
Research and Development



SARAH2, A Near Field Exposure Assessment Model for Surface Water



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SARAH2, A Near Field Exposure Assessment Model
for Surface Water

by

Scarlett B. Vandergrift and Robert B. Ambrose, Jr.

Assessment Branch
Environmental Research Laboratory
Athens, GA 30613

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ATHENS, GA 30613

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FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Assessment Branch develops state-of-the-art mathematical models for use in water quality evaluation and management.

The calculational framework and many of the equations incorporated into this model were originally developed for EPA's Office of Solid Waste (OSW) in support of the regulation of land disposal for hazardous wastes. These have been updated in response to public comment, private peer review, and continuing improvements in environmental science. Additional equations have been added to address toxicant disposal through wastewater treatment facilities. The resulting Near Field Exposure Assessment Model, (SARAH2) is not meant to represent OSW policy on analysis of land disposal facilities. Rather, it is intended to provide analysts the means to rapidly explore the consequences of a variety of exposure and effects scenarios resulting from disposal of toxicants. Appropriate application of the model will provide valuable information on which to base pollution management decisions by various industrial, state, and Federal organizations.

Rosemarie C. Russo, Ph.D.
Director
Environmental Research Laboratory
Athens, Georgia

ABSTRACT

The nearfield surface water model (SARAH2) calculates maximum allowable hazardous waste concentrations based upon predicted exposure to humans or aquatic life from contaminated surface water. The surface water contamination pathways analyzed in SARAH include groundwater leachate from a land disposal facility, storm runoff from a land disposal facility, and discharge through a waste water treatment facility or lagoon. The human exposure pathways considered include ingestion of treated drinking water and consumption of contaminated fish. Acceptable leachate or treated industrial waste discharge constituent concentrations are estimated by a "back calculation" procedure starting from chemical safety criteria in surface water, drinking water, or fish. "Forward calculations" predict the instream concentrations from leachate or discharge concentrations.

SARAH2 is an interactive, menu-driven computer program with three default data sets that can be rapidly modified. The analytical solutions for contaminant behavior in a catchment or stream near the facility allow rapid, multiple calculations needed for good sensitivity analysis. SARAH2 is a modular FORTRAN program; modifications and expansions are obtained by the addition of new modules. The first version is written for a VAX 11/785 minicomputer. A subsequent version will operate on personal computers.

This report covers a period from January 1987 to May 1, 1988.

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SECTION 1

INTRODUCTION

Industrial wastes containing potentially hazardous chemicals are often disposed of through wastewater treatment facilities or land disposal sites. Contamination of surface water and exposure of humans and aquatic life to hazardous chemicals can occur from industrial wastes discharged from wastewater treatment facilities or leaked from land disposal sites. If expected exposure levels are too high, industrial wastes must be pretreated to an acceptable level before introduction to municipal treatment plants or disposal sites. To help the analyst establish minimum pretreatment levels, the original surface water assessment model (R.B. Ambrose and S.B. Vandergrift) was developed to "back calculate" appropriate pretreatment concentrations from chemical safety criteria for exposure to humans and aquatic life. SARAH2 also allows "forward calculations" to determine the chemical concentrations in-stream. SARAH2 allows the user to screen a list of chemicals and identify those that should be restricted or more fully treated before discharge from an industrial plant or surface impoundment.

The first step in a screening analysis is to describe a set of scenarios that might lead to the undesired consequences. As illustrated in Figure 1.1, three contaminant sources considered in SARAH2 are industrial wastewater effluent, a land disposal site, and a surface impoundment. The pathways or loading routes to surface water are: 1. direct discharge, 2. overland runoff, and 3. leaching to groundwater. Once in surface water, chemicals are advected, dispersed, and degraded by several mechanisms. The resulting aqueous concentrations may result in exposure to aquatic life and to humans through drinking water or consuming fish. Figure 1.2 outlines the contamination scenarios considered in SARAH2.

The second step is to assign probabilities to each event (for example: occurrence of a release or failure). It is virtually certain that aqueous chemicals introduced at a wastewater treatment facility will be discharged in the effluent. On the other hand, the probability that chemical solids introduced to some land disposal sites will escape through runoff or leaching can be very small. Design and operating requirements for land disposal facilities are promulgated under Parts 264 and 265 of the Resource Conservation and Recovery Act (RCRA). For example, RCRA may require liners, leachate collection and removal systems, ground water monitors, corrective actions, and runoff controls. SARAH2 assumes failure of all controls, leading to surface water contamination from both a ground water and a surface runoff route (the probability of occurrence of various scenarios is set to 1.0). SARAH2 helps the analyst investigate the consequences of these scenarios.

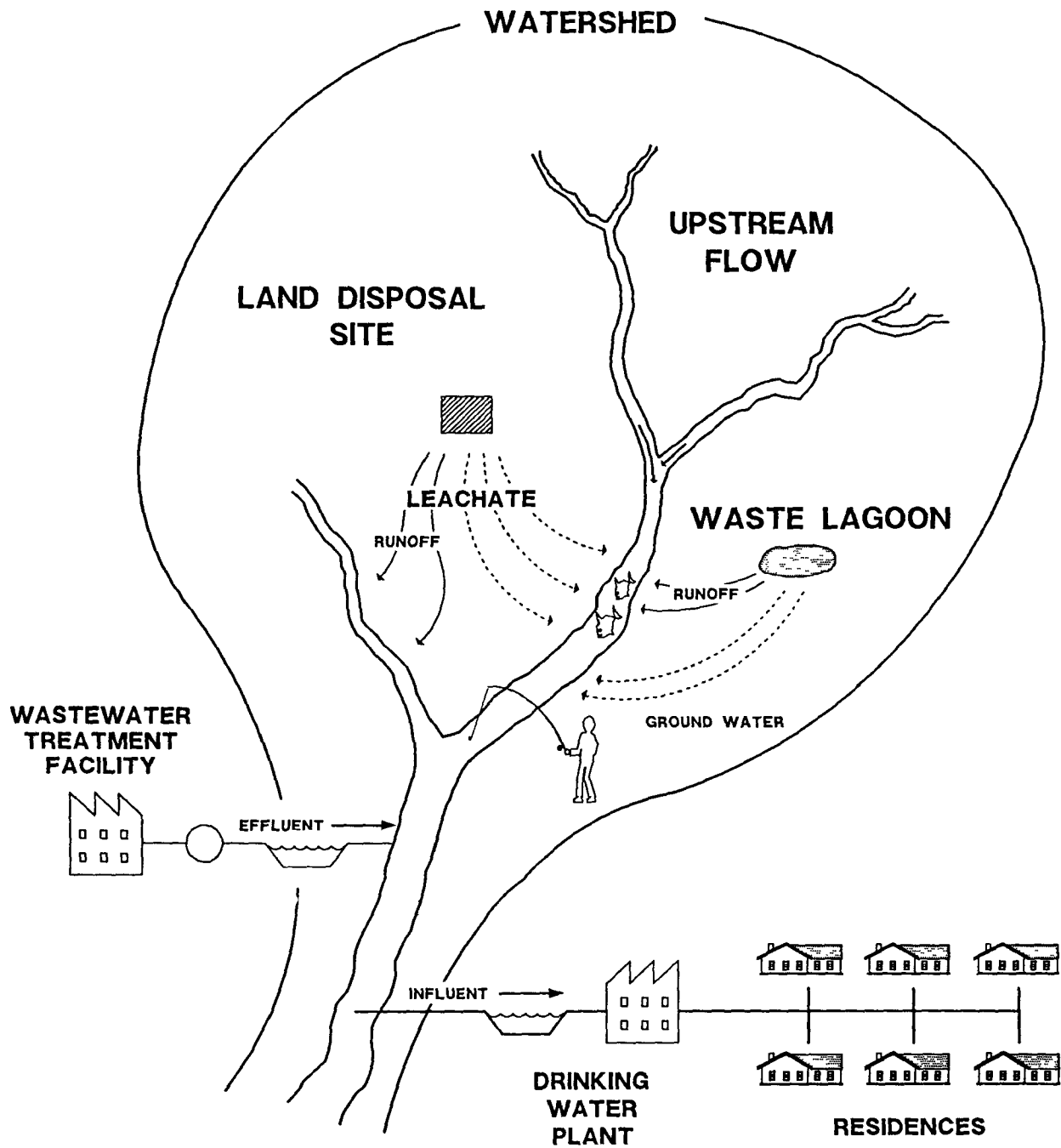


Figure 1.1 Routes of Exposure to Hazardous Chemicals in Surface Water

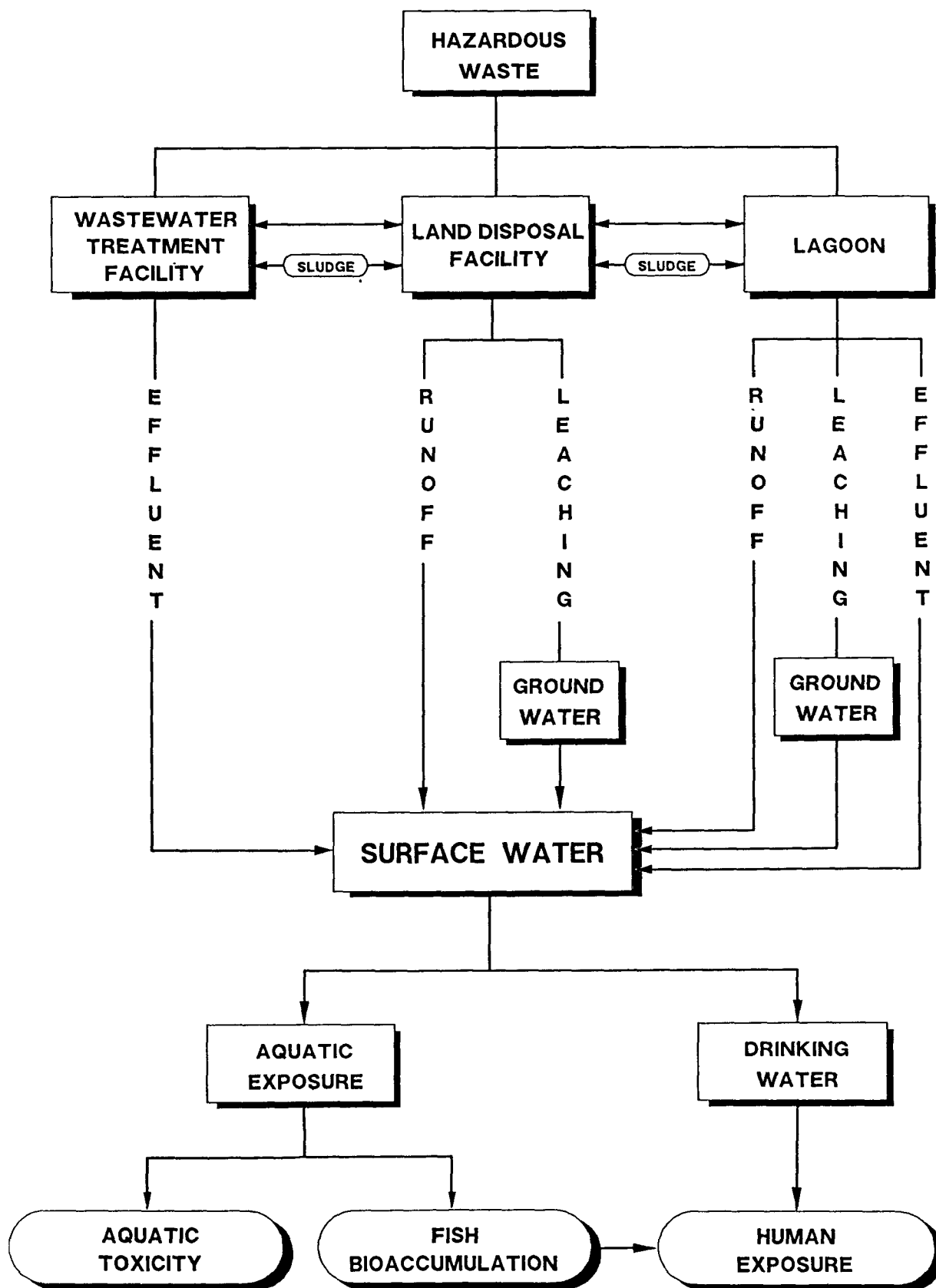


Figure 1.2 Schematic of Exposure Routes

The third step is to investigate the consequences of each scenario and control failure. Aquatic and human exposure to hazardous chemicals at excessive concentrations can result in such undesired consequences as chronic toxicity in aquatic organisms and human health effects. The SARAH2 analysis begins with criteria set to protect against such adverse impacts. A stream concentration criterion is designated to protect aquatic life resident in the stream. Dose criteria set to protect humans must be translated to drinking water and fish concentrations assuming specified patterns of water and fish consumption. SARAH2 begins its back calculations with these resulting "safe" concentrations and assumes that lower concentrations produce no adverse effects. The forward calculations begin with leachate or industrial stream concentrations and predict the surface water chemical concentration profile.

SARAH2 consists of nine surface water contamination scenarios: (1) leaching from a landfill and subsequent delivery of contaminated ground water to streams; (2) steady runoff from a landfill from a design storm event that is stored for a 24-hour period and released over a short time period into a receding stream; (3) catastrophic storm runoff from a design storm event; (4) steady loading of an industrial wastewater effluent, (5) pulse loading of an industrial wastewater effluent, (6) contaminant loading from a lagoon leaching to the groundwater (7) contaminant loading through a steady overflow from a lagoon that has exceeded its free board depth, (8) contaminant loading by a pulse overland flow after a catastrophic lagoon dam failure, and (9) contaminant loading by the direct discharge of lagoon wastewater effluent. For each contamination route, SARAH2 can consider up to three potential adverse effects: (a) human exposure through consumption of contaminated drinking water, (b) human exposure through consumption of contaminated fish, and (c) toxicity to the aquatic community. Unrealistic combinations of contaminant release and adverse effects are not implemented in SARAH2, as discussed in later sections.

This manual contains three main sections that can be used independently. The first, Potential Exposure Pathways, characterizes the potential pathways leading to human and environmental exposure. This section describes each step and associated contaminant reduction factor from the source to a specified distance downstream. Using the defined reduction factors, this section sets up the final equations that compute the in-stream concentration (by forward calculations) or the maximum allowable leachate, overflow runoff, or discharge concentrations (by backward calculations).

The second, Development of Equations, documents the equations and assumptions underlying the model components. This section describes the procedures developed for evaluating the influence of wastewater discharge or land disposal on human health and the environmental impacts. The overall approach is based on a "back-calculation" method to identify acceptable wastewater or leachate concentrations given health-based or environmental thresholds that are not to be exceeded at specified exposure points (or routes). This section characterizes potential pathways leading to human and environmental exposure, evaluates the likelihood of exposure for each pathway, and sets up back-calculation procedures for those pathways and exposure routes that are likely.

SECTION 2

POTENTIAL EXPOSURE PATHWAYS

Pathways leading to contamination of surface water and exposure to aquatic organisms and humans begin with the disposal of industrial wastes in waste water treatment (including lagoons) or land disposal facilities. The sources of contamination modeled in SARAH2 are: a land disposal facility, surface impoundment, and an industrial waste water treatment facility. The pathways modeled in SARAH2 are ground water transport, surface runoff, and direct discharge.

As illustrated by Figure 2, not all sources contaminate surface water by all pathways. The following is the list of exposure scenarios modeled in SARAH2.

1. Steady ground water loading from a landfill.
2. Steady storm runoff from a landfill.
3. Catastrophic storm runoff from a landfill.
4. Continuous treatment facility discharge loading.
5. Batch treatment facility discharge loading.
6. Steady ground water loading from a lagoon.
7. Steady overflow and runoff from a lagoon.
8. Catastrophic failure and runoff from a lagoon.
9. Steady direct discharge from a lagoon.

A release rate estimation involves the determination of both the contaminant concentration in the release and the volumetric flux of the release. Modeling the release rate of toxic constituents can thus be done in terms of either instantaneous time-varying releases or the annual average release (i.e., steady state release rate based on an annual average). Rainstorms come in discrete intervals separated by dry periods. Using steady state equations to model rainfall-induced leaching, however, assumes that 1/365th of the annual recharge occurs each day (Versar, Inc., 1987).

The overall approach of this model is to define all possible contaminant reductions. Equations are then developed to define each reduction factor in later sections.

In this section, each scenario will be analyzed from source to stream to determine the reduction factors necessary to compute maximum leachate or overflow concentrations. A summary of all reduction factors are listed in Table 2.1.

In many scenarios, equations will be repeated from previous scenarios. Although these sub-sections may seem redundant, they deserve repeating due to the fact that the source or effect may vary and slightly alter the final equation. Also, the equations derived in this section are too important to the overall solution scheme of SARAH2 to be deleted. Therefore, it is suggested that the user does not read this section in its entirety, but only the section(s) pertaining to the scenario of interest.

Nine sets of scenarios are considered. The nine sets (1, 2, 3, 4, 5, 6, 7, 8, and 9) are distinguished from one another by the pathway and source through which contaminants reach and eventually enter the stream. Each set consists of three potential exposure routes (A, B, and C) that threaten humans or aquatic organisms. These are summarized in Table 2.2.

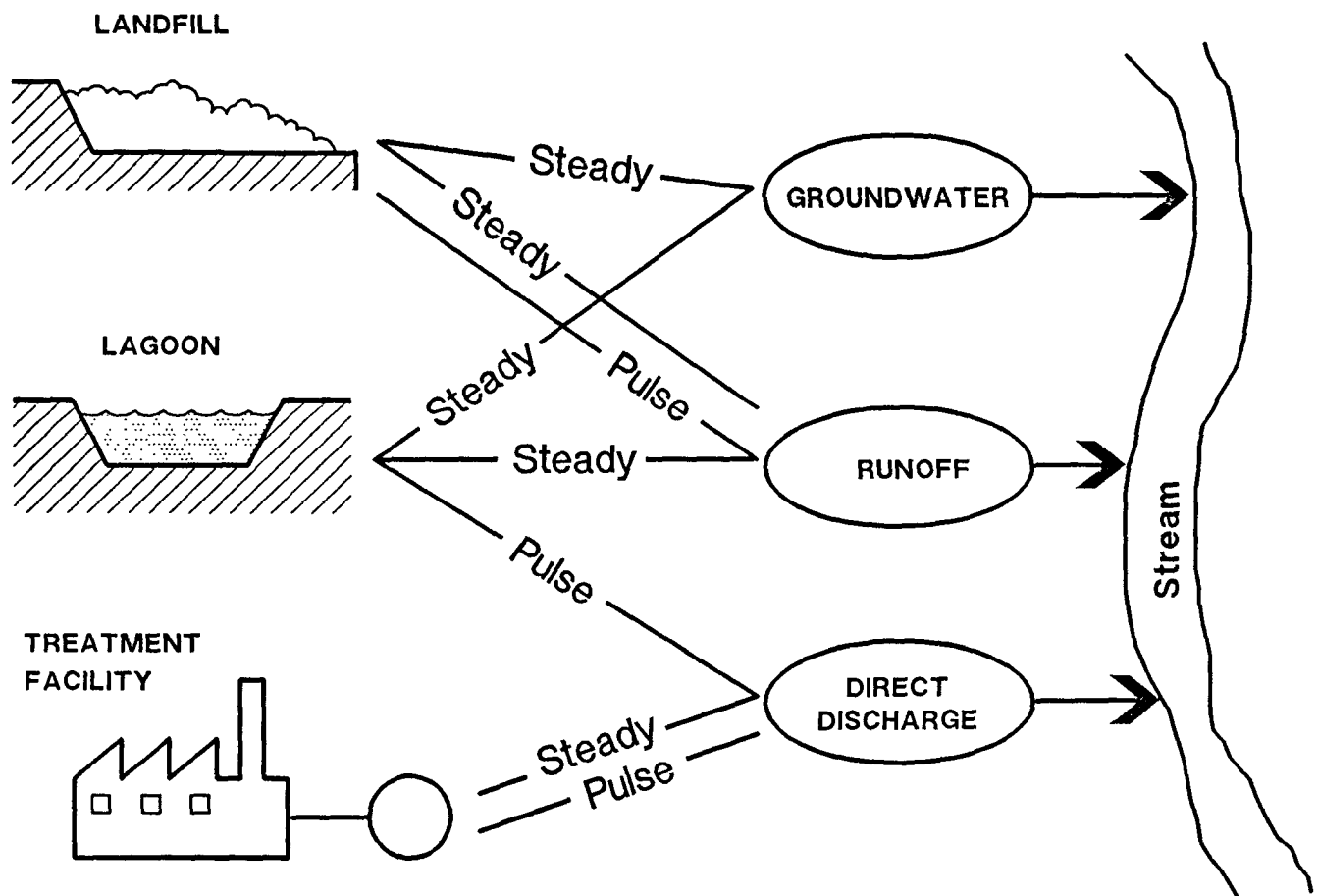


Figure 2. SARAH2 source and pathway combinations.

