 0.1	49	< 0.1	2.2	479	16	< 0.1	< 0.01	0.10
	5-10	< 0.01	< 0.1	85	< 0.1	2.2	641	19	< 0.1	< 0.01	0.12
	10-15	< 0.01	< 0.1	68	< 0.1	2.6	652	18	< 0.1	< 0.01	0.19
	15-25	< 0.01	< 0.1	91	< 0.1	3.3	867	28	< 0.1	< 0.01	0.24
3 Detention Pond	0-1	< 0.01	< 0.1	107	< 0.1	3.5	762	29	< 0.1	< 0.01	0.16
	1-5	< 0.01	< 0.1	137	< 0.1	3.1	1030	35	< 0.1	< 0.01	0.25
	5-10	< 0.01	< 0.1	187	< 0.1	2.6	1450	38	< 0.1	< 0.01	0.40
	10-15	< 0.01	< 0.1	246	< 0.1	0.9	1610	7	< 0.1	< 0.01	0.12
	15-25	< 0.01	< 0.1	355	< 0.1	0.7	2210	4	< 0.1	< 0.01	0.32
3 Control Area	0-1	< 0.01	< 0.1	166	< 0.1	4.2	793	49	< 0.1	< 0.01	0.27
	1-5	< 0.01	< 0.1	161	< 0.1	15	721	43	< 0.1	< 0.01	1.40
	5-10	< 0.01	< 0.1	409	< 0.1	35	2000	77	< 0.1	< 0.01	2.44
	10-15	< 0.01	< 0.1	499	< 0.1	52	1970	81	< 0.1	< 0.01	5.34
	15-25	< 0.01	< 0.1	378	< 0.1	39	2220	85	< 0.1	< 0.01	1.81
4 Detention Pond	0-1	< 0.01	2.0	313	< 0.1	2.4	2830	31	< 0.1	0.91	1.65
	1-5	< 0.01	< 0.1	107	< 0.1	0.9	1260	16	< 0.1	0.15	0.60
	5-10	< 0.01	< 0.1	25	< 0.1	0.3	508	4	< 0.1	< 0.01	0.20
	10-15	< 0.01	< 0.1	25	< 0.1	0.3	593	2	0.1	0.02	0.19
	15-25	0.02	< 0.1	24	< 0.1	0.2	540	1	1.4	0.09	0.34

TABLE 3-54 -- CONTINUED

SITE	DEPTH LAYER (cm)	SEDIMENT METAL RELEASE (µg/g dry sediment)									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	0-1	< 0.01	3.7	117	< 0.1	5.8	535	61	2.9	0.31	1.13
	1-5	0.14	1.8	134	< 0.1	8.6	515	40	3.7	0.27	1.35
	5-10	0.14	2.7	131	< 0.1	8.6	585	76	5.5	0.31	1.14
	10-15	0.01	< 0.1	53	< 0.1	1.3	512	9	3.6	0.27	0.74
	15-25	< 0.01	< 0.1	40	< 0.1	0.4	572	7	2.7	0.15	0.47
5 Retention Pond	0-1	< 0.01	0.9	15	< 0.1	2.7	198	63	< 0.1	< 0.01	0.30
	1-5	< 0.01	0.2	14	< 0.1	2.3	325	78	< 0.1	< 0.01	0.26
	5-10	< 0.01	< 0.1	4.1	< 0.1	0.4	337	35	< 0.1	< 0.01	< 0.01
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	0.3	579	24	< 0.1	< 0.01	0.13
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	0.1	782	20	< 0.1	< 0.01	0.36
5 Detention Pond	0-1	< 0.01	< 0.1	14	< 0.1	1.0	217	96	< 0.1	< 0.01	0.06
	1-5	< 0.01	< 0.1	< 0.1	< 0.1	0.1	153	22	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	< 0.1	< 0.1	< 0.1	0.2	226	16	< 0.1	0.06	0.03
	10-15	< 0.01	< 0.1	< 0.1	< 0.1	0.2	218	12	< 0.1	0.04	0.03
	15-25	< 0.01	< 0.1	< 0.1	< 0.1	0.1	214	12	< 0.1	0.04	0.03
5 Control Area	0-1	< 0.01	0.2	42	< 0.1	0.7	239	66	< 0.1	0.20	0.36
	1-5	< 0.01	< 0.1	< 0.1	< 0.1	< 0.1	6	< 1	< 0.1	< 0.01	< 0.01
	5-10	< 0.01	0.3	11	< 0.1	1.0	385	29	< 0.1	0.10	0.46
	10-15	< 0.01	< 0.1	19	< 0.1	0.3	151	33	< 0.1	0.03	0.22
	15-25		< 0.1	4.7	< 0.1	0.4	167	13	< 0.1	0.06	0.22

TABLE 3-55

SUMMARY OF METAL SEDIMENT ASSOCIATIONS IN DEPTH LAYERS AT THE FIVE STUDY SITES

SITE	SPECIES	PERCENT OF TOTAL METAL RELEASE BY SPECIES									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
1 Swale Area	Soluble	4.2	5.8	0.6	5.7	2.7	0.2	0.5	0.3	1.9	1.0
	Exchange	57.4	37.7	3.4	45.5	3.4	8.6	4.6	54.3	44.7	3.7
	Fe/Mn	22.1	47.2	35.6	26.8	5.4	70.1	57.5	32.3	30.6	39.8
	Carbonate	4.2	1.6	2.4	5.7	2.7	0.7	0.3	3.9	7.5	4.7
	Organic	12.1	7.7	58.0	16.3	85.8	20.4	37.1	9.2	15.3	50.8
1 Control Area	Soluble	0.9	0.5	0.8	1.5	4.1	0.6	0.7	0.3	1.7	1.1
	Exchange	30.1	14.0	2.6	23.1	32.2	5.4	3.0	31.1	33.2	7.7
	Fe/Mn	2.0	53.0	44.8	11.5	8.2	62.0	67.2	1.1	14.0	26.4
	Carbonate	65.4	22.5	7.5	69.9	8.2	3.0	14.9	50.5	32.4	29.6
	Organic	1.6	10.0	44.3	4.0	47.3	29.0	14.2	3.0	18.7	35.2
2 Swale Area	Soluble	0.4	0.2	0.1	0.3	0.9	0.8	0.2	0.2	0.6	0.3
	Exchange	21.7	4.9	1.2	1.4	1.4	0.1	0.1	0.2	9.3	1.7
	Fe/Mn	25.8	60.5	39.9	15.2	15.2	40.9	78.2	48.0	47.8	45.2
	Carbonate	48.2	28.7	7.1	3.1	3.1	1.9	1.5	37.5	29.2	14.0
	Organic	3.9	5.7	51.7	79.4	79.4	56.3	20.0	14.1	13.1	38.8
2 Control Area	Soluble	1.0	0.4	0.0	0.7	4.0	0.3	0.3	0.4	1.9	1.0
	Exchange	24.4	3.0	3.4	16.5	3.3	0.4	0.3	0.1	23.8	5.9
	Fe/Mn	7.1	55.0	30.4	45.8	10.7	53.3	79.8	37.3	21.1	36.0
	Carbonate	65.3	30.1	6.4	35.8	5.3	1.4	2.4	59.5	48.4	20.9
	Organic	2.2	11.5	59.8	1.2	76.7	44.6	17.2	2.7	4.8	36.2

TABLE 3-55 -- CONTINUED

SITE	SPECIES	PERCENT OF TOTAL METAL RELEASE BY SPECIES									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
3 Retention Pond	Soluble	2.2	1.4	0.0	1.6	1.7	0.2	0.5	2.4	0.8	0.9
	Exchange	36.1	10.2	0.4	30.2	2.5	0.0	0.5	2.4	35.5	1.8
	Fe/Mn	8.4	59.9	54.1	18.4	28.4	61.2	81.9	14.9	33.5	61.9
	Carbonate	51.1	24.4	4.6	47.9	9.2	7.7	4.4	77.9	29.4	10.9
	Organic	2.2	4.1	40.9	1.9	58.2	30.9	12.7	2.4	0.8	24.5
3 Detention Pond	Soluble	3.8	3.9	0.0	1.7	2.8	0.0	0.8	4.6	1.4	0.6
	Exchange	14.4	41.1	0.1	55.7	5.1	0.1	0.8	4.6	36.5	1.0
	Fe/Mn	3.8	23.2	45.8	14.0	21.2	57.1	76.1	5.6	21.1	70.8
	Carbonate	74.2	27.9	2.3	27.4	10.6	10.0	5.3	80.6	39.6	11.9
	Organic	3.8	3.9	51.8	1.2	60.3	32.8	17.0	4.6	1.4	15.7
3 Control Area	Soluble	6.2	0.6	0.4	0.3	0.6	0.1	0.3	1.7	0.9	0.3
	Exchange	49.3	25.4	0.8	37.5	1.1	0.2	0.4	1.7	30.3	1.4
	Fe/Mn	12.1	46.2	42.1	42.3	16.3	42.5	76.1	38.9	43.6	34.8
	Carbonate	30.0	27.2	4.1	19.7	6.1	4.7	0.8	56.0	24.3	3.5
	Organic	2.4	0.6	52.6	0.2	75.9	52.5	22.4	1.7	0.9	60.0
4 Detention Pond	Soluble	9.7	1.4	1.6	2.4	8.1	0.4	1.1	3.0	1.6	1.5
	Exchange	57.9	10.6	1.5	67.8	8.1	2.9	2.3	18.0	24.5	5.1
	Fe/Mn	16.5	78.2	38.8	11.5	9.6	55.2	85.3	4.8	52.2	45.3
	Carbonate	12.2	3.3	4.5	15.9	8.1	13.0	3.7	63.4	8.1	14.5
	Organic	3.7	6.5	53.6	2.4	66.1	28.5	7.6	10.8	13.6	33.6

TABLE 3-55 -- CONTINUED

SITE	SPECIES	PERCENT OF TOTAL METAL RELEASE BY SPECIES									
		Cd	Zn	P	Mn	Cu	Al	Fe	Pb	Ni	Cr
4 Control Area	Soluble	1.7	0.3	0.6	1.1	1.5	0.4	0.4	0.8	3.9	1.1
	Exchange	67.1	19.5	1.3	36.6	2.4	3.0	0.5	17.9	18.8	3.8
	Fe/Mn	16.7	58.7	59.0	37.7	20.1	65.9	89.5	28.4	51.8	42.2
	Carbonate	11.5	17.0	6.4	23.5	3.0	8.9	0.7	22.9	3.2	7.7
	Organic	3.0	4.5	32.7	1.1	73.0	21.8	8.9	30.0	22.3	45.2
5 Retention Pond	Soluble	7.4	0.2	4.1	1.9	5.2	7.3	4.0	4.4	7.2	11.1
	Exchange	24.7	1.6	3.2	53.0	5.2	1.1	0.3	4.6	9.1	4.9
	Fe/Mn	13.4	35.6	60.5	10.6	23.9	56.0	81.7	6.8	35.3	32.2
	Carbonate	52.7	62.2	10.1	32.6	5.2	9.1	8.0	83.7	47.8	37.4
	Organic	1.8	0.4	22.1	1.9	60.5	26.5	6.0	0.5	0.6	14.4
5 Detention Pond	Soluble	8.2	1.7	3.2	3.4	18.6	4.5	1.6	10.0	12.7	24.4
	Exchange	66.4	3.4	9.0	59.9	18.6	1.8	1.0	43.5	47.4	15.0
	Fe/Mn	11.2	43.4	69.4	12.2	14.0	48.0	85.1	3.4	30.6	25.9
	Carbonate	12.1	50.4	3.4	21.1	11.6	24.6	6.6	42.1	5.9	28.8
	Organic	2.1	1.1	15.0	3.4	37.2	21.1	5.7	1.0	3.4	5.9
5 Control Area	Soluble	0.7	1.3	4.3	1.5	18.0	2.9	1.4	2.2	2.5	6.1
	Exchange	17.5	5.2	11.4	28.2	11.5	1.8	0.8	11.9	10.5	5.9
	Fe/Mn	14.4	45.0	37.9	9.5	13.1	52.5	76.8	9.5	9.6	13.7
	Carbonate	66.8	45.9	22.0	59.0	16.4	11.3	5.1	76.1	74.7	59.1
	Organic	0.6	2.6	24.4	1.8	41.0	31.5	15.9	0.3	2.7	15.2

channel are associated primarily with relatively weak soluble and exchange fractions. These weak sediment bonding mechanisms suggest that metal species may be easily released from the sediment phase into either surface waters or groundwaters under conditions which exist along the swale channel.

With the exception of copper, relatively strong associations were found for all metals along the wet swale channel with Fe/Mn oxide fractions which are believed to be somewhat more stable sediment mechanisms than either soluble or exchangeable bonds. In the case of zinc, aluminum and iron, this fraction represented the dominant bonding force in sediments along the swale channel. Carbonate sediment associations represented a relatively small portion of the total release for all metal species. Significant organic associations were also found for most metal species along the swale channel, and for phosphorus, copper and chromium organic associations represented the dominant sediment bonding mechanism. Metal species exhibiting a strong organic association are generally expected to be more stable and to be released to a lesser degree from sediments than other metal species.

Sediment bonding mechanisms in the control area at site 1 appeared to be somewhat stronger than those measured along the swale channel. The relatively weak soluble and exchangeable bonds for all metals except copper and chromium appeared to be much less significant along the control area than along the swale area. Stronger bonding mechanisms such as Fe/Mn fractions, carbonate fractions and organic associations were more dominant for many metal species. The increase in carbonate associations was particularly evident for virtually all metal species. These differences in sediment characteristics suggest that metal associations in sediments in the control area may be more stable and released to a lesser degree than sediments along the swale area.

Site 2 - Dry Swale Channel

As seen in Table 3-55, the importance of soluble and exchange fractions along the swale channel at the dry swale site (site 2) were significantly less than observed along the wet swale channel. Soluble associations were extremely small for all metal species and with the exception of cadmium, manganese and nickel, exchange fractions were small as well. The dominant bonding mechanisms for metal species in sediments along the dry swale appeared to be the relatively stable Fe/Mn, carbonate and organic fractions. Zinc, manganese, iron, lead, nickel and chromium were most strongly associated with iron and manganese oxides, while cadmium was strongly associated with carbonates. Phosphorus, copper and aluminum exhibited strong organic bonds. In general, it appeared that bonding mechanisms for metals within the sediments of the dry swale site were substantially stronger and presented less potential for release into groundwaters than those observed along the wet swale channel.

Bonding mechanisms for heavy metals in sediments at the control area at site 2 were similar to those observed along the swale channel. Although slight differences existed in the percentages associated with a particular metal sediment fraction, the dominant bonding mechanism for all metal species was the same in both swale and control areas, with the possible exceptions of aluminum and nickel. There appeared to be little difference in the sediment stability for metal species between these two areas.

Site 3 - Residential Dual Pond Site

With few exceptions, metal sediment speciation at the residential dual pond site appeared to be relatively similar for the retention and detention pond sediments. Soluble metal associations of approximately 1% or greater were found in both ponds for cadmium, zinc, manganese, copper, lead and nickel. Relatively large exchangeable fractions were also observed for cadmium, zinc, manganese and nickel, suggesting that these metals were bound into the sediments in relatively weak associations and may be subject to leaching or mobilization from the sediments into the water phase.

Strong sediment associations with Fe/Mn oxides were found for zinc, phosphorus, copper, aluminum, iron, nickel and chromium. In the case of zinc, phosphorus, aluminum, iron and chromium, Fe/Mn oxide bonds represented the dominant bonding force for these metal species in the pond sediments of both retention and detention areas. Relatively strong carbonate associations were found for virtually all metals with carbonate associations representing the dominant bonding mechanism for cadmium and lead within the sediments of each pond.

Significant organic associations were also found for all metal species. In the case of copper, as well as phosphorus in sediments of the detention pond, organic bonds represented the dominant bonding mechanism. Based upon the sediment speciations for each of the individual metal species, cadmium, zinc, manganese, and nickel existed in significant associations with relatively weak soluble and exchange fractions and should exhibit a potential for release of these metal ions from the sediment phase to the water phase. On the other hand, relatively strong sediment bonding mechanisms were observed for phosphorus, copper, aluminum, iron, lead and chromium. Each of these metals would be expected to exhibit relatively little potential for release from the sediments into the water phase.

Sediment metal speciation within the control area, with the possible exceptions of cadmium, zinc and lead, appeared to shift toward increased associations with the more stable sediment bonds and decreased associations with the less stable sediment bonds. For example, phosphorus, copper, aluminum, iron and chromium exhibited increases in stable organic associations and decreases in less stable soluble and exchangeable forms within soils collected in the control area. On the other hand, cadmium exhibited a significant increase in percentage of both soluble and exchangeable forms within the control area compared to those measured in the retention and detention ponds.

Site 4 - Residential Wet Detention Facility

As seen in Table 3-55, virtually all measured metal species exhibited a relatively high soluble fraction within sediments collected within the detention pond. This soluble fraction found in sediments of the detention pond was substantially greater, with the exceptions of aluminum and nickel, than soluble fractions measured in soils of the control area. Several metal species, such as cadmium, zinc, manganese, lead and nickel, were found to have relatively large exchangeable fractions within sediments of the detention pond as well.

Significant Fe/Mn sediment associations were observed for virtually all metal species, representing the dominant bonding mechanisms for zinc, aluminum, iron, nickel and chromium. A similar pattern was observed in the sediments collected within the control area. Although significant levels of carbonate fractions were found for virtually all heavy metals, carbonate sediment associations represented the dominant bonding mechanism only for lead. Stable organic associations were found to be the dominant bonding mechanisms for phosphorus and copper in sediments of the detention pond.

Sediments collected within the control area were found to exhibit stronger bonding mechanisms for certain heavy metals compared with those measured in sediments of the detention pond, while exhibiting weaker bonding mechanisms for other heavy metals. For example, both cadmium and zinc were found to have an increased percentage of relatively weak exchange associations within sediments of the control area compared with associations measured in the detention pond. Phosphorus and aluminum were found to have decreased percentages of stable organic fractions and increases in less stable Fe/Mn fractions. The remaining heavy metals appeared to exhibit increases in the strength of sediment bonding mechanisms. For example, manganese exhibited reductions in weak exchangeable fractions within the detention pond and increases in more stable Fe/Mn and carbonate associations within the control area. Decreased associations with exchangeable bonds were also observed for nickel and chromium which exhibited increases in stable organic associations within the control area.

Site 5 - Commercial Dual Pond Facility

Sediment metal associations in pond and control areas at the commercial dual pond facility were quite variable between the three locations and between individual metal species. In the sediments of the retention pond, the dominant bonding mechanism for heavy metals appeared to be relatively strong Fe/Mn, carbonate and organic fractions. These stronger associations represented the dominant bonding mechanisms for all heavy metals with the exception of manganese, which was associated primarily with the exchange fraction. However, in spite of the dominance of strong sediment-metal associations, each of the heavy metals also exhibited relatively large exchangeable and soluble fractions, particularly cadmium, nickel and chromium. Therefore, even though the majority of sediment associated metals were bound with relatively strong fractions, significant release of metal ions, particularly cadmium and manganese, can be expected under conditions which exist in the sediments of the retention pond.

As seen in Table 3-55, virtually all metal species exhibited increased associations with weaker sediment bonding mechanisms in sediments of the detention pond compared with sediments in the retention pond. For example, the dominant bonding mechanism for cadmium in the retention pond was found to be relatively strong carbonate bonds, while within the sediments of the detention pond the primarily bonding mechanism was weak exchange associations. Manganese also increased in exchangeable fractions, as did copper, lead, nickel and chromium. Substantial increases in soluble metal associations were also observed within sediments of the detention pond for cadmium, zinc, manganese, copper, lead, nickel and chromium while the percentage of relatively stable organic associations decreased in the sediments of the detention pond for virtually every heavy metal. It is apparent that conditions which exist in the sediments of the detention pond created an environment which was less favorable for the retention and accumulation of metal species within the pond.

With the possible exception of copper, bonding mechanisms for metals in the sediments of the control area were similar to those found in sediments of the retention pond. The primary bonding mechanisms for metals found in the control area appeared to be Fe/Mn, carbonate and organic fractions. Soluble metal fractions were somewhat lower for most metal species in the control area than in the retention pond, while exchangeable fractions for many metal species were greater in the control area than in the retention pond. Overall, however, the potential for release of metal species into surface waters or groundwaters should be relatively similar between the retention and control areas.

Characteristics of Groundwater at the Five Study Sites

Chemical characteristics of groundwater beneath swale, pond and control areas at each of the five study sites was monitored using a total of 12 multi-port groundwater monitoring wells installed at locations described in Chapter 2. Groundwater monitoring was conducted from each of the five sample ports at each monitoring well on a monthly basis for a 12-month period from January to December 1987. A complete listing of general chemical characteristics and heavy metal concentrations measured in monitoring wells at the five sites is given in the Appendices to this report contained in a separate document.

The results of groundwater monitoring at each of the five study sites are presented in the following sections. Simple descriptive statistics, such as number of observations, mean values, range of values and the coefficient of variation were calculated for each sample port at each of the 12 monitoring wells. Presentation of these detailed summary statistics required a total of 70 separate table pages. These tables have been grouped together in an appendix at the end of this volume, titled as Appendix A. References will be made to these tables where appropriate in the text. Only mean values of chemical parameters will be presented in tables contained in this chapter.

Statistical analyses were also performed using analysis of variance procedures to test for equality of mean values for both general groundwater constituents and heavy metals beneath control and stormwater treatment areas. Separate analyses were conducted for each of the five test sites. In these analyses, data from the five sample ports for an individual well were grouped together to form a single data set. This grouping of data allowed statistical testing for equality of means in groundwater characteristics beneath control and stormwater management areas which was independent of influence from any individual sample port. The multiple comparison technique of Tukey was used to detect where significant differences or similarities occurred between the various wells. Tukey's test is generally considered to be conservative and will often produce findings of significant difference more frequently than other multiple comparison techniques such as those of Bonferonni or Scheffe. Since the purpose of these investigations was to detect any potential evidence of groundwater pollution by stormwater management systems, a conservative comparison test was thought to be appropriate.

Site 1 - Wet Swale Site

Detailed summary statistics for general water quality characteristics in groundwater samples collected from beneath the wet swale channel at site 1 are given in Table A-1. A total of 12 samples were collected at each of the five sample ports during 1987. In general, variability in chemical characteristics for measured parameters appears to be substantially less in groundwaters than observed for the same parameters in surface waters along the wet swale channel. The most variable parameters in groundwater appear to be alkalinity, orthophosphorus, organic phosphorus, total phosphorus and color. The range of concentrations for virtually all measured parameters extended over less than one order of magnitude, while variability in concentrations in surface water samples extended over several orders of magnitude for many of the measured parameters.

Detailed summary statistics for water quality characteristics in groundwater samples collected from the control well are given in Table A-2. A total of 12 samples were collected from each sample port during 1987. In general, variability in concentrations of measured parameters in the control area appears to be similar to that measured beneath the swale area. The only exception to this generality is sulfate, which appears to be considerably more variable in the control area than in the swale area.

A summary of mean water quality characteristics in the swale area is given in Table 3-56. Groundwater beneath the swale area can be characterized as moderately acidic (with a mean pH value of approximately 4.5), low in alkalinity (with mean values at most sample ports of less than 1 mg/l), moderately reduced (with redox potentials ranging from -85 to -89 mv), high in ammonia (with measured values near 1 mg/l) and generally low in concentrations of total phosphorus. Concentrations of most measured parameters appeared to decrease with increasing groundwater depth. These reductions with increasing depth were most apparent for pH, conductivity, alkalinity, nitrate, organic nitrogen, total nitrogen, organic phosphorus, total phosphorus, color and dissolved solids. In addition, concentrations of many measured parameters appeared to be similar over the first three sample ports, with substantially different concentrations

TABLE 3-56

MEAN WATER QUALITY CHARACTERISTICS IN THE SWALE AREA AT THE WET SWALE SITE (SITE 1)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	5.92	4.59	4.39	4.34	4.26	4.32
Spec. Cond.	μmhos/cm	211	218	206	212	102	145
Temperature	°C	22.31	22.56	22.75	22.90	23.17	23.36
Dissolved O_2	mg/l	1.5	0.7	0.5	0.5	0.5	0.5
ORP	mv	- 39	- 86	- 87	- 85	- 88	- 89
Alkalinity	mg/l	68.2	3.2	0.5	0.2	0.2	0.5
Ammonia	mg/l	236	929	944	952	845	824
Nitrate	μg/l	12	14	10	11	< 10	< 10
Diss. Organic N	μg/l	470	392	384	382	234	167
Total N	μg/l	881	1335	1338	1345	1087	998
Diss. Ortho-P	μg/l	155	23	26	13	22	18
Diss. Organic P	μg/l	25	9	7	7	6	6
Total P	μg/l	217	31	33	19	27	24
Chloride	mg/l	33	73	69	72	35	38
Sulfate	mg/l	9.6	16.9	15.9	17.3	9.4	22.1
BOD	mg/l	5.0	3.0	2.3	2.1	2.5	2.4
Color	Pt-Co Units	88	69	50	51	36	35
T.D.S.	mg/l	139	127	119	120	74	98
V.D.S.	mg/l	53	38	40	39	34	38

found at the bottom two sample ports. This trend was readily apparent for conductivity, ammonia, organic nitrogen, total nitrogen, chloride, color and dissolved solids. This trend suggests that chemical characteristics within the top 1.0 m were similar for many parameters but different than groundwater characteristics at 2.5 m or 5.0 m.

Mean characteristics of surface waters measured along the wet swale channel are also included in Table 3-56 for comparison purposes. Groundwaters beneath the swale channel appear to be lower in pH, dissolved oxygen, redox potential, alkalinity, organic nitrogen, orthophosphorus, organic phosphorus, total phosphorus, BOD, color and dissolved solids than those measured in surface waters along the swale channel. Concentrations of ammonia increased substantially beneath the swale area with groundwater concentrations approximately four times concentrations of ammonia measured in surface water. Groundwater concentrations of total nitrogen also increased beneath the swale channel, primarily as a result of increases in ammonia. Concentrations of chloride appeared to double in groundwater beneath the swale channel within the first 1 m. Sulfate concentrations increased by approximately 70-80% beneath the swale channel within the top 1 m.

Mean water quality characteristics in the control area at the wet swale site are given in Table 3-57. Similar to groundwater characteristics beneath the swale area, groundwater in the control area was acidic (with a mean pH value of approximately 4.40) and low in alkalinity with a moderately reduced redox condition. Groundwater concentrations of total nitrogen and total phosphorus were similar to values measured beneath the swale channel.

TABLE 3-57

MEAN WATER QUALITY CHARACTERISTICS IN THE CONTROL AREA AT THE WET SWALE SITE (SITE 1)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	4.38	4.43	4.52	4.38	4.25
Spec. Cond.	μmhos/cm	603	436	270	93	171
Temperature	°C	23.45	23.57	23.54	23.75	23.76
Dissolved O_2	mg/l	0.7	0.6	0.5	0.5	0.5
ORP	mv	- 74	- 89	- 89	- 94	- 83
Alkalinity	mg/l	0.1	1.0	1.8	0.9	0.4
Ammonia	μg/l	806	644	427	347	1693
Nitrate	μg/l	16	17	13	< 10	< 10
Diss. Organic N	μg/l	352	297	561	447	861
Total N	μg/l	1174	958	1001	801	2562
Diss. Ortho-P	μg/l	20	15	16	28	29
Diss. Organic P	μg/l	8	10	7	8	15
Total P	μg/l	28	25	23	36	44
Chloride	mg/l	208	149	81	30	45
Sulfate	mg/l	57.2	40.7	24.4	6.8	24.0
BOD	mg/l	3.5	3.8	3.6	3.5	2.2
Color	Pt-Co Units	127	126	107	39	35
T.D.S.	mg/l	351	244	171	67	94
V.D.S.	mg/l	82	76	57	33	38

However, unlike the consistent groundwater characteristics found within the top 1 m beneath the swale channel, groundwater characteristics in the control area varied considerably for most parameters at all measured depths. For example, parameters such as conductivity, ammonia, chloride, sulfate, color and dissolved solids exhibited relatively high values at the 0.1 m sample port with declining concentrations with increasing groundwater depth through the 2.5 m sample port. Groundwater concentrations of virtually all measured parameters increased somewhat at the 5 m sample port. Groundwater concentrations for many parameters in the top 1 m of the control area were substantially higher than those measured in the top 1 m beneath the swale site. These increased concentrations were particularly apparent for conductivity, chloride, sulfate, color and dissolved solids. General groundwater parameters beneath the swale channel appear to be less variable and lower in concentration for many parameters than in groundwater beneath the control area.

Detailed summary statistics for dissolved heavy metal concentrations in groundwaters beneath the swale channel and in the control area are presented in Tables A-3 and A-4, respectively. In general, variability in concentrations of heavy metals in groundwaters beneath both swale and control areas appeared to be similar to that observed for general groundwater parameters. The most variable heavy metals in groundwater were zinc, manganese, copper and, to a lesser extent, iron. The greatest variability in all metal species was found in the top 1 m of groundwater with generally lower variability in concentrations at depths of 2.5 m and 5.0 m. The range of variability for heavy metal concentrations often exceeded one order of magnitude within the top 1 m and was generally less than one order of magnitude at sample ports below that depth.

The results of an ANOVA comparison of general groundwater characteristics between swale and control areas is given in Table 3-58. Significant differences in groundwater characteristics between swale and control sites were found for only eight of the 19 measured parameters including, conductivity, organic nitrogen, chloride, sulfate, BOD, color and dissolved solids. Data sets represented by different letters in the final column of Table 3-58 were found to be significantly different at the 0.05 level of significance. In each of these cases, concentrations measured beneath the control area were found to be higher than those measured beneath the swale channel. Even though significant differences were not observed between swale and control areas for the remaining parameters listed in Table 3-58, mean concentrations of all parameters, with the exceptions of alkalinity and ammonia, were found to be higher in the control area than beneath the swale channel. It seems apparent that the continued operation of the wet swale channel as a stormwater management system is having no measurable effects on groundwaters beneath the swale channel for the measured general chemical parameters.

Mean concentrations of dissolved heavy metals in groundwaters beneath the swale channel are given in Table 3-59. In general, with the exceptions of aluminum and iron, groundwater concentrations of heavy metals were relatively low beneath the swale channel. Elevated concentrations of aluminum and iron were present within the top 1 m of groundwater with substantial reductions in concentrations of both metals at groundwater depths below 1 m. Several heavy metals such as manganese, iron, lead,

TABLE 3-58

ANOVA COMPARISON OF GENERAL GROUNDWATER CHARACTERISTICS BETWEEN SWALE AND CONTROL AREAS AT THE WET SWALE SITE (SITE 1)

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
pH	s.u.	4.2	Control	4.39	60	NSD[1]
			Swale	4.38	60	
Spec. Cond.	μS/cm	99.9	Control	314	60	A
			Swale	176	60	B
Temperature	°C	88.9	Control	23.61	60	NSD
			Swale	22.95	60	
ORP	mv	13.0	Control	- 86	60	NSD
			Swale	- 87	60	
Alkalinity	mg/l	13.6	Swale	0.9	60	NSD
			Control	0.8	60	
NH_3-N	μg/l	83.3	Swale	899	60	NSD
			Control	783	60	
NO_3-N	μg/l	74.1	Control	12	60	NSD
			Swale	10	60	
Diss. Org. N	μg/l	98.6	Control	504	60	A
			Swale	312	60	B
Total N	μg/l	53.0	Control	1299	60	NSD
			Swale	1221	60	
Diss. Ortho-P	μg/l	32.0	Control	22	60	NSD
			Swale	20	60	
Diss. Org. P	μg/l	92.6	Control	10	60	NSD
			Swale	7	60	
Total P	μg/l	71.4	Control	31	60	NSD
			Swale	27	60	

TABLE 3-58 -- CONTINUED

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cl	mg/l	99.9	Control	103	60	A
			Swale	57	60	B
SO_4	mg/l	99.4	Control	30.6	60	A
			Swale	16.3	60	B
BOD	mg/l	99.9	Control	3.3	60	A
			Swale	2.4	60	B
Color	Pt-Co units	99.9	Control	87	60	A
			Swale	48	60	B
T.D.S.	mg/l	99.9	Control	185	60	A
			Swale	108	60	B
V.D.S.	mg/l	99.9	Control	57	60	A
			Swale	38	60	B

1. No significant difference at the 0.05 level.

TABLE 3-59

MEAN CONCENTRATION OF HEAVY METALS IN THE SWALE AREA AT THE WET SWALE SITE (SITE 1)

(All concentrations in μg/l)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	3.60/5.33	2.99	3.87	3.36	4.12	2.89
Zn	10.2/17.1	15.5	19.1	16.9	16.1	13.5
Mn	26.0/34.5	29.2	17.2	11.7	11.1	8.42
Cu	11.4/16.6	12.7	16.2	12.7	12.5	10.2
Al	101/234	734	922	1027	602	593
Fe	1255/1931	2986	1736	1155	813	480
Pb	93.4/114	36.8	33.8	32.4	29.4	30.3
Ni	30.4/36.0	14.2	12.5	11.2	12.3	9.75
Cr	6.64/7.56	3.85	3.32	3.29	3.23	3.37

1. Dissolved Concentration/Total Concentration

nickel and chromium exhibited reductions in concentrations with increasing groundwater depth.

A comparison of dissolved and total metal concentrations in surface water along the swale channel is also provided in Table 3-59. With the exceptions of aluminum and iron, groundwater concentrations of heavy metals were substantially less in most cases than total concentrations in surface waters along the swale channel. Groundwater concentrations for many heavy metals such as cadmium, manganese, lead, nickel and chromium are equal to or less than dissolved metal concentrations in surface waters along the swale channel. Only aluminum exhibited groundwater concentrations which exceeded both dissolved and total concentrations measured in surface water.

Mean groundwater concentrations of heavy metals at the control area are presented in Table 3-60. In general, groundwater concentrations for all heavy metals appeared to be greater in the control area than in groundwater beneath the swale channel. These increased concentrations were particularly apparent for zinc, copper, aluminum, iron, lead, nickel and chromium. Groundwater concentrations of heavy metals in the control area appeared to decrease significantly at the 2.5 m and 5.0 m depths with concentrations at these sample ports similar to values measured beneath the swale area.

An ANOVA comparison of dissolved heavy metal concentrations beneath swale and control areas is given in Table 3-61. Significant differences between swale and control areas were found at the 0.05 level of significance for aluminum, iron, lead and chromium. For each of these heavy metals, concentrations were greater beneath the control area than beneath the swale channel. Even though significant differences were not observed for the remaining heavy metals, it should be noted that mean concentrations

TABLE 3-60

MEAN CONCENTRATION OF HEAVY METALS IN THE CONTROL AREA AT THE WET SWALE SITE (SITE 1)

(All concentrations in μg/l)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	3.75	4.60	4.25	3.89	3.33
Zn	27.3	26.3	23.1	13.6	16.8
Mn	31.8	41.3	35.1	5.83	6.17
Cu	17.1	25.7	14.4	10.0	11.0
Al	1666	1531	1055	331	807
Fe	5157	5984	5632	803	939
Pb	66.1	55.3	48.2	25.9	32.3
Ni	22.5	17.0	13.0	9.95	11.2
Cr	5.79	5.68	4.90	3.35	3.72

TABLE 3-61

ANOVA COMPARISON OF DISSOLVED HEAVY METAL CONCENTRATIONS BENEATH SWALE AND CONTROL AREAS AT THE WET SWALE SITE (SITE 1)

DISSOLVED HEAVY METAL	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN CONC. (μg/l)	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cd	90.2	Control	3.96	60	NSD[1]
		Swale	3.45	60	
Zn	87.2	Control	21.4	60	NSD
		Swale	16.2	60	
Mn	92.5	Control	24.1	60	NSD
		Swale	15.5	60	
Cu	63.8	Control	15.7	60	NSD
		Swale	12.8	60	
Al	99.1	Control	1078	60	A
		Swale	776	60	B
Fe	99.9	Control	3703	60	A
		Swale	1434	60	B
Pb	97.4	Control	45.6	60	A
		Swale	32.5	60	B
Ni	89.2	Control	14.7	60	NSD
		Swale	12.0	60	
Cr	99.5	Control	4.69	60	A
		Swale	3.42	60	B

1. No significant difference at the 0.05 level.

within the control area were greater than concentrations measured beneath the swale channel for each of these metal species as well. There is no evidence to indicate that the wet swale channel has resulted in increased groundwater concentrations beneath the swale channel for any of the measured heavy metal species.

Site 2 - Dry Swale Site

Detailed summary statistics for general water quality characteristics in groundwater samples collected beneath the swale channel at the dry swale site are given in Table A-5. A total of two groundwater samples were collected from the 0.5 m sample port, nine from the 1.0 m sample port, and twelve each from the 2.5 m and 5.0 m sample ports. Although groundwater was present at the 0.1 m sample port on most collection dates, the volume of water was generally inadequate to provide sufficient sample volume for analysis of chemical parameters.

Many of the general water quality parameters listed in Table A-5 exhibited relatively low variability in measured values during the 12-month study period. However, several parameters such as ammonia, nitrate, organic nitrogen, organic phosphorus, BOD and color were highly variable at each of the measured sample ports. The measured range of values for these parameters, especially for species of nitrogen, generally covered two to three orders of magnitude, with some ranges exceeding three orders of magnitude.

Mean water quality characteristics from groundwaters in the swale area are indicated in Table 3-62. Groundwaters beneath the swale channel were characterized as slightly acidic with a mean pH of approximately 6.5 in the upper groundwater layers,

TABLE 3-62

MEAN WATER QUALITY CHARACTERISTICS IN THE SWALE AREA AT THE DRY SWALE SITE (SITE 2)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	--	6.49	6.46	6.31	5.05
Spec. Cond.	μmhos/cm	--	227	206	233	75
Temperature	°C	--	23.13	25.67	25.23	25.28
Dissolved O_2	mg/l	--	2.9	2.3	2.5	0.6
ORP	mv	--	219	225	236	162
Alkalinity	mg/l	--	149	105	67.5	33.2
Ammonia	μg/l	--	104	71	11	15
Nitrate	μg/l	--	309	635	2963	875
Diss. Organic N	μg/l	--	280	1153	1151	576
Total N	μg/l	--	693	1859	4125	1466
Diss. Ortho-P	μg/l	--	130	142	85	32
Diss. Organic P	μg/l	--	20	28	21	25
Total P	μg/l	--	150	170	105	57
Chloride	mg/l	--	8	8	11	17
Sulfate	mg/l	--	7.3	10.3	11.2	3.6
BOD	mg/l	--	4.7	2.4	1.9	1.8
Color	Pt-Co Units	--	35	44	25	16
T.D.S.	mg/l	--	146	142	170	48
V.D.S.	mg/l	--	48	45	65	21

decreasing gradually to an average of 5.05 at a groundwater depth of 5 m. This decline in pH with increasing water depth was accompanied by a decline in alkalinity as well, decreasing from approximately 149 mg/l near the surface to 33 mg/l at the 5.0 m level. Groundwater redox potentials indicate oxidized conditions to a depth of 2.5 m with reduced conditions at the final 5.0 m port.

As seen in Table 3-62, concentrations of ammonia declined rapidly with increase in groundwater depth, while concentrations of nitrate, organic nitrogen and total nitrogen increased with increasing groundwater depth up to the 2.5 m port. Concentrations of all phosphorus species increased slightly from the 0.5 m to the 1.0 m depth with general decreases in concentration after a depth of 1 m. Measured concentrations of chloride, sulfate and color were relatively low at all sample ports. Measured values of BOD were found to be highest in the upper groundwater levels with rapid decreases in concentration with increasing groundwater depth.

Detailed summary statistics of general water quality characteristics in groundwater samples collected beneath the control area at the dry swale site are given in Table A-6. A total of one groundwater sample was collected from the 0.5 m sample port, eight samples from the 1.0 m sample port, seven samples from the 2.5 m sample port and twelve from the 5.0 m sample port. No samples were collected from the 0.1 m sample port at this site. Variability in chemical characteristics at the control site were similar to those found beneath the swale site. Although the majority of chemical parameters exhibited relatively low variability, a larger degree of variability was observed for species of nitrogen, organic phosphorus, BOD and color.

Mean water quality characteristics beneath the control area at the dry swale site are indicated in Table 3-63. Groundwater beneath the control area was somewhat acidic with a mean value of approximately 6.0 in the surface layers and a gradual decrease in concentration with increasing groundwater depth. Measured values for alkalinity appeared to be somewhat lower in the control area than those found beneath the swale area with a gradual decrease in concentration with increasing groundwater depth. With the exception of the 1.0 m sample port, groundwaters beneath the control area were generally found to be under oxidized conditions.

Concentrations of all nitrogen species appeared to increase with increasing groundwater depth. At the 0.5 m and 1.0 m sample depths, the dominant nitrogen species appeared to be organic nitrogen which comprised approximately 75% of the total nitrogen measured. However, at the 2.5 m and 5.0 m sample ports, nitrate became the dominant species, comprising 60-65% of the total nitrogen found. Concentrations of phosphorus in groundwaters were relatively small for all measured species. At groundwater depths of 0.5 m and 1.0 m, orthophosphorus was the dominant phosphorus species in groundwater, comprising 77% and 62% of the total phosphorus, respectively. At the 2.5 m and 5.0 m sample ports, organic phosphorus became the dominant species found, comprising 57 and 65% of the total nitrogen, respectively. As observed beneath the swale site, measured concentrations of chloride, sulfate and color were relatively low in groundwaters beneath the control area.

An ANOVA comparison of general groundwater characteristics between swale and control areas is given in Table 3-64. Statistically significant differences were observed between the two sites for seven of the nineteen measured general groundwater parameters

TABLE 3-63

MEAN WATER QUALITY CHARACTERISTICS IN THE CONTROL AREA AT THE DRY SWALE SITE (SITE 2)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	--	6.00	5.92	4.84	5.40
Spec. Cond.	μmhos/cm	--	178	126	97	129
Temperature	°C	--	23.22	25.69	25.70	24.83
Dissolved O_2	mg/l	--	2.7	1.9	3.0	2.7
ORP	mv	--	261	92	255	215
Alkalinity	mg/l	--	83.8	36.6	19.5	23.4
Ammonia	μg/l	--	< 10	19	44	30
Nitrate	μg/l	--	58	170	1727	1380
Diss. Organic N	μg/l	--	176	556	847	866
Total N	μg/l	--	239	735	2618	2276
Diss. Ortho-P	μg/l	--	10	31	17	24
Diss. Organic P	μg/l	--	3	20	24	45
Total P	μg/l	--	13	50	42	69
Chloride	mg/l	--	13	11	17	11
Sulfate	mg/l	--	5.0	18.0	12.9	17.2
BOD	mg/l	--	0.9	3.6	1.2	2.1
Color	Pt-Co Units	--	22	68	22	22
T.D.S.	mg/l	--	105	87	76	93
V.D.S.	mg/l	--	36	25	34	41

TABLE 3-64

ANOVA COMPARISON OF GENERAL GROUNDWATER CHARACTERISTICS BETWEEN SWALE AND CONTROL AREAS AT THE DRY SWALE SITE (SITE 2)

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
pH	s.u.	7.16	Control Swale	5.43 5.93	28 35	NSD[1]
Spec. Cond.	μS/cm	99.9	Swale Control	171 122	35 28	A B
Temperature	°C	2.7	Swale Control	25.24 25.23	35 28	NSD
ORP	mv	48.1	Swale Control	207 191	35 28	NSD
Alkalinity	mg/l	99.9	Swale Control	70.0 28.3	35 28	A B
NH_3-N	μg/l	20.4	Swale Control	33 29	35 28	NSD
NO_3-N	μg/l	70.4	Swale Control	1497 1074	35 28	NSD
Diss. Org. N	μg/l	37.2	Swale Control	904 748	35 28	NSD
Total N	μg/l	77.1	Swale Control	2434 1851	35 28	NSD
Diss. Ortho-P	μg/l	99.9	Swale Control	84 24	35 28	A B
Diss. Org. P	μg/l	56.7	Control Swale	31 24	28 35	NSD
Total P	μg/l	99.9	Swale Control	108 55	35 28	A B

TABLE 3-64 -- CONTINUED

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cl	mg/l	21.3	Control	13	28	NSD
			Swale	12	35	
SO_4	mg/l	99.9	Control	15.9	28	A
			Swale	8.1	35	B
BOD	mg/l	6.8	Control	2.2	28	NSD
			Swale	2.2	35	
Color	Pt-Co units	47.1	Control	35	28	NSD
			Swale	27	35	
T.D.S.	mg/l	99.1	Swale	120	35	A
			Control	87	28	B
V.D.S.	mg/l	88.2	Swale	44	35	NSD
			Control	35	28	

1. No significant difference at the 0.05 level.

including, conductivity, dissolved oxygen, alkalinity, orthophosphorus, total phosphorus, sulfate and total dissolved solids. For each of these parameters, except dissolved oxygen and sulfate, measured concentrations in groundwater were found to be higher beneath the swale area than beneath the control area. For parameters such as alkalinity, orthophosphorus and total phosphorus, measured concentrations beneath the swale area were more than twice those found beneath the control area. It should be noted that even though no significant differences were detected between groundwater concentrations beneath the swale and control sites, the majority of groundwater parameters were highest in concentration beneath the swale area. This trend is particularly evident for species of nitrogen and phosphorus, although concentrations of both nitrogen and phosphorus are generally low under both swale and control areas.

