RECOMMENDED APPLICATIONS

Two applications of DSD are recommended. First, it should be used in highway design, either for new facilities or reconstruction (improvement) of "below-standard" facilities. The locations where DSD should be applied are generally characterized by conditions that create the potential need for drivers to depart from simple steering and speed-control maneuvers to follow the road. DSD is also recommended for use at special-feature locations where drivers could experience problems in handling information. These locations generally include interchanges—especially freeway-to-freeway—intersections, toll plazas, pavement-width reductions (lane drops), and any other location where unusual or unexpected maneuvers are required.

For all design situations, the higher values are suggested for especially complex areas such as interchanges that have left-hand exits or multiple exits in close proximity. The lower values should be considered minimally acceptable.

The second suggested application is for traffic control techniques at hazardous locations. More specifically, the criteria can be used to determine the need for and location of advance warning signs. In using Table 1 to determine the appropriate DSD, the 85th percentile speed rather than design speed should be used. In addition, although the higher values are recommended for defining the DSD, ranges of values are given to provide the flexibility that is often required in the positioning of advance warning signs.

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Use of Overland Flow in Storm-Water Management on Interstate Highways

John H. Bell, Airan Consultants, Inc., Coral Gables, Florida
Martin P. Wanielista, Florida Technological University, Orlando

An assessment of the potential of shallow-water ditches and shoulder areas adjacent to roadways for deposition of heavy metals is reported. The metals examined in the field were those that result from automobile emissions and the wear of automotive parts: lead, zinc, copper, chromium, and nickel. Cadmium content was also measured. The highest concentrations of metals were found in roadside plant and animal populations. These, however, contained the least metals in mass. Soils adjacent to the edge of the pavement contained the greatest mass of metals. In general, the topsoil contained higher concentrations of metals than subsurface soils. Lead was shown to be relatively immobilized by the soil, whereas other metals were more mobile. Design equations for estimating the volume of shallow-water storage areas for rainfall excess (runoff) are presented. In general, the use of overland flow with shallow ditch areas was shown to be effective for the control of runoff and its associated pollution content.

Storm-water runoff in the United States is receiving considerable attention, primarily as a result of federal regulations such as the Federal Water Pollution Control Act and the Clean Water Act. Runoff pollutants from highway surfaces had been documented as early as 1957 (1), when high concentrations of lead in soils adjacent to highways were reported. More recent studies (2, 3) have identified zinc, copper, chromium, cadmium, nickel, and other metals in highway runoff waters. On a mass basis, Shaheen (2) compared highway runoff with sanitary sewage for comparable land uses and populations and determined that the masses of lead, zinc, and chromium in highway runoff were, respectively, 1000, 20, and 300 times greater than amounts of those metals encountered in sanitary sewage. Such a comparison should be viewed with caution, however, because the chemistry of highway drainage and its mode of discharge are very different from those of sewage effluent.

The automobile is the predominant source of lead, as well as some other heavy metals, near highways. The combustion of leaded gasoline is generally acknowledged to be the major source of lead, but some lead also results from the wear of tires, in which lead oxide is used as a filler material (2). Zinc also results from tire wear and from the leakage of crankcase oil, in which high concentrations of zinc are used as a stabilizer (1). Chromium, copper, and nickel are produced by the wear of metal plating, bearings, bushings, and other moving parts in the engine (2).

From the viewpoint of environmental health, lead is not required by any form of life and at high levels is known to be toxic to plants, animals, and humans (4). Although zinc, copper, and chromium are essential to most life forms in trace amounts, high levels of these metals have also been shown to be toxic.

The ultimate fate of metals in highway runoff depends to a great degree on the areas immediately adjacent to the paved surface. Environments adjacent to paved roadways are not similar. The shoulder and ditch areas may be impervious or pervious to various degrees. The physical and chemical properties of the soil and the extent of vegetative cover vary widely. In addition, overland flow of water and channelization to a discharge point are options in design. If overland flow is the drainage design, heavy metals in the runoff are exposed to soil, vegetation, and, to some extent, animal life in the shoulder and ditch area. Some metals are removed through this exposure. The extent of removal depends primarily on the characteristics of the right-of-way area. If the drainage design is channelized flow (i.e., concrete drainage channels or deep ditches), there is generally no opportunity for the removal of heavy metals by soil or vegetation. In these situations, "first-flush" volumes of runoff can be diverted to and stored in available ditch areas or specially constructed ponds to reduce the discharge of metals and other pollutants into receiving water bodies.

RESEARCH OBJECTIVES

The major objective of this research was the management of storm-water runoff to reduce concentrations of metals. Based on the results of previous studies, which indicate that soil is a significant "sink" for heavy metals (5, 6), it was postulated that overland flow of storm water from impervious surfaces to a ditch before discharge to lands or surface water bodies adjacent to highway rights-of-way would be effective in reducing concentrations of metals. The overland flow of runoff would promote exposure of metals to the soil and thus make maximum use of the ability of the soil to retain these metals.