2.1 LANDFILL/GROUNDWATER

Scenario 1 (steady ground water loading from a landfill) assumes (1) liner failure, (2) that the landfill is hydraulically connected to the stream, and (3) that 1/365th of the annual rainfall recharge occurs each day. Leachate enters the aquifer directly below the land disposal unit and is transported by ground water flow until it intersects a surface water body.

TABLE 2.1 List of Reduction Factors

Reduction Factor	Definition
ζ_{WD}	Reduction factor due to wastewater treatment
ζ_{DW}	Reduction factor due to treatment of the drinking water
ζ_{EXP}	Aquatic exposure factor
ζ_F	Bioconcentration factor due to the biochemical exchange processes with the fish
ζ_g	Reduction factor due to transport in the ground water
ζ_R	Reduction factor due to dilution during runoff processes
ζ_{sg}	Reduction factor due to ground water and stream entry point
ζ_{SU}	Reduction factor due to dilution of the upstream concentration by ground water, precipitation or effluent
ζ_x	Reduction factor due to longitudinal mixing and degradation in the stream (one dimensional)
$\zeta_{x,y}$	Reduction factor due to lateral and longitudinal mixing and degradation in the stream (two dimensional)
$\zeta_{x,y}$	Laterally averaged reduction factor $\zeta_{x,y}$. (This is equal to (ζ_x))

TABLE 2.2 SUMMARY OF POTENTIAL EXPOSURE SCENARIOS

SCENARIO	SOURCE PATHWAY	EXPOSURE ROUTE
1A	groundwater seepage from a landfill	human exposure via drinking water
1B		human exposure via fish consumption
1C		direct exposure of aquatic organisms
2A	steady surface runoff from a landfill	human exposure via drinking water
2B		human exposure via fish consumption
2C		direct exposure of aquatic organisms
3A	pulse surface runoff from a landfill	human exposure via drinking water
3B		human exposure via fish consumption
3C		direct exposure of aquatic organisms
4A	steady discharge from an industrial wastewater treatment facility	human exposure via drinking water
4B		human exposure via fish consumption
4C		direct exposure of aquatic organisms
5A	batch discharge from an industrial wastewater treatment facility	human exposure via drinking water
5B		human exposure via fish consumption
5C		direct exposure of aquatic organisms

TABLE 2.2 (CONT.) SUMMARY OF POTENTIAL EXPOSURE SCENARIOS

SCENARIO	SOURCE PATHWAY	EXPOSURE ROUTE
6A	groundwater seepage from a lagoon	human exposure via drinking water
6B		human exposure via fish consumption
6C		direct exposure of aquatic organisms
7A	steady overflow and surface runoff from a lagoon	human exposure via drinking water
7B		human exposure via fish consumption
7C		direct exposure of aquatic organisms
8A	pulse failure surface runoff from a lagoon	human exposure via drinking water
8B		human exposure via fish consumption
8C		direct exposure of aquatic organisms
9A	steady discharge from a lagoon	human exposure via drinking water
9B		human exposure via fish consumption
9C		direct exposure of aquatic organisms

2.1A Scenario 1A: Exposure to Humans through Drinking Water Contaminated by Landfill Leachate

This scenario consists of four stages between failure of the landfill containment facility and the exposure of the contaminant to humans via drinking water (Figure 2.1.1). Through these stages, the concentration is successively reduced from the leachate concentration, C_L , to the concentration in drinking water, C_{DW} . The relationship between C_{DW} , C_U , and C_L is given by (forward calculation):

$$C_{DW} = \zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_{DW} C_L + \zeta_{SU} \zeta_x \zeta_{DW} C_U$$

where ζ_g , ζ_{Sg} , ζ_x and ζ_{DW} are reduction factors due to transport in ground water, mixing at the area of leachate entry into the stream, transport in the stream, and treatment in the drinking water plant. ζ_{SU} is the dilution factor for the upstream concentration by the ground water flow, C_U is the upstream chemical concentration and $\overline{\zeta_{x,y}}$ is the average concentration reduction factor for downstream transformation.

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the reference dose concentration, C_{RFD} .

Thus:

$$C_{DW} = C_{RFD} \quad (2.1.2)$$

and the maximum allowable leachate concentration must be (backward calculation):

$$C_L = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_{DW}} \quad (2.1.3)$$

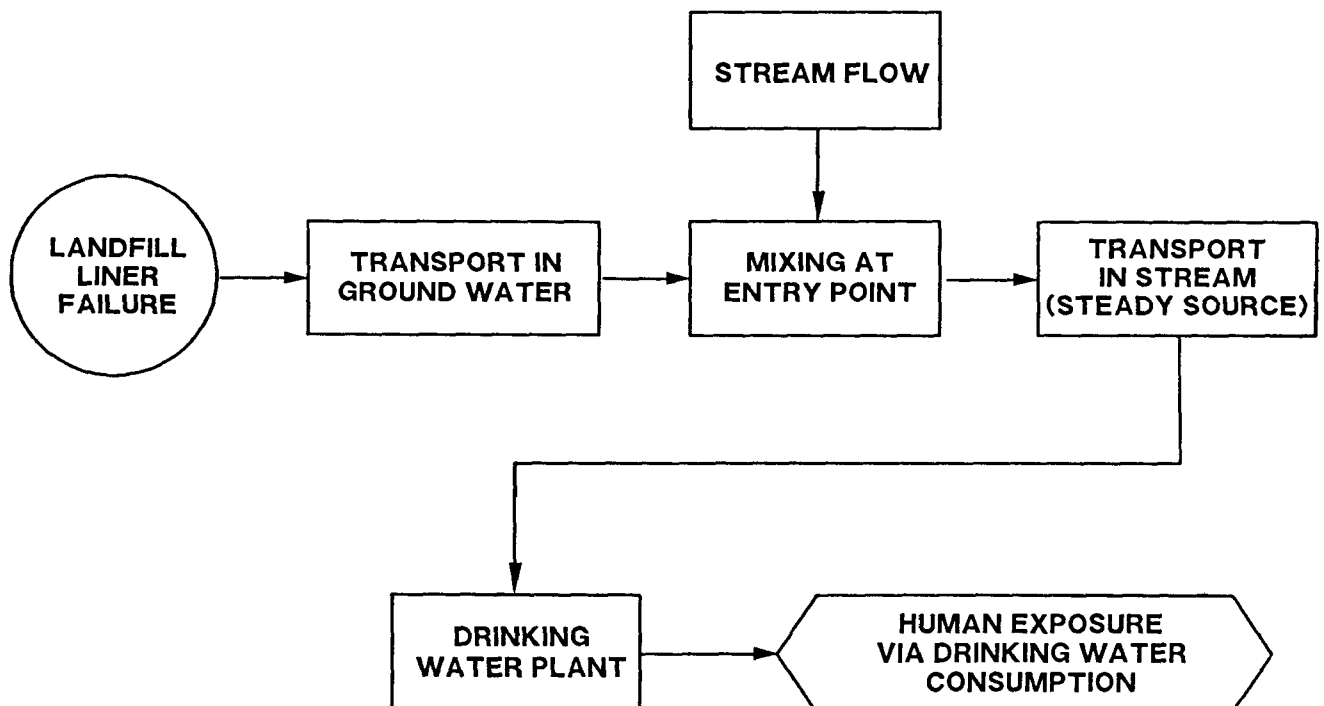


Figure 2.1.1 Flow chart for Scenario 1A

2.1B Scenario 1B: Exposure to Humans through Consumption of Fish Contaminated by Landfill Leachate

This scenario consists of three stages between the landfill containment failure and human exposure via consumption of fish residing in the contaminated surface water (Figure 2.1.2). Through these stages, the input concentration is successively reduced from the leachate concentration, C_L , to the stream concentration, and then increased to the bioconcentrated level in the fish, C_F . The relation between C_L , C_U , and C_F is given by (forward calculation):

$$C_F = \zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_F C_L + \zeta_{SU} \zeta_x \zeta_F C_U$$

where ζ_F is the bioconcentration factor due to the biochemical exchange processes with the fish.

For back-calculation, the average concentration in the fish, C_F , can be equated to a reference intake bioaccumulation concentration, C'_{RFD} . Thus:

$$C_F = C'_{RFD} \quad (2.1.5)$$

and the maximum allowable leachate concentration is given by (backward calculations):

$$C_L = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_F} \quad (2.1.6)$$

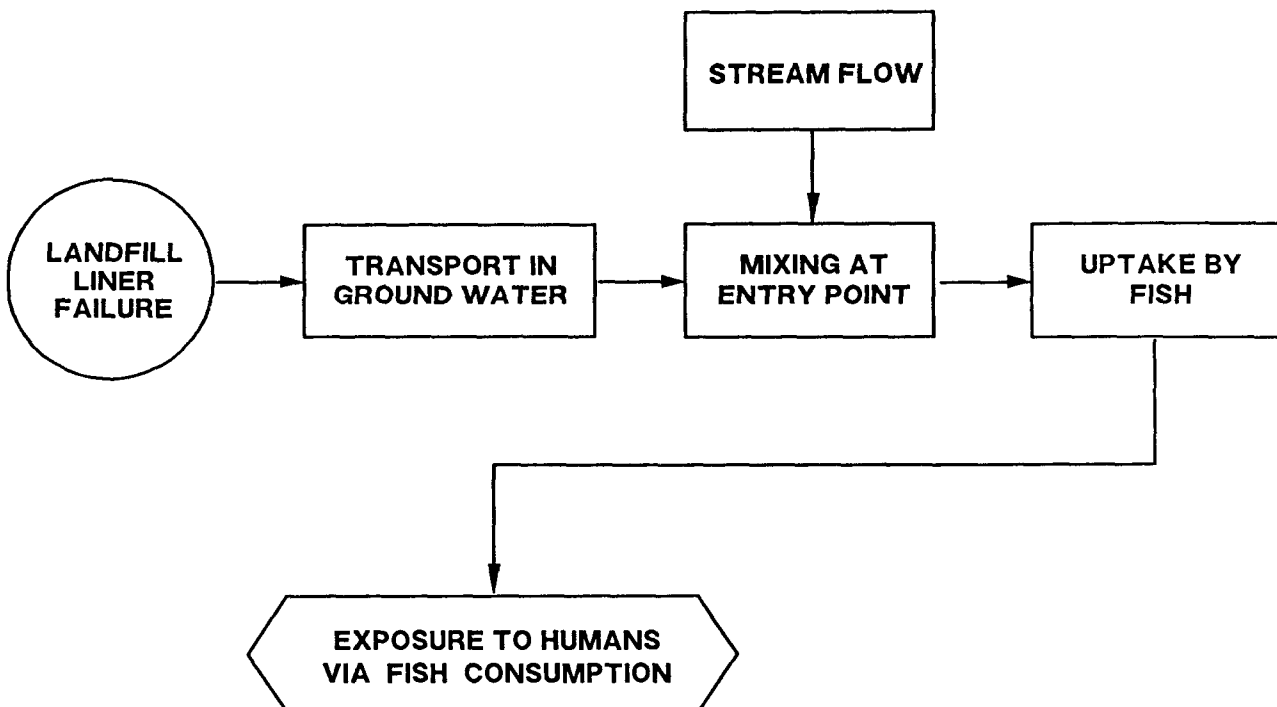


Figure 2.1.2 Flow chart for Scenario 1B

2.1C Scenario 1C: Exposure of Aquatic Life due to Landfill Leachate

This scenario consists of two stages between the landfill containment unit failure and aquatic exposure (Figure 2.1.3). Through these stages, the input concentration is successively reduced from the leachate concentration, C_L , to the average stream concentration, C_0 . The relationship between C_L , C_U , and C_0 is given by (forward calculation):

$$\bar{C}_0 = \zeta_g \zeta_{Sg} \zeta_{x,y} \zeta_{EXP} C_L + \zeta_{SU} \zeta_x \zeta_{EXP} C_U$$

where:

ζ_{EXP} = aquatic exposure factor

For back-calculation, the average concentration in the stream can be equated to a specified Continuous Concentration Water Quality Criteria, CCC. Thus:

$$\bar{C}_0 = CCC \quad (2.1.8)$$

and the maximum allowable leachate concentration is given by (backward calculation):

$$C_L = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\zeta_g \zeta_{x,y} \zeta_{Sg} \zeta_{EXP}} \quad (2.1.9)$$

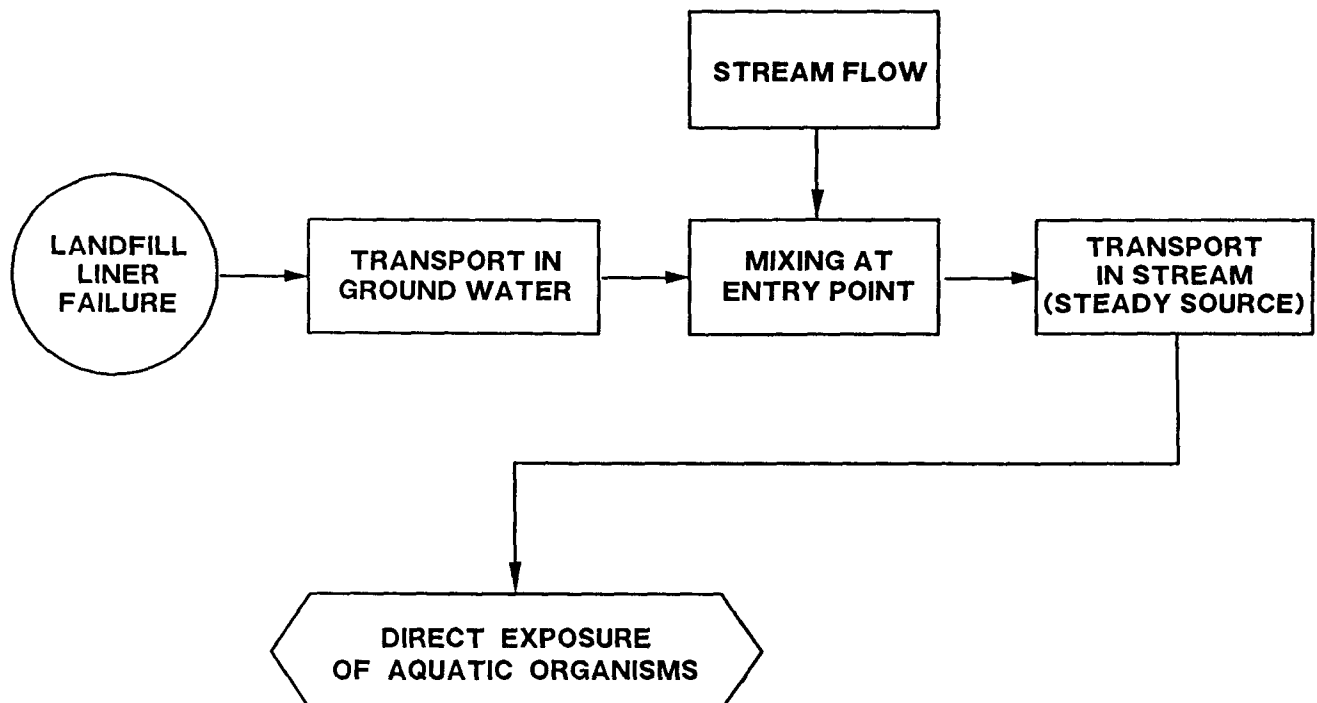


Figure 2.1.3 Flow chart for Scenario 1C

2.2 LANDFILL/STEADY STORM RUNOFF

Scenario 2 (steady storm runoff of a landfill) assumes that 1) the once in 25 year storm event occurs, 2) the contaminated catchment overflows, and 3) runoff occurs continuously throughout the storm.

2.2A Scenario 2A: Exposure to Humans through Drinking Water Contaminated by a Steady Landfill Runoff from a Design Storm Event--

This scenario consists of four stages between the landfill containment failure and exposure of the contaminant to humans via drinking water (Figure 2.2.1). Through these stages, the concentration is successively reduced from the runoff concentration, C_R , to the concentration in the drinking water, C_{DW} . The relationship between C_{DW} , C_U , and C_R is given by (forward calculation):

$$C_{DW} = \zeta_R \zeta_{x,y} \zeta_{DW} C_R + \zeta_{SU} \zeta_x \zeta_{DW} C_U$$

where ζ_R , ζ_{SU} , ζ_x , and ζ_{DW} are reduction factors due to dilution during runoff, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

Because of the pulse runoff loading condition, the concentration C_{DW} is time dependent. Thus, it is averaged over a 1-day period. This average concentration, $\langle C_{DW} \rangle$, can then be equated to the reference dose C_{RFD} . It follows that:

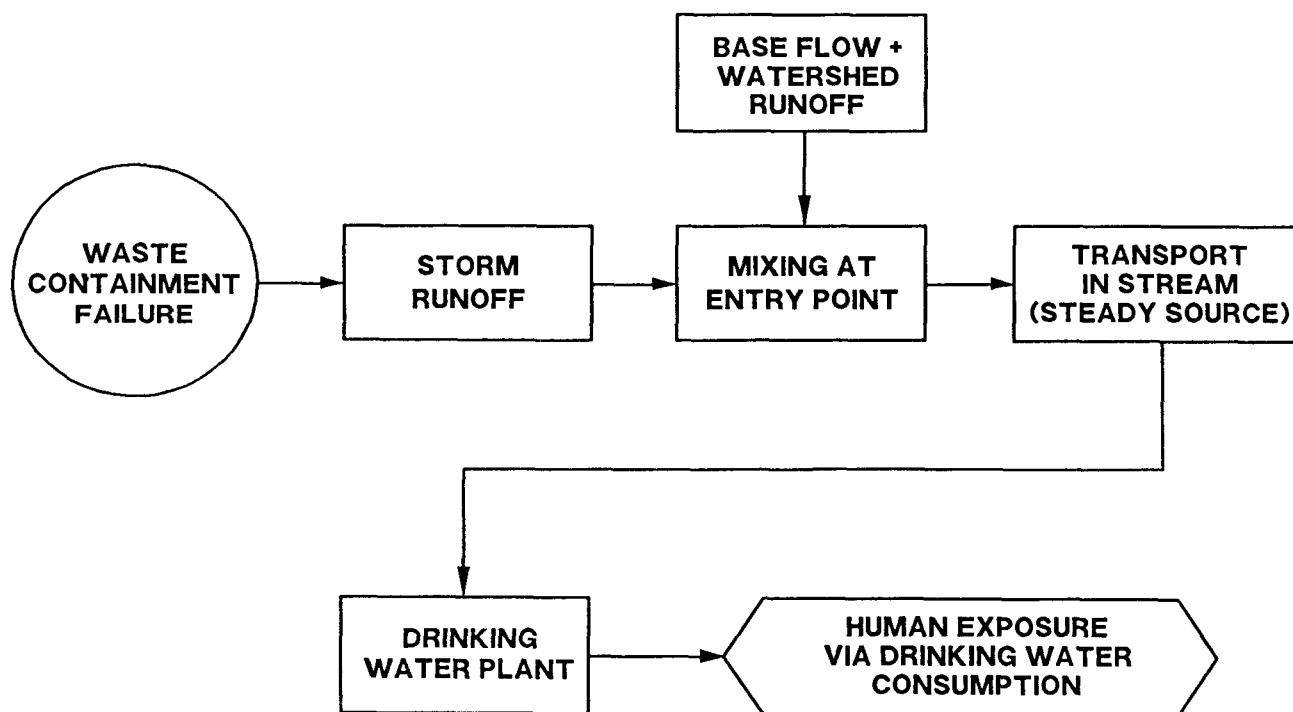


Figure 2.2.1 Flow chart for Scenario 2A

$$\langle C_{DW} \rangle = C_{RFD} \quad (2.2.2)$$

and the maximum allowable runoff concentration is given by (backward calculation):

$$C_R = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{DW} \rangle} \quad (2.2.3)$$

where angular brackets are used to denote the 1-day average of the enclosed quantity.

