Guide for Assessing Water-Quality Impacts of Highway Operations and Maintenance

RICHARD R. HORNER AND BRIAN W. MAR

A 5-year effort to characterize highway runoff in Washington State resulted in the accumulation of data from more than 500 storms at nine locations and the development of a guide for assessing aquatic impacts of operating highways. The data were used to construct a simple model that expresses cumulative pollutant loadings as functions of highway segment length, average runoff coefficient, and vehicles traveling during storm periods. To assess pollutant loadings and concentrations in runoff from an individual storm, cumulative distributions were analyzed to determine the probability of specific loading and concentration values being exceeded in a given case. Bioassay studies of highway runoff indicated toxicity to aquatic life when heavy deposition of metals from high traffic volumes (>10,000 vehicles per day) or high concentrations of metals in rainfall caused concentrations in runoff to exceed lethal levels. Draining highway runoff through grass channels 200 to 300 ft long greatly reduced concentrations of solids and metals and the consequent toxic effects. The impact assessment guide incorporates these results in a stepwise procedure for use by highway designers and environmental impact analysts in the Pacific Northwest. The guide is organized in three analysis levels, ranging from a rapid screening method intended to identify those cases with a low probability of extensive impacts (level 1) to a detailed evaluation focusing on impact mitigation (level 3). It presents methods for assessing the water-quality impacts of winter maintenance and special problems in addition to the effects of runoff from routinely operating highways.

Comprehensive studies of the characteristics, transport, and environmental effects of runoff from operating highways, as a specific component of general storm drainage, are few in number. Several investigations, however, have thoroughly treated some aspect of the subject. Early work was concerned primarily with deposition of contaminants on urban streets (1-3). This theme was also the subject of more recent work (4-6). Sylvester and DeWalle (7) and Soderlund and Lehtinen (8) were among the first to derive pollutant mass loadings for highways, an effort supplemented by the Municipality of Metropolitan Seattle (9,10). Shaheen (11) advanced the development of pollutant loading information by vacuuming and flushing Washington, D.C., area highways and statistically relating mass loadings to traffic density. Several researchers in the United Kingdom have also been active in characterizing the water quality of highway runoff (12-14).

The Envirex Division of Rexnord Corporation and the California Department of Transportation conducted fairly comprehensive highway runoff studies at multiple sites over periods of several years. The Envirex investigation (15,16) covered five sites in different parts of the country to represent different climatic and traffic conditions. It concluded with the development of a deposition model for predicting the accumulation of pollutants in the periods before storms and a washoff model for forecasting contaminant removal in the runoff. The California study (17) was concerned primarily with thoroughly characterizing the physical, chemical, and biological constituents in California highway runoff. A later report of this work (18) also dealt with the effects of runoff through bioassays in which algae were exposed to highway drainage.

Thus, the literature reflects attention to the origin, characteristics, transport, effects, and modeling of highway runoff. Missing from the research record, however, is assimilation of these various results for the purposes of assessing environmental impact and applying mitigative measures.

The Washington State Department of Transportation (DOT) sponsored a 5-year research effort encompassing all of the elements that determine the nature of highway runoff water quality and its effect on water bodies that receive highway drainage. Preliminary investigation (19) indicated that approaches that were valid elsewhere often were not applicable in the Pacific Northwest because of the unique features of its climate. Therefore, the research was directed at developing and verifying methods that could be used reliably in the region. The ultimate objective of the program was to construct models and protocols that would provide convenient means of analyzing the impacts of operating highways on water resources. The products of the research effort were incorporated in a guide (20) for conducting water-quality impact assessments of highway operations and maintenance. The guide is described in detail in this paper and the supporting research project and its results are summarized.

SUMMARY OF RESEARCH PROGRAM

Experimental Design

One of the first issues faced in the research program was whether to base monitoring on discrete samples collected throughout storms or on composites representing entire storms. Sampling equipment was developed (21,22) to collect composite samples from a storm economically, and the decision was made to sacrifice the better characterization of the pollutographs of a relatively few storms (discrete samples) in favor of composite data from many storm events. This equipment has been used to sample approximately 550 storms at nine locations in Washington State.

The major elements of the sampling system are a calibrated flow splitter and a composite sample collector. Flow splitters contain a series of parallel vertical dividers aligned with the flow that separate the runoff into successively smaller portions. Flow splitters were installed on slopes to ensure supercritical flow and uniform distribution of runoff over the base. The flow splitters were sized to capture a set proportion of the design storm for each site, typically about 1 to 2 percent.

Monitoring sites were selected to represent the range of conditions on Washington State highways. Table 1 gives the highway and environmental char-

Table 1. Summary of characteristics of highway runoff monitoring sites.

Category	Characteristic
General climate	Marine lowlands, Cascade Mountains, arid central basin, dry eastern uplands
Average annual precipitation	7 to >100 in.
Setting	General urban, urban residential, rural open and forested, rural agricultural
Highway type	Limited access, arterial, at-grade, bridge sections
Pavement	Concrete, asphalt, sulfur-extended asphalt
Average daily traffic (one direction)	2,000 to 53,000

acteristics covered among the nine sites, which represented the wide variation in climate and land use type in the state as well as the major highway configurations.

