Harvey H. Harper III

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FATE OF HEAVY METALS IN STORMWATER MANAGEMENT SYSTEMS

HARVEY H. HARPER
YOUSEF A. YOUSEF
MARTIN P. WANIELISTA
Department of Civil Engineering and Environmental Sciences
University of Central Florida
Orlando, Florida

ABSTRACT

The State of Florida requires that stormwater originating within a new project or development be managed and treated within the boundaries of the development to protect surface waters. Retention and exfiltration systems are the most common management practices. Theoretically these provide complete removal efficiency up to the design capacity since none of the stormwater reaches the receiving water body by direct inflow. The fate of various pollutants once entering these systems is not known, particularly whether heavy metals remain in them locked tightly by a chemical or physical association or slowly disperse outward over a much larger area to other water bodies. Investigations on an 8-year-old stormwater retention facility (1.5 ha) in Orlando, Fla., to define movement of heavy metals into and out of the basin seek to answer these questions. Stormwater runoff has been collected and analyzed from the input pipe for approximately 1 year. In addition, both wet and dry bulk precipitation are being collected to estimate the relative significance of each input source. Forty-five separate 3 cm core samples were collected from within the pond, divided into four sections and analyzed for zinc, cadmium, copper, aluminum, iron, lead, nickel, chromium, and phosphorus as well as moisture and organic contents. Movements of heavy metals from the inlet were estimated using the top 1 cm values. While zinc and lead were removed rapidly from solution near the outfall, other metals such as copper and aluminum were mobile. Deposition of metals correlated highly with the chemical speciation of the metal at the time of input. The role of plants in trapping and removing heavy metals is also under investigation. Although a large portion of the metals seem to remain within the basin, a certain fraction may leave the pond through percolation and groundwater movement. Five multilevel wells installed from the edge of the pond outward monitor downward or horizontal movement. Groundwater monitoring will continue throughout the typically wet summer season.

INTRODUCTION

Within the past decade a substantial amount of research has accumulated on water pollution caused by the operation of motor vehicles, mainly on the potential aquatic toxicity of heavy metals such as lead, zinc, and chromium. Heavy metals have been proposed by several researchers as the major toxicant present in highway runoff samples (Shaheen, 1975; Winters and Gidley, 1980). Many heavy metals are known to be toxic in high concentrations to a wide variety of aquatic plants and animals (Wilber and Hunter, 1977).

Two of the most popular techniques for management of pollution from highway runoff are roadside swales and detention/retention facilities. Many States now require that specified amounts of excess rainfall from developed areas be collected and treated in such systems. However, with continual inputs of toxic elements, especially heavy metals, the resulting accumulations may begin to present a toxicity or pollution potential to surrounding surface waters or ground water, particularly if metal species begin to migrate out of or away from the stormwater management systems.

No definitive studies have been conducted to determine the fate of toxic species, especially heavy metals, in these stormwater management systems. This paper presents the preliminary results of research conducted on a stormwater retention facility receiving highway runoff near Orlando, Fla. Concentrations of heavy metals in stormwater runoff entering this facility were compared with average concentrations within the retention pond and also with groundwater concentrations beneath the pond to aid in determining the fate of heavy metals in these systems.

SITE DESCRIPTION

The site selected for this investigation is the Maitland Interchange on Interstate 4. This interchange, located north of the city of Orlando, was constructed in 1976 (Fig. 1). Three borrow pits dug to provide fill for constructing the overpass remain to serve as stormwater detention/retention facilities. The ponds are interconnected by large culverts so that when the northeastern pond (Pond A) exceeds the design level it can discharge to the northwestern pond (Pond B). The northwestern pond has the capability to discharge to the southwestern pond (referred to hereafter as the West Pond) when design elevations are exceeded. However, since the volume of both Pond A and Pond B are quite large relative to their receiving watersheds, it is anticipated that a discharge from Ponds A or B to the West Pond would occur only as a result of an extreme rainfall event. In the 2 years in which these investigations have been conducted no surface exchange of waters between Ponds A and B and the West Pond has been observed. Therefore, under normal conditions, the only input into the West Pond is by way of a 45 cm concrete culvert that drains much of the Maitland Boulevard overpass. Discharge from the West Pond travels to Lake Lucien through a large culvert. A flashboard riser system regulates the water level in the West Pond, and a discharge rarely occurs to Lake Lucien. Because of the well defined nature of both the inputs and outputs to the West Pond, this system was chosen for investigation.