To investigate the effectiveness of overland flow in this regard, field sampling and statistical analysis were conducted for shoulder and ditch areas adjacent to several representative highways in central Florida. The specific objectives of these investigations were to determine the following:

1. Metal concentrations in soils, plants, animals, surface water, and groundwater;
2. The relative mobility of metals transported by overland flow by distance from the edge of the pavement and depth into the soil;
3. The total metal-carrying capacity of soils; and
4. The volume of shallow-water retention areas required to remove impurities if channelized flow (not overland flow) is the method of handling storm water.

The last activity in this list recognized the fact that some bridge and roadway drainage cannot be designed to use overland flow.

BASIC DATA RESULTS

Concentrations and masses of metals, as well as estimates of the retention capacity of sinks adjacent to the paved highways, were determined. Eleven sampling sites in east-central Florida were used. The sites were chosen to provide a range of geographic locations, highway ages, number of traffic lanes, drainage and soil conditions, and traffic volumes. The methods and procedures used are described in detail elsewhere (7, 8).

The analysis of metal concentrations in roadside plants, animals, surface water (standing water in roadside ditches or ponds), groundwater, and soil can be used to determine the relative mass of metals in each. This makes it possible to identify the major sinks for these metals in roadside environments. For example, summary statistics for lead concentrations are given in Table 1. The highest concentration of lead was found in animals and the lowest concentration in surface water and groundwater. Comparative data for water from various Florida sources are given below (1 mg/kg = 1 ppm):

Water	Lead Concentration (mg/kg) Average	Range
Groundwater from dry sampling site, I-95, Titusville	0.1	–
Upper Floridan aquifer, Orlando	<0.5	–
Lower Floridan aquifer, Orlando	<0.005	–
Apalachicola River	–	0.0021-0.0062

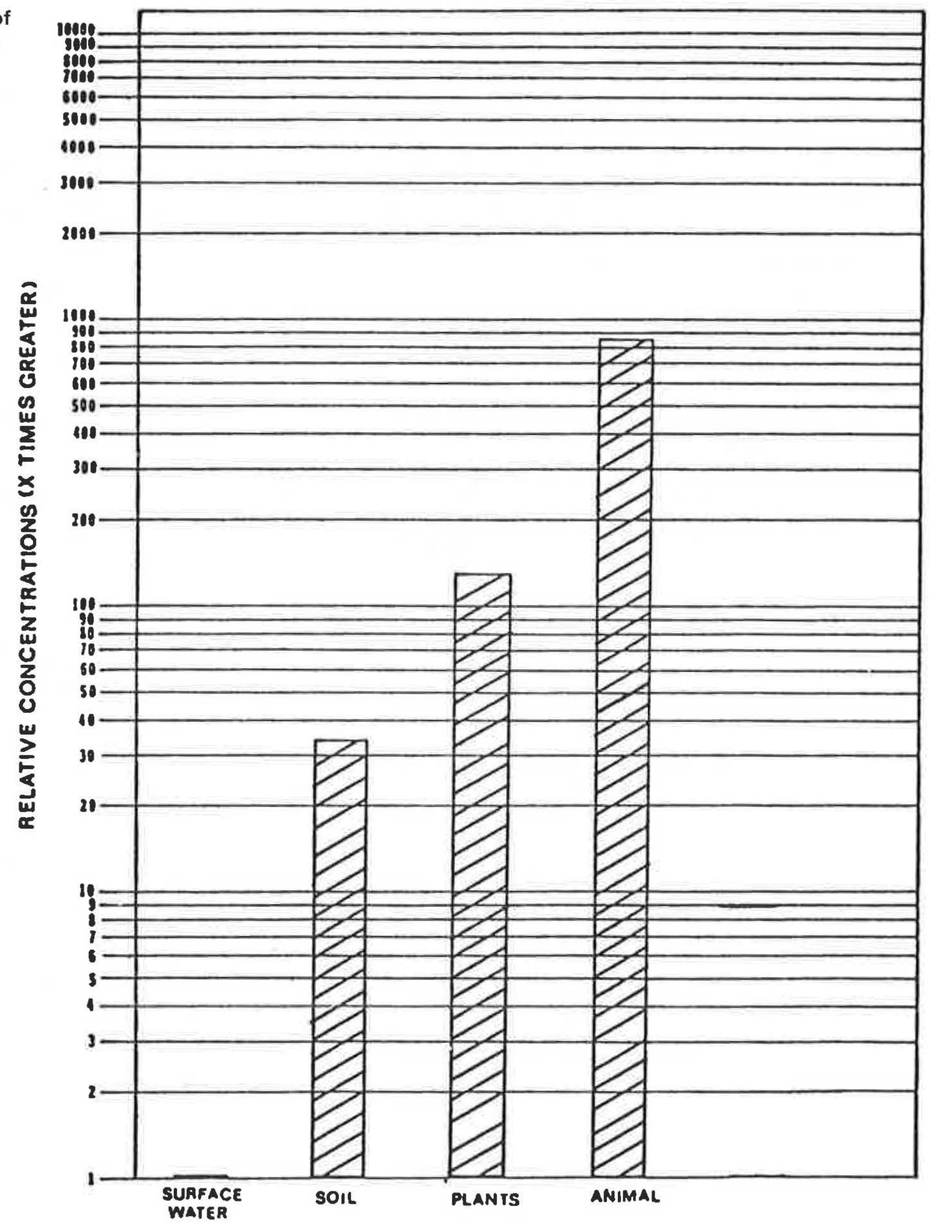
The maximum contaminant level (MCL) specified in the Florida Safe Drinking Water Act is an average 0.05 mg/kg. Clearly, total lead concentrations in some surface water samples exceeded the standards. The dissolved fraction of lead in surface waters, as well as the

Table 1. Summary statistics on lead concentrations.