Detailed summary statistics for dissolved heavy metals in groundwaters beneath swale and control areas are presented in Tables A-7 and A-8, respectively. As observed for heavy metal concentrations in groundwaters beneath the wet swale site, variability in groundwater concentrations of heavy metals were generally lower than that found for general chemical characteristics. The most variable heavy metals in both swale and control areas appeared to be copper, aluminum, iron and zinc.

Mean heavy metal concentrations in groundwater beneath the dry swale channel are summarized in Table 3-65. With the exceptions of aluminum, iron and possibly cadmium, concentrations of heavy metals appeared to be higher beneath the dry swale area than beneath the wet swale channel. These increased concentrations were particularly apparent for zinc, copper, lead and nickel, which exhibited concentrations approximately twice those measured beneath the wet swale channel. Concentrations of

TABLE 3-65

MEAN CONCENTRATION OF HEAVY METALS IN THE SWALE AREA AT THE DRY SWALE SITE (SITE 2)

(All concentrations in μg/l)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	--	2.60	4.12	3.85	1.92
Zn	--	44.5	34.7	28.5	22.7
Mn	--	18.0	14.1	13.9	10.2
Cu	--	24.0	20.1	22.6	14.0
Al	--	297	560	232	128
Fe	--	554	549	313	239
Pb	--	73.0	81.7	88.0	48.0
Ni	--	31.5	28.1	28.8	17.1
Cr	--	17.5	14.2	13.3	9.34

dissolved chromium beneath the dry swale channel were approximately five times those measured beneath the wet swale channel. However, it should be noted that with the exceptions of nickel and chromium, groundwater concentrations of heavy metals beneath the dry swale are substantially less than heavy metal concentrations found in stormwater runoff infiltrating into the dry swale channel. Groundwater concentrations of most heavy metals appeared to decrease with increasing groundwater depth, although cadmium, aluminum, iron and lead exhibited increased concentrations at the 1.0 m sample port.

Mean concentrations of heavy metals in groundwater beneath the control area at the dry swale site are given in Table 3-66. In general, groundwater concentrations of most heavy metals appeared to be lower in surface layers at the control area than in surface layers measured beneath the dry swale channel. However, groundwater concentrations of heavy metals beneath the control site did not exhibit the generalized decrease in concentration with increasing groundwater depth observed for groundwater beneath the swale channel. In fact, groundwater concentrations of cadmium, copper, aluminum, lead and chromium were higher at the 5.0 m sample port than at the 0.5 m sample port beneath the control area.

An ANOVA comparison of dissolved heavy metal concentrations between swale and control areas at the dry swale site is given in Table 3-67. A significant difference between groundwater heavy metal concentrations at the 0.5 m level of significance was found only for iron, with groundwater concentrations in the control area exceeding those measured beneath the swale channel by approximately a factor of three. Even though significant differences were not observed in groundwater concentrations between swale and control areas for the remaining heavy metals, groundwater heavy metal

TABLE 3-66

MEAN CONCENTRATION OF HEAVY METALS IN THE CONTROL AREA AT THE DRY SWALE SITE (SITE 2)

(All concentrations in $\mu g/l$)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	--	2.30	2.54	2.37	2.58
Zn	--	35.0	34.4	33.9	30.3
Mn	--	15.0	25.1	18.0	12.0
Cu	--	16.0	14.3	24.0	21.3
Al	--	230	239	206	429
Fe	--	380	2854	369	373
Pb	--	57.0	71.8	57.7	64.3
Ni	--	24.0	20.5	21.6	20.8
Cr	--	11.0	11.9	13.3	12.7

TABLE 3-67

ANOVA COMPARISON OF DISSOLVED HEAVY METAL CONCENTRATIONS BENEATH SWALE AND CONTROL AREAS AT THE DRY SWALE SITE (SITE 2)

DISSOLVED HEAVY METAL	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN CONC. (μg/l)	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cd	93.0	Swale	3.19	35	NSD[1]
		Control	2.51	28	
Zn	51.9	Swale	32.5	28	NSD
		Control	29.0	35	
Mn	92.5	Swale	17.4	28	NSD
		Control	12.9	35	
Cu	16.4	Swale	19.8	28	NSD
		Control	19.1	35	
Al	30.6	Swale	312	28	NSD
		Control	285	35	
Fe	97.5	Swale	1081	28	A
		Control	362	35	B
Pb	65.9	Swale	71.8	35	NSD
		Control	64.5	28	
Ni	87.0	Swale	24.8	35	NSD
		Control	21.0	28	
Cr	5.6	Swale	12.6	28	NSD
		Control	12.5	35	

1. No significant difference at the 0.05 level.

concentrations were generally greater beneath the control area than beneath the swale channel. The only exceptions to this generality are cadmium, lead and nickel which exhibited slightly greater concentrations beneath the swale area than beneath the control area. Based upon this somewhat favorable comparison between heavy metal concentrations in swale and control areas, there is little evidence to suggest that infiltration of runoff into groundwater along the dry swale channel is causing increased concentrations of heavy metals in groundwater at this site.

Site 3 - Residential Dual Pond Site

A summary of detailed water quality statistics for general water quality parameters in groundwater samples collected beneath the retention pond at the residential dual pond site is given in Table A-9. A total of twelve groundwater samples were collected from each sample port at this well. A large degree of variability was observed in groundwater concentrations for many of the measured parameters. Large variability was observed for redox potential, which varied from highly reduced to oxidized conditions at all sample ports, virtually all species of nitrogen, organic phosphorus, chloride, color and to a lesser extent, dissolved solids. Concentrations of many parameters such as ammonia, nitrate, organic nitrogen, organic phosphorus, chloride and color generally exceeded three orders of magnitude.

A summary of mean water quality characteristics in the retention pond area is given in Table 3-68. Groundwater beneath the retention pond is characterized as slightly acidic with measured pH values ranging from 6.2 to approximately 7.0. Mean pH values in groundwater were much lower than the mean pH value of 8.22 for surface water in

TABLE 3-68

MEAN WATER QUALITY CHARACTERISTICS IN THE RETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.22	6.55	6.22	6.31	7.03	6.98
Spec. Cond.	μmhos/cm	196	232	227	218	203	243
Temperature	°C	25.28	24.11	24.45	24.28	24.38	24.55
Dissolved O_2	mg/l	8.2	1.2	1.0	1.8	3.0	1.7
ORP	mv	365	43	23	61	113	41
Alkalinity	mg/l	63.4	50.2	80.0	73.7	67.2	87.5
Ammonia	mg/l	42	455	991	920	110	609
Nitrate	μg/l	42	477	47	652	74	41
Diss. Organic N	μg/l	414	409	394	294	323	449
Total N	μg/l	708	1341	1432	1276	507	1099
Diss. Ortho-P	μg/l	59	74	52	46	58	106
Diss. Organic P	μg/l	36	23	14	18	19	24
Total P	μg/l	141	97	66	64	77	129
Chloride	mg/l	29	31	27	27	31	32
Sulfate	mg/l	19.9	26.0	4.9	4.8	6.5	4.7
BOD	mg/l	5.2	4.6	7.4	6.2	3.8	7.1
Color	Pt-Co Units	39	30	64	65	30	33.3
T.D.S.	mg/l	133	139	138	137	133	153
V.D.S.	mg/l	35	42	45	43	40	42

the retention pond. Measured values of redox potential in groundwater beneath the retention pond were all less than 200 mv, indicating a reduced environment. The mean redox potential of 365 mv measured in surface water in the retention pond suggests a highly oxidized environment. Measured concentrations of alkalinity were similar between groundwater and surface locations.

In general, concentrations of nitrogen and phosphorus in groundwater beneath the retention pond were relatively low in value. The most important nitrogen species in groundwaters appeared to be ammonia and nitrate which together accounted for approximately 70-80% of total nitrogen measured at each sample port. The most important phosphorus species in groundwater was dissolved orthophosphorus which also accounted for approximately 70-80% of the total phosphorus measured. However, unlike the gradual trends for increasing or decreasing concentrations of groundwater parameters observed at sites 1 and 2, no such trends were apparent for either nitrogen or phosphorus. Concentrations of total nitrogen in groundwater were greater than concentrations of total nitrogen in surface water for most sample ports, while concentrations of total phosphorus in groundwater were less than concentrations measured within the retention pond water.

As observed at the previous sites, concentrations of chloride and sulfate were relatively low in groundwaters beneath the pond. Groundwater concentrations of chloride were similar to concentrations measured within the retention pond. Groundwater concentrations of sulfate increased slightly at the 0.1 m sample depth over concentrations measured in surface water but decreased substantially at depths greater than 0.1 m. In general, concentrations of BOD, color and dissolved solids were similar in both groundwater and surface water.

A detailed summary of water quality statistics for groundwater sampled from the detention pond well is given in Table A-10. A total of twelve groundwater samples were collected from each of the five sample ports with the exception of the 0.1 m port from which eleven samples were collected. Similar to characteristics observed in groundwater collected beneath the retention pond, considerable variability was observed in measured groundwater concentrations of redox potential, nitrate, organic nitrogen, orthophosphorus, organic phosphorus, total phosphorus, BOD and color. The range of concentration exhibited by these parameters exceeded three orders of magnitude in many cases. Also, as observed in groundwater beneath the retention pond, the redox potential in groundwater varied from highly reduced to oxidized at each sample port during the 12-month study period.

Mean water quality characteristics in the detention pond area are summarized in Table 3-69. Groundwater pH values beneath the detention pond were slightly acidic and appeared to decrease in value with increasing groundwater depth. In general, groundwater pH values beneath the detention pond were somewhat lower than those measured beneath the retention pond at all sample depths. Mean values for alkalinity, which ranged from approximately 35-40 mg/l in the first 1 m of groundwater, were substantially lower than alkalinity values measured within the retention pond. Although mean values for redox potential indicated generally reduced conditions at all groundwater depths beneath the detention pond, groundwater redox values were substantially higher beneath the retention pond than beneath the detention pond. Mean values of pH within the detention pond were similar to those found within the retention pond and were substantially greater than pH concentrations found in groundwater. Redox conditions

TABLE 3-69

MEAN WATER QUALITY CHARACTERISTICS IN THE DETENTION POND AREA AT THE RESIDENTIAL DUEL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.19	6.25	6.14	6.23	5.51	5.70
Spec. Cond.	μmhos/cm	260	238	239	260	402	414
Temperature	°C	26.50	24.52	24.43	24.92	24.00	24.09
Dissolved O_2	mg/l	10.8	2.1	1.7	1.9	0.7	1.4
ORP	mv	308	79	111	108	173	185
Alkalinity	mg/l	55.9	35.1	35.3	40.0	18.6	44.5
Ammonia	mg/l	39	132	110	100	54	147
Nitrate	μg/l	382	475	505	553	1691	3990
Diss. Organic N	μg/l	720	454	363	426	785	1078
Total N	μg/l	1388	1061	978	1079	2530	5215
Diss. Ortho-P	μg/l	11	18	11	15	6	10
Diss. Organic P	μg/l	24	7	6	7	4	7
Total P	μg/l	82	25	18	21	10	17
Chloride	mg/l	32	29	29	32	14	64
Sulfate	mg/l	32.1	44.5	51.3	53.0	83.1	82.4
BOD	mg/l	3.3	2.2	2.2	2.4	1.7	1.7
Color	Pt-Co Units	33	34	38	35	20	23
T.D.S.	mg/l	173	147	158	170	250	272
V.D.S.	mg/l	63	50	57	60	76	104

within the detention pond water indicated oxidized conditions on all sample dates, compared with generally reduced conditions found in groundwater.

Concentrations of both total nitrogen and total phosphorus appeared to be lower within the first meter of groundwater beneath the detention pond than was observed beneath the retention pond. The dominant nitrogen species in groundwater at all depths was nitrate, followed closely by organic nitrogen. The dominant form of phosphorus in groundwater beneath the detention pond was dissolved orthophosphate. Groundwater concentrations of ammonia and nitrate appeared to be greater within the first meter beneath the pond than in surface water above the pond, while concentrations of organic nitrogen appeared to be less in groundwater than in surface water above the pond. Concentrations of both total nitrogen and total phosphorus were lower in the first meter of groundwater than in surface water contained within the detention pond.

Groundwater concentrations of chloride within the first meter were similar to concentrations measured within the detention pond surface water and also similar to concentrations measured in both surface and groundwater at the retention pond. On the other hand, groundwater concentrations of sulfate beneath the detention pond were generally higher than those found in surface water and also higher than sulfate concentrations measured beneath the retention pond. Groundwater concentrations for color and dissolved solids appeared to be similar beneath both retention and detention ponds.

Detailed summary statistics for water quality characteristics in groundwater samples collected from the control area are indicated in Table A-11. A total of nine groundwater samples were collected from the 0.1 m sample port, eleven from the 0.5 m sample port and twelve each from the 1.0 m, 2.5 m and 5.0 m sample ports. Similar to trends observed in the retention and detention pond wells, considerable variability was found for groundwater concentrations of many parameters, including alkalinity, nitrate, ammonia, orthophosphorus, organic phosphorus, total phosphorus, BOD and color. In general, the variability in these parameters observed in the control well was substantially greater than the variability observed at either the retention or detention sites.

A summary of mean water quality characteristics in the control area is given in Table 3-70. Groundwater beneath the control site was acidic, with mean pH values ranging from approximately 4.1 to 5.4, and substantially lower than pH values measured beneath either the detention or retention pond areas. Measured values of alkalinity were also extremely low in the control groundwater. Mean values of redox potential indicated a generally reduced environment similar to that found beneath the detention pond site.

Groundwater concentrations of total nitrogen in the first meter beneath the control site were substantially lower than concentrations measured beneath either of the ponds. The dominant nitrogen species at the 0.1 m and 0.5 m depths was organic nitrogen, comprising approximately 60-80% of the total nitrogen found at these depths. At groundwater depths of 1.0 m and below, nitrate became the dominant species, comprising between 70-90% of the total nitrogen found at these depths. Groundwater concentrations of total phosphorus were comprised primarily of dissolved orthophosphorus at all sample depths. In general, groundwater concentrations of total phosphorus in the control area exceeded levels measured beneath the detention and retention ponds.

Groundwater concentrations of chloride beneath the control area were relatively low and were similar to those measured beneath the retention and detention ponds.

TABLE 3-70

MEAN WATER QUALITY CHARACTERISTICS IN THE CONTROL AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	4.09	4.49	5.36	5.28	5.34
Spec. Cond.	μmhos/cm	283	297	315	245	216
Temperature	°C	24.91	24.60	24.44	24.47	24.22
Dissolved O_2	mg/l	2.2	0.8	0.5	1.3	0.7
ORP	mv	81	90	73	174	163
Alkalinity	mg/l	0.1	2.0	11.4	11.6	7.5
Ammonia	μg/l	15	18	120	18	25
Nitrate	μg/l	37	75	833	2282	2951
Diss. Organic N	μg/l	266	155	240	405	224
Total N	μg/l	318	248	1193	2705	3200
Diss. Ortho-P	μg/l	105	64	22	118	10
Diss. Organic P	μg/l	27	18	7	42	7
Total P	μg/l	132	83	28	160	17
Chloride	mg/l	33	33	30	24	23
Sulfate	mg/l	82.4	88.8	96.7	62.0	67.6
BOD	mg/l	1.7	1.7	1.7	1.6	1.5
Color	Pt-Co Units	25	34	21	16	20
T.D.S.	mg/l	191	201	217	170	146
V.D.S.	mg/l	68	55	65	46	43

However, groundwater concentrations of sulfate were relatively high beneath the control area and were much greater than groundwater concentrations measured beneath either detention or retention pond areas. Mean concentrations of BOD, color and dissolved solids were relatively low beneath the control area.

An ANOVA comparison of general groundwater characteristics between pond and control areas at the residential dual pond site is given in Table 3-71. With the exceptions of only temperature and dissolved organic phosphorus, significant differences were observed between the three areas for all of the general groundwater parameters. As discussed previously, data sets represented by different letters in the table column for Tukey's multiple comparison are significantly different at the 0.05 level.

In general, groundwaters beneath the retention pond exhibited significantly higher concentrations of alkalinity, ammonia, BOD and color. Groundwater beneath retention, detention and control areas was found to be statistically similar for concentrations of organic nitrogen, orthophosphorus, total phosphorus and chloride. Statistically similar groundwater characteristics were observed between detention and control areas for ORP, ammonia, nitrate, total nitrogen, BOD, color and dissolved solids. It appears, therefore, that groundwaters beneath the retention pond contained elevated levels of alkalinity, ammonia, BOD and color when compared to either detention or control areas, while groundwater beneath the detention pond contained elevated levels of chloride and organic nitrogen when compared to either retention or control areas. For the remaining general groundwater parameters, detention and retention areas were statistically similar to the control site.

TABLE 3-71

ANOVA COMPARISON OF GENERAL GROUNDWATER CHARACTERISTICS BETWEEN POND AND CONTROL AREAS AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
pH	s.u.	99.9	Retention	6.62	60	A
			Detention	5.97	59	B
			Control	4.96	56	B
Spec. Cond.	μS/cm	99.9	Detention	311	59	A
			Control	270	56	B
			Retention	225	60	B
Temperature	°C	2.1	Control	24.51	56	NSD[1]
			Detention	24.38	59	
			Retention	24.35	60	
ORP	mv	99.8	Detention	132	59	A
			Control	119	56	A
			Retention	56	60	B
Alkalinity	mg/l	99.9	Retention	71.7	60	A
			Detention	34.5	59	B
			Control	6.9	56	C
NH_3-N	μg/l	99.9	Retention	617	60	A
			Detention	109	59	B
			Control	41	56	B
NO_3-N	μg/l	99.9	Detention	1458	59	A
			Control	1320	56	A
			Retention	140	60	B
Diss. Org. N	μg/l	99.9	Detention	625	59	A
			Retention	374	60	B
			Control	259	56	B
Total N	μg/l	96.1	Detention	2191	59	A
			Control	1621	56	A
			Retention	1131	60	B
Diss. Ortho-P	μg/l	97.9	Retention	67	60	A
			Control	62	56	A
			Detention	12	59	B
Diss. Org. P	μg/l	89.7	Control	20	56	NSD
			Retention	20	60	
			Detention	6	59	
Total P	μg/l	97.1	Retention	87	60	A
			Control	82	56	A
			Detention	18	59	B

TABLE 3-71 -- CONTINUED

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cl	mg/l	99.9	Detention	46	59	A
			Retention	29	60	B
			Control	28	56	B
SO_4	mg/l	99.9	Control	79.2	56	A
			Detention	63.1	59	B
			Retention	9.4	60	C
BOD	mg/l	99.9	Retention	5.8	60	A
			Detention	2.0	59	B
			Control	1.6	56	B
Color	Pt-Co units	97.5	Retention	44	60	A
			Detention	30	59	B
			Control	23	56	B
T.D.S.	mg/l	99.9	Detention	200	59	A
			Control	185	56	A
			Retention	140	60	B
V.D.S.	mg/l	99.9	Detention	70	59	A
			Control	55	56	A
			Retention	43	60	B

1. No significant difference at the 0.05 level.

As seen in Tables 3-68 through 3-70, the extent of elevated groundwater concentrations beneath either retention or detention ponds appeared to be limited to the top 1.0 m of groundwater. Groundwater characteristics at the 2.5 m and 5.0 m levels were substantially different for most parameters than characteristics found at the top 1.0 m, suggesting that these deeper groundwater layers were affected by sources other than the operation of the stormwater management facility. The conclusion that groundwater effects were apparently limited to the top 1.0 m of groundwater at this dual pond site is consistent with conclusions reached for both the wet and dry swale sites.

Detailed summary statistics for heavy metal concentrations in retention, detention and control areas at the residential dual pond site is given in Tables A-12 through A-14, respectively. As observed for the previous study sites, heavy metal concentrations in groundwater were generally less variable than for the general chemical parameters. With the exceptions of manganese and iron, heavy metals in groundwater beneath the retention and detention ponds appeared to be relatively stable in value, with the majority of fluctuations in values covering less than one order of magnitude. However, heavy metal concentrations beneath the control area exhibited substantially more variability than beneath either of the ponds. This variability was particularly apparent for manganese, aluminum and iron. Groundwater concentrations of manganese in the control area approached 2 mg/l, with maximum aluminum concentrations of approximately 21 mg/l and a maximum iron concentration of approximately 1.36 mg/l.

Mean heavy metal concentrations in groundwaters in the retention pond area are given in Table 3-72. In general, groundwater concentrations of most heavy metals, with the exceptions of cadmium and lead, appeared to be relatively low in groundwaters

TABLE 3-72

MEAN CONCENTRATION OF HEAVY METALS IN THE RETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

(All concentrations in $\mu g/l$)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	4.80/6.19	5.25	5.00	6.12	5.14	6.14
Zn	14.2/18.6	18.5	13.5	19.3	14.5	12.3
Mn	17.4/24.7	52.1	95.6	90.0	22.4	41.8
Cu	18.2/21.0	14.4	10.9	13.7	13.6	12.8
Al	551/693	262	158	223	391	187
Fe	77.8/119	403	755	752	56.1	160
Pb	162/178	153	154	152	156	182
Ni	29.5/32.3	24.5	23	25.2	24.0	26.1
Cr	18.6/20.1	17.4	17	16.8	17.1	19.4

1. Dissolved Concentration/Total Concentration

beneath the retention pond. Groundwater concentrations of all measured heavy metals, with the exceptions of iron and manganese, were lower in groundwater beneath the retention pond than in surface water contained within the retention pond. A clear trend of increasing or decreasing concentration with increasing groundwater depth did not appear to be present for most heavy metals beneath the retention pond.

A summary of mean heavy metal concentrations in the detention pond area is given in Table 3-73. Groundwater concentrations of cadmium, zinc, copper, lead, nickel and chromium beneath the detention pond were similar to those measured beneath the retention pond. Groundwater concentrations of manganese appeared to be substantially higher beneath the detention pond, while groundwater concentrations of aluminum appeared to be somewhat lower. With the exceptions of iron and manganese, groundwater concentrations of all heavy metals were lower in groundwater beneath the detention pond than in surface water contained within the detention pond.

Mean concentrations of heavy metals in groundwater in the control area are given in Table 3-74. Groundwater concentrations of iron, lead, nickel and chromium in the control area were similar to concentrations measured in groundwaters measured beneath the retention and detention ponds. However, groundwater concentrations of cadmium, zinc, manganese, copper and aluminum appeared to be substantially greater than concentrations measured beneath either of the stormwater management ponds. A trend of decreasing groundwater concentration with increasing groundwater depth is apparent, at least within the top 1.0 m for zinc, copper, aluminum and chromium.

An ANOVA comparison of dissolved heavy metal concentrations beneath pond and control areas is given in Table 3-75. Significant differences in groundwater

TABLE 3-73

MEAN CONCENTRATION OF HEAVY METALS IN THE DETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

(All concentrations in μg/l)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	5.51/7.16	5.77	5.81	4.95	6.17	6.32
Zn	15.4/20.1	19.3	18.2	17.2	19.4	20.1
Mn	30.0/39.7	137	186	134	57.4	58.2
Cu	16.5/20.8	12.7	13.0	11.4	14.1	15.1
Al	569/853	199	152	150	142	167
Fe	54.4/148	689	486	281	104	117
Pb	186/194	161	140	157	166	172
Ni	31.1/32.5	26.3	23.4	26.6	26.7	27.4
Cr	20.5/21.1	17.2	15.9	17.7	18.6	18.9

1. Dissolved Concentration/Total Concentration

TABLE 3-74

MEAN CONCENTRATION OF HEAVY METALS IN THE CONTROL AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

(All concentrations in μg/l)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	6.20	6.94	6.32	6.28	5.30
Zn	33.7	27.8	18.7	33.8	16.6
Mn	239	443	141	40.2	55.8
Cu	21.3	16.1	11.2	19.4	15.8
Al	5412	2786	388	1114	354
Fe	337	444	209	158	79.4
Pb	141	150	166	145	127
Ni	27.7	28.7	28.3	25.9	21.3
Cr	19.2	18.2	18.4	16.8	14.4

TABLE 3-75

ANOVA COMPARISON OF DISSOLVED HEAVY METAL CONCENTRATIONS BENEATH POND AND CONTROL AREAS AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

DISSOLVED HEAVY METAL	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN CONC. (μg/l)	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cd	42.6	Control	6.19	56	NSD[1]
		Detention	5.82	59	
		Retention	5.53	60	
Zn	99.7	Control	25.7	56	A
		Detention	18.8	59	B
		Retention	15.6	60	B
Mn	98.6	Control	176	56	A
		Detention	114	59	B
		Retention	60.4	60	B
Cu	92.1	Control	16.5	56	NSD
		Retention	13.3	60	
		Detention	13.1	59	
Al	99.9	Control	1815	56	A
		Retention	244	60	B
		Detention	162	59	B
Fe	89.8	Retention	425	60	NSD
		Detention	336	59	
		Control	237	56	
Pb	82.1	Detention	159	59	NSD
		Retention	159	60	
		Control	146	56	
Ni	52.6	Control	26.3	56	NSD
		Detention	26.0	59	
		Retention	24.6	60	
Cr	8.2	Detention	17.7	59	NSD
		Retention	17.6	60	
		Control	17.3	56	

1. No significant difference at the 0.05 level.

concentrations at the 0.05 level of significance were detected for zinc, manganese and aluminum. In each case, groundwater concentrations beneath the control area were greater than those found beneath either the retention or detention ponds. Although significant differences were not observed for the remaining heavy metals, groundwater concentrations of cadmium, copper and nickel were greater beneath the control area than beneath either of the ponds. Groundwater concentrations of iron were greatest beneath the retention pond, while concentrations of lead and chromium were slightly greater beneath the detention pond. It seems apparent that the operation of the dual pond system is having little or no detectable effect on groundwater characteristics of heavy metals in the vicinity of the stormwater management system.

Site 4 - Residential Wet Detention Site

Detailed summary statistics for general water quality characteristics in groundwater samples collected beneath the detention pond at the residential wet detention facility are given in Table A-15. A total of eleven samples were collected from 0.1 m sample port, with twelve samples collected from each of the remaining sample ports. With only a few exceptions, general groundwater parameters beneath the wet detention pond appear to be less variable in concentration than found in groundwaters at the previous three sites. The most variable parameters measured at this site were found to be redox potential, organic phosphorus, total phosphorus and sulfate. Variability in the remaining general chemical characteristics were less than one order of magnitude in range.

A summary of water quality characteristics in the detention pond area is given in Table 3-76. Groundwaters beneath the detention pond were found to be somewhat acidic, with a mean value of approximately 6.35 near the surface, decreasing steadily to a value of 4.62 at a depth of 5.0 m. Concentrations of alkalinity also decreased rapidly with increasing groundwater depth. This same general trend of decreasing concentrations with increasing groundwater depth was observed for conductivity as well as for redox potential. Redox potential in groundwaters beneath the pond indicated a reduced environment on all sample dates.

Groundwater concentrations of total nitrogen were relatively low at all depths, with measured concentrations of approximately 1 mg/l or less. The two dominant nitrogen species were ammonia and organic nitrogen which together comprised 85-95% of the total nitrogen measured in groundwater beneath the pond. Concentrations of total nitrogen in groundwater were similar to those found in surface water within the detention pond, although the distribution of species had changed somewhat. Concentrations of ammonia had increased substantially in groundwater compared to values measured within the pond, while concentrations of organic nitrogen decreased substantially over those measured within the pond.

Concentrations of total phosphorus in groundwaters beneath the pond were relatively high in value compared with concentrations measured at the other study sites. Groundwater concentrations of total phosphorus were similar to those measured in surface water above the pond. Both orthophosphorus and organic phosphorus were important dissolved species contributing to total phosphorus measured in groundwater,

TABLE 3-76

MEAN WATER QUALITY CHARACTERISTICS IN THE DETENTION POND AREA AT THE RESIDENTIAL DETENTION POND (SITE 4)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.53	6.35	5.82	5.62	4.82	4.62
Spec. Cond.	μmhos/cm	95	104	81	70	32	26
Temperature	°C	25.71	24.25	24.40	24.43	24.56	24.74
Dissolved O_2	mg/l	9.4	1.0	0.5	0.5	0.5	0.5
ORP	mv	328	- 3	- 47	- 36	- 62	- 77
Alkalinity	mg/l	44.1	46.7	32.1	23.7	4.8	3.8
Ammonia	mg/l	13	391	662	440	53	48
Nitrate	μg/l	14	< 10	< 10	13	30	16
Diss. Organic N	μg/l	641	475	412	383	100	158
Total N	μg/l	860	874	1083	836	183	405
Diss. Ortho-P	μg/l	17	50	76	89	37	49
Diss. Organic P	μg/l	50	83	67	107	81	54
Total P	μg/l	147	133	134	186	119	104
Chloride	mg/l	10	11	12	13	14	12
Sulfate	mg/l	3.0	3.6	2.3	2.7	2.8	2.5
BOD	mg/l	3.8	3.3	3.8	4.1	3.1	3.0
Color	Pt-Co Units	31	59	66	64	41	28
T.D.S.	mg/l	75	80	63	57	30	38
V.D.S.	mg/l	36	35	29	28	12	19

while organic phosphorus was the primary dissolved species contributing to total phosphorus in surface water.

Groundwater concentrations of chloride, sulfate and dissolved solids were relatively low in groundwaters beneath the pond and similar in value to concentrations found within the detention pond surface water. Groundwater concentrations of color, although relatively low in value, were approximately twice those found within surface water.

Detailed summary statistics of mean water quality characteristics in groundwater samples collected from the control well are given in Table A-16. A total of seven samples were collected from the 0.1 m depth, eleven from the 0.5 m depth and twelve each from the remaining three sample ports. Considerable variability was observed in groundwater characteristics for many of the measured parameters in the control well, including alkalinity, ammonia, organic nitrogen, orthophosphorus, organic phosphorus, total phosphorus, BOD, color and volatile dissolved solids. Variability in groundwater characteristics within the control well appeared to be substantially greater than variability observed beneath the detention pond.

Mean water quality characteristics in the control area are presented in Table 3-77. Groundwater beneath the control area was found to be relatively acidic, with pH values of approximately 4.3 at all sample depths. Levels of alkalinity were also low, with mean values less than 2 mg/l at all depths. Based upon measured values for redox potential, groundwater in the control area was found to be slightly oxidized within the top 1.0 m, with reduced conditions existing at depths below 1.0 m. Conductivity values were relatively low and uniform at all depths.

TABLE 3-77

MEAN WATER QUALITY CHARACTERISTICS IN THE CONTROL AREA AT THE RESIDENTIAL DETENTION POND (SITE 4)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	4.33	4.34	4.31	4.26	4.36
Spec. Cond.	μmhos/cm	72	53	49	53	55
Temperature	°C	24.41	23.88	24.03	24.08	24.14
Dissolved O_2	mg/l	2.7	0.7	0.5	0.5	0.5
ORP	mv	270	269	222	41	43
Alkalinity	mg/l	0.4	0.8	1.4	0.6	1.1
Ammonia	μg/l	23	15	33	69	39
Nitrate	μg/l	1268	203	113	63	85
Diss. Organic N	μg/l	214	118	131	119	138
Total N	μg/l	1505	336	227	251	262
Diss. Ortho-P	μg/l	9	5	6	6	10
Diss. Organic P	μg/l	5	13	9	10	34
Total P	μg/l	15	17	15	16	45
Chloride	mg/l	8	11	12	14	16
Sulfate	mg/l	12.0	9.8	7.1	6.6	7.9
BOD	mg/l	1.3	1.3	1.5	1.8	1.9
Color	Pt-Co Units	28	30	28	40	61
T.D.S.	mg/l	57	41	38	40	45
V.D.S.	mg/l	26	17	17	20	21

Groundwater concentrations of total nitrogen were relatively high at the surface sample port, with a mean value of approximately 1.5 mg/l, contributed primarily by nitrate. Groundwater concentrations of total nitrogen decreased substantially at the remaining groundwater depths. Groundwater concentrations of total phosphorus were also extremely low beneath the control area, with values approximately 10% of those measured beneath the detention pond.

Groundwater concentrations of chloride, sulfate, BOD, color and dissolved solids were extremely low in groundwater beneath the control area. Concentrations of chloride appeared to be similar to those measured in groundwaters beneath the detention pond, while sulfate concentrations appeared to be somewhat higher beneath the control area.

An ANOVA comparison of general groundwater characteristics between pond and control areas is given in Table 3-78. With the exceptions of only conductivity, temperature, chloride, color and volatile dissolved solids, significant differences were found at the 0.05 level for all general groundwater parameters beneath detention pond and control areas. Groundwater concentrations of pH, alkalinity, ammonia, organic nitrogen, total nitrogen, orthophosphorus, organic phosphorus, total phosphorus, BOD and total dissolved solids were higher beneath the detention pond than in the control area. Groundwater concentrations of ORP and sulfate were higher beneath the control area than beneath the detention pond. For many parameters, concentration differences in groundwaters beneath the two areas were quite significant. For example, mean groundwater concentrations of ammonia were approximately 8.6 times greater beneath the detention pond than beneath the control area. Groundwater concentrations of orthophosphorus and total phosphorus were approximately 8.6 and 6.1 times greater,

TABLE 3-78

ANOVA COMPARISON OF GENERAL GROUNDWATER CHARACTERISTICS BETWEEN POND AND CONTROL AREAS AT THE RESIDENTIAL DETENTION SITE (SITE 4)

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
pH	s.u.	99.9	Detention	5.43	59	A
			Control	4.32	54	B
Spec. Cond.	μS/cm	87.0	Detention	62	59	NSD[1]
			Control	55	54	
Temperature	°C	45.0	Detention	24.48	59	NSD
			Control	24.09	54	
ORP	mv	99.9	Control	158	54	A
			Detention	- 46	59	B
Alkalinity	mg/l	99.9	Detention	21.8	59	A
			Control	0.9	54	B
NH_3-N	μg/l	99.9	Detention	317	59	A
			Control	37	54	B
NO_3-N	μg/l	99.9	Control	264	54	A
			Detention	15	59	B
Diss. Org. N	μg/l	99.9	Detention	303	59	A
			Control	138	54	B
Total N	μg/l	97.5	Detention	635	59	A
			Control	439	54	B
Diss. Ortho-P	μg/l	99.9	Detention	60	59	A
			Control	7	54	B
Diss. Org. P	μg/l	99.9	Detention	78	55	A
			Control	15	54	B
Total P	μg/l	99.9	Detention	135	55	A
			Control	22	54	B

TABLE 3-78 -- CONTINUED

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cl	mg/l	21.6	Control	13	54	NSD
			Detention	12	59	
SO_4	mg/l	99.9	Control	8.3	54	A
			Detention	2.8	59	B
BOD	mg/l	99.9	Detention	3.5	59	A
			Control	1.6	54	B
Color	Pt-Co units	87.9	Detention	52	59	NSD
			Control	38	54	
T.D.S.	mg/l	98.7	Detention	53	59	A
			Control	43	54	B
V.D.S.	mg/l	88.0	Detention	24	59	NSD
			Control	20	54	

1. No significant difference at the 0.05 level.

respectively, beneath the detention pond than beneath the control area. The operation of this detention facility appeared to be contributing total nitrogen as well as total phosphorus into groundwaters beneath the pond.

Detailed summary statistics for concentrations of dissolved heavy metals in groundwaters beneath detention and control areas are presented in Tables A-17 and A-18, respectively. As observed at the previous study sites, groundwater concentrations of heavy metals were relatively stable in groundwater beneath the detention pond. The most variable heavy metals appeared to be copper, aluminum and iron. Variability in heavy metals beneath the control area were substantially greater than found beneath the detention pond. In groundwaters beneath the control area, large variability was observed for manganese, copper, iron and chromium. In general, groundwater concentrations of heavy metals beneath the control area appeared to be both higher in value as well as more variable for many of the metal species measured.

Mean heavy metal concentrations in the detention pond area are given in Table 3-79. Groundwater concentrations of all heavy metals measured beneath the detention pond were relatively low in value. Some metal species exhibited a slight tendency for decreases in concentration with increasing groundwater depth, particularly at depths in excess of 1.0 m. Groundwater concentrations for most heavy metals appeared to be similar within the top 1.0 m of groundwater. Concentrations measured at the 2.5 m and 5.0 m sample ports also appeared to be relatively similar for most metal species and somewhat lower in value than concentrations measured within the top 1.0 m. With the exceptions of manganese and iron, groundwater concentrations of all heavy metals were

TABLE 3-79

MEAN CONCENTRATION OF HEAVY METALS IN THE DETENTION POND AREA AT THE RESIDENTIAL DETENTION POND (SITE 4)

(All concentrations in μg/l)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	4.52/5.30	5.45	4.17	3.89	3.24	3.20
Zn	13.4/16.4	16.9	16.3	14.2	12.6	13.3
Mn	6.09/9.48	16.8	15.3	16.5	10.3	4.29
Cu	11.1/15.7	8.77	9.79	9.33	9.79	6.46
Al	692/1526	457	384	532	275	252
Fe	70.4/175	262	418	614	484	170
Pb	69.5/79.9	67.1	57.4	45.9	28.0	25.8
Ni	11.2/13.4	12.4	11.7	11.0	9.06	8.47
Cr	7.31/8.84	7.29	7.47	6.40	4.68	4.25

1. Dissolved Concentration/Total Concentration

found to be equal to or less than total metal concentrations found in surface waters above the detention pond.

Heavy metal concentrations in groundwaters beneath the control area are given in Table 3-80. With the exceptions of cadmium and lead, groundwater concentrations for all measured heavy metals were found to be substantially higher in groundwaters beneath the control pond than beneath the pond. Highest concentrations for most heavy metals beneath the control area were found near the groundwater surface, with decreasing concentrations at increasing groundwater depths. This general tendency was observed for all metal species except iron. Groundwater concentrations of zinc and aluminum beneath the control area were several times greater than concentrations measured beneath the wet detention pond.

An ANOVA comparison of dissolved heavy metal concentrations beneath pond and control areas is presented in Table 3-81. Significant differences in groundwater concentrations for heavy metals at the 0.05 level of significance were found for zinc, manganese, copper, aluminum and iron. For each of these heavy metals, concentrations measured beneath the control area exceeded values measured beneath the wet detention pond. In general, groundwater concentrations for most heavy metals appeared to be equal to or less than heavy metal concentrations measured in surface water within the wet detention pond. Groundwater concentrations for the majority of heavy metals measured appeared to be significantly lower beneath the detention pond than in the control area.

TABLE 3-80

MEAN CONCENTRATION OF HEAVY METALS IN THE CONTROL AREA AT THE RESIDENTIAL DETENTION POND (SITE 4)

(All concentrations in $\mu g/l$)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	3.93	3.81	2.68	2.92	3.20
Zn	1045	137	58.2	68.8	60.8
Mn	41.7	31.3	7.25	14.4	15.6
Cu	24.7	29.2	13.1	9.54	9.29
Al	1717	822	538	337	358
Fe	297	575	280	1016	1038
Pb	64.1	42.3	33.9	33.7	35.1
Ni	19.3	15.1	9.02	9.98	11.1
Cr	9.49	6.35	5.17	4.74	5.43

TABLE 3-81

ANOVA COMPARISON OF DISSOLVED HEAVY METAL CONCENTRATIONS BENEATH POND AND CONTROL AREAS AT THE RESIDENTIAL DETENTION SYSTEM (SITE 4)

DISSOLVED HEAVY METAL	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN CONC. (μg/l)	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cd	91.0	Control	3.24	54	NSD[1]
		Detention	3.97	59	
Zn	99.9	Control	205	54	A
		Detention	14.6	59	B
Mn	96.6	Control	20.1	54	A
		Detention	12.6	59	B
Cu	96.1	Control	16.3	54	A
		Detention	8.83	59	B
Al	99.9	Control	664	54	A
		Detention	381	59	B
Fe	99.4	Control	674	54	A
		Detention	392	59	B
Pb	69.9	Control	39.7	54	NSD
		Detention	44.4	59	
Ni	83.7	Control	12.3	54	NSD
		Detention	10.5	59	
Cr	5.3	Control	5.93	54	NSD
		Detention	6.00	59	

1. No significant difference at the 0.05 level.

Site 5 - Commercial Dual Pond Facility

Detailed water quality statistics for groundwater samples collected beneath the retention pond at the commercial dual pond site are given in Table A-19. A total of twelve groundwater samples were collected from each of the five sample ports during 1987. As observed at the other groundwater monitoring locations, chemical characteristics for certain groundwater parameters exhibited extreme variability during the 12-month study period. This variability was particularly evident for concentrations of ammonia, nitrate, organic phosphorus, chloride, sulfate, BOD and color. In contrast, relatively little variability was observed in concentrations of pH, conductivity, alkalinity and dissolved solids.

Mean water quality characteristics in the retention pond area are summarized in Table 3-82. Groundwater beneath the retention pond was found to be slightly acidic, with measured pH values primarily in excess of 6.0. Measured values for redox potential in groundwater indicated a mildly reduced condition. Alkalinity in groundwater beneath the retention pond was found to be relatively high, with values in excess of 125 mg/l within the top 1.0 m of groundwater. Measured values of pH in surface water above the retention pond were approximately equal to values measured in the shallow groundwater beneath the pond. However, measured values of both redox potential and alkalinity were found to be substantially less in surface water than in groundwater beneath the pond.