The West Pond has an approximate surface area of 1.3 ha and an average depth of 1.5 m. The pond maintains a large standing crop of filamentous algae, particularly *Chara,* virtually year round. Because of the shallow water depth and large amount of algal production, the pond waters remain in a well oxygenated state. The sediment material is predominately sand which is covered by a 1 cm layer of organic matter.

Maitland Boulevard crosses over Interstate 4 by means of a bridge overpass created during construction of the interchange. The Maitland Boulevard bridge consists of two sections, one carrying two lanes of eastbound traffic and an exit lane, the other carrying two lanes of westbound traffic and another exit lane. Traffic volume on Maitland Boulevard is approximately 12,000 average daily traffic (ADT) eastbound and 11,000 westbound. Traffic volume on I-4 through the Maitland Interchange is approximately 42,000 ADT eastbound and westbound.

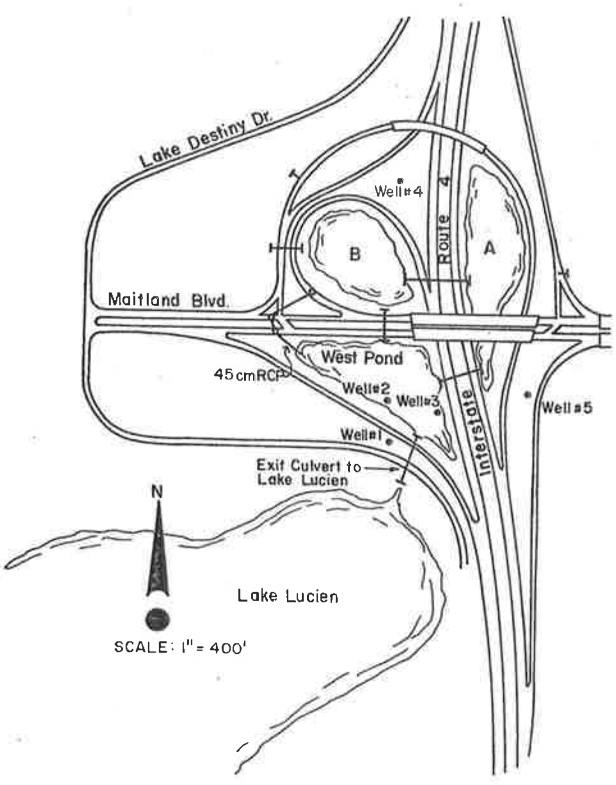

Figure 1.—Study site at Maitland Interchange.

FIELD INVESTIGATIONS

Field investigations conducted during 1982 and 1983 at the West Pond were divided into the following tasks: (1) determination of the quantity of heavy metals entering the West Pond by way of stormwater runoff; (2) determination of the average heavy metal concentrations in the retention basin water; (3) assessment of the accumulation of heavy metals in the sediments of the pond; and (4) monitoring of heavy metal concentrations in ground waters beneath the retention basin. To determine the quantity of heavy metals entering the West Pond by way of stormwater runoff an Isco automatic sampler was installed on the 45 cm stormsewer line. Flow-weighted composite samples were collected over a 1 year period for 16 separate storm events representing a wide range of rainfall intensities and antecedent dry periods. Samples were analyzed for Cd, Cu, Zn, Pb, Ni, Cr, and Fe using argon plasma emission spectroscopy, and an average concentration was calculated for each metal for the year.

To determine the average concentrations of heavy metals in the West Pond water, samples were collected on a biweekly basis for 1 year. Each of the five samples was analyzed separately for the heavy metals listed, and an average value was calculated for each metal on each sampling date.