Item	No. of Samples	Concentration (mg/kg) Range	Average	Standard Deviation	Coefficient of Variation
Surface water					
Total	28	0.0012-0.27	0.218	0.265	122
Dissolved	27	0.009-0.04	0.026	0.041	158
Sediment	3	0.001-5.8	1.949	3.335	171
Soil					
All samples	85	0.16-53.0	7.787	10.600	136
Topsoil	47	0.25-53.0	10.591	11.823	112
13 cm deep	38	0.16-25.0	4.320	9.600	222
Plants					
All samples[a]	17	3.15-65.0	29.57	17.38	59
Dry sites	11	26.4-65.0	27.34	15.46	57
Wet sites	6	3.15-53.4	33.65	16.03	48
Animals					
All samples	4	27.6-429	191.1	176.5	92
Dry sites (grubs)	2	220.5-429	324.8	147.4	45
Wet sites (minnows)	2	27.6-29.2	28.4	1.1	4

Note: 1 mg/kg = 1 ppm.
Lead removable by dilute acid extraction (0.75 normal).
[a]Dry weight.

Figure 1. Relative concentrations of lead in four types of roadside sinks.



measured lead content of a groundwater sample adjacent to I-95, was within standards. The coefficients of variation illustrate that more consistent estimates of the average were possible for animal and plant samples. However, since soil at various depths and distance from the edge of the pavement were included in the average statistics, variability should be expected in the results of the soil analysis.

Relative concentrations of lead from Table 1 are shown in Figure 1. Comparative charts of concentrations of lead, zinc, copper, chromium, cadmium, and nickel all show that the highest concentrations are found in animal life. However, very little animal life was found in the roadside environments investigated. Therefore, if concentrations are converted to mass loading of metals per meter of highway, the greatest quantity of metals is found in the soils. Figure 2 shows the relative mass of lead in each of the potential sinks per meter of highway.

The assumptions used to convert average concentration to mass per meter of roadway were average conditions at the sampling sites along I-75, I-95, FL-50, FL-405, and US-1. The shoulder width, not including the ditch area, was calculated as approximately 12.25 m (40 ft). The weight of soil in an area that measures 12x1 m (40x3.3 ft) and is 15 cm (6 in) deep is approximately 2.2 Mg (2.4 tons). Samples of grass were weighed and, for a 12-m^2 (130-ft^2) area, the weight was estimated at 5.91 kg (13 lb). "Grubs" (believed to be june bug larvae) or resident animals were difficult to find. A total of twelve 1-m^2 (11-ft^2), 15-cm-deep areas were examined. Approximately 4 grubs/m^2 (0.4 grub/ft^2) were found. The average weight per animal was about 0.35 g. The volume of water per meter of highway was estimated at 560 L (148 gal), which assumes a 0.3-m (1-ft) average depth 2 m (6.5 ft) wide. Thus, by knowing concentration and mass of media, the mass of metals can be calculated. Example calculations for copper are as follows (1 mg/L = 0.125 mg/gal; 1 mg/kg = 1 ppm; 1 kg = 2.2 lb):

Type of Sink	Calculation per Meter of Roadway		Mass (mg)	Ratio
Water	0.033 mg/L x 560 L	=	18.48	23

Type of Sink	Calculation per Meter of Roadway		Mass (mg)	Ratio
Soil	0.688 mg/kg x 2200 kg	=	1514	1892
Plants	36.3 mg/kg x 5.91 kg	=	214	268
Animals	43.4 mg/kg x 0.018 kg	=	0.80	1

The weight given for animals is the average weight of grubs and minnows per meter.

These results indicate that the soil is the major sink for heavy metals in roadside areas. This is consistent with the findings of several other studies of the fate of highway-related heavy metals. Studies by Motto and others (9), Lagerwerff and Specht (10), Singer and Hanson (11), and Olson and Skogerboe (12), to name but a few, have shown elevated levels of lead and zinc in roadside soils. Concentrations of lead as high as 7000 mg/kg have been reported (12). A study of the mass inputs and outputs of highway-related lead in urban and rural basins was performed by Rolfe and Jennett (6), who calculated that 75 percent of the total lead input by automobiles in the urban basin was leaving that basin by way of streamflow but that only 2 percent was leaving the rural basin as streamflow. They concluded that the soil was accumulating a large portion of the lead input to the rural basin and, based on measurements, estimated that the equivalent of 30 years of automobile lead emissions were contained in the soil.

Evidence developed in our study shows that, once heavy metals are retained by the soil, they are effectively immobilized and generally do not leach downward. This was found to be true particularly for lead. Other metals appeared to be somewhat more mobile in the soil so that some leaching could occur. At every sampling site, metal concentrations decreased with both depth into the soil and distance from the edge of the pavement. Table 2 gives an example of lead concentrations in surface and subsurface [10-15 cm (6-8 in)] soils at edge-of-pavement and ditch locations. These lead concentrations represent the total lead extractable by concentrated acid solution (previous results are for dilute acid extractions). Table 2 also gives comparative results from four other studies that appear to be consistent with the results of the study discussed in this paper.

