Highway Water Quality Control—Summary of 15 Years of Research

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The year 1989 marked the completion of a major segment of FHWA's environmental research program. More than 15 years of water quality research have been supported by FHWA and state highway agencies. Since the early 1970s, FHWA has supported a four-phase research program in non–point-source pollution from highway runoff. Phase I identified the constituents of highway runoff and developed a data base of highway runoff quality and quantity. Phase 2 identified the sources and migration patterns of highway runoff constituents and further developed the Phase 1 data base. Phase 3 results indicated that highway facilities with low-to-medium average daily traffic (less than 30,000 vehicles per day) exhibited minimal impact on receiving waters. Phase 4 developed a new predictive procedure for estimating the pollutant loadings from highway sources, and identified practical, effective, and implementable mitigation measures to reduce or eliminate the impacts from highway runoff. The need for further environmental research is discussed.

The National Environmental Policy Act of 1969 (Public Law 91–190) requires that all federal agencies prepare environmental impact statements on major federal or federally regulated actions. The Clean Water Act (Public Law 92–500) established a comprehensive national water quality program. The overall objective of this legislation is to report and maintain the chemical, physical, and biological integrity of U.S. waters. The 1977 amendments to the Clean Water Act required federal agencies to cooperate with state and local agencies to develop comprehensive solutions to prevent, reduce, and eliminate pollution.

The growing awareness of the potential threat to the environment by highway runoff and the corresponding lack of information as to the true nature and extent of this threat established the need to initiate a highway water quality research program. FHWA initiated a four-phased cooperative federal and state research and development program to identify and quantify the effects of highway runoff, and to develop measures for protecting the environment from adverse effects. The four phases of the program are as follows:

- Phase 1. Identify and quantify the constituents of highway runoff,
- Phase 2. Identify the sources of the constituents and their migration paths from the highway to the receiving waters,
- Phase 3. Analyze the effects of the constituents in receiving waters, and
- Phase 4. Develop the necessary abatement and treatment methodologies for objectionable constituents.

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RESULTS OF PHASE 1

The objectives of Phase 1 were to identify and quantify the constituents of highway runoff. In order to accomplish these objectives, a total of 159 storm events were monitored at six sites between the spring of 1976 and September 1977. The data were evaluated for relationships between rainfall and runoff; highway runoff pollutant loadings and variation with time; differences in pollutant characteristics from paved and nonpaved areas; and correlation of pollutants among measured parameters as well as highway operation–related factors. Table 1 presents a summary of the water quality data from Phase 1. The results of Phase 1 are documented in a six-volume report titled *Constituents of Highway Runoff* (*1–6*).

The data generated from the study were used to develop a predictive procedure to provide highway designers and others with a simplified tool to predict the quantity and quality of rainfall-generated highway runoff (*3*). The procedure is made up of four components corresponding to the following functions: rainfall, runoff, pollutant washoff, and constitutent loading. The predictive procedure calculates the volume of runoff given rainfall volume using equations developed from the monitoring data and regression analyses. Because the rainfall-to-runoff relationship is dependent on site characteristics, an equation was developed for each of three basic site types, as follows (*4*):

- Type 1. Totally paved bridges or overpasses (100 percent paved),
- Type 2. Partially paved sections with curbs and inlets along the paved areas (30 to 40 percent paved), and
- Type 3. Rural sites with flush shoulders, grassy ditch conveyances to inlets (20 to 30 percent paved).

RESULTS OF PHASE 2

The overall objectives of Phase 2 were to identify the sources of highway pollutants and to investigate their deposition and accumulation within the highway system, and their subsequent removal from the highway system to the surrounding environment. The research was also to identify opportunities for pollutant mitigation. The complete findings from Phase 2 are documented in a four-volume report, *Sources and Migration of Highway Runoff Pollutants* (*7–10*).