The data collected at each site included continuous, automatic traffic counts and, for each storm, precipitation and runoff volumes. Samples were transported to the laboratory directly from local sites or by parcel mail from remote locations and preserved until analysis. Analyses were performed for total suspended solids (TSS), three metals (lead, zinc, and copper), nutrients (total phosphorus, total Kjeldahl nitrogen, and nitrate plus nitrite-nitrogen), and general measures of organic constituents (chemical oxygen demand and total organic carbon). Sampling and analytic procedures have been reported elsewhere (23-26). One study demonstrated no measurable degradation of the constituents of interest during the sample transport period (23). Measured concentrations and flow volumes were used to estimate pollutant loadings in units of mass per unit of highway length. Tests demonstrated that comparable loading estimates resulted from samples from the composite tank and composites made from discrete samples collected simultaneously by an automatic sampler (21,22).

Pollutant Transport Mechanisms

It was observed during the research that the major sources of pollutants in highway runoff are deposition from vehicles, transport from surrounding lands, pavement wear, accidental spills, and certain maintenance procedures. The data demonstrated that pollutants deposited by vehicles primarily resulted from the spray-washing of material adhering to the undercarriages of vehicles as they travel on wet roadways during the extended rainy periods that occur in western Washington (23,24).

Mechanisms that tend to remove pollutants from highways include hydrologic and vehicular scrubbing, maintenance, and natural and traffic-generated winds. The eruption of Mount St. Helens midway in the project provided an opportunity to observe directly the result of traffic-generated winds. This mechanism is considered to be of major importance in pollutant removal (23,24). In the Pacific Northwest, the transport of highway pollutants appears to be more a function of kinetic energy provided by moving vehicles than by the low-intensity rainfall.

Pollutant Loading Analysis

As the data base developed, an investigation was conducted of the associations among pollutant loadings and a number of site and storm characteristics, including volume, duration, and intensity of precipitation, antecedent dry period, total traffic, and vehicles traveling during storm periods. The analysis that exhibited the most consistent pattern for the various sampling sites and contaminants monitored was an analysis of cumulative pollutant mass per unit of highway length versus cumulative traffic volume during storms (23,24). Figure 1 shows the results for one station. The relationship exhibited a step function form in which the steps were associated with occurrences of winter sanding or, on a few occasions, volcanic eruptions. The fall and spring periods were characterized by linear relationships. When similar plots were observed for all sampling sites, it was seen that the slopes of the lines differed among sites and between winter and other seasons at each site.

Because of these apparent differences, it was natural to hypothesize that site runoff coefficients should have a major influence on the cumulative pollutant mass loading entering the runoff. When this variable was introduced, TSS runoff rates at the various stations fell into two distinct groups: western Washington sites with relatively low rates and eastern Washington sites with substantially higher rates. The elevated rates at arid eastern Washington locations resulted from deposition of loose soils on roadways by relatively high and continuous winds. The relationships can be expressed by a simple linear equation in which TSS loading is proportional to the product of cumulative vehicles during storms (VDS) and runoff coefficient (RC) (23, 24):

$$\text{TSS loading} = (K)(\text{VDS})(\text{RC}) \quad (1)$$

Because TSS loading is directly proportional to runoff flow rate, the constant of proportionality (K), which is the TSS runoff rate at a runoff coefficient of 1, can be established as follows (25,26):

$$K_{(RC=1)} - K_{(RC=n)}/n \quad (2)$$

The mean constant (± one standard error) for western Washington locations was 6.4 ± 0.8 lb/highway mile/1000 VDS (27). By observing runoff after large, intense storms that thoroughly cleaned highway surfaces, it was found that the constant fell to approximately 3 lb/highway mile/1000 VDS, which represents the direct contribution of vehicles alone and excludes import from adjacent land uses (27). The reduction in the loading factor is short-lived, and one or more dry days restore enough solids to return it to approximately the mean value. K for eastern Washington locations was estimated, on the basis of considerably fewer data than were available for western Washington, to be 26 ± 2 lb/highway mile/1000 VDS (27).

Other pollutants generally exhibited a relationship to cumulative VDS similar to that of TSS. Again, a linear relationship during the spring and fall was evident, broken by steps coincident with sanding. The similarities of form among the plots suggested that the various contaminants were transported primarily in combination with the solids and that their loadings could be estimated as proportions of TSS loadings (25,26):

$$(\text{Specific pollutant loading})\ (P)\ (\text{TSS loading}) \quad (3)$$

The coefficients of proportionality (P) are analogous to potency factors sometimes used in SWMM, STORM, and other models (28). The coefficients derived from the data given in Table 2 can be taken as constants at any Washington State location for organics and nutrients or as linear functions of average daily traffic (ADT) for heavy metals (27).

These equations were developed on the basis of cumulative measures and are thus applicable to assessing total loadings over a time span that includes a number of storms (monthly or annually). However, they are deficient in predicting loadings for individual storms with precision (27). It is hypothesized that there is a cyclic accumulation and washoff of pollutants and that the buildup is associated with small storms that wash the undersides of vehicles. Larger storms then periodically wash the road surface. Therefore, loadings in a given locale are highly variable over a short time but are more constant over the longer term when normalized for traffic and runoff coefficient. In regions such as the Pacific Northwest, where many storms do not have sufficient intensity to clean highways thoroughly, accurate assessment of individual storm loading with a deterministic model is problematic. As discussed in the next section, analyzing loading probability

Figure 1. Cumulative TSS versus cumulative traffic volumes during storms for WA-520 site.