Figure 2. Relative masses of lead in four types of sinks per meter of highway.

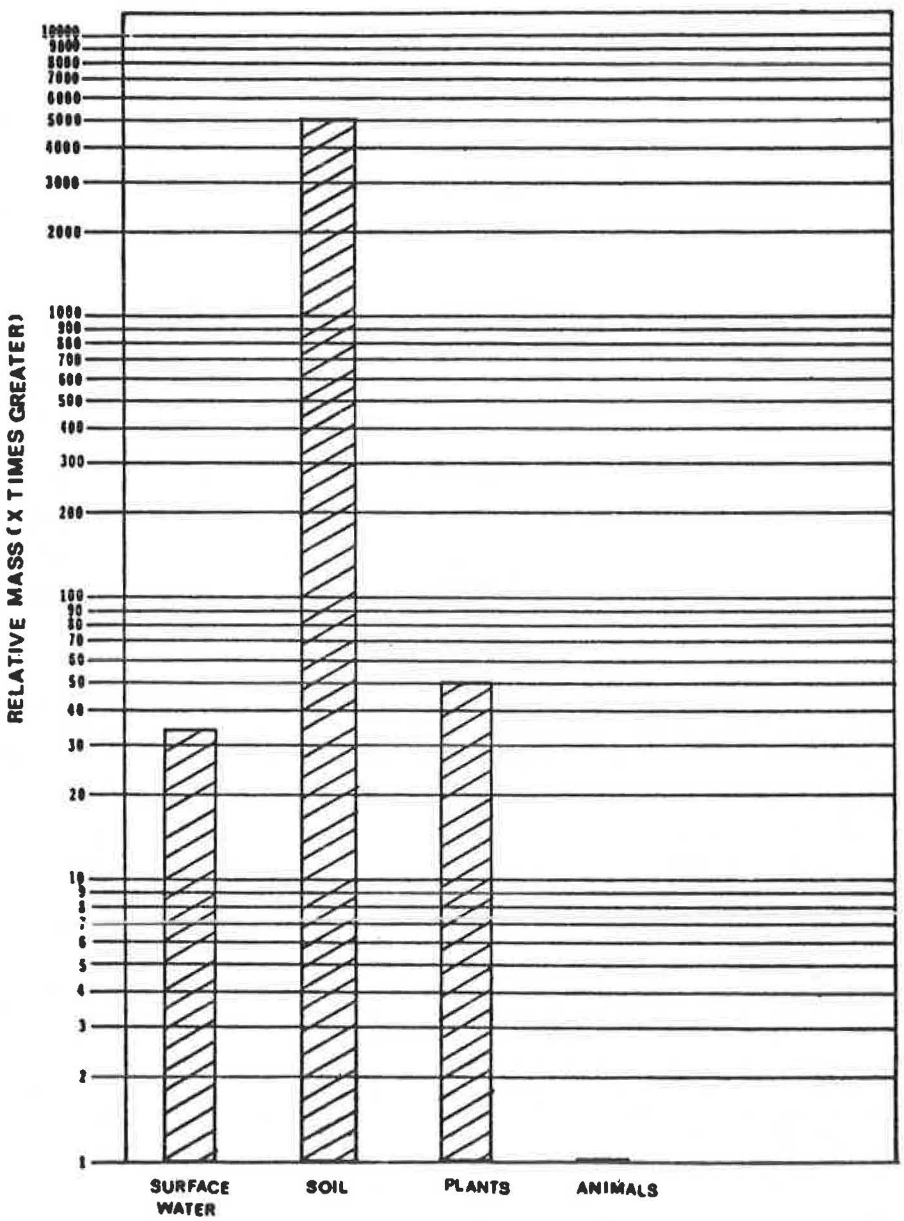


Table 2. Total lead content in roadside soil and grass as a function of distance from traffic and depth in soil profile.

Location	Distance from Road (m)	Dry Weight of Lead (mg/kg) Grass	Soil Profile Layer 0-5 cm	5-10 cm	10-15 cm
West of US-1, near Plant	8	68.2	522	460	416
Industry Station, Belts-	16	47.5	378	260	104
ville, MD	32	26.3	164	108	69
West of southbound lanes,	8	51.3	540	300	98
Washington-Baltimore	16	30.0	202	105	60
Parkway, Bladensburg, MD	32	18.5	140	60	38
West of I-29, Platte City,	8	21.3	242	112	95
MO	16	12.5	140	104	66
	32	7.5	61	55	60
North of Seymour Road,	8	31.3	150	29	11
Cincinnati, OH	16	26.0	101	14	8.2
	32	7.6	55	10	6.1
All sites, edge	0	50.4	822	-	60
Central Florida, ditch[a]	12	27.5	365	-	180

[a] Buildup of humus materials on bottom of ditch.

Table 3. Probable soil components or metal forms in various ranges of soil density.

