Highway Runoff Water Quality Research Implementation Manual

Volume 1

Water Quality Criteria
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16. Abstract

The Washington State Department of Transportation (WSDOT)/University of Washington Highway Runoff Water Quality research project, conducted from 1977 to 1982, produced a number of results of potential use to WSDOT. An effort was required to implement these results in the Department's procedures. One phase of implementation completed previously involved preparation of a guide for assessing the impacts of operating highways on aquatic ecosystems and training WSDOT personnel in its use. The present phase involved formulating decision criteria in a number of water quality problem areas of concern to WSDOT and determining the need for revisions to department documents for consistency with the research results and the new criteria. The results of this phase are presented in a two volume implementation manual and a separate document listing the suggested modifications to four existing WSDOT manuals. Volume 1 of the implementation manual states the criteria, which were developed for: 1) identification of waters potentially sensitive to impact by operating highways; 2) the use of vegetated drainage courses to treat highway runoff; 3) the use of retention/detention facilities for highway stormwater drainage; 4) disposal of ditch cleaning spoils; 5) the use of woodwaste fills for highway construction; 6) highway sanding; 7) dilution of highway runoff in a receiving water; 8) highway cleaning; and 9) stream channel modification for highway construction. Volume 2 presents the basis of each criterion listed in Volume 1, including references to the research results and other literature, the reasoning followed, development of equations, etc.

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Washington State
Highway Runoff Water Quality Research
Implementation Manual

Volume 1

Water Quality Criteria

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FOREWARD

This manual presents criteria for implementing the results of the Washington State Department of Transportation (WSDOT)/University of Washington Highway Runoff Water Quality research project completed in 1982. It consists of two volumes: Volume 1 states criteria for the protection of water resources in nine potential problem areas associated with operating highways; and Volume 2 presents the basis for these criteria. Companion documents to this manual are: (1) Suggested Revisions to WSDOT Manuals for Implementing Washington State Highway Runoff Water Quality Research Results; (2) Highway Hydraulic Manual (Washington State Department of Highways, 1972) and (3) Guide for Water Quality Impact Assessment of Highway Operations and Maintenance (Horner and Mar, 1982). The Highway Hydraulic Manual guides the design of highway drainage systems. The third document should be consulted to conduct a detailed environmental assessment when the water quality criteria in this manual indicate that such an assessment is recommended. Other manuals issued by the Washington State Department of Transportation also cover aspects of these issues and should be consulted, as appropriate, in the design, specification, construction planning, and maintenance planning phases.

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SECTION 1

CRITERIA FOR IDENTIFICATION OF WATERS POTENTIALLY SENSITIVE TO HIGHWAY RUNOFF

Introduction

The Washington State Department of Transportation (WSDOT)/University of Washington Highway Runoff Water Quality research project derived a guide to assess the impact of operating highways on the surface fresh waters of the state (Horner and Mar, 1982). Highways that have average daily traffic under 10,000 and comprise less than one percent of the receiving water catchment normally do not create significant water quality impacts. For highway projects not meeting those conditions the project developed recommendations for avoiding or reducing impacts to aquatic ecosystems (Mar et al., 1982). These recommendations are applied only when waters sensitive to the potential impacts are involved. The impact assessment guide determines the need for these measures through a quantitative analysis and the application of objective critera. The procedure requires data on the highway segment, its drainage system, and the receiving water body. These data may not be available until some design work has been accomplished and some study of the adjacent environment has been undertaken.

An identification of potential sensitivity indicates that appropriate recommendations should be considered. A determination of relative insensitivity of the water body to the highway effects indicates that operation of the highway segment will have insignificant impact on the aquatic system.

The criteria are arranged according to water body type: (1) Streams and Rivers, and (2) Lakes. Within each water body type, criteria are stated for designated beneficial uses that may be affected by an operating highway. The water should be considered potentially sensitive if any criteria indicate such.

Criteria were developed by comparing the potential effects of highway operations on water quality with State Water Quality Standards, Chapter 173-201 WAC. The highway effects were estimated assuming direct drainage to the receiving water. When sensitivity is demonstrated, mitigation should be considered during project development. The Water Quality Standards classify fresh and marine surface water in five general water use and criteria classes. For each class, the characteristic uses are listed, followed by quantitative and qualitative standards. Other classification systems also were consulted and are referenced as appropriate.

