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16. Abstract

This report summarizes the research undertaken to identify and quantify the constituents of highway runoff. Research efforts included: 1) an extensive literature review, 2) developing guidelines for establishing and conducting a highway runoff monitoring program, 3) extensive monitoring of rainfall related runoff at six highway sites around the country over a 12 to 16 month period, 4) developing a computer program to store and analyze the data collected, and 5) developing a predictive procedure that can be used as an analytical tool for preparation of Environmental Impact Statements.

Results of this study have been documented in a six volume publication titled "Constituents of Highway Runoff". Titles of the six volumes of this publication are:

FHWA-RD-	Subtitle	
81/042	Vol. I	State-of-the-Art Report
81/043	Vol. II	Procedure Manual for Monitoring of Highway Runoff
81/044	Vol. III	Predictive Procedure for Determining Pollutant Characteristics in Highway Runoff
81/045	Vol. IV	Characteristics of Runoff From Operating Highways. Research Report
81/046	Vol. V	Highway Runoff Data Storage Program and Computer User's Manual
81/047	Vol. VI	Executive Summary

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FOREWORD

This report is composed of six volumes: Volume I documents the constituents of highway stormwater runoff and their pollutional effects; Volume II contains detailed procedures for conducting a monitoring and analysis program for highway runoff pollutant data; Volume III describes a simple predictive procedure for estimating runoff quantity and quality from highway systems; Volume IV is the research report discussing research approach and findings; Volume V contains the computer users manual for a highway runoff data storage program and Volume VI is an executive summary. The report will be of interest to planners, designers and researchers involved in evaluation of highway stormwater runoff contributions to nonpoint sources of water pollution.

Research in Water Quality Changes due to Highway Operations is included in the Federally Coordinated Program of Highway Research and Development as Task 3 of Project 3E, "Reduction of Environmental Hazards to Water Resources Due to the Highway System". Mr. Byron N. Lord is the Project and Task Manager.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each FHWA Regional office, Division office and State highway agency. Direct distribution is being made to the Division offices.

for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

INTRODUCTION

The growing awareness of the threat to the environment by highway runoff has resulted in research to identify and quantify the effects of this runoff and develop measures for protection of the environment from any adverse effects. The Federal Highway Administration (FHWA), charged with the responsibility for protecting the environment from pollution from highway sources, has approached the problem in a four phase research program. The objective of each phase is as follows:

1. Identify and quantify the constituents of highway runoff.
2. Identify the sources of these pollutants and migration paths from the highway to the receiving water.
3. Analyze the effects of these pollutants in receiving waters.
4. Develop the necessary abatement/treatment methodology for objectionable constituents.

This report summarizes Phase I of the above program. Objectives of the Phase I included not only identification and quantification of highway runoff constituents, but also development of a predictive procedure that can be used as an analytical tool for preparation of Environmental Impact Statements (EIS). An extensive literature review was conducted at the beginning of the Phase I study and a current state-of-the-art report was prepared at the end of the study in March, 1978. A Procedural Manual has also been written for use by State highway personnel which contains detailed procedures for establishing and conducting a highway runoff monitoring program.

Results of the Phase I study have been documented in a six volume publication titled, "Constituents of Highway Runoff". Titles of the six volumes are:

I - State-of-the-Art Report
II - Procedural Manual for Monitoring of Highway Runoff
III - Predictive Procedure for Determining Pollutant Characteristics in Highway Runoff
IV - Characteristics of Runoff from Operating Highways. Research Report
V - Highway Runoff Data Storage Program and Computer Users Manual
VI - Executive Summary

METHODOLOGY

Six freeway sites were selected around the country based on the following considerations: geographic location, climatic conditions, traffic characteristics, highway design and drainage characteristics, and site accessibility and safety. Three of the selected sites were located in Milwaukee, Wisconsin, and one each in Harrisburg, Pennsylvania, Nashville, Tennessee, and Denver, Colorado. The average daily traffic (ADT) at these sites varied from a low of 24,000 at Harrisburg to a high of 149,000 at Denver. A summary of the important site characteristics is shown in Table 1.