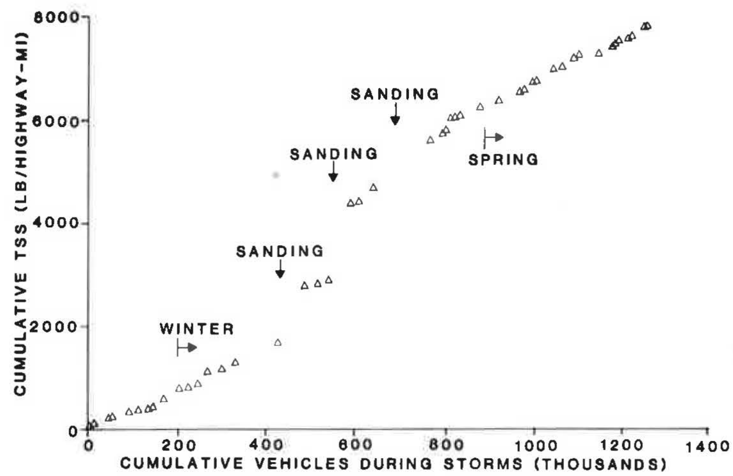


Table 2. Expressions of specific pollutant ratios recommended for use with Washington State highway runoff model.

Pollutant	Expression	R^2	Specifications
Volatile suspended solids	$P_{VSS} = 0.2$	--	All sites
Chemical oxygen demand	$P_{COD} = 0.4$	--	All sites
Lead	$P_{Pb} = 1.5 \times 10^{-4} + (8.7 \times 10^{-8})$ (ADT)	0.978	Western Washington sites
	$P_{Pb} = 5.3 \times 10^{-4} + (2.8 \times 10^{-8})$ (ADT)	0.996	Eastern Washington sites
Zinc	$P_{Zn} = 1.5 \times 10^{-4} + (3.0 \times 10^{-8})$ (ADT)	0.864	Western Washington sites
	$P_{Zn} = 2.0 \times 10^{-4} + (3.2 \times 10^{-7})$ (ADT)	0.932	Eastern Washington sites
Copper	$P_{Cu} = 7.9 \times 10^{-5} + (2.7 \times 10^{-9})$ (ADT)	0.739	All sites
Total Kjeldahl nitrogen	$P_{TKN} = 2.7 \times 10^{-3}$	--	Western Washington sites
	$P_{TKN} = 1.2 \times 10^{-3}$	--	Eastern Washington sites
Nitrate plus nitrite - nitrogen	$P_{NO_3+NO_2\text{-}N} = 2.0 \times 10^{-3}$	--	All sites
Total phosphorus	$P_{TP} = 2.1 \times 10^{-3}$	--	All sites

distributions proved a successful approach to this problem.

Analysis of Individual Event Concentrations and Loadings

In addition to assessing cumulative impacts by means of the loading equations, it is necessary to evaluate acute effects on receiving waters. To do so, individual event concentrations and loadings must be expressed. Storm runoff pollutant concentrations are highly variable from site to site, from storm to storm, and even within storms. As previously noted, loadings also have considerable spatial and temporal variability. When faced with similar data collected in the Nationwide Urban Runoff Program (NURP), the U.S. Environmental Protection Agency (EPA) (29) determined that the data were lognormally distributed and that the distributions could be analyzed to determine the probability of specific concentrations being exceeded in any storm.

The same analysis was used with the Washington State data on highway runoff water quality. The data were aggregated into eastern and western Washington and high- and low-traffic groupings and plotted as probabilities of a given value being exceeded in any storm versus the logarithm of the concentration or loading exceeded (27). The concentrations used were those in the composite samples, which represented the event mean values. These plots were essentially linear and demonstrated the lognormality of the data. Figure 2 shows an example of the most useful form of these charts, in which each pollutant concentration and loading case was graphed separately and curves were added to represent reductions of contaminants by set amounts as a result of removal by treatment methods, dilution by receiving waters, or a combination of the two. Where available, established water-quality criteria were shown to provide a basis for judging effect and assessing impact.

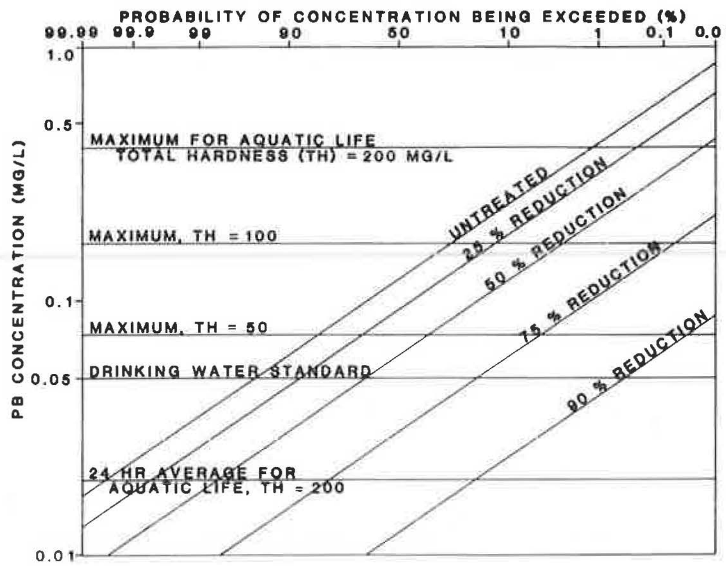
Special Studies

Several special studies were performed within the research program to document particular aspects of highway runoff water quality. Most relevant were the special studies involving trace organic and heavy-metal contaminants, the toxicity of highway runoff to aquatic life, and the effectiveness of vegetated drainage courses in reducing pollutant concentrations and their toxicities.

