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STORMWATER MANAGEMENT FOR HIGHWAY PROJECTS

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Introduction

Highway right-of-way's have many opportunities for stormwater management. For example, in suburban and rural areas, interchange cloverleaves provide locations suitable for detention facilities or biofiltration devices, while median strips and shoulder areas can contain grass swale drainages. In most cases, these controls should be suitable to provide adequate levels of stormwater treatment. However in some areas, additional controls may be required, especially to prevent detrimental effects associated with accidents involving transportation of hazardous materials.

There are many site-specific conditions that effect the potential problems that a highway may have on local water resources. Investigations are therefore needed to understand these local conditions and to develop the most cost-effective stormwater control program for a highway project. A highway runoff investigation can include the following main components:

- Investigate local resources and identify control objectives (identify areas having critical surface and groundwater resources and uses of these waters),
- characterize surface and subsurface flow paths,
- determine pollutant sources and runoff characteristics,
- study features affecting treatability of highway runoff, and
- conduct pilot-scale treatability tests before full-scale design and evaluation.

This paper is based on a presentation made at the *Symposium on the Pollution of Water Sources from Road Run-Off,* on March 19, 2001, at Tel Aviv University, Israel. It attempts to summarize some of the important features of highway runoff that should be considered when designing and carrying out a local investigation. This information should also be useful when making preliminary assessments of the potential problems that may occur and to help make preliminary selections of the components of an effective highway runoff control program. This paper includes discussions on: water quality problems associated with highway development, highway runoff characterization, and treatment of highway runoff. Conclusions and a list of references are also included.

Water Quality Problems Associated with Highway Development

The major water quality problems associated with highways include: erosion runoff during the construction period, stormwater runoff during the life of the highway, infrequent accidents involving toxic or hazardous materials, and associated surface and groundwater contamination.

Highway Construction Erosion

Many site characteristics affect the discharge of erosion materials from a construction site, including rain energy, soil texture, slope, and the use of erosion control practices. In addition, maintenance of heavy equipment at construction sites can also contribute pollutants. In some cases, highways must frequently cross over, or go near, streams and rivers. If construction must take place in streams, dramatically increased water pollution problems may occur.

Much data is available to illustrate the potential magnitude of erosion from construction sites. As one example, Table 1 lists measured suspended solids concentrations and particle sizes for monitored construction sites in the Birmingham, AL, area (Nelson 1996). As shown in this table, high rain intensities are associated with dramatically increased suspended solids concentrations and larger particle sizes, while less intense rains are associated with smaller particle sizes and lower suspended solids concentrations. Erosion rates can vary greatly, with typical values of about 20 to 30 tons per acre per year in most areas of the US, but can increase to 100 to 300 tons per acre per year in areas of the southeast that have very high rain energies, fine-grained soils, and steep slopes. It can be difficult to achieve adequate levels of erosion control in many areas due to the small size of the particulates in the runoff and the high levels of control needed. Careful planning and prevention of erosion have been shown to be more effective than reducing the sediment from the flowing water (Barrett, *et al.* 1995).

Table 1. Construction Site Erosion Runoff Characteristics (Nelson 1996)

	Low Intensity Rains (<0.25 in/hr)	**Moderate Intensity Rains (about 0.25 in/hr)**	**High Intensity Rains (>1 in/hr)**
Suspended solids (mg/L)	400	2,000	25,000
Particle size, median (µm)	3.5	5	8.5

Increased Flow Rates and Runoff Pollutant Concentrations

A well-known detrimental effect associated with increasing the paved area in a drainage area is increased runoff volumes and flowrates. Figure 1 illustrates these increased runoff characteristics associated with a developed watershed, compared to an undeveloped watershed, in Bellevue, WA, (Richey 1982). In this example, the increased flowrates are seen to be about three to five times greater for the developed area compared to the undeveloped area. In addition, the increased runoff volumes are several times larger for the developed area compared to the undeveloped area. Increased durations of high flows affect receiving waters and aquatic life by enlarging the cross-sectional areas of the streambed and obvious associated instability and scour. This direct habitat destruction is likely responsible for most of the aquatic life problems found in streams affected by increased amounts of pavement.

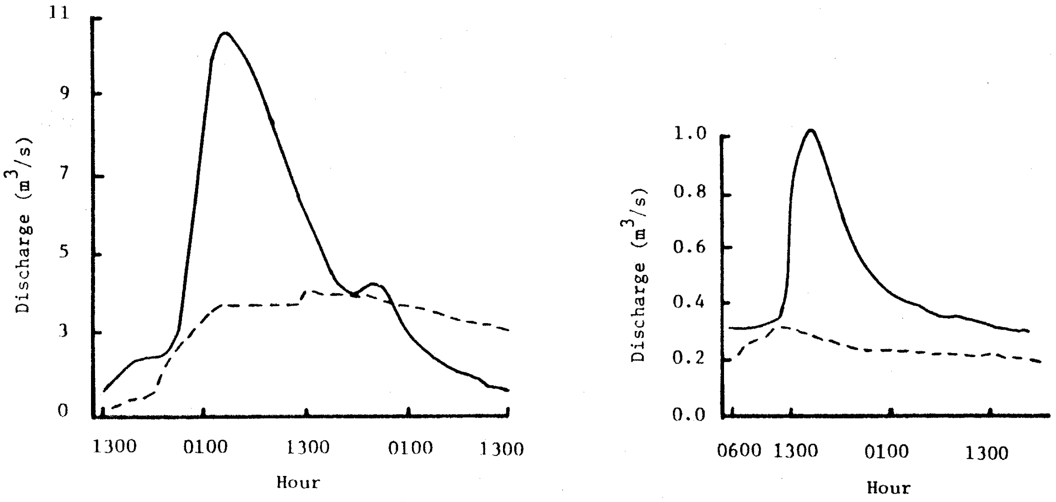

Figure 1. High flow rates in urban area compared to rural area, Bellevue, WA (Richey 1982.)

In addition to increased periods of high flows, elevated concentration of pollutants are also found in receiving waters affected by increased amounts of pavement. The durations of high concentrations may also be quite long. Figure 2 is an example of a monitored storm series in Five-Mile Creek in Birmingham, AL (Easton 2000). The durations of elevated turbidity and dissolved solids concentrations in this receiving water (and interstitial sediment water) is several times longer than the duration of the elevated flows. Many receiving water evaluations assume that the durations of these elevated concentrations is similar to the duration of elevated flows. These increased durations of contaminated conditions can dramatically increase the effects on receiving water uses (especially water supply, aquatic life and recreation uses).