Density Range (g/cm^3)	Probable Soil Components and Metal Forms
<1.5	Organic matter and organically bound metals
1.5-2.0	Organic matter and possibly clay with adsorbed organic matter; metals organically bound or adsorbed on clay minerals directly
2.0-2.5	Some organic matter, light minerals, and light clays; metals organically bound or adsorbed on clay minerals; Cr may be present as a precipitate
2.5-2.9	Bulk of the inorganic soil components, including sand, clay, silt, and other minerals; very few organics likely to be present; metals likely to be adsorbed by clay minerals or in precipitated form (Cr and Zn)
2.9-3.3	Dense minerals and possibly clays with adsorbed heavy metals; probably no organics; metals in adsorbed or precipitated form (Cr and Zn precipitates have densities in this range but not Pb)
>3.3	Dense minerals, possibly some clay with adsorbed heavy metals; metals probably in precipitated form (Pb, Zn, Cr)

ESTIMATES OF METAL-RETAINING CAPACITY OF SOIL

Now that soil has been identified as a major sink for highway-related heavy metals and it has been shown that heavy metals, once retained by the soil, are effectively immobilized, it would appear that using overland flow of runoff, to promote exposure to the soil of dissolved or suspended heavy metals, is probably an effective means of removing these materials. First, however, the capacity of the soil to retain heavy metals must be determined. To estimate this capacity, two basic approaches could be used:

1. The stoichometric approach, in which the chemical principles of the reactions that take place between soil and heavy metals are used to calculate a theoretical maximum capacity, and
2. The empirical approach, in which statistical correlations between soil properties and capacity for metal retention are used.

In this work, we first used the stoichometric approach. Findings made during the course of the study indicated, however, that the empirical approach might be more practical. Nevertheless, an explanation of the stoichometric approach is provided here to point up the difficulties involved in making estimates of soil retention capacity and because it leads to some key findings on interactions between soils and heavy metals.

Stoichometric Approach

To understand the stoichometric approach, it is first necessary to understand that there are a number of simultaneous chemical and physical reactions by which soil is able to retain heavy metals. Examples of these include adsorption, ion exchange, chemical precipitation, and organo-metallic-complex formation. Each reaction has its own kinetics of metal retention and its own saturation capacity and is affected by a unique set of environmental parameters, such as temperature, pH, and soil moisture.

The bulk metal-retaining capacity of the soil is the sum of the retention capacity attributable to each of the individual reactions. If sufficient information were available, this could be calculated theoretically by using basic chemistry considerations. Because of the number of reactions and their complexity, it would be impossible to make such calculations if all were of equal, or nearly equal, importance to overall metal-retaining capacity. But, if a single reaction could be isolated as most important, efforts could be focused on the chemistry of this reaction. For example, if it could be determined that the majority of lead entering the soil formed a specific compound—say, lead sulfate—then the lead-retaining capacity of the soil could be estimated based on knowledge of the reaction between lead in the runoff and sulfate in the soil.

This rationale was used in attempts to identify the most important reactions between soil and the heavy metals in runoff. It was determined that physically separating field soil samples into components according to density was the most useful way to accomplish this. Soil samples were separated into density ranges. Then, based on observations and tests of the separated fractions and knowledge of the density of the various compounds or complexes of soil and heavy metals, the probable chemical forms present in each density range were assessed. These data are given in Table 3. Identification of compounds by this method is by no means absolute, but it can be used as an indicator.

Soil fractions from each density range of a sample were analyzed for lead, zinc, and chromium content. If the greatest quantities of a metal were consistently found in a single density range, it could be postulated that that metal was generally forming one of the compounds given for that range in Table 3. An example of such an analysis is given below for an edge-of-pavement surface sample ($1\ g/cm^3 = 0.036\ lb/in^3$; 1 mg/kg = 1 ppm):

Density Range (g/cm^3)	Weight Fraction of Soil (%)	Lead Amount (mg/kg)	Lead Percentage of Total
<1.5	0.23	1 610	1.8
1.5-2.0	1.9	1 750	4.4
2.0-2.5	10.5	531	2.9
2.5-2.9	86.0	57	14.8
2.9-3.3	0.53	7 560	7.9
>3.3	0.84	71 300	68.2

As indicated, about 68 percent of the lead in that sample was in the most dense fraction. According to Table 3, this would mean that the lead was probably in the form of an inorganic lead compound rather than associated with soil particles or organic material.

Analysis of other edge-of-pavement surface samples produced similar results for lead. It is also interesting to note that Olson and Skogerboe (12) performed similar tests on highway soils and obtained comparable results. They carried the analysis one step further and found that the lead in the most dense fraction was in the form of lead sulfate.

In our study, however, analysis of samples from other locations in the right-of-way (i.e., subsurface and ditch samples) obtained very different results. In these samples, the metals were distributed generally throughout the density ranges. In some samples, the least dense fraction [$<1.5\ g/cm^3$ ($<0.054\ lb/in^3$)], which was determined to be primarily organic matter, contained substantial amounts of the metals. Therefore, in looking at the right-of-way as a whole, no single reaction can be identified as most important for the retention of heavy metals by the soil. It is for this reason that it is not practical to use the stoichometric approach.

Some important conclusions can, however, be drawn from these analyses:

1. It is clear that reactions between soils and heavy metals are site specific. This means that, in areas where removal of metals by the soil is critical, site-specific studies should be performed.
2. The organic portion of the soil is, in many cases, very important to its ability to retain heavy metals.