2.2.B Scenario 2B: Exposure to Humans through Consumption of Fish Contaminated by Steady Landfill Runoff from the Design Storm Event--

This scenario consists of four stages between the landfill containment failure and exposure of contaminant to humans via consumption of fish (Figure 2.2.2). Through these stages, the input concentration is altered from the runoff concentration, C_R , to the average concentration in the fish, C_F . The infrequency of design runoff events and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans. Consequently, the backward or forward calculation formulas are not developed.

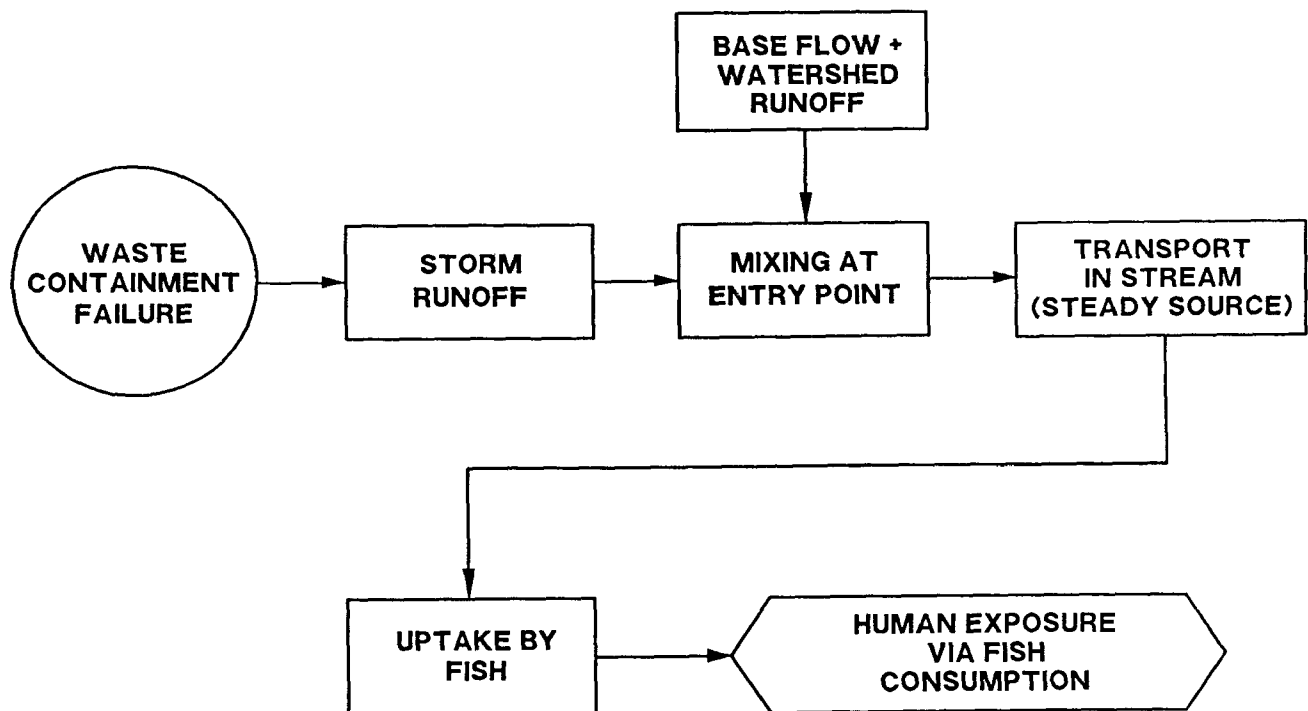


Figure 2.2.2 Flow chart for Scenario 2B

2.2.C Scenario 2C: Exposure of Aquatic Life to Steady Landfill Runoff from a Design Storm Event--

This scenario consists of three stages between the landfill containment unit failure and aquatic exposure (Figure 2.2.3). Through these stages, the input concentration is reduced from the runoff concentration, C_R , to the stream concentration $C_{x,y}$. The relationship between C_R , C_U and $C_{x,y}$ is given by (forward calculation):

$$\overline{C_{x,y}} = \langle C_R \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle + C_U \zeta_{SU} \zeta_x \zeta_{EXP} \quad (2.2.4)$$

For back-calculation, the average concentration in the stream can be equated to the CCC by:

$$\overline{C_{x,y}} = CCC \quad (2.2.5)$$

and the maximum allowable runoff concentration is given by (backward calculation):

$$C_R = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle} \quad (2.2.6)$$

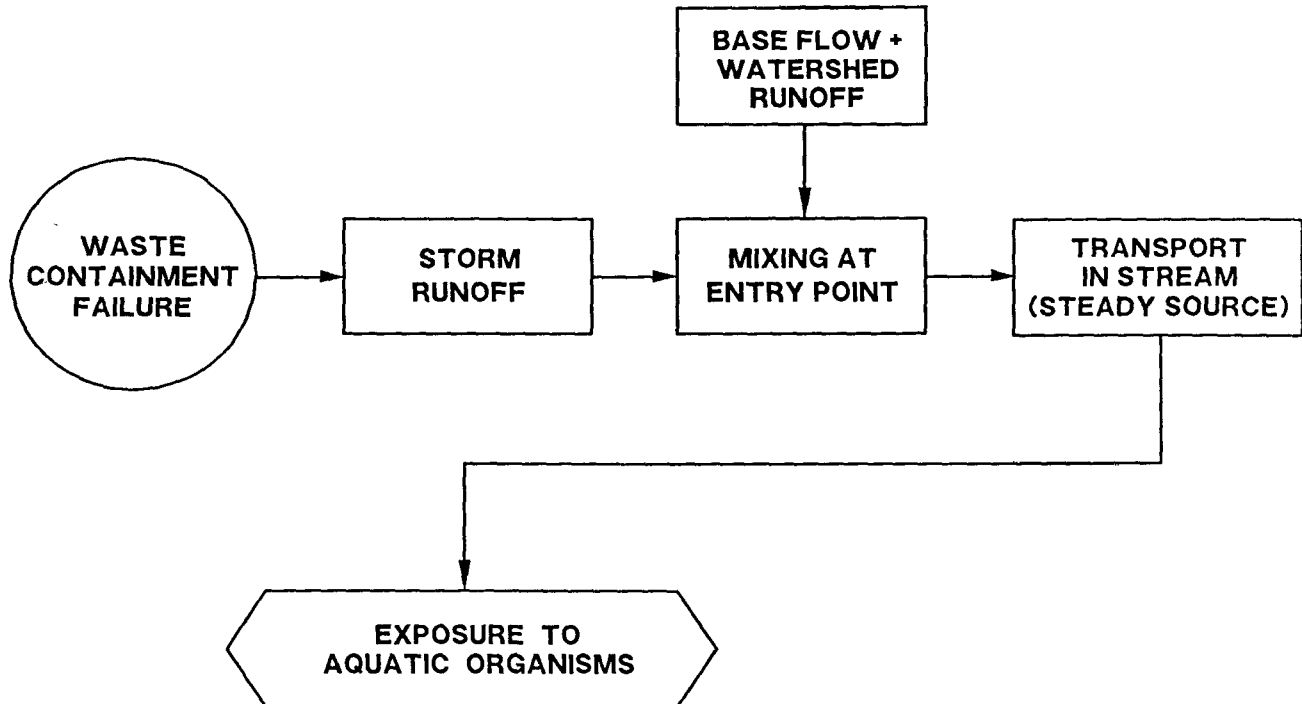


Figure 2.2.3 Flow chart for Scenario 2C

2.3 LANDFILL/CATASTROPHIC STORM RUNOFF

Scenario 3A (catastrophic storm runoff of a landfill) assumes that once the design storm event occurs, the contaminated catchment design fails, and the adjacent surface water is loaded within a one hour time period.

2.3A Scenario 3A: Exposure to Humans through Drinking Water Contaminated by Catastrophic Landfill Runoff Loading to the Stream--

This scenario consists of four stages between the landfill containment failure and exposure of the contaminant to humans via drinking water (Figure 2.3.1). Through these stages, the concentration is successively reduced from C_R to C_{DW} .

In a similar manner to Scenario 2A, a daily averaged concentration in drinking water, $\langle C_{DW} \rangle$, is obtained and equated to C_{RFD} . This yields the following equation for the maximum runoff concentration, C_R , (backward calculation):

$$C_R = \frac{C_{RFD} \cdot \zeta_{SU} \cdot \zeta_x \cdot \zeta_{DW} \cdot C_U}{\langle \zeta_R \cdot \zeta_{x,y} \cdot \zeta_{DW} \rangle} \quad (2.3.1)$$

where ζ_R , ζ_{SU} , ζ_x , and ζ_{DW} are reduction factors due to dilution during runoff, initial mixing of runoff and upstream flow, transport in the stream, and drinking water treatment, respectively.

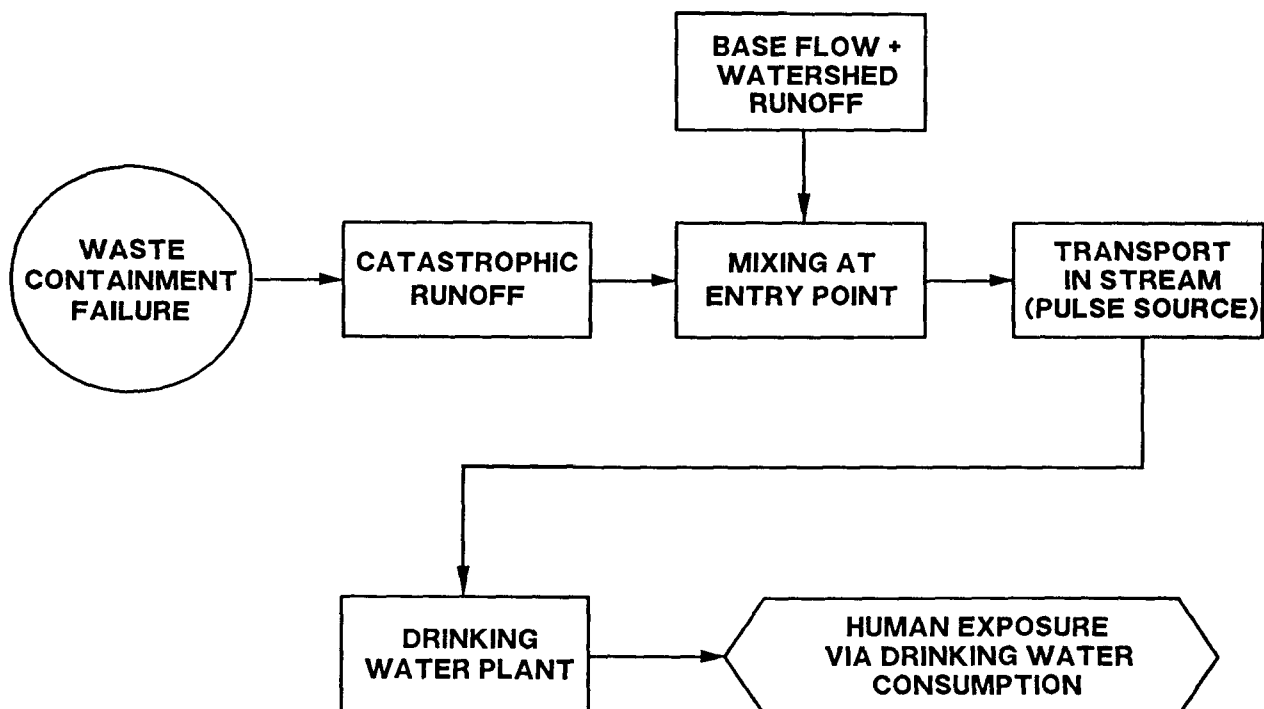


Figure 2.3.1 Flow chart for Scenario 3A

2.3B Scenario 3B: Exposure to Humans through Consumption of Fish by Catastrophic Runoff Loading--

This scenario consists of four stages between the landfill containment failure and exposure of the contaminant to humans via consumption of fish (Figure 2.3.2). Through these stages, the concentration is successively reduced from C_R to C_F . For reasons given in Scenario 2B, significant contaminant doses to humans are ruled out. Back-calculation formulas are not developed.

2.3C Scenario 3C: Exposure of Aquatic Life due to Leachate Carried through Catastrophic Runoff Loading to the Stream--

This scenario consists of three stages between the landfill containment unit failure and aquatic exposure (Figure 2.3.3). Through these stages, the input concentration is reduced from the runoff concentration, C_R , to the stream concentration $C_{x,y}$. The relationship between $C_{x,y}$, C_U , and C_R is given by (forward calculation):

$$\overline{C_{x,y}} = \langle C_R \text{ } f_R \text{ } f_{x,y} \text{ } f_{EXP} \rangle + C_U \text{ } f_{SU} \text{ } f_x \text{ } f_{EXP} \quad (2.3.2)$$

To determine whether a potential health hazard due to surface water contamination exists, the stream concentration can be equated to a specified Continuous Concentration Water Quality Criteria, CCC. Thus:

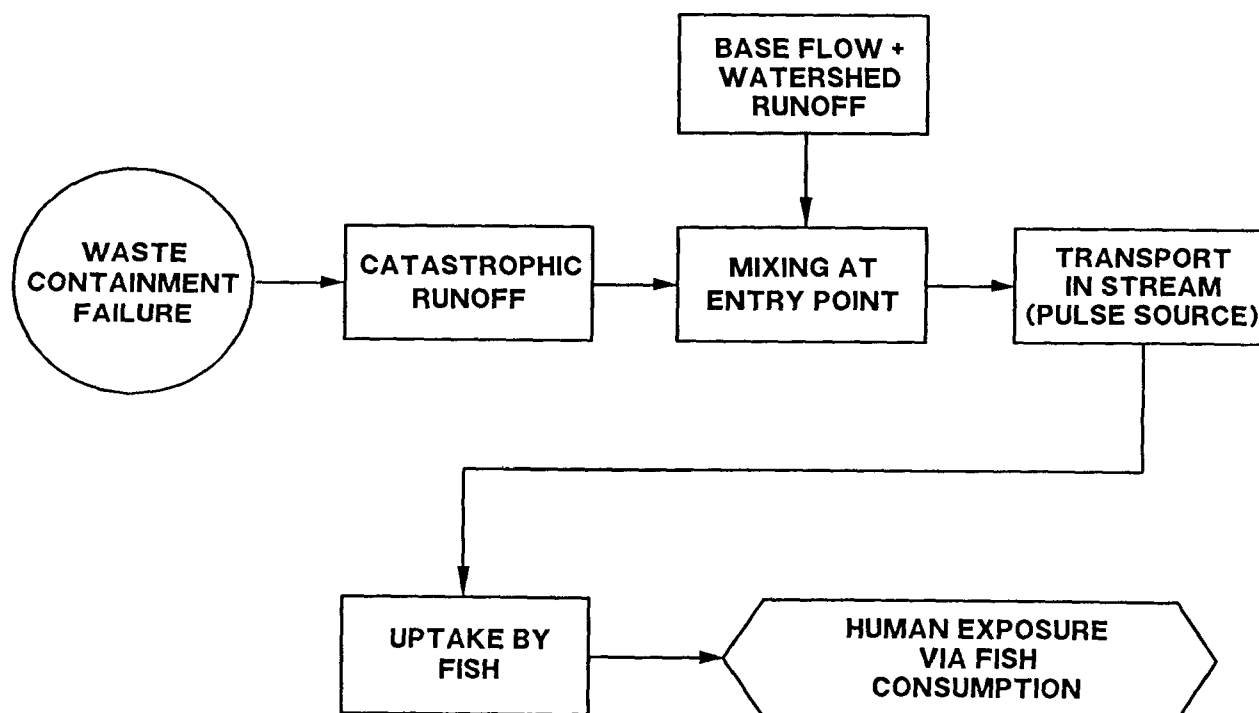


Figure 2.3.2 Flow chart for Scenario 3B

$$\overline{C_{x,y}} = CCC \quad (2.3.3)$$

and the maximum allowable concentration is given by (backward calculation):

$$C_R = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{< \zeta_R \zeta_{x,y} \zeta_{EXP} >} \quad (2.3.4)$$

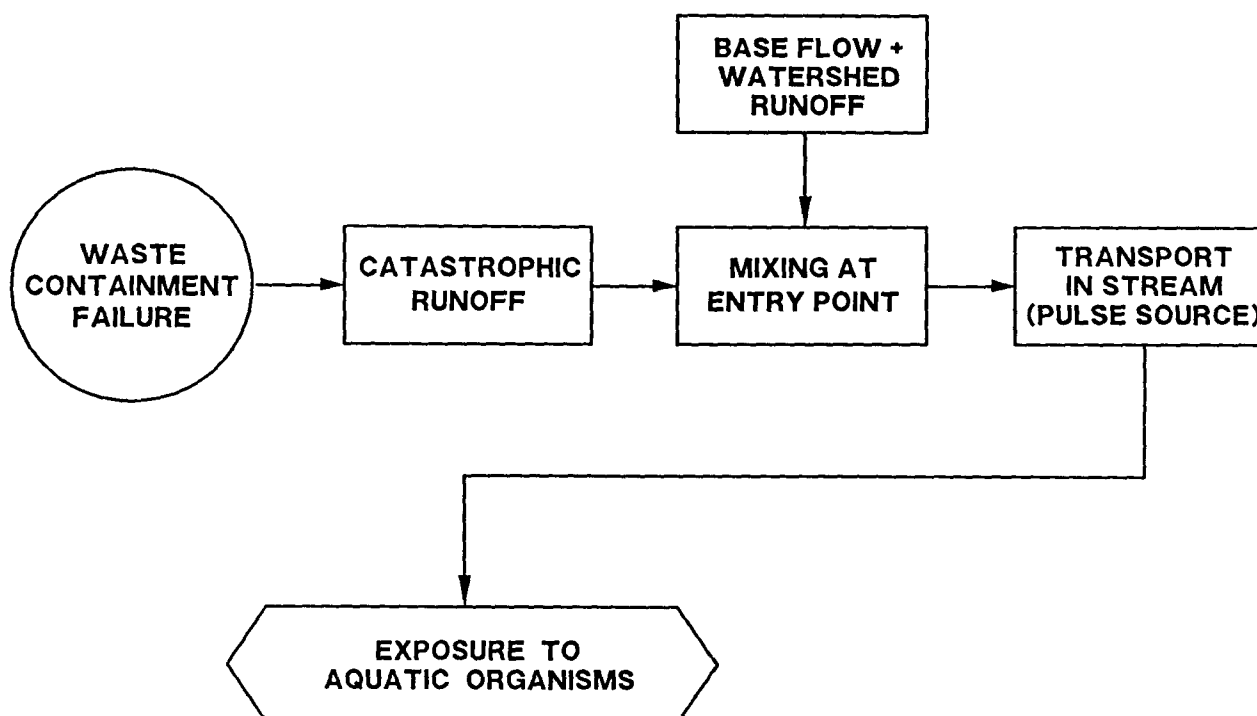


Figure 2.3.3 Flow chart for Scenario 3C

2.4 INDUSTRIAL WASTE/CONTINUOUS DISCHARGE

Scenario 4 (continuous industrial discharge loading) assumes a direct discharge from a treatment facility is occurring at a steady daily load with a constant concentration.