The investigation of trace organics demonstrated that toxic organic contaminants, if detectable at all, were primarily adsorbed on solid particles (30). An important consequence of this finding is that removing TSS from runoff also reduces organics as well as other pollutants associated with the solids. The absence of an impact due to TSS is currently regarded as a valid indication that organics likewise would not impair the receiving water. The toxicity demonstrated in certain highway runoff samples was thought to be caused chiefly by dissolved metals (27,31).

Toxicity bioassays were performed on a green alga, a cladoceran zooplankter, and rainbow trout fry by using runoff from highways representing a variety of conditions (27,31). Toxicity was absent in the case of highways transporting less than 10,000 ADT in a single direction. The highways rep-

Figure 2. Lead concentration versus exceedence probability distribution for low traffic volumes in western Washington.



resented in these tests had a range of vehicle types and operating modes. Toxic responses were particularly pronounced when specimens were exposed to runoff from a high-volume freeway (approximately 50,000 ADT in one direction) where the local rainfall contained elevated zinc concentrations. Runoff was less toxic for a case in which a highway had a similar traffic volume but the rainfall was lower in zinc. Toxicities to algae (27) and rainbow trout fry (30) were greatly reduced when the runoff was channeled through a grass-lined ditch 250 ft long.

Further investigation documented the effectiveness of vegetated channels in removing solids and other pollutants associated with them from highway runoff. A 200-ft channel was found to be capable of decreasing total suspended solids, chemical oxygen demand, and total lead by approximately 80 percent. More soluble metals, such as zinc and copper, were reduced by approximately 60 percent (32). An unvegetated portion of the channel did not provide filtering action. Residues deposited in such channels were easily entrained by subsequent runoff.

On the basis of these special studies it was concluded that highway location and design should ensure protection of receiving water biota by providing adequate dilution of contamination in runoff or treatment by means of drainage through vegetation, especially when lanes carrying more than 10,000 vehicles/day are involved. Subsequent maintenance practices should promote this protection by minimizing the use of fine sands and road salts in winter operations and maintaining drainage channels in vegetation.

IMPACT ASSESSMENT METHODOLOGY

Scope

The findings of the Washington State DOT/University of Washington research project on highway runoff water quality and relevant material from the stormwater runoff literature were incorporated in a guide for assessing water quality and aquatic ecological impacts of operating highways (20). The assessment approach is responsive to guidelines issued by EPA (33) and is specifically oriented toward the operating requirements and conditions of Washington State highways.

The potential effects of highway operations on water quality are

1. Increases in peak flows in receiving streams;
2. Erosion and sediment transport into receiving waters;
3. Degradation of the quality of receiving water bodies, possible impairment of their beneficial uses, and harm to aquatic biota due to drainage of contaminants incidentally deposited on the roadway; and
4. Effects on receiving water as a result of maintenance procedures.

The guide provides techniques for assessing each of these impacts and recommends strategies for reducing the severity of the identified impacts. It also treats special problems in water-quality impact assessment.

General Approach

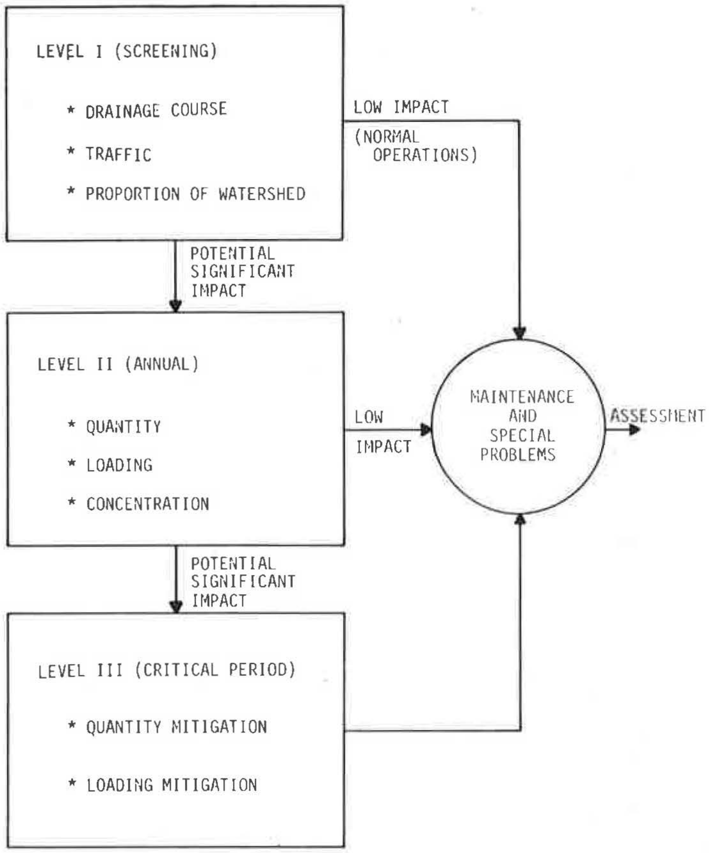
The guide is generally organized as follows:

1. Data needed for preparation of a water-quality assessment (based on EPA guidelines and the particular need for applying the methods developed in the guide),
2. Procedures for assessing the impacts of normal highway operations on water quantity and quality, and
3. Treatment of impacts related to maintenance and special problem areas.