Empirical Approach

The second approach to estimating metal-retaining capacity, the empirical approach, has been illustrated by Zimdahl and Skogerboe (13). They found from laboratory tests that the capacity of a particular soil to adsorb lead can be reasonably predicted based on a correlation equation that involves cation exchange capacity (CEC)—the ability of the soil to adsorb cations, such as heavy metals—and pH. This equation, determined from an analysis of the lead-fixation capacity of 18 soils, is

$$N = 2.81 \times 10^{-6}\ CEC + 1.07 \times 10^{-5}\ pH - 4.93 \times 10^{-5} \qquad (1)$$

where

N = moles of lead per gram of soil at saturation,
CEC = cation exchange capacity of the soil (meq/100 g), and
pH = soil pH in units.

A regression coefficient of 0.971 was obtained, and the calculated values of N generally agreed within 10-20 percent with experimentally determined values.

In light of the finding that interactions between soil and heavy metals depend greatly on site-specific factors, it is felt that estimates of the metal-retaining capacity of soil that are based strictly on laboratory studies should be used with extreme caution. If the reactions that occur are site specific, so will be the metal-retaining capacity. The best means of estimating this capacity would probably be a combination of laboratory and field tests. Batch tests and column (breakthrough) tests should be conducted on soil samples taken from representative areas adjacent to the highway under consideration.

However, as a "first-cut" estimate of the lead-retaining capacity of the soils studied, the regression equation developed by Zimdahl and Skogerboe (13) was used. Values for CEC and pH for each sample were entered, and capacity N was calculated to range from 3.97×10^{-5} to 7.74×10^{-5} moles Pb/gram. The corresponding concentrations range from 8220 to 16 030 mg/kg. This means that, if the soils analyzed in this work behaved like those tested by Zimdahl and Skogerboe (13), they would have an additional capacity to fix lead that would range from 10 to 500 times their existing lead content.

STORAGE VOLUME FOR RUNOFF

Hydrologic Considerations

To limit the quantity of pollutants discharged from a highway right-of-way, the infiltration characteristics of the shoulders can be used to retain some metals. The more mobile metals and other potential pollutants can be retained in shallow-water ditches, where most metals will deposit in the sediment. When shoulders or earthen areas are not available for overland flow, such as rainfall excess (runoff) from bridge or limited right-of-way areas, then retention ponds with underdrains or natural percolation would be valuable for treating the first flush of storm water. The major question is the dimensions of these ditches or ponds that should be allocated for retention of storm waters.

Other methods of storm-water treatment are available and should be examined before the use of shallow-water ditches or construction of retention ponds.

A general equation to express the allocation of waters within a highway right-of-way would be

$$R_T = R_{RW} + R_O \qquad (2)$$

where

R_T = volume of total runoff that requires treatment,
R_{RW} = volume of runoff from the right-of-way, and
R_O = volume of runoff from outside the right-of-way.

At the beginning of a storm, precipitation infiltrates into the ground and is stored in surface depressions or otherwise abstracted. Rainfall intensity and distribution vary during a storm, producing variable quantities of runoff. Eventually, a saturation level is reached and runoff water is equivalent to precipitation. Thus, the highway shoulders and ditches receive runoff at a variable rate, but the volume of runoff for a storm can be predicted. Depending on the water table and soil-water conditions, runoff waters will percolate or remain on the surface as excess (runoff). The factors that affect the amount of runoff from a given area are the intensity and duration of rainfall, the characteristics of the soil drainage, the amount of vegetative cover, the amount of impervious surface (i.e., pavement), and topographic characteristics (e.g., slopes and depressions).

Example 1

Many mathematical formulas have been developed to model rainfall-runoff relations. One such formula has been developed by the Soil Conservation Service (SCS) of the U.S. Department of Agriculture (14) for use on urban watersheds. This formula is also useful for predicting roadway runoff and is applied here as an illustrative example.

Consider a section of roadway 28.7 m (94 ft) wide with 10.4 m (34 ft) of paved, otherwise impervious, area. The length of roadway drainage is 739 m (2424 ft) (like an I-95 area). The entire area drains as overland flow into an outfall at the lowest elevation.

The runoff from this highway section during a storm event can be calculated as follows by using the SCS procedure (14) (since the SCS formula is based on U.S. customary units of measurement, no SI equivalents are given in these calculations):

1. From an evaluation of soil type, soil moisture, ground cover, and percentage of impervious area, a weighted curve number is established. The curve number is used to estimate the potential for infiltration and the total infiltration or saturation capacity of a soil. For the roadway under consideration, the soil is assumed to be type B (moderately well drained) under average moisture conditions (condition 2). The ground cover is assumed to be fair grass over 50-75 percent of the pervious area. The percentage of impervious area is 36 percent. The weighted curve number (CN) is determined as follows:

Type of Land	Percentage of Total Area	CN	Weighted CN
Pavement	36	90	32
Pervious (grassed slope and ditch)	64	69	44
Total			76