To determine the accumulation and vertical distribution of heavy metals in the sediments, a series of 2.5 cm diameter core samples were collected to a depth of 6.8 cm. Forty-three separate core samples were collected in the 1.3 ha West Pond, and metal concentrations in sediment layers 0–0.8 cm, 0.8–2.8 cm, 2.8–4.8 cm, and 4.8–6.8 cm were measured for each core sample. Metal concentrations in the 0–0.8 cm layer were used to investigate horizontal movement of heavy metals from the point of discharge into the pond. Average metal concentrations in each of the core sections were used to determine the extent of vertical migration.

To investigate the possibility of groundwater contamination by leaching of heavy metals from stormwater management systems, five multiport monitoring wells were installed at locations indicated in Figure 1. Two of the monitoring wells were installed at the edges of the West Pond with the remaining three installed at various locations surrounding the stormwater management system. The wells were designed so that all of the sample ports were housed in a single casing to minimize soil disturbance and reduce recovery time for obtaining representative ground water samples compared to other monitoring well designs such as cluster wells.

A schematic of the monitoring well design is shown in Figure 2. All wells were installed to a depth of 6 meters with sample ports at 0.1 m, 0.5 m, 1.0 m, 3.0 m, and 6.0 m below the average water table depth in the area of the well. Ground water samples were collected from each sample port on a monthly basis using a peristaltic pump. Approximately 10 l of ground water were pumped and discarded from each port before a sample was collected. Samples were analyzed for heavy metals as described previously.

EXPERIMENTAL RESULTS AND DISCUSSION

Removal of Particulate Metal Species

A comparison of average heavy metal concentrations in stormwater runoff and in the West Pond is given in Table 1. Concentrations of heavy metals measured in the incoming stormwater appear to exist predominately in associations with particulate matter. Particulate fractions accounted for 42 percent of the total cadmium, 86 percent of total zinc, 47 percent of total copper, 94 percent of total lead, 89 percent of total nickel, 67 percent of total chromium, and 96 percnt of the total iron. To determine the horizontal mobility of these particulate fractions the metal concentrations measured in the top layer of the core samples were plotted as a function of distance from the stormwater inlet into the pond. The results of these determinations are shown in Figure 3. It can be seen that both lead and zinc reached a peak concentration in the upper sediments at a point very near the stormwater inlet. For these metals peak deposition occurred at a distance of approximately 15 meters from the point of discharge. Concentrations of both lead and zinc appeared to peak and decline quickly with increasing distance. This pattern suggests that a large portion of the particulate forms of these metals is associated with relatively heavy particles which tend to settle rapidly.

As seen in Figure 3, chromium concentrations reached a peak at a distance of 30 meters from the discharge point. The decline in chromium concentrations with increasing distance was not so pronounced as for lead and zinc. This behavior suggests that chromium in stormwater runoff is associated with a wider range of particulate sizes and densities than lead or zinc. The behavior of copper and nickle species in stormwater runoff appears to be quite similar. Both of these metals did not reach a definite peak, but tended to settle out fairly uniformly over a relatively large distance. This suggests that the particle sizes characteristic of particulate copper and zinc in stormwater runoff are much smaller and more mobile than those for lead, zinc, or chromium. It appears, therefore, that lead and zinc in highway stormwater runoff

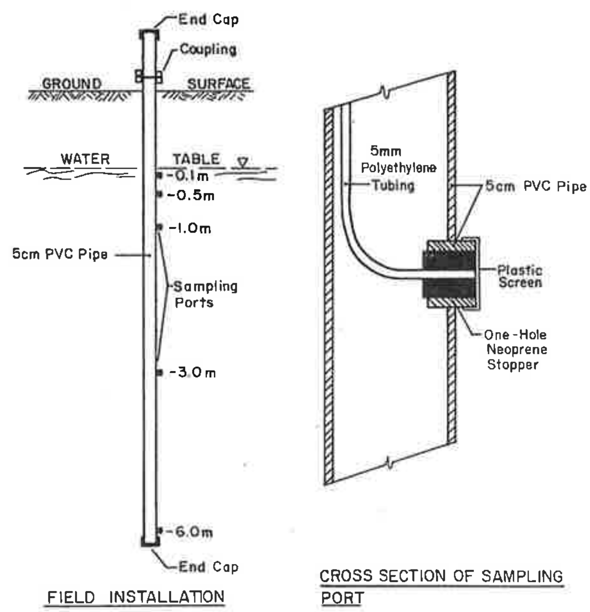

Figure 2.—Schematic diagram of the multiport groundwater sampling device.