2.4A Scenario 4A: Exposure to Humans through Drinking Water Contaminated by a Continuous Industrial Discharge--

This scenario consists of four stages between the industrial waste stream and exposure of the contaminant to humans via drinking water (Figure 2.4.1). Through these stages, the concentration is successively reduced from

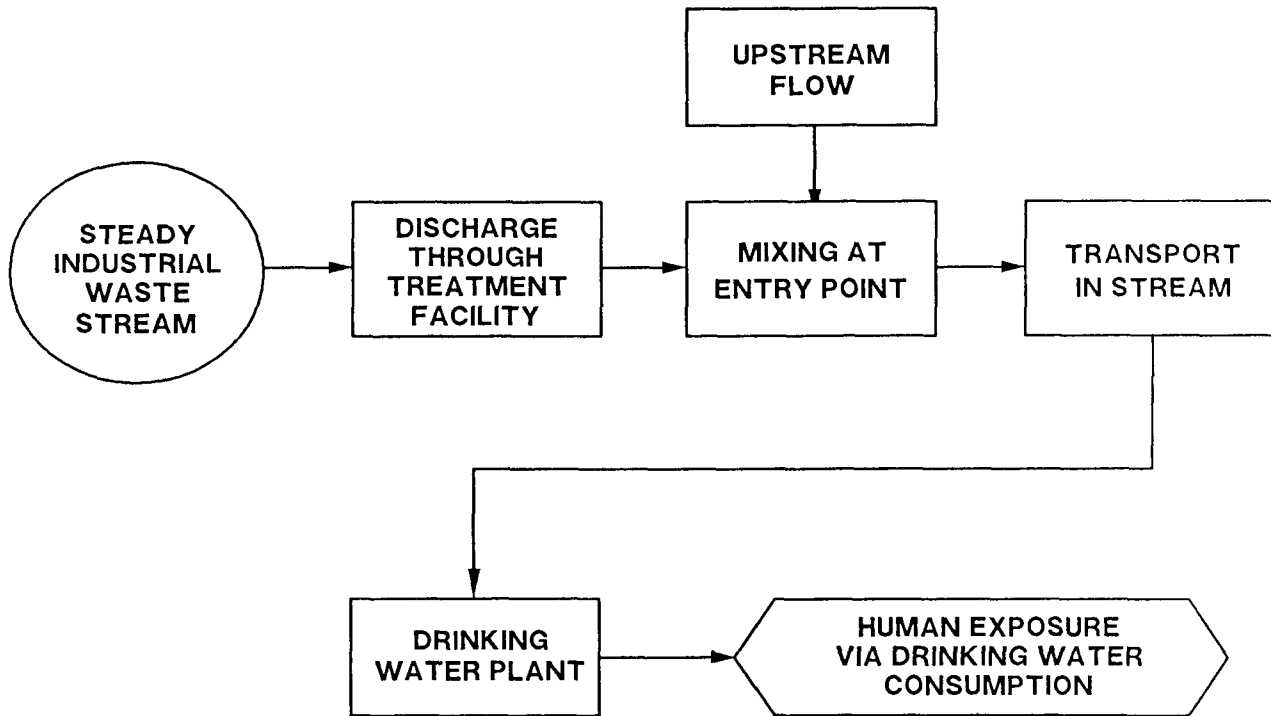


Figure 2.4.1 Flow chart for Scenario 4A

the industrial waste concentration, C_W , to the concentration in the drinking water C_{DW} . The relationship between C_{DW} , C_U , and C_W is given by (forward calculation):

$$C_{DW} = \zeta_D \zeta_{x,y} \zeta_{DW} C_W + \zeta_{SU} \zeta_x \zeta_{DW} C_U \quad (2.4.1)$$

where ζ_D , ζ_{SU} , $\zeta_{x,y}$, and ζ_{DW} are reduction factors due to wastewater treatment, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the reference dose, C_{RFD} . Thus:

$$C_{DW} = C_{RFD} \quad (2.4.2)$$

and the maximum allowable concentration is given by (backward calculation):

$$C_W = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\zeta_D \zeta_{x,y} \zeta_{DW}} \quad (2.4.3)$$

2.4B Scenario 4B: Exposure to Humans through Consumption of Fish Contaminated by a Continuous Industrial Discharge--

This scenario consists of four stages between the industrial waste stream and human exposure via consumption of fish residing in the contaminated surface water (Figure 2.4.2). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W , to the average stream concentration through a specified reach. Then it is increased to the bioconcentrated level in the fish, C_F . The relationship between C_W , C_U , and C_F is given by (forward calculation):

$$C_F = \zeta_D \zeta_{x,y} \zeta_F C_W + \zeta_{SU} \zeta_x \zeta_F C_U \quad (2.4.4)$$

For back-calculation, the average concentration in the fish, C_F , can be equated to a specified reference bioaccumulation concentration, C_{ADI} . Thus:

$$C_F = C'_{RFD} \quad (2.4.5)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_W = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_D \zeta_{x,y} \zeta_F} \quad (2.4.6)$$

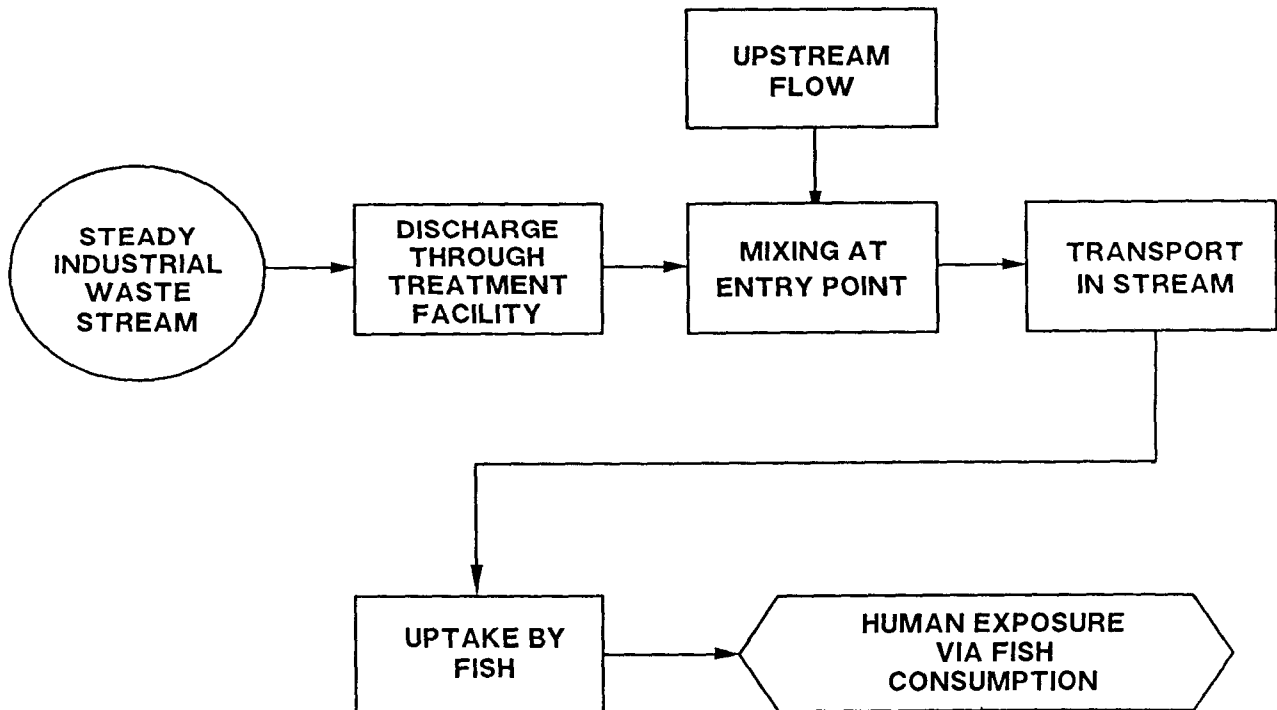


Figure 2.4.2 Flow chart for Scenario 4B

2.4C Scenario 4C: Exposure of Aquatic Life due to a Continuous Industrial Discharge--

This scenario consists of three stages between the industrial waste stream and aquatic exposure (Figure 2.4.3). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W , to the average stream concentration, $C_{x,y}$. The relation between C_W , C_U , and $C_{x,y}$ is given by (forward calculation):

$$\bar{C}_{x,y} = \zeta_D \zeta_{x,y} C_W + \zeta_{SU} \zeta_x C_U \quad (2.4.7)$$

For back-calculation, the average concentration in the stream can be equated to the CCC by:

$$\bar{C}_{x,y} = CCC \quad (2.4.8)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_W = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\zeta_D \zeta_{x,y} \zeta_{EXP}} \quad (2.4.9)$$

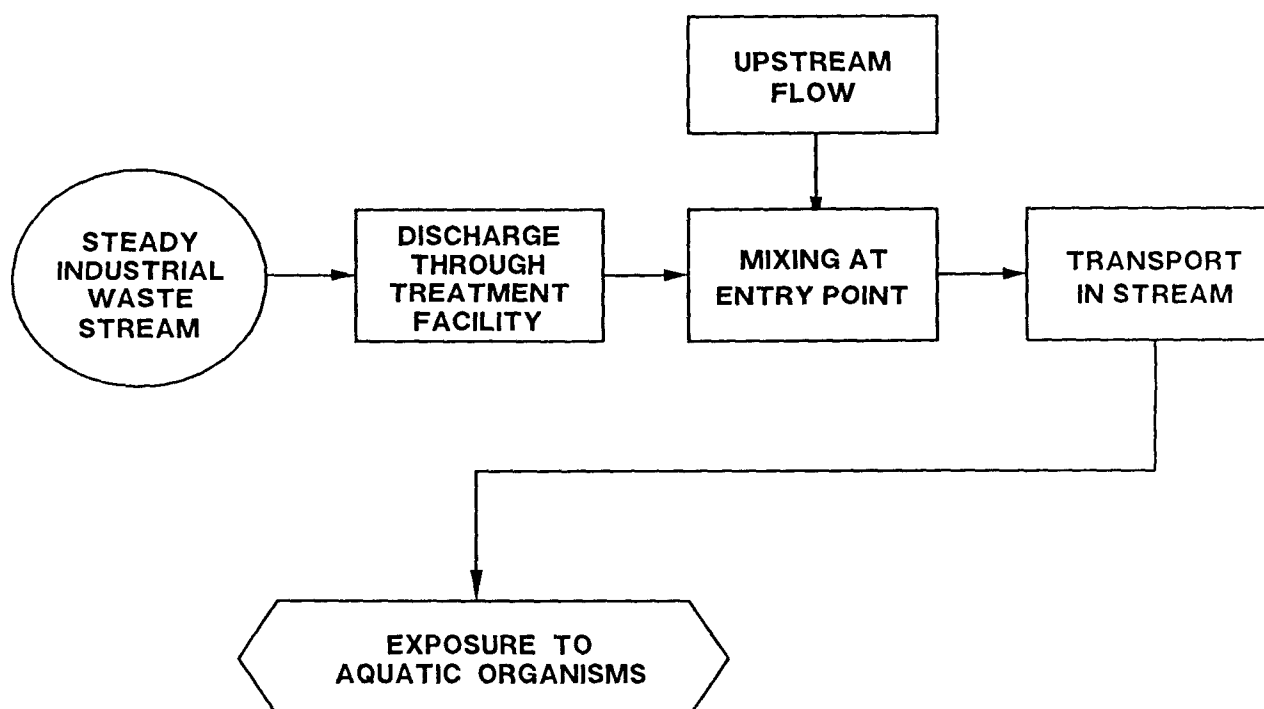


Figure 2.4.3 Flow chart for Scenario 4C

2.5 INDUSTRIAL WASTE/PULSE DISCHARGE

Scenario 5 (Batch industrial discharge loading) assumes a direct discharge from a treatment facility within a one hour (or less) time period.

2.5A Scenario 5A: Exposure to Humans through Drinking Water Contaminated by a Pulse Industrial Discharge--

This scenario consists of four stages between the industrial waste stream and exposure of the contaminant to humans via drinking water (Figure 2.5.1). Through these stages, the concentration is successively reduced from C_W to C_{DW} . In a similar manner to Scenario 4A, a time-averaged concentration in drinking water, $\langle C_{DW} \rangle$, is obtained and equated to C_{RFD} to yield the following equation for the maximum discharge concentration, C_W (backward calculation):

$$C_W = \frac{C_{RFD} \cdot \zeta_{SU} \cdot \zeta_x \cdot \zeta_{DW} \cdot C_U}{\langle \zeta_D \cdot \zeta_{x,y} \cdot \zeta_{DW} \rangle} \quad (2.5.1)$$

where ζ_D , ζ_{SD} , $\zeta_{x,y}$, and ζ_{DW} are reduction factors due to wastewater treatment, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

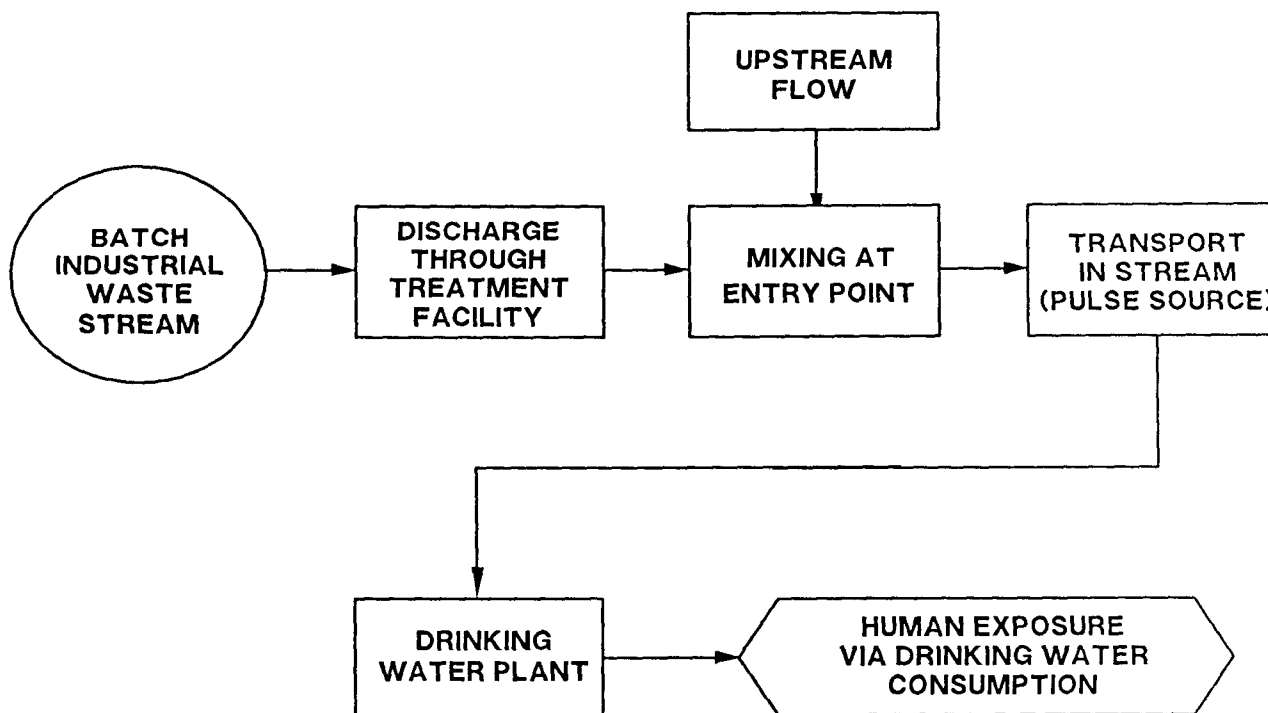


Figure 2.5.1 Flow chart for Scenario 5A

2.5B Scenario 5B: Exposure to Humans through Consumption of Fish Contaminated by a Pulse Industrial Discharge--

This scenario consists of four stages between the industrial waste stream and human exposure via consumption of fish residing in the contaminated surface water (Figure 2.5.2). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W , to the average stream concentration throughout a specified reach. Then it is increased to the bioconcentrated level in the fish, C_F . A time-averaged bioconcentrated level in the fish, $\langle C_F \rangle$, is obtained and equated to a specified reference bioaccumulation concentration, C_{RFD} . Thus (backward calculation):

$$\langle C_W \rangle = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\langle \zeta_D \zeta_{x,y} \zeta_F \rangle} \quad (2.5.2)$$

2.5C Scenario 5C: Exposure of Aquatic Life due to a Pulse Industrial Discharge--

This scenario consists of three stages between the industrial waste stream and aquatic exposure (Figure 2.5.3). Through these stages, the input concentration is successively reduced from the industrial waste concentration,

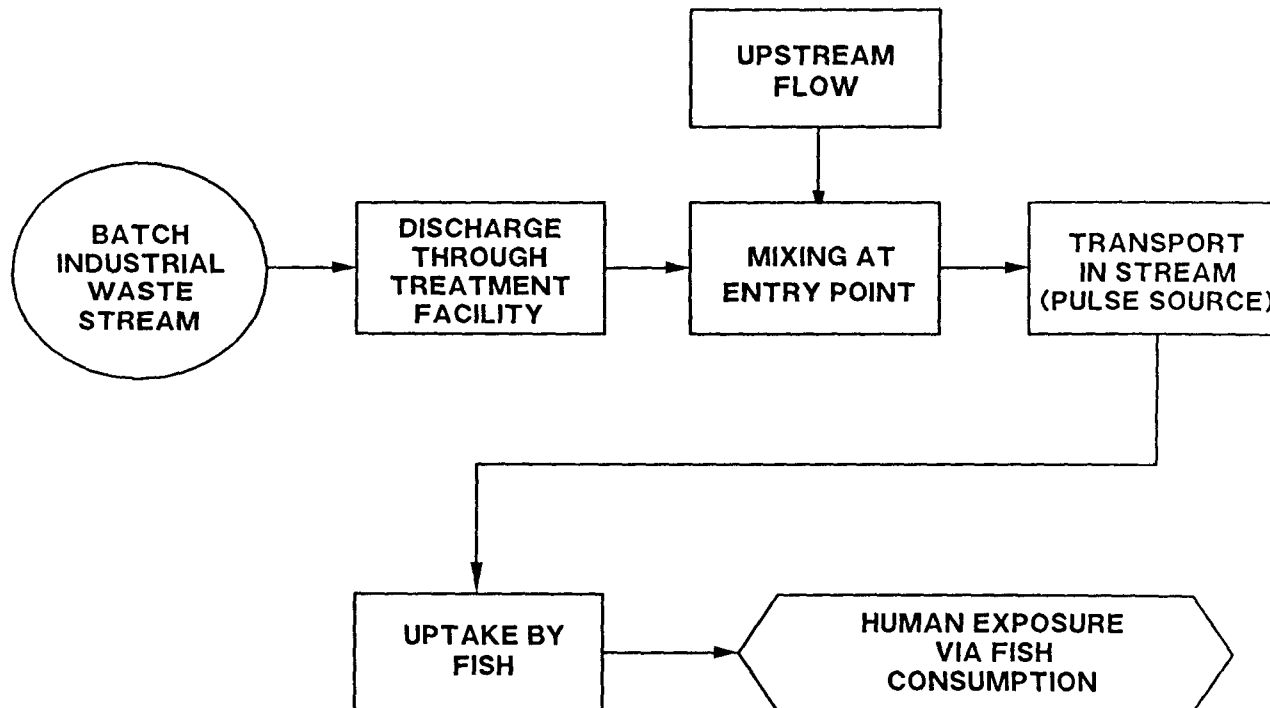


Figure 2.5.2 Flow chart for Scenario 5B

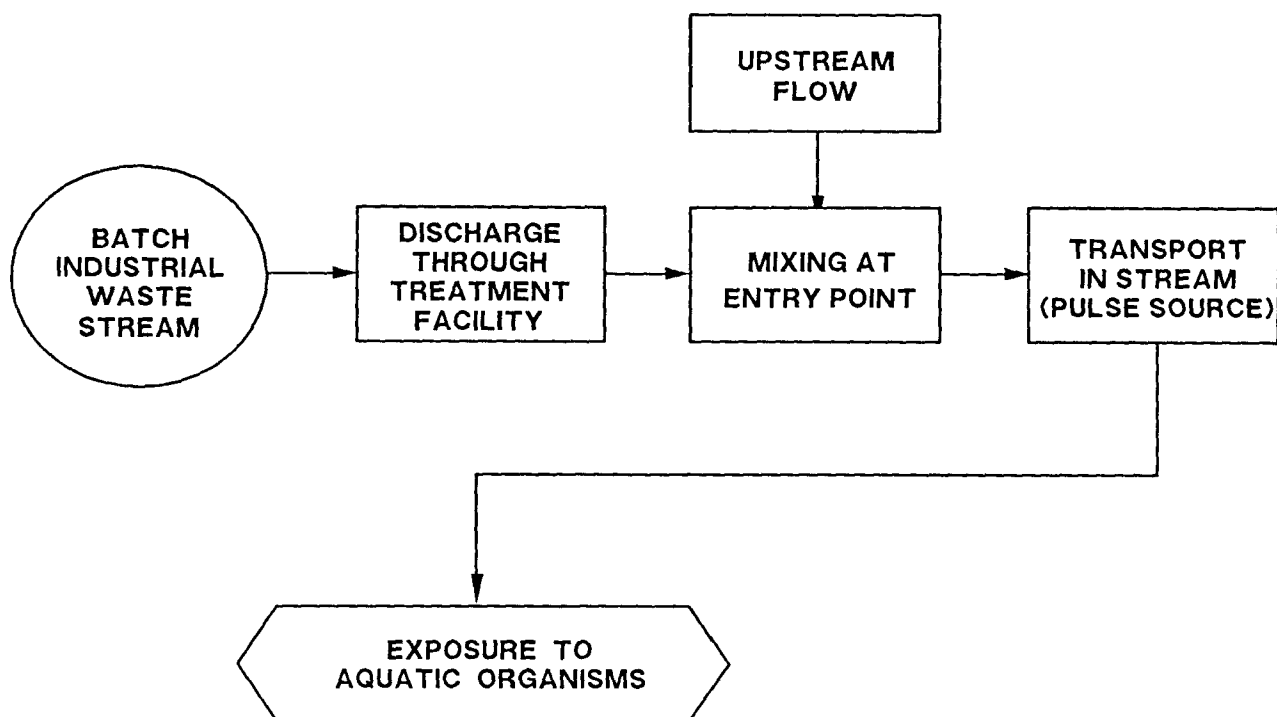


Figure 2.5.3 Flow chart for Scenario 5C

C_W , to the time and stream averaged concentration, $\langle C_{SD} \rangle$. The relationship between C_W , C_U , and $\langle C_{SD} \rangle$ is given by (forward calculation):

$$\langle C_{SD} \rangle = \langle \zeta_D \zeta_{EXP} \zeta_{SD} \zeta_{x,y} \rangle C_W + \zeta_{SU} \zeta_{EXP} \zeta_x C_U$$