Groundwater concentrations of both total nitrogen and total phosphorus were found to be relatively low in groundwater beneath the pond. The largest mean groundwater concentration for total nitrogen, approximately 1.6 mg/l, was found at the

TABLE 3-82

MEAN WATER QUALITY CHARACTERISTICS IN THE RETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	6.58	6.24	6.24	6.04	5.77	6.30
Spec. Cond.	μmhos/cm	300	488	434	410	286	218
Temperature	°C	21.47	22.80	23.28	22.79	22.92	23.17
Dissolved O_2	mg/l	1.1	3.4	3.8	1.0	0.6	0.6
ORP	mv	72	117	125	118	116	83
Alkalinity	mg/l	135	205	162	127	78.3	79.1
Ammonia	mg/l	392	1216	639	231	110	306
Nitrate	μg/l	24	11	15	39	15	36
Diss. Organic N	μg/l	569	365	383	341	186	322
Total N	μg/l	1230	1592	1037	611	311	664
Diss. Ortho-P	μg/l	10	33	25	37	138	141
Diss. Organic P	μg/l	19	32	24	23	11	23
Total P	μg/l	51	65	48	60	149	163
Chloride	mg/l	20	29	37	48	59	19
Sulfate	mg/l	1.8	1.5	1.1	1.4	1.5	1.9
BOD	mg/l	4.6	8.7	6.0	3.9	1.9	3.7
Color	Pt-Co Units	95	293	272	160	64	48
T.D.S.	mg/l	204	318	282	257	190	144
V.D.S.	mg/l	76	86	76	54	33	48

0.1 m sample port, with rapid decreases in total nitrogen with increasing groundwater depth. Ammonia was the dominant nitrogen species at groundwater depths of 0.1 m and 0.5 m, while organic nitrogen became the dominant nitrogen species at groundwater depths of 1.0 m and greater. Concentrations of nitrate were relatively low in groundwater and in surface water as well. Groundwater concentrations of ammonia at the 0.1 m and 0.5 m depths were substantially greater than surface water concentrations, while groundwater concentrations of organic nitrogen were found to be substantially lower than surface water values at the same depths.

Groundwater concentrations of total phosphorus were approximately equal to those found in surface waters up to a depth of 1.0 m. Within this zone, both orthophosphorus and organic phosphorus were important forms contributing to total phosphorus.

Groundwater concentrations of both chloride and sulfate were found to be relatively low in groundwaters beneath the retention pond and similar to values measured in surface waters within the pond. However, groundwater concentrations of BOD, color and dissolved solids were found to be relatively higher in groundwaters, particularly within the top 1.0 m. Groundwater concentrations for each of these parameters exceeded those measured in surface waters within the pond.

Detailed summary statistics of water quality characteristics in groundwater samples collected from the detention pond well are presented in Table A-20. A total of twelve groundwater samples were collected from each sample port during this study. Variability in measured concentrations of general groundwater parameters appeared to be similar to that measured in groundwater beneath the retention pond. The most variable parameters in groundwater beneath the retention pond appeared to be ammonia, nitrate, organic phosphorus, chloride, sulfate and color.

A summary of mean water quality characteristics in the detention pond area is given in Table 3-83. Groundwater beneath the detention pond was characterized as slightly acidic, with measured pH values between 6.4 and 6.8, compared with a surface water pH value of 7.49. Alkalinity in groundwater beneath the detention pond was found to be relatively high and similar in value to that measured beneath the retention pond. Groundwater concentrations of alkalinity were somewhat higher than the mean alkalinity values measured within surface water. Based upon measured values for redox potential, groundwater beneath the detention pond exists in a reduced environment with decreasing redox potential at increasing groundwater depths. Surface water within the detention pond was well oxidized based upon the mean redox value of 342 mv.

Concentrations of both total nitrogen and total phosphorus were relatively low in groundwater beneath the detention pond and lower at most groundwater locations than concentrations measured beneath the retention pond. The dominant groundwater species beneath the detention pond was found to be organic nitrogen, although ammonia was also an important species. As observed in groundwaters beneath the retention pond, ammonia concentrations beneath the detention pond were greater than those measured in surface water, while concentrations of organic nitrogen were found to be somewhat lower than concentrations found in surface water. Groundwater concentrations of total phosphorus were generally lower than mean total phosphorus values found in the detention pond surface water. However, concentrations of chloride and color appeared to be somewhat

TABLE 3-83

MEAN WATER QUALITY CHARACTERISTICS IN THE DETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	MEAN GROUNDWATER CONCENTRATIONS				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	7.49	6.67	6.80	6.56	6.39	6.45
Spec. Cond.	μmhos/cm	305	450	338	338	453	399
Temperature	°C	26.12	25.98	26.61	25.33	24.95	25.18
Dissolved O_2	mg/l	9.5	5.5	4.9	3.5	0.7	0.7
ORP	mv	342	141	144	127	79	76
Alkalinity	mg/l	149	225	158	150	185	176
Ammonia	mg/l	81	468	344	325	367	405
Nitrate	μg/l	25	12	71	86	< 10	< 10
Diss. Organic N	μg/l	723	515	446	419	545	593
Total N	μg/l	1079	995	861	830	917	1004
Diss. Ortho-P	μg/l	7	11	10	8	40	96
Diss. Organic P	μg/l	16.4	11	9	9	9	10
Total P	μg/l	46	21	19	17	48	105
Chloride	mg/l	17	39	37	51	77	61
Sulfate	mg/l	2.4	0.9	2.2	2.4	2.7	2.4
BOD	mg/l	4.2	3.9	3.6	3.2	3.4	3.5
Color	Pt-Co Units	70	136	108	102	134	116
T.D.S.	mg/l	198	301	238	235	307	286
V.D.S.	mg/l	65	79	65	72	98	84

elevated in groundwaters. Total dissolved solids concentrations also appeared to be somewhat elevated in groundwater beneath the detention pond.

Detailed summary statistics of mean water quality characteristics in groundwater samples collected from the control well are presented in Table A-21. A total of twelve groundwater samples were collected from each sample port at the control well during this study. Variability in concentrations for general groundwater constituents appeared to be similar to those observed in the retention and detention ponds.

A summary of mean water quality characteristics in the control area is given in Table 3-84. Groundwater beneath the control area was found to be low in pH with mean pH values ranging between 5.3 and 5.4. Mean values of ORP and alkalinity also appeared to be substantially lower beneath the control area than beneath the retention or detention ponds. Groundwater concentrations of total nitrogen in the control area were found to be extremely elevated. Mean values for total nitrogen within the top 1.0 m ranged from approximately 6.3 mg/l to 7.1 mg/l. This total nitrogen was contributed approximately equally by both ammonia and dissolved organic nitrogen. Total phosphorus concentrations in groundwater beneath the control area appeared to be similar to those measured beneath each of the ponds. Within the first 1.0 m of groundwater, organic phosphorus was the dominant groundwater species, while orthophosphorus became dominant at depths in excess of 1.0 m.

Groundwater concentrations of chloride and sulfate appeared to be relatively low beneath the detention pond. BOD values found in groundwaters appeared to be similar to those within the detention and retention areas. However, groundwater concentrations

TABLE 3-84

MEAN WATER QUALITY CHARACTERISTICS IN THE CONTROL AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	5.33	5.33	5.37	5.32	5.42
Spec. Cond.	μmhos/cm	269	264	261	269	276
Temperature	°C	23.17	23.80	23.92	24.09	24.16
Dissolved O_2	mg/l	1.0	2.2	0.9	0.5	0.6
ORP	mv	67	65	57	35	13
Alkalinity	mg/l	63.5	71.2	65.4	71.9	76.2
Ammonia	μg/l	3773	3527	2871	2134	2005
Nitrate	μg/l	< 10	29	< 10	< 10	14
Diss. Organic N	μg/l	3020	3517	3407	2572	2197
Total N	μg/l	6801	7073	6286	4713	4216
Diss. Ortho-P	μg/l	24	18	18	129	120
Diss. Organic P	μg/l	35	30	31	25	28
Total P	μg/l	59	48	50	154	148
Chloride	mg/l	22	25	26	28	25
Sulfate	mg/l	9.7	10.4	9.4	7.9	8.2
BOD	mg/l	5.2	5.0	5.0	5.3	10.0
Color	Pt-Co Units	498	504	480	422	399
T.D.S.	mg/l	298	293	287	298	300
V.D.S.	mg/l	170	216	162	166	166

of color were substantially greater beneath the control area than beneath either of the two ponds.

An ANOVA comparison of general groundwater characteristics between pond and control areas is presented in Table 3-85. Significant differences were found between pond and control areas for all of the measured general groundwater parameters. Groundwater concentrations beneath the detention and retention ponds were found to be significantly greater than groundwater concentrations beneath the control area for ORP, alkalinity, nitrate and chloride. Groundwater concentrations beneath the control area were found to have significantly higher concentrations of ammonia, total nitrogen, organic phosphorus, sulfate, BOD, color, total dissolved solids and volatile dissolved solids than found beneath the detention or retention ponds.

Detailed summary statistics for dissolved heavy metal concentrations in groundwater beneath retention, detention and control sites are given in Tables A-22, A-23 and A-24, respectively. As observed at the previously studied sites, variability in concentrations of heavy metals in groundwaters appeared to be less than that observed for general groundwater parameters. The most variable heavy metals appeared to be zinc, aluminum, iron and copper.

A summary of mean heavy metal concentrations in the retention pond area is given in Table 3-86. Groundwater concentrations of most heavy metals appeared to be greatest near the surface layers, with decreasing concentrations at increasing groundwater depths. Concentrations for several heavy metals, including zinc, manganese, iron, lead and nickel, were somewhat elevated in groundwaters beneath the pond, particularly

TABLE 3-85

ANOVA COMPARISON OF GENERAL GROUNDWATER CHARACTERISTICS BETWEEN POND AND CONTROL AREAS AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
pH	s.u.	99.9	Detention	6.57	60	A
			Retention	6.12	60	B
			Control	5.35	60	C
Spec. Cond.	μS/cm	99.9	Detention	397	60	A
			Retention	367	60	A
			Control	268	60	B
Temperature	°C	99.9	Detention	25.61	60	A
			Control	23.83	60	B
			Retention	22.99	60	B
ORP	mv	99.9	Detention	113	60	A
			Retention	112	60	A
			Control	48	60	B
Alkalinity	mg/l	99.9	Detention	179	60	A
			Retention	130	60	B
			Control	69.6	60	C
NH_3-N	μg/l	99.9	Control	2862	60	A
			Retention	500	60	B
			Detention	382	60	B
NO_3-N	μg/l	97.5	Detention	36	60	A
			Retention	23	60	A
			Control	13	60	B
Diss. Org. N	μg/l	99.9	Control	2943	60	A
			Detention	625	60	B
			Retention	374	60	B
Total N	μg/l	99.9	Control	5818	60	A
			Detention	922	60	B
			Retention	843	60	B
Diss. Ortho-P	μg/l	99.9	Retention	75	60	A
			Control	62	60	A
			Detention	33	60	B
Diss. Org. P	μg/l	99.9	Control	30	60	A
			Retention	22	60	A
			Detention	9	60	B
Total P	μg/l	99.9	Retention	97	60	A
			Control	92	60	A
			Detention	42	60	B

TABLE 3-85 -- CONTINUED

PARAMETER	UNITS	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN VALUE	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cl	mg/l	99.9	Control	30	60	A
			Retention	22	60	A
			Detention	9	60	B
SO_4	mg/l	99.9	Control	9.2	60	A
			Detention	2.1	60	B
			Retention	1.5	60	B
BOD	mg/l	99.9	Control	6.1	60	A
			Retention	4.9	60	B
			Detention	3.5	60	B
Color	Pt-Co units	99.9	Control	461	60	A
			Retention	167	60	B
			Detention	119	60	B
T.D.S.	mg/l	99.9	Control	295	60	A
			Detention	273	60	A
			Retention	238	60	B
V.D.S.	mg/l	99.9	Control	176	60	A
			Detention	80	60	B
			Retention	80	60	B

1. No significant difference at the 0.05 level.

TABLE 3-86

MEAN CONCENTRATION OF HEAVY METALS IN THE RETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

(All concentrations in μg/l)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	11.50/15.7	5.50	4.12	3.92	3.27	1.97
Zn	25.2/38.5	54.8	32.5	31.8	24.8	20.8
Mn	41.4/55.0	99.6	67.4	42.3	13.4	20.8
Cu	17.5/23.5	17.0	13.8	16.6	11.9	11.2
Al	165/264	517	222	196	136	118
Fe	2124/3909	12,186	11,608	9,465	3,243	1,230
Pb	121/135	173	141	114	79.8	98.5
Ni	30.7/34.8	43.3	31.8	26.6	20.2	26.6
Cr	8.9/11.6	19.6	16.1	13.2	9.72	10.4

1. Dissolved Concentration/Total Concentration

within the top 1.0 m. Concentrations for most heavy metals in groundwater lower than 1.0 m were substantially lower than those within the first 1.0 m.

Groundwater concentrations of certain heavy metals such as zinc, manganese, aluminum, lead and nickel, exceeded total metal concentrations in surface waters at the 0.1 m or 0.5 m depths, but dropped below surface water concentrations at groundwater depths of 1.0 m and greater. Concentrations of iron appeared to be particularly elevated in groundwater beneath the retention pond, with mean concentrations ranging from approximately 9.5 mg/l to 12.2 mg/l within the first 1.0 m.

Mean heavy metal concentrations in the detention pond area are presented in Table 3-87. Groundwater concentrations of certain heavy metals such as zinc, manganese, copper and iron, appeared to be substantially lower than those found beneath the retention pond. However, groundwater concentrations of cadmium, lead, nickel and chromium appeared to be greater beneath the detention pond than beneath the retention pond. It should be noted that the groundwater concentrations of lead monitored beneath the detention pond were some of the highest lead values measured at any site during this study. Most heavy metals beneath the detention pond exhibited a trend of decreasing concentrations with increasing groundwater depth.

A summary of heavy metal concentrations beneath the control area is given in Table 3-88. Heavy metal concentrations in groundwaters beneath the control area appeared to be somewhat elevated for heavy metals such as aluminum, iron and lead, while exhibiting relatively low concentrations of cadmium, zinc, manganese and copper. A trend of either increasing or decreasing concentration with increasing groundwater depth did not appear to be present for most metal species in the control area.

TABLE 3-87

MEAN CONCENTRATION OF HEAVY METALS IN THE DETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

(All concentrations in μg/l)

HEAVY METALS	MEAN SURFACE WATER CONC.[1]	MEAN GROUNDWATER CONCENTRATIONS				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	11.0/14.8	5.84	5.74	6.99	7.65	5.93
Zn	24.2/31.5	30.9	35.3	31.3	32.7	31.3
Mn	22.8/39.8	88.9	66.8	59.9	78.5	66.3
Cu	21.1/26.1	13.6	19.2	12.4	13.9	13.3
Al	167/340	379	579	319	211	201
Fe	801/1933	3947	3158	3389	6511	5021
Pb	144/161	230	198	190	185	167
Ni	33.8/42.3	58.7	47.5	44.3	44.7	42.6
Cr	10.2/12.8	22.5	20.3	17.9	17.6	17.1

1. Dissolved Concentration/Total Concentration

TABLE 3-88

MEAN CONCENTRATION OF HEAVY METALS IN THE CONTROL AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

(All concentrations in μg/l)

HEAVY METALS	MEAN GROUNDWATER CONCENTRATIONS				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	2.97	3.60	3.74	2.89	3.65
Zn	33.5	35.8	34.3	46.5	28.9
Mn	16.7	17.4	17.5	18.6	30.6
Cu	11.8	13.3	11.4	13.8	12.8
Al	1,911	1,840	1,605	1,388	909
Fe	19,921	19,487	17,290	12,761	11,435
Pb	96.1	106	164	108	110
Ni	24.0	24.1	25.0	24.7	27.9
Cr	14.4	15.4	15.2	16.7	15.2

TABLE 3-89

ANOVA COMPARISON OF DISSOLVED HEAVY METAL CONCENTRATIONS BENEATH POND AND CONTROL AREAS AT THE COMMERCIAL DUAL POND SYSTEM (SITE 5)

DISSOLVED HEAVY METAL	PROB. OF UNEQUAL MEANS	WELL SITE	MEAN CONC. (μg/l)	NO. OF OBS.	TUKEY'S MULTIPLE COMPARISON
Cd	99.9	Detention	6.43	60	A
		Retention	3.76	60	B
		Control	3.37	60	B
Zn	14.2	Control	35.8	60	NSD[1]
		Retention	32.9	60	
		Detention	32.3	60	
Mn	99.9	Detention	72.1	60	A
		Retention	48.7	60	B
		Control	20.2	60	C
Cu	34.4	Detention	14.5	60	NSD
		Retention	14.1	60	
		Control	12.7	60	
Al	99.9	Control	1531	60	A
		Detention	338	60	B
		Retention	238	60	B
Fe	99.9	Control	16179	60	A
		Retention	7546	60	B
		Detention	4405	60	C
Pb	99.9	Detention	194	60	A
		Retention	121	60	B
		Control	117	60	B
Ni	99.9	Detention	47.6	60	A
		Retention	29.7	60	B
		Control	25.1	60	B
Cr	99.4	Detention	19.1	60	A
		Control	15.4	60	A B
		Retention	13.8	60	B

[1] No significant difference at the 0.05 level.

An ANOVA comparison of dissolved heavy metal concentrations beneath pond and control areas is given in Table 3-89. Significant differences in groundwater concentrations were found for all heavy metals except zinc and copper. Groundwater concentrations of aluminum and iron were found to be significantly higher beneath the control area than beneath either pond. Groundwater concentrations beneath the detention pond were found to be substantially greater than those beneath either retention or control areas for cadmium, manganese, lead, nickel and chromium. In summary, groundwater concentrations beneath the retention pond appeared to be similar to those beneath the control area for most heavy metals. Elevated concentrations of certain heavy metals appeared to be present beneath the detention pond only.

CHAPTER 4

DISCUSSION

The discussion of experimental results contained in this chapter is intended to present a logical progression of the fate of pollutants in the various types of stormwater management systems evaluated in this research, with particular emphasis on the potential for migration of pollutants into groundwaters. This discussion will begin with a review of the characteristics of stormwater runoff collected at the five study sites, along with comparisons from other published runoff studies. The fate and settling characteristics of stormwater related pollutants upon entering each of the stormwater management systems will be examined. Sediment bonding mechanisms will be used to evaluate the stability of sediment pollutant associations in the sediments of each stormwater management system along with the potential for resolubilization. The potential for migration of stormwater related pollutants into groundwaters will be discussed.

Characterization of Stormwater Runoff at the Five Study Sites

A comparison of mean general water quality characteristics in stormwater runoff collected at the five study sites is given in Table 4-1. Mean pH values were relatively similar between the five study sites with overall mean values ranging from 6.51 to 7.22. The lowest mean pH values (6.51 and 6.78) were found at the two highway runoff sites, while the largest mean pH values (7.15 and 7.22) were found at the two residential sites.

TABLE 4-1

COMPARISON OF MEAN GENERAL WATER QUALITY CHARACTERISTICS IN STORMWATER RUNOFF COLLECTED AT THE FIVE STUDY SITES

PARAMETER	UNITS OF MEASUREMENT	HIGHWAY SITE 1	HIGHWAY SITE 2	RESIDENTIAL SITE 3	RESIDENTIAL SITE 4	COMMERCIAL SITE 5
pH	s.u.	6.51	6.78	7.15	7.22	6.96
Spec. Cond.	μmhos/cm	150	111	83	109	131
Alkalinity	mg/l	41.9	41.9	50.1	57.9	69.3
NH_3-N	μg/l	88	131	34	202	90
NO_2 + NO_3-N	μg/l	400	542	628	262	484
Diss. Organic N	μg/l	543	807	841	2880	639
Part. Organic N	μg/l	570	672	342	1280	314
Total N	μg/l	1601	2152	1845	4624	1527
Diss. Ortho-P	μg/l	64	159	49	106	18
Diss. Organic P	μg/l	34	126	59	822	28
Total P	μg/l	229	550	198	1698	189
Chlorides	mg/l	10	8	11	20	16
Sulfates	mg/l	21.0	8.6	11.5	5.2	13.1
BOD	mg/l	6.9	4.2	6.5	9.5	11.6
Color	Pt-Co Units	56	50	39	53	27
T.D.S.	mg/l	117	88	85	125	180
V.D.S.	mg/l	43	34	29	56	52
Turbidity	NTU	21.8	29.2	9.6	13.1	30.3
S.S.	mg/l	34.0	66.5	30.1	63.2	111.4
V.S.S.	mg/l	20.9	32.6	14.0	28.3	36.6

Mean values of conductivity also appeared to be relatively similar, with a range from 83 μmhos/cm to 150 μmhos/cm. Mean measured values of alkalinity were also similar with a range of values from 41.9 mg/l to 69.3 mg/l. It is interesting to note that mean alkalinity values at the two highway sites were identical.

Mean concentrations of nitrogen species exhibited substantial variability between the five study sites, with a range of values from 34 μg/l to 202 μg/l. Both the highest and lowest mean concentrations of ammonia were found at residential sites, with the lowest concentration (34 μg/l) measured at site 3 and the highest mean concentration (202 μg/l) found at site 4. With the exception of site 4, mean values for ammonia appeared to be relatively small at each of the study sites.

A considerable variability was also observed in mean concentrations of nitrate, with a range of values from 262 μg/l to 628 μg/l. As observed for ammonia, both the highest and lowest mean values for nitrate were found at residential study sites, although the trend was reversed from that found for ammonia with the largest value for nitrate found at site 3 and the lowest mean value found at site 4. Mean nitrate values at the remaining study sites appeared to be relatively similar.

Substantial differences in mean concentrations between the five study sites were also observed for both dissolved and particulate organic nitrogen. The highest mean values for each of these species was found in the residential runoff at site 4. Mean values of dissolved organic nitrogen at the remaining study sites were relatively similar. The lowest mean values of particulate organic nitrogen were found at sites 3 and 5 with mean values of 342 μg/l and 314 μg/l, respectively.

Considerable variability is evident in Table 4-1 for concentrations of total nitrogen, primarily as a result of fluctuations in concentrations of organic nitrogen. The highest mean value for total nitrogen (4624 μg/l) was found in residential runoff at site 4. Residential runoff found at site 3 contained a much lower concentration of total nitrogen with a mean value of only 1845 μg/l. The lowest mean value of total nitrogen (1527 μg/l) was found at the commercial site.

Considerable variability was observed in mean concentrations of dissolved orthophosphorus at the five study sites, with mean values ranging from 18 μg/l at site 5 to 159 μg/l in highway runoff at site 2. As observed previously for species of nitrogen, the mean value of orthophosphorus in residential runoff at site 4 was approximately twice that found in the residential runoff at site 3. An even greater variability was observed in concentrations of dissolved organic phosphorus, with concentrations ranging from 28 μg/l at the commercial site to 822 μg/l in residential runoff at site 4. Dissolved organic phosphorus also appeared to be somewhat elevated in highway runoff at site 2 with a mean value of 126 μg/l.

Mean values for total phosphorus were also found to be extremely variable. The highest value for total phosphorus was found in residential runoff at site 4 with a value of 1698 μg/l. The lowest concentrations of total phosphorus were found in residential runoff at site 3 and in commercial runoff at site 5, with values of 198 μg/l and 189 μg/l, respectively. Mean values for total phosphorus were relatively high at each of the highway sites. The mean value of 550 μg/l for total phosphorus found in highway runoff at site 2 is approximately twice the value of 229 μg/l found at site 1.

Mean values for chloride were relatively low at each of the five study sites, ranging in value from 8 mg/l in highway runoff at site 2 to 20 mg/l in residential runoff at site 4. Measured values of sulfates also appeared to be relatively low at each of the study sites, with the possible exception of the mean value of 21.0 mg/l found in highway runoff at site 1. Mean concentrations at the remaining sites ranged from 5.2 mg/l to 13.1 mg/l.

Mean values of BOD found in runoff appeared to be somewhat elevated, particularly at the residential and commercial sites. The highest mean value of BOD was found in runoff at the commercial site, with a mean of 11.6 mg/l. Mean BOD values in residential runoff at sites 3 and 4 was found to be 6.5 mg/l and 9.5 mg/l, respectively. BOD concentrations in highway runoff appeared to be somewhat lower than those found in the residential and commercial runoff, with values of 6.9 mg/l and 4.2 mg/l at sites 1 and 2, respectively.

Considerable variability was found in mean values for turbidity and suspended solids between the five study sites. In general, the lowest values for turbidity, suspended solids and volatile suspended solids were found in residential runoff at site 3. The highest mean values of turbidity, suspended solids and volatile suspended solids were found in commercial runoff at site 5 with mean values for each of these parameters approximately three times greater than values measured at site 3. As observed with several other general parameters, mean values measured in residential runoff at site 4 were approximately 50-100% greater than values measured at site 3. Also, mean values measured in highway runoff at site 2 were approximately 50-100% greater than values measured in highway runoff at site 1.

A comparison of mean heavy metal concentrations in stormwater runoff collected at the five study sites is given in Table 4-2. Several important trends are readily apparent in this data. First, concentrations of heavy metals appeared to be greater in highway runoff collected at sites 1 and 2 than in runoff collected at the other three sites. As observed with many of the general chemical parameters, mean concentrations of most heavy metals were greater in runoff measured at site 2 than at site 1.

Second, concentrations of heavy metals in commercial runoff appear to be similar to that found in highway runoff, particularly runoff collected at site 1. With the exception of chromium, and to a lesser extent lead, concentrations of heavy metals in residential runoff were substantially lower than concentrations found in either highway or commercial runoff. Also, as observed with many of the general stormwater parameters, concentrations of heavy metals in residential runoff at site 4 were greater than those found in runoff at site 3.

Several of the mean heavy metal values presented in Table 4-2 appear to be somewhat elevated, particularly in runoff measured at the two highway sites. Elevated runoff concentrations were particularly apparent for cadmium, zinc, aluminum, iron, lead and nickel.

With the exceptions of aluminum, iron and manganese, the most common stormwater related heavy metals measured at the five study sites were lead, zinc and copper. Stormwater concentrations of nickel were similar to copper at several of the study sites. Lead, zinc and copper together accounted for approximately 81% and 89% of the dissolved species, and 87% and 94% of the total metal species found in highway runoff at sites 1 and 2, respectively. These three metals contributed 79% and 85% of

TABLE 4-2

MEAN HEAVY METAL CONCENTRATIONS IN STORMWATER RUNOFF COLLECTED AT THE FIVE STUDY SITES

PARAMETER		HIGHWAY SITE 1	HIGHWAY SITE 2	RESIDENTIAL SITE 3	RESIDENTIAL SITE 4	COMMERCIAL SITE 5
Cd -	Diss.	5.99	5.55	1.86	3.06	4.49
	Total	8.45	8.35	2.17	5.02	8.15
Zn -	Diss.	83.7	107	19.2	29.9	46.9
	Total	170	272	44.9	88.9	168
Mn -	Diss.	16.9	8.37	11.1	9.78	10.5
	Total	31.3	31.5	23.1	28.4	29.9
Cu -	Diss.	25.1	25.4	21.8	22.1	18.4
	Total	49.8	66.9	27.4	32.9	31.3
Al -	Diss.	133	99.1	115	156	93.3
	Total	974	2160	537	1800	1270
Fe -	Diss.	105	95.4	55.8	31.8	115
	Total	1120	1450	420	464	1100
Pb -	Diss.	129	74.6	93.1	100	62.1
	Total	224	343	132	158	136
Ni -	Diss.	42.0	14.9	21.1	14.4	18.9
	Total	46.0	19.7	29.2	19.7	27.6
Cr -	Diss.	8.71	5.35	11.7	9.00	5.55
	Total	13.1	13.6	16.5	15.3	13.0

the dissolved, and 81% and 87% of the total metal concentrations found in residential runoff at sites 3 and 4, respectively. At the commercial site, lead, copper and zinc contributed 82% of the dissolved and 87% of the total metal species found.

A considerable degree of variability is evident in the mean water quality characteristics presented in Table 4-1 for stormwater runoff collected at the five study sites, even between sites in the same land use category. For example, large differences existed between mean chemical characteristics found at the two highway sites in spite of the fact that these two study sites were located within several miles of each other along the same interstate highway and have virtually identical average daily traffic (ADT) loadings. These differences were particularly apparent for nitrogen, phosphorus, suspended solids and heavy metals. Mean concentrations of total nitrogen, total phosphorus and suspended solids in highway runoff measured at site 2 were 34%, 140% and 96% greater, respectively, than concentrations of the same parameters measured in highway runoff at site 1. A similar trend was apparent for concentrations of heavy metals. With the exceptions of only cadmium and nickel, concentrations of heavy metals were found to be higher in highway runoff collected at site 2 than in runoff collected at site 1.

Since characteristics of rain events such as rainfall amount, rainfall intensity and antecedent dry period are known to affect concentrations of pollutants found in stormwater runoff, one possible explanation for the differences observed between the two sites could be simply differences in characteristics of rain events monitored. However, it should be noted that approximately 40-50% of rain events monitored at the two sites were common rainfall events.

It is also interesting to note that, based upon the general hydrologic characteristics of the two study sites as presented in Table 2-1, concentrations of pollutants in stormwater might be expected to have been higher at site 1 than at site 2. As seen in Table 2-1, the drainage areas for each site were approximately equal. However, site 1 consisted of a 100% directly connected impervious area on a very steep watershed slope with a time of concentration of only 6 minutes, compared with a directly connected impervious area of 18% at site 2, a much milder slope and a time of concentration of approximately 45 minutes. The watershed characteristics typical of site 1 are characteristics which would be expected to transport pollutant loads easily and quickly to the stormwater outfall lines, tending to concentrate stormwater pollutants rather than dilute them.

Perhaps the best explanation for the observed differences in chemical characteristics of highway runoff at the two sites may be related to the differences in runoff coefficients between the two study sites. Site 1 had an estimated runoff coefficient of 0.95, while site 2 had a runoff coefficient of only 0.63. Assuming that approximately equal pollutant loads were contributed onto the roadway surface within each of these watershed areas between monitored rain events, the pollutant loading at site 1 would be diluted in a much larger volume of water than the pollutant loading at site 2, creating lower constituent concentrations at site 1 than at site 2.

Substantial differences are also evident between the chemical characteristics of residential runoff collected at site 3 and at site 4. Residential runoff collected at site 4 was found to have substantially higher concentrations of total nitrogen, total phosphorus, BOD and suspended solids than found at site 3. Concentrations of total nitrogen, total phosphorus, BOD and suspended solids at site 4 were approximately 151%, 756%, 46% and 110% greater, respectively, than concentrations measured at site 3. These differences in chemical characteristics are also contrary to what may be predicted based upon the general hydrologic characteristics of the two sites presented in Table 2-1. Site 3 contains an impervious area of 65% compared with only 34% at site 4. The percentage of directly connected area at site 3 is also slightly greater than that found at site 4. Both the average watershed slope and time of concentration at site 3 are greater than the same parameters for site 4. Based on these differences, one would again expect to find a greater pollutant load and a more complete transport of pollutants from the watershed during rain events at site 3 than at site 4, yet the reverse has been found in actual measurements of chemical parameters.

As observed for sites 1 and 2, a partial explanation for these differences may lie in differences between the runoff coefficients for the two sites. The larger runoff coefficient of 0.66 for site 3, compared with 0.44 for site 4, would be expected to produce a larger runoff volume and a substantial dilution effect when compared with the volume of runoff generated at site 4. However, differences in concentration values found in Tables 4-1 and 4-2 appear to be substantially greater than would be caused by differences in runoff coefficients alone.

Another possible factor affecting characteristics of runoff at the two residential sites may be differences in characteristics of rain events monitored, as previously considered for sites 1 and 2. However, as seen in Table 3-2, there are no common monitoring dates for stormwater runoff at sites 3 and 4. Correlations between stormwater runoff quality and storm event characteristics were presented for each of the five sites in Table 3-24, and significant correlations were found between rainfall characteristics such as rainfall intensity, event duration and antecedent dry period with a number of stormwater parameters. Antecedent dry period was found to be an important predictor of runoff concentrations of many heavy metals, turbidity and organic nitrogen at the two residential sites. However, the range of antecedent dry periods for monitored events at the two sites, indicated in Table 3-2, appeared to be distributed approximately equally. The inability to explain differences in runoff characteristics by differences in watershed characteristics, hydrologic parameters or storm event characteristics further underscores the poorly understood nature of stormwater quality processes.

A comparison of stormwater characteristics measured at the residential and commercial sites with runoff characteristics from two other studies is given in Table 4-3. One of the studies used for comparison purposes was the Nationwide Urban Runoff Study (NURP) conducted by EPA at sites across the United States during the early 1980s. The second source used for comparison was a literature review performed by Harper (1990) of stormwater characteristics and loading rates for various land use categories and pollutant types from stormwater studies conducted in central and south Florida. This survey, which included over forty stormwater research projects, was performed as part of the SWIM improvement project for Tampa Bay.

As seen in Table 4-3, estimates of stormwater pollutant concentrations for orthophosphorus, total phosphorus, total nitrogen and BOD were relatively similar for the NURP study values and the survey conducted by Harper (1990). However, mean concentrations of both total nitrogen and total phosphorus at site 3 were lower than

TABLE 4-3

COMPARISON OF STORMWATER CHARACTERISTICS MEASURED AT THE RESIDENTIAL AND COMMERCIAL SITES WITH OTHER RUNOFF STUDIES

PARAMETER	UNITS	RESIDENTIAL LAND USE				COMMERCIAL LAND USE		
		SITE 3	SITE 4	NURP STUDY	HARPER (1990)	SITE 5	NURP STUDY	HARPER[1] (1990)
Ortho-P	μg/l	49	106	143	190	18	80	225
Total P	μg/l	198	1698	383	350	189	201	285
Total N	μg/l	1845	4624	2636	2170	1527	1751	1950
BOD	mg/l	6.5	9.5	10.0	8.0	11.6	9.3	12.1
S.S.	mg/l	30.1	63.2	101	21.5	111	69	83
Total Cu	μg/l	27	33	33	--	31	29	--
Total Pb	μg/l	132	158	144	50	136	104	116
Total Zn	μg/l	45	89	135	67	168	226	125

1. Average of low intensity and high intensity commercial uses.

values presented in the NURP study or by Harper, while mean concentrations of total phosphorus and total nitrogen at site 4 were greater than presented in these studies. Mean concentrations of BOD were relatively similar between the two sites and in the two studies. Mean concentrations of total copper and total lead at sites 3 and 4 were similar to values reported in the NURP study, while total concentrations of zinc were similar to values reported by Harper. With the exception of orthophosphorus, stormwater characteristics measured in commercial runoff at site 5 were similar to those presented in the NURP study and by Harper.

A comparison of stormwater characteristics measured at the two highway sites with highway runoff data measured by Harper in 1985 is presented in Table 4-4. Harper conducted a detailed investigation of the characteristics of highway runoff at the Maitland Interchange, located north of Orlando, during 1983-84. As seen in Table 4-4, mean concentrations of virtually all parameters measured at sites 1 and 2 were greater than values reported by Harper (1985). For example, mean values of conductivity, total nitrogen, total phosphorus, cadmium, zinc, manganese, copper, aluminum, iron, lead, nickel and chromium were higher at sites 1 and 2 than at the Maitland site recorded by Harper.

Increased concentrations are particularly apparent at sites 1 and 2 for concentrations of heavy metals which, in general, were approximately two to three times greater than concentrations of heavy metals reported by Harper (1985). The most significant factor contributing to these increased concentrations at sites 1 and 2 may be differences in traffic loading. The average daily traffic (ADT) at the Maitland site during the study conducted by Harper was approximately 15,800 vehicles/day, while the average

TABLE 4-4

COMPARISON OF STORMWATER CHARACTERISTICS MEASURED AT THE TWO HIGHWAY SITES WITH HIGHWAY RUNOFF DATA MEASURED BY HARPER (1985)

PARAMETER		UNITS OF MEASUREMENT	SITE 1	SITE 2	HARPER (1985)
pH		--	6.51	6.78	7.05
Spec. Cond.		µmhos/cm	150	358	104
Alkalinity		mg/l	41.9	30.0	41.0
NH_3-N		µg/l	88	131	180
NO_2 + NO_3-N		µg/l	400	542	290
Organic N		µg/l	1113	1479	930
Total N		µg/l	1601	2152	1400
Diss. Ortho-P		µg/l	64	159	70
Total P		µg/l	229	550	170
Cd -	Diss.	µg/l	5.99	5.55	1.7
	Total	µg/l	8.45	8.35	2.2
Zn -	Diss.	µg/l	83.7	107	44.0
	Total	µg/l	170	272	73.9
Mn -	Diss.	µg/l	16.9	8.37	2.7
	Total	µg/l	31.3	31.5	9.5
Cu -	Diss.	µg/l	25.1	25.4	28.6
	Total	µg/l	49.8	66.9	38.6
Al -	Diss.	µg/l	133	99.1	125
	Total	µg/l	974	2160	561
Fe -	Diss.	µg/l	105	95.4	77.9
	Total	µg/l	1120	1450	378
Pb -	Diss.	µg/l	129	74.6	33.0
	Total	µg/l	224	343	178
Ni -	Diss.	µg/l	42.0	14.9	2.5
	Total	µg/l	46.0	19.7	3.4
Cr -	Diss.	µg/l	8.71	5.35	2.5
	Total	µg/l	13.1	13.6	4.2

daily traffic count at sites 1 and 2 during 1987 was approximately 60,000-70,000 vehicles/day. The comparison presented in Table 4-4 certainly supports the theory that the characteristics of highway runoff are related to the intensity of vehicle activity.

Characteristics of Surface Water at the Five Study Sites

A comparison of mean general water quality characteristics in surface water samples collected at the five study sites is given in Table 4-5. As discussed in Chapter 2, both the wet swale channel at site 1 and the retention pond at the dual pond system for site 5 contained dense vegetative communities of cattails and other emergent species. The remaining pond systems, consisting of the retention and detention ponds at site 3, the wet detention pond at site 4 and the detention pond at site 5, consisted primarily of open water bodies.

It seems apparent that the dense vegetative growth along the wet swale channel and in the retention pond at site 5 had a significant effect on the water quality characteristics of surface water at these two sites. As seen in Table 4-5, surface water at these two sites was found to have the lowest mean values of pH, the lowest surface water temperatures, lowest mean values for dissolved oxygen and redox potential, and the highest measured values for ammonia. Measured pH values in the two vegetated systems were less than 7, while pH values measured within the open water sites were greater than 7. Surface water temperatures in the two vegetated systems ranged from 21.47° C to 22.31° C, compared with a range of 25.28° C to 26.5° C at the open water sites. Dissolved oxygen concentrations within the vegetated systems ranged from 1.1 mg/l to 1.5 mg/l, with reduced values of redox potential. Dissolved oxygen

TABLE 4-5

MEAN GENERAL WATER QUALITY CHARACTERISTICS IN SURFACE WATER SAMPLES COLLECTED AT THE FIVE STUDY SITES

PARAMETER	UNITS OF MEASUREMENT	WET SWALE SITE 1	DUAL POND SYSTEM SITE 3		WET DETENTION POND SITE 4	DUAL POND SYSTEM SITE 5	
			RETENTION	DETENTION		RETENTION	DETENTION
pH	s.u.	5.92	8.22	8.19	8.53	6.58	7.49
Spec. Cond.	μmhos/cm	211	196	260	95	300	305
Temperature	°C	22.31	25.28	26.50	25.70	21.47	26.12
Dissolved O_2	mg/l	1.5	8.2	10.8	9.4	1.1	9.5
ORP	mv	- 39	365	308	328	72	342
Alkalinity	mg/l	68.2	63.4	55.9	44.1	135.3	149.3
NH_3-N	μg/l	236	42	39	13	392	81
NO_2 + NO_3-N	μg/l	12	42	382	14	24	25
Diss. Organic N	μg/l	470	414	720	641	569	723
Part. Organic N	μg/l	163	210	247	192	245	250
Total N	μg/l	884	708	1385	859	1234	1079
Diss. Ortho-P	μg/l	155	59	11	17	10	7
Diss. Organic P	μg/l	25	36	24	50	19	16
Total P	μg/l	217	141	82	147	51	46
Chlorides	mg/l	33	29	32	10	17	17
Sulfates	mg/l	9.5	19.9	32.1	3.0	1.8	2.4
BOD	mg/l	5.0	5.2	3.3	3.8	4.6	4.2
Color	Pt-Co Units	88	39	33	31	95	70
T.D.S.	mg/l	139	133	173	75	204	198
V.D.S.	mg/l	53	35	63	36	76	65
Turbidity	NTU	5.4	4.4	4.0	6.6	7.8	8.5
S.S.	mg/l	4.0	7.1	6.9	11.4	7.4	12.7
V.S.S.	mg/l	3.2	5.5	4.7	5.4	8.0	8.9

concentrations within the open water systems ranged from 8.2 mg/l to 10.8 mg/l, with highly oxidized conditions and redox potential. Ammonia concentrations within the vegetated systems ranged from 236 μg/l to 392 μg/l, with values ranging from 13 μg/l to 81 μg/l at the open water sites. In addition, the two vegetated sites also exhibited the highest mean values for color.

The previously described differences in physical and chemical characteristics of surface water in the vegetated stormwater systems can be attributed to several factors. First, physical shading of the water column by the vegetation reduced the ambient surface water temperature compared with that found in open water sites. This reduction in solar radiation also caused a decrease in photosynthetic activity which contributed to conditions of low dissolved oxygen. However, decomposition of organic debris from vegetation also consumed oxygen from the water column. The combination of these two factors generally created a reduced environment. Decomposition of vegetative products also released organic acids which contributed to increases in color and decreases in pH. As a result, the dense vegetative communities along the wet swale and in the retention pond at site 5 appeared to degrade rather than improve water quality for the parameters discussed.

Surface water concentrations of nitrite, with the exception of the detention pond at site 3, were extremely low at all sites, with values ranging from 12 μg/l to 42 μg/l. The mean nitrate value measured in surface water of the detention pond at site 3 was extremely elevated in comparison, with a mean value of 382 μg/l. Elevated values of organic nitrogen were also found in the detention pond at site 3.

Mean values for orthophosphorus were greatest in the wet swale channel, followed by the retention pond at site 3. Mean concentrations were approximately equal at the remaining surface water sites, ranging from 7 μg/l to 1 μg/l. Elevated values of total phosphorus were found along the wet swale channel, within the retention pond at site 3 and in the wet detention pond at site 4, with mean values of 217 μg/l, 141 μg/l and 147 μg/l, respectively. Mean values of total phosphorus found in the detention pond at site 3, the retention pond at site 5 and the detention pond at site 5 were substantially lower in value, with concentrations of 82 μg/l, 51 μg/l and 46 μg/l, respectively.

It is useful to evaluate stormwater management systems in terms of the quality of discharges which may potentially leave these systems and be transported to downstream water bodies. As seen in Table 4-5, surface water discharges from the wet detention pond at site 4 contributed the lowest concentrations of total nitrogen with a mean value of 859 μg/l, followed by the wet swale with a total nitrogen concentration of 884 μg/l, the commercial dual pond system with an exit concentration of 1079 μg/l and the residential dual pond system with an outflow concentration of 1385 μg/l. Lowest concentrations of total phosphorus were found in discharges from the commercial dual pond system at 46 μg/l, the residential dual pond system at 82 μg/l, the wet detention pond at 147 μg/l and the wet swale channel at 217 μg/l.

Sulfate concentrations at each of the study sites were relatively low, with the exception of the retention and detention ponds at site 3, with mean values of 19.9 mg/l and 32.1 mg/l, respectively. Measured concentrations of BOD were also relatively low at each of the sites, ranging from 3.3 mg/l to 5.2 mg/l. Measurements of turbidity were low at all sites, with the highest values occurring within the wet detention pond and in both ponds at the commercial dual pond site. This trend was also observed for suspended solids.