Table 1.—Comparison of average heavy metal concentrations in stormwater runoff and in the retention basin (West Pond) at Maitland Interchange.

	Average Values in Incoming Stormwater			Average Values in Retention Basin Water			Percent Change Through Retention Basin	
Parameter	Dissolved	Total	Percent Dissolved	Dissolved	Total	Percent Dissolved	Dissolved	Total
pH	5.90	5.90	—	5.97	5.97	—	+15	+15
Cadmium	1.1*	1.9	58	0.8	1.0	80	−27	−47
Zinc	50	347	14	5.8	6.4	91	−88	−98
Copper	32	60	53	14	16	88	−56	−73
Lead	43	723	6	16	22	73	−63	−97
Nickel	3.2	28	11	1.8	2.3	78	−44	−92
Chromium	3.3	10	33	2.3	3.4	68	−30	−66
Iron	48	1176	4	20	61	33	−58	−95
Number of samples	16	16	—	34	34	—	—	—

*All metal concentrations listed as μg/l.

are associated with larger, more dense particles which will settle quickly from the point of discharge. Chromium appears to be associated with both a smaller average particle size and a wider range of particles than lead or zinc. The very mobile characteristics of copper and nickel indicate a relatively small particle size.

The results shown in Figure 3 can be useful in designing stormwater retention facilities aimed at the removal of heavy metals. By examining the metal concentrations in the sediments of existing stormwater management facilities, the distance from the inlet source at which metal concentrations began to approach background levels can be determined. If this distance is assumed to be the maximum distance over which heavy metals will settle out then the outfall structure can be placed at a distance from the inputs that equals or exceeds the zone of settling in order to optimize metal particle removal.

It should be noted that the triangular design of the West Pond (see Fig. 1) produced a situation that caused storm water coming in through the 45 cm inlet to spread out quickly in a large, wide area. This design caused the inlet velocity to decrease rapidly and aided in settling of particulate species. A narrow design with a relatively rapid flowthrough velocity would decrease metal removal efficiencies.

Removal of Dissolved Species of Heavy Metals

As seen in the average West Pond water quality listed in Table 1, total metal concentrations are reduced substantially when compared with the incoming storm water. With the exception of cadmium, removal of particulate forms of heavy metals exceeded 70 percent in the retention facility. As a result, the ratio of dissolved forms of heavy metals to total metal concentrations has increased considerably in the retention pond water. Whereas heavy metals associated with the incoming storm water were largely particulate in nature, the average heavy metal species in the retention pond water are largely dissolved in nature. It is interesting to note, however, that concentrations of dissolved species of heavy metals are also much lower in the retention pond water than in the incoming stormwaters. It appears, therefore, that not only are particulate forms of various heavy metals readily removed from the water column upon entering the retention pond, but dissolved species are removed as well. Removal of stormwater-generated dissolved species of heavy metals in the West Pond averaged between 27 percent for cadmium and 88 percent for zinc.

It has been reported by numerous researchers that the greater part of dissolved heavy metals entering or being transported by natural water systems can, under normal physiochemical conditions, be rapidly removed from the water phase and concentrated in the sediment phase (Wilber and Hunter, 1977; Guthrie and Cherry, 1979; Hem and Durum, 1973). Although the exact mechanisms responsible for removing dissolved species in the stormwater runoff were not determined, it is believed that several of the following processes may have been involved at this site: (1) precipitation; (2) cation exchange and adsorption; (3) co-precipitation of hydrous Fe/mn oxides; and (4) association with organic molecules.