For back-calculation, the average concentration in the stream can be equated to a specified CCC. Thus:

$$\langle C_{SD} \rangle = CCC \quad (2.5.4)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_W = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_D \zeta_{EXP} \zeta_{x,y} \rangle} \quad (2.5.5)$$

2.6 LAGOON/GROUND WATER

Scenario 6 (steady ground water loading from a lagoon) 1) assumes the waste leaves the lagoon by percolating through the clay liner or the native soil, or 2) it permeates the flexible membrane liner (FML). Since precipitation has a minimal influence on leachate generation, the liquid waste will percolate to the watertable under the influence of gravity at a rate deter-

mined by the permeability of the liner and the head or underlying soil (Versar Inc., 1987).

Except for the source, scenario 6 is essentially the same as scenario 1. Therefore, equations will be the same except for the source term.

2.6A Scenario 6A: Exposure to Humans through Drinking Water Contaminated by Lagoon Leachate Carried By Ground Water--

This scenario consists of four stages between failure of the lagoon liner and the exposure of the contaminant to humans via drinking water (Figure 2.6.1). Through these stages, the concentration is successivley reduced from the leachate concentration, C_L , to the concentration in drinking water, C_{DW} . The relationship between C_{DW} , C_U , and C_L is given by (forward calculation)

$$C_{DW} = \zeta_g \zeta_{Sg} \zeta_{x,y} \zeta_{DW} C_L + \zeta_{SU} \zeta_x \zeta_{DW} C_U \quad (2.6.1)$$

where ζ_g , ζ_{Sg} , ζ_{SU} , ζ_x , and ζ_{DW} are reduction factors due to transport in ground water, mixing at the area of leachate entry into the stream, transport in the stream, and reduction in the drinking water plant. ζ_{SU} is the dilution factor for the upstream concentration by the ground water flow.

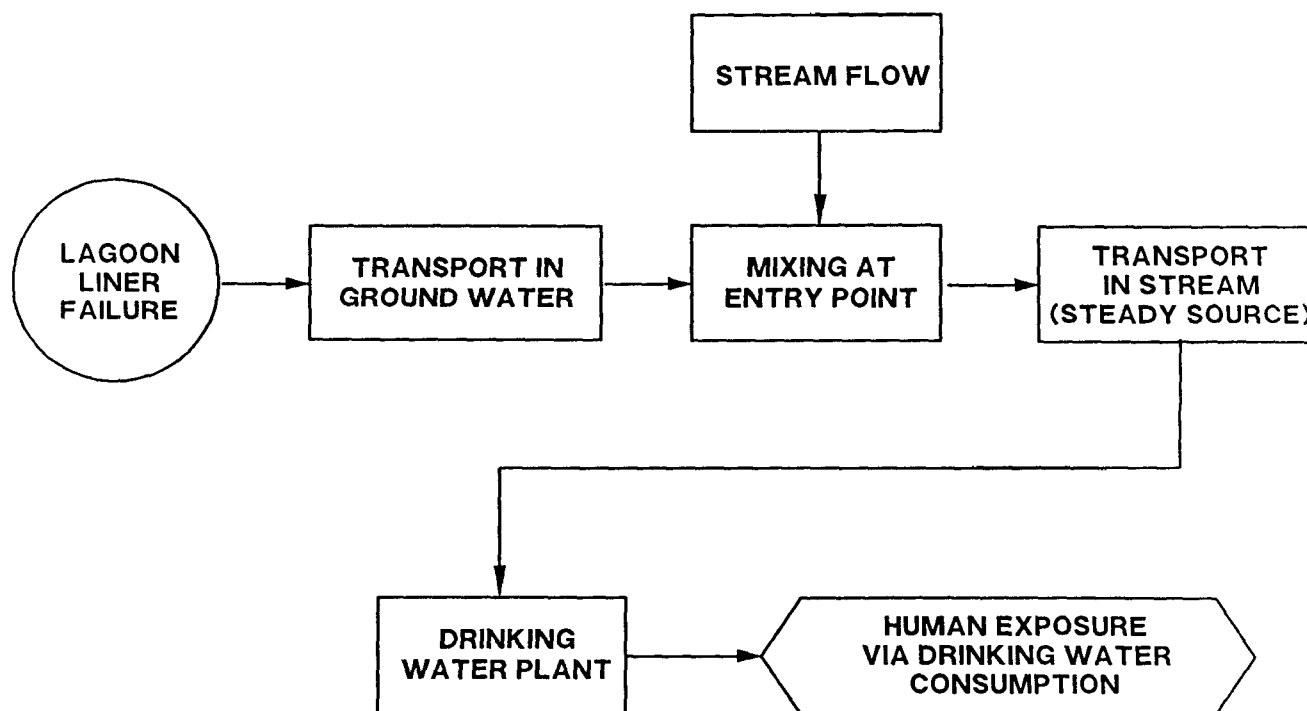


Figure 2.6.1 Flow chart for Scenario 6A

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the reference dose, C_{RFD} . Thus:

$$C_{DW} = C_{RFD} \quad (2.6.2)$$

and the maximum allowable leachate concentration must be (backward calculation):

$$C_L = \frac{C_{RFD} \cdot \zeta_{SU} \cdot \zeta_x \cdot \zeta_{DW} \cdot C_U}{\zeta_g \cdot \zeta_{Sg} \cdot \zeta_{x,y} \cdot \zeta_{DW}} \quad (2.6.3)$$

2.6B Scenario 6B: Exposure to Humans through Consumption of Fish Contaminated by Lagoon Leachate Carried through Ground Water

This scenario consists of three stages between the containment failure and human exposure via consumption of fish residing in the contaminated surface water (Figure 2.6.2). Through these stages, the input concentration is successively reduced from the leachate concentration, C_L , to the stream concentration, and then increased to the bioconcentrated level in the fish, C_F . The relation between C_L , C_U , and C_F is given by (forward calculation):

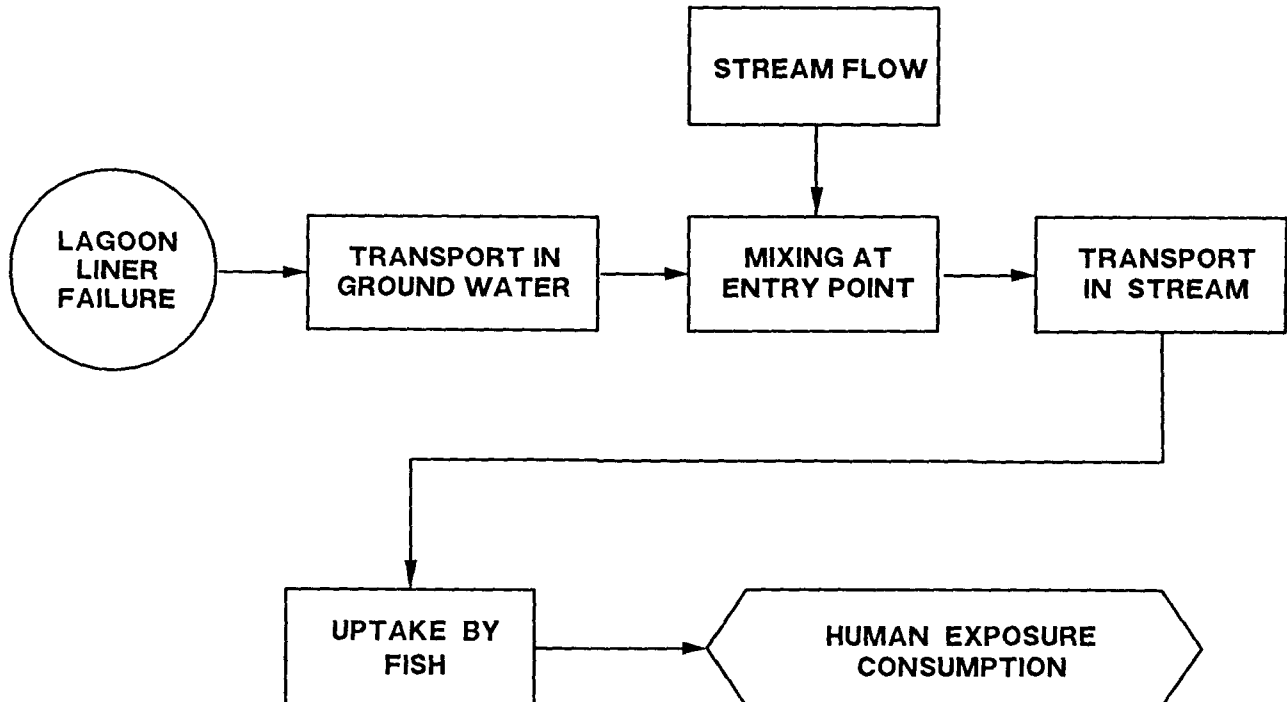


Figure 2.6.2 Flow chart for Scenario 6B

$$C_F = \zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_F C_L + \zeta_{SU} \zeta_x \zeta_F C_U \quad (2.6.4)$$

where ζ_F is the bioconcentration factor due to the biochemical exchange processes within the fish.

For back-calculation, the average concentration in the fish, C_F , can be equated to a specified reference bioaccumulation concentration, C'_{RFD} . Thus:

$$C_F = C'_{RFD} \quad (2.6.5)$$

and the maximum allowable leachate concentration is given by (backward calculations):

$$C_L = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_F} \quad (2.6.6)$$

2.6C Scenario 6C: Exposure of Aquatic Life due to Lagoon Leachate Carried through Ground Water

This scenario consists of two stages between the waste containment unit failure and aquatic exposure (Figure 2.6.3). Through these stages, the input concentration is successively reduced from the leachate concentration, C_L , to the average stream concentration, C_0 . The relationship between C_L , C_U , and C_0 is given by (forward calculation):

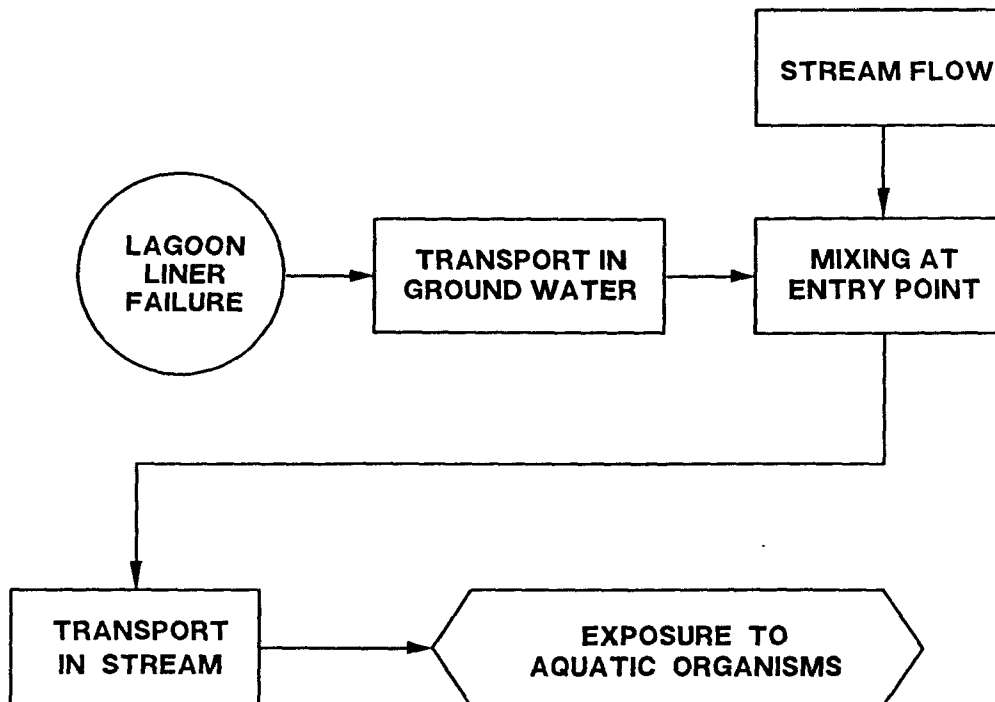


Figure 2.6.3 Flow chart for Scenario 6C

$$\bar{C}_0 = \zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_{EXP} C_L + \zeta_{SU} \zeta_x \zeta_{EXP} C_U \quad (2.6.7)$$

For back-calculation, the average concentration in the stream can be equated to the criteria, CCC. Thus:

$$\bar{C}_0 = CCC \quad (2.6.8)$$

and the maximum allowable leachate concentration is given by (backward calculation):

$$C_L = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\zeta_g \zeta_{Sg} \overline{\zeta_{x,y}} \zeta_{EXP}} \quad (2.6.9)$$

2.7 LAGOON/STEADY OVERFLOW

Scenario 7 (steady overflow from a lagoon) assumes the depth of the lagoon has exceeded its free-board-depth due to the addition of rainfall. The loading event occurs over a time period greater than an hour, but less than one day.

Except for the source, scenario 7 is essentially the same as scenario 2. Therefore, equations will remain the same except the source term.

2.7A Scenario 7A: Exposure to Humans through Drinking Water Contaminated by Steady Lagoon Overflow.

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via drinking water (Figure 2.7.1). Through these stages, the concentration is successively reduced from the overflow concentration, C_R , to the concentration in the drinking water, C_{DW} . The relationship between C_{DW} , C_U , and C_R is given by (forward calculation):

$$C_{DW} = \langle \zeta_R \zeta_{x,y} \zeta_{DW} C_R \rangle + \zeta_{SU} \zeta_x \zeta_{DW} C_U \quad (2.7.1)$$

where ζ_R , ζ_{SU} , ζ_x , and ζ_{DW} are reduction factors due to dilution during overflow and initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

Because of the pulse loading condition, the concentration C_{DW} is time dependent. Thus, it is averaged over a 1-day period. This average concentration, $\langle C_{DW} \rangle$, can then be equated to the specified reference dose C_{RFD} . It follows that:

$$\langle C_{DW} \rangle = C_{RFD} \quad (2.7.2)$$

and the maximum allowable overflow concentration is given by (backward calculation):

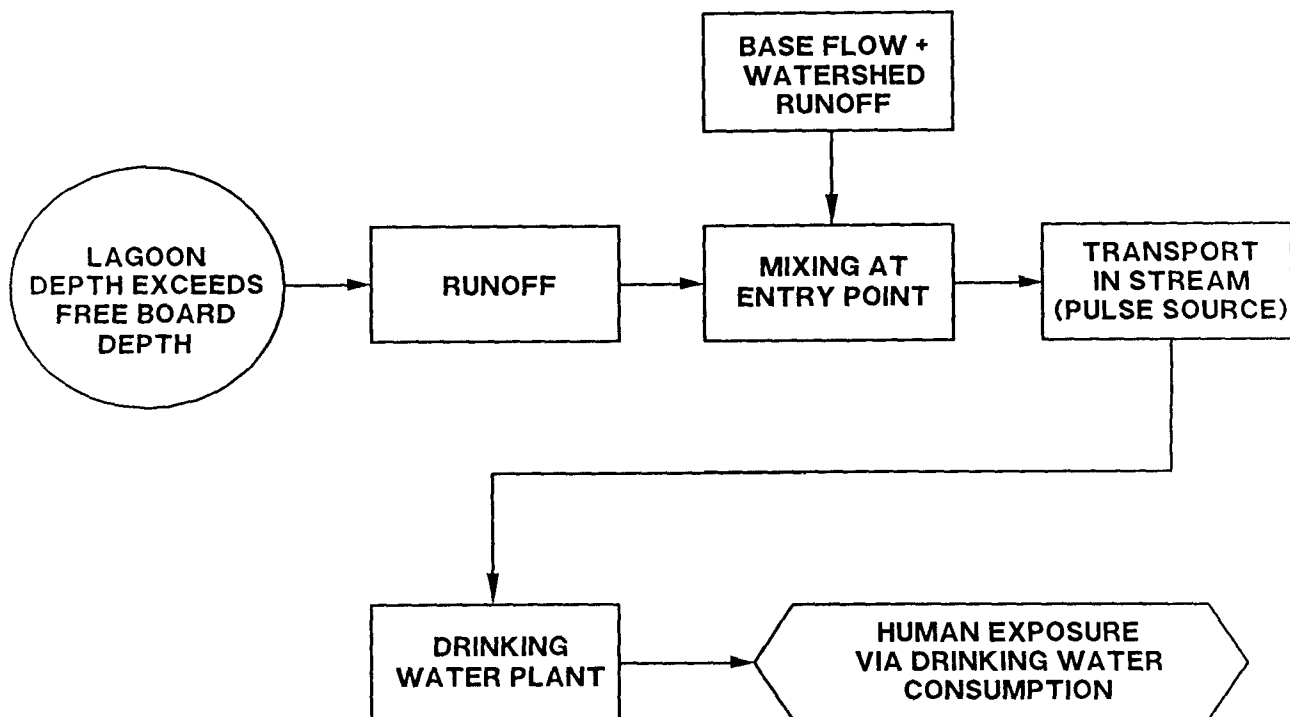


Figure 2.7.1 Flow chart for Scenario 7A

$$C_R = \frac{C_{RFD} \cdot \zeta_{SU} \cdot \zeta_x \cdot \zeta_{DW} \cdot C_U}{\langle \zeta_R \cdot \zeta_{x,y} \cdot \zeta_{DW} \rangle} \quad (2.7.3)$$

where angular brackets are used to denote the 1-day average of the enclosed quantity.

2.7B Scenario 7B: Exposure to Humans through Consumption of Fish Contaminated by Steady Lagoon Overflow

This scenario consists of four stages between the waste containment failure and exposure of contaminant to humans via consumption of fish (Figure 2.7.2). Through these stages, the input concentration is altered from the overflow concentration, C_R , to the average concentration in the fish, C_F .

The infrequency of this event and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans. Consequently, the backwards or forward-calculation formulas are not developed.