A comparison of mean heavy metal concentrations in surface water collected at the five study sites is given in Table 4-6. With the exceptions of iron and aluminum, concentrations of all heavy metals appeared to be lowest within surface water of the wet detention pond at site 4, while the highest concentrations for most heavy metals were found within the retention and detention ponds in the commercial dual pond system at site 5. Surface water at the wet detention pond at site 4 was found to contain significantly lower levels of manganese, lead, nickel and chromium than surface water within the other sites. On the other hand, surface water concentrations for total aluminum were higher within the wet detention pond than at any other site. It should also be noted that with the exception of iron, the majority of heavy metal species within surface waters at each of the sites were found to be in a dissolved form, with dissolved fractions of most metals exceeding 80%.

A comparison with State of Florida Class III Water Quality Criteria for heavy metals in surface waters is given in the final column of Table 4-6. Surface water within each of the stormwater management systems was found to have total metal concentrations less than the allowable Class III criteria for copper, nickel and chromium. Each of the stormwater management systems, with the exception of site 5, met the allowable surface water criterion of 30 μg/l for zinc. Surface water discharges from the detention pond at site 5 were found to have a mean zinc concentration of 31.5 μg/l.

The maximum allowable concentration of 1000 μg/l for total iron was met by the dual pond system at site 3 and the wet detention pond at site 4, but was exceeded by both

TABLE 4-6

MEAN HEAVY METAL CONCENTRATIONS IN SURFACE WATER SAMPLES COLLECTED AT THE FIVE STUDY SITES

(All Concentrations in $\mu g/l$)

PARAMETER		WET SWALE SITE 1	DUAL POND SYSTEM SITE 3		WET DETENTION POND SITE 4	DUAL POND SYSTEM SITE 5		STATE OF FLORIDA CH. 17-3 CLASS III CRITERIA[1]
			RETENTION	DETENTION		RETENTION	DETENTION	
Cd -	Diss.	3.60	4.80	5.51	4.52	11.5	11.0	--
	Total	5.33	6.19	7.16	5.30	15.7	14.9	0.8
Zn -	Diss.	10.2	14.1	15.4	13.4	25.2	24.2	--
	Total	17.1	18.6	20.1	16.4	38.5	31.5	30
Mn -	Diss.	26.0	17.4	29.9	6.09	41.4	22.7	--
	Total	34.5	24.7	39.7	9.48	55.0	39.8	NONE
Cu -	Diss.	11.4	18.2	16.5	11.1	17.5	21.1	--
	Total	16.6	21.0	20.8	15.7	23.5	26.1	30
Al -	Diss.	101	551	569	692	165	167	--
	Total	234	693	853	1526	264	340	NONE
Fe -	Diss.	1258	77.8	54.4	70.4	2124	801	--
	Total	1931	119	148	175	3909	1933	1000
Pb -	Diss.	93.4	162	186	69.5	121	144	--
	Total	114	177	194	79.9	135	161	30
Ni -	Diss.	30.3	29.5	31.1	11.2	30.7	33.6	--
	Total	36.0	32.0	32.5	13.4	34.8	42.3	100
Cr -	Diss.	6.64	18.6	20.5	7.31	8.92	10.2	--
	Total	7.56	20.1	21.1	8.84	11.7	12.8	50

1. Chapter 17-3, Florida Administrative Code (1990)

the wet swale and the commercial dual pond system with total iron concentrations of 1931 μg/l and 1933 μg/l, respectively. Surface water concentrations within all of the stormwater management systems exceeded the allowable criterion for cadmium of 0.8 μg/l, with measured values of total cadmium within the stormwater management systems ranging from 5.3 μg/l to 14.9 μg/l. Surface water concentrations of total lead in each of the stormwater management systems also exceeded the allowable surface water criterion of 30 μg/l, with surface water values ranging from approximately 80 μg/l to 194 μg/l.

Removal Efficiencies for Stormwater Pollutants at the Five Study Sites

This section presents a comparison of removal efficiencies for stormwater pollutants in each of the five stormwater management systems. A comparison of concentration-based removal efficiencies will be presented for both general water quality parameters and heavy metals. A detailed analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at each of the five sites will also be presented. Finally, estimates of mass removal efficiencies for each of the five systems will be provided.

Concentration-Based Removal Efficiencies

A comparison of concentration-based removal efficiencies for general water quality parameters at the five study sites is given in Table 4-7. The wet swale channel was capable of reducing input concentrations of all measured stormwater pollutants, with the exceptions of conductivity, orthophosphorus, chloride and sulfate. Concentrations

TABLE 4-7

CONCENTRATION-BASED REMOVAL EFFICIENCY FOR GENERAL WATER QUALITY PARAMETERS AT THE FIVE STUDY SITES

PARAMETER	WET SWALE SITE 1	DRY SWALE SITE 2	DUAL POND SITE 3[1]		WET DETENTION POND SITE 4	DUAL POND SITE 5	
			RET. POND	SYS. REM.		RET. POND	SYS. REM.
Spec. Cond.	+5	+223	+136	+213	-13	+129	+133
Alkalinity	-11	-28	+27	+12	-24	+95	+115
NH_3-N	+11	+8	+24	+15	-94	+336	-10
NO_2 + NO_3-N	-52	-2	-93	-39	-95	-95	-95
Diss. Organic N	-13	-16	-51	-14	-78	-11	+13
Part. Organic N	-64	-47	-39	-28	-85	-22	-20
Total N	-40	-21	-62	-25	-81	-19	-29
Diss. Ortho-P	+30	+48	+20	-78	-84	-44	-61
Diss. Organic P	-18	+5	-39	-58	-94	-32	-43
Total P	-17	-13	-29	-59	-91	-73	-76
Chlorides	+110	0	+173	+191	-50	+6	+6
Sulfates	+5	+403	+73	+179	-42	+256	+159
BOD	-48	+55	-20	-48	-60	-60	-64
Color	-11	+20	0	-15	-42	+256	+159
T.D.S.	-3	+3	+57	+104	-40	+13	+10
V.D.S.	-9	+15	+21	+117	-36	+46	+25
Turbidity	-57	-34	-54	-58	-50	-74	-72
S.S.	-81	-59	-76	-77	-82	-93	-89
V.S.S.	-78	-51	-60	-60	-94	-78	-75

1. RET. = Retention Pond
SYS. REM = System Removal

of total nitrogen, total phosphorus, BOD and suspended solids were reduced by 40%, 17%, 48% and 81%, respectively.

In comparison, concentration-based removal efficiencies for stormwater inputs into the dry swale channel appeared to be substantially less than those found within the wet swale channel. Reductions in concentration were observed only for alkalinity, species of nitrogen, total phosphorus, turbidity, suspended solids and volatile suspended solids, while the other measured parameters increased during flow through the swale channel.

Differences in concentration-based removal efficiencies presented in Table 4-7 for the wet and dry swale systems suggest that the wet swale is more effective in attenuating stormwater loadings than the dry swale. However, it should be noted that virtually no infiltration occurred along the wet swale channel during rain events. Under these conditions, the input volume of stormwater runoff is approximately equal to the output volume of stormwater runoff. Therefore, the concentration-based removal efficiencies for the wet swale channel given in Table 4-7 closely reflect the mass removal efficiencies achieved by this system. On the other hand, in excess of 80% of stormwater inputs into the dry swale channel infiltrated into the ground before reaching the outfall. As a result, the overall mass reduction efficiency of the dry swale channel is extremely high, although this efficiency is not reflected in the concentration-based removal efficiencies listed in Table 4-7.

Concentration-based system removal efficiencies for the two dual pond sites appeared to be relatively similar for many of the measured parameters. Neither system was capable of producing significant reductions in conductivity, ammonia, dissolved organic nitrogen, chloride, sulfate, total dissolved solids or volatile dissolved solids.

However, both systems were capable of reducing concentrations of total nitrogen and total phosphorus, with reductions of 25% and 59% for total nitrogen and total phosphorus, respectively, at site 3 and reductions of 29% and 76%, respectively, at site 5. Reductions in BOD and suspended solids were also similar between the two sites, with reductions of 48% and 77% for BOD and suspended solids, respectively, at site 3 and reductions of 64% and 89% for the same parameters at site 5.

It was apparent for many parameters that the primary removal processes at these dual pond sites occurred within the retention ponds with the final detention pond providing little additional improvement in water quality. In fact, removal efficiencies for many parameters actually decreased after migration into the final detention pond. The primary removal mechanisms for total nitrogen, total phosphorus, BOD and suspended solids in these systems occurred within the retention pond.

The reductions in concentrations of total nitrogen reported for these two systems were achieved primarily through reductions in concentrations of nitrate and, to a lesser extent, particulate organic nitrogen. These dual pond systems appeared to have very little ability to reduced concentrations of either ammonia or dissolved organic nitrogen. Concentration reductions in total phosphorus were achieved by a combination of reductions in orthophosphorus, organic phosphorus and particulate-bound phosphorus.

The wet detention system at site 4 was the only stormwater management system which provided significant removal efficiencies for all of the measured stormwater parameters. Concentrations of total nitrogen were reduced by approximately 81% within this system. Unlike the other stormwater management systems which were unable to remove ammonia, the wet detention pond achieved removal efficiencies for ammonia in excess of 90%. Substantial reductions were also achieved for concentrations of both dissolved and particulate organic nitrogen, with removal efficiencies of 78% and 85%, respectively.

The wet detention facility was also capable of providing significant reductions in total phosphorus, with an overall removal efficiency of 91%. Excellent removal efficiencies were achieved for both orthophosphorus and dissolved organic phosphorus. The wet detention pond was also the only system studied which reduced input concentrations of chloride, sulfate and color. A removal efficiency of approximately 60% was achieved for BOD. Suspended solids and volatile suspended solids were reduced in concentration by approximately 80-95%.

A comparison of concentration-based removal efficiencies for heavy metals at the five study sites is presented in Table 4-8. Both the wet and dry swale channels were able to provide reductions in input concentrations of total heavy metals into the swale channel. Total concentrations of lead, aluminum, copper and zinc were reduced by approximately 50% or more during flow through the channel. Concentrations of the remaining heavy metals, including chromium, nickel, iron, manganese and cadmium, were reduced in concentration by approximately 30-40%. Concentration-based removal efficiencies for heavy metals during flow through the dry channel appeared to be relatively consistent, with all removal efficiencies in the range of 40-50%.

Removal of heavy metal species within the two dual pond sites was relatively poor for most metal species. The dual pond systems were capable of providing significant reductions in concentrations of total zinc and total copper only, while concentrations of the remaining heavy metals either increased within the pond system or were reduced by

TABLE 4-8

CONCENTRATION-BASED REMOVAL EFFICIENCIES FOR HEAVY METALS AT THE FIVE STUDY SITES

PARAMETER		WET SWALE SITE 1	DRY SWALE SITE 2	DUAL POND SYSTEM SITE 3		WET DETENTION POND SITE 4	DUAL POND SYSTEM SITE 5	
				RETENTION POND	SYSTEM REMOVAL		RETENTION POND	SYSTEM REMOVAL
Cd -	Diss.	-36	-55	+158	+196	+48	+155	+145
	Total	-41	-49	+185	+230	+ 6	+93	+82
Zn -	Diss.	-47	-24	-26	-20	-55	-46	-48
	Total	-69	-49	-59	-55	-82	-77	-81
Mn -	Diss.	-37	-16	+57	+169	-381	+294	+116
	Total	-28	-49	+7	+72	-67	+84	+33
Cu -	Diss.	-30	-10	-17	-24	-50	-5	+15
	Total	-56	-46	-23	-24	-52	-25	-17
Al -	Diss.	-28	+16	+379	+395	+344	+77	+79
	Total	-75	-51	+29	+59	-15	-79	-73
Fe -	Diss.	+63	-2	+39	-3	+121	+1747	+597
	Total	-39	-51	-72	-65	-62	+255	+76
Pb -	Diss.	-27	-13	+74	+100	-31	+95	+132
	Total	-50	-51	+34	+47	-49	-1	+18
Ni -	Diss.	-34	-31	+40	+47	-22	+62	+78
	Total	-31	-40	+11	+11	-32	+26	+53
Cr -	Diss.	-21	-8	+59	+75	+19	+61	+84
	Total	-37	-40	+22	+28	-42	-11	-2

insignificant percentages. Concentrations of cadmium, manganese, lead and nickel increased substantially within these systems above input values measured in stormwater runoff. Although these systems provided moderate removal efficiencies for nutrients, BOD and suspended solids, they performed poorly in reducing concentrations of heavy metals.

The wet detention pond at site 4 provided good removal efficiencies for all heavy metal, with the exception of cadmium. Zinc was reduced in concentration within this system by approximately 82%, manganese by 67%, iron by 62%, copper by 52%, lead by 49%, chromium by 42% and nickel by 32%. With the exceptions of cadmium and aluminum, concentration-based removal efficiencies achieved within this system appeared to be the best achieved within any of the studied stormwater management systems.

In summary, the wet detention system provided the most consistent removal efficiencies for both general water quality parameters and heavy metals. Although each of the swale sites appeared to be capable of reducing concentrations of heavy metals, these systems performed poorly in reducing concentrations of common stormwater pollutants such as total nitrogen, total phosphorus and BOD. A similar case could be made for each of the dual pond sites, which provided relatively good removal efficiencies for common stormwater pollutants but very poor removal efficiencies for heavy metals. Concentrations of many heavy metals actually increased within these systems over input stormwater values.

Attenuation Mechanisms for Nutrients and Heavy Metals

An analysis was conducted for each of the five stormwater management systems to further evaluate mechanisms responsible for reductions in pollutant concentrations within these systems. This analysis was conducted for species of nitrogen, phosphorus and heavy metals. Total concentrations for each of these parameters were divided into dissolved and particulate forms so that removal processes for each of these forms could be evaluated separately.

An analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at the wet swale site (site 1) is given in Table 4-9. This table, along with similar tables for the other study sites, is divided into three major sections. First, characteristics of stormwater runoff entering the wet swale are presented in terms of concentrations for both dissolved and particulate forms. Second, this same division into dissolved and particulate species is given for outflow from each of these systems. For the two swale sites, the outflow concentrations actually measured for runoff traveling along the swale channel were used. For the three pond sites, mean surface water concentrations were used. The final column lists the percent change in concentration for both dissolved and particulate species which occurred during migration of stormwater runoff through each system.

Input concentrations of nitrogen in stormwater runoff at the wet swale site were approximately equally divided between inorganic, organic and particulate organic species. Phosphorus, on the other hand, was dominated by particulate organic species. Of the measured heavy metals, lead, copper, nickel, chromium, manganese and cadmium

TABLE 4-9

ANALYSIS OF ATTENUATION MECHANISMS FOR NUTRIENTS AND HEAVY METALS IN STORMWATER RUNOFF AT THE WET SWALE SITE (SITE 1)

PARAMETER		STORMWATER RUNOFF		SWALE OUTFLOW		PERCENT CHANGE
		MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL	
N:	Inorg.[1]	488	30	290	30	-41
	Diss. Org.	543	34	471	49	+44
	Part. Org.	570	36	203	21	-42
P:	Inorg.[2]	64	28	83	44	+30
	Diss. Org.	34	15	28	15	-18
	Part. Org.	131	57	79	41	-40
Cd:	Diss.	6.0	71	3.8	76	-36
	Part.	2.5	29	1.2	24	-52
Zn:	Diss.	83.7	49	44.3	84	-47
	Part.	86.3	51	8.5	16	-90
Mn:	Diss.	16.9	54	10.6	47	-37
	Part.	14.4	46	11.9	53	-17
Cu:	Diss.	25.1	50	17.7	81	-30
	Part.	24.7	50	4.1	19	-83
Al:	Diss.	133	14	95.8	39	-28
	Part.	841	86	148	61	-82
Fe:	Diss.	105	9	171	25	+63
	Part.	1015	91	508	75	-50
Pb:	Diss.	129	58	93.6	84	-27
	Part.	95	42	18.4	16	-81
Ni:	Diss.	42.0	91	27.6	87	-34
	Part.	4.0	9	4.0	13	0
Cr:	Diss.	8.7	66	6.9	83	-21
	Part.	4.4	34	1.4	17	-68

1. Sum of ammonia, nitrite and nitrate

2. Orthophosphorus

exhibited dissolved fractions in excess of 50%, while zinc, iron and aluminum were found primarily in particulate form.

During migration through the swale channel, two important mechanisms were observed. First, input concentrations of both dissolved and particulate species decreased for the majority of heavy metal species measured. However, these reductions in concentrations were more apparent for the particulate species than for the dissolved species. For example, removal of particulate species of lead, zinc, copper and aluminum ranged from 80-90%, while reductions in dissolved concentrations ranged from approximately 30-40%.

It appears, therefore, that the primary mechanism responsible for reductions in total metal concentrations during flow through the wet swale channel is simply a settling process for particulate metal species into the sediments along the swale channel. Only two heavy metals (nickel and manganese) exhibited larger removal efficiencies for dissolved fractions than for particulate fractions. The net result of these removal processes is that the percentage of dissolved forms for most metals increased in the swale outflow, while the percentage of particulate forms decreased. Removal mechanisms for nitrogen and phosphorus appeared to be somewhat different. Nitrogen was removed primarily by reductions in inorganic and particulate organic nitrogen, while phosphorus was removed primarily by reductions in organic phosphorus.

An analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at the dry swale site is given in Table 4-10. Similar to stormwater characteristics observed at site 1, nitrogen species were approximately equally divided between organic and inorganic, while particulate organic fractions constituted the

TABLE 4-10

ANALYSIS OF ATTENUATION MECHANISMS FOR NUTRIENTS AND HEAVY METALS IN STORMWATER RUNOFF AT THE DRY SWALE SITE (SITE 2)

PARAMETER		STORMWATER RUNOFF		SWALE OUTFLOW		PERCENT CHANGE
		MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL	
N:	Inorg.[1]	673	31	674	39	0
	Diss. Org.	807	38	681	40	-16
	Part. Org.	672	31	352	21	-48
P:	Inorg.[2]	159	29	235	49	+48
	Diss. Org.	126	23	132	27	+5
	Part. Org.	265	48	114	24	-57
Cd:	Diss.	5.6	67	2.5	58	-55
	Part.	2.8	33	1.8	42	-36
Zn:	Diss.	107	39	81.4	58	-24
	Part.	165	61	58.6	42	-64
Mn:	Diss.	8.4	27	7.0	43	-17
	Part.	23.1	73	9.1	57	-61
Cu:	Diss.	25.4	38	22.9	63	-10
	Part.	41.5	62	13.3	37	-68
Al:	Diss.	99.1	5	115	11	+16
	Part.	2061	95	955	89	-54
Fe:	Diss.	95.4	7	97.5	14	+2
	Part.	1355	93	608	86	-55
Pb:	Diss.	74.6	22	65.1	39	-13
	Part.	268	78	102	61	-62
Ni:	Diss.	14.9	76	10.3	87	-31
	Part.	4.8	24	1.5	13	-69
Cr:	Diss.	5.4	40	4.9	60	-9
	Part.	8.2	60	3.3	40	-60

1. Sum of ammonia, nitrite and nitrate

2. Orthophosphorus

dominant phosphorus species present. Of the heavy metals measured at this site, only nickel and cadmium were found initially with dissolved fractions in excess of 50%.

Significant reductions in particulate species were observed for all metals during migration along the swale channel. With the exception of cadmium, removal of particulate species ranged from approximately 55-70%. Particulate species of cadmium were removed by only 36%. Removal efficiencies for dissolved metal species along the dry swale channel were substantially less, with the majority of removal efficiencies less than 30%. Dissolved concentrations of iron and aluminum actually increased during flow along the swale channel. Similar to the trends observed for heavy metals, the dominant removal mechanisms for both nitrogen and phosphorus appears to be removal of particulate-bound matter.

Although removal efficiencies and attenuation mechanisms for the two swale sites appeared to be similar, it should be emphasized that removal processes within these two systems were somewhat different. Removal processes for particulate matter at both sites consisted primarily of settling of discrete particles contained within the runoff flow. However, removal mechanisms for dissolved species may be somewhat different. Removal of dissolved ions along the dry swale channel occurred primarily as a result of adsorption of metal species onto the surface soil along the channel. Adsorption of metal ions onto the sediment surface may also occur at site 1, but the dense vegetative growth severely restricted the available contact between the sediments and the water column. Therefore, a large portion of the removal efficiencies for dissolved species observed at site 1 may simply be due to dilution effects when the incoming stormwater runoff mixes with surface water already contained in the swale channel.

An analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at the residential dual pond system is given in Table 4-11. Dissolved fractions represented the dominant species found in the runoff flow for nutrients and heavy metals with the exceptions of zinc, iron, aluminum and manganese which existed primarily as particulate runoff species. After migration into the retention pond, significant reductions in particulate fractions are observed for virtually all species of heavy metals and nutrients. The only exception to this was found for cadmium which exhibited a substantial increase in both dissolved and particulate forms within the retention pond. Removal efficiencies for dissolved species within the retention pond were generally quite poor, with many metal species exhibiting increases in dissolved species within the pond. Relatively large reductions were observed for all species of nitrogen within the pond. As a result of these significant reductions in particulate species within the pond, the dominant metal form within the pond was the dissolved ion, with dissolved fractions ranging from approximately 65-93%.

Final system removal efficiencies which include the effects of the detention pond are given in the last column of Table 4-11. Removal efficiencies for most heavy metal species improved very little during migration through the detention pond. Some metal species appeared to exhibit additional removal of particulate forms, but appeared to increase in dissolved concentrations. Increases in dissolved concentrations compared to runoff inputs were apparent for lead, nickel, chromium, aluminum, manganese and cadmium. Although the dual pond system was capable of providing removal of particulate metal species through settling processes within the retention and detention ponds, the system was clearly incapable of reducing dissolved concentrations of heavy

TABLE 4-11

ANALYSIS OF ATTENUATION MECHANISMS FOR NUTRIENTS AND HEAVY METALS IN STORMWATER RUNOFF AT THE RESIDENTIAL DUAL POND SYSTEM (SITE 3)

PARAMETER	STORMWATER RUNOFF		RETENTION POND WATER		PERCENT REMOVAL IN RET. POND	DETENTION POND WATER		SYSTEM PERCENT REMOVAL
	MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL		MEAN (μg/l)	PERCENT OF TOTAL	
<u>Nitrogen</u>:								
Inorganic[1]	662	36	84	12	-87	421	30	-32
Diss. Organic	841	46	414	58	-51	720	52	-14
Part. Organic	342	18	210	30	-39	247	18	-28
<u>Phosphorus</u>:								
Inorganic[2]	49	25	59	42	+20	11	13	-78
Diss. Organic	59	30	36	26	-39	24	29	-59
Part. Organic	90	45	46	33	-49	47	57	-48
<u>Cadmium</u>:								
Dissolved	1.9	86	4.8	77	+153	5.5	76	+189
Particulate	0.3	14	1.4	23	+367	1.7	24	+467
<u>Zinc</u>:								
Dissolved	19.2	43	14.1	76	-27	15.4	77	-20
Particulate	25.7	57	4.5	24	-82	4.7	23	-82
<u>Manganese</u>:								
Dissolved	11.1	48	17.4	70	+57	29.9	75	+169
Particulate	12.0	52	7.3	30	-39	9.8	25	-18
<u>Copper</u>:								
Dissolved	21.8	80	18.2	87	-17	16.5	79	-24
Particulate	5.6	20	2.8	13	-50	4.3	21	-23

TABLE 4-11 -- CONTINUED

PARAMETER	STORMWATER RUNOFF		RETENTION POND WATER		PERCENT REMOVAL IN RET. POND	DETENTION POND WATER		SYSTEM PERCENT REMOVAL
	MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL		MEAN (μg/l)	PERCENT OF TOTAL	
Aluminum:								
Dissolved	115	21	551	80	+379	569	67	+395
Particulate	422	78	142	20	-66	284	33	-33
Iron:								
Dissolved	55.8	13	77.8	65	+39	54.4	37	-3
Particulate	364	87	41.2	35	-89	93.6	63	-74
Lead:								
Dissolved	93.1	71	162	92	+74	186	96	+100
Particulate	38.9	29	15.0	8	-61	8.0	4	-79
Nickel:								
Dissolved	21.1	72	29.5	91	+40	31.1	96	+47
Particulate	8.1	28	2.8	9	-65	1.4	4	-83
Chromium:								
Dissolved	11.7	71	18.6	93	+59	20.5	97	+75
Particulate	4.8	29	1.5	7	-69	0.6	3	-88

metals. In fact, dissolved concentrations of most heavy metals appeared to increase during migration through the pond system.

An analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at the residential wet detention site is presented in Table 4-12. Dissolved species represented the dominant pollutant form for inputs of nutrients and heavy metals, with the exceptions of zinc, iron, aluminum and manganese which were found primarily in a particulate form. During migration through the detention pond, significant removal efficiencies were obtained for both inorganic and organic species of nitrogen and phosphorus. Removal efficiencies for particulate metal species were generally in excess of 50% for all measured heavy metals, with removal efficiencies for particulate manganese, zinc and lead exceeding 80%. The detention pond was also capable of providing reductions in dissolved metal species for all heavy metals except iron, aluminum and cadmium which increased in concentration. The combined removal efficiencies for both dissolved and particulate forms of nutrients and heavy metals appeared to be better at the wet detention site than at any of the other study sites.

An analysis of attenuation mechanisms for nutrients and heavy metals in stormwater runoff at the commercial dual pond facility is given in Table 4-13. The majority of stormwater parameters measured at the commercial site were present primarily in the particulate form. The exceptions to this generality appeared to be cadmium, nitrogen, nickel and copper which exhibited large dissolved fractions. During migration through retention pond water, significant removal efficiencies were achieved for particulate fractions for all parameters measured, except iron and cadmium, which increased in concentration of particulate species within the retention pond.

TABLE 4-12

ANALYSIS OF ATTENUATION MECHANISMS FOR NUTRIENTS AND HEAVY METALS IN STORMWATER RUNOFF AT THE RESIDENTIAL WET DETENTION POND (SITE 3)

PARAMETER		STORMWATER RUNOFF		SWALE OUTFLOW		PERCENT CHANGE
		MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL	
N:	Inorg.[1]	464	10	27	3	-94
	Diss. Org.	2880	62	641	75	-78
	Part. Org.	1281	28	192	22	-85
P:	Inorg.[2]	106	6	17	12	-84
	Diss. Org.	822	48	50	34	-94
	Part. Org.	770	46	80	54	-90
Cd:	Diss.	3.1	61	4.5	85	+45
	Part.	2.0	39	0.8	15	-60
Zn:	Diss.	29.9	34	13.4	82	-55
	Part.	59.0	66	3.0	18	-95
Mn:	Diss.	9.8	35	6.1	64	-38
	Part.	18.6	65	3.4	36	-82
Cu:	Diss.	22.1	67	11.1	71	-50
	Part.	10.8	33	4.6	29	-57
Al:	Diss.	156	9	692	45	+344
	Part.	1644	91	834	55	-49
Fe:	Diss.	31.8	7	70.3	40	+121
	Part.	432	93	105	60	-76
Pb:	Diss.	100	63	69.5	87	-31
	Part.	58.0	37	10.4	13	-82
Ni:	Diss.	14.4	73	11.2	84	-22
	Part.	5.3	27	2.2	16	-58
Cr:	Diss.	9.0	59	7.3	83	-19
	Part.	6.3	41	1.5	17	-76

1. Sum of ammonia, nitrite and nitrate

2. Orthophosphorus

TABLE 4-13

ANALYSIS OF ATTENUATION MECHANISMS FOR NUTRIENTS AND HEAVY METALS IN STORMWATER RUNOFF AT THE COMMERCIAL DUAL POND SYSTEM (SITE 5)

PARAMETER	STORMWATER RUNOFF		RETENTION POND WATER		PERCENT REMOVAL IN RET. POND	DETENTION POND WATER		SYSTEM PERCENT REMOVAL
	MEAN (µg/l)	PERCENT OF TOTAL	MEAN (µg/l)	PERCENT OF TOTAL		MEAN (µg/l)	PERCENT OF TOTAL	
Nitrogen:								
Inorganic[1]	574	38	416	34	-28	106	10	-83
Diss. Organic	639	42	569	46	-11	723	67	+13
Part. Organic	314	20	245	20	-22	250	23	-20
Phosphorus:								
Inorganic[2]	18	10	10	20	-44	7	15	-61
Diss. Organic	28	15	19	37	-32	16	35	-43
Part. Organic	143	75	22	43	-85	23	50	-84
Cadmium:								
Dissolved	4.5	55	11.5	73	+156	11.0	74	+144
Particulate	3.7	45	4.2	27	+14	3.8	26	+3
Zinc:								
Dissolved	46.9	28	25.2	65	-46	24.2	77	-48
Particulate	121	72	13.3	35	-89	7.3	23	-94
Manganese:								
Dissolved	10.5	35	41.4	75	+294	22.7	57	+116
Particulate	19.4	65	13.6	25	-28	17.1	43	-12
Copper:								
Dissolved	18.4	59	17.5	74	-5	21.1	81	+15
Particulate	12.9	41	6.0	26	-53	5.0	19	-61

TABLE 4-13 -- CONTINUED

PARAMETER	STORMWATER RUNOFF		RETENTION POND WATER		PERCENT REMOVAL IN RET. POND	DETENTION POND WATER		SYSTEM PERCENT REMOVAL
	MEAN (μg/l)	PERCENT OF TOTAL	MEAN (μg/l)	PERCENT OF TOTAL		MEAN (μg/l)	PERCENT OF TOTAL	
<u>Aluminum</u>:								
Dissolved	93.3	7	165	63	+77	167	49	+78
Particulate	1177	93	99.0	37	-92	173	51	-85
<u>Iron</u>:								
Dissolved	115	10	2124	54	+1747	801	41	+597
Particulate	985	90	1785	46	+81	1132	59	+15
<u>Lead</u>:								
Dissolved	62.1	46	121	90	+95	144	89	+132
Particulate	73.9	54	14.0	10	-81	17.0	11	-77
<u>Nickel</u>:								
Dissolved	18.9	68	30.7	88	+62	33.6	79	+78
Particulate	8.7	32	4.1	12	-53	8.7	21	0
<u>Chromium</u>:								
Dissolved	5.6	43	8.9	77	+59	10.2	80	+82
Particulate	7.4	57	2.7	23	-64	2.6	20	-65

The overall system removal efficiency, presented in the final column of Table 4-13, is very similar to that achieved within the retention pond for the majority of metal and nutrient species. It appears obvious that, similar to the results found at site 3, the addition of the final detention pond provided no substantial increase in the pollutant removal capability of the stormwater management system. Concentrations of some parameters such as iron, cadmium and manganese actually increased during migration through the detention pond.

Removal efficiencies and processes found in the commercial dual pond system are similar to those found within the residential dual pond system, with two notable exceptions. First, the commercial dual pond system provided little or no pollutant attenuation for particulate species of nickel and iron, while substantial reductions in particulate forms of these metals were observed within the residential system. Second, removal efficiencies for particulate aluminum within the commercial system appeared to be substantially greater than removal efficiencies measured within the residential pond.

Estimates of Mass Removal Efficiencies

In addition to the concentration-based removal efficiencies presented in the previous section, estimates of mass removal efficiencies were also conducted for the wet swale channel, the dry swale channel, the residential dual pond site and the residential wet detention pond. Mass removal efficiencies were not estimated for the commercial dual pond system because of inadequate information on hydrologic inputs and outputs for this system.

Mass removal efficiencies were calculated based upon differences in estimated mass input and output from each system for nutrients and heavy metals. The input mass into each system was calculated by multiplying the mean runoff concentration for a particular parameter times the estimated annual runoff volume for each site based upon the hydrologic characteristics for drainage basin area and runoff coefficient presented in Table 2-1. An annual average of 50 inches of rainfall was assumed for each site. Estimates of mass output from each system were calculated in a similar fashion. The discharge concentration for a particular parameter was multiplied by an estimate of the total hydrologic discharge from each system based upon discussions on site hydrology presented in Chapter 3.

Estimates of mass removal efficiencies for stormwater pollutants at the wet and dry swale sites are presented in Table 4-14. As discussed previously, estimates of mass input were based upon mean stormwater runoff characteristics measured at each of the two sites. Estimates of mass output for the two swale channels were based upon measured concentrations for runoff outflow from each channel during actual storm events, as presented in Tables 3-4 and 3-6 for the wet swale channel, and in Tables 3-8 and 3-10 for the dry swale channel.

As discussed in Chapter 3, infiltration of stormwater runoff into the wet swale channel is minimal during storm events. It was concluded that for any given rain event, the volume of runoff entering the swale channel would closely approximate the volume of water discharging from the swale channel to downstream water bodies. Therefore, it was assumed that hydraulic outputs from the wet swale channel were equal to hydraulic inputs into the swale channel. On the other hand, the dry swale channel was

TABLE 4-14

ESTIMATES OF MASS REMOVAL EFFICIENCIES FOR STORMWATER POLLUTANTS AT THE WET AND DRY SWALE CHANNELS

PARAMETER	WET SWALE CHANNEL			DRY SWALE CHANNEL		
	INPUT (kg)	OUTPUT (kg)	MASS REMOVAL	INPUT (kg)	OUTPUT (kg)	MASS REMOVAL
NH_3-N	0.503	0.560	+11	0.551	0.120	-78
NO_3-N	2.285	1.097	-52	2.281	0.448	-80
Organic N	6.357	3.850	-39	6.224	0.869	-86
Total N	9.144	5.506	-40	9.057	1.437	-84
Ortho-P	0.366	0.474	+30	0.669	0.198	-70
Total P	1.308	1.085	-17	2.315	0.405	-83
BOD	39.41	20.56	-48	17.68	5.471	-69
S.S.	194.2	36.55	-81	279.9	23.15	-87
Total Cd	0.048	0.028	-42	0.035	0.004	-89
Total Zn	0.971	0.302	-69	1.145	0.118	-90
Total Mn	0.179	0.129	-28	0.133	0.014	-89
Total Cu	0.284	0.125	-56	0.282	0.030	-89
Total Fe	6.397	3.878	-39	6.102	0.593	-90
Total Al	5.563	1.394	-75	9.090	0.901	-90
Total Pb	1.279	0.640	-50	1.444	0.141	-90
Total Ni	0.263	0.180	-32	0.083	0.010	-88
Total Cr	0.075	0.047	-37	0.057	0.007	-88

characterized by highly permeable sandy soils which infiltrated runoff water rapidly. Visual observations of swale performance during rain events indicated that virtually all runoff entering the swale channel infiltrated into the ground prior to reaching the outfall inlet for the majority of rain events. It was conservatively estimated in Chapter 3 that approximately 80% of the general runoff inflow into the swale channel would infiltrate into the soil on an annual basis. Therefore, it was assumed that the hydraulic flow leaving the dry swale channel on an annual basis would be equal to approximately 20% of the hydraulic inflow into the channel.

Since hydraulic inputs and outputs from the wet swale channel were assumed to be approximately equal on an annual basis, the mass removal efficiencies for the wet swale channel presented in Table 4-14 are identical to the concentration-based removal efficiencies presented in Tables 3-4 and 3-6. However, since the vast majority of hydraulic inputs into the dry swale channel were infiltrated into groundwaters, mass removal efficiencies for the dry swale system were substantially higher than those estimated for the wet swale channel. Mass removal of total nitrogen along the dry swale channel was approximately 84%, compared with only 40% in the wet swale channel. Removal efficiencies for total phosphorus in the dry swale channel were approximately 83%, compared with only 17% in the wet swale channel. Removal efficiencies for BOD and suspended solids in the dry swale channel were also substantially greater than those measured in the wet swale channel. The dry swale channel also exhibited excellent removal efficiencies for total concentrations of all heavy metals, with removal efficiencies ranging from 88-90% for all heavy metal species.

On an annual mass loading basis, the dry swale channel was far superior to the wet swale channel in terms of reducing mass loadings of stormwater inputs to downstream water bodies. Removal efficiencies achieved within the dry swale channel were equivalent to those normally associated with a properly designed and operated retention system where annual pollutant removal efficiencies of 80-90% are generally achieved.

Estimates of mass removal efficiencies for stormwater pollutants at the residential dual pond system and the residential wet detention pond are given in Table 4-15. Input concentrations of stormwater pollutants for both systems were based upon mean stormwater characteristics for each individual site. Output concentrations for both sites were assumed to be equal to mean surface water concentrations within each system. For the residential dual pond system, surface water concentrations within the detention pond were used since discharges from the system occur from this pond. For the wet detention pond mean surface water characteristics were used.

As discussed in Chapter 3, the majority of hydraulic inputs into the residential dual pond system were totally retained within the system. The retention pond rarely reached its exit orifice elevation, suggesting that the majority of inputs into the detention system were totally retained within that pond. Based on records of piezometric elevations and observations of system performance during actual rain events, it was estimated that approximately 80% of all runoff inputs into the dual pond system were retained within the system without discharges to off-site water bodies. Therefore, hydraulic outputs from the residential dual pond system were assumed to equal 20% of the hydraulic inputs into the system.

TABLE 4-15

ESTIMATES OF MASS REMOVAL EFFICIENCIES FOR STORMWATER POLLUTANTS AT THE RESIDENTIAL DUAL POND SYSTEM AND WET DETENTION POND

PARAMETER	RESIDENTIAL DUAL POND SYSTEM			WET DETENTION POND		
	INPUT (kg)	OUTPUT (kg)	MASS REMOVAL	INPUT (kg)	OUTPUT (kg)	MASS REMOVAL
NH_3-N	0.852	0.195	-77	11.48	0.148	-99
NO_3-N	15.74	1.915	-88	14.89	0.159	-99
Organic N	29.65	4.857	-84	236.4	9.466	-96
Total N	46.24	6.957	-85	262.7	9.773	-96
Ortho-P	1.228	0.055	-96	6.023	0.193	-97
Total P	4.962	0.411	-92	96.48	1.670	-98
BOD	162.9	17.04	-90	539.8	43.18	-92
S.S.	754.4	34.58	-95	3591	129.5	-96
Total Cd	0.054	0.036	-33	0.285	0.060	-79
Total Zn	1.125	0.101	-91	5.051	0.186	-96
Total Mn	0.579	0.199	-66	1.614	0.108	-93
Total Cu	0.687	0.104	-85	1.869	0.178	-90
Total Fe	10.53	0.742	-93	26.36	1.989	-92
Total Al	13.46	4.276	-68	102.3	17.34	-83
Total Pb	3.308	0.972	-71	8.977	0.908	-90
Total Ni	0.810	0.163	-80	1.119	0.152	-86
Total Cr	0.504	0.106	-79	0.869	0.100	-88

For similar reasons, it was conservatively estimated in Chapter 3 that approximately 80-90% of all hydraulic inputs into the wet detention pond were retained within the system, with the primary removal and drawdown mechanisms being evaporation from the water surface and infiltration of pond water into the ground. Therefore, hydraulic outputs from the wet detention pond were also conservatively assumed to equal 20% of the input values.

As seen in Table 4-15, the residential dual pond system provided excellent mass removal efficiencies for the majority of measured stormwater pollutants. Removal efficiencies for total nitrogen, total phosphorus, BOD and suspended solids within this system were estimated to be approximately 85%, 92%, 90% and 95%, respectively. With the exception of cadmium, removal efficiencies in excess of 65% were observed for all measured heavy metals, with removal efficiencies for iron and zinc in excess of 90%. It should be noted, however, that the primary reason for the relatively high removal efficiencies achieved within this system was the large amount of water retained within the system on an annual basis, since concentrations of many measured parameters increased within the detention pond above input concentrations measured in the stormwater inflow.

Extremely high mass removal efficiencies were achieved within the wet detention pond for all measured stormwater parameters. Mass removal efficiencies for total nitrogen, total phosphorus, BOD and suspended solids were approximately 96%, 98%, 92% and 96%, respectively. With the exception of cadmium, removal efficiencies for all measured heavy metals were approximately 80-90%. Mass removal efficiencies for zinc, manganese and iron exceeded 90%. Unlike the dual pond system, the excellent mass removal efficiencies achieved by the wet detention pond resulted from a combination of large hydraulic retention and substantial reductions in input runoff concentrations within the pond.

Although a number of mechanisms may be responsible for differences in mass removal efficiencies between the dual pond system and the wet detention pond, the most likely explanation is related to differences in biological communities between the two systems. Physically, the two systems appear somewhat similar, with approximately equal water depths, side slopes and watershed-to-pond surface area ratios. However, the amount and diversity of biological communities are quite different between the two sites.

Both the retention and detention pond at the dual pond site appear to be relatively sterile. The sides and bottom of the retention pond are covered with a dark organic soil with no vegetation of any kind. The bottom and sides of the detention pond are constructed primarily of sandy soils with a sparse covering of grass-type vegetation along the sides and bottom. On the other hand, the wet detention pond contained a diverse biological community of algae, small rooted macrophytes, small species of fish, aquatic insects and a large community of benthic organisms, particularly clams. Unlike the very dense vegetative communities found along the wet swale channel and at the commercial dual pond site which negatively affected water quality characteristics, the diverse biological community of the wet detention pond apparently provided a substantial enhancement for pollutant attenuation mechanisms within that system.

Sediment Characteristics at the Five Study Sites

The significance of heavy metal accumulations and sediment characteristics at each of the five study sites will be discussed in this section. A discussion of horizontal distributions of heavy metals will be presented first, followed by a discussion on vertical distributions and attenuation.

Horizontal Distributions of Heavy Metals

Heavy metal concentrations in the top 1 cm of pond and swale sediments at each of the five study sites were used to evaluate the horizontal distributions of heavy metals within each of the stormwater management systems. These horizontal distributions indicated that upon entering the stormwater management system, the majority of heavy metals associated with stormwater runoff settle out relatively quickly and are deposited near the point of input for the runoff flow. The horizontal distribution of heavy metals also appeared to be substantially affected by the percentage of particulate forms for each metal species in the stormwater runoff and also the type of stormwater management system.

The most common heavy metals found in soils and sediments of the five stormwater management systems were lead and zinc, with sediment concentrations of lead generally exceeding those of zinc. As seen in Figures 3-15 and 3-16, sediment concentrations of both lead and zinc increased rapidly with increasing distance along the swale channel at each of the swale sites. Peak sediment concentrations of lead and zinc were found at distances of 25-70 m along the swale channel. As indicated in Figures 3-17 and 3-18, rapid settling and attenuation of both zinc and lead was observed in sediments at the residential wet detention pond as well. Peak sediment concentrations within this system were reached at distances of 40-60 m from the inflow point. It should be noted that both lead and zinc exhibited relatively high particulate fractions in stormwater runoff at each of these sites which presumably accounts, at least in part, for the similar settling characteristics for these metal species between the three sites.

As discussed in Chapter 3, sediment concentrations in the 0-1 cm layer of the dry swale channel for both lead and zinc were substantially greater than sediment concentrations found along the wet swale channel, in spite of the fact that the wet swale channel has been receiving stormwater runoff for a much longer period than the dry swale channel. It was also emphasized previously that the majority of runoff inputs into the dry swale channel infiltrate directly into groundwater, while stormwater inputs into the wet swale channel typically pass straight through the system. The elevated concentrations of heavy metals found in sediments at site 2 are presumably a result of attenuation and uptake of lead and zinc in the upper soil layers during infiltration into groundwaters. The substantial accumulations present in these upper layers is an indication of the ability of these soils to attenuate and retain inputs of these heavy metals.

Horizontal accumulations of chromium, copper, nickel and cadmium along the two swale channels and within the wet detention pond exhibited substantially lower sediment concentrations and broader settling patterns than observed for lead and zinc. Inputs of chromium, copper, nickel and cadmium in stormwater runoff at each of these three sites were primarily in a dissolved form, with relatively small particulate fractions. As a result of the low percentage of particulate species and the high dissolved fractions, these metal species settled out over much larger distances and exhibited less pronounced settling patterns than observed for lead and zinc.