The procedure for normal operations is organized in three levels of analysis, which increase in precision, detail, comprehensiveness, and the quantity of effort required. Maintenance issues and special problems considered are winter sanding and deicing; pesticide applications; construction of woodwaste fills, which is fairly common in the Pacific Northwest; accident spills; and problems related to groundwater. In the case of groundwater, specific reference is made to draft EPA guidelines for assessing the impacts of highways that impinge on designated sole-source aquifers (34).

Figure 3 shows a flowchart of the three levels of detail involved in the general assessment procedure. The first level of assessment merely screens a high-

Figure 3. Overall assessment procedure.



way area in terms of its proportion of the total watershed, the type of runoff drainage system, and the projected traffic volume. Highways that have low ADT, occupy a small percentage of the watershed, or discharge runoff through a vegetated drainage course may be declared to create minimal impact in normal operation. The user is then directed into an analysis of potential impacts from periodic maintenance procedures, accidental spills, and other special problem areas.

If the first level of analysis indicates a potential for a significant impact, the guide prescribes a level 2 analysis based on annual predictions. If necessary, a level 3 analysis, based on monthly projections, can be done to analyze the extent of aquatic impact more thoroughly. Level 2 and level 3 analyses focus on defining the hydrology of receiving water and pollutant loading contributions from the various land uses in the watershed in some detail. The impact of the highway is evaluated in the context of the total burden created by all activities in the watershed.

The second level of analysis guides the user through assessments of peak stream discharge and pollutant loading increases expected to result from the presence of the highway as well as an estimate of the frequency with which given contaminant concentrations would be exceeded. Decision criteria are presented in each instance to judge whether level 3 analysis is warranted. The loading model developed from the research data is the basis for the loading assessment; the probability charts prepared from the data are used in frequency analysis.

The level 3 procedure emphasizes more thorough analysis of the hydrologic and water-quality conditions indicated at level 2 to be of potential significance. Consideration of mitigation measures for demonstrated problems is recommended as well as repeated analysis to forecast their effectiveness. As in level 1, at the conclusion of levels 2 and 3 the analyst is directed to a consideration of special problems.

Levels of Analysis

Level 1

Figure 3 outlines the sequence of steps involved in level 1. In more detail, these steps are as follows:

1. If all runoff discharges by way of a vegetated drainage course at least 200 ft long, go to step 3; otherwise, proceed to step 2.
2. If projected ADT is less than 10,000, proceed to step 3; otherwise, perform level 2 analysis.
3. Determine the total area of the watershed located upstream from the highway runoff discharge point. If there are multiple discharge points, base the determination on the one located farthest downstream.
4. Determine the total area of impervious roadway surface that contributes runoff to the receiving water.
5. If the ratio of impervious roadway surface to total watershed area is less than 0.01, declare no impact from ordinary runoff and proceed to step 6. Otherwise, perform level 2 analysis.
6. Analyze impacts associated with the particular maintenance practices anticipated or any special problem areas.

Each decision criterion has a basis in the research results. The minimum length of vegetated channel is the length identified (32) as reliably providing 60 to 80 percent reduction of major pollutants in highway runoff. The traffic criterion is that below which no toxic effects appeared in bioassays (31). As for the ratio of highway surface to watershed area, it is assumed that the runoff is diluted in the receiving stream in approximately the same ratio. Highway runoff can contain concentrations of toxicants comparable to LC_{50}'s (concentrations lethal to 50 percent of the organisms in an acute bioassay) (31). A common means of protecting aquatic life is to limit receiving water concentrations to $0.01 \times LC_{50}$. In addition, investigation of the relationship between pollutant concentration and exceedence probability distributions (Figure 2) indicates that a dilution ratio of about 100:1 is generally required to ensure only a slight probability (<0.1 percent) that established water-quality criteria will be exceeded. With a high dilution ratio of ordinary runoff and either low traffic volume or drainage over a vegetated drainage course, it can be stated with some assurance that impact would be insignificant and a more detailed analysis can be avoided.

Level 2

The level 2 assessment of runoff quantity is based on procedures from general practice and the literature because no hydrologic modeling was performed as part of the research project. In its present form, the guide recommends estimating the design for the 25-year-recurrence-interval storm according to the rational method used by the Washington State DOT (35). The procedure can be modified to use a more advanced technique such as the unit hydrograph or a computerized model.

The highway runoff rate should be compared with receiving-stream peak discharge for the same design storm condition. This peak discharge can be established through analysis of the gauging record, if a sufficient one exists, by using an extreme-value (type 1) distribution (36) or, where there is no adequate gauging record, a U.S. Geological Survey procedure developed for the state of Washington (37). An appropriate hydrologic model can also be used to determine design peak stream flow as a percentage increase under the design conditions. If this increase exceeds a permitted amount or is judged to be excessive, the user is directed to level 3 to design detention facilities.