Fate of Heavy Metals in the Sediments

It appears from the results presented previously that the fate of a large portion of both the suspended and

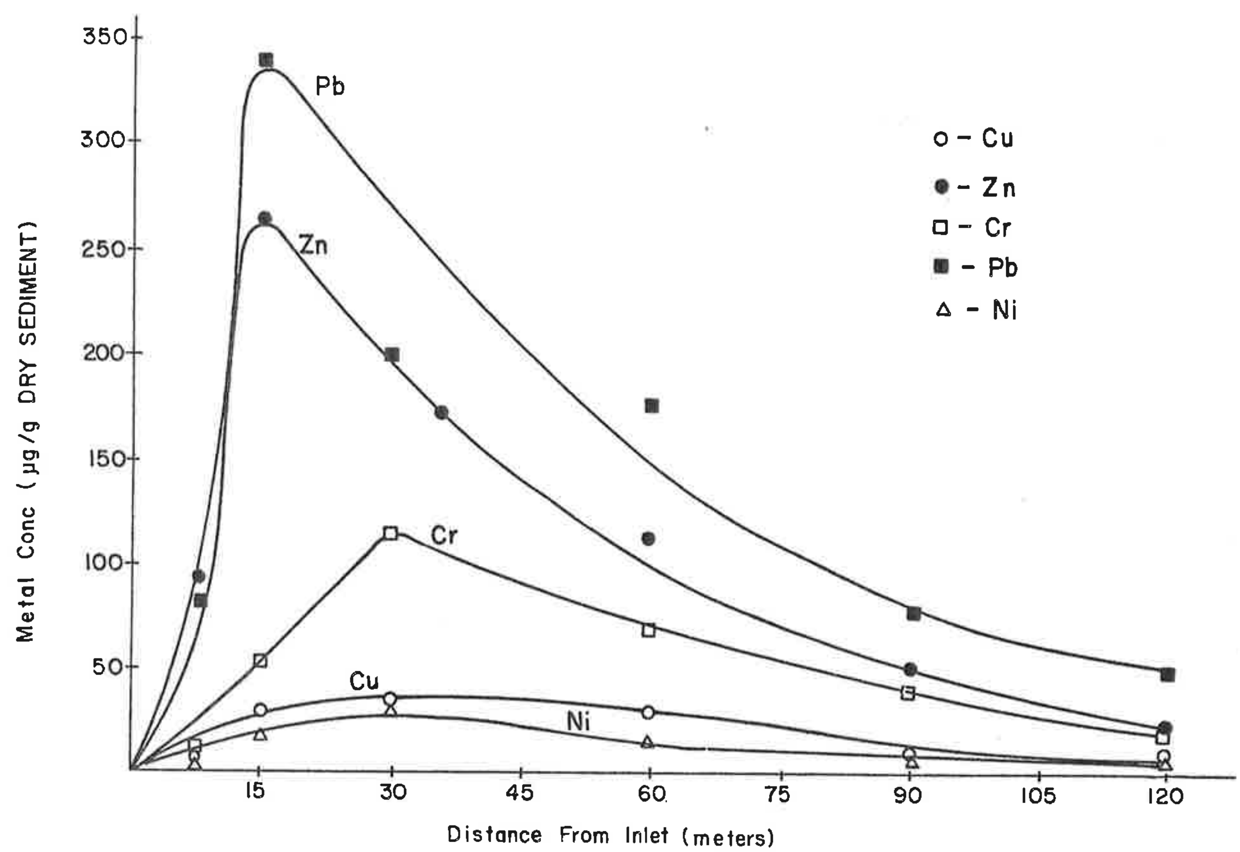

Figure 3.—Concentrations of selected heavy metals in the top 1 cm of sediments in the Maitland detention pond as a function of distance from the stormwater inlet.

dissolved fractions of storm water associated heavy metals is ultimate deposition by a wide variety of mechanisms into the bottom sediments of the receiving water body. After several years of this continual deposition, a large accumulation of heavy metals may develop in the sediments. This concentrated layer of heavy metals may present a potential pollution hazard if leaching were to occur.