Sources of information on the beneficial uses of a particular water body are:

Washington State Department of Social and Health Services, Division of Health, Water Supply and Waste Section

Washington State Department of Fisheries, Salmon and Shellfish Administrations, and the Stream Catalogs issued by the department (Williams et al., 1975; Phinney et al., 1975)

Washington State Department of Game, Fisheries Management

Washington State Department of Ecology, Regional Offices

U.S. Geological Survey, Tacoma and Spokane offices amd Water Resources Data Publications

County and local health departments

Local water authorities

Other possible water users

The criteria do not take into account cumulative effects resulting from superimposing highway impacts on those of other activities influencing the receiving water body. If deterioration exists, the water may have reduced capacity to assimilate further wastes. The basis of most of the criteria is a 0.1 percent probability (one storm in every 1000 storms) of violating a water quality standard. Potential sensitivity on the basis of this condition and the history of the water body subjects those cases where cumulative effects are possible to analysis using the impact assessment guide. The guide accounts for cumulative effects from all activities in the watershed.

Domestic water supply and fish use are the beneficial uses of surface waters that these criteria are designed to protect. Other beneficial uses are judged to be invulnerable to the effects of operating highways, protected by these more stringent standards, or must be considered individually.

1.01. Beneficial Uses of Streams and Rivers

Domestic Water Supply

A stream or river used for domestic water supply is potentially sensitive to impact by direct drainage from a highway if the ratio of highway area to watershed area is more than the critical value, R_c, determined from the following equation:

$$R_C = \frac{C_W}{C_H} R_T$$

where: C_W = watershed runoff coefficient (ratio of runoff volume to precipitation volume) (Table 1-1)

C_H = highway runoff coefficient (Table 1-2)

R_T = permitted ratio of highway area to watershed area for the beneficial use based on traffic, with equal runoff coefficients. The watershed area is the total area of land surface in the watershed of the stream or river located upstream of the runoff discharge point. The highway area is the total area of highway right-of-way contributing runoff to the stream or river.

Western Washington -- $R_T = -1.86 \times 10^{-6}$ ADT + 0.093

Eastern Washington -- $R_T = -1.53 \times 10^{-6}$ ADT + 0.029

ADT = average daily traffic

In addition to the above conditions, a stream or river used for domestic water supply is potentially sensitive to impact by sodium chloride deicing agent. Use only the amount of deicing agent necessary for traffic safety.

Fish Habitat

The pot ntial sensitivity of a stream or river used for fish migration, rearing, spawning, and/or harvesting is determined according to the formula for domestic water supply and the following equations for R_T:

Western Washington -- $R_T = -5.27 \times 10^{-7}$ ADT + 0.037

Eastern Washington -- $R_T = -1.23 \times 10^{-6}$ ADT + 0.031

In addition to the above conditions, a stream or river used for fish habitat is potentially sensitive to impact by sodium chloride deicing agent. Use only the amount of deicing agent necessary for traffic safety.

1.02. Beneficial Uses of Lakes

WAC 173-201-045/5, Lake Class, includes reservoirs with mean detention times of more than 15 days and reservoirs established on natural lakes.

Lake Eutrophication

A lake is potentially sensitive to eutrophication caused by direct drainage from a highway if the lake surface area is less than the value determined from an equation in the following set:

Western Washington interior lowlands -- $A = \frac{15.55\ (ADT)\ L}{\bar{z}\ (\rho + \rho^{0.5})}$

Western Washington high mountain and coastal locations -- $A = \frac{27.99\ (ADT)\ L}{\bar{z}\ (\rho + \rho^{0.5})}$

Eastern Washington low altitude arid areas -- $A = \frac{25.27\ (ADT)\ L}{\bar{z}\ (\rho + \rho^{0.5})}$

Eastern Washington higher altitude semi-arid areas -- $A = \frac{37.91\ (ADT)\ L}{\bar{z}\ (\rho + \rho^{0.5})}$

where:
- A = lake surface area (acres)
- L = highway segment length (miles)
- $\bar{z}$ = lake mean depth (ft)
- ADT = average daily traffic
- ρ = lake flushing rate (yr^{-1})

Note: If lake data are not available, assistance may be obtained from the WSDOT Headquarters Hydraulic Section and from guidance in Volume 2.