The flowchart shown in Figure 4 provides a guide to the level 2 annual pollutant loading assessment. Fundamentally, it requires that the analyst compare anticipated highway runoff pollutant loadings with loadings already present in the receiving water. These preexisting loadings can be established either by using data on stream water quality and flow, where these are sufficient, or from the land use characteristics of the watershed. The procedure encompasses discharges to standing bodies of water (lakes and wetlands) as well as streams. Its rather arbitrary decision criterion for determining whether further analysis is recommended is a loading increase of more than 10 percent for any pollutant deposited in the receiving water as a result of the highway.

In applying this component of the procedure, TSS loading is first estimated according to the relationship presented in Equation 1. Use of the equation requires an estimate of the annual VDS, which may be proportioned from ADT projections by

$$\text{VDS/year} = \text{ADT}\ [\text{wet hours per year}/(24\ \text{hr/day})] \quad (4)$$

Meteorological records are not routinely kept for the mean duration of precipitation. In the case of Washington State, however, a 16-year record of such data was compiled by the Pacific Northwest River Basin Commission for 32 locations (38). Other data were obtained from the National Climatic Center in Asheville, North Carolina. The record is sufficient to establish satisfactorily mean wet hours per year at almost any location of interest. The data also permitted the derivation of a linear regression equation by which hours of precipitation per year can be calculated as a function of mean annual precipitation. The equation has a high coefficient of determination (0.990) because rainfall intensities are generally light throughout Washington State, although total quantities vary radically.

The TSS loading estimated from Equation 1 should be modified to reflect any runoff treatment provided. The guide presents approximate pollutant reduction capacities of various lengths of vegetated channel derived from the research results. The estimation of highway contaminant loadings is completed by applying Equation 3 to the estimation of chemical oxygen demand, metals, and nutrients from the expected TSS loading and the specific pollutant ratios.

Preexisting pollutant loadings in the runoff receiving water may be estimated from stream water quality and flow data, if they are adequate, or from published loadings from the various land uses in the watershed for lakes and wetlands and inadequately documented stream cases. Provided that consistent units are maintained, the annual pollutant loading in the stream can be estimated from the product of the average discharge and the mean contaminant concentration. For standing water or where hydrologic and water-quality data are lacking, export resulting from general types of land use can be estimated from information taken from the literature and tabulated in the guide and added to known point source loadings to obtain total loadings. Using these data is substantially less satisfactory than using stream records because of the evident dispersion created by combining results from many locations collected by widely differing procedures.

Level 2 gives an additional eutrophication assessment procedure to be used when the receiving water is a lake. This procedure is based on phosphorus loading criteria presented by Vollenweider and Dillon (39).

The final component of level 2 is an assessment of pollutant concentrations based on individual storm events. The key to conducting this analysis is to use an appropriate graph of the type illustrated in Figure 2. The first step is to estimate pollutant reduction factors due to treatment and dilution. Treatment factors can be estimated for vegetated channel drainage according to the guidelines derived from the research or from the performance characteristics of detention or other control devices. The mean dilution ratios (DR) can be approximated as follows:

For streams,

$$DR = Q/(Q + \bar{Q}_s) \quad (5)$$

For lakes or wetlands,

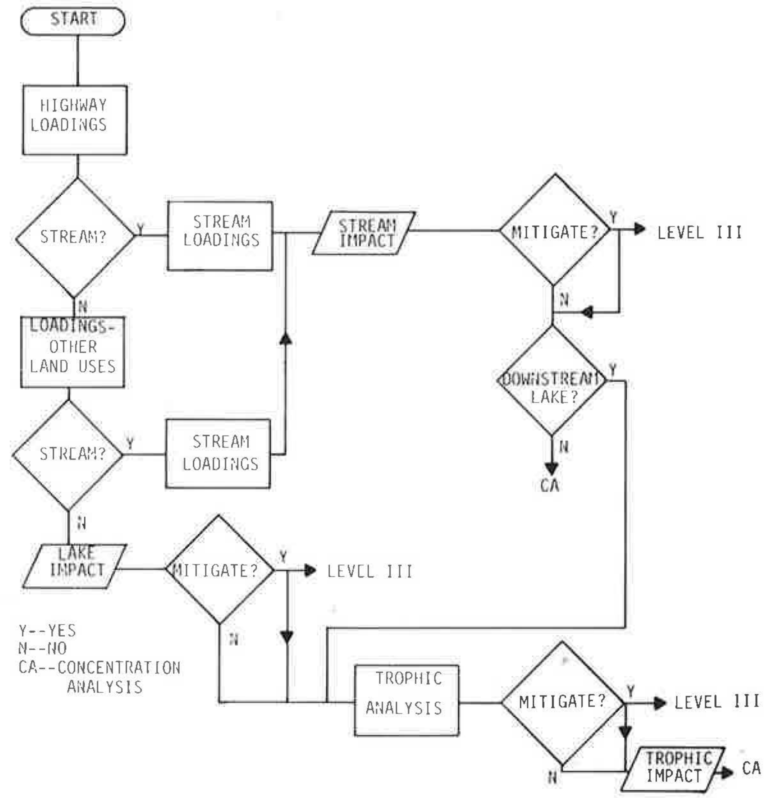
$$DR = QT/(QT + V) \quad (6)$$

where

Q = design highway runoff flow rate,
$\bar{Q}_s$ = average stream discharge,
T = design storm runoff duration, and
V = lake or wetland water volume.