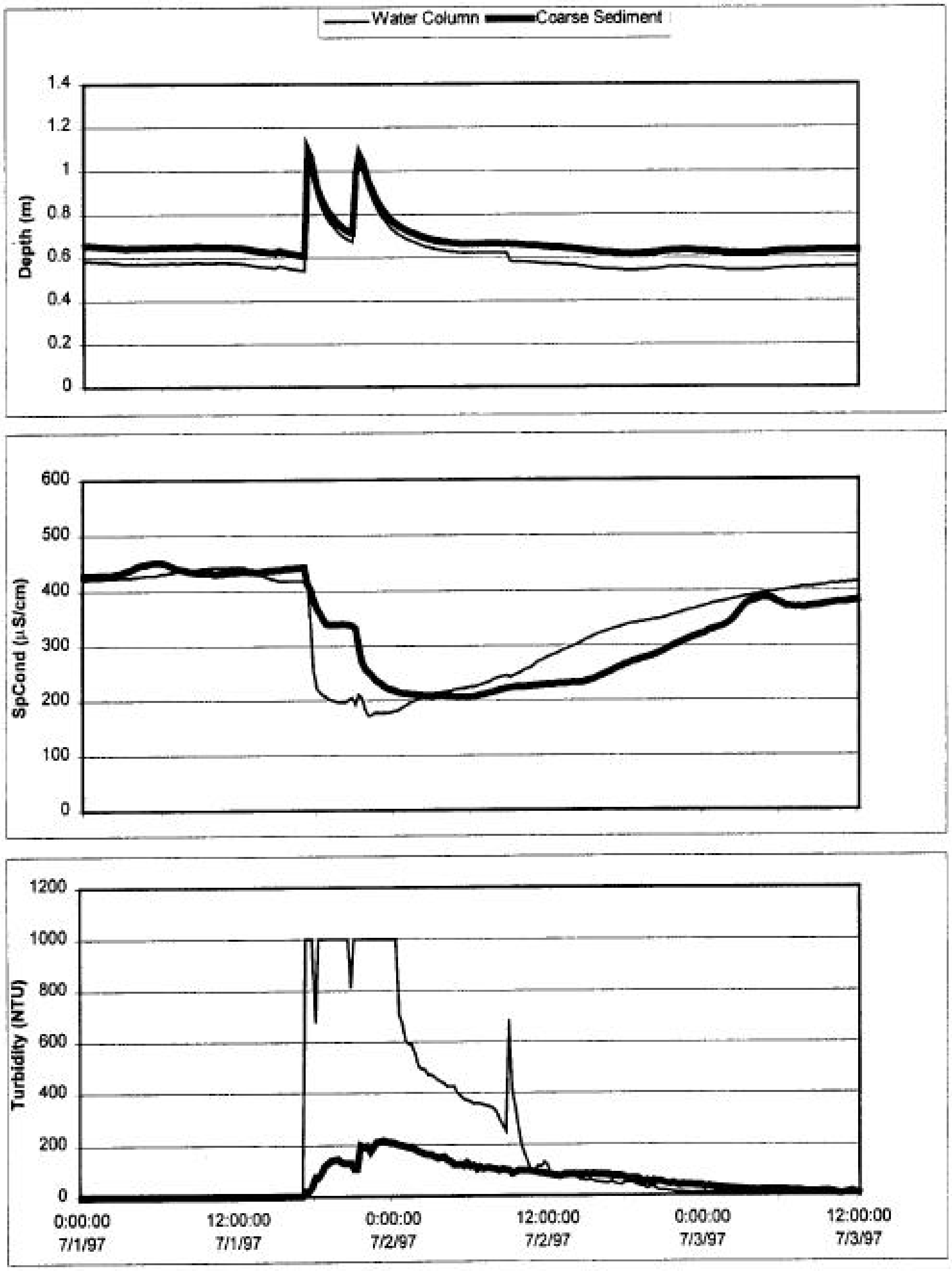

Figure 2.Long duration of elevated high turbidity and dissolved solids during rain events (Easton 2000).

In addition to elevated turbidity and suspended solids concentrations during periods of construction, runoff from paved roadways also contains elevated concentrations of heavy metals. Figure 3 shows the probability of exceeding critical lead concentrations at a low-traffic highway site in western Washington (Horner and Mar 1984). This figure shows that untreated stormwater from this highway likely exceeds the maximum allowable aquatic life concentrations for lead during more than half of the rains for moderate to low hardness conditions and would require removal of more than 90% of the lead to meet the drinking water standard.

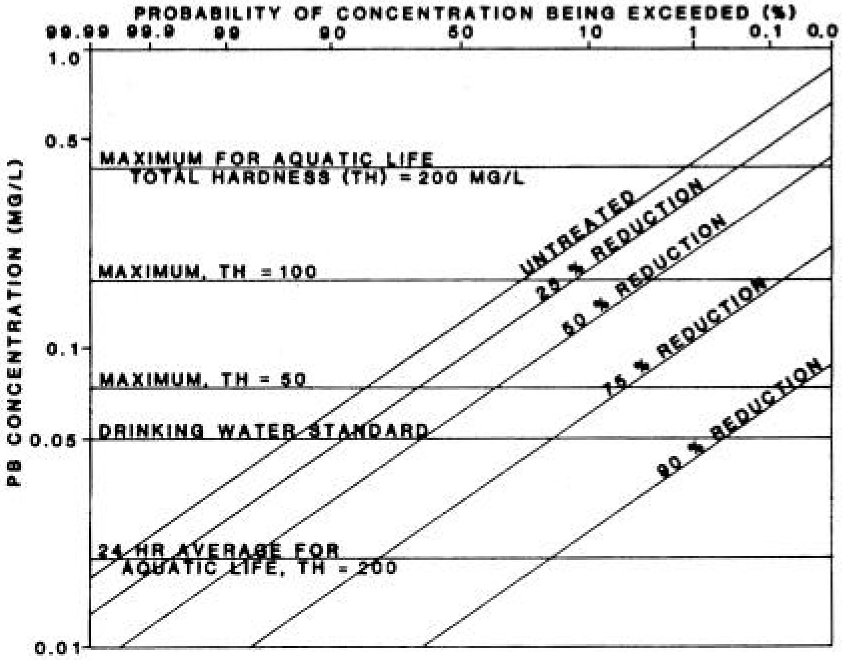

Figure 3. Probability of lead in highway runoff exceeding various water quality standards, low traffic volume highway in western WA (Horner and Mar 1984).

Potential Groundwater Contamination

Groundwater contamination by stormwater can also be serious. Nonintentional contamination may occur during natural infiltration at nonpaved areas, while intentional contamination can occur where stormwater is used to recharge groundwater, when infiltration of stormwater occurs in grass drainage swales, in infiltration trenches, at porous pavement sites, and in percolation ponds. Stormwater infiltration practices should therefore be used with extreme caution in areas where important groundwater is susceptible to contamination.

The following discussion is summarized from several recent publications that contained reviews of research projects that investigated the groundwater contamination potential by stormwater (Pitt, *et al.* 1994 and 1996; and Pitt, *et al.* 1999). General causes of concern indicating probable groundwater contamination potential for stormwater pollutants include:

- high mobility (low sorption potential) in the vadose zone,
- high abundance (high concentrations and high detection frequencies) in stormwater, and
- large soluble fractions (small fraction associated with particulates which would have little removal potential using conventional stormwater sedimentation controls) in the stormwater.

The contamination potential is the lowest rating of the influencing factors. As an example, if no pretreatment was to be used before percolation through surface soils, the mobility and abundance criteria are most important. If a compound was mobile, but was in low abundance (such as for VOCs), then the groundwater contamination potential would be low. However, if the compound was mobile and was also in high abundance (such as for sodium chloride, in certain conditions), then the groundwater contamination potential would be high. If sedimentation pretreatment was to be used before infiltration, then some of the pollutants will likely be removed before infiltration. In this case, all three influencing factors (mobility, abundance in stormwater, and soluble fraction) would be considered important. As an example, chlordane would have a low contamination potential with sedimentation pretreatment, while it would have a moderate contamination potential if no pretreatment was used. In addition, if subsurface infiltration/injection was used instead of surface percolation, the compounds would most likely be more mobile, making the abundance criteria the most important, with some regard given to the filterable fraction for operational considerations.

Nitrates are one of the most frequently encountered contaminants in groundwater. Whenever nitrogen-containing compounds come into contact with soil, a potential for nitrate leaching into groundwater exists. Roadway runoff has been documented as the major source of groundwater nitrogen contamination in urban areas of Florida (Hampson 1986; Schiffer 1989; and German 1989). This occurs from both vehicular exhaust onto road surfaces and onto adjacent soils, and from roadside fertilization of landscaped areas. Roadway runoff also contains phosphorus from motor oil use and from other nutrient sources, such as bird droppings and animal remains, that has contaminated groundwaters (Schiffer 1989). Nitrate has leached from fertilizers and affected groundwaters under turf grasses in urban areas, including at golf courses, parks and home lawns (Petrovic 1990; Ku and Simmons 1986; and Robinson and Snyder 1991). Nitrates have a low to moderate groundwater contamination potential for both surface percolation and subsurface infiltration/injection practices because of its relatively low concentrations found in most stormwaters. If the stormwater nitrate concentration were high, then the groundwater contamination potential would likely also be high.

Urban pesticide contamination of groundwater can result from municipal and homeowner use of pesticides for pest control and their subsequent collection in stormwater runoff. Pesticides that have been found in urban groundwaters include: 2,4-D, 2,4,5-T, atrazine, chlordane, diazinon, ethion, malathion, methyl trithion, silvex, and simazine. Heavy repetitive use of mobile pesticides on irrigated and sandy soils likely contaminates groundwater. The most mobile pesticides include: 2,4-D, acenaphthylene, alachlor, atrazine, cyanazine, dacthal, diazinon, dicamba, malathion, and metolachlor. Fungicides and nematocides must be mobile in order to reach the target pest and hence, they generally have the highest groundwater contamination potential. Pesticides are used in urban areas, primarily for weed and insect control in houses, along roadsides, in parks, on golf courses, and on private lawns (Racke and Leslie 1993). The pesticide loading in runoff water has been correlated to the amount of impervious cover and to the distance the runoff will travel prior to infiltration or decomposition, as shown in Austin, Texas by Butler, *et al.* (1987). Samples from the upper part of the Floridan aquifer have contained detectable amounts of diazinon, malathion, 2,4-D, ethion, methyl trithion, silvex, and 2,4,5-T (German 1989). Atrazine and simazine groundwater contamination was related to their use to control weeds along roadways (Domagalski, *et al.* 1992). Lindane and chlordane have moderate groundwater contamination potentials for surface percolation practices (with no pretreatment) and for subsurface injection (with minimal pretreatment). The groundwater contamination potentials for both of these compounds would likely be substantially reduced with adequate sedimentation pretreatment.