Domestic Water Supply

A lake used for domestic water supply is potentially sensitive to impact by direct drainage from a highway if the residence time of water in the lake ($1/\rho$, in years) is less than 0.8 times the distance between the water intake and runoff discharge (in miles). If they are separated by a greater spacing, the lake is potentially sensitive if the ratio $C_H I A_H/(C_H I A_H + V_L)$ is more than the critical value of the dilution ratio,

D_C, where:

ρ = flushing rate (yr^{-1})

C_H = highway runoff coefficient (Table 1-2)

I = precipitation quantity (inches) in an average period equal in length to the residence time of water in the lake (I = water residence time in years x average annual precipitation from Table 1-3)

A_H = total area of highway right-of-way contributing runoff (acres)

V_L = lake volume (ft^3)

V_L = mean depth x surface area. In the case where highway runoff discharges to an embayment with restricted water circulation, the water residence time and volume of the embayment should be used if the intakes are located in the embayment.

Western Washington -- $D_C = -1.86 \times 10^{-6}$ ADT + 0.093

Eastern Washington -- $D_C = -1.53 \times 10^{-6}$ ADT + 0.029

ADT = average daily traffic

Note: If the water residence time cannot be determined, spacing between the water intake and runoff discharge point of at least one mile is generally sufficient in lakes of approximately 1000 acres or smaller.

Fish Habitat

The potential sensitivity of a lake used for fish migration, rearing, spawning, and/or harvesting is determined according to the formula for domestic water (based on spacing between a critical habitat and runoff discharge) and the following equations for D_C:

Western Washington -- $D_C = -5.27 \times 10^{-7}$ ADT + 0.037

Eastern Washington -- $D_C = -1.23 \times 10^{-6}$ ADT + 0.031

Table 1-1. Watershed Runoff Coefficient Values (Washington State Department of Highways, 1972)

Surface	Runoff Coefficient		
	Flat	Rolling (2% - 10%)	Hilly (Over 10%)
Pavement and Roofs	0.90	0.90	0.90
Earth Shoulders	0.50	0.50	0.50
Drives and Walks	0.75	0.80	0.85
Gravel Pavement	0.50	0.55	0.60
City Business Areas	0.80	0.85	0.85
Apartment Dwelling Areas	0.50	0.60	0.70
Suburban, Normal Residential	0.45	0.50	0.55
Dense Residential Sections	0.60	0.65	0.70
Lawns, Sandy Soil	0.10	0.15	0.20
Lawns, Heavy Soil	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Slide Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay and Loam	0.50	0.55	0.60
Cultivated Land, Sand and Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	0.90
Parks and Cemetaries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland and Forests	0.10	0.15	0.20
Meadows and Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Note: For catchments comprised of various surfaces, a composite runoff coefficient can be estimated as $C = \frac{\Sigma C_i A_i}{\Sigma A_i}$, where Σ means summation, C_i = runoff coefficient of surface i, and A_i = area of surface i.

Table 1-2. Highway Runoff Coefficient Values (Horner and Mar, 1982)

Highway Characteristics	C_H
Constructed at grade and entirely paved and curbed	0.75
Elevated and entirely paved	0.70
At grade and partially paved[a]	$C_p + (C_I - C_p) X$

[a] C_p = runoff factor for pervious surface (use value from Table A1.1 or 0.45 as default value).

C_I = runoff factor for impervious highway surface (use 0.70 as default value).

X = fraction of total right-of-way surface that is impervious.

Table 1-3. Average Annual Precipitation for Locations in Washington State

Location	Average Annual Precipitation (in inches)	Reference[a]
Everett	35.39	1
Kennewick	7.59	1
Olympia	50.74	2
Port Angeles	25.02	1
Prosser	7.88	1
Quillayute	104.99	2
Seattle (Seattle - Tacoma Airport)	38.79	2
Seattle (urban)	35.65	2
Snoqualmie Pass	104.61	1
Spokane	17.42	2
Stampede Pass	91.06	2
Sunnyside	6.81	1
Vancouver	40.23	1
Walla Walla	16.01	2
Wapato	7.28	1
Wenatchee	8.95	1
Yakima	8.00	2

[a] 1 -- U.S. Department of Commerce (1973)

2 -- U.S. Department of Commerce (1980)

SECTION 2

CRITERIA FOR SPECIFICATION OF VEGETATED FILTER AREAS

Introduction

A recommendation of the WSDOT/University of Washington Highway Runoff Water Quality research project was that vegetation be considered as a treatment medium for highway runoff when mitigation is necessary. Vegetated treatment may be the most cost-effective means of treating highway runoff for improvement of its water quality when treatment is required. The research established that vegetated channels improved runoff water quality. Other studies have indicated that broad vegetated surfaces (overland flow) would also be effective in treating highway runoff.