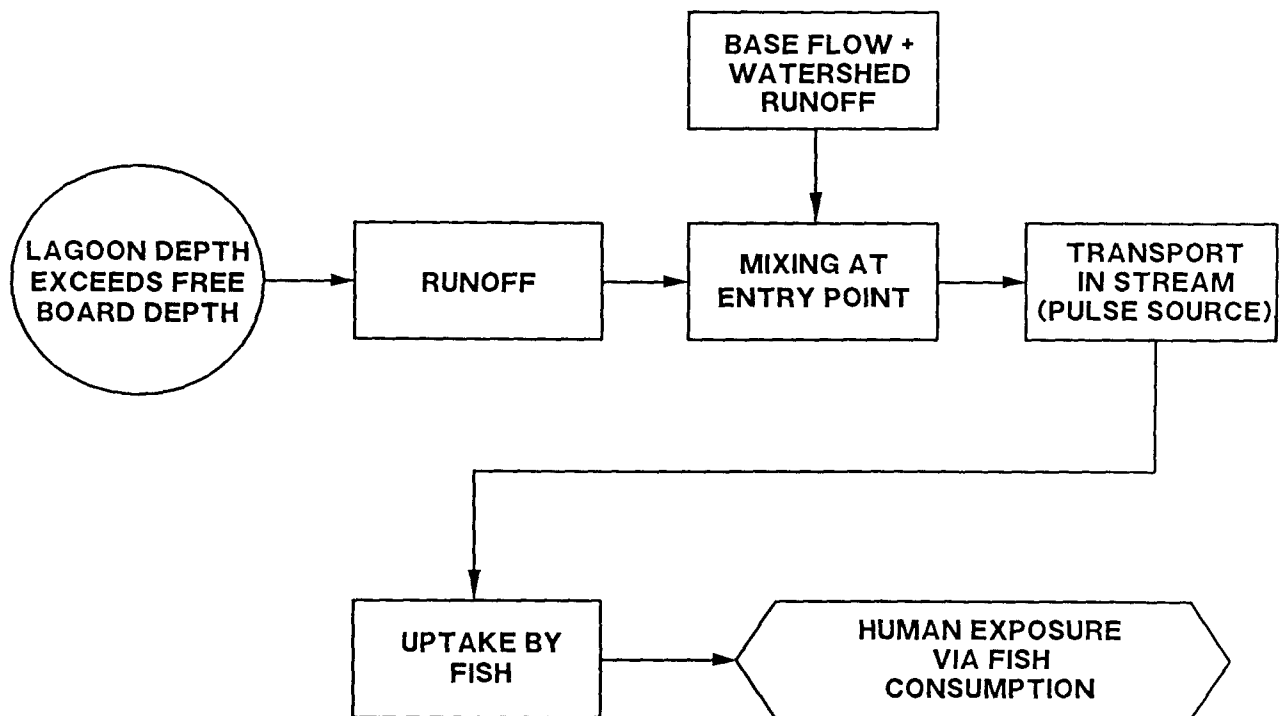


Figure 2.7.2 Flow chart for Scenario 7B

2.7C Scenario 7C: Exposure of Aquatic Life by Steady Lagoon Overflow Loading

This scenario consists of three stages between the waste containment unit failure and aquatic exposure (Figure 2.7.3). Through these stages, the input concentration is reduced from the overflow concentration, C_R to the stream concentration $C_{x,y}$.

The relation between C_R , C_U and $\bar{C}_{x,y}$ is given by (forward calculations):

$$\bar{C}_{x,y} = f_R f_{x,y} f_{x,y} f_{EXP} C_R + f_{SU} f_x f_{EXP} C_U \quad (2.7.4)$$

For back calculation, the average concentration in the stream can be equated to the CCC by:

$$\bar{C}_{x,y} = CCC \quad (2.7.5)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_R = \frac{CCC - \zeta_{SU} \zeta_{EXP} \zeta_x C_U}{\langle \zeta_R \zeta_{EXP} \zeta_{x,y} \rangle} \quad (2.7.6)$$

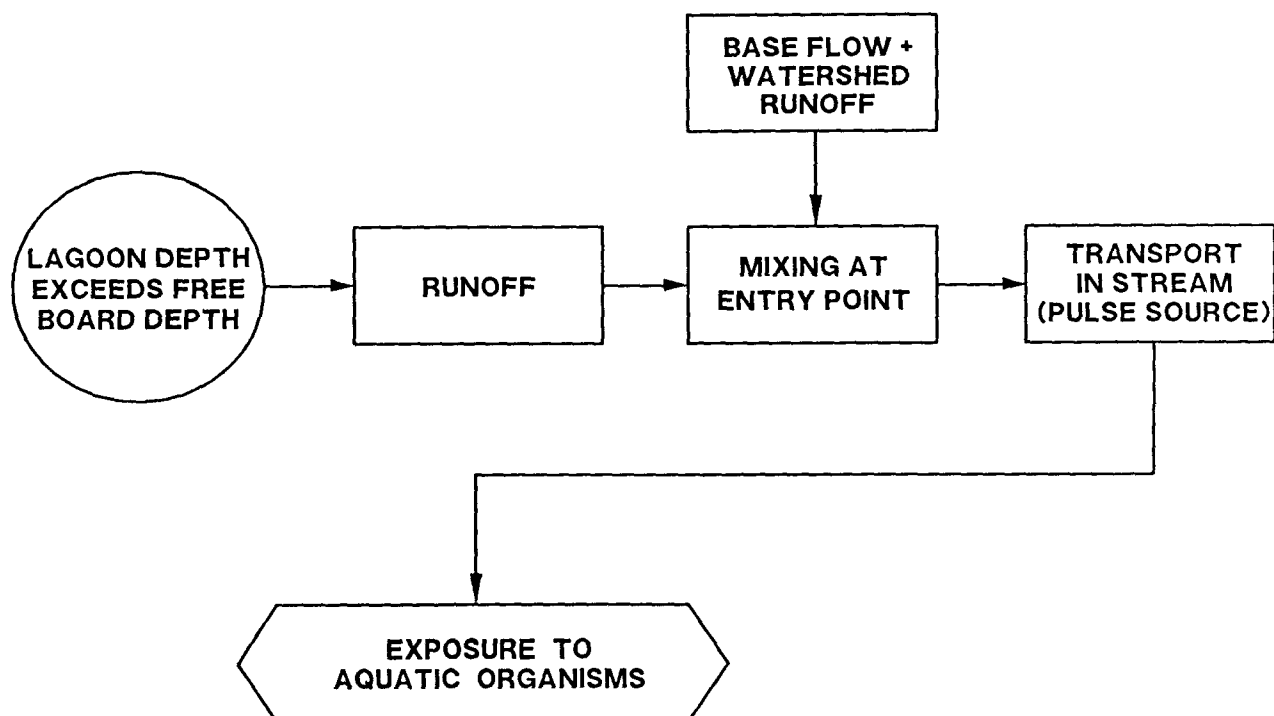


Figure 2.7.3 Flow chart for Scenario 7C

2.8 LAGOON/PULSE FAILURE

Scenario 8 (catastrophic release from a lagoon) assumes a dam or berm failure due to poor design or a storm. Release occurs over a time period equal to or less than one hour.

Except for the source, scenario 8 is essentially the same as scenario 3. Therefore, equations will remain the same except for the source term.

2.8A Scenario 8A: Exposure to Humans through Drinking Water Contaminated by Lagoon through Catastrophic Failure

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via drinking water (Figure

2.8.1). Through these stages, the concentration is successively reduced from C_R to C_{DW} .

In a similar manner to Scenario 7A, a daily averaged concentration in drinking water, $\langle C_{DW} \rangle$, is obtained and equated to C_{RFD} to yield the following equation for the maximum release concentration, C_R , (backward calculation):

$$C_R = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{DW} \rangle} \quad (2.8.1)$$

where ζ_R , ζ_{SU} , ζ_x , and ζ_{DW} are reduction factors due to, dilution during runoff, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

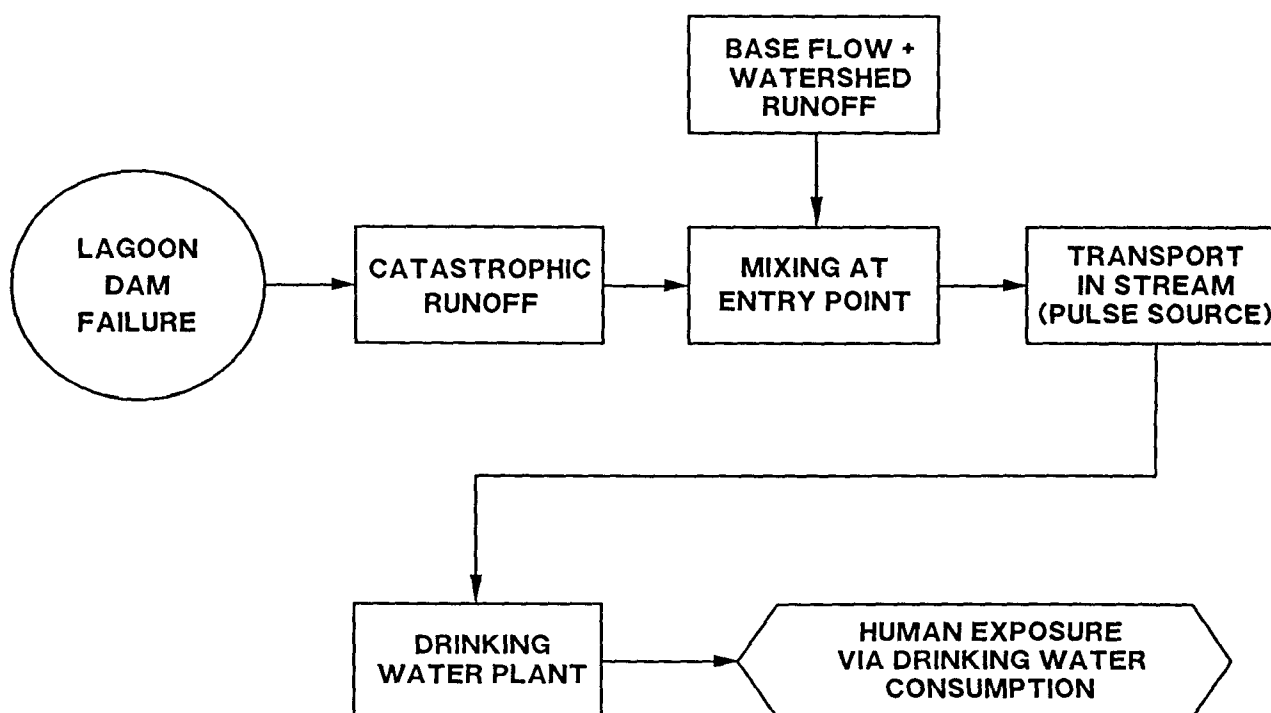


Figure 2.8.1 Flow chart for Scenario 8A

2.8B Scenario 8B: Exposure to Humans through Consumption of Fish Contaminated by Lagoon through Catastrophic Failure

This scenario consists of four stages between the waste containment failure and exposure of the contaminant to humans via consumption of fish (Figure 2.8.2). Through these stages, the lagoon concentration is successively reduced to C_F .

The infrequency of this event and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans. Consequently, neither the backwards or forward-calculation formulas are not developed.

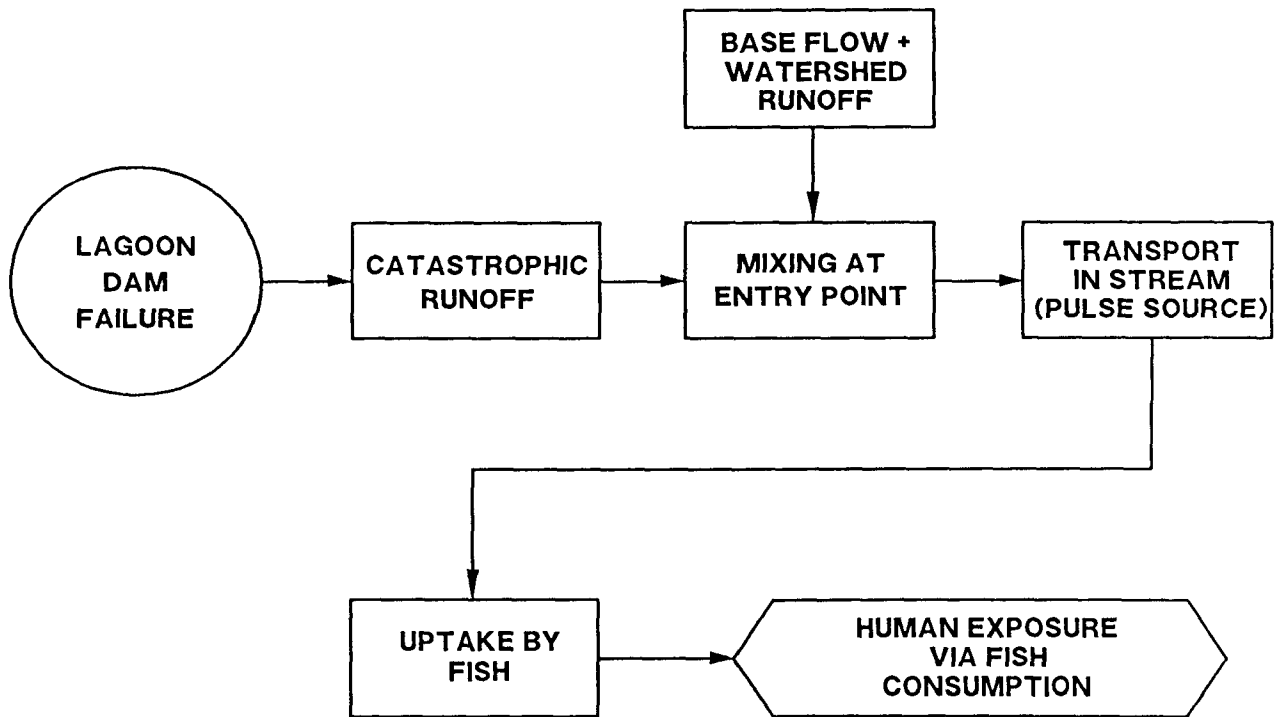


Figure 2.8.2 Flow chart for Scenario 8B

2.8C Scenario 8C: Exposure of Aquatic Life due to Catastrophic Lagoon Failure

This scenario consists of three stages between the waste containment unit failure and aquatic exposure (Figure 2.8.3). Through these stages, the input concentration is reduced from the release concentration, C_R , to the stream concentration $C_{x,y}$.

The relationship between C_R , C_U , and $\bar{C}_{x,y}$ is given by the time averaged equation (forward calculation):

$$\bar{C}_{x,y} = \langle \zeta_R \zeta_{SU} \zeta_{x,y} \zeta_{EXP} \rangle C_R + \zeta_{SU} \zeta_x \zeta_{EXP} C_U \quad (2.8.2)$$

$$\bar{C}_{x,y} = CCC \quad (2.8.3)$$

and the maximum allowable release concentration is given by (backward calculation):

$$C_R = \frac{CCC - \zeta_{SU} \zeta_{EXP} \zeta_x C_U}{\langle \zeta_R \zeta_{EXP} \zeta_{x,y} \rangle} \quad (2.8.4)$$

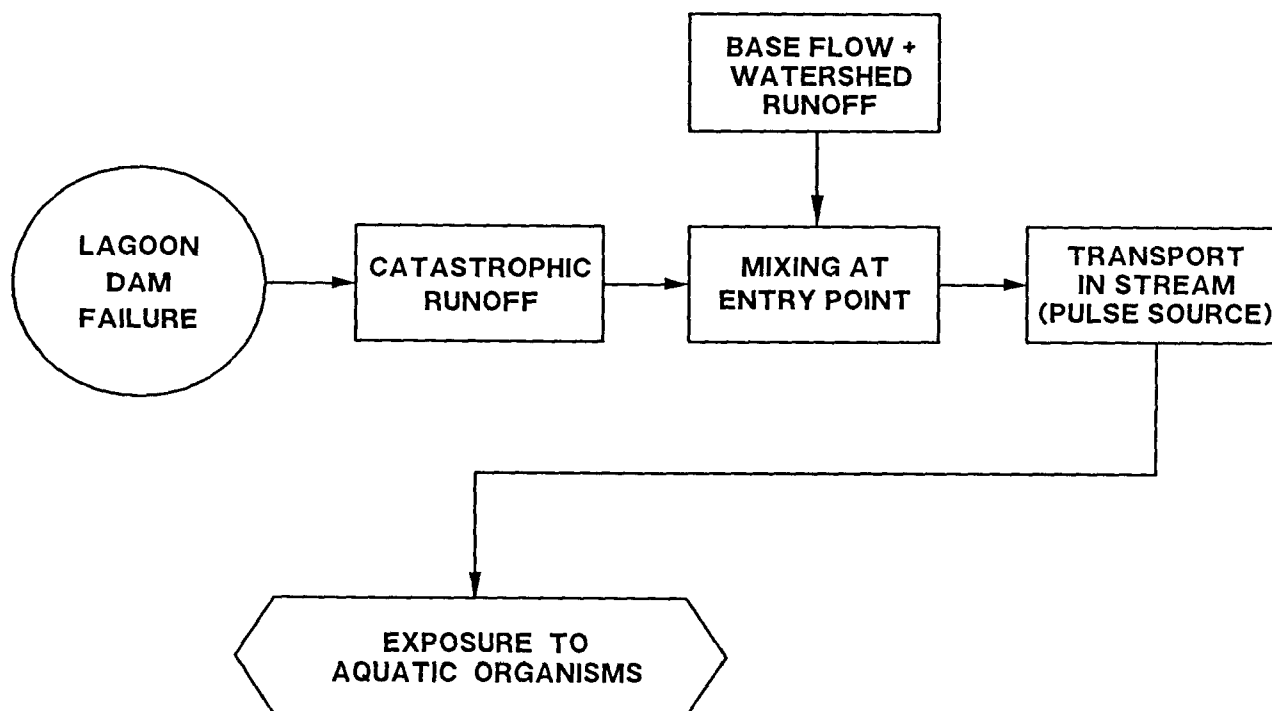


Figure 2.8.3 Flow chart for Scenario 8C

2.9 LAGOON/CONTINUOUS DISCHARGE

Scenario 9 (steady direct discharge from a lagoon) assumes that the lagoon contents are directly discharged into the surface water at a constant concentration, and a constant rate. The discharge occurs over a time period of one day.

Except for the source, scenario 9 is essentially the same as scenario 4. Therefore, equations will remain the same except for the source term.

2.9A Scenario 9A: Exposure to Humans through Drinking Water Contaminated by a Continuous Discharge--from a Lagoon

This scenario consists of four stages between the industrial waste stream and exposure of the contaminant to humans via drinking water (Figure 2.9.1).

Through these stages, the concentration is successively reduced from the industrial waste concentration, C_W , to the concentration in the drinking water C_{DW} . The relationship between C_{DW} , C_U , and C_W is given by (forward calculation):

$$C_{DW} = \zeta_D \zeta_{x,y} \zeta_{DW} C_W + \zeta_{SU} \zeta_x \zeta_{DW} C_U \quad (2.9.1)$$

where ζ_D , ζ_{SU} , $\zeta_{x,y}$, and ζ_{DW} are reduction factors due to waste-water treatment, initial mixing at the stream entry area, transport in the stream, and drinking water treatment, respectively.