Although further investigation was required to obtain the sources of some highway pollutants, including pathogenic indicator bacteria, asbestos, and polychlorinated biphenols (PCB), the sources for many others were found to be ade-

TABLE 1 HIGHWAY RUNOFF DATA FROM ALL SIX MONITORING SITES IN PHASE 1 RESEARCH (4)

	Pollutant concentration mg/l		Pollutant Loadings lb/ac/event		Pollutant Loadings lb/ac/in-runoff	
	Ave.	Range	Ave.	Range	Ave.	Range
pH		6.5 - 8.1				
TS	1,147	145-21,640	51.8	0.04-535.0	260	33 - 4,910
SS	261	4 - 1,156	14.0	0.008-96.0	59	0.9 - 375
VSS	77	1 - 837	3.7	0.004-28.2	17	0.2 - 190
BOD_5	24	2 - 133	0.88	0.000- 4.1	5.4	0.5 - 30
TOC	41	5 - 290	2.1	0,002-11.5	9.3	1.1 - 66
COD	14.7	5 - 1,058	6.9	0.004-34.3	33	1.1 - 240
TKN	2.99	0.1 - 14	0.15	0.000-1.04	0.68	0.02 - 3.17
NO_2+NO_3	1.14	0.01- 8.4	.069	0.000-0.42	0.26	0.002- 1.90
TPO_4	0.79	0.05-3.55	.047	0.000-0.36	0.18	0.011- 0.81
Cl	386	5 -13,300	13.0	0.008- 329	88	1.1 - 3,015
Pb	0.96	0.02-13.1	.058	0.000- 4.8	0.22	0.005- 2.97
Zn	0.41	0.01- 3.4	.022	0.000- 0.8	0.093	0.002-0.771
Fe	10.3	0.1 -45.0	0.50	0.000- 3.5	2.34	0.023- 10.2
Cu	0.103	0.01-0.88	.0056	0.000-.029	0.023	0.002-0.199
Cd	0.040	0.01-0.40	.0017	0.000-.014	0.009	0.002-0.091
Cr	0.040	0.01-0.14	.0028	0.000-.029	0.009	0.002-0.032
Hg $x10^{-3}$	3.22	0.13-67.0	00059	0.000-.002	0.730	0.029- 15.2
Ni	9.92	0.1 - 49	0.27	0.007-1.33	2.25	0.023- 11.2
TVS	242	26 -1,522	9.34	0.01 -44.0	55	5.98 - 345

quately documented in the literature. Because of the detailed nature of the pollutant source studies, the majority of the monitoring was conducted at the Milwaukee I-94 site. Table 2 presents some of the common constituents of highway runoff and their identified sources.

Data were also collected at all monitoring sites to evaluate the qualitative and quantitative aspects of background pollutant loading to the highway system, pollutants originating from the highway system, and the mechanism of pollutant dispersion within and transfer out of the highway system. Variables that affect pollutant deposition, accumulation, and removal were measured to facilitate data evaluation. These variables include traffic characteristics, maintenance activities, and climatic conditions. Field studies were conducted for a minimum 12-month period on four sites to evaluate seasonal effects on a number of parameters. The elements of the field data collection are as follows (7):

- Atmospheric deposition,
- Total suspended particulate,
- Saltation (bouncing particulate),
- Highway surface loads (monitored through sweeping and flushing studies),
- Runoff quantity and quality,
- Ground water percolation (monitored by lysimeters),
- Soil and vegetation,
- Traffic characteristics,
- Highway maintenance activities, and
- Climatological conditions.

Characteristics of the four monitoring sites are presented in Table 3.

Background bulk precipitation data (wet and dry deposition) indicate total particulate matter (TPM) loadings, solids in the atmosphere that are washed out by rainfall or drop out, were approximately four times higher at the urban sites than at the rural sites. Similarly, background metals deposition was higher at the urban sites. The data also indicated dry deposition (dust fall) is a more important source of metals than wet deposition (rain).

Runoff data indicated the highway system has a large capacity to buffer the runoff of acid precipitation. The prevalence of acid rain in the United States and the apparent ability of highway systems to buffer this acid rain may have important implications with regard to pollutant migration from the highway through areas adjacent to the highway. The solubility of metals is a function of pH, the quantity of anionic complexing agents, and the organic matter present. At reduced pH values, soluble metals would be easier to remove from the highway surface, would tend to migrate further, and would be more accessible for bioaccumulation. The significant buffering capacity of the highway system serves to minimize this potential.