The Highway Runoff Water Quality project produced a guide to assist in conducting environmental assessments of highway projects (Horner and Mar, 1982). Its provisions on pollutant mitigation were phrased in terms of a "vegetated drainage course", defined to be an engineered channel or surface appropriate for overland flow, maintained in grasses or other low plant growth. This document will refer to these as "vegetated filter areas."

The following vegetated filter area criteria reflect both hydraulic/hydrologic and water quality performance. They insure effective transport of the flow and provide runoff treatment as a side benefit.

2.01. Feasibility of Vegetated Filter Areas

Vegetated filters should be considered for highway runoff that otherwise would discharge directly to a sensitive receiving water. A vegetated filter area will be feasible if the following conditions exist:

1. Soils and moisture adequate to grow relatively dense grass stands
2. Sufficient space available
3. Downslope no greater than 8 percent, unless extra space can be made available to compensate for faster runoff and maintain equivalent residence time.

If vegetated filter areas do not appear feasible but mitigation of runoff contamination is necessary, consider other methods, such as detention facilities or relocation or redesign of the highway segment.

2.02. Design of Vegetated Filter Areas

A. Vegetated channels

1. Provide a channel at least 200 ft in length.
2. Determine the channel dimensions according to the design storm condition and the Highway Hydraulic Manual. Manning's roughness coefficient (n) should be selected to represent the maximum density and height of vegetation expected.
3. If the slope is greater than 8 percent, increase the length and/or cross-sectional area sufficiently to compensate for faster runoff and maintain equivalent residence time.

Note: A channel not meeting these conditions will provide reduced treatment. The adequacy of the resulting treatment should be analyzed further.

B. Vegetated slopes

1. Provide a slope length of at least 100 ft over which runoff can flow.
2. Determine drainage field width according to the appropriate maximum hydraulic loading rate for the design storm:

   0.5 inch per day if slope exceeds 5%, slope length is less than 150 ft, or the location has a harsh winter climate

   1.1 inch per day if the evapotranspiration or percolation rate is relatively high

   0.5-1.1 inch per day under other conditions
3. If the slope is greater than 8%, increase the area sufficiently to compensate for faster runoff and to maintain equivalent residence time.

Note: A slope not meeting these conditions will provide reduced treatment. The adequacy of the resulting treatment should be analyzed further.

2.03. Maintenance of Vegetated Filter Areas

1. Sediment removal--The need to remove sediments should be evaluated on the basis of sediment accumulation, hydraulic requirements, or retarded vegetation growth due to settled solids. Sediment removal should allow time for regrowth before fall precipitation. Following sediment removal, vegetation should be restored as needed.

2. Woody vegetation should be removed from vegetated filter areas when necessary to assure hydraulic capacity or avoid shading out grasses.

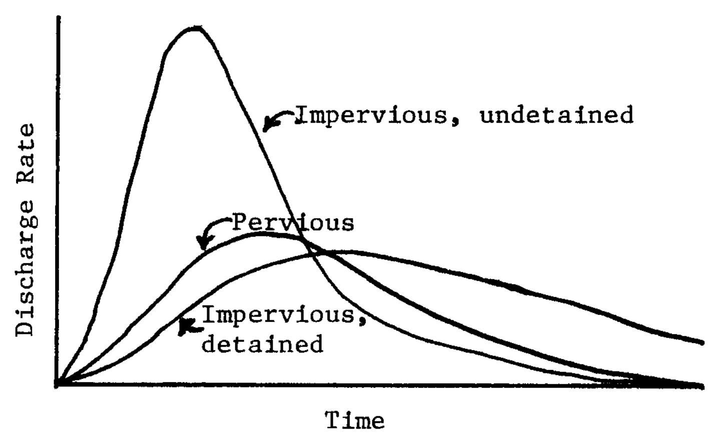
SECTION 3

CRITERIA FOR SPECIFICATION OF DETENTION FACILITIES

Introduction

Detention facilities are basins in which storm runoff is held to reduce peak discharges and improve water quality. They are often required by regulation to reduce peak discharges and the resulting peak-flow increases in receiving waters. Detention facilities may be tanks or excavated ponds, although only the latter are feasible in most highway situations. They are sometimes referred to as sedimentation, settling, or siltation basins, especially in construction applications.