It is recommended that Q be estimated by using

Figure 4. Flowchart of level 2 procedure for pollutant loading assessment.



the rational method or an alternative procedure, where intensity (I) is the average for the 25-year-recurrence-interval, 24-hr-duration storm as given by an isopluvial map of the National Oceanic and Atmospheric Administration (40). The overall pollutant reduction factor is then the product of the decimal-fraction efficiency due to treatment and the dilution ratio.

As an example of the use of the probability distribution charts, consider the lead concentration for the western Washington low-traffic-volume case illustrated in Figure 2. In waters with a total hardness of 50 mg/L as $CaCO_3$, the log probability plot predicts an 83 percent probability of the maximum concentration for aquatic life protection being exceeded if highway runoff is untreated and undiluted; i.e., about 5 of every 6 storms would cause a lead violation. If, however, a 90 percent reduction in lead could be achieved through treatment or dilution or both, the probability of the water-quality criterion being exceeded would drop to 0.04 percent, or approximately 1 storm in 2,500 would result in a violation. As with the loading assessment, the analyst must apply judgment to decide whether to proceed to a level 3 analysis of further mitigative action.

Level 3

Level 3 has an arrangement parallel to that of level 2 in that it comprises assessments of runoff quantity, accumulated pollutant loadings, and individual event occurrences. The particular procedure would be applied, however, only for the specific problem(s) identified as potentially significant in the level 2 analysis.

Level 3 differs from the previous level in several ways. The quantity assessment emphasizes design, or redesign, of detention facilities, using customary highway design procedures, to prevent excessive increases in stream peak flow. The loading assessment is for the monthly period in which the most hours of rainfall occurred rather than annual as in level 2, and a more detailed definition of land use is used. Otherwise, the loading analysis is identical to the level 2 procedure.

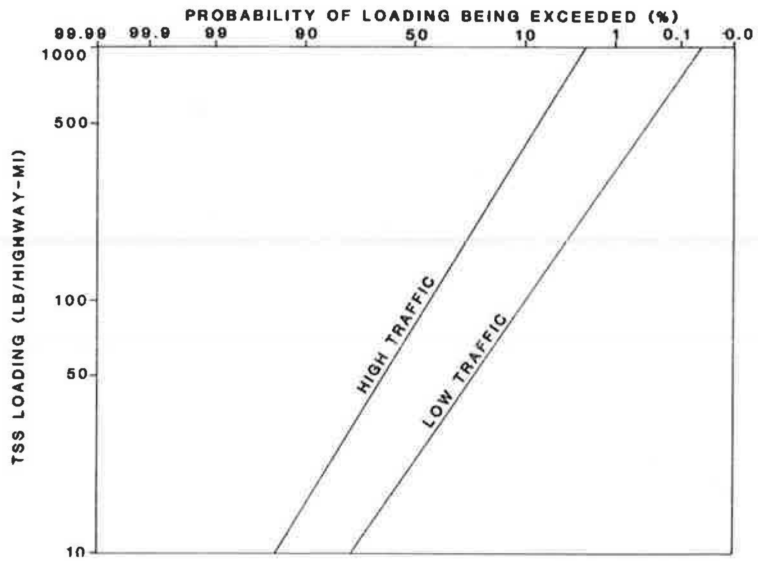
The individual event assessment is directed at water-quality impact mitigation and provides a basis for the design of control facilities. That basis is shown in Figure 5 in the form of a TSS loading-probability distribution for western Washington (an analogous plot exists for eastern Washington). The analyst may select a design probability--e.g., the loading exceeded in only 10 percent of the storms--to use in selecting and sizing the control device. Pollutants other than TSS may be brought into the analysis through use of the multipliers given in Table 2.

Assessment of Impacts Associated with Maintenance Practices and Special Problem Areas

The assessment methodology described applies only to the aquatic impacts associated with ordinary runoff events on normally operating highways. Periodic and extraordinary phenomena must be analyzed separately. Included in this category are winter sanding and deicing, pesticide application, construction practices that create continuing effects on surface waters, and accidental spills. The assessment document provides guidance in these areas although without the specificity made possible by the large data base underlying the routine evaluation.

The various pollutant loadings are augmented by the presence of sand. Winter data demonstrated that sanding contributed a major portion of TSS seasonally, the amount varying with the sand application rate and other sources of solids. The results were

Figure 5. TSS loading versus exceedence probability distribution for high and low traffic volumes in western Washington.



insufficient to model the proportion of applied sand entering the runoff. Thus, currently it is necessary to estimate the proportion roughly on the basis of sand characteristics, plowing, and sweeping.

The research demonstrated that the ratios of other pollutants to the TSS associated with sanding were equal to those given in Table 2 for the high-traffic-volume sites. With lower traffic volume, pollutant deposition failed to saturate the sand particles and the ratios were substantially lower on a cumulative basis (41). It is recommended, therefore, that the loadings of other pollutants be established according to the procedures given for levels 2 and 3 when ADT is projected to exceed 10,000. With lower traffic volume, the assessment should reflect the elevated TSS loading due to sanding but should not augment the loadings of other pollutants in proportion to the TSS resulting from sanding.