In summary, it appears that heavy metals which exhibit significant particulate fractions in runoff inputs, such as lead and zinc, settled out and become immobilized in the sediments within a distance of 25-70 m from the point of input. Heavy metals which exhibited large dissolved fractions appeared to settle out over much broader areas with no sharp peaks in sediment concentrations.

Vertical Distributions of Heavy Metals

In general, measured concentrations of heavy metals in soils and sediments at the five study sites exhibited highest concentrations in the surface layer, with a declining concentration with increasing depth. This same general trend was observed for nitrogen, phosphorus and organic content as well. The rapid decline in concentrations for most metals was found to exhibit an exponential decay relationship when fitted to the model: $\ln (C/C_o) = K \times (\text{depth})$.

Vertical distributions of heavy metals at the two swale sites were relatively similar. Sediment concentrations of zinc, iron and lead were extremely elevated along the swale channels and decreased rapidly with increasing depth. Sediment concentrations within the control areas were found to be lower in value at all depths than those measured along the swale. In addition, the attenuation curves for concentrations of heavy metals within the control areas were much less pronounced than found within the swale area. This same general pattern was observed for sediment concentrations of manganese, nickel and chromium as well. With few exceptions, sediment concentrations of heavy metals in both swale and control areas reached similar values in the final 15-25 cm core layer.

It seems apparent that both the wet and dry swale channels are capable of accumulating heavy metals at concentrations far in excess of those found within the control area. These sediment accumulations are contained primarily in the surface layers, reaching background levels at depths of 15-25 cm.

Vertical distributions of heavy metals within sediments of the wet detention pond at site 4 were similar to those exhibited at the two swale sites. Elevated concentrations of zinc, iron and lead were present in the upper surface layers with a rapid decline in concentration with increasing sediment depth. This trend was observed for sediment concentrations of chromium, nickel and manganese as well. Sediment concentrations of each of these metals approached sediment concentrations found within the control area within the first 5 cm. Attenuation characteristics for heavy metals were virtually identical at depths below 5 m for the pond and control areas. It appears that accumulations of heavy metals within the wet detention pond have migrated no further than the top 5 cm.

Vertical distributions of heavy metals at the residential and commercial dual pond sites also indicated highest metal concentrations near the surface with decreasing concentrations at increasing sediment depths. However, in several cases, metal concentration measured within the detention pond exceeded those found within the retention pond. In addition, distribution patterns appeared to be more random within the sediments of these systems than found at the other study sites. However, it should be noted that at the time of this study, the dual pond systems had been in operation for less than two years and distinct attenuation patterns for heavy metals may not have had sufficient time to develop.

Relationships Between Stormwater, Sediments and Surface Water Characteristics

A series of correlation analyses were conducted in an attempt to evaluate general predictive mechanisms between stormwater inputs, sediment concentrations and surface water characteristics for the five stormwater management systems. A combined data set was formed for the five study sites which contained characteristics of stormwater inflow, sediments and surface water. Correlation analyses were conducted to evaluate significant mechanisms affecting water quality within stormwater management systems in general.

A summary of correlations between inflow stormwater concentrations and water column concentrations for general parameters are presented in Table 4-16. Characteristics of stormwater inputs were found to be correlated at the 0.05 level of significance with only two of the general chemical parameters, pH and dissolved organic phosphorus. Correlations between input stormwater characteristics and water column concentrations for the remaining general parameters exhibited poor correlations, with many correlation coefficients exhibiting a negative value. This analysis suggests that general water column characteristics for parameter such as those listed in Table 4-16 were independent of stormwater inputs into the stormwater management system. Apparently, other processes were responsible for regulating water quality characteristics within these systems other than inputs of stormwater runoff.

Correlations were also performed to evaluate the influence of stormwater and sediments on surface water concentrations of heavy metals within stormwater management systems. Significant correlations were found between sediment metal concentrations and water column concentrations of dissolved cadmium, total cadmium and total iron (see Table 4-17). Correlations between sediment characteristics and

TABLE 4-16

CORRELATIONS BETWEEN INFLOW STORMWATER CONCENTRATIONS AND WATER COLUMN CONCENTRATIONS FOR GENERAL CHEMICAL PARAMETERS

PARAMETER	CORRELATION BETWEEN STORMWATER CONCENTRATION AND WATER COLUMN CONCENTRATION	
	CORRELATION COEFFICIENT	PROBABILITY OF SIGNIFICANT CORRELATION
pH	0.924	99.2
Spec. Cond.	0.237	34.9
Alkalinity	0.790	93.8
NH_3-N	-0.072	10.7
NO_3-N	0.569	76.2
Diss. Organic N	0.204	30.1
Part. Organic N	-0.564	75.7
Total N	-0.326	47.1
Diss. Ortho-P	0.245	36.0
Diss. Organic P	0.861	97.2
Total P	0.265	38.9
Sulfate	0.025	3.7
BOD	-0.098	14.7
Color	-0.262	38.4
T.D.S.	0.517	70.7
V.D.S.	0.202	29.9
S.S.	0.603	79.5
V.S.S.	0.683	86.5

TABLE 4-17

CORRELATIONS BETWEEN SEDIMENT CONCENTRATIONS, STORMWATER CONCENTRATIONS AND SURFACE WATER CONCENTRATIONS OF HEAVY METALS

HEAVY METAL	CORRELATION BETWEEN SEDIMENT METAL CONCENTRATION AND WATER COLUMN METAL CONCENTRATION		CORRELATION BETWEEN STORMWATER METAL CONCENTRATION AND WATER COLUMN METAL CONCENTRATION	
	CORRELATION COEFFICIENT	PROB. OF SIGNIFICANT CORRELATION	CORRELATION COEFFICIENT	PROB. OF SIGNIFICANT CORRELATION
<u>Dissolved Metals</u>				
Cd	0.834	96.1	0.049	7.4
Zn	0.716	89.1	-0.049	7.4
Mn	-0.277	40.5	-0.018	2.6
Cu	0.405	57.4	-0.847	96.7
Fe	0.080	12.0	0.787	93.7
Al	0.623	81.4	0.411	58.2
Pb	-0.173	25.8	0.040	6.0
Ni	-0.698	87.7	0.371	63.0
Cr	-0.450	63.0	0.721	89.4
<u>Total Metals</u>				
Cd	0.857	97.1	0.473	65.7
Zn	0.718	89.2	0.565	75.7
Mn	-0.288	42.0	0.213	31.5
Cu	0.425	60.0	-0.458	64.0
Fe	0.875	97.8	0.367	52.5
Al	0.089	13.4	0.846	96.6
Pb	-0.098	14.6	-0.375	53.6
Ni	-0.519	70.8	0.528	71.8
Cr	-0.466	64.8	0.748	91.3

surface water concentrations for the remaining heavy metals were relatively weak and, in some cases, resulted in negative values. This analysis suggests that the sediments were important predictors of heavy metals concentrations for only cadmium and iron.

Correlations between stormwater metal concentrations and water column concentrations produced significant relationships with water column concentrations of dissolved copper and total aluminum. As observed for general water quality parameters, input stormwater concentrations of heavy metals did not have a strong correlation with heavy metal concentrations found in surface water.

The lack of significant correlations between characteristics of sediments and stormwater and water column concentrations suggests that the water column concentrations developed as a result of processes which were independent of both sediments and stormwater inputs. These processes may include physical factors such as sedimentation, coagulation or adsorption, chemical processes such as precipitation, along with biological uptake in the water column of the stormwater management system.

Effects of Stormwater Management Systems at the Five Study Sites on Underlying Groundwaters

The effects of continued operation of each of the five stormwater management systems on underlying groundwaters are discussed in the following sections. In this discussion, groundwater characteristics were compared with surface water characteristics to evaluate the potential for leaching of pollutants into groundwaters. The results of the speciation experiments for phosphorus and heavy metals are used to explain increased or decreased solubility of certain metals in groundwater at different sites.

Site 1 - Wet Swale Site

A comparison of general water quality characteristics in surface water and groundwater in the swale area at the wet swale site is given in Table 4-18. Mean surface water concentrations for each of the listed parameters are presented, along with ratios of groundwater concentrations to surface water concentrations for each of the five groundwater sampling depths beneath the swale. A ratio less than 1.00 indicates groundwater concentrations less than surface water concentrations, while a ratio greater than 1.00 indicates groundwater concentrations in excess of surface water values.

As seen in Table 4-18, groundwater concentrations for the majority of the general water quality parameters were less than those found in surface water within the swale. However, groundwater concentrations of ammonia appeared to be elevated at depths extending to the 5.0 m sample port. Concentrations of total nitrogen also appeared to be somewhat elevated in groundwater, primarily as a result of the increased concentrations of ammonia. Increased concentrations of total nitrogen also appeared to extend to depths of 5.0 m, although concentrations at the 5.0 m depth were only slightly in excess of those measured along the swale channel. Groundwater concentrations of chloride and sulfate also appeared to exist in elevated concentrations which extended to a depth of 1.0 m below the swale channel.

A comparison of heavy metal concentrations in groundwater and surface water along the swale area is given in Table 4-19. Ratios are provided within the table of groundwater concentrations to both total and dissolved metal concentrations in surface water. Many of the heavy metals, such as cadmium, manganese, lead, nickel and chromium, exhibited groundwater concentrations which were equal to or less than surface

TABLE 4-18

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE SWALE AREA AT THE WET SWALE SITE (SITE 1)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	5.92	0.78	0.74	0.73	0.72	0.73
Alkalinity	mg/l	68.2	0.05	0.01	0.00	0.00	0.01
Ammonia	mg/l	236	3.94	4.00	4.03	3.58	3.49
Nitrate	μg/l	12	1.17	0.83	0.92	0.83	0.83
Diss. Organic N	μg/l	470	0.83	0.82	0.81	0.50	0.36
Total N	μg/l	881	1.52	1.52	1.53	1.23	1.13
Diss. Ortho-P	μg/l	155	0.15	0.17	0.08	0.14	0.12
Diss. Organic P	μg/l	25	0.36	0.28	0.28	0.24	0.24
Total P	μg/l	217	0.14	0.15	0.09	0.12	0.11
Chloride	mg/l	33	2.21	2.09	2.18	1.06	1.09
Sulfate	mg/l	9.6	1.76	1.66	1.80	0.98	2.30
BOD	mg/l	5.0	0.60	0.46	0.42	0.50	0.48
Color	Pt-Co Units	88	0.78	0.57	0.58	0.41	0.40
T.D.S.	mg/l	139	0.91	0.86	0.86	0.53	0.71
V.D.S.	mg/l	53	0.72	0.75	0.74	0.64	0.72

TABLE 4-19

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE SWALE AREA AT THE WET SWALE SITE (SITE 1)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	3.60 5.33	0.83 0.56	1.08 0.73	0.93 0.53	1.14 0.77	0.80 0.54
Zn	10.2 17.1	1.52 0.91	1.87 1.12	1.66 0.99	1.58 0.94	1.32 0.79
Mn	26.0 34.5	1.12 0.85	0.66 0.50	0.45 0.34	0.43 0.32	0.32 0.24
Cu	11.4 16.6	1.11 0.77	1.42 0.98	1.11 0.77	1.10 0.75	0.89 0.61
Al	101 234	7.27 3.14	9.13 3.94	10.2 4.40	5.96 2.57	5.87 2.53
Fe	1255 1931	2.38 1.55	1.38 0.90	0.92 0.60	0.65 0.42	0.38 0.25
Pb	93.4 114	0.39 0.32	0.36 0.30	0.35 0.28	0.31 0.26	0.32 0.27
Ni	30.4 36.0	0.47 0.39	0.41 0.35	0.37 0.31	0.40 0.34	0.32 0.27
Cr	6.64 7.56	0.58 0.51	0.50 0.44	0.50 0.44	0.49 0.43	0.51 0.45

1. Dissolved Concentration/Total Concentration

water concentrations of both dissolved and total metal species for each of the five groundwater ports. Other metal species, such as iron and copper, exhibited elevated concentrations in groundwater beneath the swale channel, extending to a depth of approximately 1 m. Groundwater concentrations of zinc beneath the swale channel were generally less than total zinc concentrations in surface water, but exceeded concentrations of dissolved zinc. Groundwater concentrations of aluminum appeared to be substantially elevated compared with surface water concentrations at all groundwater depths. However, both aluminum and iron are common constituents of soils and groundwater and it is not uncommon to find elevated concentrations of both metals in groundwater. There is no reason to conclude that these elevated groundwater concentrations are due to operation of the wet swale system.

With few exceptions, the data presented in Tables 4-18 and 4-19 provide strong evidence that the operation of the wet swale system is not resulting in a significant impact on groundwater quality beneath the swale channel. Groundwater concentrations of virtually all parameters measured were lower in groundwaters beneath the channel than in surface water contained within the channel. Several parameters, such as chloride, sulfate, copper and iron, exhibited elevated concentrations which were confined primarily within the top 1.0 m of groundwater. With the exception of cadmium, groundwater concentrations of each heavy metal at depths greater than 1.0 m were equal to or less than water quality criteria for Class III surface waters specified in Chapter 17-3 of the Florida Administrative Code.

Site 2 - Dry Swale Site

A comparison of general water quality characteristics of runoff inflow and groundwater beneath the dry swale channel is given in Table 4-20. Since runoff inputs constituted the primary source of water infiltrating through the swale channel, these concentrations were used for comparisons with groundwater values.

In general, groundwater concentrations of all general parameters, with the exceptions of alkalinity, BOD and dissolved solids, were lower in groundwater beneath the swale channel than in runoff inflow into the swale channel. The majority of measured parameters exhibited substantially lower concentrations in groundwater than found in runoff inputs. Groundwater concentrations of several parameters, such as nitrate, organic nitrogen and chloride, appeared to increase in the lower groundwater layers. However, it is unlikely that these increases were related to inputs from the swale channel since groundwater concentrations above these levels were substantially lower.

Groundwater concentrations of cadmium, zinc, copper and lead were approximately equal to or less than input runoff concentrations for both dissolved and total species at all groundwater depths. Groundwater concentrations of manganese, aluminum, iron, nickel and chromium generally exceeded dissolved metal concentrations found in runoff, but in most cases were substantially lower than total metal concentrations found in runoff inputs. It should also be noted that, with the exceptions of cadmium and lead, concentrations of each heavy metal at groundwater depths greater than 1.0 m were equal to or less than water quality criteria for Class III surface waters specified in Chapter 17-3 of the Florida Administrative Code.

TABLE 4-20

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF RUNOFF AND GROUNDWATER IN THE SWALE AREA AT THE DRY SWALE SITE (SITE 2)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/RUNOFF				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	6.78	--	0.96	0.95	0.93	0.74
Alkalinity	mg/l	91.9	--	3.56	2.51	1.61	0.79
Ammonia	mg/l	131	--	0.79	0.54	0.08	0.11
Nitrate	μg/l	542	--	0.57	1.17	5.47	1.61
Diss. Organic N	μg/l	807	--	0.35	1.43	1.43	0.71
Total N	μg/l	2152	--	0.32	0.86	1.92	0.68
Diss. Ortho-P	μg/l	159	--	0.82	0.89	0.53	0.20
Diss. Organic P	μg/l	126	--	0.16	0.22	0.17	0.20
Total P	μg/l	550	--	0.27	0.31	0.19	0.10
Chloride	mg/l	8	--	1.00	1.00	1.38	2.13
Sulfate	mg/l	8.6	--	0.85	1.20	1.30	0.42
BOD	mg/l	4.2	--	1.12	0.57	0.45	0.43
Color	Pt-Co Units	50	--	0.70	0.88	0.50	0.32
T.D.S.	mg/l	88	--	1.66	1.61	1.93	0.55
V.D.S.	mg/l	34	--	1.41	1.32	1.91	0.62

With few exceptions, groundwater concentrations of measured parameters were found to be substantially lower than concentrations of the same parameters in runoff inputs into the swale channel. Even though infiltration along the swale channel was extremely rapid, this infiltration process was apparently effective in reducing pollutant concentrations for virtually all measured parameters.

As seen in Table 4-21, groundwater concentrations of manganese, nickel and chromium exceeded dissolved metal concentrations in runoff inflow to the swale. These elevated concentrations of dissolved metals in groundwater suggest that particulate species of these metals which are trapped along the swale channel may be slowly releasing dissolved metal ions into groundwater.

It should be noted that groundwater concentrations of heavy metals and phosphorus beneath the dry swale channel were somewhat higher for many species than found beneath the wet swale channel. For example, groundwater concentrations of copper, lead and nickel beneath the dry swale channel were approximately twice that found beneath the wet swale channel. Concentrations of chromium beneath the dry swale channel were approximately four times greater than those found beneath the wet swale channel. These differences cannot be explained by differences in loading rates into the two channels, since the estimates of heavy metal loadings into the two channels, presented in Table 4-14, were approximately equal for most metal species.

The most likely explanation for these differences in groundwater characteristics is that the rapid infiltration processes which occur along the dry swale channel, although extremely effective in reducing concentrations of all measured parameters, were less effective in retaining runoff pollutants than the very slow migration processes which

TABLE 4-21

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE SWALE AREA AT THE DRY SWALE SITE (SITE 2)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	5.55	--	0.47	0.74	0.69	0.35
	8.35	--	0.31	0.49	0.46	0.23
Zn	107	--	0.42	0.32	0.27	0.21
	272	--	0.16	0.13	0.10	0.08
Mn	8.37	--	2.15	1.68	1.66	1.22
	31.5	--	0.57	0.45	0.44	0.32
Cu	25.4	--	0.94	0.79	0.89	0.55
	66.9	--	0.36	0.30	0.34	0.21
Al	99.1	--	3.00	5.65	2.34	1.29
	2160	--	0.14	0.26	0.11	0.06
Fe	95.4	--	5.81	5.75	3.28	2.51
	1451	--	0.38	0.38	0.22	0.16
Pb	74.6	--	0.98	1.10	1.18	0.64
	343	--	0.21	0.24	0.26	0.14
Ni	14.9	--	2.11	1.89	1.93	1.15
	19.7	--	1.60	1.43	1.46	0.87
Cr	5.35	--	3.27	2.65	2.49	1.75
	13.6	--	1.29	1.04	0.98	0.69

1. Dissolved Concentration/Total Concentration

occurred along the wet swale channel. Heavy metals migrating downward through the wet swale channel moved in a very slow manner with multiple opportunities for uptake or attenuation by a variety of physical, chemical and biological mechanisms. Attenuation mechanisms for heavy metals during rapid infiltration through the soils along the dry swale channel were primarily limited to those involving physical adsorption or perhaps exchange reactions. However, the opportunity for these processes was substantially reduced by the rapid movement of the water through the soil.

Overall, however, the dry swale system appeared to be an extremely effective type of stormwater management system. As seen in Table 4-14, the removal and attenuation of stormwater pollutants along the swale channel was extremely high for all measured parameters. There is little evidence to indicate that the rapid infiltration processes involved along this channel are contributing significant loadings of pollutants to groundwaters.

Site 3 - Residential Dual Pond Site

A comparison of general water quality characteristics for surface water and groundwater in the retention pond area at the residential dual pond site is given in Table 4-22. With the exceptions of ammonia, nitrate, total nitrogen and volatile dissolved solids, groundwater concentrations of general chemical parameters were approximately equal to or less than values measured in surface water within the retention pond. Elevated concentrations of both ammonia and nitrate were primarily limited to the upper 1.0 m of groundwater, with a substantial decrease in concentration observed after a depth of 1.0 m. Increased concentrations for total nitrogen were also limited within the top 1.0

TABLE 4-22

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE RETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.22	0.80	0.76	0.77	0.86	0.85
Alkalinity	mg/l	63.4	0.79	1.26	1.16	1.06	1.38
Ammonia	mg/l	42	10.83	23.60	21.90	2.62	14.50
Nitrate	μg/l	42	11.36	1.12	15.52	1.76	0.98
Diss. Organic N	μg/l	414	0.99	0.95	0.71	0.78	1.08
Total N	μg/l	708	1.89	2.02	1.80	0.72	1.55
Diss. Ortho-P	μg/l	59	1.25	0.88	0.78	0.98	1.80
Diss. Organic P	μg/l	36	0.64	0.39	0.50	0.53	0.67
Total P	μg/l	141	0.69	0.47	0.45	0.55	0.91
Chloride	mg/l	29	1.07	0.93	0.93	1.07	1.10
Sulfate	mg/l	19.9	1.31	0.25	0.24	0.33	0.24
BOD	mg/l	5.2	0.88	1.42	1.19	0.73	1.37
Color	Pt-Co Units	39	0.77	1.64	1.67	0.77	0.85
T.D.S.	mg/l	133	1.05	1.04	1.03	1.00	1.15
V.D.S.	mg/l	35	1.20	1.29	1.23	1.14	1.20

m. Other parameters such as orthophosphorus and chloride exhibited elevated concentrations at the 0.1 m depth only.

A comparison of heavy metal concentrations in surface water and groundwater beneath the retention pond is given in Table 4-23. With the exception of manganese and, to a lesser extent zinc and cadmium, groundwater concentrations of heavy metals were generally lower than both dissolved and total concentrations measured in surface water above the pond. Elevated concentrations of manganese, zinc and cadmium were attenuated rapidly at groundwater depths below 1.0 m and approached concentrations present within surface water at the 2.5 m depth.

Similar to the conclusions reached for the wet swale channel and the dry swale channel, with the exception of species of nitrogen and perhaps manganese, operation of the retention pond appeared to have little effect on groundwater concentrations beneath the pond. Concentrations for the majority of measured parameters were either equal to or less than surface water concentrations measured within the retention pond. For those species which exhibited elevated concentrations in groundwaters, the extent of these elevated concentrations appeared to be limited to groundwater depths between 1.0 m and 2.5 m. Groundwater concentrations of both total nitrogen and total phosphorus were relatively low and should not pose a significant threat to surface waters in the event that this groundwater should migrate and enter into a surface water system. With the exceptions of cadmium and lead, groundwater concentrations for all heavy metals were also extremely low, with values less than the Class III surface water criteria at all groundwater depths.

TABLE 4-23

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE RETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	4.80 6.19	1.09 0.85	1.04 0.81	1.28 0.99	1.07 0.83	1.28 0.99
Zn	14.2 18.6	1.30 0.99	0.95 0.73	1.36 1.04	1.02 0.78	0.87 0.66
Mn	17.4 24.7	2.99 2.11	5.49 3.87	5.17 3.64	1.29 0.91	2.40 1.69
Cu	18.2 21.0	0.79 0.69	0.60 0.52	0.75 0.65	0.75 0.65	0.70 0.61
Al	551 693	0.48 0.38	0.29 0.23	0.40 0.32	0.71 0.56	2.06 1.34
Fe	77.8 119	5.18 3.39	9.70 6.34	9.67 6.32	0.72 0.47	2.06 1.34
Pb	162 178	0.94 0.86	0.95 0.84	0.94 0.85	0.96 0.88	1.12 1.02
Ni	29.5 32.3	0.83 0.76	0.78 0.71	0.85 0.78	0.81 0.74	0.88 0.81
Cr	18.6 20.1	0.94 0.87	0.91 0.85	0.90 0.84	0.92 0.85	1.04 0.97

1. Dissolved Concentration/Total Concentration

The apparent leaching of cadmium and manganese into groundwaters may be related to the speciation for cadmium and manganese within the sediments of the retention pond. As seen in Table 3-55, both cadmium and manganese were found to exist in significant exchange fractions within the sediments of the retention pond. As discussed previously, these exchange fractions are generally weak associations which are subject to solubilization and transport into the groundwater flow. The remaining heavy metals, which did not exhibit a potential for leaching into groundwaters, were bound by stronger sediment associations.

A comparison of general water quality characteristics for surface water and groundwater in the detention pond area is presented in Table 4-24. Similar to characteristics observed for groundwater beneath the retention pond, concentrations of both ammonia and nitrate were elevated in groundwaters beneath the detention pond. However, concentrations of total nitrogen appeared to be substantially less in groundwaters than in surface waters. Elevated concentrations of dissolved orthophosphorus and color were apparent within the top 1.0 m of groundwater beneath the pond, while sulfate concentrations were elevated at all levels beneath the pond.

A comparison of heavy metal concentrations in surface water and groundwater beneath the detention pond is presented in Table 4-25. Groundwater/surface water relationships beneath the detention pond were similar to those found beneath the retention pond. Groundwater concentrations of copper, lead, nickel and chromium were lower than both dissolved and total concentrations found in surface waters. However, elevated concentrations in groundwater were observed for manganese, cadmium and zinc. Elevated groundwater concentrations for zinc and manganese extended to the 5.0 m

TABLE 4-24

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.19	0.76	0.75	0.76	0.67	0.70
Alkalinity	mg/l	55.9	0.63	0.63	0.72	0.33	0.80
Ammonia	mg/l	39	3.38	2.82	2.56	1.38	3.77
Nitrate	µg/l	382	1.24	1.32	1.45	4.43	10.45
Diss. Organic N	µg/l	720	0.63	0.50	0.59	1.9	1.58
Total N	µg/l	1388	0.76	0.70	0.78	1.82	3.76
Diss. Ortho-P	µg/l	11	1.64	1.00	1.36	0.55	0.91
Diss. Organic P	µg/l	24	0.29	0.25	0.29	0.17	0.29
Total P	µg/l	82	0.30	0.27	0.26	0.12	0.21
Chloride	mg/l	32	0.91	0.91	1.00	2.31	2.00
Sulfate	mg/l	32.1	1.39	1.60	1.65	2.59	2.57
BOD	mg/l	3.3	0.67	0.67	0.73	0.52	0.52
Color	Pt-Co Units	33	1.03	1.15	1.06	0.61	0.70
T.D.S.	mg/l	173	0.85	0.91	0.98	1.45	1.57
V.D.S.	mg/l	63	0.79	0.90	0.95	1.21	1.65

TABLE 4-25

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	5.51 7.16	1.05 0.81	1.05 0.81	0.90 0.69	1.12 0.86	1.15 0.88
Zn	15.4 20.1	1.25 0.96	1.18 0.91	1.12 0.86	1.26 0.97	1.31 0.00
Mn	30.0 39.7	4.57 3.45	6.20 4.69	4.47 3.38	1.91 1.45	1.94 1.47
Cu	16.5 20.8	0.77 0.61	0.79 0.62	0.69 0.55	0.85 0.68	0.92 0.72
Al	569 853	0.35 0.23	0.27 0.18	0.26 0.18	0.25 0.17	0.29 0.20
Fe	54.4 148	12.7 4.66	8.93 3.28	5.17 1.90	1.91 0.70	2.15 0.79
Pb	186 194	0.87 0.83	0.75 0.72	0.84 0.81	0.89 0.86	0.92 0.89
Ni	31.1 32.5	0.85 0.81	0.75 0.72	0.86 0.82	0.86 0.82	0.88 0.84
Cr	20.5 21.1	0.84 0.82	0.78 0.75	0.86 0.84	0.91 0.88	0.92 0.90

[1] Dissolved Concentration/Total Concentration

depth, while elevated concentrations of cadmium were attenuated within a depth of 1.0 m. As seen in Table 3-55, cadmium, zinc and manganese exhibited high percentages of exchange fractions within the sediments of the detention pond which increased the potential for solubilization into groundwater.

Groundwater concentrations of both total nitrogen and total phosphorus were extremely low in groundwater beneath the detention pond. Groundwater concentrations of all heavy metals, with the exceptions of cadmium and lead, were also extremely low beneath the detention pond and met Class III surface water criteria at all groundwater depths.

Based upon the information presented in Tables 4-22 through 4-25, the operation of the dual pond system appeared to have a minimal effect on groundwater characteristics beneath the ponds. For the majority of measured parameters, groundwater concentrations beneath the ponds were equal to or less than concentrations measured within the ponds.

Site 4 - Residential Wet Detention Pond Site

A comparison of general water quality characteristics for surface water and groundwater in the detention pond area at the residential detention pond site is presented in Table 4-26. Concentrations of nitrate, organic nitrogen, BOD and dissolved solids were equal to or less than surface water concentrations in shallow groundwater beneath the pond. However, elevated concentrations were observed within the first 1.0 m for ammonia, total nitrogen, orthophosphorus, organic phosphorus, chloride and color. For the majority of these parameters, substantial reductions in groundwater concentrations were observed between the 1.0 m and 2.5 m depths.

TABLE 4-26

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE RESIDENTIAL DETENTION POND (SITE 4)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	8.53	0.74	0.68	0.66	0.57	0.54
Alkalinity	mg/l	44.1	1.06	0.73	0.54	0.11	0.08
Ammonia	mg/l	13	30.08	50.92	33.85	4.08	3.69
Nitrate	μg/l	14	0.71	0.71	0.93	2.14	1.14
Diss. Organic N	μg/l	641	0.74	0.64	0.60	0.16	0.25
Total N	μg/l	860	1.02	1.26	0.97	0.21	0.47
Diss. Ortho-P	μg/l	17	2.94	4.47	5.24	2.18	2.88
Diss. Organic P	μg/l	50	1.66	1.34	2.14	1.62	1.08
Total P	μg/l	147	0.90	0.91	1.27	0.81	0.71
Chloride	mg/l	10	1.10	1.20	1.30	1.40	1.20
Sulfate	mg/l	3.0	1.20	0.77	0.90	0.93	0.83
BOD	mg/l	3.8	0.87	1.00	1.08	0.87	0.79
Color	Pt-Co Units	31	1.90	2.13	2.06	1.32	0.90
T.D.S.	mg/l	75	1.07	0.84	0.76	0.40	0.51
V.D.S.	mg/l	36	0.97	0.81	0.78	0.33	0.53

The relatively high groundwater to surface water ratios exhibited for many of the parameters listed in Table 4-26 were primarily a result of the extremely low surface water concentrations rather than elevated concentrations of these parameters in groundwaters. Even though groundwater concentrations of total nitrogen, orthophosphorus and total phosphorus exceeded surface water concentrations at certain groundwater depths, these groundwater concentrations were still relatively low and would pose no threat to surface waters should this groundwater migrate away from the pond site.

A comparison of heavy metal concentrations in surface water and groundwater beneath the detention pond is given in Table 4-27. Groundwater concentrations of copper, lead, nickel and chromium were approximately equal to or lower than both dissolved and total concentrations for these same parameters in surface waters within the pond. As observed previously at the residential dual pond site, elevated concentrations of manganese, zinc and cadmium existed in shallow groundwater beneath the pond. Elevated concentrations of cadmium extended to a depth of 0.1 m, while elevated concentrations of zinc extended to a depth of 1.0 m, with elevated levels of manganese extending to depths between 2.5 m and 5.0 m. However, it should be noted that even though concentrations of certain heavy metals exceeded those found in surface waters, all heavy metal concentrations, with the exception of cadmium, were extremely low in groundwaters beneath the wet detention pond. Concentrations of all heavy metals in groundwater at depths below 1.0 m met the general Class III surface water criteria specified in Chapter 17-3.

TABLE 4-27

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE RESIDENTIAL DETENTION POND SITE (SITE 4)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	4.52 5.30	1.21 1.03	0.92 0.79	0.86 0.73	0.72 0.61	0.71 0.60
Zn	13.4 16.4	1.26 1.03	1.22 0.99	1.06 0.87	0.94 0.77	0.99 0.81
Mn	6.09 9.48	5.44 1.77	2.51 1.61	2.71 1.74	1.69 1.09	0.70 0.45
Cu	11.1 15.7	0.79 0.56	0.88 0.62	0.84 0.59	0.88 0.62	0.58 0.41
Al	692 1526	0.66 0.30	0.55 0.25	0.77 0.35	0.40 0.18	0.38 0.17
Fe	70.4 175	3.72 1.50	5.94 2.39	8.72 3.51	6.88 2.77	2.41 0.97
Pb	69.5 79.9	0.97 0.84	0.83 0.72	0.66 0.57	0.40 0.35	0.37 0.32
Ni	11.2 13.4	1.11 0.93	1.04 0.87	0.98 0.82	0.81 0.68	0.78 0.63
Cr	7.31 8.84	1.00 0.82	1.02 0.85	0.88 0.72	0.64 0.53	0.58 0.48

1. Dissolved Concentration/Total Concentration

Similar to the findings at the previous study sites, there is little evidence to indicate that operation of the wet detention system is having a negative impact on groundwater resources beneath the pond. Elevated groundwater concentrations in excess of surface water concentrations were generally limited for most parameters to within the top 1.0 m beneath the detention pond.

Site 5 - Commercial Dual Pond System

A comparison of general water quality characteristics for surface water and groundwater in the retention pond area at the commercial dual pond site is given in Table 4-28. Unlike the trends observed at the previous sites, groundwater concentrations for many of the measured general parameters exceeded those found in surface water within the retention pond. Elevated groundwater concentrations were observed for ammonia, total nitrogen, orthophosphorus, organic phosphorus, total phosphorus, chloride, BOD, color and dissolved solids. However, the extent of these elevated groundwater concentrations generally appeared to be limited to within the first meter of groundwater beneath the pond, although elevated levels for phosphorus species extended to depths of 5.0 m. In general, groundwater concentrations of total nitrogen, total phosphorus and BOD were relatively low in groundwaters beneath the pond.

A comparison of heavy metal concentrations in surface water and groundwater at the retention pond is given in Table 4-29. Groundwater concentrations of cadmium and copper were lower than both dissolved and total concentrations found in surface water at all groundwater depths. Other heavy metals, such as zinc, manganese, lead and nickel, exhibited elevated concentrations within the first 1.0 m of groundwater, with

TABLE 4-28

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE RETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	6.58	0.95	0.95	0.92	0.88	0.96
Alkalinity	mg/l	135	1.52	1.20	0.94	0.58	0.59
Ammonia	mg/l	392	3.10	1.63	0.59	0.28	0.78
Nitrate	µg/l	24	0.46	0.63	1.63	0.63	1.50
Diss. Organic N	µg/l	569	0.64	0.67	0.60	0.33	0.57
Total N	µg/l	1230	1.29	0.84	0.50	0.25	0.54
Diss. Ortho-P	µg/l	10	3.30	2.50	3.70	13.80	14.10
Diss. Organic P	µg/l	19	1.68	1.26	1.21	0.58	1.21
Total P	µg/l	51	1.27	0.94	1.18	2.92	3.20
Chloride	mg/l	20	1.45	1.85	2.40	2.95	0.95
Sulfate	mg/l	1.8	0.83	0.61	0.78	0.83	1.6
BOD	mg/l	4.6	1.89	1.30	0.85	0.41	0.80
Color	Pt-Co Units	95	3.08	2.86	1.68	0.67	0.51
T.D.S.	mg/l	204	1.56	1.38	1.26	0.93	0.71
V.D.S.	mg/l	76	1.13	1.0	0.71	0.43	0.63

TABLE 4-29

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE RETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	11.5 15.7	0.48 0.35	0.36 0.26	0.34 0.25	0.28 0.21	0.17 0.13
Zn	25.2 38.5	2.17 1.42	1.29 0.84	1.26 0.83	0.98 0.64	0.83 0.54
Mn	41.4 55.0	2.41 1.81	1.63 1.23	1.02 0.77	0.32 0.24	0.50 0.38
Cu	17.5 23.5	0.97 0.72	0.79 0.59	0.95 0.71	0.68 0.51	0.64 0.48
Al	165 264	3.13 1.96	1.35 0.84	1.19 0.74	0.82 0.52	0.72 0.45
Fe	2124 3909	5.74 3.12	5.47 2.97	4.46 2.42	1.53 0.83	0.58 0.31
Pb	121 135	1.43 1.28	1.17 1.04	0.94 0.84	0.66 0.59	0.81 0.73
Ni	30.7 34.8	1.41 1.24	1.04 0.91	0.87 0.76	0.66 0.58	0.87 0.76
Cr	8.9 11.6	2.20 1.69	1.81 1.39	1.48 1.14	1.09 0.84	1.17 0.90

1. Dissolved Concentration/Total Concentration

substantial reductions in concentrations at deeper groundwater depths. As seen in Table 3-86, groundwater concentrations for all heavy metals, except lead, were extremely low beneath the retention pond. All heavy metal concentrations in groundwaters beneath the retention pond, except lead, met the general Class III surface water criteria at depths below 1.0 m.

A comparison of general water quality characteristics for surface water and groundwater in the detention pond area is presented in Table 4-30. The majority of measured parameters exhibited groundwater concentrations which were equal to or less than concentrations found in surface water. However, elevated levels of ammonia, nitrate, orthophosphorus, chloride, color and dissolved solids were found in groundwaters beneath the pond. However, it should be noted that even though these groundwater concentrations exceeded surface water values, the concentrations are generally low for most of these parameters.

A comparison of heavy metal concentrations in surface water and groundwater in the detention pond area is given in Table 4-31. Groundwater to surface water ratios for the detention pond were similar to those found for the retention pond. Groundwater concentrations of cadmium and copper were less than both dissolved and total concentrations found in surface waters at all groundwater depths. Elevated groundwater concentrations were observed for zinc, manganese, lead, nickel and chromium. Unlike trends observed for concentrations of heavy metals at other study sites, elevated concentrations beneath the detention pond appeared to extend to the 5.0 m sample depth.

Concentrations of heavy metals in groundwaters beneath the detention pond were greater than concentrations found beneath the retention pond for virtually all metal

TABLE 4-30

COMPARISON OF GENERAL WATER QUALITY CHARACTERISTICS OF SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

PARAMETER	UNITS	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/ SURFACE WATER				
			0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	--	7.49	0.89	0.91	0.88	0.85	0.86
Alkalinity	mg/l	149	1.51	1.06	1.01	1.24	1.18
Ammonia	mg/l	81	5.78	4.25	4.01	4.53	5.00
Nitrate	μg/l	25	0.48	2.84	3.44	0.40	0.40
Diss. Organic N	μg/l	723	0.71	0.62	0.58	0.75	0.82
Total N	μg/l	1079	0.92	0.80	0.77	0.85	0.93
Diss. Ortho-P	μg/l	7	1.57	1.43	1.14	5.71	13.71
Diss. Organic P	μg/l	16.4	0.67	0.55	0.55	0.55	1.64
Total P	μg/l	46	0.46	0.41	0.37	1.04	2.28
Chloride	mg/l	17	2.29	2.18	3.00	4.53	3.59
Sulfate	mg/l	2.4	0.38	0.92	0.00	1.13	0
BOD	mg/l	4.2	0.93	0.86	0.76	0.81	0.83
Color	Pt-Co Units	70	1.94	1.54	1.46	1.91	1.66
T.D.S.	mg/l	198	1.52	1.20	1.19	1.55	1.44
V.D.S.	mg/l	65	1.22	1.0	1.11	1.51	1.29

TABLE 4-31

COMPARISON OF HEAVY METAL CONCENTRATIONS IN SURFACE WATER AND GROUNDWATER IN THE DETENTION POND AREA AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METAL	MEAN SURFACE WATER CONC.	RATIO OF GROUNDWATER/SURFACE WATER[1]				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	11.0	0.53	0.52	0.64	0.70	0.54
	14.8	0.39	0.39	0.47	0.52	0.32
Zn	24.2	1.28	1.46	1.29	1.35	1.29
	31.5	0.98	1.12	0.99	1.04	0.99
Mn	22.8	3.90	2.93	2.63	3.44	2.91
	39.8	2.23	1.68	1.51	1.97	1.67
Cu	21.1	0.64	0.91	0.59	0.66	0.63
	26.1	0.52	0.74	0.48	0.53	0.51
Al	167	2.27	3.47	1.91	1.26	1.20
	340	1.11	1.70	0.94	0.62	0.59
Fe	801	4.93	3.94	4.23	8.13	6.27
	1933	2.04	1.63	1.75	3.37	2.60
Pb	144	1.60	1.38	1.32	1.28	1.16
	161	1.43	1.23	1.18	1.15	1.04
Ni	33.8	1.74	1.41	1.31	1.32	1.26
	42.3	1.39	1.12	1.05	1.06	1.01
Cr	10.2	2.21	1.99	1.75	1.73	1.68
	12.8	1.76	1.59	1.40	1.38	1.34

1. Dissolved Concentration/Total Concentration

species. These differences in groundwater concentrations can be explained, at least in part, by differences in sediment bonding mechanisms between the two ponds. As seen in Table 3-55, large exchange fractions were found in the sediments of the detention pond for cadmium, manganese, lead, nickel and chromium which should result in increased solubility of these metal ions in groundwaters beneath the detention pond. Each of these heavy metals which exhibited a strong exchange association was, in fact, found in elevated concentrations in groundwaters beneath the detention pond. On the other hand, these same metal species were bound by relatively strong Fe/Mn or carbonate fractions in sediments of the retention pond which would substantially reduce the solubility of these metal species in groundwater beneath that pond.

In spite of the differences in groundwater characteristics between the retention and detention ponds, it appears that the operation of the commercial dual pond facility does not have a significant impact on groundwater resources beneath the ponds. However, the groundwater impacts of this system are clearly more severe than those exhibited by the other systems.

Factors Affecting Groundwater Characteristics Beneath Stormwater Management Systems

A series of correlation analyses were conducted to investigate factors important in regulating characteristics of groundwaters beneath stormwater management systems. Correlation analyses were used to investigate the influence of stormwater, sediments and surface water on groundwater concentrations at each of the five study sites. Regression analyses were used to investigate relationships between dissolved metal concentrations in groundwaters and other predictive chemical parameters important in regulating concentrations of each of the measured heavy metals.

Correlations between inflow stormwater concentrations and groundwater characteristics for general chemical parameters are presented in Table 4-32. In this analysis, correlations were conducted between inflow stormwater characteristics for a particular parameter and groundwater concentrations of that same parameter at each of the five sample ports. Data from each of the five study sites was grouped together to form a common data base. In this table, the correlation coefficient is given on the top line of each individual entry indicating the correlation between a parameter in stormwater and that same parameter in groundwater. The number below the correlation coefficient for each entry indicates the probability of a significant correlation between a stormwater parameter and that same parameter in groundwater. Probabilities of 95% or greater are assumed to be statistically significant at the 0.05 level of significance.

Significant correlations between stormwater characteristics and groundwater characteristics were observed for only a few of the general chemical parameters. Significant correlations were observed between stormwater and groundwater pH values to a depth of 0.1 m. Significant correlations with alkalinity in stormwater appear to extend to a depth of approximately 1 m. Significant correlations were also observed between stormwater and groundwater concentrations of nitrate and dissolved solids at a depth of 0.1 m, while significant correlations between stormwater and groundwater existed for organic phosphorus to depths extending to 5 m. However, correlations between stormwater and groundwater were extremely poor for the remaining parameters, with many of the correlations exhibiting negative values. It appears that stormwater

TABLE 4-32

CORRELATIONS BETWEEN INFLOW STORMWATER CONCENTRATIONS AND GROUNDWATER CONCENTRATIONS FOR GENERAL CHEMICAL PARAMETERS

PARAMETER	CORRELATION COEFFICIENT/ PROBABILITY OF SIGNIFICANT CORRELATION				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	0.873 97.7	0.725 89.7	0.762 92.2	0.515 70.4	0.442 62.0
Spec. Cond.	0.381 54.4	0.296 43.1	0.279 40.8	-0.149 22.2	-0.268 39.2
Alkalinity	0.939 99.5	0.893 98.4	0.864 97.4	0.727 89.8	0.665 85.1
NH_3-N	0.084 12.6	0.113 16.9	-0.079 11.9	-0.046 7.0	-0.425 60.0
NO_3-N	0.816 95.2	0.574 76.7	0.843 96.5	0.531 72.2	0.520 70.9
Diss. Organic N	0.366 52.5	0.212 31.3	0.060 8.9	-0.432 60.7	-0.341 49.2
Total N	-0.612 80.4	-0.038 5.6	-0.204 30.2	-0.331 47.8	-0.238 35.1
Diss. Ortho-P	0.385 54.9	0.780 93.3	0.705 88.2	-0.470 65.3	-0.579 77.2
Diss. Organic P	0.939 99.5	0.954 99.7	0.984 99.9	0.985 99.9	0.901 98.6
Total P	0.764 92.3	0.908 98.8	0.942 99.5	0.418 59.1	0.099 14.8
SO_4	0.102 15.3	0.124 18.5	0.135 20.1	-0.039 5.8	0.100 15.0
BOD	0.601 79.3	0.154 22.9	-0.016 2.4	0.015 2.3	-0.079 11.8
Color	-0.624 81.5	-0.642 83.1	-0.693 87.3	-0.607 79.9	-0.611 80.2
T.D.S.	0.823 95.6	0.703 88.1	0.639 82.8	0.345 49.7	0.107 16.0
V.D.S.	0.369 52.8	0.059 9.0	-0.097 14.5	-0.228 33.6	-0.407 57.7

characteristics, with the exception of perhaps a few parameters, have very little effect on characteristics of groundwater beneath a stormwater management system.