The most commonly occurring organic compounds that have been found in urban groundwaters include phthalate esters (especially bis(2-ethylhexyl)phthalate) and phenolic compounds. Other organics more rarely found, possibly due to losses during sample collection, have included the volatiles: benzene, chloroform, methylene chloride, trichloroethylene, tetrachloroethylene, toluene, and xylene. Groundwater contamination from organics, like from other pollutants, occurs more readily in areas with sandy soils and where the water table is near the land surface. 1,3-dichlorobenzene may have a high groundwater contamination potential for subsurface infiltration/injection (with minimal pretreatment). However, it would likely have a lower groundwater contamination potential for most surface percolation practices because of its relatively strong sorption to vadose zone soils. Both pyrene and fluoranthene would also likely have high groundwater contamination potentials for subsurface infiltration/injection practices, but lower contamination potentials for surface percolation practices because of their more limited mobility through the unsaturated zone (vadose zone). Others (including benzo(a)anthracene, bis (2-ethylhexyl) phthalate, pentachlorophenol, and phenanthrene) may also have moderate groundwater contamination potentials, if surface percolation with no pretreatment, or subsurface injection/infiltration is used. These compounds would have low groundwater contamination potentials if surface infiltration was used with sedimentation pretreatment. Volatile organic compounds (VOCs) would also have high groundwater contamination potentials if present in the stormwater (likely at the scene of highway accidents, for some industrial and commercial facilities, and vehicle service establishments, but unlikely for most other areas).

In general, studies of recharge basins receiving large metal loads found that most of the heavy metals are removed either in the basin sediment or in the vadose zone. Dissolved metal ions are removed from stormwater during infiltration mostly by adsorption onto the near-surface particles in the vadose zone, while the particulate metals are filtered out at the soil surface. Metals may be a problem when infiltrating stormwater using a rapid infiltration system (Crites 1985), such as a dry well. Most metals have very low solubilities at the pH levels found in most natural waters and they are readily removed by either sedimentation or sorption removal processes (Hampson 1986). Many are also filtered, or otherwise sorbed, in the surface layers of soils in infiltrating devices when using surface infiltration. Nickel and zinc would likely have high groundwater contamination potentials if subsurface infiltration/injection was used. Chromium and lead would have moderate groundwater contamination potentials for subsurface infiltration/injection practices. All metals would likely have low groundwater contamination potentials if surface infiltration was used with sedimentation pretreatment.

Viruses have been detected in groundwater where stormwater recharge basins were located short distances above the aquifer. Enteric viruses are more resistant to environmental factors than enteric bacteria and they exhibit longer survival times in natural waters. The two most important attributes of viruses that permit their long-term survival in the environment are their structure and very small size. Once the virus reaches the groundwater, it can travel laterally through the aquifer until it is either adsorbed or inactivated. The major bacterial removal mechanisms in soil are straining at the soil surface and at intergrain contacts, sedimentation, sorption by soil particles, and inactivation. Because of their larger size than for viruses, most bacteria are retained near the soil surface due to the straining effect. Viruses were detected in groundwater on Long Island at sites where stormwater recharge basins were located less than thirty-five feet above the aquifer (Vaughn, *et al*. 1978). At other locations, viruses have likely been removed from the percolation water by either adsorption and/or inactivation. As expected, the highest bacteria and virus groundwater concentrations occur when the water table is near the land surface (Boggess 1975). Enteroviruses likely have a high groundwater contamination potential for all percolation practices and subsurface infiltration/injection practices, depending on their presence in stormwater (such as if contaminated with sanitary sewage). Other pathogens, including *Shigella*, *Pseudomonas aeruginosa*, and various protozoa, would also have high groundwater contamination potentials if subsurface infiltration/injection practices are used.

Salt applications for winter traffic safety is a common practice in many northern areas and the sodium and chloride, which are collected in the snowmelt, travel down through the vadose zone to the groundwater with little attenuation. Salts that are still in the percolation water after it travels through the vadose zone will contaminate the groundwater. At three stormwater infiltration locations in Maryland, the nearby use of deicing salts and their subsequent infiltration to the groundwater shifted the major-ion chemistry of the groundwater to a chloride-dominated solution. Although deicing occurred only three to eight times a year, increasing chloride concentrations were noted in the groundwater throughout the 3-year study, indicating that groundwater systems are not easily purged of conservative contaminants, even if the groundwater flow rate is relatively high. Sodium and/or calcium concentrations also were constantly elevated in the groundwater beneath and downgradient of the infiltration devices (Wilde 1994). Chloride would likely have a high groundwater contamination potential in areas where road salts are used for traffic safety, irrespective of the pretreatment, infiltration or percolation practice used.

The Technical University of Denmark (Mikkelsen, *et al*. 1996a and 1996b) has been involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. They found that heavy metals and PAHs present little groundwater contamination threat, if surface infiltration systems are used. However, they express concern about pesticides which are much more mobile. Mull (1996) stated that traffic areas are the third most important source of groundwater contamination in Germany (after abandoned industrial sites and leaky sewers). The most important contaminants are chlorinated hydrocarbons, sulfate, organic compounds, and nitrates.

Kobriger and Geinoplos (1984) studied groundwater contamination associated with highway runoff at a major highway location in the Milwaukee, WI, area. Table 2 summarizes some of the observed elevated concentrations that were found in this groundwater. Elevated concentrations of lead, zinc, and copper were noted in the groundwater up to 12 meters from the roadway, while concentrations of these metals and solids appeared to reach background concentrations at distances approaching 25 meters.

Table 2. Groundwater Pollutant Concentrations Near Major Highway, Milwaukee, WI (mean concentration at distance from edge of pavement) (Kobriger and Geinoplos 1984)

all mg/L	2 m	12 m	24.5 m
Total solids	2150	326	379
Lead	1.5	0.2	nd
Zinc	0.88	0.80	0.08
Copper	1.2	0.16	0.03

Shaw and Berndt (1990) examined groundwater contamination associated with runoff from paved areas in Stevens Point, WI. Although the most dramatic contamination was caused by the use of salt for deicing on winter roadways, elevated heavy metals and polyaromatic hydrocarbons (PAHs) were found in groundwaters close to infiltration areas and in areas having shallow groundwater. In areas having surface infiltration and deeper groundwater, few heavy metals had elevated concentrations. The major source of the contamination was found to be direct infiltration of stormwater in road side drainage ditches. In several instances, very high levels of petroleum hydrocarbons in the groundwater were thought to be associated with spilled fuel that entered the drainage systems during an accident.

One of the earliest examinations of stormwater impacts on groundwater from highway projects was noted in the Austin, TX, area where concern was expressed about development in the Edwards aquifer recharge area. This area has Karst geology that allows surface runoff to quickly drain to the groundwater with immediate downstream effects in the Barton Springs area. Elevated concentrations of suspended solids and hide turbidity levels are noted in this recreation area quickly after rainfall starts. The concern for this obvious contamination of the Edwards aquifer lead to one of the earliest stormwater control programs in the U.S. that specifically addressed groundwater contamination. Land use controls and special treatment programs for stormwater were required in the recharge area. As an example, special controls were acquired after the construction of the MoPac freeway. Concern was expressed over infiltrating stormwater in the grass swale drainages in the freeway lengths that passed over the aquifer recharge zone, in addition to potential contamination associative with accidents involving transported hazardous and toxic materials. Special control devices were therefore installed where the roadway crossed the recharge areas. These controls were designed to contain the entire potential loss from any truck moving along the roadway, preventing the spilled material from affecting the local groundwater.

Releases of Toxic and Hazardous Materials during Highway Accidents

Accidents involving the release of toxic or hazardous materials during their transportation may also cause severe environmental and social problems. Becker, *et al*. (2001) recently examined transportation-related accidents involving hazardous materials in Alabama using data from the US Coast Guard's National Response Center (http://www.nrc.uscg.mil/). In the past 10 years, more than 1700 transportation related accidents have occurred in Alabama involving hazardous materials. Of the 226 reported accidents in 1998, there were 20 deaths and 27 injuries. In addition, two accidents resulted in evacuations, and nine accidents resulted in road closures. Twenty seven percent of the 226 reported 1998 Alabama transportation-related accidents occurred on highways, and more than half of the accidents directly affected water.