To investigate the potential movement of sediment deposited heavy metals the vertical distribution of heavy metals in the 43 sediment cores were examined, and the average metal concentrations in sediment layers 0-0.8, 0.8-2.8, 2.8-4.8, and 4.8-6.8 cm were calculated. Since the heavy metal content in the 4.8-6.8 cm layer was very similar to heavy metal concentrations measured in nearby soils unaffected by stormwater runoff, these concentrations were considered equal to background values and subtracted from each of the others. The vertical distributions of Zn, Pb, Cr, Ni, Cu, and Fe in sediment cores collected in the West Pond are shown in Figure 4. It can be seen from Figure 4 that the metal concentrations decreased in an exponential fashion with increasing sediment depth and can be modeled as follows:

$$C = C_0 e^{-kz}$$

where: C = metal concentration at a desired sediment depth (μg/g dry wt)
z = the sediment depth (cm)
C_0 = metal concentration of the sediment at the surface (μg/g dry wt).
and k = metal reduction constant (1/cm)

This model was found to fit the heavy metals tested with a correlation coefficient of 0.99 or better. The metal reduction constants (k values) were 1.36 for Zn, 1.14 for Cr, 1.03 for Pb, 1.03 for Ni, 0.98 for Fe, and 0.92 for Cu (Yousef et al. 1983). It appears, therefore, that accumulated heavy metals are attenuated very quickly during movement through sediment material. Attenuation of metals was found to be essentially complete at a depth of approximately 5.0 cm with normal background concentrations below that depth. Although all heavy metals tested are attenuated quickly, it appears from the calculated metal reduction constants that the vertical mobility of heavy metals can be arranged in the following order:

least mobile: Zn < Cr < Pb = Ni < Fe < Cu: most mobile.

It can be concluded, therefore, that heavy metals deposited within this pond, upon reaching the sediments, were transformed into very stable associations that remained near the sediment surface and declined rapidly in concentrations with increasing depth.

Potential for Groundwater Contamination by Heavy Metals

A comparison of average total heavy metal concentrations in the retention basin water, in the top 0.8 cm sediment layer, and in groundwater samples collected beneath the retention basin is given in Table 2. Because of the 7-year accumulation of heavy metals from stormwater runoff in the sediments, the concentrations of sediment-associated metals have magnified considerably when compared to the average retention basin concentrations. Magnification factors for sediment-associated metals range from 287 g/ml for cadmium to 6,838 g/ml for chromium when compared to average retention basin concentrations. One of the potential problems associated with this accumulation is the possibility for leaching and downward movement of heavy metals into ground waters. If movement of heavy metals is found to occur, then these stormwater management facilities could have tremendous pollution potential since they are in widespread use.

In spite of the large accumulation of heavy metals in the sediments of the retention pond, there is no evidence to indicate that leeching of metals is occurr-