To determine whether a potential health hazard due to surface water contamination exists, the drinking water concentration can be equated to the specified reference dose, C_{RFD} . Thus:

$$C_{DW} = C_{RFD} \quad (2.9.2)$$

and the maximum allowable waste concentration is (backward calculation):

$$C_W = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\zeta_D \zeta_{x,y} \zeta_{DW}} \quad (2.9.3)$$

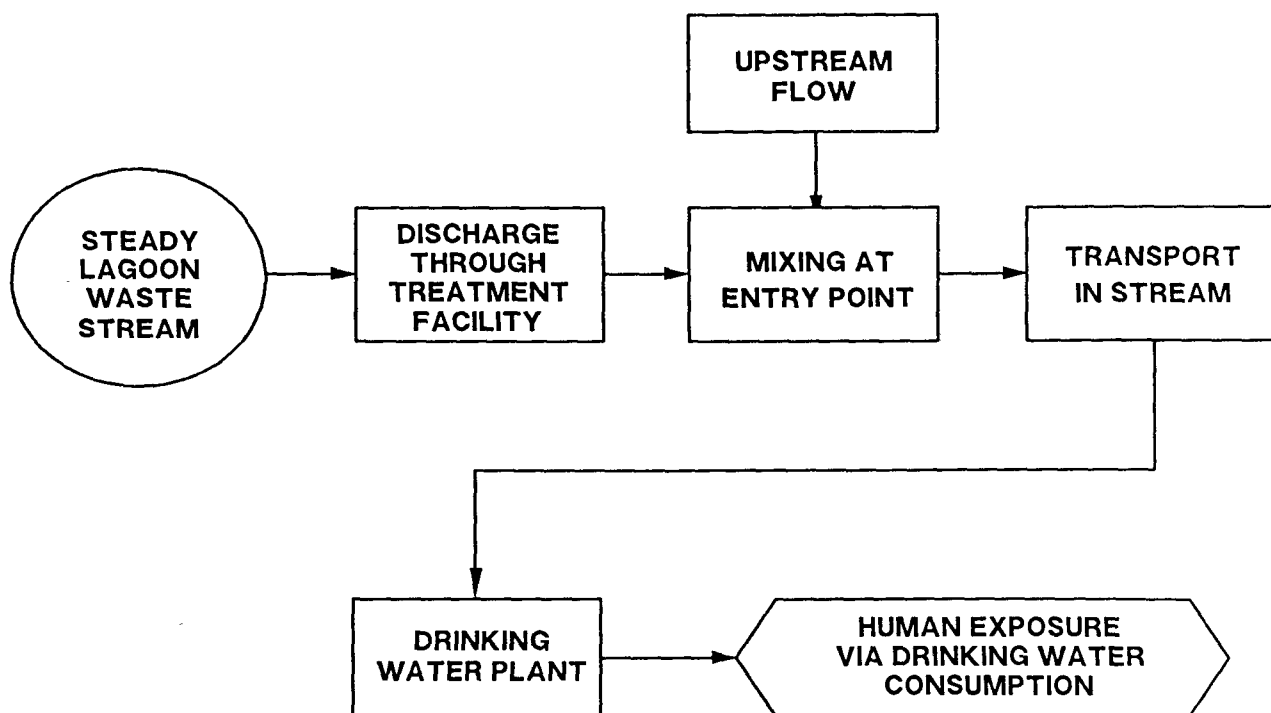


Figure 2.9.1 Flow chart for Scenario 9A

2.9B Scenario 9B: Exposure to Humans through Consumption of Fish Contaminated by a Continuous Discharge--from a Lagoon

This scenario consists of four stages between the industrial waste stream and human exposure via consumption of fish residing in the contaminated surface water (Figure 2.9.2). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W , to the average stream concentration through a specified reach, and then increased to the bio-concentrated level in the fish, C_F . The relation between C_W , C_U , and C_F , is given by (forward calculation):

$$C_F = \zeta_D \zeta_{x,y} \zeta_F C_W + \zeta_{SU} \zeta_x \zeta_F C_U \quad (2.9.4)$$

For back calculation, the average concentration in the fish, C_F , can be equated to a specified reference intake bioaccumulation concentration, C'_{RFD} . Thus:

$$C_F = C'_{RFD} \quad (2.9.5)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_W = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_D \zeta_{x,y} \zeta_F} \quad (2.9.6)$$

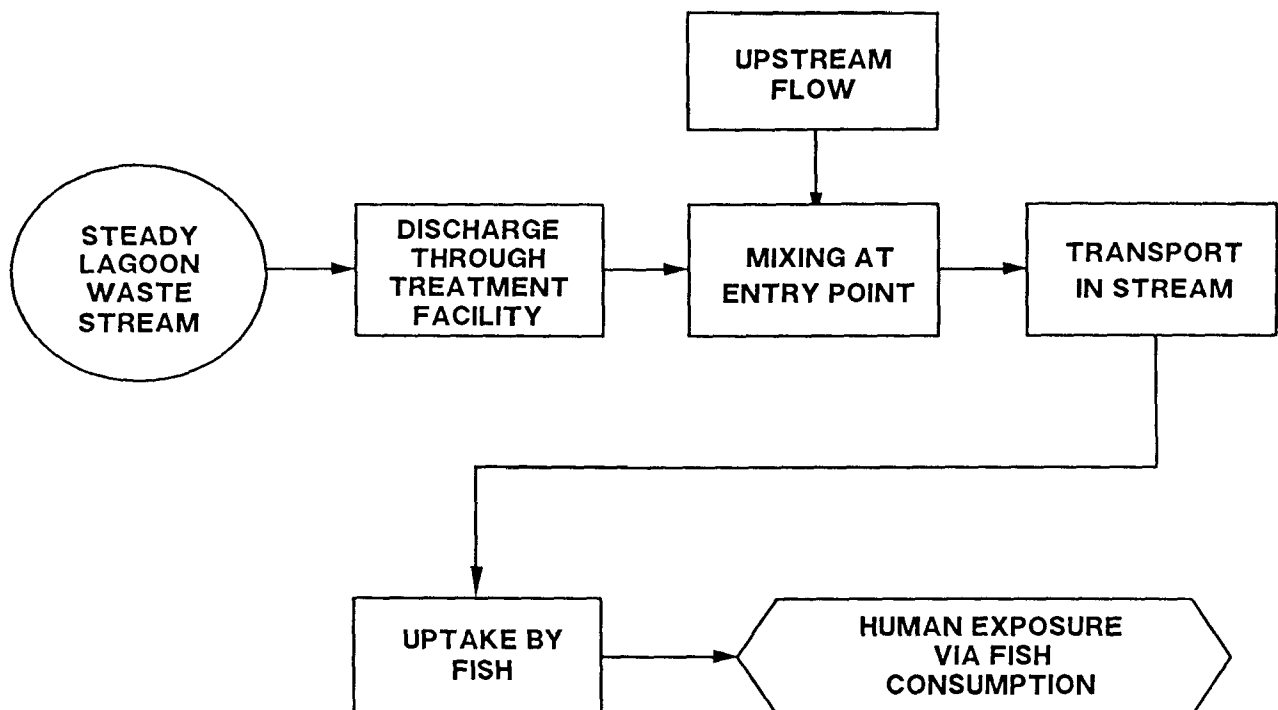


Figure 2.9.2 Flow chart for Scenario 9B

2.9C Scenario 9C: Exposure of Aquatic Life due to a Continuous Discharge-- from a Lagoon

This scenario consists of three stages between the industrial waste stream and aquatic exposure (Figure 2.9.3). Through these stages, the input concentration is successively reduced from the industrial waste concentration, C_W . $C_{x,y}$ is given by (forward calculation):

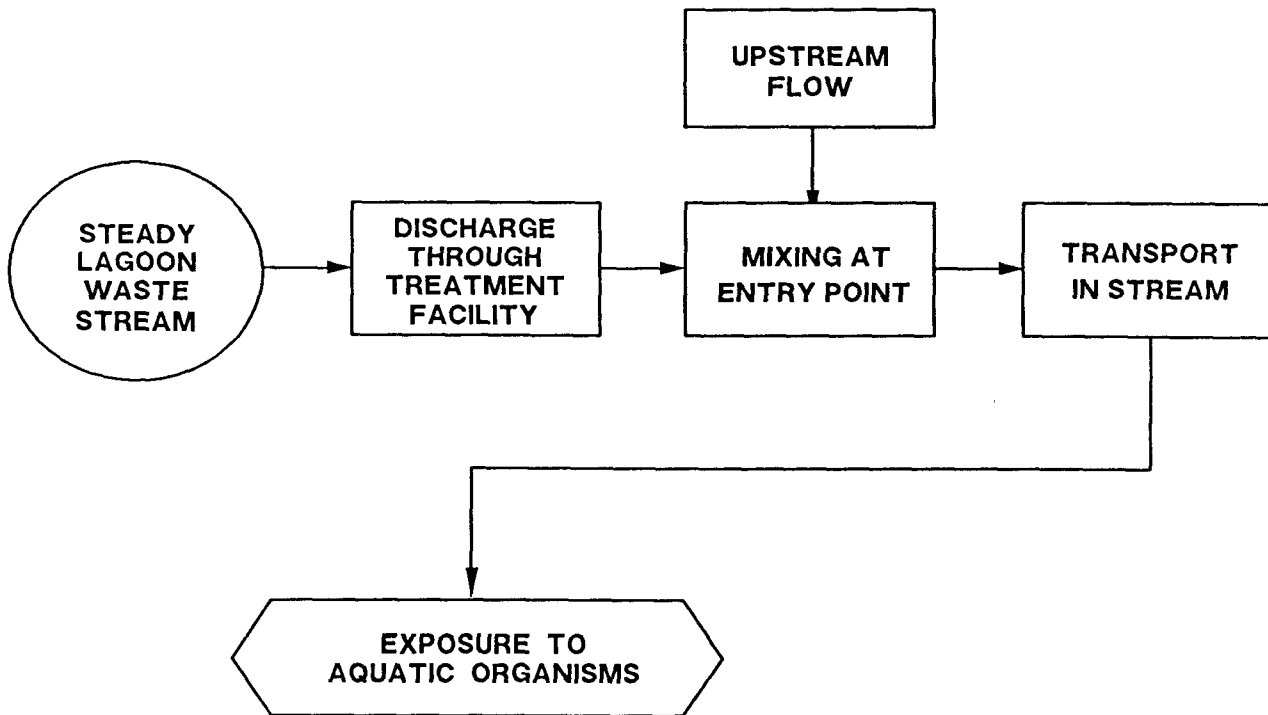


Figure 2.9.3 Flow chart for Scenario 9C

$$\bar{C}_{x,y} = \zeta_D \zeta_{x,y} \zeta_{EXP} C_W + \zeta_{SU} \zeta_x \zeta_{EXP} C_U \quad (2.9.7)$$

For back-calculation, the average concentration in the stream can be equated to the CCC by:

$$\bar{C}_{x,y} = CCC \quad (2.9.8)$$

and the maximum allowable discharge concentration is given by (backward calculation):

$$C_W = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\zeta_D \zeta_{x,y} \zeta_{EXP}} \quad (2.9.9)$$

A complete summary of all forward and backward calculations is given in Table 2.3.

TABLE 2.3 SUMMARY OF FORWARD AND BACKWARD CALCULATIONS

EFFECT A (Drinking Water)		
Scenario	Backwards	Forward
1 and 6	$C_L = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{DW}}$	$C_{x,y} = \frac{C_L \zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{DW}}{C_U \zeta_{SU} \zeta_x \zeta_{DW}}$
2 and 7	$C_R = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{DW} \rangle}$	$C_{x,y} = \frac{\langle C_R \zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{DW} \rangle}{C_U \zeta_{SU} \zeta_x \zeta_{DW}}$
3 and 8	$C_R = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,g} \zeta_{DW} \rangle}$	$C_{x,y} = \frac{\langle C_R \zeta_R \zeta_{x,y} \zeta_{DW} \rangle}{C_U \zeta_{SU} \zeta_x \zeta_{DW}}$
4 and 9	$\begin{matrix} C_W \\ \text{(or } C_L) \end{matrix} = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{DW} \rangle}$	$C_{x,y} = \frac{C_W \zeta_D \zeta_{x,y} \zeta_{DW}}{C_U \zeta_{SU} \zeta_x \zeta_{DW}}$
5	$C_R = \frac{C_{RFD} - \zeta_{SU} \zeta_x \zeta_{DW} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{DW} \rangle}$	$\langle C_{x,y} = \frac{C_R \zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{DW}}{C_U \zeta_{SU} \zeta_x \zeta_{DW}} \rangle$
EFFECT B (Fish Consumption)		
Scenario	Backward	Forward
1 and 6	$C_L = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_g \zeta_{sg} \zeta_{x,y} \zeta_F}$	$C_{x,y} = \frac{C_L \zeta_g \zeta_{sg} \zeta_{x,y} \zeta_F}{C_U \zeta_{SU} \zeta_x \zeta_F}$
2 and 7	Not modeled	
3 and 8	Not modeled	

TABLE 2.3 SUMMARY OF FORWARD AND BACKWARD CALCULATIONS (Continued)

EFFECT B (Cont.)		
Scenario	Backward	Forward
4 and 9	$C_w = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_D \zeta_{x,y} \zeta_F}$ (or C_L)	$C_{x,y} = \frac{C_w \zeta_D \zeta_{x,y} \zeta_F}{+ C_U \zeta_{SU} \zeta_x \zeta_F}$
5	$C_w = \frac{C'_{RFD} - \zeta_{SU} \zeta_x \zeta_F C_U}{\zeta_D \zeta_{sg} \zeta_{x,y} \zeta_F}$ (or C_L)	$C_{x,y} = \frac{C_w \zeta_D \zeta_{x,y} \zeta_F}{+ C_U \zeta_{SU} \zeta_x \zeta_F}$
EFFECT C (Aquatic Exposure)		
Scenario	Backward	Forward
1 and 6	$C_L = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{EXP}}$	$C_{x,y} = \frac{C_L \zeta_g \zeta_{sg} \zeta_{x,y} \zeta_{EXP}}{+ C_U \zeta_{SU} \zeta_x \zeta_{EXP}}$
2 and 7	$C_R = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle}$	$C_{x,y} = \frac{\langle C_R \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle}{+ C_U \zeta_{SU} \zeta_x \zeta_{EXP}}$
3 and 8	$C_R = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle}$	$C_{x,y} = \frac{\langle C_R \zeta_R \zeta_{x,y} \zeta_{EXP} \rangle}{+ C_U \zeta_{SU} \zeta_x \zeta_{EXP}}$
4 and 9	$C_R = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_D \zeta_{x,y} \zeta_{EXP} \rangle}$ (or C_L)	$C_{x,y} = \frac{\langle C_w \zeta_D \zeta_{x,y} \zeta_{EXP} \rangle}{+ C_U \zeta_{SU} \zeta_x \zeta_{EXP}}$
5	$C_w = \frac{CCC - \zeta_{SU} \zeta_x \zeta_{EXP} C_U}{\langle \zeta_D \zeta_{x,y} \zeta_{EXP} \rangle}$	$C_{x,y} = \frac{\langle C_w \zeta_D \zeta_{x,y} \zeta_{EXP} \rangle}{+ C_U \zeta_{SU} \zeta_x \zeta_{EXP}}$

2.10 Overview of the Analyses--

Scenario 1A: Exposure to humans through drinking water due to landfill leaching

- o Release from landfill facility to ground water
- o Transport in ground water to surface water body
- o Mixing with the stream
- o Transport in stream to drinking water intake
- o Treatment of drinking water

Scenario 1B: Exposure to humans through fish consumption due to landfill leaching

- o Release from landfill facility to ground water
- o Transport in ground water to surface water body
- o Mixing with the stream
- o Uptake by fish through gills, gut, and skin

Scenario 1C: Exposure to aquatic organisms due to landfill leaching

- o Release from landfill facility to ground water
- o Transport in ground water to surface water body
- o Mixing with the stream

Scenario 2A: Exposure to humans through drinking water due to steady runoff from a landfill

- o Surface runoff from landfill facility
- o Overland transport assuming no reduction in mass
- o Mixing with the stream
- o Transport in stream to drinking water intake
- o Treatment of drinking water

Scenario 2B: Exposure to humans through fish consumption due to steady runoff from a landfill facility

Not modeled.

- Scenario 2C: Exposure to aquatic organisms due to steady runoff from a landfill facility
- Not modeled.
- Scenario 3A: Exposure to humans through drinking water due to pulse runoff from a landfill facility
- o Surface runoff loading from landfill facility
 - o Overland transport assuming no reduction in mass
 - o Mixing with the stream
 - o Transport in the stream to drinking water intake
 - o Treatment of drinking water
- Scenario 3B: Exposure to humans through fish consumption due to pulse runoff from a landfill facility
- Not modeled.
- Scenario 3C: Exposure to aquatic organisms due to pulse runoff from a landfill facility
- Not modeled.
- Scenario 4A: Exposure to humans through drinking water due to a steady industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with the stream
 - o Transport in stream to drinking water intake
 - o Treatment of drinking water
- Scenario 4B: Exposure to humans through fish consumption due to a steady industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with stream
 - o Uptake by fish through gills, gut, and skin

- Scenario 4C: Exposure to aquatic organisms due to a steady industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with the stream
- Scenario 5A: Exposure to humans through drinking water due to a pulse industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with the stream
 - o Transport in stream to drinking water intake
 - o Treatment of drinking water
- Scenario 5B: Exposure to humans through fish consumption due to a pulse industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with stream
 - o Uptake by fish through gills, gut, and skin
- Scenario 5C: Exposure to aquatic organisms due to a pulse industrial waste discharge
- o Discharge to treatment facility
 - o Dilution and degradation in treatment facility
 - o Mixing with the stream
- Scenario 6A: Exposure to humans through drinking water due to lagoon leaching
- o Release from lagoon waste facility to ground water
 - o Transport in ground water to surface water body
 - o Mixing with the stream
 - o Transport in stream to drinking water intake

- o Treatment of drinking water
- Scenario 6B: Exposure to humans through fish consumption due to lagoon leaching
- o Release from lagoon waste facility to ground water
 - o Transport in ground water to surface water body
 - o Mixing with the stream
 - o Uptake by fish through gills, gut, and skin
- Scenario 6C: Exposure to aquatic organisms due to lagoon leaching
- o Release from landfill facility to ground water
 - o Transport in ground water to surface water body
 - o Mixing with the stream
- Scenario 7A: Exposure to humans through drinking water due to steady runoff from an overflowing lagoon
- o Overflow from lagoon waste facility
 - o Overland transport assuming no reduction in mass
 - o Mixing with the stream
 - o Transport in stream to drinking water intake
 - o Treatment of drinking water
- Scenario 7B: Exposure to humans through fish consumption due to steady runoff from an overflowing lagoon
- o Overflow from lagoon waste facility
 - o Overland transport assuming no reduction in mass
 - o Mixing with the stream
 - o Uptake by fish thorough gills, gut, and skin
- Scenario 7C: Exposure to aquatic organisms due to steady runoff from an overflowing lagoon
- o Overflow from lagoon waste facility
 - o Overland transport assuming no reduction in mass

- o Mixing with stream
- Scenario 8A: Exposure to humans through drinking water due to catastrophic lagoon dam failure
- o Surface runoff loading from failed lagoon facility
 - o Overland transport assuming no reduction in mass
 - o Mixing with the stream
 - o Transport in the stream to drinking water intake
 - o Treatment of drinking water
- Scenario 8B: Exposure to humans through fish consumption due to catastrophic lagoon dam failure
- o Pulse surface runoff loading from failed waste lagoon
 - o Overland transport assuming no reduction in mass
 - o Mixing with the stream
 - o Uptake by fish through gills, gut, and skin
- Scenario 8C: Exposure to aquatic organisms due to catastrophic lagoon dam failure
- o Pulse surface runoff event from failed waste lagoon
 - o Overland transport assuming no reduction in mass
 - o Mixing with stream
- Scenario 9A: Exposure to humans through drinking water due to a steady industrial waste lagoon discharge
- o Discharge to lagoon
 - o Dilution and degradation in lagoon
 - o Mixing with the stream
 - o Transport in stream to drinking water intake
 - o Treatment of drinking water
- Scenario 9B: Exposure to humans through fish consumption due to a steady lagoon discharge

- o Discharge to lagoon
- o Dilution and degradation in treatment facility
- o Mixing with stream
- o Uptake by fish through gills, gut, and skin

Scenario 9C: Exposure to aquatic organisms due to a steady lagoon discharge

- o Discharge to lagoon facility
- o Dilution and degradation in lagoon facility
- o Mixing with the stream

SECTION 3

DEVELOPMENT OF EQUATIONS

The fundamental principle underlying this model is conservation of mass. The equations solved by SARAH2 describe mass fluxes of chemicals in leachate, effluent, runoff, and stream. Often, however, stream standards and waste requirements are specified in terms of concentrations. For each step, mass flux equations are developed and then presented as a series of concentration reductions (or enhancements) between the waste release and the point of exposure, then the equations describing reduction factors are developed corresponding to the various contaminant pathways.