The research showed that the atmospheric deposition of highway-generated TPM and associated metals onto areas adjacent to the highway is related to average daily traffic (ADT), wind speed and direction, available surface load, and terrain and landscape features. The study concluded that the impact area for highway-generated TPM was approximately 35 m from the edge of pavement for urban sites and 15 m for rural sites.

Runoff from the paved and unpaved areas were segregated to determine pollutant loadings leaving the highway drainage system and to develop insights into the hydraulics of pollutant movement. At sites with curbs and gutters, the contribution of the unpaved area to the total pollutant constituent load removed by runoff was negligible. At sites with flush shoulders, the unpaved area contributed approximately 17 percent of the total load for most constituents. This outcome was the apparent result of solids and pollutants associated with the solids accumulated in the distress and median lanes becoming trapped against the curbs and available to be picked up by runoff from the pavement. In the noncurbed areas, the solids are not trapped and are free to be dispersed into the nonpaved areas. Although the flush shouldered areas showed a higher

TABLE 2 HIGHWAY RUNOFF CONSTITUENTS AND THEIR PRIMARY SOURCES (7)

Constituents	Primary Sources
Particulate	Pavement wear, vehicles, atmosphere, maintenance
Nitrogen, Phosphorus	Atmosphere, roadside fertilizer application
Lead	Leaded gasoline (auto exhaust), tire wear (lead oxide filler material), lubricating oil and grease, bearing wear
Zinc	Tire wear (filler material), motor oil (stabilizing additive), grease
Iron	Auto body rust, steel highway structures, (guard rails, etc.), moving engine parts
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides
Cadmium	Tire wear (filler material), insecticide application
Chromium	Metal plating, moving engine parts, break lining wear
Nickel	Diesel fuel and gasoline (exhaust), lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Manganese	Moving engine parts
Cyanide	Anticakeing compounds (ferric ferrocyanide, sodium ferrocyanide, yellow prussiate of soda) used to keep deicing salt granular
Sodium/Calcium, Chloride	Deicing salts
Sulphate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate
PCB	Spraying of highway rights-of-way, background atmospheric deposition, PCB catalyst in synthetic tires

proportion of the pollutant load coming from the nonpaved area, the total pollutant loads were significantly smaller.

Soils data indicated metals and sodium concentrations were located in the top soil layers (upper 10 cm). Concentrations were also highest adjacent to the highway and decreased with distance from the highway. Chlorides did not show this gradient. Lysimeter data indicated that chlorides were leached from the upper soil layer shortly after the spring thaw. Uptake of metals and sodium by vegetation was generally related to concentration of these constituents in the topsoil layer. The vegetation and soils data indicated that normal ecosystem processes might be affected within the first couple of meters adjacent to the highway, but beyond this distance no impacts were detected.

RESULTS OF PHASE 3

The next step, after identifying the constituents of highway runoff, their sources, and their migration paths, was to determine the magnitude and extent of the impacts of highway stormwater runoff on receiving waters and to provide guidance for assessing impacts caused by highway stormwater runoff. An extensive field monitoring and laboratory analysis program was conducted at three sites: two streams and a lake. Results indicated that for highway facilities with low-to-medium ADT (less than 30,000 vehicles per day), there is minimal impact to receiving waters and their associated floral and faunal communities. Results of this research are documented in a five-volume report, *Effects of Highway Runoff on Receiving Waters* (*11–15*).

Acute-toxicity bioassays were performed using undiluted runoff from highways with ADT ranging from 12,000 to 120,000 vehicles per day. These bioassays were conducted to simulate worse-case shock loadings on the receiving waters for durations of no more than several days. Certain assumptions were implicit in this assessment: (a) the quality of the receiving water may be temporarily degraded, but will rapidly return to its previous state; (b) detrimental substances in the runoff water are flushed out of the receiving waters and do not linger; and (c) detrimental effects on aquatic biota are caused by direct toxicity, not indirect or delayed effects. Bioassays were run on an alga (*Selenastrum capricornutum*), water flea (*Daphnia magna*), amphipod (*Gammarus pseudolimnaeus*), isopod (*Asellus intermedius*), mayfly (*Hexagenia* sp.), and flathead minnow (*Pimephales promelas*).