By far, the most common (and the largest) classes of material spilled were petroleum oils and fuels (fuel oil, crude oil, kerosene, gasoline and diesel fuel). Ammonia material spills were also common. In addition to these, ethylene glycol was also commonly spilled. Many of the most hazardous substances were only associated with one or a very few number of incidents in the ten years of study, and only relatively small quantities of some materials were lost. However, more than 20 hazardous material categories (including ammonium nitrate, fuel oil, mixed hazardous wastes, molten aluminum, propionic acid, liquid and granular fertilizers, styrene, aniline, jet fuel, methyl ethyl ketone, battery recycling wastes, molten sulfur, automobile gasoline, formic acid mixtures, and monochloroacetic acid) had median spill quantities of more than 1,000 lbs lost in each accident.

If transportation accidents involving hazardous materials are lost in sensitive areas and not contained, these materials can cause severe environmental and social problems. Becker, *et al.* (2001) reviewed several case studies describing the social problems and also presented an outline for evaluating the risks associated with losses of different materials during transportation accidents.

Monitoring Needs to Evaluate Site-Specific Problems Associated with Highway Development

A number of different monitoring approaches must be used in order to evaluate receiving waters affects associated with highway development. Table 3 shows the key weight-of-evidence components for assessing stormwater effects (Burton and Pitt 2001). This table shows the many monitoring components that may be necessary for these evaluations. High-priority evaluations including examinations of the benefit community in the sentiment. Laboratory-based water toxicity evaluations, and both sediment and water *in situ* toxicity tests are also important. In addition, basic sediment and water quality analyses stressing heavy metals, organic compounds, and conventional pollutants should also be conducted. Finally, flow measurements and habitat assessments are also needed in a basic receiving water evaluation. When groundwater contamination is an issue, this list needs to be greatly expanded to consider both soil and groundwater properties.

Table 3. Key Weight of Evidence Components for Assessing Stormwater Effects (Burton and Pitt 2001)

Study Component	**Media being tested**	**Difficulty**
Benthic Community	Sediment (**high priority**)	Low difficulty
Fish Community	Water (medium priority)	Medium difficulty
Toxicity – lab based	Sediment (medium priority) Water (**high priority**)	Low-medium difficulty
Toxicity – *in-situ*	Sediment and water (**high priority**)	Low-medium difficulty
Bioaccumulation – benthic and fish	Organism (medium priority)	Medium-high difficulty
Bioaccumulation – passive	Water (low priority)	Medium-high difficulty
Chemical analyses (metals, organics, and conventional constituents)	Sediment and water (**high priority**)	Medium-high difficulty
Flow measurements	Water (**high priority**)	Low difficulty
Habitat assessments	Stream (**high priority**)	Low difficulty

Highway Runoff Characterization

Monitoring highway runoff must consider seasonal effects, and differences due to rain intensity, duration, and interevent periods. The effects of traffic characteristics, including the numbers of vehicles, the percentage of truck traffic, and emission controls, plus different pavement types, may also affect highway runoff quality and should therefore be included in the design of a highway runoff monitoring program.

Typical Highway Runoff Water Quality Conditions

Table 4 summarizes results from the EPA's Nationwide Urban Runoff Program (NURP) (EPA 1983). Median and 90th percentile concentrations are shown for some of the more common constituents of concern in stormwater runoff. These data were mostly for residential areas but did include some commercial and a few industrial and highway sites. Table 5 is a summary prepared by the University of Texas (Barrett, *et al.* 1995) showing concentrations of highway stormwater constituents from many different monitoring projects from throughout the country. This table also shows the annual unit area pollutant loadings from these monitored highway sites.

Table 4. Nationwide Urban Runoff Program (NURP) Runoff Characterization Summary (EPA 1983)

Constituent (mg/L, unless otherwise noted)	Median Concentration	90th Percentile Concentration
Suspended solids (SS)	100	300
Chemical Oxygen Demand (COD)	65	140
Total Phosphorus (P)	0.33	0.70
Total Kjeldahl Nitrogen (TKN)	1.5	3.3
Nitrite plus nitrate (NO_2+NO_3)	0.68	1.8
Total copper (Cu) (μg/L)	34	96
Total lead (Pb) (μg/L)	144	350
Total zinc (Zn) (μg/L)	160	500

Table 5. Highway Runoff Characteristics (summarized from many studies, as reported by Barrett, *et al.* 1995)

Constituent	Concentration (mg/L, unless otherwise noted)	Annual Unit Area Loading (kg/ha/yr)
Suspended solids	45-798	314-11,900
Total Kjeldahl Nitrogen	0.24-55	1.7-32
Nitrite plus nitrate	0.15-1.6	0.8-8.0
Phosphorus	0.11-1.0	0.6-8.2
Chemical Oxygen Demand	15-270	130-3900
Cadmium	nd-0.04	0.007-0.04
Copper	0.022-7.0	0.03-4.7
Chromium	nd-0.04	0.01-0.1
Lead	0.07-1.8	0.08-21
Zinc	0.056-0.93	0.22-10

In most cases the concentrations of runoff from highway sites are substantially greater than the concentrations observed during NURP. As an example, the maximum highway copper concentrations were about 7 mg/L, while the 90th percentile during NURP was less than 0.01 mg/L. In addition, the highway copper minimum level was similar to the median NURP copper level. Similar elevated concentrations are also seen for the other heavy metals. The suspended solids, nutrients, and COD maximum concentrations for highway runoff were all about twice the 90th percentile recorded during NURP.

Table 6 shows the variables that have been found to affect the loads for different constituents found in highway runoff (Barrett, *et al*. 1995). Storm volume (rain depth) has an important influence for all of the pollutants listed. Storm intensity, storm duration, and antecedent traffic also affected the loadings for many of the pollutants. A highway stormwater monitoring program should therefore consider these important factors.

Table 6. Variables Affecting Highway Runoff Quality (Barrett, *et al.* 1995)

	Storm duration	Storm volume	Storm intensity	Vehicles during storm	Antecedent dry period length	Antecedent traffic count
Suspended solids		*	*		*	
Zinc	*	*				*
COD	*	*	*		*	*
Phosphorus	*	*	*			*
Nitrate		*	*			*
Lead		*	*	*		
Copper	*	*		*		
Oil and grease		*		*		

Kayhanian, *et al*. (2001) recently published a summary of the stormwater management program being conducted by Caltrans (the California Department of Transportation). Table 7 is a summary of the highway runoff quality data being collected at about 100 locations throughout California, during the 1999-2000 monitoring season. Some of their notable finding include:

- Generally, these concentrations are similar to those reported elsewhere and compare with the earlier FHWA (Federal Highway Administration) results for highway runoff.
- Some correlations of concentrations with highway traffic levels were found for most pollutants.
- More than 30% (based on median values) of the total arsenic, cadmium, chromium, copper, nickel, silver, and zinc were associated with the dissolved fractions.
- First-flush (high concentrations) occurring at the beginning of individual storms was not always observed. They are also investigating expected higher concentrations during the initial storms of the rain season.
- Special litter studies found that vegetative debris constituted about half of the collected litter (by weight), and plastic and Styrofoam materials were the next largest categories. Cigarette butts constituted the largest fraction by count.
- Erosion control investigations found that bonded fiber mats and coconut blanket erosion mats provided nearly 100% erosion prevention, and straw blankets, wood-fiber blankets, and incorporation of wheat straw, all provided more than 90% erosion prevention.

Monitoring pollutant sources should also be an important consideration during highway runoff projects. There are a number of different sources for the pollutants found in highway runoff. Atmospheric deposition, exhaust emissions, pavement wear, tire wear, and soil erosion all have been found to be important contributors of highway runoff pollutants. Knowing the street dirt accumulation rates and removal mechanisms is needed in order to assess alternative management programs. Washoff during rain storms, and fugitive dust losses due to traffic and wind turbulence, greatly affect the role of different stormwater management practices. In addition, the pollutant concentrations associated with different particle sizes also influence stormwater treatment effectiveness.

Roadside erosion materials have been found to be one of the largest sources of particulate material found on streets. Once on the roads, the local soils become contaminated with vehicle exhaust and other pollutants on the road surface. Table 8 lists typical concentrations of the road surface particulates found on streets summarized from many U.S. studies. These concentrations are all much greater than the chemical concentrations found in the natural soils.