As illustrated below, the typical hydrograph pattern (discharge rate versus time plot) associated with impervious areas is a sharp increase to a peak discharge relatively soon after runoff begins. Detention facilities capture some of the drainage for slow release later. The criteria below reduce peak flows and improve water quality.



Discharge may be by overflow, through pipes with or without controls, by evaporation or transpiration, or by infiltration to groundwater. Detention facilities frequently are employed for temporary water pollution control during highway construction, and it may be possible to retain some of these installations permanently.

Detention facilities generally remove most solids but lesser portions of other pollutants. Vegetated filter areas and detention facilities can be employed in series when both peak-flow attenuation and pollutant reduction are needed.

3.01. Requirement for Detention Facilities

A detention facility should be considered when any of the following conditions occur:

1. Attenuation of peak runoff discharge rates is required by regulation.
2. Highway runoff volumes significantly increase discharge rates in a potentially sensitive stream or river.
3. Especially heavy solids loadings are expected to be introduced to a potentially sensitive receiving water.
4. Mitigation of runoff pollutants is necessary, but vegetated filter areas would be infeasible.

3.02. Design Criteria and Considerations for Detention Facilities

A. Criteria

In the absence of regulatory agency criteria, detention facilities should be designed according to the following minimum criteria:

1. Design storm--10-year frequency, two-hour duration
2. Detention time--two hours, which is equivalent to 7,200 cubic feet per cfs design runoff
3. Water surface area--540 square feet per cfs design runoff

B. Considerations -- In addition to the above minimum criteria, the following non-mathematical factors should also be considered.

1. Design--Place the inlet and outlet as far apart as possible to minimize short-circuiting. Flow distance between the two may be increased by baffles. Velocity dissipators may be necessary at the inlet.

2. Siting--Utilize natural terrain to minimize construction costs and improve aesthetics. Loops at interchanges and natural depressions are often suitable sites. After determining the detention basin size required to meet the design criteria, evaluate those existing features to determine how much additional capacity is needed and where it can be most economically attained.

3. Safety--Public access should be restricted if the basin could be hazardous or an aesthetic nuisance.

4. Discharge--Basin discharge may be by overflow or pipe outlet to an open or closed drainage system, by infiltration into the ground, or by evaporation or transpiration into the air. All basins should have an emergency overflow so that the facility will not be damaged if the intended discharge fails to function or runoff in excess of the design storm occurs.

5. Accidental Spills--Additional measures may be required at some sites to protect surface or ground waters from accidental spills of hazardous materials. These measures could include baffles to retain buoyant materials or sealing to prevent infiltration into sensitive ground water.

6. Mosquito Control--Local authorities may prohibit standing water in basins to control breeding of mosquitos.

7. Construction Basins--It may be possible to utilize a construction sedimentation basin permanently if it is in the proper location, has adequate capacity, and final grading and landscaping can occur.

3.03. Maintenance of Detention Facilities

Inspect the detention facility periodically to determine the need for cleaning and repair. Sediments should be removed when capacity is less than needed or when sediment resuspension and loss in the outflow may occur.

SECTION 4

CRITERIA FOR HANDLING OF SPOILS

Introduction

Roadside debris and ditch sediments accumulate pollutants. This accumulation is likely to be heaviest along heavily traveled highways. Accidental spills could introduce highly toxic materials in concentrated doses. The criteria that follow reduce the volumes of spoils that must be handled and prevent release of contaminants.

4.01. Criteria for Spoils Disposal

Roadside sweeping, catch basin sediments, and ditch cleaning spoils should be disposed of to avoid introduction of contaminants to water. The disposal site should have the following characteristics:

1. Minimal slope
2. Not in a drainage channel for runoff from upslope areas toward a water body
3. At least 200 ft from a water body; preferably, having vegetation between the disposal site and the water body
4. Not overlying sensitive aquifer

Disposal of sediments removed from the top two inches and the first 30 ft of mud drainage ditches, or the first 150 ft of vegetated ditches, serving more than 10,000 ADT should be further protected by one of the following measures:

1. Dispose in an area normally not accessible to the public and isolate by spreading and vegetating, plowing into the soil and vegetating, or burying and covering.
2. Place in an approved landfill as a last resort.