Monitoring of highway runoff was conducted for a minimum of 12 months at each site. A total of 159 storm events were monitored during the study.

All sites were instrumented for monitoring of: precipitation, dustfall, runoff flow volume, and runoff quality. Traffic and highway maintenance data for the various sites were obtained through the respective State highway departments.

Monitoring stations were maintained by U.S. Geological Survey personnel in Harrisburg, Nashville, and Denver. The contractor maintained and operated monitoring equipment at all three sites in Milwaukee, and performed analytical determinations on runoff samples collected at all sites for all constituents except bacteria and asbestos. Bacteria analyses were conducted at the respective sites. Asbestos analyses were performed by McCrone Associates of Chicago, Illinois.

Discrete water quality samples were collected via two ISCO samplers at intervals of 5 and 15 minutes during all storm events. In addition, manual discrete samples were collected for oil and grease, bacteria, pesticide and Polychlorinated Biphenyl (PCB) analyses for as many storms as possible. These samples were air freighted to Envirex in ice-packed coolers for analyses. Samples were then composited manually in proportion to flow rate. Both flow-composited as well as selected discrete samples were analyzed for selected water quality parameters. All analytical determinations were performed in accordance with Standard Methods or EPA approved techniques. The flow-composited samples permitted calculation of the total pollutant loadings to receiving waters for each storm event. Discrete sample analyses were utilized to study the pattern of pollutant discharge during a runoff event. A "Procedural Manual for Determining Pollutant Characteristics in Highway Runoff" was developed out of this monitoring effort.

The large volume of data generated from the selected monitoring locations were cataloged and stored in a computer using a data storage program developed for this purpose. The data storage program will allow researchers and other interested users ready access to the project data. The program also provides a readily available and convenient means for storage and analysis of environmental and operational data collected during future highway runoff studies.

Table 1. Characteristics of selected sites.

Location	Type	ADT	Precipitation in./yr		Drainage area, acres		% Paved	Surface type	Highway length, ft	No. of lanes	Type of section	Curb/ barrier	Outfall/ manhole size, in.
			Total	Snowfall	Total	Paved							
Milwaukee, WI I-794	Urban	53,000	30	40-60	2.1	2.1	100	Concrete	813	8	Elevated	Yes	24
Milwaukee, WI Hwy. 45	Urban	85,000	30	40-60	106.0	33.0	31	Concrete	9,500	6	Cut & Fill	Yes	72
Milwaukee, WI Hwy. 45	Urban	85,000	30	40-60	2.5	0.0	0	Grass cover	500	-	Fill	-	15
Harrisburg, PA I-81	Rural	24,000	40	20-30	18.5	5.0	27	Concrete	2,000	6	Fill	No	36
Nashville, TN I-40	Urban	88,000	55	1-20	55.6	20.5	37	Concrete	6,200	6	Cut	Yes	48
Denver, CO I-25	Urban	149,000	20	60-100	35.3	13.2	37	Asphalt	3,600	10	Fill	No	30

metric conversion units: 1 inch = 2.54 cm; 1 ft = 0.305 m; 1 acre = 0.405 ha

SUMMARY OF FINDINGS

1. Predictive Procedure

Data generated during this study were used to develop a predictive procedure that will provide highway designers and other interested individuals/agencies with a simplified tool to predict the quantity and quality of rainfall generated highway runoff. The procedure is made up of four components corresponding to the following functions:

- Rainfall - runoff
- Pollutant build-up
- Pollutant wash-off
- Constituent loadings

Rainfall - Runoff. The predictive procedure calculates the volume of runoff for a given rainfall volume using equations which were developed from monitoring data and regression analyses. Since the rainfall to runoff relationship is dependent upon site characteristics, an equation was developed for each of three basic site types which were defined using general site characteristics from the six previously listed monitoring locations. The three site types are:

- Type 1 - all-paved, bridges or overpasses (100 percent paved)
- Type 2 - partially paved with curbs and inlets along the paved area (30 to 40 percent paved)
- Type 3 - rural sites with flush shoulders, grassy ditch conveyance to inlets (20 to 30 percent paved)