Correlations between inflow stormwater concentrations and groundwater concentrations of heavy metals are presented in Table 4-33. No significant correlations were observed between stormwater concentrations and groundwater concentrations of heavy metals for any of the measured metal species. This analysis presents strong evidence that groundwater concentrations of heavy metals are generally independent of the characteristics of stormwater runoff entering the stormwater management system.

Correlations between sediment metal concentrations and groundwater concentrations of heavy metals were also performed, and the results of this analysis are presented in Table 4-34. In this analysis, the mean sediment metal concentration in the top 25 cm beneath each of the stormwater management systems was used as the characteristic sediment value for each heavy metal for a particular stormwater management system. Heavy metal concentrations in groundwater were assumed to equal the mean heavy metal concentrations measured at each of the five sample ports. This analysis was intended to evaluate whether high metal concentrations in the upper sediment layers may be causing metals to leach downward to lower groundwater layers.

As seen in Table 4-34, no significant correlations were observed between sediment characteristics and groundwater concentrations of any of the measured heavy metals. The correlation coefficients were extremely low for most metal species, with some exhibiting negative correlations. This data also presents strong evidence that groundwater concentrations of heavy metals are independent of sediment concentrations of the same heavy metals in the basins of stormwater management systems.

TABLE 4-33

CORRELATIONS BETWEEN INFLOW STORMWATER CONCENTRATIONS AND GROUNDWATER CONCENTRATIONS OF HEAVY METALS

HEAVY METAL	SPECIES	CORRELATION COEFFICIENT/ PROBABILITY OF SIGNIFICANT CORRELATION				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	Diss.	-0.688/86.9	-0.508/69.6	-0.071/10.6	-0.160/23.9	-0.364/52.5
	Total	-0.431/60.7	-0.462/64.4	-0.016/2.4	-0.124/18.5	-0.483/66.8
Zn	Diss.	0.104/15.5	0.342/49.3	0.161/23.9	0.188/27.8	0.071/10.6
	Total	0.510/69.8	0.757/91.8	0.577/76.9	0.573/76.6	0.464/64.6
Mn	Diss.	-0.391/55.7	-0.144/21.4	-0.062/9.3	-0.336/48.5	-0.148/22.1
	Total	-0.418/59.1	-0.820/95.4	-0.861/97.3	-0.228/33.7	-0.442/62.0
Cu	Diss.	-0.585/77.7	-0.049/7.4	-0.514/70.3	-0.280/41.0	-0.358/51.4
	Total	-0.219/32.3	0.413/58.5	-0.102/15.3	-0.293/42.7	-0.593/78.5
Al	Diss.	-0.379/54.2	-0.364/52.2	-0.195/28.8	0.332/48.0	-0.123/18.4
	Total	0.421/59.4	0.234/34.4	0.234/34.5	-0.115/17.2	0.018/2.7
Fe	Diss.	0.688/86.9	0.624/81.4	0.636/82.6	0.674/85.8	-0.590/78.2
	Total	0.679/86.2	0.588/78.0	0.598/79.0	0.681/86.4	0.566/75.9
Pb	Diss.	-0.499/68.6	-0.353/50.8	-0.257/37.7	-0.112/16.8	-0.002/0.2
	Total	-0.766/92.4	-0.699/87.8	-0.659/84.5	-0.555/73.7	-0.512/70.1
Ni	Diss.	-0.387/55.1	-0.376/53.7	-0.360/51.7	-0.252/37.0	-0.333/48.1
	Total	-0.233/34.4	-0.235/34.6	-0.234/34.5	-0.133/19.8	-0.209/30.8
Cr	Diss.	-0.039/5.8	0.076/11.4	0.243/35.7	0.353/50.8	0.447/62.6
	Total	0.112/16.7	0.232/34.1	0.383/54.6	0.459/64.0	0.541/73.2

TABLE 4-34

CORRELATIONS BETWEEN SEDIMENT METAL CONCENTRATIONS AND GROUNDWATER CONCENTRATIONS OF HEAVY METALS

PARAMETER	CORRELATION COEFFICIENT/ PROBABILITY OF SIGNIFICANT CORRELATION				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	0.059 8.9	-0.153 22.8	-0.021 3.2	-0.091 13.6	-0.474 65.8
Zn	0.561 75.3	0.918 99.0	0.827 95.8	0.864 97.4	0.777 93.1
Mn	-0.413 58.4	-0.355 51.0	-0.379 54.2	-0.006 0.9	-0.258 37.9
Cu	0.217 32.0	0.879 97.9	0.113 16.9	0.601 79.3	0.399 56.7
Al	0.079 11.8	-0.007 1.1	0.216 31.9	0.005 0.8	0.063 9.4
Fe	-0.059 8.9	-0.101 15.1	-0.064 9.6	0.251 36.8	0.249 36.6
Pb	0.121 18.0	0.088 13.1	0.075 11.2	0.093 13.8	-0.075 11.3
Ni	-0.010 1.5	-0.060 9.0	-0.211 31.1	-0.251 36.8	-0.305 44.3
Cr	-0.389 55.5	-0.369 52.8	-0.501 68.9	-0.517 70.7	-0.551 74.3

Correlations between surface water concentrations and groundwater concentrations of general chemical parameters are presented in Table 4-35. Significant correlations of surface water and groundwater were observed for many of the measured general chemical parameters. Significant correlations between surface water and groundwater were observed for both conductivity and alkalinity to groundwater depths of 2.5 m. Significant correlations were observed for ammonia to a groundwater depth of approximately 0.1 m. Significant correlations were also observed to depths of 5.0 m for both dissolved organic phosphorus and sulfate. Total dissolved solids in surface water and groundwater were positively correlated to depths of approximately 2.5 m, while volatile dissolved solids were correlated to a depth of approximately 0.1 m. The data presented in Table 4-35 suggests that for many general parameters, surface water characteristics may have been the most important factor regulating groundwater concentrations of the same parameters.

Correlations between dissolved and heavy metal concentrations in surface waters and groundwater heavy metal concentrations are presented in Table 4-36. Significant correlations were observed between surface water metal concentrations and groundwater metal concentrations for zinc to a depth of 2.5 m, and iron to a depth of 1.0 m beneath stormwater management systems. Although these are the only two metal species which exhibited differences at the 0.05 level of significance, relatively high correlation coefficients were also observed between surface water and groundwater concentrations of manganese and copper extending to a depth of approximately 0.1 m, and lead, nickel and chromium extending to a depth of 5.0 m. Correlations presented in Table 4-36 between surface water and groundwater concentrations of heavy metals were substantially

TABLE 4-35

CORRELATIONS BETWEEN SURFACE WATER CONCENTRATIONS AND GROUNDWATER CONCENTRATIONS FOR GENERAL CHEMICAL PARAMETERS

PARAMETER	CORRELATION COEFFICIENT/ PROBABILITY OF SIGNIFICANT CORRELATION				
	0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
pH	0.741 90.8	0.558 75.1	0.613 80.5	0.404 57.3	0.260 38.1
Spec. Cond.	0.898 98.5	0.918 99.0	0.962 99.8	0.858 97.1	0.786 93.7
Alkalinity	0.949 99.6	0.903 98.6	0.900 98.5	0.855 97.0	0.794 94.1
ORP	0.456 63.6	0.330 47.7	0.421 59.4	0.414 58.6	0.361 51.8
NH_3-N	0.951 99.7	0.242 35.7	-0.028 4.1	0.317 45.9	0.305 44.4
NO_3-N	0.678 86.1	0.995 99.9	0.598 79.0	0.999 99.9	0.998 99.9
Diss. Organic N	0.728 89.9	0.282 41.2	0.843 96.5	0.555 74.7	0.551 74.3
Total N	0.245 3.7	-0.739 90.7	-0.468 65.0	0.684 86.6	0.664 85.0
Diss. Ortho-P	0.053 8.0	0.026 4.0	-0.242 35.6	-0.282 41.2	-0.398 56.5
Diss. Organic P	0.814 95.2	0.796 94.2	0.845 96.6	0.888 98.2	0.845 96.6
Total P	0.258 37.8	0.325 47.0	0.196 29.1	-0.233 34.3	-0.443 62.1
SO_4	0.993 99.9	0.852 96.9	0.885 96.6	0.857 97.1	0.840 96.4
BOD	0.396 56.3	0.154 22.9	0.439 61.6	0.436 61.2	0.668 85.3
Color	0.743 91.0	-0.642 83.1	0.647 83.5	0.408 57.8	0.377 53.8
T.D.S.	0.883 98.0	0.703 88.1	0.973 99.9	0.856 97.0	0.748 91.3
V.D.S.	0.838 96.3	0.059 9.0	0.735 90.4	0.487 67.3	0.577 76.9

TABLE 4-36

CORRELATIONS BETWEEN DISSOLVED AND TOTAL HEAVY METAL CONCENTRATIONS IN SURFACE WATERS AND DISSOLVED HEAVY METALS IN GROUNDWATERS

SURFACE WATER HEAVY METAL	SPECIES	CORRELATION COEFFICIENT/ PROBABILITY OF SIGNIFICANT CORRELATION				
		0.1 m	0.5 m	1.0 m	2.5 m	5.0 m
Cd	Diss.	0.522/71.1	0.232/34.2	0.358/51.4	0.265/38.8	-0.100/15.0
	Total	0.452/54.8	0.201/29.7	0.327/47.3	0.256/37.6	-0.129/19.2
Zn	Diss.	0.878/97.9	0.906/98.7	0.951/99.6	0.863/97.3	0.799/94.4
	Total	0.961/99.8	0.904/98.7	0.961/99.8	0.809/94.9	0.691/87.1
Mn	Diss.	0.686/86.7	0.369/52.9	0.227/33.5	0.090/13.5	0.185/27.4
	Total	0.728/89.9	0.351/50.5	0.234/34.4	0.291/42.4	0.351/50.5
Cu	Diss.	0.640/82.9	0.439/61.6	0.465/64.7	0.702/88.0	0.741/90.8
	Total	0.699/87.8	0.570/76.3	0.546/73.8	0.622/81.3	0.679/86.2
Al	Diss.	-0.634/82.3	-0.613/80.5	-0.350/50.4	-0.228/33.6	-0.358/51.4
	Total	-0.367/52.5	-0.372/53.3	-0.121/18.1	-0.191/28.4	-0.201/29.7
Fe	Diss.	0.934/99.4	0.889/98.2	0.869/97.6	0.461/64.3	0.250/36.8
	Total	0.958/99.7	0.917/99.0	0.914/98.9	0.594/78.7	0.389/55.4
Pb	Diss.	0.691/87.1	0.744/91.0	0.853/96.9	0.902/98.6	0.943/99.5
	Total	0.690/87.1	0.747/91.2	0.852/96.9	0.905/98.7	0.943/99.5
Ni	Diss.	0.604/79.6	0.613/80.4	0.639/82.8	0.649/83.7	0.681/86.4
	Total	0.681/86.3	0.685/86.7	0.677/86.1	0.698/87.7	0.694/87.4
Cr	Diss.	0.460/64.1	0.539/73.0	0.731/90.2	0.810/94.9	0.847/96.7
	Total	0.579/77.2	0.652/83.9	0.816/95.2	0.871/97.6	0.906/98.7

stronger than correlations presented with stormwater or sediment concentrations. Surface water concentrations of heavy metals were clearly the most significant of the evaluated predictive variables for regulating concentrations of heavy metals in groundwater.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Field and laboratory investigations were conducted from October 1986 through June 1988 to evaluate and quantify potential groundwater impacts from common stormwater management systems in various contributing land use types typical of Central Florida. Five study sites were selected, including: (1) an interstate highway site which discharged to a roadway wet swale system; (2) an interstate highway site which discharged to a sandy, dry roadside swale system; (3) a dual pond system receiving residential runoff; (4) a shallow wet detention basin receiving runoff from a duplex residential area; and (5) a highly impervious commercial site discharging to a dual pond treatment system.

Surface Water and Groundwater Hydrology at the Five Study Sites

Groundwater hydrology was monitored at each of the five study sites using piezometers installed at depths of 1 m below the groundwater table to indicate shallow piezometric elevations and at depths of 5 m below the groundwater surface to indicate deep piezometric elevations. Two piezometers were installed with each monitoring well.

In general, groundwater piezometric elevations at the five study sites were influenced primarily by precipitation events. Changes in piezometric elevations occurred rapidly following rain events, with maximum elevations generally reached within 24 hours. However, decreases in piezometric elevations following extreme rain events occurred slowly, often requiring 30 to 60 days to recover to initial values. Groundwater piezometric elevations and gradients along with local hydrology were more important in determining the infiltration characteristics of stormwater management systems than characteristics of soils within the swale or pond area.

Considerable variability was observed in both vertical and horizontal hydraulic gradients at each of the five study sites. Each site exhibited horizontal and vertical gradients which indicated periods of water migration both toward and away from the stormwater management systems. A summary of site hydrology for each of the five study sites is given in the following sections.

Site 1 - Wet Swale Site

With the exception of only two monitoring dates during 1987, the wet swale area maintained a permanent pool of water which ranged in depth from 0.0 m (0.0 ft) to 0.6 m (2.0 ft), with an average of approximately 0.3 m (1.0 ft). In general, piezometric elevations in the control area were slightly higher than those measured in the swale channel, indicating a potential for migration of groundwaters from the control area toward the swale. A small baseflow was observed in the swale channel on virtually all monitoring dates, presumably resulting from groundwater seepage into the swale. Both vertical and horizontal hydraulic gradients indicated a potential for migration of waters into the swale channel during most of the study period. In general, vertical hydraulic gradients at this site were substantially larger in value than horizontal gradients.

The primary direction of groundwater movement at this site appeared to be toward and into the swale channel. Infiltration from the swale channel into groundwaters was minimal, except following extreme rain events. Therefore, for any given rain event, the volume of runoff entering the swale channel closely approximated the volume of runoff water discharging from the swale channel into the downstream stormsewer system.

Site 2 - Dry Swale Site

The dry swale channel was characterized by highly permeable sandy soils which infiltrated runoff water rapidly. Estimates of infiltration rates in the swale channel indicated a range of infiltration values from a low of 29.2 cm/hr (11.5 in/hr) in September to 38.6 cm/hr (15.2 in/hr) in March. Visual observations of swale performance during rain events indicated that virtually all runoff entering the swale channel infiltrated into the ground prior to reaching the outfall inlet. Discharges from the swale channel were observed only during period of intense rainfall activity which would input large amounts of runoff into the swale in a short period of time. Based on field observations during a number of rain events, it was conservatively estimated that approximately 80% of the general runoff inflow into the swale channel infiltrated into the soil on an annual basis.

Groundwater piezometric elevations beneath the dry swale channel were extremely variable during 1987, with a range of fluctuation of approximately 1.2 m (4 ft). Water table depths beneath the swale channel ranged from 1.47 m (4.82 ft) to 2.63 m (8.63 ft) during the study period. Piezometric elevations at this site responded quickly to infiltration from extreme rain events. A single extended rain event of approximately 20 cm (8.0 in) over a 36-hour period during March caused a rapid increase in groundwater elevation beneath the swale channel of approximately 1.02 m (3.35 ft) within 24 hours following the rain event. This increase in piezometric elevation dissipated slowly over a period of approximately 60 days.

In general, both vertical and horizontal groundwater gradients appeared to be very small at this site. With only a few exceptions, vertical hydraulic gradients were found to be near zero throughout most of 1987. Horizontal groundwater gradients, although small in magnitude, indicated a net movement of groundwater away from the swale area for virtually all measurement dates in 1987. The dominant direction of groundwater flow at this site was clearly horizontal rather than vertical.

Site 3 - Residential Dual Pond Site

Piezometric elevations at this site were highly variable throughout 1987. Piezometric fluctuations correlated closely to inputs into the stormwater management system as a result of storm events. Piezometric elevations within the retention pond were consistently greater than piezometric elevations measured in either the detention or control areas. In general, piezometric elevations within the detention pond appeared to be slightly greater than those measured in the control area.

Both retention and detention ponds exhibited periods with and without permanent pools of water. In general, both ponds were consistently dry during the typical dry season months from January through June, and maintained a permanent pool of water during the typically wet season months of July through November. Water surface elevations within the retention pond approached the diversion weir elevation to the detention pond on only three recorded occasions during the study period. The detention pond also rarely reached its exit orifice elevation, suggesting that the majority of inputs of runoff into the detention pond were totally retained within that pond. Based on estimates of mass inputs into the pond systems and observations of system performance during actual rain events, it was estimated that approximately 80-90% of all runoff inputs into this dual pond system were retained within the system without discharges to off-site water bodies.

Estimated seepage rates for the retention pond were calculated based upon changes in water surface elevations over a specific time interval minus the measured evaporation losses at the site. Infiltration rates were minimal during January and February, but increased steadily during the first six months of 1987, reaching a peak of approximately 4.4 cm/day during the summer months.

Site 4 - Residential Wet Detention Pond

Piezometric elevations in the wet detention pond exhibited a wide range of fluctuations, with a range in values of approximately 1.5 m (5.0 ft) during the study period. In general, piezometric elevations responded quickly to inputs of runoff from rain events with a slow but continuous decline in elevation following these events. With only a few exceptions, water surface elevations within the detention pond remained below the pond control elevation at all times during the study period. It was conservatively estimated that more than 80-90% of all hydraulic inputs into the detention pond were totally retained within the system with the primarily removal and drawdown mechanisms being evaporation from the water surface and infiltration of pond water into the ground.

Infiltration rates through the pond bottom were affected by both season and rainfall, with a maximum infiltration rate of approximately 7.5 cm/day during July.

In general, vertical hydraulic gradients suggested a potential for downward migration of water during the first 4-5 months of 1987, followed by a switch to a net upward gradient for the remainder of the study period. Horizontal gradients suggested a constant tendency for migration of waters out of the pond in a lateral direction. Therefore, the primary mechanism for exfiltration of pond water into the ground at this site appeared to be a lateral migration rather than a direct vertical movement.

Site 5 - Commercial Dual Pond Site

The retention and detention ponds of the commercial dual pond system were small, shallow stormwater ponds constructed in a high water table area with bottom pond elevations lower than the normal groundwater elevation. In general, piezometric elevations in the control area were somewhat greater than those measured in either pond, while the retention pond elevations exceeded those measured in the detention pond. Although a small downward vertical gradient was observed at times, the dominant movement of groundwater at this site appeared to be in the horizontal direction toward the stormwater management ponds. The detention pond appeared to act as a collector for both horizontal and vertical migration of groundwater.

One wall of the retention pond is constructed as a vertical filter which contains a 0.91 m (3.0 ft) wide layer of #9 stone as filter media. Runoff inputs into the retention pond quickly pass through the vertical filter box by way of PVC inlet pipes on the retention pond side of the filter. Although direct measurements could not be taken, this filter system apparently allowed runoff inputs into the retention pond to enter the detention pond at a rapid rate since field measurements indicated that the design high water level of the retention pond was never reached during the 12-month study period. Inputs into the detention pond were discharged through a structure with a control elevation set at the bottom elevation of the detention pond. As a result, detention times for runoff inputs within this system were relatively short.

Characteristics of Stormwater Runoff at the Five Study Sites

Flow-weighted composite stormwater runoff samples were collected at each of the five study sites for selected rain events during 1987. A minimum of eight rainfall events were monitored at each study site. In general, monitored storm events covered a wide range of rainfall amounts, durations and antecedent dry periods.

Event mean concentrations of general chemical parameters measured in stormwater runoff at the five study sites were extremely variable from event to event. The measured range of values for many parameters exceeded two to three orders of magnitude. In general, the largest degree of variability was observed for runoff event concentrations of total nitrogen, organic phosphorus, total phosphorus, BOD, chloride and dissolved solids. Event mean concentrations of virtually all general chemical parameters were found to exhibit a log-normal distribution.

Event mean concentrations of heavy metals in stormwater runoff at the five study sites were generally less variable than observed for general chemical parameters. The measured range of event mean concentrations for most heavy metals was less than one order of magnitude. Both dissolved and total event mean concentrations for all heavy metals exhibited log-normal distributions.

A considerable degree of variability was also observed in the overall mean water quality characteristics for stormwater runoff collected at the five study sites. This variability was present even between sites in the same land use category. For example, large differences existed between mean chemical characteristics found at the two highway sites in spite of the fact that these two study sites were located within several miles of each other along the same interstate highway and had virtually identical average daily traffic loadings. These differences were particularly apparent for mean concentrations of total nitrogen, total phosphorus, suspended solids and heavy metals. Mean concentrations of total nitrogen, total phosphorus and suspended solids in highway runoff measured at site 2 were 34%, 140% and 96% greater, respectively, than concentrations of the same parameters measured in highway runoff at site 1. A similar trend was apparent for concentrations of heavy metals between the two sites. It was suggested that these differences in runoff characteristics could be related to either differences in characteristics of rain events monitored at the two sites or to differences in runoff coefficients between the two study sites.

Substantial differences were also evident in overall mean values for chemical characteristics of residential runoff collected at sites 3 and 4. Residential runoff collected at site 4 was found to have substantially higher mean concentrations of total nitrogen, total phosphorus, BOD and suspended solids than found in runoff collected at site 3. Concentrations of total nitrogen, total phosphorus, BOD and suspended solids at site 4 were approximately 151%, 756%, 46% and 110% greater, respectively, than concentrations measured at site 3. It was suggested that these differences in chemical characteristics may be due to differences in runoff coefficients between the two sites as well as differences in characteristics of monitored rain events.

However, in spite of the extreme variability in mean runoff characteristics between the five study sites, several general trends were suggested. First, mean concentrations of total nitrogen at the two residential sites (3235 μg/l) exceeded concentrations measured at the two highway sites (1877 μg/l), which exceeded the mean concentration at the commercial site (1527 μg/l). The dominant nitrogen species at each site was organic nitrogen which accounted for approximately 62-90% of the total nitrogen found. Nitrate nitrogen was the next most important nitrogen species found at all sites with ammonia contributing only 2-6% of total nitrogen.

Mean concentrations of total phosphorus were greatest at the residential sites with a mean of 948 μg/l compared with 390 μg/l at the highway sites and 189 μg/l at the commercial site. In general, dissolved and particulate phosphorus species were approximately equal in concentration at the residential and highway sites. The dominant phosphorus in commercial runoff was particulate species which contributed 76% of the total phosphorus measured.

In contrast, mean concentrations of BOD were highest in commercial runoff (11.6 mg/l), followed by residential (8.0 mg/l), and highway (5.6 mg/l) sites. The commercial site also contributed the highest levels of suspended solids (111.4 mg/l) compared with 50.3 mg/l at the highway sites and 46.7 mg/l at the residential sites, as well as turbidity with a mean of 30.3 NTU for commercial runoff compared with 25.5 NTU for highway runoff and 11.4 NTU for residential runoff.

With the exceptions of aluminum, iron and manganese, the most common stormwater related heavy metals measured at the five study sites were lead, zinc and copper. Stormwater concentrations of nickel were similar to copper at several of the study sites. Lead, zinc and copper together accounted for approximately 81% and 89% of the dissolved species, and 87% and 94% of the total metal species found in highway runoff at sites 1 and 2, respectively. These three metals contributed 79% and 85% of the dissolved, and 81% and 87% of the total metal concentrations found in residential runoff at sites 3 and 4, respectively. At the commercial site, lead, copper and zinc contributed 82% of the dissolved and 87% of the total metal species found.

Mean concentrations of heavy metals appeared to be greater in highway runoff collected at sites 1 and 2 than in runoff collected at the other three sites. Concentrations of heavy metals in commercial runoff appeared to be similar to that found in highway runoff. With the exception of chromium, concentrations of heavy metals in residential runoff were substantially lower than concentrations found in either highway or commercial runoff.

Regression and correlation procedures were used to evaluate relationships between rainfall event characteristics such as total rainfall, event duration, average intensity and antecedent dry period with chemical characteristics of the runoff flow. A separate analysis was conducted for each site and runoff land use type. Antecedent dry period was the most commonly correlated rainfall characteristic in terms of predicting concentrations of stormwater constituents. Antecedent dry period was found to be an important predictor for runoff concentrations of ammonia and BOD in highway runoff at site 2. Antecedent dry period was also found to be important in predicting runoff concentrations of most heavy metals, turbidity and organic nitrogen at the two residential sites as well as ammonia at the commercial site.

Significant negative correlations were found between total rainfall and event mean concentrations for many measured parameters. This trend of decreasing concentrations with increasing rainfall amounts is presumably related to a first-flush phenomenon. These negative correlations were observed for particulate organic nitrogen and dissolved organic phosphorus in highway runoff at site 1, as well as for particulate organic nitrogen, total phosphorus and BOD in residential runoff at site 4.

In spite of the significant correlations between rainfall characteristics and certain water quality parameters, the majority of measured parameters did not exhibit significant correlations with measured characteristics of the monitored rain events. This inability to explain differences in runoff characteristics by differences in watershed characteristics, hydrologic parameters or storm event characteristics further underscores the poorly understood nature of stormwater quality processes.

Characteristics of Surface Water at the Five Study Sites

Surface water samples were collected at sites 1, 3, 4 and 5 from January to December, 1987 on a biweekly basis from swale and pond areas. In general, water quality characteristics in surface waters were similar for most parameters with the exceptions of the wet swale channel at site 1 and the retention pond at the dual pond system for site 5. Each of these systems contained dense vegetative communities of cattails and other emergent species, while the remaining pond systems consisted primarily of open water bodies.

It is apparent that the dense vegetative growth along the wet swale channel and in the retention pond at site 5 had a significant effect on the water quality characteristics of surface water at these two sites. Surface water at these two sites was found to have the lowest mean values of pH, surface water temperatures, dissolved oxygen and redox potential and the highest measured values for ammonia. Dissolved oxygen concentrations within these vegetated systems ranged from 1.1 mg/l to 1.5 mg/l, while dissolved oxygen concentrations within the open water systems ranged from 8.2 mg/l to 10.8 mg/l. Mean concentrations of ammonia within the vegetated systems ranged from 236 μg/l to 392 μg/l, compared with values ranging from 13 μg/l to 81 μg/l at the open water sites. The two vegetated sites also exhibited the highest mean values for color.

These differences in physical and chemical characteristics of surface water in the vegetated stormwater systems was attributed to two factors. First, physical shading of the water column by the vegetation caused a reduction in ambient surface water temperature as well as solar radiation which reduced photosynthetic activity. In addition, decomposition of organic debris from vegetation also consumed oxygen from the water column which created a reduced environment and also released organic acids which contributed to increased color and decreased pH. The dense vegetated communities along the wet swale and in the retention pond at site 5 appeared to degrade rather than improve water quality.

Measured concentrations of both general chemical parameters and heavy metals in surface water from ponds and in swale areas were, in general, less variable than observed for runoff inputs to these systems. Surface water discharges from the wet detention pond at site 4 had the lowest concentrations of total nitrogen, with a mean value of 859 μg/l, followed by the wet swale with a total nitrogen concentration of 884 μg/l, the commercial dual pond system with an exit concentration of 1079 μg/l, and the residential dual pond system with an outflow concentration of 1385 μg/l. The lowest concentrations of total phosphorus were found in discharges from the commercial dual pond system at 46 μg/l, followed by the residential dual pond system at 82 μg/l, the wet detention pond at 147 μg/l and the wet swale channel at 217 μg/l. In general, concentrations of BOD, suspended solids and turbidity were relatively low in surface waters at each of the study sites.

With the exceptions of iron and aluminum, concentrations of all heavy metals appeared to be lowest in surface water of the wet detention pond at site 4, while the highest concentrations of heavy metals were found within the retention and detention ponds in the commercial dual pond system at site 5. Surface water within the wet detention pond at site 4 was found to contain significantly lower levels of manganese, lead, nickel and chromium than surface water at the other sites. With the exception of iron, the majority of heavy metal species within surface waters at each of the study sites were found to be in a dissolved form, with dissolved fractions for most metals exceeding 80%.

Surface water within each of the stormwater management systems was found to have total metal concentrations less than the allowable State of Florida Class III Surface Water Criteria for copper, nickel and chromium. Each of the stormwater management systems, with the exception of site 5, met the allowable surface water criterion of 30 μg/l for zinc. The maximum allowable surface water concentration of 1000 μg/l for total iron was met by the dual pond system at site 3 and the wet detention pond at site 4, but was exceeded by the other systems. Surface water concentrations within all of the stormwater management systems exceeded the allowable criterion for cadmium of 0.8 μg/l, with measured values of total cadmium ranging from 5.3 μg/l to 14.9 μg/l. Surface water concentrations of total lead in each of the stormwater management systems also exceeded the allowable surface water criterion of 30 μg/l, with surface water values ranging from approximately 80 μg/l to 194 μg/l.

Concentration-Based Removal Efficiencies for the Five Stormwater Management Systems

The wet swale channel was capable of reducing input concentrations of all measured stormwater pollutants with the exceptions of conductivity, orthophosphorus, chloride and sulfate. Concentrations of total nitrogen, total phosphorus, BOD and suspended solids were reduced by 40%, 17%, 48% and 81%, respectively. In comparison, concentration-based removal efficiencies for stormwater inputs into the dry swale channel appeared to be substantially less than those found within the wet swale channel. Concentration reductions were observed only for alkalinity, species of nitrogen, total phosphorus, turbidity, suspended solids and volatile suspended solids, while the other measured parameters increased during flow through the dry swale channel.

Concentration-based system removal efficiencies for the two dual pond sites appeared to be relatively similar for many of the measured parameters. Neither system was capable of producing significant reductions in conductivity, ammonia, dissolved organic nitrogen, chloride, sulfate, total dissolved solids or volatile dissolved solids. However, both systems decreased input concentrations of total nitrogen and total phosphorus, with reductions of 25% and 59% for total nitrogen and total phosphorus, respectively, at site 3, and reductions of 29% and 76%, respectively, at site 5. Reductions in BOD and suspended solids were also similar between the two sites, with reductions of 48% and 77% for BOD and suspended solids, respectively, at site 3, and reductions of 64% and 89% for the same parameters at site 5. The primary removal processes at these dual pond sites occurred within the retention ponds with the final detention pond providing little additional improvement in water quality. In fact, removal efficiencies for many parameters actually decreased after migration into the final detention ponds.

The wet detention system at site 4 was the only stormwater management system which provided significant reductions in concentration for all of the measured stormwater parameters. Concentrations of total nitrogen were reduced by approximately 81% within this system. Unlike the other stormwater management systems which were unable to remove ammonia, the wet detention pond achieved removal efficiencies for ammonia in excess of 90%. Substantial reductions were also achieved for concentrations of both dissolved and particulate organic nitrogen, with removal efficiencies of 78% and 85%, respectively.

The wet detention facility was also capable of providing significant reductions in total phosphorus, with an overall removal efficiency of 91%. Excellent removal efficiencies were achieved for both orthophosphorus and dissolved organic phosphorus as well. The wet detention pond was also the only system studied which provided significant removal efficiencies for chloride, sulfate and color. Concentration reductions of approximately 80-95% were found for suspended solids and volatile suspended solids.

Both the wet and dry swale channels were able to provide reductions in input concentrations of total heavy metals during travel along the swale channel. Total concentrations of lead, aluminum, copper and zinc were reduced by approximately 50% or more during flow through each channel. Concentrations of the remaining heavy metals, including chromium, nickel, iron, manganese and cadmium, were reduced in concentration by approximately 30-40%. Concentration-based removal efficiencies for heavy metals during flow through the dry swale channel appeared to be relatively consistent, with all removal efficiencies in the range of 40-50%.

Removal of heavy metal species within the dual pond sites was relatively poor for most metal species. The dual pond systems were capable of providing significant reductions in concentrations of total zinc and total copper only, while concentrations of the remaining heavy metals either increased within the pond system or were reduced by small percentages. Concentrations of cadmium, manganese, lead and nickel increased substantially within these systems above input values measured in stormwater runoff. Although these systems provided moderate removal efficiencies for nutrients, BOD and suspended solids, they performed poorly in reducing concentrations of heavy metals.

The wet detention pond at site 4 provided good removal efficiencies for all heavy metals with the exception of cadmium. Zinc was reduced in concentration within this system by approximately 82%, manganese by 67%, iron by 62%, copper by 52%, lead by 49%, chromium by 42% and nickel by 32%. With the exceptions of cadmium and aluminum, concentration-based removal efficiencies for heavy metals within this system appeared to be the best achieved within any of the studied stormwater management systems.

The wet detention system provided the most consistent removal efficiencies for both general water quality parameters and heavy metals. Although each of the swale sites appeared to be capable of reducing concentrations of heavy metals, these systems performed poorly in reducing concentrations of common stormwater pollutants such as total nitrogen, total phosphorus and BOD. A similar case could be made for each of the dual pond sites, which provided relatively good removal efficiencies for common stormwater pollutants but very poor removal efficiencies for heavy metals.

Attenuation Mechanisms for Nutrients and Heavy Metals

An analysis was conducted on each of the five stormwater management systems to evaluate mechanisms responsible for reductions in pollutant concentrations within these systems. Total measured concentrations of nutrients and heavy metals were subdivided into dissolved and particulate forms so that removal processes for each of these forms could be evaluated separately.

During migration of stormwater inputs through the various stormwater management systems, input concentrations of both dissolved and particulate species of nutrients and heavy metals decreased for the majority of species measured. However, concentration reductions were generally greater for the particulate species than for the dissolved species. For example, removal of particulate species of lead, zinc, copper and aluminum along the wet swale channel ranged from 80-90%, while reductions in dissolved concentrations ranged from approximately 30-40%. It appears that the primary mechanism responsible for reductions in total metal concentrations within each of the stormwater management systems is simply a settling process for particulate metal species.

The net result of these removal processes is an increase in the percentage of dissolved forms for most metals and nutrients in the outflow or surface water and a decrease in the percentage of particulate forms. Removal mechanisms for nitrogen and phosphorus appeared to be somewhat different than those exhibited by metal species. Concentration reductions in total nitrogen were primarily achieved by removal of inorganic as well as particulate organic nitrogen, while phosphorus was removed primarily by reductions in dissolved and particulate organic phosphorus.

Attenuation mechanisms for nutrients and heavy metals at the two dual pond systems were relatively similar. Both systems were capable of providing significant removal of particulate fractions of both nutrients and heavy metals. However, concentration-based removal efficiencies for dissolved species within both retention ponds were generally quite poor with several metal species exhibiting increases in dissolved species within the pond above values measured in the incoming stormwater flow.

Migration of runoff water through the final detention pond of the dual pond systems resulted in very little improvement in removal efficiencies. Although some metal species appeared to exhibit some additional removal of particulate forms, increases in dissolved concentrations were observed for the majority of heavy metals measured. The dual pond systems were capable of providing removal of particulate metal species through settling processes within the retention and detention ponds, but these systems were clearly incapable of reducing dissolved concentrations of heavy metals.

The residential wet detention pond at site 4 was the only stormwater management system which provided significant removal for both particulate and dissolved species of heavy metals and nutrients. Removal efficiencies for particulate metal species were generally in excess of 50% for all measured heavy metals, with removal efficiencies for particulate manganese, zinc and lead exceeding 80%. The detention pond also provided reductions in dissolved species of all heavy metals except iron, aluminum and cadmium.

Estimates of Mass Removal Efficiencies

Estimates of mass removal efficiencies were also conducted for the wet swale channel, the dry swale channel, the residential dual pond site and the residential wet detention pond. Mass removal efficiencies were not estimated for the commercial dual pond system because of inadequate information on hydrologic inputs and outputs for this system.

Since hydrologic inputs and outputs from the wet swale channel were assumed to be approximately equal on an annual basis, estimates of mass removal efficiencies were identical to the concentration-based removal efficiencies. On the other hand, since approximately 80% of the hydraulic inputs into the dry swale channel infiltrate into groundwaters, mass removal efficiencies for the dry swale system were substantially higher than those estimated for the wet swale channel. Mass removal of total nitrogen along the dry swale channel was approximately 84%, compared with only 40% in the wet swale channel. Removal efficiencies for total phosphorus in the dry swale channel were approximately 83%, compared with only 17% in the wet swale channel. The dry swale channel also exhibited excellent mass removal efficiencies for heavy metals, with removal efficiencies ranging from 88-90% for all heavy metal species.

On an annual mass loading basis, the dry swale channel was far superior to the wet swale channel in terms of reducing mass loadings of stormwater inputs to downstream water bodies. Removal efficiencies achieved within the dry swale channel were equivalent to those normally associated with a properly designed and operated off-line retention system where annual pollutant removal efficiencies of 80-90% are generally achieved.

The residential dual pond system at site 3 provided excellent mass removal efficiencies for the majority of measured stormwater pollutants. Removal efficiencies for total nitrogen, total phosphorus, BOD and suspended solids within this system were estimated to be approximately 85%, 92%, 90% and 95%, respectively. With the exception of cadmium, removal efficiencies in excess of 65% were observed for all measured heavy metals. It should be noted, however, that the primary reason for the relatively high removal efficiencies achieved within this system was the large amount of water retained within the system on an annual basis, since concentrations of many measured parameters actually increased within the detention pond above input concentrations measured in the stormwater inflow.

Extremely high mass removal efficiencies were achieved within the wet detention pond at site 4 for all measured stormwater parameters. Mass removal efficiencies for total nitrogen, total phosphorus, BOD and suspended solids were approximately 96%, 98%, 92% and 96%, respectively. With the exception of cadmium, removal efficiencies for all measured heavy metals were approximately 80-90%. Unlike the dual pond system, removal efficiencies achieved by the wet detention pond resulted from a combination of large hydraulic retention and substantial reductions in input runoff concentrations within the pond.

Horizontal Distribution of Heavy Metals and Nutrients in Swale and Pond Areas

Heavy Metal concentrations in the top 1 cm of pond and swale sediments at each of the five study sites were used to evaluate the horizontal distributions of heavy metals within each of the stormwater management systems. These horizontal distributions indicated that upon entering the stormwater management system, the majority of heavy metals associated with stormwater runoff settled out relatively quickly and were deposited near the point of input for the runoff flow. The horizontal distribution of heavy metals also appeared to be substantially affected by the percentage of particulate forms for each metal species in the stormwater runoff and also the type of stormwater management system.

The most common heavy metals found in soils and sediments of the five stormwater management systems were lead and zinc, with sediment concentrations of lead generally exceeding those of zinc. Sediment concentrations of both lead and zinc increased rapidly with increasing distance along the swale channel at each of the swale sites. Peak sediment concentrations of lead and zinc were found at distances of 25-70 m along the swale channels. Rapid settling and attenuation of both zinc and lead was observed in sediments at the residential wet detention pond as well. Peak sediment concentrations within this system were reached at distances of 40-60 m from the inflow point. The relatively high particulate fractions of both lead and zinc in stormwater runoff at each of these sites may explain the similar settling characteristics for these metal species between the three sites.

Horizontal accumulations of chromium, copper, nickel and cadmium along the two swale channels and within the wet detention pond exhibited substantially lower sediment concentrations and broader settling patterns than observed for lead and zinc. Inputs of chromium, copper, nickel and cadmium in stormwater runoff at each of these three sites were primarily in a dissolved form, with relatively small particulate fractions. As a result of the low percentage of particulate species and the high dissolved fractions, these metal species settled out over much larger distances and exhibited less pronounced settling patterns than observed for lead and zinc.

In general, sediment concentrations of all heavy metals, nitrogen, phosphorus and organic content were substantially lower in newly constructed stormwater management facilities, such as the residential and commercial dual pond sites, than found in sediments collected from older stormwater management sites. In general, sediment concentrations within the 0-1 cm layer of retention and detention ponds at these newly constructed sites were similar to those found within control areas.

Surface sediment concentrations of nitrogen and phosphorus did not exhibit the characteristic accumulation patterns exhibited by heavy metals. In fact, sediment concentrations of nitrogen and phosphorus were found to be higher in control areas than in swale or pond areas for many of the study sites.

Vertical Attenuation of Heavy Metals and Nutrients

In general, concentrations of all heavy metals, with the exception of aluminum, were highest in the surface layer of swale and pond areas with a decreasing concentration with increasing depth. This same general trend was also observed for organic content, phosphorus, and to a lesser extent, nitrogen. Vertical distributions of zinc, lead, iron, nickel and chromium were higher in sediments within swale and pond areas than found in sediments beneath the control area. These differences were substantially more pronounced in sediments from the older stormwater management systems than in sediments from the newly constructed facilities. Sediment concentrations of copper and cadmium appeared to be relatively similar in both stormwater management areas and control areas for both the older and newly constructed facilities.

Sediment concentrations of heavy metals were attenuated rapidly with increasing sediment depth. For the majority of metal species measured, sediment concentrations in the final 15-25 cm layer were similar in both swale and control areas. This suggests that the increase in sediment metal concentrations resulting from inputs of stormwater runoff has been limited to within the top 10-15 cm below swale and pond areas.

The vertical attenuation of heavy metals in the top 25 cm of swale, pond and control areas was found to fit a semi-log relationship of the form: $\ln (C/C_o) = K \times (\text{Depth})$, where K represents the slope of the semi-log fit and is an indication of the rate of attenuation of sediment concentrations with increasing sediment depth. With few exceptions, the calculated values of R-square for these regression models were generally in excess of 0.90 for each heavy metal.

These rapid attenuation patterns for most heavy metals suggest that metals are being retained primarily in the surface soil layers with very little tendency for downward migration of sediment-bound metal species. Differences in attenuation coefficients for heavy metals between the dry swale channel and the wet swale channel suggest that the dry swale channel is more effective in retaining heavy metals within the sediments than observed for the wet swale channel.

The rapid attenuation in sediment concentrations observed for heavy metal species in swale and pond areas was generally not observed for nitrogen and phosphorus. In fact, sediment concentrations of both nitrogen and phosphorus were found to be higher within control area soils for many sites than in sediments beneath swales or ponds. Swale or pond systems appear to be much less effective in retaining nitrogen and phosphorus within the sediments than for heavy metals.

Estimates of mean attenuation coefficients for metal sediment concentrations were calculated for each of the measured heavy metals. Based upon these calculated mean coefficients, the following order is predicted for sediment attenuation and stability in the sediments of swale and pond systems:

Most Rapid Attenuation	zinc > lead > cadmium > manganese > copper > iron > chromium > nickel > aluminum	Least Rapid Attenuation

Relationships Between Sediment Grain Size and Heavy Metal Content

Surface soil layers in the top 5 cm of stormwater management systems exhibited elevated percentages of both coarse and fine grain soil particles when compared to soil characteristics in layers deeper than 5 cm. These elevated amounts of coarse and fine grain particles are presumably due to settling and decomposition of stormwater pollutants. These changes in soil characteristics in the top 5 cm were substantially more pronounced in the older stormwater management systems than in the newly constructed systems.