Undiluted highway runoff was not acutely toxic to the flathead minnow. Fish exposed to the runoff water did, however,

TABLE 3 CHARACTERISTICS OF SITES IN PHASE 2 RESEARCH (*7*)

Location	Type	ADT Vehicles/ Day	Precipitation inches/year Total	Snow-Fall	Acres Total	Acres Paved	% Paved	Surface Type	Hwy Length ft	Number of Travel Lanes	Type of Section	Curb/ Barrier
Milwaukee Wisconsin I-94	Urban	116,000	30	45	7.60	4.90	64	Asphalt	1,373	8	cut/fill	yes
Sacramento California US-50	Urban	85,900	17	0	2.45	2.01	82	Concrete	1,400	8	at grade	yes
Harrisburg Pennsylvania I-81	Rural	27,800	38	35	2.81	1.05	45	Concrete	1,345	4	cut/ at grade	no
Efland N.Carolina I-85	Rural	25,000	41	9	2.49	1.27	51	Asphalt	1,025	4	at grade	no

demonstrate some sluggishness, implying some stress. The isopod was insensitive to exposure to undiluted highway runoff. The amphipod demonstrated some sensitivity to exposure to undiluted runoff from the 12,000-ADT site. Of the observed mortality, no more than 40 percent could be attributed to the direct toxicity of the water. The mayfly nymphs showed slight sensitivity to undiluted highway runoff. Exposure to the 120,000-ADT undiluted runoff did not affect the nymphs from hatching into adults. The *Daphnia* was not sensitive to the 12,000-ADT undiluted runoff in a 96-hr flowthrough assay, nor to 120,000-ADT undiluted runoff in a 48-hr static test. Algal assays, a long-term chronic toxicity test, demonstrated adverse effects of undiluted runoff water on algal growth. The results of the assays using 120,000-ADT water demonstrated a probable heavy metal stress on algae.

As was mentioned, the bioassays represented a worst-case scenario. Under normal conditions, highway runoff is significantly diluted on entering the receiving waters. Therefore, these results indicate that highway runoff would have minimal (if any) toxic effect under normal conditions.

The results from the field monitoring sites indicated that the highway right-of-way contributed a small percentage (0.03 to 5 percent, depending on the site location and constituent being measured) of the total watershed load. Water quality impacts from highway runoff during storm events were not apparent. At the Lower Neahbin Lake site, direct discharge of highway runoff from the bridge deck caused localized increases in metals and salts in near shore sediments and cattails (*Typha* sp.). Metal concentrations found in the cattails were found to decrease to background levels within 65 ft of the input point. The ultimate impact of these accumulations is uncertain.

RESULTS OF PHASE 4

The completion of Phase 4 during 1989 brought to a close this focused research effort on highway runoff water quality. This phase was accomplished through three research efforts. The first study, documented in a four-volume report, *Management Practices for Mitigation of Highway Stormwater Runoff Pollution* (*16–19*), identified practical, effective, and implementable mitigation measures to reduce or eliminate the impacts of highway runoff. These measures were to serve as interim guidance until the completion of the research program.

A second study used the vast amount of data collected through FHWA contract research, federally assisted state studies, U.S. Environmental Protection Agency's Nationwide Urban Runoff Program, and state highway agency sponsored research to develop an improved prediction model to estimate pollutant loadings from the highway. This research, documented in a four-volume report, *Evaluation of Pollutant Impacts from Highway Stormwater Runoff* (*20–23*), also includes a computerized version of the model. The results are based on 993 individual storm events at 31 highway sites in 11 states. Impact prediction is based on a methodology previously developed and applied to urban runoff and adapted for highway runoff application (*24*).

The final study in Phase 4 evaluated the use of retention, detention, and overland flow systems as potential mitigation measures. As an initial step in the study, interim design guidelines were developed (*25*). These design guidelines were then refined on the basis of the results of laboratory and field evaluations and are documented in a two-volume report, *Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff* (*26,27*).