Table 7. 1999-2000 Caltrans Highway Monitoring Data (Kayhanian, *et al.*, 2001)

	Range	**Median**
Conventional Constituents (mg/L, unless otherwise noted)		
Chemical Oxygen Demand (COD)	10-390	100
Hardness (as $CaCO_3$)	3.3-448	42
Total dissolved solids (TDS)	14-470	88
Total suspended solids (TSS)	3-4800	76
Turbidity (NTU)	9.9-290	110
Metals (µg/L)		
Aluminum (total)	29-12,600	1900
Aluminum (dissolved)	2.2-2500	19
Arsenic (total)	1-17	1.4
Arsenic (dissolved)	0.5-10	1
Cadmium (total)	0.5-378	0.69
Cadmium (dissolved)	0.25-13	0.25
Chromium (total)	1-100	6.7
Chromium (dissolved)	0.5-22	2.1
Copper (total)	1-800	29
Copper (dissolved)	1-154	11
Iron (total)	4.1-24,000	2300
Iron (dissolved)	1-7500	50
Lead (total)	1-2300	31
Lead (dissolved)	1-160	1.6
Nickel (total)	0.91-317	7.9
Nickel (dissolved)	0.5-36	2.5
Silver (total)	0.25-82	0.25
Silver (dissolved)	0.25-1	0.25
Zinc (total)	5-2400	150
Zinc (dissolved)	1-1180	45
Nutrients (mg/L)		
Ammonia, as N	0.19-4	1.1
Nitrate, as N	0.1-9.5	1
Nitrite, as N	0.05-1.7	0.05
Ortho-phosphate, as P	0.03-1.0	0.14
Total Kjeldahl Nitrogen (TKN)	0.1-57	1.8
Total phosphorus	0.05-10	0.18
Microbiological (#/100 mL)		
Total Coliforms	20-500,000	1300
Fecal Coliforms	17-160,000	230
Oil and Grease (mg/L)	1-226	6

Table 8. Street Dirt Chemical Quality (Pitt 1979 and 1985; Bannerman, *et al.* 1983; and others)

Constituent	**mg constituent/kg total solids**
Phosphorus	400-1500
Total Kjeldahl Nitrogen	290-4300
Chemical Oxygen Demand	65,000-340,000
Copper	110-420
Lead	530-7500
Zinc	260-1200
Cadmium	<3-5
Chromium	31-180

Accumulation and Washoff of Roadway Particulates

The amount of street dirt particulates on a road varies for different land uses, road textures, seasons and traffic conditions. Figure 4 is a plot showing the variations in street dirt loadings for different street textures in San Jose, CA (Pitt 1979). The accumulation rates (slopes of the loading curves) were similar for these two test sites, but the loadings varied dramatically for the different street textures. Rough streets always have higher loadings as the particulates are protected in the indentations on the street. Rain, wind and traffic turbulence, and street cleaning, all have reduced abilities in removing this material on rough streets compared to smooth streets. In addition, during dry weather, the street dirt can accumulate to much higher levels than during wet weather when frequent rainfall keeps the loadings at reduced levels. The washoff of street surface particulates is dependent mostly on the amount of rainfall (Pitt 1987). During heavy rains, more of the street dirt is removed than during lighter rains. However, in most cases the amount that is removed during any individual rain is quite small compared to the total loading on the street. Pitt (1987) found that the maximum amount of washoff of street dirt is usually only between 10 and 15 percent of the total loading on the street. However, much more of the smaller particles are washed off than the larger particles during rains, as shown on Figure 5.

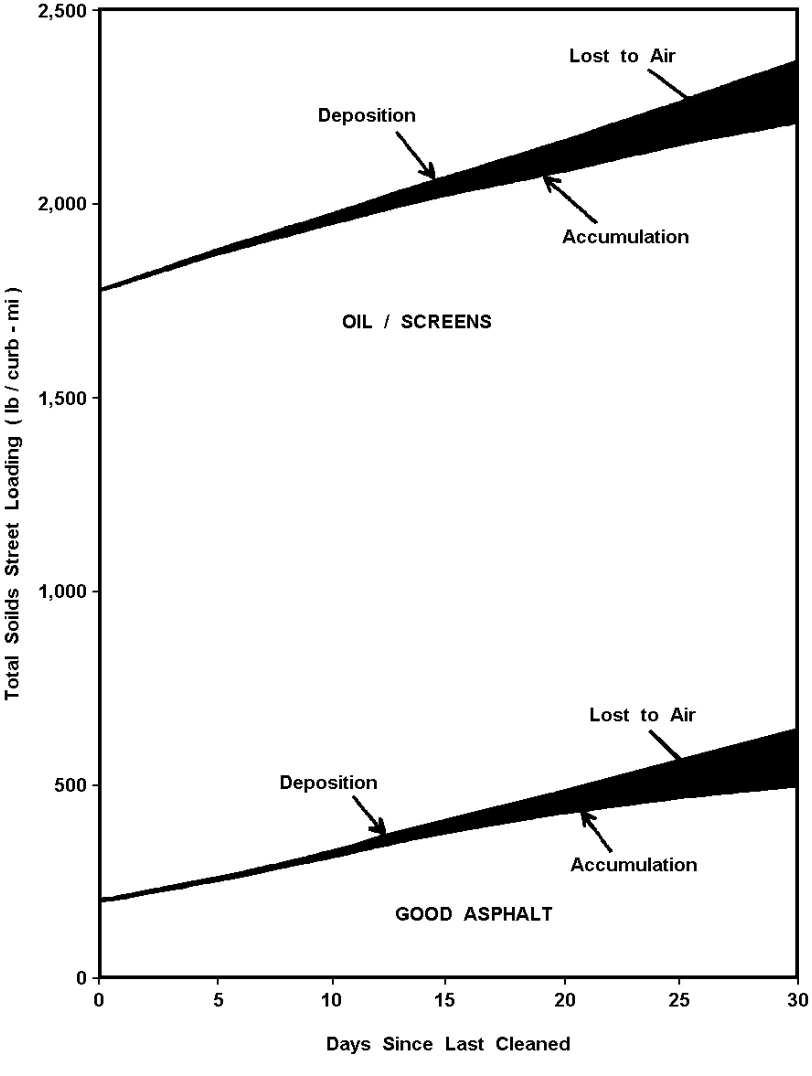

Figure 4. Street dirt accumulations for different textured roadways (Pitt 1979).

Figure 5 shows the washoff of different sizes of street surface particulates during observed rains in Bellevue WA (Pitt 1985). As shown, the small particles < 63 µm in diameter can have washoff rates of 35 to 50 percent, while the largest particle sizes actually may increase in loadings on the street due to wash on of erosion materials from nearby land.

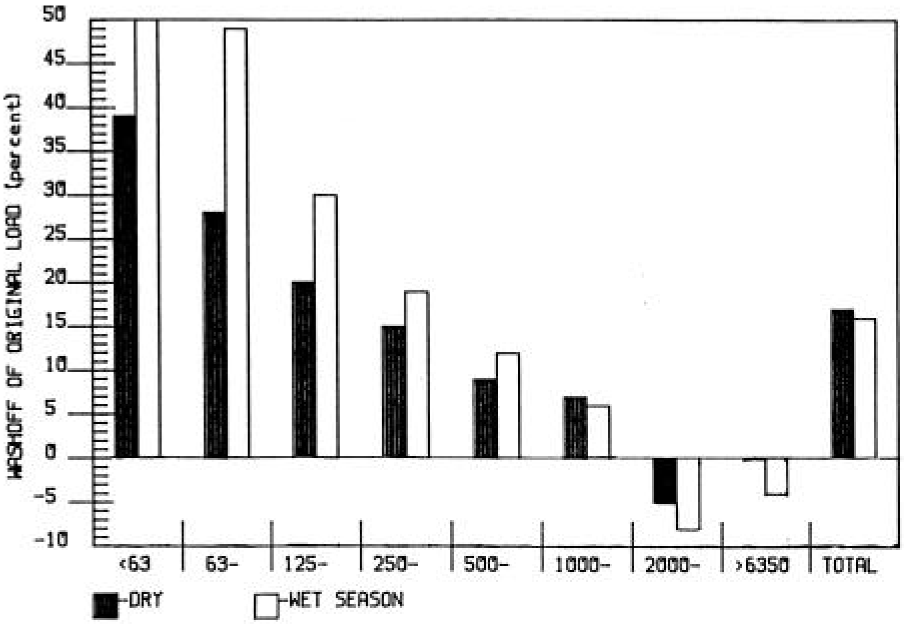

Figure 5. Observed street dirt washoff during rains, Bellevue, WA (Pitt 1984)

Fugitive dust losses can be large and account for much of the street dirt materials removed from highways. Table 9 shows the fugitive dust losses from different pavements as a function of vehicle activity during tests conducted in San Jose, CA (Pitt 1979), for example.