SECTION 5

CRITERIA FOR WOODWASTE FILL LEACHATE CONTROL

Introduction

Woodwaste used as fill material has the potential to leach contaminants into surface and groundwater. Research has defined the extent of these problems (Vause et al., 1980) and is the basis for the following criteria. These criteria apply to all waters.

5.01. Criteria for Woodwaste Fill Leachate Control

One or a combination of the following measures may be necessary to mitigate the effects of leachate pollution and avoid violating water quality standards.

1. Use woodwaste that is at least one year old.

2. Presoak woodwaste until leachate pollutant concentrations are acceptable.

3. Prevent or reduce the entrance of water to a woodwaste fill.

4. Dilute leachate to hold pollutant concentrations within acceptable limits. A procedure for analyzing dilution is presented in the Guide for Water Quality Impact Assessment of Highway Operations and Maintenance (Horner and Mar, 1982) and in Section 7 of this manual.

5. Treat leachate to hold pollutant concentrations within the acceptable limits.

SECTION 6

CRITERIA FOR HIGHWAY SANDING

Introduction

On highways receiving relatively heavy sand applications the sand represents a significant proportion of the total annual solids loading in highway runoff (Asplund et al., 1980). Like other particles, sand can also transport contaminants.

6.01. Criteria for Highway Sanding

When runoff from a highway receiving sand applications can enter a potentially sensitive surface water body, use relatively large and/or dense particles to reduce the ability of runoff to transport the sand and associated pollutants.

SECTION 7

CRITERIA FOR HIGHWAY RUNOFF DILUTION

Introduction

Highways normally occupy minor portions of the catchments of water bodies receiving highway runoff. Therefore, contaminants are diluted in the larger receiving water volume. These criteria provide a general basis for determining the adequacy of dilution.

7.01. Criteria for Highway Runoff Dilution

A. General Criterion

If measured or projected highway traffic volume is more than 10,000 ADT, conduct an impact assessment using the guide (Horner and Mar, 1982). If the projected ADT is less than 10,000 and the impervious highway area is less than one percent of the drainage basin, Level I of the Guide established there would be no significant impact from highway runoff.

B. Specific Cases

The dilution ratio is the highway runoff flow rate divided by the sum of the receiving water and highway runoff flow rates.

Pollutant concentrations in a mixture of highway runoff and receiving water can be estimated as follows:

$$C_M = \frac{C_H Q_H + C_W QW}{Q_H + Q_W}$$

where: C_M = concentration after mixing

C_H and C_W = pollutant concentrations in highway runoff and receiving water, respectively

Q_H and Q_W = flow rate of highway runoff and receiving water, respectively

SECTION 8

CRITERIA FOR HIGHWAY CLEANING

Introduction

Highway cleaning operations may reduce the quantities of contaminants entrained by storm runoff. These operations include vacuuming-sweeping and flushing. Sweeping without a vacuum generally misses small particles that create the most harmful effects in aquatic ecosystems (U.S. Environmental Protection Agency, 1982).

This section pertains to routine cleaning only; cleaning up accidental spills is regulated by other public agencies.

8.01 Criteria for Highway Cleaning

A. Vacuuming-Sweeping

Highway vacuuming-sweeping should be performed when large quantities of relatively large particles can be carried by storm runoff into a potentially sensitive receiving water. This situation may occur under the following conditions:

1. Heavy winter sand application
2. Highway lies in a cut with a particularly erosive slope
3. Construction, agricultural, or logging vehicles deposit solid materials on the highway.

B. Flushing

Highway flushing could be considered if the following conditions are met:

1. The necessary equipment is available.
2. The material would not be flushed into a sensitive receiving water.

SECTION 9

CRITERIA FOR STREAM CHANNEL MODIFICATION

Introduction

Stream course modifications have created severe environmental impacts. Long-term impacts resulted from poor aquatic habitat, interference with fish migrations, increased erosion and sedimentation, riparian vegetation removal, and isolation of the stream from its flood plain.

9.01. Criteria for Stream Channel Modification

1. Stream channel modification should be undertaken only if no feasible alternative exists.

2. The modified channel should maintain the stream gradient and cross-section.

3. The modified channel should maintain the approximate current velocity distribution of the undisturbed stream reach.

4. The modified channel should replicate the original pool and riffle pattern.

5. The modified reach should be stabilized to assure erosion protection, especially on the outside of meanders and under bank-full conditions. One measure of bank stabilization should be replacement of riparian vegetation, including shading.