The resultant equations relating runoff volume to rainfall volume for the three site types are as follows:

Type I

$$Q = 0.969\ R - 0.019$$

Type II

$$Q = 0.470\ R^{1.369}\ DD^{-0.086}$$

Type III

$$Q = 0.845\ R^{1.892}\ DD^{-0.654}$$

where; Q = runoff volume (inches)
R = rainfall volume (inches)
DD = dry days to last storm event

A linear equation produced the most significant correlation when regression analysis techniques were applied to monitoring data for the Type I site. For the Type II and Type III sites, the most significant equations were obtained when log normalized values for total rain and dry days were used.

The average runoff rate in inches per hour has the highest correlation with the actual pounds of pollutant discharged as determined through regression analyses. In order for the predictive procedure to calculate duration runoff, rainfall duration is used in a series of equations to produce the runoff duration for each event. Prestorm history and site characteristics are again used to predict runoff duration. Equations relating rainfall, runoff duration, dry days and site characteristics were developed from the monitoring program's extensive data base. The duration of runoff and runoff volume is then used as average runoff intensity which is the mechanism for wash-off of pollutants from the highway area.

Pollutant Build-up and Wash-off. Build-up and wash-off of pollutants from the highway drainage area is performed in the predictive procedure using a carrier pollutant as the mechanism of each process. The carrier pollutant used in the procedure is total solids since it had the best correlation with 16 other commonly used water quality parameters. Build-up of total solids on the drainage area is simulated in the model using a build-up rate K_1 which is calculated in the following manner:

$$K_1 = 0.007\ (ADT^{0.89})$$

where; K_1 = total solids in lb/mile/day
ADT = average daily traffic in vehicles per day

The K_1 factor is then used at the site being modeled to accumulate solids on the drainage area surface during the prestorm dry period.

Removal of the carrier pollutant from the highway area is accomplished in the predictive procedure using the standard wash-off equation with the following format:

$$P_D = P_o\ (1-e^{-K_2 r})$$

where; P_D = pounds of total solids washed off
P_o = initial surface loading (pounds of total solids)
= K_1 x dry days x site length in miles
K_2 = wash-off coefficient
r = average runoff intensity in inches/hour

K_2 values are selected in the predictive procedure based upon site characteristics and range from 5.0 to 12.0.

Constituent Loadings. The predictive procedure has, to this point, determined the mass of total solids washed off for each rainfall event. The transformation of total solids into pounds of biochemical oxygen demand (BOD), heavy metals, nutrients or any other of 16 available parameters is performed using individual equations for each site. These equations have been developed using more than one thousand individual chemical analyses from the monitoring program for correlation of parameters. Total loading (lb) and concentration (mg/l) of each parameter is listed in the predictive procedure output.

Predictive Procedure Results. The predictive procedure was incorporated into a set of equations for input to a computer. This format allows the predictive procedure to simulate runoff quantity and quality from continuous precipitation records covering months or years of data. Output from the predictive procedure was compared to measured quality data from five monitoring sites of the subject study. Accuracy of the predictive procedure for predicting the total solids load for the entire monitoring period at each site was 12 percent low at Milwaukee I-794, 15 percent high at Milwaukee Hwy. 45, 15 percent high at Nashville, 1 percent high at Harrisburg and 37 percent high at Denver. The verification of the model output was accomplished using data from an FHWA project in Dallas, Texas, which were independent of the subject project. The model predicted total solids loadings for the Texas site that were 34 percent higher than the measured loadings. Further research should be continued for the refinement of the predictive procedure as additional data become available at Dallas, Texas, and from other states.

Predictive Procedure Limitations. Because of complex interactions of rainfall, runoff and traffic on a highway, following are some limitations of the predictive procedure that need to be improved upon during future research.

1. The predictive procedure assumes the highway area to be uniformly characterized by the three site types that are listed. Significant variations in a site may have widely varying results.