Table 9. Fugitive Dust Losses from Roadways (Pitt 1979)

Study Area and Asphalt Condition	Fugitive Dust Loss per Length of Road (lb/curb-mile/day)	Fugitive Dust Loss per Vehicle Use (grams/vehicle-mile)
Keyes, good asphalt	6	0.33
Keyes, oil and screens overlay	4	18
Tropicana, good asphalt	6	2.5

Treatment of Highway Runoff

Many factors affect the treatability of highway runoff pollutants. These may include the particle size distribution, the association of pollutants with different particle sizes (especially the “dissolved” size fraction), the settling rate of the particulates, the mobility of the pollutants in the vadose zone, the soil contamination potential long the flow paths, and the fugitive dust resuspension rate. The most important of these factors for many control practices is probably the particle size distribution. Figure 6 shows typical particle size distributions for many runoff samples obtained at the intake to the Monroe Street detention pond in Madison, WI (USGS and Wisconsin DNR data). This plot includes bedload samples captured using special sampling devices, along with the suspended solids and dissolved solids particle size distributions. The median particle size ranges from about 2 to 30 µm, while the average median particle size is about 8 µm. As much as 40% of the sample mass may be larger than 100 µm in diameter, although < 20% is a more common value for these larger sizes. In addition, only about 10% of the particles may be larger than 1 mm in size, while 10 to 30% of the particles are < 1 µm in size. Highway runoff samples may contain more of the larger particle sizes than shown on this plot, possibly due to increased energy from the fast vehicles traveling on the roads during rains.

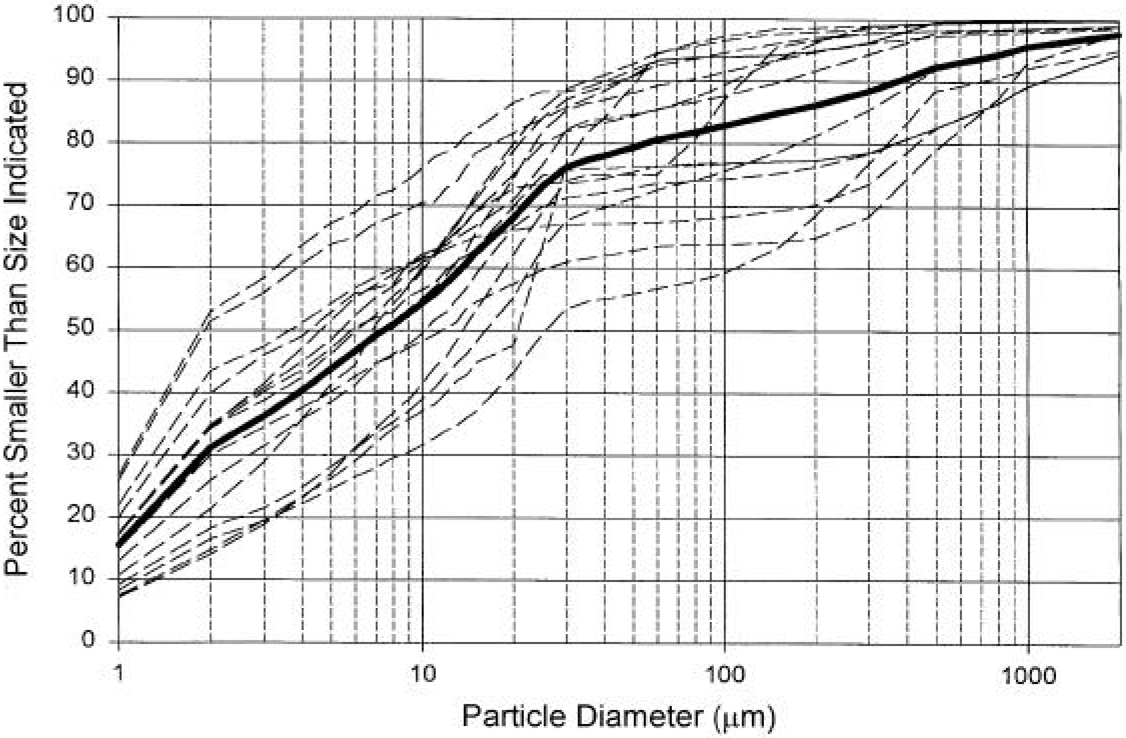

Figure 6. Stormwater particle size distribution, Madison, WI (USGS and WI DNR data).

Street Cleaning

Conventional street cleaning equipment preferentially removes the larger particle sizes from the street. In many cases, the loadings of small particles on the streets may actually increase, as shown on Figure 7. This figure shows two performance plots for different street textures in San Jose, CA (Pitt 1979). The plot for the rough oil and screens surfaced street showed only about an 8 percent overall reduction in total solids loading with street cleaning, with the effectiveness ranging from about 35 percent for the largest particles to an increase in loading of about 10 percent for the smallest sizes. On the smooth asphalt street, the street cleaning equipment performed much better, but still only showed a 12 percent reduction in loading for the smallest particle sizes that are most likely to be washed off during rains.

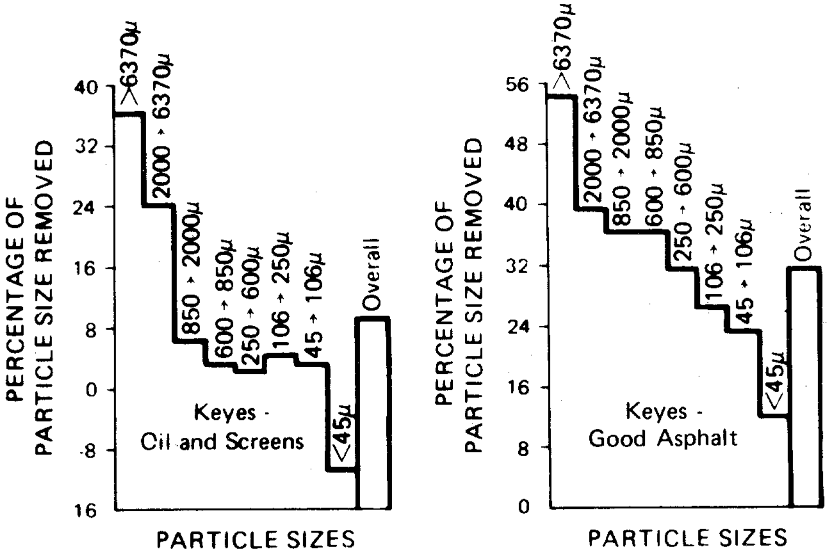

Figure 7. Street cleaning effectiveness for different particle sizes and street textures, San Jose, CA (Pitt 1979).

Grass Swale Drainages

Another common stormwater management practice used for highway runoff control is grass swale drainages. These are frequently used in median strips and in the shoulder areas of suburban and rural roadways. It is difficult to use swales in high-density urban locations. Table 10 is a summary of the pollutants concentrations found in grass drained sections of the MoPac highway in Austin, TX, along with concentration reductions compared to similar highway areas that have sealed drainages (Barrett, *et al.* 1995). This table shows concentration reductions of about 30 to more than 80%, while flow reductions are reported to be 90%. The overall mass reductions for the pollutants would therefore be at least 90%, and possibly more based on the additional concentration reductions reported.

Table 10. Removal of MoPac Highway Runoff Pollutants at Grass Swale Sites, Austin, TX (Barrett, *et al.* 1995).

	Roadway concentrations (mg/L)	**Concentration reductions in swales (%)**
Suspended solids	104	74
Chemical Oxygen Demand	51	35
Nitrates	0.88	59
Phosphates	0.15	31
Oil and grease	3.9	88
Copper	0.014	48
Lead	0.014	35
Zinc	0.074	74
Runoff volume		90% mass reduction of all of the above, at least

Wet Detention Ponds

Wet detention ponds are also a commonly used stormwater control practice for highways as they can be located in interchange areas at major road crossings. In many cases, wet detention ponds or wetlands can be constructed even in urban areas where this land cannot be used for other purposes. Wet ponds can provide high levels of control (approaching 90% reductions in suspended solids and pollutants mostly associated with particulate matter). However, in order to work well, they must be designed properly. The most critical aspect is that they must be relatively large (the normal water surface should generally be about 3% of the paved area plus about 0.5% of the nonpaved area in the watershed, plus they need to have at least 3 feet of standing water at all times to prevent scour).