Correlation analyses were conducted to investigate relationships between sediment grain size distributions and heavy metal concentrations in soil layers at the five study sites. Significant correlations, with a probability in excess of 99%, were found between all of the measured heavy metals and sediment organic content. Metal associations with organic content were particularly strong for iron and nickel. Sediment metal content was also strongly correlated with particle sizes greater than 2 mm in diameter. These significant associations presumably represent heavy metals bound to large organic particles such as leaves or other organic debris. Strong correlations were also found between heavy metal content and soil particles smaller than 0.075 mm in diameter, generally classified as silt. It appears that heavy metals within the sediments of the five stormwater management systems were primarily associated with particle sizes that were greater than 2 mm in diameter and also with silt particles less than 0.075 mm in diameter, but were poorly correlated with medium or fine sand particles.

Relationships Between Stormwater, Sediments and Surface Water Characteristics

Correlation analyses were conducted to evaluate general predictive mechanisms between stormwater inputs, sediment concentrations and surface water characteristics for the five stormwater management systems. A combined data set was used from the five study sites which contained characteristics of stormwater inflow, sediments and surface water. Correlation analyses were conducted to evaluate significant mechanisms affecting water quality within stormwater management systems in general.

Surface water characteristics for both general parameters and heavy metals were found to be relatively independent of stormwater inputs into the stormwater management system. Significant correlations between stormwater inputs and surface water characteristics were found for only four parameters, including pH, dissolved organic phosphorus, dissolved copper and total aluminum. Surface water characteristics were also found to be relatively independent of sediment characteristics. Sediments were found to be important predictors of surface water concentrations for only two heavy metals, cadmium and iron.

The lack of significant correlations between characteristics of sediments and stormwater and water column concentrations suggests that the water column characteristics developed as a result of processes which were independent of both sediments and stormwater inputs. These processes may include physical factors such as sedimentation, coagulation or adsorption, chemical processes such as precipitation, along with biological uptake in the water column of the stormwater management system.

Effects of Stormwater Management Systems on Underlying Groundwaters

Groundwater characteristics beneath stormwater management systems were compared with surface water characteristics as well as groundwater characteristics in control areas to evaluate the potential for leaching of stormwater pollutants into groundwaters. The results of the speciation experiments for phosphorus and heavy metals were used to explain increased or decreased solubility of certain metals in groundwater at different sites.

Site 1 - Wet Swale Site

The data collected during this research provides strong evidence that the operation of the wet swale system is not resulting in a significant impact on groundwater quality beneath the swale channel. Groundwater concentrations of virtually all measured general parameters as well as heavy metals were found to be lower beneath the swale channel than in groundwaters in the control area.

Groundwater concentrations of virtually all measured parameters were lower in groundwaters beneath the swale than in surface water contained within the swale. Several parameters, such as chloride, sulfate, copper and iron, exhibited elevated concentrations in groundwaters beneath the swale channel which were confined primarily within the top 1 m of groundwater. With the exception of cadmium, groundwater concentrations of all heavy metals at depths greater than 1.0 m were equal to or less than water quality criteria for Class III Surface Waters specified in Chapter 17-3 of the Florida Administrative Code.

Site 2 - Dry Swale Site

In general, groundwater concentrations of all general parameters, with the exceptions of alkalinity, BOD and dissolved solids, were lower in groundwater beneath the dry swale channel than in runoff inflow into the swale channel. The majority of measured parameters exhibited substantially lower concentrations in shallow groundwater beneath the swale than found in runoff inputs. Groundwater concentrations of several parameters, such as nitrate, organic nitrogen and chloride, appeared to increase in the lower groundwater layers. However, it is unlikely that these increases were related to inputs from the swale channel since groundwater concentrations in upper levels were substantially lower.

Groundwater concentrations of cadmium, zinc, copper and lead were approximately equal to or less than input runoff concentrations for both dissolved and total species at all groundwater depths. Groundwater concentrations of manganese, aluminum, iron, nickel and chromium generally exceeded dissolved metal concentrations found in runoff, but in most cases were substantially lower than total metal concentrations found in runoff inputs. With the exceptions of cadmium and lead, concentrations of each heavy metal at groundwater depths greater than 1.0 m were equal to or less than water quality criteria for Class III Surface Waters specified in Chapter 17-3 of the Florida Administrative Code. Even though infiltration along the swale channel was extremely rapid, this infiltration process was apparently effective in reducing pollutant concentrations for virtually all measured parameters.

Groundwater concentrations of heavy metals and phosphorus beneath the dry swale channel were somewhat higher for many species than found beneath the wet swale channel. Groundwater concentrations of copper, lead and nickel beneath the dry swale channel were approximately twice that found beneath the wet swale channel. Concentrations of chromium beneath the dry swale channel were approximately four times greater than those found beneath the wet swale channel. The most likely explanation for these differences in groundwater characteristics is that the rapid infiltration processes which occur along the dry swale channel, although extremely effective in reducing concentrations of all measured parameters, were less effective in retaining runoff pollutants than the very slow migration processes which occurred along the wet swale channel. Groundwater concentrations for most measured parameters were slightly higher beneath the swale area than beneath the control area.

Overall, the dry swale system appears to be an extremely effective type of stormwater management system. The removal and attenuation of stormwater pollutants along the swale channel was extremely high for all measured parameters. There is little evidence to indicate that the rapid infiltration processes involved along this channel are contributing significant loadings of pollutants to groundwaters.

Site 3 - Residential Dual Pond Site

With the exceptions of ammonia, nitrate, volatile dissolved solids and manganese, concentrations of measured parameters in groundwater beneath the retention pond were either equal to or less than surface water concentrations measured within the pond. For those species which exhibited elevated concentrations in groundwater, the extent of these elevated concentrations appears to be limited to groundwater depths between 1.0 m and 2.5 m. Groundwater concentrations of both total nitrogen and total phosphorus were relatively low and should not pose a significant threat to surface waters in the event this groundwater should migrate and enter into a surface water system. With the exceptions of cadmium and lead, groundwater concentrations for all heavy metals were also extremely low with values less than the Class III Surface Water criteria at all groundwater depths.

The apparent leaching of cadmium and lead into groundwaters may be related to the speciation for cadmium and lead within the sediments of the retention pond. Both cadmium and lead were found to exist in significant exchange fractions within the sediments of the retention pond. These exchange fractions are generally weak metal associations which are subject to solubilization and transport into the groundwater flow. The remaining heavy metals which did not exhibit a potential for leaching into groundwaters were bound by stronger sediment associations.

Groundwater characteristics beneath the detention pond were similar to those found beneath the retention pond. Groundwater concentrations of both total nitrogen and total phosphorus were extremely low in groundwater beneath the detention pond, although concentrations of both ammonia and nitrate exceeded values measured within surface waters of the detention pond.

Groundwater concentrations of all heavy metals, with the exceptions of cadmium and lead, were also extremely low beneath the detention pond. Groundwater concentrations of copper, lead, nickel and chromium were lower than both dissolved and total concentrations found in surface waters. However, groundwater concentrations of manganese, cadmium and zinc exceeded values measured within surface water. Elevated groundwater concentrations for zinc and manganese extended to the 5.0 m depth, while elevated concentrations of cadmium were attenuated within a depth of 1 m. Cadmium, zinc and manganese exhibited high percentages of weak exchange fractions within the sediments of the detention pond which increased the potential for solubilization into groundwater. Concentrations of all heavy metals in groundwater, with the exceptions of cadmium and lead, were lower than the Class III Surface Water criteria at all groundwater depths.

Based upon the results of this research, the operation of the dual pond system appears to have a minimal effect on groundwater characteristics beneath the ponds. For the majority of measured parameters, groundwater concentrations beneath the ponds were equal to or less than surface water concentrations measured within the ponds.

Site 4 - Residential Wet Detention Pond Site

In general, groundwater concentrations of general water quality parameters and heavy metals were relatively low at all groundwater depths beneath the wet detention pond. Although groundwater concentrations of many general parameters exceeded surface water concentrations in groundwater extending to depths of 1.0-2.5 m, these exceedances are more a result of extremely low surface water concentrations rather than elevated concentrations of these parameters in groundwaters.

Even though concentrations of certain heavy metals exceeded those found in surface waters, all heavy metal concentrations, with the exception of cadmium, were extremely low in groundwaters beneath the wet detention pond. Concentrations of all heavy metals in groundwater at depths below 1.0 m met the general Class III Surface Water criteria specified in Chapter 17-3 of the Florida Administrative Code.

Similar to conclusions reached at the previous study sites, there is little evidence to indicate that operation of the wet detention system is having a negative impact on groundwater resources beneath the pond. Although groundwater concentrations exceeded surface water concentrations for many parameters, these elevated concentrations were generally limited to within the top 1.0 m beneath the detention pond.

Site 5 - Commercial Dual Pond System

Unlike the trends observed at the previous study sites, groundwater concentrations beneath the retention pond for many of the measured general parameters exceeded concentrations found in surface water within the retention pond. Elevated groundwater concentrations were observed for ammonia, total nitrogen, orthophosphorus, organic phosphorus, total phosphorus, chloride, BOD, color and dissolved solids. However, the extent of these elevated groundwater concentrations generally appeared to be limited to within the first 1.0 m of groundwater beneath the pond.

Groundwater concentrations for all heavy metals, except lead, were extremely low beneath the retention pond. Although groundwater concentrations for several heavy metals exceeded concentrations found in surface water, these elevated concentrations were generally contained within the first 1.0 m of groundwater. All heavy metal concentrations in groundwater beneath the retention pond, except lead, met the general Class III Surface Water criteria at depths below 1.0 m. In general, groundwater concentrations of general chemical parameters and heavy metals were lower beneath the retention pond than beneath the detention or control areas.

Concentrations of general water quality parameters in groundwater beneath the detention pond were generally low in value, although groundwater concentrations for many parameters exceeded values found in surface water. Measured concentrations of general parameters beneath the detention pond often exceeded groundwater concentrations measured beneath the retention pond.

In general, concentrations of heavy metals in groundwaters beneath the detention pond were greater than concentrations found beneath the retention pond for virtually all metal species. Groundwater concentrations of all heavy metals, except copper and cadmium, exceeded values measured in surface water within the detention pond. Unlike trends observed for concentrations of heavy metals at the other study sites, elevated groundwater concentrations of heavy metals beneath the detention pond appeared to extend to the 5.0 m sample depth.

The differences in groundwater concentrations beneath the detention and retention ponds can be explained, at least in part, by differences in sediment bonding mechanisms between the two ponds. Large exchange fractions were found in the sediments of the detention pond for cadmium, manganese, lead, nickel and chromium which resulted in increased solubility of these metal ions in groundwaters beneath the detention pond.

In spite of the differences in groundwater characteristics between the retention and detention ponds, it appears that the operation of the commercial dual pond facility does not have a significant impact on groundwater resources beneath the ponds. However, the groundwater impacts of this system are clearly more severe than those exhibited by the other systems.

Factors Influencing Groundwater Characteristics Beneath Stormwater Management Systems

Correlation analyses were used to investigate the influence of stormwater, sediments and surface water on groundwater concentrations at each of the five sites. Correlations between stormwater characteristics and groundwater characteristics were observed for only a few of the general chemical parameters such as pH, alkalinity, nitrate and dissolved solids. The extent of these correlations was generally limited to within the top 1.0 m of groundwater. No significant correlations were observed between stormwater concentrations and groundwater concentrations of heavy metals for any of the measured metal species. It appears that stormwater characteristics, with the exception of perhaps a few parameters, had very little effect on characteristics of groundwater beneath a stormwater management system.

No significant correlations were observed between sediment characteristics and groundwater concentrations of any of the measured heavy metals. Correlation coefficients between sediment metal concentrations and groundwater metal concentrations were extremely low for most metal species, with some exhibiting negative correlations. This data presents strong evidence that groundwater concentrations of heavy metals were independent of sediment metal concentrations in the basins of stormwater management systems. The lack of significant correlations between sediment characteristics and groundwater concentrations suggests that the continuous accumulation of heavy metals and nutrients in the sediments of stormwater management systems may not pose a significant threat to groundwater resources.

Correlations between surface water characteristics and groundwater characteristics suggest that for many chemical parameters surface water characteristics may be the most important factor regulating groundwater concentrations of the same parameters. Significant correlations between surface water and groundwater were found for conductivity, alkalinity, ammonia, dissolved organic phosphorus, sulfate and dissolved solids.

Significant positive correlations were observed between surface water and groundwater for only two metal species, zinc and iron. Although only these two metal species exhibited significant differences at the 0.05 level of significance, relatively high correlation coefficients were observed between surface water and groundwater concentrations for the majority of heavy metal species. Surface water concentrations of heavy metals were clearly more significant in regulating groundwater concentrations of heavy metals than either stormwater or sediment characteristics.

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APPENDIX

APPENDIX A

DETAILED SUMMARY STATISTICS FOR THE GROUNDWATER SAMPLES COLLECTED AT THE FIVE STUDY SITES

TABLE A-1

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE SWALE AREA AT THE WET SWALE SITE (SITE 1) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	4.59	4.11-6.01	10.6	12	4.39	3.85-5.82	11.5	12	4.34	3.80-5.77	11.9
Spec. Cond.	µmhos/cm	12	218	152-283	18.8	12	206	140-275	20.6	12	212	137-287	21.9
Temperature	°C	12	22.56	17.02-27.36	16.4	12	22.75	18.46-26.42	12.3	12	22.89	19.09-26.39	10.7
Dissolved O_2	mg/l	12	0.69	0.1-1.9	82.1	12	0.5	0.1-1.0	58.6	12	0.5	0.1-1.1	65.6
ORP	mv	12	-86	(-159)-14	60.2	12	-87	(-140)-(-15)	51.8	12	-85	(-142)-18	57.9
Alkalinity	mg/l	12	3.2	0.0-15.7	157	12	0.5	0.0-5.2	285	12	0.2	0.0-2.3	331
NH_3-N	µg/l	12	929	527-1260	29.6	12	944	541-1414	29.9	12	952	527-1312	29.3
NO_2 + NO_3-N	µg/l	12	14	<10-41	90.3	12	10	<10-28	82.8	12	11	<10-25	62.6
Diss. Organic N	µg/l	12	392	<10-854	69.1	12	384	<10-930	75.4	12	382	51-1074	77.9
Diss. Ortho-P	µg/l	12	23	4-53	68.5	12	26	<1-140	154	12	13	<1-56	126
Diss. Org. P	µg/l	12	9	0-42	137	12	7	0-19	88.5	12	7	0-21	102
Total P	µg/l	12	31	9-57	59.0	12	33	6-148	126	12	19	4-59	88.8
Chloride	mg/l	12	73	39-119	36.7	12	69	33-113	35.3	12	72	38-125	39.8
Sulfate	mg/l	12	16.9	5.7-29.6	43.3	12	15.9	7.4-28.3	46.4	12	17.3	7.2-29.7	41.3
BOD	mg/l	12	2.9	1.3-6.6	50.0	12	2.3	0.2-6.4	67.2	12	2.1	0.1-6.1	73.9
Color	Pt-Co Units	12	69	16-128	53.8	12	50	1-144	73.9	12	51	1-174	99.1
T.D.S.	mg/l	12	127	88-153	17.8	12	119	82-149	19.1	12	120	73-155	24.0
V.D.S.	mg/l	12	38	3-78	58.6	12	40	14-72	44.5	12	39	15-85	49.9

1. Number of samples
2. Coefficient of variation

TABLE A-1 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	12	4.26	3.69-5.81	13.5	12	4.32	3.78-5.84	12.9
Spec. Cond.	μmhos/cm	12	102	92-116	7.9	12	145	127-167	7.4
Temperature	°C	12	23.18	20.82-25.73	6.7	12	23.36	21.85-25.31	4.5
Dissolved O_2	mg/l	12	0.5	0.1-1.0	62.3	12	0.5	0.1-1.0	63.5
ORP	mv	12	-88	(-147)-(-5)	51.8	12	-89	(-153)-(-12)	53.7
Alkalinity	mg/l	12	0.2	0.0-1.0	190	12	0.5	0.0-2.4	189
NH_3-N	μg/l	12	845	542-1030	20.3	12	824	519-1972	46.2
NO_2 + NO_3-N	μg/l	12	8	<10-22	69.9	12	7	<10-15	59.0
Diss. Organic N	μg/l	12	234	<10-775	98.4	12	167	<10-373	79.9
Diss. Ortho-P	μg/l	12	22	8-57	64.3	12	18	6-32	45.0
Diss. Org. P	μg/l	12	6	0-17	104	12	6	0-16	90.0
Total P	μg/l	12	27	14-63	52.5	12	24	13-43	41.1
Chloride	mg/l	12	35	21-50	31.2	12	38	20-54	35.3
Sulfate	mg/l	12	9.4	6.3-13.0	22.6	12	22.1	14.8-29.0	19.7
BOD	mg/l	12	2.5	1.0-5.7	47.7	12	2.4	0.9-5.8	58.4
Color	Pt-Co Units	12	36	<1-132	95.1	12	35	1-132	109
T.D.S.	mg/l	12	74	36-167	52.5	12	98	58-247	50.5
V.D.S.	mg/l	12	34	4-73	64.6	12	38	6-89	59.1

1. Number of samples
2. Coefficient of variation

TABLE A-2

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE CONTROL WELL AT THE WET SWALE SITE (SITE 1) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	4.38	3.70-5.95	12.8	12	4.43	3.73-6.09	13.2	12	4.52	3.87-6.15	12.9
Spec. Cond.	μmhos/cm	12	603	308-1032	37.7	12	436	213-843	41.5	12	270	101-687	68.1
Temperature	°C	12	23.45	19.64-27.82	12.4	12	23.51	20.08-27.40	10.6	12	23.54	20.58-26.89	8.8
Dissolved O_2	mg/l	12	0.7	0.3-1.6	68.8	12	0.6	0.2-1.4	73.8	12	0.5	0.1-1.2	69.5
ORP	mv	12	-74	(-157)-38	77.6	12	-87	(-165)-(-22)	51.3	12	-89	(-159)-(-18)	48.8
Alkalinity	mg/l	12	0.1	0.0-0.5	210	12	1.0	0.0-10.0	283	12	1.8	0.0-17.1	270
NH_3-N	μg/l	12	806	461-1198	30.5	12	644	325-1160	37.8	12	427	326-609	18.1
NO_2 + NO_3-N	μg/l	12	16	<10-49	95.2	12	17	<10-59	93.8	12	13	<10-53	110
Diss. Organic N	μg/l	12	352	<10-740	68.1	12	297	<10-536	58.7	12	561	81-2465	112
Diss. Ortho-P	μg/l	12	20	6-44	68.6	12	15	<10-37	81.6	12	16	<1-41	81.4
Diss. Org. P	μg/l	12	8	0-18	88.0	12	10	0-28	101	12	7	0-30	119
Total P	μg/l	12	29	11-56	54.2	12	25	10-57	57.0	12	23	10-52	55.2
Chloride	mg/l	12	209	98-391	46.6	12	149	57-302	49.8	12	81	3-148	50.1
Sulfate	mg/l	12	57.2	17.9-161.0	97.4	12	40.7	3.3-165.0	121	12	24.4	1.6-99.6	132
BOD	mg/l	12	3.5	1.2-5.7	33.7	12	3.8	2.4-6.1	25.8	12	3.6	2.1-6.1	34.0
Color	Pt-Co Units	12	127	62-328	64.9	12	126	44-328	67.8	12	107	29-336	79.5
T.D.S.	mg/l	12	351	94-587	41.6	12	244	73-496	51.4	12	171	88-384	54.2
V.D.S.	mg/l	12	82	9-210	65.8	12	76	29-131	37.8	12	57	26-92	35.4

1. Number of samples
2. Coefficient of variation

TABLE A-2 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	4.38	3.85-5.88	12.9	12	4.25	3.67-5.83	13.4
Spec. Cond.	µmhos/cm	12	93	72-166	27.9	12	171	160-195	5.3
Temperature	°C	12	23.76	21.74-26.20	6.1	12	23.76	22.51-25.73	4.6
Dissolved O_2	mg/l	12	0.5	0.1-1.1	68.5	12	0.5	0.1-1.0	67.3
ORP	mv	12	-94	(-165)-(-4)	48.3	12	-83	(-164)-4	-58.4
Alkalinity	mg/l	12	0.9	0.0-5.2	180	12	0.4	0.0-3.2	269
NH_3-N	µg/l	12	347	234-488	22.1	12	1693	728-2330	37.2
NO_2 + NO_3-N	µg/l	12	7	<10-19	63.8	12	8	<10-30	95.5
Diss. Organic N	µg/l	12	447	54-1710	93.6	12	861	39-2527	95.6
Diss. Ortho-P	µg/l	12	28	14-70	50.5	12	29	4-125	112
Diss. Org. P	µg/l	12	8	0-34	145	12	15	0-35	77.6
Total P	µg/l	12	36	16-82	49.6	12	44	16-160	88.0
Chloride	mg/l	12	30	10-49	35.2	12	45	26-67	33.0
Sulfate	mg/l	12	6.8	2.1-20.7	74.4	12	24.0	10.8-30.9	25.5
BOD	mg/l	12	3.5	2.3-5.4	31.8	12	2.2	0.9-5.4	52.9
Color	Pt-Co Units	12	39	5-120	73.2	12	35	5-168	124
T.D.S.	mg/l	12	67	39-138	39.3	12	94	56-170	28.9
V.D.S.	mg/l	12	33	10-72	58.1	12	38	18-57	40.3

1. Number of samples
2. Coefficient of variation

TABLE A-3

SUMMARY OF DISSOLVED HEAVY METALS IN SWALE AREA SAMPLES COLLECTED AT THE WET SWALE SITE (SITE 1)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	2.99	1.5-4.3	34.3	12	3.87	1.5-5.9	40.9	12	3.36	1.2-6.0	44.1
Zn	12	15.5	4.0-53	86.5	12	19.1	5.0-60	75.9	12	16.9	<1.0-59	93.2
Mn	12	29.2	7.0-96	97.1	12	17.2	6.0-57	86.9	12	11.7	5.0-34	71.6
Cu	12	12.7	4.0-32	77.0	12	16.2	4.0-59	98.8	12	12.7	4.0-47	93.8
Al	12	734	279-1266	41.8	12	922	371-1284	30.7	12	1027	609-1645	31.2
Fe	12	2986	466-7505	87.1	12	1736	301-4023	71.0	12	1155	237-2775	71.2
Pb	12	36.8	4.0-87	61.5	12	33.8	4.0-99	76.8	12	32.4	<1.0-97	79.2
Ni	12	14.2	7.7-24	40.4	12	12.5	5.1-29	55.6	12	11.2	1.4-28	65.1
Cr	12	3.85	<0.5-9.6	65.4	12	3.32	<1.0-5.7	48.9	12	3.29	2.0-5.5	45.1

1. Number of samples
2. Coefficient of variation

TABLE A-3 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	4.12	2.0-6.3	28.1	12	2.89	<0.5-7.3	77.2
Zn	12	16.1	3.0-49	77.5	12	13.5	<1.0-46	86.9
Mn	12	11.1	4.0-27	54.9	12	8.42	5.0-17	39.1
Cu	12	12.5	2.0-45	108	12	10.2	4.0-27	80.0
Al	12	602	397-921	30.5	12	593	404-871	26.4
Fe	12	813	196-2094	67.3	12	480	183-874	46.5
Pb	12	29.4	9.0-81	68.7	12	30.3	4.0-76	67.1
Ni	12	12.3	4.3-27	55.0	12	9.75	<0.5-22	64.7
Cr	12	3.23	1.7-7.3	52.5	12	3.37	1.8-6.0	42.4

1. Number of samples
2. Coefficient of variation

TABLE A-4

SUMMARY OF DISSOLVED HEAVY METALS IN CONTROL WELL SAMPLES COLLECTED AT THE WET SWALE SITE (SITE 1)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	3.75	<0.5-6.5	53.0	12	4.60	2.4-8.0	38.4	12	4.25	1.0-7.9	44.9
Zn	12	27.3	7.0-118	113	12	26.3	6.0-108	103	12	23.1	4.0-106	117
Mn	12	31.8	10-87	69.7	12	41.3	12-150	108	12	35.1	4.0-130	130
Cu	12	17.1	<1.0-68	116	12	25.7	5.0-130	140	12	14.4	2.0-51	111
Al	12	1666	683-3384	55.7	12	1531	522-2981	56.1	12	1055	357-3323	78.5
Fe	12	5157	2636-16,900	76.3	12	5984	2068-18,100	86.7	12	5632	672-20,800	112
Pb	12	66.1	27-193	73.2	12	55.3	21-184	79.4	12	48.2	17-173	90.6
Ni	12	22.5	8.8-58	69.8	12	17.0	7.4-44	59.6	12	13.0	4.9-35	73.7
Cr	12	5.79	2.9-12	53.6	12	5.68	2.9-15	61.1	12	4.90	2.5-12	57.8

1. Number of samples
2. Coefficient of variation

TABLE A-4 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	3.89	<0.5-8.0	50.8	12	3.33	1.8-6.5	38.4
Zn	12	13.6	4.0-42	74.3	12	16.8	3.0-50	71.8
Mn	12	5.83	2.0-18	85.2	12	6.17	3.0-19	70.1
Cu	12	10.0	<1.0-32	95.6	12	11.0	2.0-35	88.5
Al	12	331	216-484	29.2	12	807	290-1318	36.3
Fe	12	803	500-1188	24.2	12	939	155-1336	47.5
Pb	12	25.9	10-68	66.1	12	32.3	10-82	68.0
Ni	12	9.95	1.9-28	82.3	12	11.2	3.5-35	82.8
Cr	12	3.35	<1.0-9.2	69.3	12	3.72	1.7-10	64.4

1. Number of samples
2. Coefficient of variation

TABLE A-5

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE SWALE WELL AT THE DRY SWALE AREA (SITE 2) DURING 1987

PARAMETER	UNITS	0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	s.u.	2	6.49	6.20-6.78	6.3	9	6.46	5.91-7.02	6.6
Spec. Cond.	μmhos/cm	2	227	222-231	2.8	9	206	180-220	7.1
Temperature	°C	2	23.13	22.83-23.42	1.8	9	25.67	22.60-29.20	9.2
Dissolved O_2	mg/l	2	2.9	1.0-4.8	92.7	9	2.3	1.2-4.4	52.6
ORP	mv	2	219	159-279	38.8	9	225	142-296	23.4
Alkalinity	mg/l	2	148.5	109.0-188.0	37.6	9	105.0	34.5-212.0	46.3
NH_3-N	μg/l	2	104	<10-203	135	9	71	<10-175	98.1
NO_2 + NO_3-N	μg/l	2	309	18-599	133	9	635	<10-1330	89.8
Diss. Organic N	μg/l	2	280	64-495	109	9	1153	<10-5860	157
Diss. Ortho-P	μg/l	2	130	112-148	19.6	9	142	96-181	22.2
Diss. Organic P	μg/l	2	20	6-33	97.9	9	28	0-60	80.6
Total P	μg/l	2	150	118-181	29.8	9	170	96-241	29.0
Chloride	mg/l	2	8	5-11	53.0	9	8	2-13	40.6
Sulfate	mg/l	2	7.3	4.1-10.4	61.4	9	10.3	1.8-28.6	79.5
BOD	mg/l	2	4.7	1.4-7.9	98.8	9	2.4	0.3-8.3	110
Color	Pt-Co Units	2	35	12-58	92.9	9	44	4-140	96.2
T.D.S.	mg/l	2	146	136-156	9.7	9	142	88-186	19.8
V.D.S.	mg/l	2	48	44-52	11.8	9	45	24-67	31.5

1. Number of samples
2. Coefficient of variation

TABLE A-5 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	s.u.	12	6.31	5.65-7.00	6.5	12	5.05	4.35-6.17	12.5
Spec. Cond.	µmhos/cm	12	233	192-287	15.8	12	75	64-97	13.7
Temperature	°C	12	25.23	23.46-27.58	5.8	12	25.28	24.08-27.18	3.9
Dissolved O_2	mg/l	12	2.5	0.9-5.0	52.5	12	0.6	0.2-1.1	50.9
ORP	mv	12	236	54-345	33.1	12	162	3-249	51.7
Alkalinity	mg/l	12	67.5	5.2-170	66.2	12	33.2	12.6-196.0	155
NH_3-N	µg/l	12	11	<10-30	79.0	12	15	<10-46	87.4
NO_2 + NO_3-N	µg/l	12	2963	283-9066	95.5	12	875	89-1395	50.2
Diss. Organic N	µg/l	12	1151	<10-6600	164	12	576	<10-1895	104
Diss. Ortho-P	µg/l	12	85	12-150	51.0	12	32	19-53	29.4
Diss. Organic P	µg/l	12	21	0-59	90.2	12	25	2-65	97.0
Total P	µg/l	12	105	27-168	46.7	12	57	21-98	47.9
Chloride	mg/l	12	11	3-23	56.2	12	17	9-38	49.9
Sulfate	mg/l	12	11.2	2.4-20.1	46.3	12	3.6	1.0-8.9	74.0
BOD	mg/l	12	1.9	0.1-7.8	125	12	1.8	0.1-7.5	129
Color	Pt-Co Units	12	25	<1-111	160	12	16	<1-120	206
T.D.S.	mg/l	12	170	124-233	18.5	12	48	11-88	40.5
V.D.S.	mg/l	12	65	3-119	48.2	12	21	6-45	60.3

1. Number of samples
2. Coefficient of variation

TABLE A-6

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE CONTROL WELL AT THE DRY SWALE AREA (SITE 2) DURING 1987

PARAMETER	UNITS	0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	s.u.	1	6.0	--	--	8	5.92	5.25-6.59	7.1
Spec. Cond.	µmhos/cm	1	178	--	--	8	126	99-187	24.1
Temperature	°C	1	23.22	--	--	8	25.67	22.59-28.18	8.3
Dissolved O_2	mg/l	1	2.7	--	--	8	1.9	0.5-4.2	58.7
ORP	mv	1	261	--	--	8	92	(-65)-262	117
Alkalinity	mg/l	1	83.8	--	--	8	36.6	2.1-90.0	67.2
NH_3-N	µg/l	1	10	--	--	8	19	<10-59	107
NO_2 + NO_3-N	µg/l	1	58	--	--	8	170	52-312	57.8
Diss. Organic N	µg/l	1	176	--	--	8	556	<10-2770	166
Diss. Ortho-P	µg/l	1	10	--	--	8	31	1-60	61.5
Diss. Organic P	µg/l	1	3	--	--	8	20	0-57	119
Total P	µg/l	1	13	--	--	8	50	14-83	43.3
Chloride	mg/l	1	13	--	--	8	11	7-15	26.5
Sulfate	mg/l	1	5.0	--	--	8	18.0	5.0-42.6	63.8
BOD	mg/l	1	0.9	--	--	8	3.6	0.5-12.1	115
Color	Pt-Co Units	1	22	--	--	8	68	1-248	124
T.D.S.	mg/l	1	105	--	--	8	87	48-124	29.1
V.D.S.	mg/l	1	36	--	--	8	25	11-47	51.9

1. Number of samples
2. Coefficient of variation

TABLE A-6 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	s.u.	7	4.84	4.38-6.22	13.7	12	5.40	4.63-6.15	10.0
Spec. Cond.	μmhos/cm	7	97	85-103	6.9	12	129	103-196	19.6
Temperature	°C	7	25.70	22.89-27.41	6.2	12	24.83	22.91-27.44	6.5
Dissolved O_2	mg/l	7	3.0	2.5-3.5	12.5	12	2.7	2.0-3.7	19.6
ORP	mv	7	255	157-386	28.4	12	215	121-376	36.6
Alkalinity	mg/l	7	19.5	0.0-72.2	124	12	23.4	2.6-87.9	96.3
NH_3-N	μg/l	7	44	<10-259	213	12	30	<10-253	241
NO_2 + NO_3-N	μg/l	7	1727	460-2569	44.1	12	1380	214-2390	46.7
Diss. Organic N	μg/l	7	847	<10-2900	132	12	866	<10-2270	113
Diss. Ortho-P	μg/l	7	17	6-30	54.2	12	24	<1-70	80.5
Diss. Organic P	μg/l	7	24	1-55	92.3	12	45	0-241	159
Total P	μg/l	7	42	15-76	54.2	12	69	13-241	102
Chloride	mg/l	7	17	10-23	31.1	12	11	4-21	47.5
Sulfate	mg/l	7	12.9	8.0-20.1	38.3	12	17.2	5.9-25.1	35.6
BOD	mg/l	7	1.2	0.1-4.2	124	12	2.1	0.1-7.3	123
Color	Pt-Co Units	7	22	4-111	176	12	22	<1-164	208
T.D.S.	mg/l	7	76	64-94	14.9	12	93	56-136	29.9
V.D.S.	mg/l	7	34	28-44	16.5	12	41	18-68	42.2

1. Number of samples
2. Coefficient of variation

TABLE A-7

SUMMARY OF DISSOLVED HEAVY METALS IN SWALE WELL SAMPLES COLLECTED AT THE DRY SWALE SITE (SITE 2)

HEAVY METALS	0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	2	2.60	2.3-2.9	16.3	9	4.12	1.9-8.4	53.5
Zn	2	44.5	44-45	1.6	9	34.7	3.0-70	73.5
Mn	2	18.0	18-19	0.0	9	14.1	4.0-25	53.0
Cu	2	24.0	23-25	5.9	9	20.1	5.0-34	44.5
Al	2	297	295-299	1.0	9	560	67-1595	83.1
Fe	2	554	502-605	13.2	9	549	176-919	45.0
Pb	2	73.0	72-74	1.9	9	81.7	48-115	22.3
Ni	2	31.5	30-33	6.7	9	28.1	18-44	31.5
Cr	2	17.5	14-21	28.3	9	14.2	5.3-23	53.7

1. Number of samples
2. Coefficient of variation

TABLE A-7 -- CONTINUED

HEAVY METALS	0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	3.85	1.9-7.5	50.0	12	1.92	1.0-2.6	25.6
Zn	12	28.5	3.0-54	61.6	12	22.7	5.0-48	50.1
Mn	12	13.9	6.0-23	43.0	12	10.2	2.0-16	44.6
Cu	12	22.6	9.0-60	58.2	12	14.0	6.0-39	62.9
Al	12	232	81-524	53.9	12	128	21-244	70.5
Fe	12	313	40-709	79.8	12	239	10-502	79.5
Pb	12	88.0	49-180	45.5	12	48.0	23-76	33.6
Ni	12	28.8	18-48	31.1	12	17.1	3.4-28	47.7
Cr	12	13.3	5.1-26	49.7	12	9.34	1.9-20	65.2

1. Number of samples
2. Coefficient of variation

TABLE A-8

SUMMARY OF DISSOLVED HEAVY METALS IN CONTROL WELL SAMPLES COLLECTED AT THE DRY SWALE SITE (SITE 2)

HEAVY METALS	0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	1	2.30	--	--	8	2.54	1.1-3.2	25.7
Zn	1	35.0	--	--	8	34.4	2.0-77	86.8
Mn	1	15.0	--	--	8	25.1	7.0-70	81.0
Cu	1	16.0	--	--	8	14.3	8.0-27	41.2
Al	1	230	--	--	8	239	63-490	71.9
Fe	1	380	--	--	8	2854	383-8515	98.5
Pb	1	57.0	--	--	8	71.8	39-129	47.6
Ni	1	24.0	--	--	8	20.5	7.6-32	48.4
Cr	1	11.0	--	--	8	11.9	2.9-24	70.0

1. Number of samples
2. Coefficient of variation

TABLE A-8 -- CONTINUED

HEAVY METALS	0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	7	2.37	1.2-3.0	26.4	12	2.58	1.2-4.5	34.6
Zn	7	33.9	18-44	32.7	12	30.3	4.0-72	71.8
Mn	7	18.0	14-24	20.3	12	12.0	<1.0-31	65.9
Cu	7	24.0	5.0-54	66.7	12	21.3	10-76	84.7
Al	7	206	27-292	47.9	12	429	181-918	68.5
Fe	7	369	41-580	51.5	12	373	50-858	65.7
Pb	7	57.7	30-87	37.1	12	64.3	25-116	45.1
Ni	7	21.6	10-32	40.1	12	20.8	4.4-33	48.2
Cr	7	13.3	5.6-19	39.1	12	12.7	3.4-23	57.3

1. Number of samples
2. Coefficient of variation

TABLE A-9

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE RETENTION POND WELL AT THE RESIDENTIAL DUAL POND SYSTEM (SITE 3) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	6.55	5.87-7.42	7.0	12	6.22	5.14-7.00	8.0	12	6.31	5.33-7.54	9.2
Spec. Cond.	µmhos/cm	12	232	93-338	34.9	12	227	109-518	46.2	12	218	89-517	52.1
Temperature	°C	12	24.11	16.35-29.94	16.5	12	24.45	15.25-32.16	21.6	12	24.28	14.53-32.69	22.7
Dissolved O_2	mg/l	12	1.2	0.2-6.7	150	12	1.0	0.2-6.0	160	12	1.8	0.2-5.8	108
ORP	mv	12	43	(-120)-343	284	12	23	(-118)-337	474	12	61	(-111)-330	203
Alkalinity	mg/l	12	50.2	32.1-103.0	40.1	12	80.0	46.1-177.0	43.5	12	73.7	31.4-162	48.2
NH_3-N	µg/l	12	455	<10-847	64.9	12	991	125-2430	79.1	12	920	36-2320	87.3
NO_2 + NO_3-N	µg/l	12	477	<10-3300	196	12	47	<10-139	91.6	12	62	<10-188	103
Diss. Organic N	µg/l	12	409	5-1595	133	12	394	<10-1279	95.3	12	294	<10-960	103
Diss. Ortho-P	µg/l	12	74	43-132	35.2	12	52	17-84	35.0	12	46	15-72	33.6
Diss. Org. P	µg/l	12	23	0-121	150	12	14	0-49	98.0	12	18	0-95	139
Total P	µg/l	12	97	58-253	52.9	12	66	40-108	28.3	12	64	38-137	41.6
Chloride	mg/l	12	31	7-99	80.7	12	27	8-104	102	12	27	8-105	107
Sulfate	mg/l	12	26.0	2.4-44.3	54.3	12	4.9	0.3-12.6	87.2	12	4.8	0.1-11.6	75.2
BOD	mg/l	12	4.6	0.7-10.5	69.8	12	7.4	1.1-14.8	64.6	12	6.2	1.0-13.4	74.9
Color	Pt-Co Units	12	30	<1-115	102	12	64	1-241	107	12	65	1-241	106
T.D.S.	mg/l	12	139	58-197	34.2	12	138	81-294	42.0	12	137	60-338	53.9
V.D.S.	mg/l	12	42	2-113	82.0	12	45	9-137	81.2	12	43	8-96	65.9

1. Number of samples
2. Coefficient of variation

TABLE A-9 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	7.03	6.18-9.08	10.8	12	6.98	6.43-7.69	4.4
Spec. Cond.	µmhos/cm	12	203	78-526	63.5	12	243	118-531	48.3
Temperature	°C	12	24.38	16.11-32.37	20.7	12	24.55	13.82-32.69	23.7
Dissolved O_2	mg/l	12	3.0	0.2-11.1	114	12	1.7	0.1-5.5	83.9
ORP	mv	12	113	(-108)-380	142	12	41	(-55)-347	274
Alkalinity	mg/l	12	67.2	33.5-150.0	51.9	12	87.5	51.3-162.0	35.8
NH_3-N	µg/l	12	110	<10-390	103	12	609	104-1203	65.8
NO_2 + NO_3-N	µg/l	12	74	<10-259	99.3	12	41	<10-266	177
Diss. Organic N	µg/l	12	323	<10-676	64.8	12	449	<10-1658	98.6
Diss. Ortho-P	µg/l	12	58	20-119	47.1	12	106	57-130	19.4
Diss. Org. P	µg/l	12	19	4-52	68.0	12	24	2-94	104
Total P	µg/l	12	77	34-142	45.1	12	129	54-224	27.4
Chloride	mg/l	12	31	8-106	103	12	32	7-106	100
Sulfate	mg/l	12	6.5	1.6-10.4	49.5	12	4.7	0.1-7.8	54.7
BOD	mg/l	12	3.8	0.7-9.6	79.8	12	7.1	1.1-15.2	73.8
Color	Pt-Co Units	12	30	<1-124	112	12	33.3	0.5-148.0	117
T.D.S.	mg/l	12	133	56-335	60.7	12	153	78-336	49.9
V.D.S.	mg/l	12	40	5-113	73.5	12	42	10-123	81.9

1. Number of samples
2. Coefficient of variation

TABLE A-10

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE DETENTION POND WELL AT THE RESIDENTIAL DUAL POND SYSTEM (SITE 3) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	11	6.25	5.54-7.77	9.8	12	6.14	5.14-7.34	11.0	12	6.23	5.27-7.35	10.1
Spec. Cond.	μmhos/cm	11	238	116-366	32.1	12	239	114-371	32.4	12	260	110-393	29.4
Temperature	°C	11	24.52	14.45-36.68	25.4	12	24.49	15.17-36.68	24.4	12	24.92	15.57-35.94	22.3
Dissolved O_2	mg/l	11	2.1	0.3-8.6	123	12	1.7	0.2-7.8	153	12	1.9	0.2-8.9	158
ORP	mv	11	79	(-39)-266	114	12	111	(-43)-326	94.0	12	108	(-29)-336	110
Alkalinity	mg/l	11	35.1	10.0-78.1	53.8	12	35.3	10.0-84.4	61.4	12	40.0	12.6-74.2	48.7
NH_3-N	μg/l	11	132	<10-275	66.2	12	110	<10-213	63.4	12	100	<10-296	91.1
NO_2 + NO_3-N	μg/l	11	475	<10-3400	201	12	505	<10-3480	194	12	553	<10-3470	188
Diss. Organic N	μg/l	11	454	<10-1884	140	12	363	24-2260	168	12	426	34-2200	140
Diss. Ortho-P	μg/l	11	18	3-41	71.07	12	11	1-43	102	12	15	<1-31	58.4
Diss. Org. P	μg/l	11	7	0-15	8.0	12	6	0-22	103	12	7	0-22	101
Total P	μg/l	11	25	5-54	54.9	12	18	5-65	89.7	12	21	8-53	56.1
Chloride	mg/l	11	29	11-49	34.8	12	29	16-47	31.7	12	32	18-53	33.0
Sulfate	mg/l	11	44.5	15.2-76.2	50.7	12	51.3	13.6-121.0	56.7	12	53.0	12.4-92.6	49.1
BOD	mg/l	11	2.2	0.3-7.2	84.0	12	2.2	0.1-7.3	96.0	12	2.4	0.1-8.6	101
Color	Pt-Co Units	11	34	<1-124	124	12	38	<1-124	119	12	35	<1-136	128
T.D.S.	mg/l	11	147	77-209	29.2	12	158	72-241	32.7	12	170	67-248	29.7
V.D.S.	mg/l	11	50	18-126	63.7	12	57	22-110	52.9	12	60	23-118	54.1