2. Total storage S′ (initial abstraction, infiltration, and evapotranspiration) is then estimated by using the formula

$$S' = (1000/CN) - 10 = (1000/76) - 10 = 3.16 \text{ in} \quad (3)$$

3. By using this storage term, runoff Q is calculated as follows:

$$Q = (P - 0.2S')^2/(P + 0.8S') \quad (4)$$

where P is the precipitation in inches. Substituting the value obtained for S′,

$$Q = (P - 0.63)^2/(P + 2.53) \quad (5)$$

and, for a 3-in rainfall (once-in-10-years storm),

$$Q = (3 - 0.63)^2/(3 + 2.53) = 1.01 \text{ in} \quad (6)$$

4. If it is decided to store the 1.01 in of runoff, the volume of storage required is traditionally calculated by using the formula, volume = area × runoff (in) ÷ 12 (in/ft); i.e.,

$$\text{Volume} = (2424 \times 94) \times 1.01/12 = 19\,178 \text{ ft}^3 \quad (7)$$

or 0.44 acre-feet.

Volume Calculations Considering Antecedent Conditions

The problem with the calculation given above is that the volume is considered sufficient to store all the runoff water for each storm event. During the rainy season, storms of different quantities may occur each day over a long period of time, perhaps weeks. Water in the storage area will be displaced into adjacent lands or surface water bodies, and this displaced water will carry pollutants. If the stored water can be treated before the next storm event that produces runoff, the storage capacity of the holding area will be available.

Work completed by Wanielista (15, 16) for the East Central Florida Regional Planning Council indicated that diverting first-flush storm waters into percolation ponds and underdrained storage areas and use of overland flow with percolation are cost-effective procedures. Since these land areas are already available in most roadway rights-of-way and thus additional land purchases may not be necessary, diversion for percolation, underdraining, or overland flow would be even more cost-effective.

Coaxial graphs to aid in computing the volume of treatment (storage) as a function of watershed area, soil percolation, curve number, and depth of pond have been developed. These equations considered the stochastic conditions of rainfall and used data from three weather stations in Florida, one in Illinois, and one in New York. The efficiencies obtained did not vary by more than 5 percent. Because the coaxial graphs were difficult to use and were not available for watershed areas larger than 60 hm^2 (150 acres), they were extrapolated for larger watersheds, and a series of equations were developed by using bivariate regression analysis. The correlation coefficients for the bivariate equations were never less than 0.97. The equations for estimating "pond" volume for good percolation-type soil drainage conditions in ditch or pond areas are given in Table 4, where

V_I = basin volume for impervious area, 5-ft depth (acre-feet);
A = contributing watershed area (acres);
V_5 = basin volume at 5-in depth (acre-feet);
CN = composite curve number;
V_D^A = volume of basin at depth D in type A soil (acre-feet);
V_m = minimum basin volume (acre-feet);
D = depth of basin (feet);
DI = diversion volume (in); and
12 = conversion factor (inches to feet).

It has been suggested, as part of portions of the research not included here, that shallow aerobic water conditions be maintained for purposes of hydrocarbon degradation (e.g., gas, soil, and grease). A 0.3-m (1-ft) deep ditch adjacent to a roadway would most likely be aerobic and percolate fast during and after runoff conditions. Other depths—up to 1.5 m (5 ft) for type A soils and 0.9 m (3 ft) for type D soils—are also possible. These maximum depths were established to drain the areas by percolation to prevent mosquito-breeding problems.

If overland flow into ditches parallel to the roadway surface is the design and the first 2.5 cm (1 in) of every storm-water runoff can be stored and treated, then the quantity of pollutants removed from direct surface discharge to adjacent lands and water bodies is about 99

Table 4. Calculation of pond volume for type A soils.

Diversion Volume (in)	Impervious Watershed (5-ft-deep pond)	Composite Land Use		
		5-ft-Deep Pond	1 ft < Pond Depth < 5 ft	Pond Depth = 1 ft
0.25	$V_I = 0.016(A)^{1.28}$			
0.50	$V_I = 0.046(A)^{1.18}$			
0.75	$V_I = 0.09(A)^{1.11}$	$V_5 = V_I\,[0.59 + 0.37\,(CN/100)]$	$V_D^A = V_1 + [(V_5 - V_1)/4](D - 1)$	$V_1 = (A \times DI)/12$
1.00	$V_I = 0.14(A)^{1.07}$			
1.25	$V_I = 0.20(A)^{1.04}$			

percent of the yearly runoff mass. This level of treatment is more efficient than most advanced wastewater treatment processes for industrial and sewage wastes. But the shoulders and ditches must be designed to always retain the first runoff volume.

When conduits are used to transport a number of first flushes entering the conduits at various areas (and times), the concept of first flush is no longer valid because the pollution concentrations are random. The efficiencies calculated for such a case from cumulative runoff distributions for associated rational runoff coefficients are given below (c is the rational coefficient in $Q = ciA$):

Efficiency of Conduit System with No First Flush (%)			Diversion Volume (in)
c = 0.8	c = 0.4	c = 0.2	
96	95	90	1.25
95	93	82	1.00
93	90	72	0.75
90	82	60	0.50
82	60	40	0.25

These efficiencies would be applicable to large sewered areas.