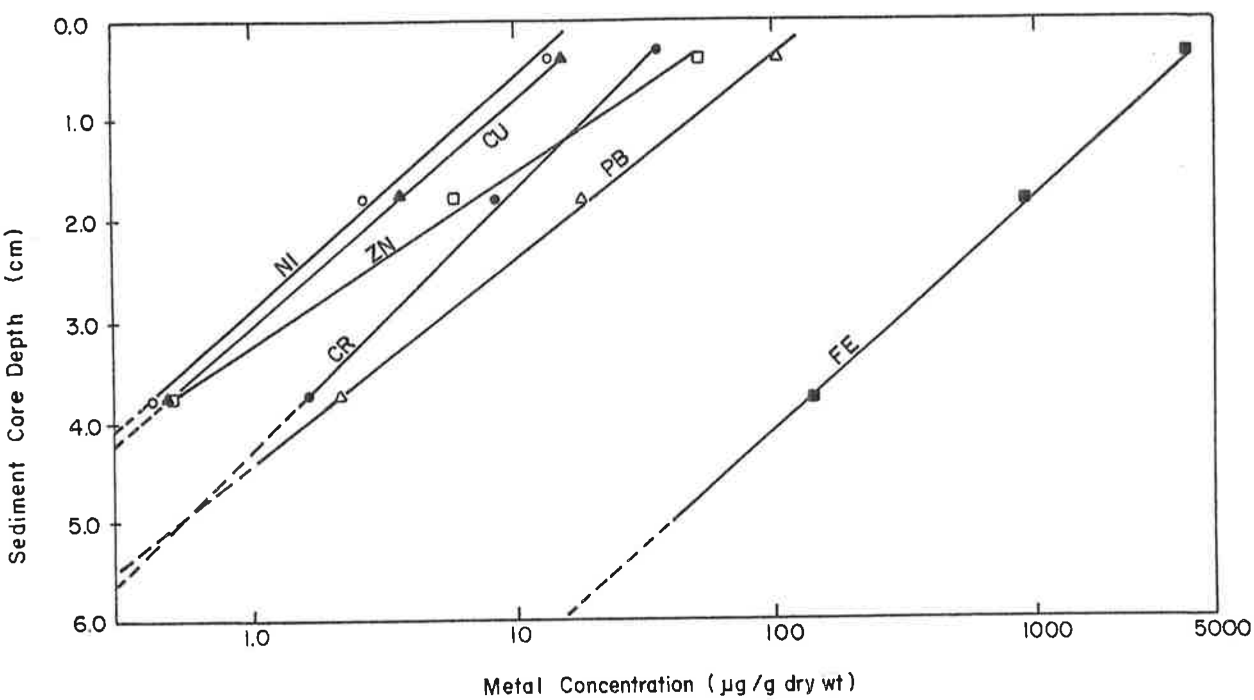

Figure 4.—Vertical transport of heavy metals through bottom sediments of a retention/detention pond at Maitland Interchange.

Table 2.—Comparison of average total heavy metal concentrations in the retention basin water, the top 1 cm of sediments, and in groundwater samples collected beneath the retention basin at Maitland Interchange.

Parameter	Average Total Concentration In Retention Basin (μg/l)	Average Sediment Concentration In Top 0.8 cm (μg/kg)	Average Total Metal Concentration In Groundwater Samples Collected Beneath the Stormwater Retention Basin (μg/l) 0.1 m	0.5 m	1.0 m	3.0 m	6.0 m
pH	5.97	—	6.01	6.17	5.79	4.91	5.02
Cadmium	1.0	287	1.3	1.3	1.6	1.3	1.0
Zinc	6.4	29,915	11	14	10	11	12
Copper	16	7,204	7.6	8.8	8.5	8.7	10
Lead	22	56,630	26	27	15	13	12
Nickel	2.3	8,064	2.2	3.2	1.5	2.3	2.3
Chromium	3.4	23,249	4.3	6.2	2.0	1.5	1.5
Number of samples	34	43	8	8	8	8	8

ing into ground waters. As seen in Table 2, the concentrations of all heavy metals tested are near or below total concentrations measured in water within the retention basin. Metal concentrations in ground waters actually appear to decrease in some cases with increasing depth in spite of a decrease in pH. It appears, therefore, that the retention facility does not contribute measurable increased heavy metal pollution to underlying ground water.

SUMMARY AND CONCLUSIONS

During this research investigating the fate of heavy metals in a stormwater retention facility, both the horizontal and vertical migrations were measured and modeled. Groundwater monitoring wells were also installed on the edges of the retention pond to monitor heavy metal movement out of the retention basin. From these studies the following conclusions were reached:

1. Heavy metals associated with stormwater runoff originating from highway surfaces are predominately particulate in form.

2. Upon entering stormwater retention basins most particulate forms of metals settle near the point of input. Lead and zinc were found to reach peak concentrations in sediments 15 m from the inlet, chromium was found to reach a peak 30 m from the inlet, while copper and nickel tended to settle out over a larger area. Sediment concentrations of all heavy metals tested appeared to approach background concentrations at a distance of 120 m.

3. Dissolved species of heavy metals contained in stormwater runoff were also removed in the retention basin. Apparent removal of dissolved species ranged from 27 percent for cadmium to 88 percent for zinc.

4. Heavy metals tend to accumulate in the sediments of the retention basin. The vertical migration of heavy metals in the sediments was found to observe an exponential decay with a rapid attenuation rate. Most heavy metals were found to be present in the top 0.8 cm with normal sediment background levels observed at a depth of 6.8 cm.

5. In spite of the accumulation of heavy metals in the sediments of the retention pond no increases in groundwater concentrations of heavy metals were observed in monitoring wells beneath the pond.

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