The five management measures that were considered cost effective for pollutant removal from highway runoff were as follows (*27*):

- Vegetation controls,
- Wet detention basins,
- Dry extended detention basins,
- Infiltration systems (also called "retention measures"), and
- Wetlands.

In addition to discussing and providing specific design guidance for the construction of these five measures, the report (*27*) also discusses the following effective nonstructural measures to reduce pollutant loadings from highway runoff:

- Curb elimination,
- Litter control,
- Deicing chemical use management,
- Pesticide and herbicide use management,
- Reduced direct discharge,
- Reduced runoff velocity, and
- Establishment and maintenance of vegetation.

Common practices that are ineffective at reducing pollutant loads include

- Street cleaning,
- Catch basins,
- Porous pavements, and
- Filtration devices for sediment control.

These practices were developed on the basis of actual field monitoring or obtained from published literature.

RELATED RESEARCH

Although the four-phased water quality research program just described was the central focus of the FHWA water quality program, other related research and implementation activities have been conducted and are currently underway that are directly and indirectly related. One study, which was a direct spinoff of the program, investigated the impacts of highway maintenance activities on water quality. The resulting four-volume report (*28–31*) identifies commonly used maintenance practices and describes each in terms of its potential for causing adverse impacts to water quality. The study identified the following six practices that could have an impact if proper measures are not taken:

- Repairing slopes, slips, and slides;
- Cleaning ditches, channels, and drainage structures;
- Bridge painting;
- Substructure repair; and
- Chemical vegetation control.

The study also provides guidelines on available methods of avoiding or mitigating these potential impacts.

Early in the program, FHWA sponsored the development of a water quality training course, offered through the National Highway Institute (NHI). In 1985, the water quality course was updated. One of the most significant products of the new course is the student workbook (*32*). It provides, in one volume, a compendium of the FHWA water quality research. The only information lacking from this text are the final results from the retention, detention, and overland flow research, and the new pollutant discharge model. The text does, however, excerpt material from the earlier interim design guidelines (*25*).

Another area of significant research has been the development of calcium magnesium acetate (CMA) as an alternative deicer. This chemical, while more costly than salt, has been shown to be effective as a deicer and to have less of an impact on the environment. The selective use of CMA in environmentally critical areas, coupled with improved storm detection and prediction, pavement condition, and winter maintenance management, can greatly aid in reducing highway runoff pollution in the snow belt regions of the country.

The last technically related area that should be discussed is the FHWA wetlands research program. To date, this program and the water quality research program have been conducted in parallel, investigating two separate but related topics of concern. One of the most significant accomplishments by FHWA in wetlands research is the development of the report, *A Method for Wetland Functional Assessment* (*33,34*), and the subsequent cooperative agreement with the U.S. Army Engineers in developing an enhanced assessment method, *The Wetland Evaluation Technique*, Version 2.0 (*35*).

FUTURE OF THE FHWA WATER QUALITY RESEARCH AND DEVELOPMENT PROGRAM

Although the four-phased research effort has resulted in considerable information and a large number of projects that now give the highway agencies the tools they need to meet the immediate challenge, more work needs to be done. Since the original work on the constituents of highway runoff, there have been a number of changes made in the fuels used in automobiles and in automobile technology. There has not been any recent research to determine how these changes may have affected highway runoff water quality and the effects to receiving waters.

With the current concern for protecting our wetland resource and the likelihood that the concept of no net loss of wetlands will become national policy, to gain a fuller understanding of how highway runoff may affect wetland systems is vital. Although some research has been conducted (*36*), a focused research effort is needed to determine whether it is feasible and prudent to use natural wetlands or wetlands constructed for wetland mitigation as a means of treating highway runoff. Under what circumstances this practice might be detrimental to the other functions of the wetland is not known.

Another area of major concern is the control of hazardous materials spilled within the highway rights-of-way. FHWA is sponsoring research to aid in determining the need for protective systems and available technology to control spills from impacting ground and surface waters. However, little if any work has been done on developing cost-effective systems that will do the job.

As part of FHWA plans for an expanded research and development budget beginning in FY 1992, provision is being made for a significantly expanded environmental research program. If the program becomes a reality, FHWA will continue to assist the state highway agencies in providing the tools needed to protect our nation's waters.

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