2. The predicted pounds of total solids washed off during a rainfall event are dependent upon model prediction of surface load at the start of the storm. If surface load is underestimated, the pounds discharged will be low.

3. The use of average runoff intensity to remove pollutants is the quickest method and easiest to calculate. Peak runoff intensities during the runoff hydrograph may be more accurate, but are too involved for this procedure.

4. Long dry periods and overlapping storms present predictive problems in determining the prestorm surface load.

5. Construction activities are difficult to simulate unless monitoring data is available to determine K_1 values.

2. Highway Runoff Constituent Characterization

Solids Data. These data refer to the following analyses: Total Solids (TS), Total Volatile Solids (TVS), Suspended Solids (SS) and Volatile Suspended Solids (VSS). The overall solids loading for all monitored events (159) at six sites are:

	Pollutant concentration, mg/l		Pollutant loadings, lb/ac-event		Pollutant loadings, lb/ac-in. of runoff	
	Avg.	Range	Avg.	Range	Avg.	Range
TS	1147	145-21640	52	0.04-535	260	33-4910
TVS	242	26-1522	9	0.01-44	55	6-345
SS	261	4-1656	14	0.008-96	59	0.9-375
VSS	77	1-837	4	0.004-28	17	0.2-190

metric conversion units: To convert lb/ac to kg/ha multiply by 1.12.

Among sites, the all-paved site, Milwaukee I-794, exhibited the largest solids loadings in lb/acre at 60 lb/acre (67 kg/ha) TS and 19.6 lb/acre (22 kg/ha) SS on an average basis. These high solids loadings at the I-794 site were due to the high pollutant wash-off efficiency of accumulated solids from the highly impervious (100 percent paved) drainage area of the site. The Harrisburg site exhibited the lowest overall average suspended solids loading at 4.7 lb/acre (5.3 kg/ha) because of factors such as rural environment, flush-shoulder type of highway design and low percentage of impervious area. Significantly higher solids loadings during winter periods compared to nonwinter periods were exhibited at sites located in Milwaukee and Harrisburg where salting/sanding is used for deicing; minimal differences in solids loadings during nonwinter and winter periods were exhibited at the Nashville site where relatively little salt/sand is used.

The average volatile fractions of total and suspended solids for nonwinter conditions ranged between 30 and 50 percent. For winter conditions, these fractions were significantly reduced due to salting/sanding for deicing.

Metals. Most heavy metals were associated with the particulate matter in highway runoff. Dissolved metal fractions were extremely small and generally were near or below detection limits. The following levels of heavy metals were present in highway runoff for all 159 storm events at the six sites:

	Pollutant concentration, mg/l		Pollutant loadings, lb/ac-event		Pollutant loading, lb/ac-in. runoff	
	Avg.	Range	Avg.	Range	Avg.	Range
Lead	0.96	0.02-13.1	0.058	0.000-0.48	0.22	0.005-2.97
Zinc	0.41	0.01-3.4	0.022	0.000-0.12	0.093	0.002-0.771
Iron	10.3	0.1-45.0	0.50	0.000-3.5	2.34	0.023-10.2
Copper	0.103	0.01-0.88	0.0056	0.000-0.029	0.023	0.002-0.199
Cadmium	0.040	0.01-0.40	0.0017	0.000-0.014	0.009	0.002-0.091
Chromium	0.040	0.01-0.14	0.0028	0.000-0.029	0.009	0.002-0.032
Nickel	9.92	0.1-49.0	0.27	0.007-1.33	2.25	0.023-11.1
Mercury	3.22[a]	0.13[a]-67.0[a]	0.00059	0.000-0.00214	0.730	0.029-15.2

a. Expressed as µg/l
metric conversion units: To convert lb/ac to kg/ha multiply by 1.12

Most of the solids and heavy metal parameters did not appear to be highly related to ADT, percent imperviousness or dustfall on a simple correlation basis. However, multiple correlation of these characteristics with solids and metal loadings data showed stronger relationships.