Figures 8 and 9 are typical probability plots showing the influent and effluent concentrations of suspended solids and dissolved chemical oxygen demand (COD) in stormwater treated by a wet detention pond located in Madison Wisconsin (USGS and Wisconsin DNR data). For suspended solids, as shown in Figure 8, the two probability plots are roughly parallel indicating large and consistent concentration reductions over a wide range of influent conditions. However, Figure 9 shows that for filtered forms of COD, concentration reductions were only found when the influent concentrations were relatively high, and there were no significant reductions when the influent had lower concentrations. These two plots illustrate the two most common types of behavior for pollutant reductions in wet detention ponds, although for many filtered pollutants, no reductions in concentrations are noted for any influent condition. In addition, wet detention ponds do not provide any reduction in runoff volume, but can have significant benefits when reducing peak flow rates. Detention ponds, and other large storage areas, can provide important locations where some of the spilled material from traffic accidents can temporarily accumulate and be safely removed before entering the receiving waters.

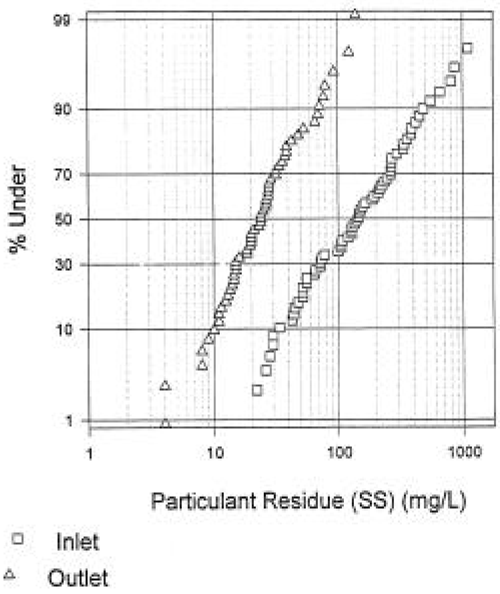

Figure 8. Reduction of suspended solids at the Monroe St. wet detention pond, Madison, WI (USGS and WI DNR data).

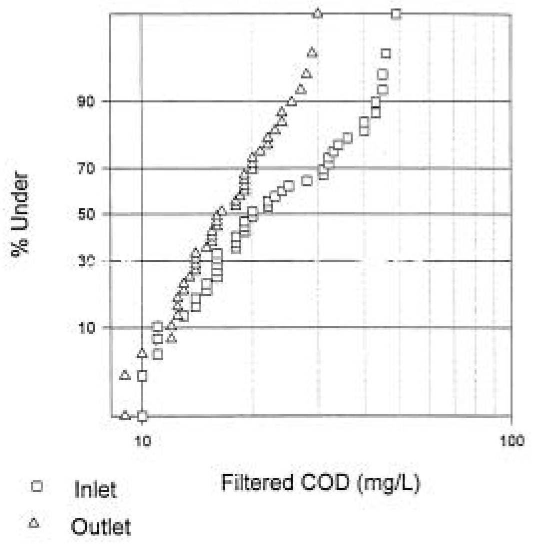

Figure 9. Reduction of dissolved COD at the Monroe St. wet detention pond, Madison, WI (USGS and WI DNR data).

Capture of Spilled Hazardous Materials

Special devices have also been designed and used in several cities to enhance the control of spilled material lost during accidents involving hazardous substances. Austin, TX, for example, has installed combination stormwater control practices at locations where the MoPac freeway crosses Barton Creek, a major aquifer recharge area for the Edwards aquifer. The grass swales along critical sections of the highway have been sealed to prevent infiltration. The special control devices incorporate small holding pond areas which are sized to hold the contents of any vehicles traveling along the highway. During wet weather, the initial portion of the runoff also flows into this offstream storage pond. With larger amounts of rainfall, the excess runoff flows into a larger dry pond area and then flows through horizontal sand filters before it is discharged to the receiving water. If there is an accident, the material that collects in these devices can be removed, minimizing potential contamination to the Edwards aquifer.

Stormwater Filtration

Stormwater filters have also been successfully used to control highway runoff. Austin, TX, and Cincinnati, OH, are locations where the benefits of different types of stormwater filters have been successfully used and evaluated. Table 11 is a summary of the influent total metal concentrations and the reductions at a highway runoff treatment location in Cincinnati (Sansalone and Hird 1999). This test site used a partial exfiltration reactor (PER) that was very effective in reducing both dissolved and particular forms of heavy metals. This device was basically a sand filter, with the sand specially treated with iron to enhance the removal and retention of the heavy metals. This device showed heavy metal reductions ranging from 70 to almost 100% for the metals tested.

Table 11. Highway Runoff Heavy Metal Removal at Partial Exfiltration Reactor (PER), Cincinnati, OH (Sansalone and Hird 1999)

	Influent Total Metal Concentration (mg/L)	**Reduction of Dissolved Metal Mass (%)**	**Reduction of Particulate Bound Metal Mass (%)**
Cadmium	2	79-97%	71-91%
Copper	40	84-97	80-95
Lead	24	71-93	84-96
Zinc	960	97-100	80-97

Treatability of Highway Runoff

The treatability of stormwater runoff can be evaluated during laboratory and pilot-scale tests to optimize different components of a treatment train. Pitt (1995) conducted a series of treatability tests using settling columns, flotation treatment, fine screening, photo-degradation, aeration, a combination of photo-degradation and aeration combined, and several different chemical addition tests. He measured reductions in toxicity of the stormwater samples for different levels a treatment using these different unit processes. Figure 10 illustrates the most consistent reductions that were observed, indicating significant improvements in stormwater toxicity when fine particles are removed from the water. In this example, particles down to about 5 to 10 µm must be removed in order to obtain 80 to 95% toxicity reductions. Removal of particulates only down to about 50 µm would only reduce the toxicity by about 30 to 65% in the series of tests illustrated. Using data such as this, Pitt, *et al*. (1997) developed and tested a special stormwater control device, the MCTT (multi-chambered treatment train) capable of large reductions in stormwater toxicants found at critical source areas.

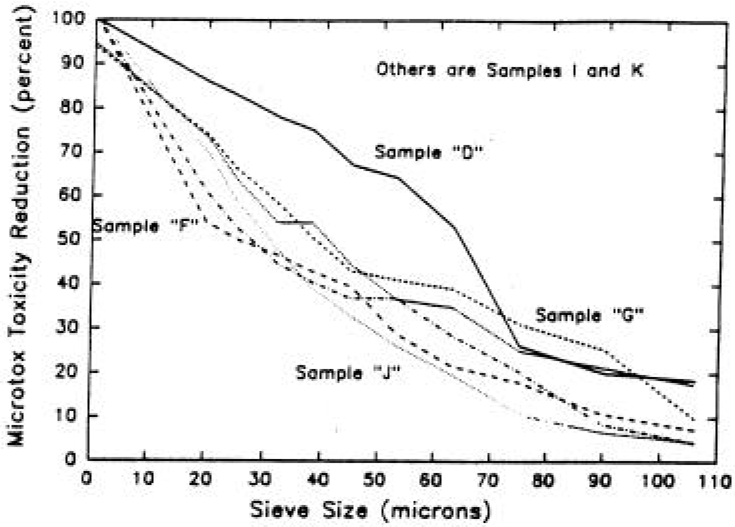

Figure 10. Reduction in stormwater toxicity as small particles are removed (Pitt, *et al.* 1997).

Recommended Highway Runoff Controls

The City of Austin, TX (1990) developed a list of specific controls that have been most commonly used for highway runoff. These controls are shown in Table 12 and illustrate the high levels of control possible with some devices. However, some devices, especially dry detention ponds, provide relatively low levels of control. There are a number of ongoing major research projects investigating the control of stormwater runoff from highways. These are briefly described in the following paragraphs.

Table 12. Removal Efficiencies of Highway Runoff at Various Control Sites, Austin, TX (City of Austin 1990)

	TSS	COD	NO_2+NO_3	TKN	PO_4	Metals
Filtration	70 to 87%	34 to 67%	-82 to -26%	18 to 32%	3 to 61%	19 to 86%
Wet pond	46	31	36	29	37	41 to 72
Dry pond	16	8	43	22	3	-64 to 19
Retention/filtration	89	82	-38	47	65	71 to 84

The largest ongoing highway runoff research project is current being conducted by Caltrans, the California Department of Transportation. This is a $30 million, five-year research effort that is examining the receiving water quality benefits and costs of structural control practices for stormwater at 39 locations in San Diego and Los Angeles Counties. Two to three years of comprehensive monitoring and evaluation will result in a large amount of data and will provide runoff control guidance for a broad range of runoff conditions. The structural stormwater controls being investigated by Caltrans includes wet detention ponds, extended detention basins, infiltration basins, biofiltration swales, multi-chambered treatment trains (MCTT), media filters, oil/water separators, drain inlet inserts, and continuous deflection separators CDS. Preliminary performance data from the first year of monitoring was recently published by Kayhanian (*et al.*) 2001, as shown in Table 13. The overall performance of these devices were grouped into the following categories: wet basins and MCTT (highest levels of pollutant concentration reductions); biofilters (strips) and sand filters (medium pollutant concentration reductions); and dry basins, biofilters (swales), and zeolite filters (lowest levels of pollutant concentration reductions). Most of these devices would provide significant and important pollutant reductions. Besides pollutant concentration reductions, the biofiltration devices would also provide large runoff volume reductions and associated mass reductions. In addition, the MCTT was designed to significantly reduce organic toxicants (specifically the PAHs), plus dissolved forms of the heavy metals, that are not shown on this summary.