1. Number of samples
2. Coefficient of variation

TABLE A-10 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	12	5.51	5.02-6.72	8.7	12	5.70	4.76-8.34	16.8
Spec. Cond.	µmhos/cm	12	402	227-757	45.3	12	414	112-536	31.0
Temperature	°C	12	24.00	17.49-30.29	15.8	12	24.9	17.78-30.21	13.6
Dissolved O_2	mg/l	12	0.7	0.2-1.8	68.2	12	1.4	0.2-10.0	190
ORP	mv	12	173	38-332	46.1	12	185	83-339	42.4
Alkalinity	mg/l	12	18.6	9.2-54.9	70.6	12	44.5	10.0-228.0	133
NH_3-N	µg/l	12	54	<10-170	119	12	147	29-320	60.8
$NO_2 + NO_3$-N	µg/l	12	1691	189-4800	86.8	12	3990	236-17,235	120
Diss. Organic N	µg/l	12	785	<10-2380	102	12	1078	<10-2950	99.6
Diss. Ortho-P	µg/l	12	6	<1-11	56.2	12	10	1-18	56.0
Diss. Org. P	µg/l	12	4	0-14	113	12	7	0-96	1.0
Total P	µg/l	12	10	4-21	48.5	12	17	4-40	57.2
Chloride	mg/l	12	74	33-145	48.9	12	64	19-122	45.1
Sulfate	mg/l	12	83.1	53.1-162.0	36.4	12	82.4	53.3-116.0	22.5
BOD	mg/l	12	1.7	0.1-7.4	126	12	1.7	0.1-6.8	115
Color	Pt-Co Units	12	20	<1-120	203	12	23	<1-120	171
T.D.S.	mg/l	12	250	145-428	37.3	12	272	68-384	35.7
V.D.S.	mg/l	12	76	41-143	40.6	12	104	24-219	54.5

1. Number of samples
2. Coefficient of variation

TABLE A-11

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE CONTROL WELL AT THE RESIDENTIAL DUAL POND SYSTEM (SITE 3) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	9	4.09	3.59-4.53	7.0	11	4.49	3.71-6.05	14.9	12	5.36	4.59-6.96	12.0
Spec. Cond.	µmhos/cm	9	283	219-404	19.1	11	297	215-396	20.5	12	315	215-413	21.5
Temperature	°C	9	24.91	19.79-28.00	11.2	11	24.60	20.45-27.58	10.3	12	24.44	20.50-27.52	9.4
Dissolved O_2	mg/l	9	2.2	0.8-4.3	54.3	11	0.8	0.3-1.8	50.8	12	0.5	0.2-1.2	60.0
ORP	mv	9	81	(-71)-378	184	11	90	(-97)-373	179	12	73	(-66)-335	174
Alkalinity	mg/l	9	0.1	0.0-0.5	300	11	2.0	0.0-10.5	182	12	11.4	6.3-25.1	42.3
NH_3-N	µg/l	9	15	<10-40	105	11	18	<10-46	68.9	12	120	<10-298	86.9
NO_2 + NO_3-N	µg/l	9	37	<10-116	106	11	75	<10-455	173	12	833	<10-4350	181
Diss. Organic N	µg/l	9	266	106-569	52.6	11	155	75-272	48.4	12	240	25-719	77.9
Diss. Ortho-P	µg/l	9	105	7-811	251	11	64	2-563	257	12	22	3-133	169
Diss. Org. P	µg/l	9	27	0-186	224	11	18	0-129	203	12	6.75	0-25	111
Total P	µg/l	9	132	12-997	246	11	83	12-692	244	12	28	5-158	150
Chloride	mg/l	9	33	18-57	51.8	11	33	16-51	46.9	12	30	17-44	32.2
Sulfate	mg/l	9	82.4	19.0-147.0	42.4	11	88.8	19.7-147.0	43.4	12	96.7	20.1-146.0	42.4
BOD	mg/l	9	1.7	0.0-6.9	142	11	1.7	0.0-5.1	93.9	12	1.7	0.2-6.3	106
Color	Pt-Co Units	9	25	<1-115	139	11	34	<1-120	110	12	21	<1-120	158
T.D.S.	mg/l	9	191	137-279	24.3	11	201	152-278	20.5	12	217	143-315	25.8
V.D.S.	mg/l	9	68	26-171	61.2	11	55	15-92	44.7	12	65	23-138	47.3

1. Number of samples
2. Coefficient of variation

TABLE A-11 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	12	5.28	4.74-6.15	9.7	12	5.34	4.66-7.21	13.6
Spec. Cond.	µmhos/cm	12	245	207-270	9.3	12	216	167-270	14.3
Temperature	°C	12	24.47	21.62-26.93	6.5	12	24.22	19.82-25.91	6.7
Dissolved O_2	mg/l	12	1.3	1.1-1.6	12.9	12	0.7	0.2-1.5	56.3
ORP	mv	12	174	31-388	72.6	12	163	39-339	65.6
Alkalinity	mg/l	12	11.6	5.2-32.8	70.6	12	7.5	4.2-14.9	35.8
NH_3-N	µg/l	12	18	<10-58	97.1	12	25	<10-101	118
NO_2 + NO_3-N	µg/l	12	2282	88-8500	137	12	2951	550-8330	88.5
Diss. Organic N	µg/l	12	405	<10-1462	98.5	12	224	5-598	81.3
Diss. Ortho-P	µg/l	12	118	4-1244	301	12	10	1-31	89.9
Diss. Org. P	µg/l	12	42	0-446	300	12	7	0-31	137
Total P	µg/l	12	160	5-1690	301	12	17	4-62	92.2
Chloride	mg/l	12	24	12-43	45.5	12	23	8-45	48.6
Sulfate	mg/l	12	62.0	28.5-101.0	36.0	12	67.6	20.9-224.0	77.7
BOD	mg/l	12	1.6	0.1-6.8	120	12	1.5	0.0-6.1	113
Color	Pt-Co Units	12	16	<1-115	204	12	20	<1-120	162
T.D.S.	mg/l	12	170	122-252	21.5	12	146	93-227	23.9
V.D.S.	mg/l	12	46	8-89	54.4	12	43	2-75	43.9

1. Number of samples
2. Coefficient of variation

TABLE A-12

SUMMARY OF DISSOLVED HEAVY METALS IN RETENTION POND WELL SAMPLES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	5.25	<0.5-13	75.2	12	5.00	<0.5-9.5	61.5	12	6.12	<0.1-15	63.5
Zn	12	18.5	9.0-37	38.8	12	13.5	<1.0-30	57.5	12	19.3	2.0-68	90.1
Mn	12	52.1	<1.0-226	114	12	95.6	5.0-225	76.2	12	90.0	10-237	96.0
Cu	12	14.4	1.0-31	67.5	12	10.9	<1.0-23	75.8	12	13.7	2.0-38	76.4
Al	12	262	90-889	82.8	12	158	101-299	35.4	12	223	74-575	68.9
Fe	12	403	21-2080	140	12	755	12-1900	80.0	12	752	16-2380	111
Pb	12	153	61-216	34.8	12	154	81-201	25.3	12	152	67-224	32.9
Ni	12	24.5	6.5-36	38.3	12	23	5.0-36	38.3	12	25.2	2.3-39	44.1
Cr	12	17.4	9.3-23	27.1	12	17	9.3-23	25.8	12	16.8	7.2-22	30.4

1. Number of samples
2. Coefficient of variation

TABLE A-12 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	5.14	0.9-11	62.1	12	6.14	2.6-15	63.2
Zn	12	14.5	6.0-37	57.5	12	12.3	<1.0-24	67.5
Mn	12	22.4	7.0-57	74.0	12	41.8	4.0-105	72.5
Cu	12	13.6	1.0-28	55.3	12	12.8	3.0-44	85.2
Al	12	391	124-902	62.4	12	187	129-267	23.8
Fe	12	56.1	11-174	89.9	12	160	11-434	92.1
Pb	12	156	76-246	30.2	12	182	93-281	28.7
Ni	12	24.0	8.5-33	33.4	12	26.1	9.5-36	37.0
Cr	12	17.1	9.5-26	27.1	12	19.4	11-29	27.3

1. Number of samples
2. Coefficient of variation

TABLE A-13

SUMMARY OF DISSOLVED HEAVY METALS IN DETENTION POND WELL SAMPLES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	5.77	2.3-11	51.6	12	5.81	1.6-11	49.6	11	4.95	2.2-7.4	37.0
Zn	12	19.3	3.0-49	61.1	12	18.2	2.0-54	74.5	11	17.2	5.0-51	75.5
Mn	12	137	19-318	62.0	12	186	5.0-447	74.5	11	134	10-417	91.3
Cu	12	12.7	3.0-33	68.8	12	13.0	3.0-38	80.2	11	11.4	<1.0-30	78.2
Al	12	199	70-519	70.4	12	152	76-356	59.5	11	150	77-337	57.0
Fe	12	689	28-1860	104	12	486	14-1180	86.9	11	281	16-952	105
Pb	12	161	78-359	46.5	12	140	81-200	30.4	11	157	82-208	29.0
Ni	12	26.3	14-48	35.1	12	23.4	8.9-37	43.2	11	26.6	14-34	28.9
Cr	12	17.2	5.7-40	50.7	12	15.9	8.6-23	28.6	11	17.7	9.9-22	21.1

1. Number of samples
2. Coefficient of variation

TABLE A-13 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	6.17	3.2-11	39.0	12	6.32	<1.0-16	66.1
Zn	12	19.4	7.0-48	53.3	12	20.1	4.0-46	66.5
Mn	12	57.4	33-81	22.2	12	58.2	10-106	60.4
Cu	12	14.1	5.0-31	55.5	12	15.1	3.0-29	53.0
Al	12	142	84-313	50.4	12	167	91-307	35.8
Fe	12	104	19-698	181	12	117	14-639	148
Pb	12	166	81-218	24.9	12	172	76-263	29.8
Ni	12	26.7	15-34	26.5	12	27.4	15-42	27.2
Cr	12	18.6	12-24	19.9	12	18.9	9.6-27	23.5

1. Number of samples
2. Coefficient of variation

TABLE A-14

SUMMARY OF DISSOLVED HEAVY METALS IN CONTROL WELL SAMPLES COLLECTED AT THE RESIDENTIAL DUAL POND SITE (SITE 3)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	9	6.20	0.8-19	95.1	11	6.94	1.5-14	57.7	12	6.32	2.0-12	46.3
Zn	9	33.7	7.0-99	87.0	11	27.8	5.0-73	71.7	12	18.7	1.0-64	83.8
Mn	9	239	10-1240	168	11	443	27-1960	145	12	141	27-394	85.3
Cu	9	21.3	11-38	40.5	11	16.1	8.0-25	36.2	12	11.2	5.0-20	42.2
Al	9	5412	164-21,000	113	11	2786	656-11,200	105	12	388	108-2020	138
Fe	9	337	41-1360	133	11	444	38-1010	85.3	12	209	34-874	111
Pb	9	141	125-165	9.7	11	150	117-184	15.8	12	166	102-192	17.0
Ni	9	27.7	20-42	24.0	11	28.7	20-36	19.5	12	28.3	20-36	18.6
Cr	9	19.2	13-36	44.3	11	18.2	13-26	22.9	12	18.4	15-21	10.7

1. Number of samples
2. Coefficient of variation

TABLE A-14 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	6.28	3.0-11	42.7	12	5.30	<0.5-9.3	64.0
Zn	12	33.8	11-127	97.5	12	16.6	7.0-35	49.0
Mn	12	40.2	32-76	29.8	12	55.8	23-100	31.3
Cu	12	19.4	6.0-61	74.5	12	15.8	4.0-35	53.0
Al	12	1114	96-11,000	279.8	12	354	90-2160	164
Fe	12	158	18-913	166	12	79.4	20-358	118
Pb	12	145	106-184	17.9	12	127	41-156	24.5
Ni	12	25.9	16-33	24.8	12	21.3	6.9-29	30.1
Cr	12	16.8	11-28	26.7	12	14.4	8.4-17	18.0

1. Number of samples
2. Coefficient of variation

TABLE A-15

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE DETENTION POND WELL AT THE RESIDENTIAL DETENTION FACILITY (SITE 4) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	11	6.35	5.73-7.21	8.4	12	5.82	5.18-6.92	8.1	12	5.62	5.03-6.88	8.5
Spec. Cond.	μmhos/cm	11	104	86-124	11.0	12	81	69-97	11.0	12	70	53-88	14.0
Temperature	°C	11	24.25	13.95-32.03	23.5	12	24.40	14.52-30.93	21.1	12	24.43	15.25-30.55	19.6
Dissolved O_2	mg/l	11	1.0	0.3-3.5	87.6	12	0.5	0.1-1.4	77.8	12	0.5	0.2-1.5	74.1
ORP	mv	11	-3	(-97)-116	467	12	-47	(-162)-64	125	12	-35.8	(-121)-52	125
Alkalinity	mg/l	11	46.7	33.5-76.2	24.5	12	32.1	23.3-48.4	22.1	12	23.7	9.0-42.1	35.5
NH_3-N	μg/l	11	391	27-857	86.0	12	662	216-1425	51.0	12	440	27-847	53.0
NO_2 + NO_3-N	μg/l	11	8	<10-24	84.0	12	9	<10-29	88.0	12	13	<10-38	85.0
Diss. Organic N	μg/l	11	475	135-964	51.0	12	412	<10-941	73.0	12	383	44-968	65.0
Diss. Ortho-P	μg/l	11	50	21-89	44.0	12	76	30-176	52.0	12	89	41-207	48.0
Diss. Org. P	μg/l	11	83	0-435	148	12	67	0-378	156	12	107	8-507	189.0
Total P	μg/l	11	133	45-493	97.0	12	134	49-459	85.0	12	186	77-619	83.0
Chloride	mg/l	11	11	3-22	60.0	12	12	4-19	47.0	12	13	6-21	46.0
Sulfate	mg/l	11	3.6	0.1-14.6	127	12	2.3	<1-10.1	136	12	2.7	0.1-10.0	129
BOD	mg/l	11	3.3	1.0-6.1	44.0	12	3.8	0.8-6.6	41.7	12	4.1	0.8-6.5	40.5
Color	Pt-Co Units	11	59	13-200	83.0	12	66	22-168	62.0	12	64	21-122	60.0
T.D.S.	mg/l	11	80	52-115	23.0	12	63	10-98	39.0	12	57	10-85	35.0
V.D.S.	mg/l	11	35	2-82	62.0	12	29	2-68	61.0	12	28	5-56	59.0

1. Number of samples
2. Coefficient of variation

TABLE A-15 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	4.82	4.25-6.04	10.1	12	4.62	4.12-5.37	9.6
Spec. Cond.	µmhos/cm	12	32	25-48	18.0	12	26	23-30	8.0
Temperature	°C	12	24.56	16.29-29.66	16.5	12	24.74	16.64-29.22	14.7
Dissolved O_2	mg/l	12	0.5	0.1-1.4	82.9	12	0.5	0.2-1.5	77.8
ORP	mv	12	-62	(-206)-54	111	12	-77	(-224)-38	81.0
Alkalinity	mg/l	12	4.8	0.0-11.0	81.3	12	3.8	0.0-22.4	174
NH_3-N	µg/l	12	53	<10-165	94.0	12	48	<10-86	55.0
$NO_2 + NO_3$-N	µg/l	12	30	<10-241	226	12	16	<10-97	168
Diss. Organic N	µg/l	12	100	<10-235	78.0	12	158	36-293	58.0
Diss. Ortho-P	µg/l	12	37	13-67	47.0	12	49	36-94	32.0
Diss. Org. P	µg/l	12	81	6-349	139	12	54	7-233	120
Total P	µg/l	12	119	23-412	109	12	104	50-293	69.0
Chloride	mg/l	12	14	7-21	40.0	12	12	6-26	56.0
Sulfate	mg/l	12	2.8	0.1-10.9	127	12	2.5	0.1-9.3	132
BOD	mg/l	12	3.1	0.5-5.9	51.9	12	3.0	0.5-6.0	54.1
Color	Pt-Co Units	12	41	1-132	109	12	28	5-124	113
T.D.S.	mg/l	12	30	6-48	41.0	12	38	24-51	23.0
V.D.S.	mg/l	12	12	<1-31	75.0	12	19	2-42	70.0

1. Number of samples
2. Coefficient of variation

TABLE A-16

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE CONTROL WELL AT THE RESIDENTIAL DETENTION FACILITY (SITE 4) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	7	4.33	3.86-4.60	6.1	11	4.34	3.65-4.77	8.2	12	4.31	3.75-4.93	9.7
Spec. Cond.	µmhos/cm	7	72	60-88	13.8	11	53	49-56	5.5	12	49	46-54	5.3
Temperature	°C	7	24.41	19.80-27.51	11.7	11	23.88	20.43-26.58	8.6	12	24.03	20.80-26.40	8.1
Dissolved O_2	mg/l	7	2.7	1.1-4.5	39.4	11	0.7	0.3-1.9	69.0	12	0.5	0.2-1.2	60.8
ORP	mv	7	270	211-444	29.3	11	269	199-444	25.8	12	222	(-14)-372	52.6
Alkalinity	mg/l	7	0.4	0.0-2.1	173	11	0.8	0.0-3.6	170	12	1.4	0.0-11.4	226
NH_3-N	µg/l	7	23	<10-70	105	11	15	<10-37	85.5	12	33	<10-120	111
NO_2 + NO_3-N	µg/l	7	1268	321-1590	36.0	11	203	31-508	79.7	12	113	<10-480	121
Diss. Organic N	µg/l	7	214	<10-561	101	11	118	<10-338	98.2	12	131	<10-246	56.9
Diss. Ortho-P	µg/l	7	9	2-17	63.9	11	5	<1-14	78.8	12	6	<1-40	173
Diss. Org. P	µg/l	7	5	0-11	72.0	11	13	0-80	182	12	9	0-35	127
Total P	µg/l	7	15	4-21	48.0	11	17	3-94	151	12	15	2-66	126
Chloride	mg/l	7	8	2-17	61.8	11	11	5-21	49.3	12	12	5-21	43.9
Sulfate	mg/l	7	12.0	3.4-19.0	39.7	11	9.8	2.6-15.6	38.4	12	7.1	0.2-14.0	58.4
BOD	mg/l	7	1.3	0.3-5.4	137	11	1.3	0.1-5.6	120	12	1.5	0.4-5.5	89.9
Color	Pt-Co Units	7	28	2-128	159	11	30	5-128	121	12	28	0.5-160.0	158
T.D.S.	mg/l	7	57	42-75	22.1	11	41	22-67	33.4	12	38	6-75	44.2
V.D.S.	mg/l	7	26	3-60	84.9	11	17	1-55	97.2	12	17	<1-36	75.8

1. Number of samples
2. Coefficient of variation

TABLE A-16 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	4.26	3.82-4.85	7.5	12	4.36	3.88-4.80	7.1
Spec. Cond.	μmhos/cm	12	53	47-58	5.7	12	55	49-60	6.0
Temperature	°C	12	24.08	21.15-25.74	5.8	12	24.14	21.62-25.19	4.1
Dissolved O_2	mg/l	12	0.5	0.2-1.2	60.3	12	0.5	0.2-1.0	63.4
ORP	mv	12	41	(-76)-183	191	12	43	(-86)-192	168
Alkalinity	mg/l	12	0.6	0.0-4.5	235	12	1.1	0.0-5.9	184
NH_3-N	μg/l	12	69	17-202	79.2	12	39	10-106	73.5
$NO_2 + NO_3$-N	μg/l	12	63	<10-427	187	12	85	<10-623	204
Diss. Organic N	μg/l	12	119	<10-256	60.9	12	138	<10-295	65.9
Diss. Ortho-P	μg/l	12	6	<1-19	85.2	12	10	1-34	89.0
Diss. Org. P	μg/l	12	10	0-54	146	12	34	0-303	241
Total P	μg/l	12	16	4-59	99.5	12	45	6-337	206
Chloride	mg/l	12	14	3-25	55.1	12	16	5-46	72.3
Sulfate	mg/l	12	6.6	0.1-14.4	65.4	12	7.9	0.4-24.0	81.6
BOD	mg/l	12	1.8	0.3-6.4	87.8	12	1.9	0.3-6.5	86.6
Color	Pt-Co Units	12	40	13-152	95.6	12	61	5-240	111
T.D.S.	mg/l	12	40	8-74	39.6	12	45	17-68	31.7
V.D.S.	mg/l	12	20	3-45	68.8	12	21	7-36	48.1

1. Number of samples
2. Coefficient of variation

TABLE A-17

SUMMARY OF DISSOLVED HEAVY METALS IN DETENTION POND WELL SAMPLES COLLECTED AT THE RESIDENTIAL DETENTION SITE (SITE 4)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	11	5.45	2.3-14	61.9	12	4.17	2.1-8.1	47.4	12	3.89	1.0-7.5	52.5
Zn	11	16.9	4.0-32	52.8	12	16.3	1.0-45	79.1	12	14.2	4.0-38	63.2
Mn	11	16.8	8.0-24	33.3	12	15.3	7.0-30	39.5	12	16.5	8.0-24	30.1
Cu	11	8.77	<1.0-15	60.5	12	9.79	<1.0-26	91.4	12	9.33	3.0-27	74.6
Al	11	457	118-1400	76.5	12	384	143-635	40.6	12	532	127-1010	56.5
Fe	11	262	95-442	44.8	12	418	99-687	42.4	12	614	174-997	45.2
Pb	11	67.1	42-82	17.9	12	57.4	45-72	12.6	12	45.9	30-63	19.1
Ni	11	12.4	4.4-29	52.3	12	11.7	7.5-35	65.1	12	11.0	7.2-31	59.2
Cr	11	7.29	3.5-12	27.9	12	7.47	5.4-17	46.8	12	6.40	4.3-17	54.0

1. Number of samples
2. Coefficient of variation

TABLE A-17 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	3.24	1.2-6.1	44.0	12	3.20	<0.5-13	107
Zn	12	12.6	2.0-35	70.4	12	13.3	3.0-27	50.5
Mn	12	10.3	2.0-26	68.5	12	4.29	<1.0-11	60.5
Cu	12	9.79	<1.0-29	100.2	12	6.46	<1.0-15	73.3
Al	12	275	<1.0-735	97.6	12	262	11-1110	106.8
Fe	12	484	33-1600	93.6	12	170	16-374	52.0
Pb	12	28.0	<1.0-57	47.4	12	25.8	<1.0-44	53.8
Ni	12	9.06	2.4-23	57.5	12	8.47	<0.5-23	73.6
Cr	12	4.68	<0.5-18	95.2	12	4.25	<0.5-11	67.4

1. Number of samples
2. Coefficient of variation

TABLE A-18

SUMMARY OF DISSOLVED HEAVY METALS IN CONTROL WELL SAMPLES COLLECTED AT THE RESIDENTIAL DETENTION SITE (SITE 4)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	7	3.93	1.2-7.8	57.1	11	3.81	<0.5-9.2	64.3	12	2.68	<0.5-5.2	47.2
Zn	7	1045	227-1430	40.9	11	137	69-209	33.1	12	58.2	18-168	76.9
Mn	7	41.7	11-100	74.6	11	31.3	3.0-116	134.2	12	7.25	1.0-18	67.6
Cu	7	24.7	4.0-87	120	11	29.2	3.0-160	164.5	12	13.1	<1.0-51	124
Al	7	1717	1310-2410	21.7	11	822	192-1730	54.0	12	538	225-898	38.2
Fe	7	297	37.0-1570	190	11	575	34-1930	125	12	280	16-1120	123
Pb	7	64.1	31-180	82.6	11	42.3	25-127	68.7	12	33.9	6.0-83	56.3
Ni	7	19.3	8.0-29	34.0	11	15.1	7.2-33	59.5	12	9.02	1.7-21	56.1
Cr	7	9.49	4.3-36	123	11	6.35	3.3-26	104	12	5.17	0.8-17	88.2

1. Number of samples
2. Coefficient of variation

TABLE A-18 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	2.92	<1.0-5.5	52.6	12	3.20	0.6-5.4	46.9
Zn	12	68.8	22-303	120	12	60.8	11-179	74.5
Mn	12	14.4	5.0-49	93.0	12	15.6	1.0-48	91.8
Cu	12	9.54	<1.0-41	113	12	9.29	<1.0-24	75.5
Al	12	337	210-518	28.4	12	358	105-1120	71.7
Fe	12	1016	207-2740	68.7	12	1038	70-3060	79.4
Pb	12	33.7	26-64	31.3	12	35.1	1.0-101	68.7
Ni	12	9.98	6.4-16	30.7	12	11.1	1.1-28	64.1
Cr	12	4.74	3.3-13	57.5	12	5.43	<1.0-21	97.3

1. Number of samples
2. Coefficient of variation

TABLE A-19

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE RETENTION POND WELL AT THE COMMERCIAL DUAL POND SYSTEM (SITE 5) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	6.24	5.74-6.84	5.4	12	6.24	5.59-6.77	5.4	12	6.04	5.45-6.65	6.6
Spec. Cond.	µmhos/cm	12	488	328-562	13.0	12	434	313-546	16.0	12	410	327-598	18.0
Temperature	°C	12	22.80	13.46-28.54	20.9	12	23.28	14.28-29.88	20.8	12	22.79	15.18-27.80	18.3
Dissolved O_2	mg/l	12	3.4	0.4-6.5	57.5	12	3.8	0.3-7.5	50.2	12	1.0	0.2-2.5	74.9
ORP	mv	12	117	41-342	68.0	12	125	86-311	49.0	12	118	75-295	50.0
Alkalinity	mg/l	12	205.0	108.0-410.0	37.5	12	161.7	84.8-271.0	31.7	12	126.9	78.5-191.0	27.7
NH_3-N	µg/l	12	1216	150-2945	82.0	12	639	143-1315	64.0	12	231	153-499	39.0
NO_2 + NO_3-N	µg/l	12	11	<10-35	84.0	12	15	<10-52	109	12	39	<10-142	122
Diss. Organic N	µg/l	12	365	<10-851	73.0	12	383	33-766	51.0	12	341	101-762	54.0
Diss. Ortho-P	µg/l	12	33	10-61	44.0	12	25	4-36	42.0	12	37	<1-58	50.0
Diss. Org. P	µg/l	12	32	0-78	80.0	12	24	0-67	102	12	23	0-48	72.0
Total P	µg/l	12	65	23-110	45.0	12	48	11-99	63.0	12	60	15-99	40.0
Chloride	mg/l	12	29	5-96	92.0	12	31	6-102	78.0	12	48	8-104	67.0
Sulfate	mg/l	12	1.5	0.1-3.8	98.2	12	1.1	0.1-3.2	104	12	1.4	0.1-3.3	91.5
BOD	mg/l	12	8.7	1.8-17.6	66.1	12	6.0	1.0-16.6	76.6	12	3.9	0.9-16.5	108
Color	Pt-Co Units	12	293	4-585	75.0	12	272	1-719	89.0	12	160	2-402	108
T.D.S.	mg/l	12	318	204-411	20.0	12	282	167-392	23.0	12	257	174-412	23.0
V.D.S.	mg/l	12	86	33-144	42.0	12	76	22-141	46.0	12	54	22-144	59.0

1. Number of samples
2. Coefficient of variation

TABLE A-19 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	5.77	5.18-6.44	7.2	12	6.30	5.78-6.96	6.9
Spec. Cond.	μmhos/cm	12	286	30-358	32.0	12	218	152-329	21.0
Temperature	°C	12	22.92	16.77-26.89	14.1	12	23.17	17.89-26.70	12.4
Dissolved O_2	mg/l	12	0.6	0.2-1.2	62.2	12	0.6	0.2-1.3	56.4
ORP	mv	12	116	45-303	55.0	12	83	28-225	64.0
Alkalinity	mg/l	12	78.3	50.2-118.0	23.9	12	79.1	62.4-102.0	14.7
NH_3-N	μg/l	12	110	45-481	108	12	306	91-548	52.0
NO_2 + NO_3-N	μg/l	12	15	<10-33	67.0	12	36	<10-176	140
Diss. Organic N	μg/l	12	186	<10-324	46.0	12	322	73-594	47.0
Diss. Ortho-P	μg/l	12	138	21-189	38.0	12	141	49-320	56.0
Diss. Org. P	μg/l	12	11	0-24	84.0	12	23	0-61	92.0
Total P	μg/l	12	149	28-204	37.0	12	163	63-333	49.0
Chloride	mg/l	12	59	11-129	68.0	12	19	9-37	48.0
Sulfate	mg/l	12	1.5	0.1-4.6	101	12	1.9	0.1-5.1	83.4
BOD	mg/l	12	1.9	0.5-4.7	66.2	12	3.7	1.7-9.1	54.8
Color	Pt-Co Units	12	64	0-187	90.0	12	48	11-83	52.0
T.D.S.	mg/l	12	190	135-269	21.0	12	144	106-174	16.0
V.D.S.	mg/l	12	33	2-63	54.0	12	48	18-92	45.0

1. Number of samples
2. Coefficient of variation

TABLE A-20

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE DETENTION POND WELL AT THE COMMERCIAL DUAL POND SYSTEM (SITE 5) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	6.67	6.19-7.23	5.0	12	6.80	6.10-7.55	6.6	12	6.56	5.90-7.12	5.2
Spec. Cond.	µmhos/cm	12	450	387-499	8.0	12	338	194-480	25.0	12	346	202-495	27.0
Temperature	°C	12	26	17-33	23.0	12	26.61	17.18-33.20	21.4	12	25.33	17.16-31.45	19.6
Dissolved O_2	mg/l	12	5.5	1.5-9.5	46.4	12	4.9	0.8-8.9	55.8	12	3.5	0.7-8.9	74.9
ORP	mv	12	141	83-318	58.0	12	144	76-309	50.0	12	127	76-352	59.0
Alkalinity	mg/l	12	224.7	194.0-353.0	18.5	12	157.9	73.3-214.0	27.3	12	150.0	63.9-216.0	34.7
NH_3-N	µg/l	12	468	<10-1478	111	12	344	21-825	93.0	12	325	13-783	97.0
NO_2 + NO_3-N	µg/l	12	12	<10-44	100	12	71	<10-185	98.0	12	86	<10-260	116
Diss. Organic N	µg/l	12	515	314-785	32.0	12	446	127-727	40.0	12	419	102-896	56.0
Diss. Ortho-P	µg/l	12	11	<1-24	74.0	12	10	<1-31	89.0	12	8	<1-20	68.0
Diss. Org. P	µg/l	12	11	0-27	81.0	12	9	0-29	92.0	12	9	0-22	84.0
Total P	µg/l	12	21	10-45	58.0	12	19	6-47	64.0	12	17	6-33	51.0
Chloride	mg/l	12	39	2-120	99.0	12	37	2-140	116	12	51	3-170	105
Sulfate	mg/l	12	0.9	0.1-7.0	215	12	2.2	0.1-7.1	97.7	12	2.4	0.1-6.9	88.4
BOD	mg/l	12	3.9	1.4-8.0	51.8	12	3.6	1.6-6.0	46.1	12	3.2	1.4-5.6	45.2
Color	Pt-Co Units	12	136	11-208	39.0	12	108	25-195	41.0	12	102	10-212	55.0
T.D.S.	mg/l	12	301	224-356	14.0	12	238	147-332	25.0	12	235	115-348	31.0
V.D.S.	mg/l	12	79	16-153	58.0	12	65	29-135	50.0	12	72	6-143	59.0

1. Number of samples
2. Coefficient of variation

TABLE A-20 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	12	6.39	5.90-6.90	4.8	12	6.45	6.01-6.93	4.7
Spec. Cond.	µmhos/cm	12	453	367-529	8.0	12	399	320-485	12.0
Temperature	°C	12	24.95	18.34-30.83	16.6	12	25.18	18.98-30.56	14.2
Dissolved O_2	mg/l	12	0.7	0.2-2.5	87.9	12	0.7	0.2-2.0	78.4
ORP	mv	12	79	14-119	37.0	12	76	14-123	40.0
Alkalinity	mg/l	12	184.8	164.0-204.0	7.1	12	175.8	149.0-207.0	9.3
NH_3-N	µg/l	12	367	33-831	77.0	12	405	35-866	70.0
NO_2 + NO_3-N	µg/l	12	5	2-5	18.0	12	6	<10-22	76.0
Diss. Organic N	µg/l	12	545	216-1070	45.0	12	593	203-1370	51.0
Diss. Ortho-P	µg/l	12	40	12-71	50.0	12	96	33-157	41.0
Diss. Org. P	µg/l	12	9	0-28	117	12	10	0-28	96.0
Total P	µg/l	12	48	14-84	50.0	12	105	36-168	40.0
Chloride	mg/l	12	77	4-230	105	12	61	4-190	109
Sulfate	mg/l	12	2.7	0.1-5.0	77.5	12	2.4	0.1-4.1	68.3
BOD	mg/l	12	3.4	0.9-5.5	39.4	12	3.5	0.8-5.6	42.8
Color	Pt-Co Units	12	134	8-228	55.0	12	116	11-200	45.0
T.D.S.	mg/l	12	307	208-364	17.0	12	286	195-382	19.0
V.D.S.	mg/l	12	98	42-183	40.0	12	84	15-142	45.0

1. Number of samples
2. Coefficient of variation

TABLE A-21

SUMMARY OF MEAN WATER QUALITY CHARACTERISTICS IN GROUNDWATER SAMPLES COLLECTED FROM THE CONTROL POND WELL AT THE COMMERCIAL DUAL POND SYSTEM (SITE 5) DURING 1987

PARAMETER	UNITS	0.1 m DEPTH				0.5 m DEPTH				1.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	–	12	5.33	4.94-5.94	5.6	12	5.33	5.01-6.03	5.6	12	5.37	5.0-5.91	5.9
Spec. Cond.	µmhos/cm	12	269	216-332	11.0	12	264	217-330	10.0	12	261	213-328	11.0
Temperature	°C	12	23.17	18.44-28.95	13.9	12	23.80	18.91-28.50	14.2	12	23.92	19.68-28.73	12.7
Dissolved O_2	mg/l	12	1.0	0.2-2.7	80.6	12	2.2	0.2-5.0	70.7	12	0.9	0.2-2.2	61.4
ORP	mv	12	67	(-67)-127	93.0	12	65	(-56)-146	84.0	12	57	(-53)-136	102
Alkalinity	mg/l	12	63.5	40.6-82.1	21.4	12	71.2	40.4-149.0	41.1	12	65.4	40.4-106.0	23.9
NH_3-N	µg/l	12	3773	732-6380	56.0	12	3527	728-5680	54.0	12	2871	215-5390	69.0
NO_2 + NO_3-N	µg/l	12	8	<10-35	115	12	29	<10-229	224	12	8	<10-46	141
Diss. Organic N	µg/l	12	3020	1600-5890	46.0	12	3517	1480-5356	37.0	12	3407	890-6480	52.0
Diss. Ortho-P	µg/l	12	24	3-195	224	12	18	4-116	173	12	18	5-100	143
Diss. Org. P	µg/l	12	35	0-79	88.0	12	30	0-67	84.0	12	31	0-61	78.0
Total P	µg/l	12	59	13-195	86.0	12	48	14-116	64.0	12	50	14-100	52.0
Chloride	mg/l	12	22	5-49	47.0	12	25	14-45	30.0	12	26	18-49	31.0
Sulfate	mg/l	12	9.7	0.1-23.1	96.1	12	10.4	0.1-22.3	89.1	12	9.4	0.1-20.9	91.6
BOD	mg/l	12	5.2	1.0-12.2	56.4	12	5.0	1.5-10.6	47.6	12	5.0	1.2-7.8	42.7
Color	Pt-Co Units	12	498	100-646	31.0	12	504	100-625	28.0	12	480	96-556	27.0
T.D.S.	mg/l	12	298	178-367	16.0	12	293	161-346	16.0	12	287	161-324	15.0
V.D.S.	mg/l	12	170	113-249	23.0	12	216	127-173	73.9	12	162	83-209	20.0

1. Number of samples
2. Coefficient of variation

TABLE A-21 -- CONTINUED

PARAMETER	UNITS	2.5 m DEPTH				5.0 m DEPTH			
		N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
pH	--	12	5.32	4.93-6.00	6.1	12	5.42	5.08-6.05	5.3
Spec. Cond.	μmhos/cm	12	269	230-310	9.0	12	276	245-301	6.0
Temperature	°C	12	24.09	20.74-27.39	9.6	12	24.16	21.49-26.83	6.7
Dissolved O_2	mg/l	12	0.5	0.1-1.0	57.5	12	0.6	0.1-1.1	60.8
ORP	mv	12	35	(-58)-108	154	12	13	(-73)-97	419
Alkalinity	mg/l	12	71.9	54.8-102.0	18.3	12	76.2	62.8-90.0	9.5
NH_3-N	μg/l	12	2134	713-3640	47.0	12	2005	399-4330	64.0
NO_2 + NO_3-N	μg/l	12	7	<10-26	85.0	12	14	<10-89	168
Diss. Organic N	μg/l	12	2572	730-4330	41.0	12	2197	1122-4010	36.0
Diss. Ortho-P	μg/l	12	129	63-212	35.0	12	120	63-184	29.0
Diss. Org. P	μg/l	12	25	0-25	62.0	12	28	0-81	96.0
Total P	μg/l	12	154	65-216	34.0	12	148	63-199	29.0
Chloride	mg/l	12	28	16-50	34.0	12	25	11-46	35.0
Sulfate	mg/l	12	7.9	0.1-18.6	93.6	12	8.2	0.1-18.6	77.2
BOD	mg/l	12	5.3	1.4-10.0	48.6	12	10.0	1.3-19.2	57.1
Color	Pt-Co Units	12	422	90-536	29.0	12	399	88-475	26.0
T.D.S.	mg/l	12	298	156-356	17.0	12	300	184-374	16.0
V.D.S.	mg/l	12	166	137-191	11.0	12	166	108-314	31.0

1. Number of samples
2. Coefficient of variation

TABLE A-22

SUMMARY OF DISSOLVED HEAVY METALS IN RETENTION POND WELL SAMPLES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	5.50	1.5-13	63.3	12	4.12	2.2-6.1	36.4	12	3.92	1.7-14	89.2
Zn	12	54.8	6.0-119	67.5	12	32.5	8.0-115	110	12	31.8	8.0-114	102
Mn	12	99.6	42-143	32.0	12	67.4	20-120	45.3	12	42.3	11-116	66.6
Cu	12	17.0	3.0-39	62.9	12	13.8	3.0-36	70.5	12	16.6	2.0-49	92.2
Al	12	517	139-1210	66.0	12	222	56-756	104	12	196	51-759	111
Fe	12	12,186	3032-22,776	56.2	12	11,608	2920-22,305	64.9	12	9465	2632-18,144	50.6
Pb	12	173	68-268	36.7	12	141	47-224	43.2	12	114	47-185	41.8
Ni	12	43.3	23-61	32.4	12	31.8	8.6-49	40.6	12	26.6	14-44	35.3
Cr	12	19.6	7.6-38	52.7	12	16.1	5.2-38	67.9	12	13.2	5.1-37	71.2

1. Number of samples
2. Coefficient of variation

TABLE A-22 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	3.27	<0.5-9.4	89.8	12	1.97	<0.5-4.1	69.1
Zn	12	24.8	1.0-70	92.5	12	20.8	1.0-53	77.4
Mn	12	13.4	5.0-21	39.4	12	20.8	6.0-32	42.2
Cu	12	11.9	2.0-28	81.5	12	11.2	2.0-39	96.5
Al	12	136	58-465	110	12	118	52-358	90.8
Fe	12	3243	1508-8784	57.7	12	1230	444-2130	46.1
Pb	12	79.8	31-113	32.3	12	98.5	42-149	39.4
Ni	12	20.2	8.7-33	36.9	12	26.6	8.2-38	38.1
Cr	12	9.72	3.4-23	63.9	12	10.4	3.2-17	41.7

1. Number of samples
2. Coefficient of variation

TABLE A-23

SUMMARY OF DISSOLVED HEAVY METALS IN DETENTION POND WELL SAMPLES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	5.84	2.6-13	58.6	12	5.74	2.5-12	47.0	12	6.99	2.8-18	60.5
Zn	12	30.9	5.0-125	142.4	12	35.3	6.0-126	122	12	31.3	3.0-124	135
Mn	12	88.9	29-134	37.9	12	66.8	44-114	34.0	12	59.9	12-122	59.5
Cu	12	13.6	1.0-36	88.9	12	19.2	3.0-53	89.9	12	12.4	2.0-35	80.4
Al	12	379	146-830	53.3	12	579	141-1165	50.1	12	319	90-825	91.2
Fe	12	3947	957-6468	43.8	12	3158	653-6898	50.7	12	3389	694-7280	50.3
Pb	12	230	142-407	34.6	12	198	76-2734	30.3	12	190	69-307	35.3
Ni	12	58.7	36-115	38.6	12	47.5	16-77	33.7	12	44.3	15-92	46.1
Cr	12	22.5	3.8-40	52.0	12	20.3	7.7-40	52.2	12	17.9	6.7-40	61.2

1. Number of samples
2. Coefficient of variation

TABLE A-23 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	7.65	2.2-19	61.3	12	5.93	1.0-12	63.1
Zn	12	32.7	4.0-110	111	12	31.3	4.0-115	119
Mn	12	78.5	39-120	35.0	12	66.3	17-118	45.3
Cu	12	13.9	3.0-33	63.6	12	13.3	3.0-29	62.4
Al	12	211	85-730	108	12	201	82-769	123
Fe	12	6511	2903-9780	36.1	12	5021	2210-9293	41.5
Pb	12	185	99-288	32.3	12	167	96-251	30.1
Ni	12	44.7	24-88	45.1	12	42.6	18-76	42.4
Cr	12	17.6	7.7-35	48.9	12	17.1	6.0-37	57.5

1. Number of samples
2. Coefficient of variation

TABLE A-24

SUMMARY OF DISSOLVED HEAVY METALS IN CONTROL WELL SAMPLES COLLECTED AT THE COMMERCIAL DUAL POND SITE (SITE 5)

HEAVY METALS	0.1 m SAMPLE PORT				0.5 m SAMPLE PORT				1.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	2.97	<0.5-9.1	90.8	12	3.60	<0.5-8.4	69.9	12	3.74	<0.5-11	79.8
Zn	12	33.5	3.0-99	103	12	35.8	5.0-109	94.6	12	34.3	6.0-106	101
Mn	12	16.7	7.0-27	35.0	12	17.4	9.0-31	39.9	12	17.5	7.0-31	45.1
Cu	12	11.8	2.0-29	70.5	12	13.3	1.0-54	110	12	11.4	<1.0-34	90.7
Al	12	1911	1145-3301	32.1	12	1840	771-3151	32.4	12	1605	909-2510	27.8
Fe	12	19,921	2820-31,305	45.3	12	19,487	2845-36,180	46.2	12	17,290	2851-35,160	50.6
Pb	12	96.1	52-161	41.6	12	106	55-177	41.0	12	164	76-361	45.4
Ni	12	24.0	13-35	33.8	12	24.1	11-36	33.9	12	25.0	10-34	38.0
Cr	12	14.4	8.3-32	56.0	12	15.4	8.6-35	56.4	12	15.2	7.6-34	56.6

1. Number of samples
2. Coefficient of variation

TABLE A-24 -- CONTINUED

HEAVY METALS	2.5 m SAMPLE PORT				5.0 m SAMPLE PORT			
	N[1]	MEAN VALUE	RANGE	C.V.[2]	N[1]	MEAN VALUE	RANGE	C.V.[2]
Cd	12	2.89	<0.5-6.2	64.2	12	3.65	<0.5-8.1	73.4
Zn	12	46.5	6.0-215	137	12	28.9	11-88	90.9
Mn	12	18.6	10-38	47.4	12	30.6	6.0-56	49.1
Cu	12	13.8	2.0-48	114	12	12.8	1.0-38	96.1
Al	12	1388	664-2346	31.7	12	909	82-1290	38.3
Fe	12	12,761	2894-28,260	52.5	12	11,435	2675-19,400	44.0
Pb	12	108	63-173	38.0	12	110	28-148	36.0
Ni	12	24.7	13-33	29.4	12	27.9	12-43	37.9
Cr	12	16.7	9.0-34	53.5	12	15.2	9.2-29	44.3

1. Number of samples
2. Coefficient of variation