Deicing impacts were not specifically investigated in the Washington State research. The guide does provide a procedure drawn from work in Massachusetts (42) for estimating sodium and chloride loadings and concentrations from prevailing application rates.

A comprehensive study of leachates from woodwaste fill sections was undertaken during the research (43). The guide presents an aquatic impact assessment protocol for that regionally important problem. Pesticide applications and accidental spills are covered qualitatively.

SUMMARY AND CONCLUSIONS

A procedure for assessing highway runoff water quality has been formulated on the basis of a large data base that represents conditions prevalent in the state of Washington. The procedure consists of a component for predicting total pollutant loadings over an extended time period and a series of charts with which the impacts of individual events can be assessed probabilistically. These elements, as well as protocols for assessing the impacts of runoff quantity and special problems, have been assembled in a guidebook for evaluating aquatic impacts due to highway operations and maintenance. It is believed that the specific research findings and the proposed impact assessment procedures apply throughout the Pacific Northwest and that the techniques used to monitor storms and analyze the data are more generally applicable.

A significant finding of the research was that highway runoff in Washington State contains lower levels of contamination than general urban drainage and, in normal runoff events, does not have a substantial impact on the quality of receiving water. For highways that carry large traffic volumes, approximately 50,000 ADT in a single direction, a high impact potential exists. That potential can be greatly reduced by avoiding direct drainage to receiving waters by way of piping or bare channels and by avoiding circumstances in which the highway runoff constitutes a substantial fraction of the receiving water flow.

Several aspects of the problem discussed in this paper stand out as areas requiring further research. The assessment guide emphasizes mitigation where impact potential is high and provides design bases for its execution. However, the state of the art is not sufficiently advanced to make full use of that information. The performance of detention basins, vegetated channels, and other control methods must be investigated over gradients in various conditions to add the necessary background for complete engineering design. The contribution of winter sanding was shown to be of considerable importance in determining instantaneous pollutant concentrations and long-term loadings. Additional research is needed to quantify those contributions more thoroughly and to incorporate them in the assessment procedure. Finally, comprehensive procedures for assessing the impact of highway runoff should be developed for other regions. Existing data sets should be reviewed with this goal in mind, and necessary additional data collection should be prescribed.

The result of the Washington State research was that limited problem areas were identified and thus a basis was provided for reducing mitigation costs overall and applying resources to those cases most in need of attention. It is possible to achieve these savings nationwide while providing environmental protection where the need is greatest.

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Soil Erosion Study of Exposed Highway Construction Slopes and Roadways

BRADLEY A. ANDERSON AND DARYL B. SIMONS

The quantities of sediment produced from construction slopes and roadways are determined, and a methodology to assist in the determination of these quantities is presented. During the study a portable rainulator was fabricated and applied to collect water runoff and soil erosion data from forest logging roads in northern California. The data collection program was conducted on 10 representative soils in the study area and included testing of cut slopes, fill slopes, road surfaces, and undisturbed sites above the roadway. The data were analyzed and used as input to a simple mathematical model. Additional input parameters were estimated and the model was calibrated. The mathematical model was found to reproduce accurately measured values of water and sediment yield from the roadways. After the mathematical model was calibrated, a procedural guide and an interactive program were developed. Both can be used to assist the forest planner in determining the sediment produced from different roadway geometries and in assessing roadway design alternatives.

Erosion resulting from the construction and use of highways is a problem that continues to plague highway planners and designers. The sediment generated during and after construction is often excessive unless proper erosion control measures are taken. These measures, which should be incorporated in every roadway design, vary in nature from vegetative to structural methods for controlling erosion. In selecting the optimum roadway design, it is necessary to estimate the erosion that will be generated as a result of the design. Hence, methods or procedures for determining these erosion quantities are essential to the selection process.

A recent study conducted by Colorado State University for Region 5 of the U.S. Forest Service (1) culminated in the development of two methods for estimating water and sediment yield from roadways of different designs. The study included (a) selection of a mathematical model to simulate the erosion processes, (b) a field data collection program to provide input to the mathematical model, (c) refinement of the mathematical model based on the collected data, and (d) generation of a procedural guide and an interactive program. The procedural guide provides the field practitioner with a simple and useful method of estimating water and sediment yields for use in road design and environmental impact analysis. The interactive program provides the same capability but eliminates the time-consuming hand calculations required by the procedural guide.

MODEL SELECTION, COMPONENTS, AND DATA INPUT

Predicting water and sediment yields that result from highway construction and use is a complex problem. Solutions to this problem depend on the accurate estimation of a wide array of variables and usually require the use of a mathematically based model. Regression models based on limited field data are unable to cope with this problem on a widespread basis because (a) they are restricted by the data from which they are developed, (b) they assume that the physical environment is both time- and space-invariant, and (c) they tend to group controlling processes into a few coefficients. This grouping decreases the usefulness of the model in examining the effects of individual processes on water and sediment yield from the road.

Physical process models, on the other hand, represent the system being modeled by decomposing it into its respective components, thus avoiding the lumping of processes or parameters. By simulating selected phenomena through separate components, each process can be individually analyzed and refined or