This table was developed by using rainfall data obtained at the Tallahassee, Florida, airport. In a comparison with data obtained at the Orlando Jetport, these data produced the lowest efficiency of storm-water treatment. Orlando has fewer storms, and they are of less intensity, duration, and quantity than those at Tallahassee. The efficiencies obtained for the Orlando area are estimated to be at least 2-4 percent higher than those given above.

Example 2

For the previous example, taking into account the factor of percolation, calculate the required ditch volume if the ditch is, on the average, 1 ft deep and the percolation rate is estimated at a minimum of 1 in/h. It is desired to store and treat at least 1 in of runoff. By using Table 4, calculate the needed volume as follows (in U.S. customary units):

$$V_I = 0.14(A)^{1.07} = 0.14(5.23)^{1.07} = 0.82 \text{ acre-feet} \quad (8)$$

or 35 760 ft^3;

$$V_5 = 0.82\,[0.59 + 0.37(76/100)] = 0.72 \text{ acre-feet} \quad (9)$$

or 31 380 ft^3; and

$$V_1 = [5.23(1)/12] = 0.44 \text{ acre-feet} \quad (10)$$

or 19 168 ft^3. Therefore, at a 1-ft depth, the area of ditch is 19 168 ft^3. For a 2440-ft-long area, the width of the ditch is 2.4 ft.

Overland flow of highway runoff into a ditch parallel to a roadway can be designed by using these equations. If no percolation is available in the ditch area, consideration should still be given to overland flow and possibly a 1-m (3.3-ft) deep ditch occupying a larger area. It is believed that the metals from highway runoff can be retained for the most part in the right-of-way areas if good percolation-type soils are used in the shouldered ditch areas.

CONCLUSIONS AND RECOMMENDATIONS

Soil, plant, animal, groundwater, and surface water samples were obtained from the shoulder and ditch areas adjacent to Florida highway rights-of-way. These samples were analyzed for metal content and hydrocarbon degradation. During this research, which extended over an 18-month period, 2221 metal determinations were done. Eleven field sites were used to represent aerobic water environments, partly anaerobic water environments [1-3 m (3.3-10 ft) deep], and different soil conditions.

The findings of previous research, which provided valuable guidance, can be summarized as follows:

1. Rates of deposition of metal from automobiles and the quantities of these pollutants in runoff waters have been well documented.
2. The transport of heavy metals by overland flow results in large amounts of these metals coming into contact with the soil, where they are generally retained. The relatively high concentrations of these metals found in soils adjacent to roadways are evidence of this.
3. When sewage is treated by land spreading, metals are found primarily in the soil.
4. The important interactions between soils and heavy metals that are involved in the retention of these metals in the soil are likely to include adsorption, ion exchange, redox reactions, and "coordinate" chemical reactions, including precipitation and complex formation.
5. Soil properties generally considered to be important in the retention of heavy metals are pH, cation exchange capacity, clay mineral content, and organic matter content.
6. Lead is particularly significant as a public health problem.
7. In laboratory studies, the capacity of soil to retain lead can be reasonably predicted by pH and cation exchange capacity. Under actual field conditions, however, many other variables may affect this capacity.

The research reported in this paper produced the following results:

1. The highest concentrations of metals along highway rights-of-way are found in animal life. However, more than 10 m^2 (1076 ft^2) of topsoil had to be "turned over" to collect enough soil insects (grubs) for one metal-detection analysis.
2. The greatest mass of metals was found in the

soil of shoulder areas—approximately 5000 times more than that found in animals.

3. Lead concentrations were considerably higher in surface soils [top 2-3 cm (0.8-1.2 in)] than in subsurface soils [15-20 cm (6-8 in)] at the same location. This was not consistently found for the other metals. Therefore, lead is generally immobilized in roadside soils.

4. The concentration of metals in the soil decreased with distance from the edge of the pavement.

5. Based on a regression equation developed by Zimdahl and Skogerboe (13), which related pH and cation exchange capacity to lead retention of a soil, the soils tested have an additional capacity to retain lead that is more than 10 times their existing lead content.

6. The organic matter in soil is important and correlates well with the ability of soil to retain metals. In general, however, other factors are also important, such as clay minerals, pH, and chemical reactions. No one removal mechanism or soil characteristic was determined to be the most important. The types of reactions that can occur are likely to be site specific.

For areas where surface water discharges from highway rights-of-way to adjacent lands are limited, the following recommendations are made for design and maintenance of the land and water. The underlying concepts for these recommendations are based on percolation rates of the land and interactions between metal and soil:

1. Rainfall excess (runoff) should be directed as overland flow as much as possible to promote water percolation and removal of metals.

2. Runoff can be diverted from open or closed conduits into shallow holding areas to remove specified quantities of pollutants.

3. A "muck blanket" should be spread on the soil before vegetation is planted to promote removal of metals.

4. Subsurface soil should be alkaline to promote removal of metals. Organic matter and clay minerals also aid in the removal of metals.

5. Soils adjacent to pavements need to be replaced periodically because of metal saturation. Care should be exercised in the disposal of these soils.

When overland flow of surface runoff waters is not possible, the first flush of runoff water can be diverted for treatment. The volume of water diverted depends on the discharge limitation. Treatment can be accomplished by storage and percolation in median or shoulder areas. Formulas for determining diversion volume and the percentage efficiency of diversion systems are given in this paper.

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