Table 13. Caltrans First-year Preliminary Performance Data for Structural Controls for Highway Stormwater (Kayhanian, *et al.* 2001) (percentage pollutant concentration reductions)

	TSS	**TKN**	**Total P**	**Cu**	**Pb**	**Zn**
Extended detention basins (dry)	64	39	44	68	70	83
Wet basins	96	34	58	100	99	95
Biofilters (swales	54	27	-8	57	64	78
Biofilters (strips)	84	50	-22	89	88	84
Media (sand) filters, Delaware styles	86	55	59	63	85	93
Media (sand) filters, Austin styles	89	60	55	57	84	81
Media (zeolite) filter	49	10	59	83	66	69
Multi-chambered treatment train (MCTT)	90	57	65	68	69	91

Another major highway runoff control research project is currently being conducted by the U.S. Geological Survey (USGS) and the Wisconsin Department of Natural Resources (WDNR). This is an ongoing three-year project that is investigating high-efficiency street cleaning as a highway runoff control. The preliminary data indicates about 30 to 40% reductions in suspended solids concentrations in the runoff during periods of weekly street cleaning, compared to periods of no street cleaning (Roger Bannerman, WDNR, personal communication).

A preliminary analysis of several promising highway stormwater controls was conducted for a typical highway section using the Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1995; Pitt, *et al.* 1999; and www.winslamm.com). The highway characteristics modeled were based on extensive field surveys of highways in the Milwaukee, WI area (Pitt 1986) and included about 30% pavement and 70% undeveloped right-of-way, indicative of suburban freeways. A traffic load of 50,000 AADT (annual averaged daily traffic) was also assumed. A nine year period of rainfall (1983 to 1991) was also modeled, using actual recorded events from Los Angeles, CA, similar to, but obviously different from, eastern Mediterranean conditions. This rain period averaged about 10.6 inches (270 mm) over about 30 rain events per year. The dry interevent periods between rains were as long as 125 days (averaging 12 days), illustrating the long dry periods that may occur in this climatic region. Typical rainfall durations were about 5 hours, but one of the 262 events modeled had a maximum duration of about 50 hours. The largest rain recorded in this period was 3.34 inches (85 mm), while the median depth was 0.15 inches (3.8 mm).

Table 14 summarizes the runoff volume and suspended solids conditions for several different treatment scenarios. The base condition shown has no stormwater controls and sealed storm drainage. The drainage swales are assumed to have soils that can infiltrate flowing water at a rate of about 0.25 in/hr (6.4 mm/hr), plus they trap particulates and associated pollutants during small events. They are assumed to be about 5 ft (1.5 m) wide if located along each of the road shoulders. They could also be located in the median strip (at twice this width) in the center of the highway. The wet detention pond is about 1.25% of the total drainage area, sized to be about 3% of the total pavement plus 0.5% of the other area. It also has about 3 ft (1 m) of standing water, at least, at all times in order to prevent previously trapped material from scouring during subsequent rains. It is assumed that the pond can be located within the cloverleaf at an interchange, or at an off-site location.

Table 14. Long-Term Modeled Performance of Basic Highway Stormwater Controls using SLAMM

	# of runoff events per year	Annual averaged Rv*	Runoff volume (ft^3/acre/yr)	% volume reduction	Suspended solids conc. (average mg/L)	% SS concentration reduction	Suspended solids mass discharge (lbs/acre/yr)	% SS mass reduction
Base conditions	29.3	0.28	12,900	base	850	base	510	base
Drainage swales	14.3	0.15	7,270	44	320	62	170	67
Wet detention pond	29.3	0.28	12,900	0	42	95	89	83
Wet pond plus swales	14.3	0.15	7,270	44	28	97	34	93

Rv is the volumetric runoff coefficient, or the fraction of rain that occurs as runoff.

For the treatment scenarios using swales, the number of runoff events per year, the Rv, and the annual runoff volume, are all reduced by 44 to 51%. The wet detention pond alone does not alter the runoff volumes being discharged, although it could be designed to provide significant peak runoff flow rate reductions, if desired. The swale reduces the suspended solids concentrations due to filtering and deposition of the particulates during small rains. During large rains, the water depth is likely too deep and the water moving too fast to allow significant particulate deposition, although particulates are still trapped associated with the infiltrating water. This swale still provides about 62% reductions in SS concentrations, along with about 67% reductions in SS mass discharges. The swale performance could be substantially improved by increasing the soil infiltration rate. As an example, an analysis using a 1.25 in/hr (32 mm/hr) infiltration rate (corresponding to a sandy loam soil) reduced the annual runoff volume discharge to about 530 ft^3/acre/yr, or about a 96% reduction compared to the base conditions. The lining soil under the swales can also be substantially improved by amending the soil with relatively large amounts of compost or other organic material. Pitt, *et al.* (2000) investigated the improvements that soil amendments can provide to both water quality and water volume, and demonstrated the problems that compacting soils can cause.

In areas having sensitive groundwater conditions, swales should not be used. In fact, the drainage should be sealed (using subsurface pipes, for example) to isolate the runoff from the soil over the critical areas. If an accident should occur, any spilled toxic or hazardous material (including the fuel from the vehicle) could contaminate the drainage system and the local groundwater. Drainage systems in sensitive areas should enable the runoff water (and any spilled material) to be captured and conveyed away from the sensitive area for treatment and discharge (or containment and recovery).

Wet detention ponds, while not affecting the runoff volume, can provide substantial suspended concentration and mass reductions. If used in conjunction with grass swales, very high levels of treatment can be possible.

Conclusions

Highway runoff has been shown to be similar in many ways to typical urban stormwater. However it has higher concentrations of many pollutants, especially for the heavy metals and petroleum hydrocarbons (receiving water problems are therefore similar, or worse, compared to the extensive problems associated with urban stormwater). Highway runoff seems to have a higher fraction of dissolved pollutants compared to most runoff (making it harder to control). Fugitive dust resuspension as a major removal mechanism for particulate material from roadways and this must be considered an important fate mechanism affecting accumulation and control of particulate pollutants.

The Texas Department of Transportation recommends that vegetated stormwater controls (such as grass swale drainages) be selected as the first option for highway runoff control. This is due to their widespread applicability, their low costs, and minimal maintenance requirements. Wet detention ponds are recommended to be used at sites where it's not possible to use vegetation controls. Infiltration practices are recommended as the least desirable because of high maintenance costs, although they can offer excellent treatment potential.

A general approach for managing highway runoff controls should include the following four components:

1) Erosion control at highway sites has been of limited success. It is very important that preventive measures are used, however. Expect elevated sediment levels in runoff in areas having clayey soils, especially during periods high rain intensities. Good planning to minimize bare exposed ground during the rainy season can be used in conjunction with mulches and mats to reduce erosion losses. Treatment of construction site runoff is difficult and is usually disappointing. However, basic levels of effort are usually needed (such as sediment ponds at large construction sites and the use of temporary mulches when extended periods of minimal site activity are expected).

2) Grass swale drainages and wet ponds have been shown to provide high levels of control for highway runoff and should be used whenever possible. Medians and shoulder areas can easily accommodate grass swales, while interchanges offer good locations for wet ponds. Reasonably high levels of treatment of typical highway runoff can be expected if these devices are suitably designed, constructed, and maintained.

3) Groundwater contamination may occur from highway runoff if close-by and shallow aquifers are located in sandy soil areas. Sealed roads and drainages, and amended soils, can be used to reduce this contamination potential. However, runoff should be diverted away from sensitive areas, and treated and discharged so as not to harm critical groundwater or surface water resources.

4) Accidental spills of hazardous materials require special consideration. Sensitive areas need containment devices, sealed roads and drainages, plus contingency plans.

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