Other Constituents. Average 5 day biochemical oxygen demand (BOD_5) values in highway runoff were generally between 2 and 133 mg/l. These values are comparable to effluent from a well operated secondary municipal treatment plant. Maximum BOD_5 values approaching 100 mg/l were exhibited in a few instances indicating that "slug" loadings of oxygen demanding pollutants are possible at times.

The biochemical oxygen demand to chemical demand (BOD/COD) ratios in highway runoff were considerably below values normally found in treated or untreated municipal wastewaters and were slightly lower than urban stormwater runoff values reported in the literature. This indicates that a higher percentage of the oxygen demanding material in highway runoff is of the nonbiodegradable types.

Nutrient loadings in highway runoff were generally comparable to urban stormwater runoff.

Sizable concentrations of the three widely used pathogenic indicator bacteria i.e., total coliforms (TC), fecal coliforms (FC), and fecal streptococci (FS) were found at all sites. The FC/FS ratios indicated origin of these bacteria from animal or bird sources. Bacteria counts were found to persist through the duration of the storm events and in successive or frequent rainfall events indicating that either these bacteria remain viable in animal and bird droppings for long periods or they are added on a regular or constant basis.

Geometric mean concentrations of polychlorinated biphenyls (PCB's) was 0.33 μg/l and generally the monitored PCB concentrations were well below the proposed 1 μg/l effluent standard for point discharge sources.

No significant concentrations of pesticides/herbicides were present in highway runoff.

Average oil and grease concentrations in monitored storm events ranged between 1 mg/l at all-grassy sites to 20 mg/l at the all paved area site (I-794). Significantly increased concentrations of oil and grease during winter conditions compared to nonwinter conditions were observed at two sites (I-794, Milwaukee and I-40, Nashville). Higher oil and grease loading (lb/acre-in. runoff) anticipated at the asphalt paved Denver site were observed.

No asbestiform material was detected in 19 out of 21 samples analyzed at five of the six monitoring sites. Analysis of several grab runoff samples collected from the roadway and exit ramp surfaces in Harrisburg and Nashville did not show any asbestiform material. No firm conclusions could be drawn for the presence of asbestiform material in two of the five samples analyzed for the Nashville site. Further investigations regarding the presence of asbestiform material in highway runoff is continued under the Phase II contract (DOT-FH-11-9357) titled, "Sources and Migration of Highway Runoff Pollutants".

Generally, the all-paved Milwaukee I-794 site showed the highest loadings for most monitored constituents. The grassy area site in Milwaukee and the flush-shoulder design Harrisburg site showed the lowest constituent loadings among the various sites monitored in the study indicating that grass covered areas contribute significantly towards reduction of pollutant loads from the highway drainage systems.

Total solids and suspended solids showed significant correlations with most monitored constituents. Total solids coefficients generally showed slightly better correlations compared to suspended solids.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Further investigations on highway generated runoff should be conducted to expand the data base generated during this study. Desirable site features that may be included in future research are: high traffic volumes (>85000 ADT), asphalt drainage areas with high degree of imperviousness (40 to 80 percent), varying right-of-way characteristics and geographical location in an arid climate area.

2. Identify the relative magnitude of pollutant dispersion in highway environment by separating the background pollution, pollutants brought onto the highway system through external sources, pollutants generated within the highway system and the mechanisms of dispersion of these pollutants within and out of the highway drainage system. These aspects are presently being investigated under a FHWA Contract No. DOT-FH-11-9357.

3. Establish the fate of pollutants in unpaved (grassy) areas. Develop long term data on the characteristics of pollutant build-up and wash-off in unpaved areas of highway right-of-ways.

4. Continue applications of the predictive procedure to determine its accuracy. Measure the actual pollutant build-up on highway surfaces to determine relationships between site characteristics and accumulation rates.

5. Analyze the impacts of highway runoff pollutants on receiving waters through instream monitoring.

6. Incorporate procedures that will enable highway departments to record more precise highway maintenance data.

7. Develop procedures to include consideration of highway runoff quality data in drainage design and planning.

8. Identify potential points of partial or complete abatement/ treatment methods for objectionable constituents.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.