This section is organized into the three sub-sections: pathways, stream transport and effects. The equations describing the mass transport, dilution, and transformation processes are developed for each pathway and each stage. Next, equations will be developed for the mass transport, dilution and transformation processes in the stream. Finally, equations describing the effects will be developed.

Pathways leading to contamination of surface water and exposure to aquatic organisms and humans begin with the disposal of industrial wastes in wastewater treatment or land disposal facilities. Wastewater effluent or land disposal leachate can enter a stream through ground water transport, surface runoff, or direct discharge. Contaminants in stream are subject to advection, lateral mixing, longitudinal mixing, physical reactions, chemical reactions and biological reactions. Aquatic organisms are exposed directly to instream concentrations. Human exposure occurs through consumption of contaminated fish or drinking water that has been processed through water treatment plants located downstream of the discharge. These sequential pathways are explored in the following sections.

3.1 PATHWAYS

The pathways can be divided into three stages or zones, that may vary according to the source: (1) the leaching or transport zone, (2) the stream interception zone and (3) the instream mixing zone. Therefore, each pathway will be sub-divided into these three stages and equations describing the mass transport, dilution, and transformation processes will be developed for each appropriate source (landfill, industrial treatment plant, and lagoon).

3.1.1 Ground Water Pathway

Contaminant leaching and transport in ground water system--The release and transport of hazardous constituents from a landfill or lagoon through the ground water pathway of the model assumes that the disposal unit, is hydraulically connected to a stream (Figure 3.1.1). When liners or leachate collectors at the base of the land disposal unit or lagoon fail, leachate enters the aquifer directly below the land disposal unit. Precipitation of metals is assumed to occur at this point, placing upper limits on their dissolved concentrations. Dissolved chemicals are then transported through the aquifer under the combined influences of 1) advection and hydrodynamic dispersion as well as 2) sorption and biochemical degradation for nonconservative species. The contaminants discharge into the surface water through the zone where the aquifer and the stream intercept.

Landfill

The mass flux at the ground water interception zone or surface water entry area, \dot{m}_g , and the mass flux of leachate, \dot{m}_{wg} may be related by (refer to Figure 3.1.1):

$$\dot{m}_g = \zeta_{Hg} \cdot \dot{m}_{wg} \quad (3.1.1)$$

where the mass flux units are expressed in grams per second, and ζ_{Hg} is a ground water attenuation factor accounting for the effects of hydrolysis in the aquifer. The average concentration at the ground water interception zone and in the leachate may be obtained by dividing the mass fluxes by the flow rates:

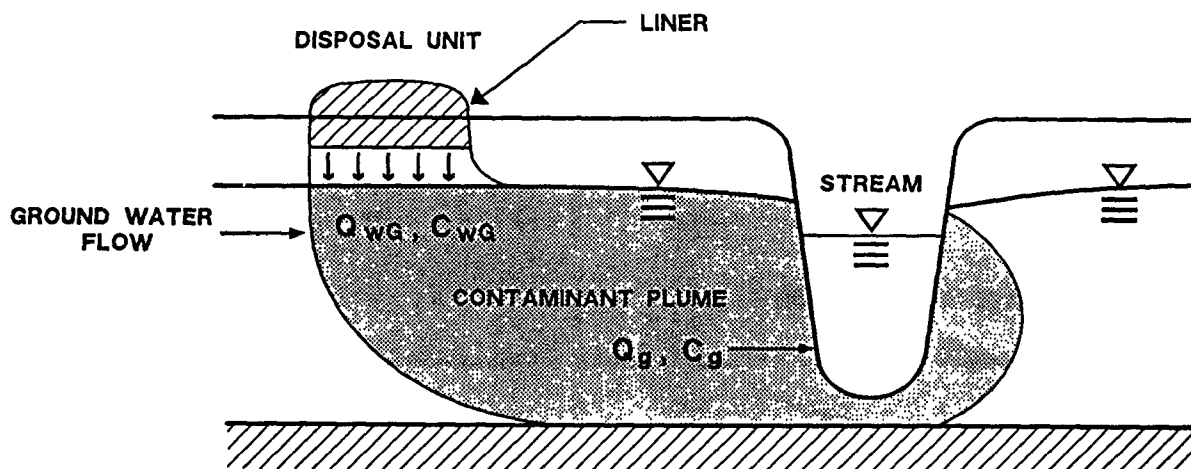


Figure 3.1.1 Variation of Dilution Factor with Stream Flow for Steady Groundwater Loading

$$\bar{C}_g = \dot{m}_g / Q_g \quad (3.1.2)$$

$$C_{wg} = \dot{m}_{wg} / Q_{wg} \quad (3.1.3)$$

where flow units are expressed in cubic meters per second, concentration units are expressed in milligrams per liter, and subscripts g and wg refer to ground water/stream interception zone, and waste site/ground water origination zone, respectively. Combining the above equations, the average concentration at the ground water interception zone and the leachate concentration may be related by:

$$\bar{C}_g = \zeta_g \cdot C_{wg} \quad (3.1.4)$$

where ζ_g is the ground water reduction (due to hydrolysis and dilution) factor:

$$\zeta_g = \zeta_{Hg} \cdot Q_{wg} / Q_g \quad (3.1.5)$$

Q_{wg} is the average volumetric rate of percolation through the land disposal site, in cubic meters per second, and may be estimated by:

$$Q_{wg} = \frac{\bar{P} \cdot (1-f_{Rw}) \cdot A_w}{100 \cdot 86400 \cdot (365.25)} \quad (3.1.6)$$

where \bar{P} is the average annual precipitation rate, in cm/year, $(1-f_{Rw})$ is the fraction of precipitation that leached through the waste site to ground water, and A_w is the surface area providing water that leaches through the disposal facility, in square meters. If the sides of the disposal facility remain properly lined, and failure occurs through the bottom only, then A_w will be equal to the actual surface area of the disposal facility.

Lagoon

The only difference between the lagoon and the landfill source is the rate of permeation or percolation. Therefore, all equations are the same subsequent to the leaching zone. The leachate mass flux equation is:

$$\dot{m}_g = \zeta_{Hg} \cdot \dot{m}_{wl} \quad (3.1.7)$$

where the \dot{m}_{wl} is the leachate mass flux rate. The average concentration at the ground water interception zone and in the leachate can be obtained by dividing the mass fluxes by the flow rates:

$$\bar{C}_g = \dot{m}_g / Q_g \quad (3.1.8)$$

$$C_{wl} = \dot{m}_{wl} / Q_{wl} \quad (3.1.9)$$

where subscripts g and wl refer to ground water/stream interception zone, and lagoon/groundwater origination zone, respectively. Combining the above equations, the average concentration at the ground water interception zone and the leachate concentration may be related by:

$$\bar{C}_g = \zeta_g \cdot C_{wl} \quad (3.1.10)$$

where ζ_g is the ground water reduction factor:

$$\zeta_g = \zeta_{Hg} \cdot Q_{wl} / Q_g \quad (3.1.11)$$

Q_{wl} is the average volumetric rate of percolation through the surface impoundment, in cubic meters per second, which depends on whether the lagoon is lined or unlined. Precipitation has a minimal influence on leachate generation, as liquid waste will percolate to the watertable under the influence of gravity. The rate-determining step is the permeability of the liner or underlying soil (if there is no liner). Under the assumptions that a clay liner is fully saturated and that the underlying soil remains unsaturated and accepts all water which flows through the liner, the steady-state value of the volumetric flux (seepage) rate, Q_{wl} , can be estimated by (Marin 1988):

$$Q_{wl} = \frac{\left(\frac{0.1 \text{ m}}{\text{cm}} \right) \left(\frac{2.8 \times 10^{-4} \text{ hr}}{\text{sec}} \right) \left(K_s \right) \left(A_{1a} \right) \left(\frac{2.54 \times 10^{-5} \text{ mil} (D_{1i}) + H_{1a}}{\text{m}} \right)}{\left(\frac{2.54 \times 10^{-5} \text{ mil}}{\text{m}} \right) (D_{1i})} \quad (3.1.12)$$

where:

Q_{wl} = volume loading rate (m^3/sec)

K_s = Darcy's coefficient, for unlined lagoons use native soil hydraulic conductivity, Table 3.1.1 (cm/hr)

A_{1a} = area of lagoon (m^2)

H_{1a} = depth of liquid in lagoon (m)

D_{1i} = liner thickness (mils)

Equation 3.1.12 models the release rate from a lagoon whether the flow through the vadose zone is saturated or unsaturated. For unlined active lagoons, the flow is typically saturated all the way to the watertable. For clay-lined lagoons, the flow is saturated through the liner and unsaturated between the liner and the watertable (assuming no breaches in the liner). Equation 3.1.12 is appropriate when analyzing lagoon releases, but should not be used for spills or other conditions where the chemicals on the surface do not pond for a long time. In

these conditions, the assumption of saturated flow (through the liner or soil) may be violated.

Equation 3.1.12 applies to liquids that are mostly water. For lagoons that contain organic fluids, however, the equations may need to be corrected. For liquids having a density or viscosity that differs from water, K_s is corrected for this different viscosity and density by calculating the term K_c , using:

$$K_c = K_{gw} \cdot D_c/D_w \cdot U_w/U_c \quad (3.1.13)$$

where:

- K_c = corrected K_s term = hydraulic conductivity of contaminant, (cm/hr).
- K_{gw} = hydraulic conductivity of groundwater, Table 3.1.1 (cm/hr).
- D = density of liquids: c = contaminant, w = water, (kg/m^3).
- U = dynamic viscosity of liquids: c = contaminant, w = water. ($\text{kg}/\text{m}\cdot\text{sec.}$)

and then substituting K_c for K_s in Equation 3.1.12.

The release rate from an intact lined landfill or lagoon can be calculated for a small group of contaminants. Failed liners can be modeled as a function of the extent of the failure using the modeling equations for clay or natural soil-lined facilities. Although a flexible membrane (FML) liner appears to allow no migration through the barrier, it may indeed be penetrated by organic compounds and contaminated water, although the rate of permeation is understandably small. The rate at which a contaminant permeates through a polymeric material has been shown to be dependent upon various properties of the permeant, such as size, shape, polarity, and other factors (Steingiser et al. 1978).

Salame and others proposed the use of a permeability equation to predict the rate of permeation of liquids and gases through various polymers (Salame 1961, 1973, 1985; Steingiser et al. 1978)

$$P_s = A_p \cdot e^{(-S\phi)} \quad (3.1.14)$$

where

- P_s = permeation rate, $\frac{\text{g} \cdot \text{mil}}{100 \text{ in}^2 \text{ day cmHg}}$
- A_p = constant solely dependent on the type of polymers used, $\frac{\text{g} \cdot \text{mil}}{100 \text{ in}^2 \text{ day cmHg}}$
- S = constant solely dependent on the type of polymers used, (cc/cal).
- ϕ = the polymer "permachor" calculated for each polymer permeant pair, (cal/cc).

Salame lists values for these parameters obtained from his extensive experimental work. These values are shown in Tables 3.1.2, 3.1.3, and 3.1.4.

For permeation of water through FMLs, polymers are categorized into five groups based on the values of the solubility parameter as shown in Table 3.1.1. This grouping was achieved after examining experimental data for about 70 different polymers (Salame 1985). The solubility parameter provides an indication of polymer interaction with water, with more interaction occurring at higher values of the solubility parameter. Examples of hydrogen bonding for polymer group 5 include hydroxyl (OH) and amid (NHCO) radicals as found in nylon and polyvinyl alcohol. The polymer with hydrogen bonding (but with the value of "delta" less than 11) does not belong to group 5. Permachor values for some selected organic liquids and for water are shown in Tables 3.1.3 and 3.1.4, respectively. The water "permachor" values for various polymers given in Table 3.1.4 apply under dry conditions. For water permeation under wet conditions, permachor values may be reduced by about 20 percent.

The term P_s can be used to calculate the release rate in cubic meters per second. P_s is multiplied by the area of the liner, and then divided by its thickness and the contaminant density. This assumes a normal water vapor pressure of 1 cm Hg at ambient temperature. The general equation is:

$$Q_{wl} = (P_s \cdot A_{li} \cdot V_p \cdot 1.79 \times 10^{-5}) / (D_{li} \cdot D_c) \quad (3.1.15)$$

where:

Q_{wl} = contaminant loading rate, (m^3/sec).
 P_s = permeation rate, (g-mil/100 in² day cmHg).
 A_{li} = area of liner, (m^2).
 V_p = vapor pressure of the compound, (cmHg).
 D_{li} = thickness of the liner, (milg).
 D_c = density of contaminant (kg/m^3).

Leachate Loading and Dilution upon Entry into the Stream

The contaminant mass flux loaded into the stream from ground water, m_{sg} , and the mass flux at the ground water interception zone, m_g , can be related by (See Figure 3.1.4):

$$m_{sg} = \zeta_i \cdot m_g \quad (3.1.16)$$

where ζ_i is the fraction of ground water from the catchment that actually contributes to stream flow. The total mass flux, m_0 , at the downstream edge of the mixing zone is the sum of the upstream mass flux, m_U , and the mass flux loaded into the stream, m_{sg} :

$$m_0 = m_{sg} + m_U \quad (3.1.17)$$

The concentration can be obtained by dividing the mass fluxes by the stream flow:

$$\bar{C}_0 = \zeta_{sg} \cdot \bar{C}_g + \zeta_{su} \cdot C_U \quad (3.1.18)$$

where \bar{C}_0 is the laterally averaged concentration at the downstream edge of the mixing zone, and ζ_{sg} and ζ_{su} are dilution factors for ground water and upstream concentrations, respectively:

TABLE 3.1.1 Descriptive Statistics for Hydraulic (K_{gw}) Conductivity (cm/hr) (Carsel, 1988)

Soil Type	Conductivity (K_{gw})			
	\bar{x}	s	CV	n
Clay ⁺	0.20	0.42	210.3	114
Clay Loam	0.26	0.79	267.2	345
Loam	1.04	1.82	174.6	735
Loamy Sand	14.59	11.36	77.9	315
Silt	0.25	0.33	129.9	88
Silt Loam	0.45	1.23	275.1	1093
Silty Clay	0.02	0.11	453.3	126
Silty Clay Loam	0.07	0.19	288.7	592
Sand	29.70	15.60	52.4	246
Sandy Clay	0.12	0.28	234.1	46
Sandy Clay Loam	1.31	2.74	208.6	214
Sandy Loam	4.42	5.63	127.0	1183

*n = Sample size, \bar{x} = Mean, s = Standard deviation CV = Coefficient of variation (percent)

⁺Agricultural soil, less than 60 percent clay

$$\zeta_{sg} = Q_{sg}/Q_s \quad (3.1.19)$$

$$\zeta_{su} = Q_U/Q_s \quad (3.1.20)$$

where Q_U is the upstream flow rate and Q_{sg} is the ground water flow from the catchment intercepted by the stream:

$$Q_{sg} = \zeta_i \cdot Q_g \quad (3.1.21)$$

and Q_s is the downstream flow rate, or the sum of Q_{sg} and Q_U .

Contaminants reaching a stream via ground water will assured to enter the water body continuously, i.e. at a steady state, and uniformly along the sides and bottom of the stream. This assumes that the ground water flow field is not influenced by the adjacent surface water (Figure 3.1.2). Therefore, for the ground water pathway, the average edge-of-stream concentration can be calculated from the leachate concentration via a ground water equation that considers advection, retardation, and chemical hydrolysis and ignores dispersion.

For this analysis, it is not necessary to calculate a full three-dimensional concentration distribution for the ground water. In fact, only the average ground water concentration across the plume is needed to the point of its interception with the stream. The average ground water attenuation factor, which is used in equation 3.1.1, can be calculated using a one-dimensional mass balance. This mass balance is equivalent to using a three-dimensional ground water equation, then averaging over the width and depth of the plume.

TABLE 3.1.2 Parameter values for Permeation Equation (at 25°C)

Parameter	<u>Liquid Organics in^a</u>		<u>Water in polymer category^b</u>				
	PE	PVC	1	2	3	4	5
A $\left[\frac{\text{g} \cdot \text{mil}}{100 \text{ in}^2 \text{ day cmHg}} \right]$	1x10 ⁴	1x10 ⁴	11.5	10.2	5.4x10 ²	25	(c)
S (cc/cal)	0.506	0.23	0.16	0.135	0.115	0.035	0.099
ϕ (cal/cc)	Table 3.1.3		Table 3.1.4				

a Source: Salame no date; Salame 1967.

b See Table 2-8 regarding polymer category. Source: Salame 1985.

c $A=0.33(0.056 \times \delta^2)$, where δ is the solubility parameter, (cal/cc)^{1/2}.

TABLE 3.1.3 Permachor Values of Some Organic Liquids in Polyethylene and PVC^a

Liquid	<u>In nonpolar polymer</u>	<u>In polar polymer</u>
	ϕ	ϕ
Acetic acid	13.0	44.0
Benzaldehyde	15.0	4.0
Benzene	5.4	7.0
2-Butoxy ethanol	24.4	75.0
Butyl acetate	13.0	5.0
Butyl alcohol	18.0	50.0
Butyl ether	10.4	46.0
Butyraldehyde	13.5	0.0
Caprylic acid	19.0	50.0
Carbon tetrachloride	5.8	22.0
p-Chlorotoluene	7.6	7.5
Cyclohexane	7.0	45.0
Dibutylphthalate	31.4	17.0
Diethylamine	10.0	5.7
Ethanol	16.0	48.0
Heptane	7.0	44.0
Mexane	6.0	43.0
Methyl ethyl ketone	12.5	1.0
Methanol	15.0	47.0
Nitroethane	15.4	7.0
1- Pentyl propanate	15.0	7.0
1-Propylamine	11.0	6.7
Trichloroethylene	5.4	3.0

TABLE 3.1.3 Permachor Values of Some Organic Liquids in Polyethylene and PVC^a (Continued)

Liquid	<u>In nonpolar polymer</u> ϕ	<u>In polar polymer</u> ϕ
o-Xylene	9.4	11.0
p-Xylene	7.4	9.0

^aPolyethylene and PVC are nonpolar and polar polymers, respectively
Sources: Salame, no date; Salame and Steingiser 1977.

TABLE 3.1.4 Water Permachor Value for Dry Polymers

Polymer	Permachor value (ϕ)
Polyvinyl alcohol	160
Polyacrylonitrile	109
Cellulose	97
Polyvinylidene chloride	87
Polycaprolactam (dry)	80
Polyacrylonitrile styrene (70/30) (Lopac)	76
Polyacrylonitrile styrene/butadiene (70/23/7) (Cycopac 930)	75
Polychlorotrifluoroethylene	71
Polyethylene terephthalate	68
Polyvinylidene fluoride (Nynar)	67
Polyacrylonitrile styrene= α /butadiene (56.27/4/13) (Cycopac 920)	65

TABLE 3.1.4 Water Permachor Value for Dry Polymers (Continued)

Polymer	Permachor value (ϕ)
Polyvinyl chloride	62
Polyoxymethylene (Delrin)	57
Polymethyl methacrylate	55
Polyvinyl acetate (dry)	45
Polystyrene/acrylonitrile (74/26)	45
Polyethylene (HD)	40
Polysulfone	34
Polypropylene	33
Polycarbonate (Lexan ³)	33
Polystyrene	28
Polyethylene (LD)	26
Polyisobutylene	17
Polyethylene/vinyl acetate (85/15)	15
Polybutadiene	8
Polymethyl pentene (TPX)	8
Polydimethyl siloxane (dry)	-4

Sources: Salame 1967; Salame no date; Salame and Steingiser 1977.

As contaminated water from the aquifer system enters the stream along the side and bottom, it mixes with surface water supplied by the upland watershed (Figure 3.1.3). Lateral mixing spreads the contaminants until lateral concentration gradients disappear. The laterally averaged concentration, C_x , increases with increasing distance reaching a maximum near the downstream edge of the contaminated ground water plume, where $x = 0$. At the section where $x = 0$, C_x corresponds to C_0 and can be calculated by a simple mass balance.

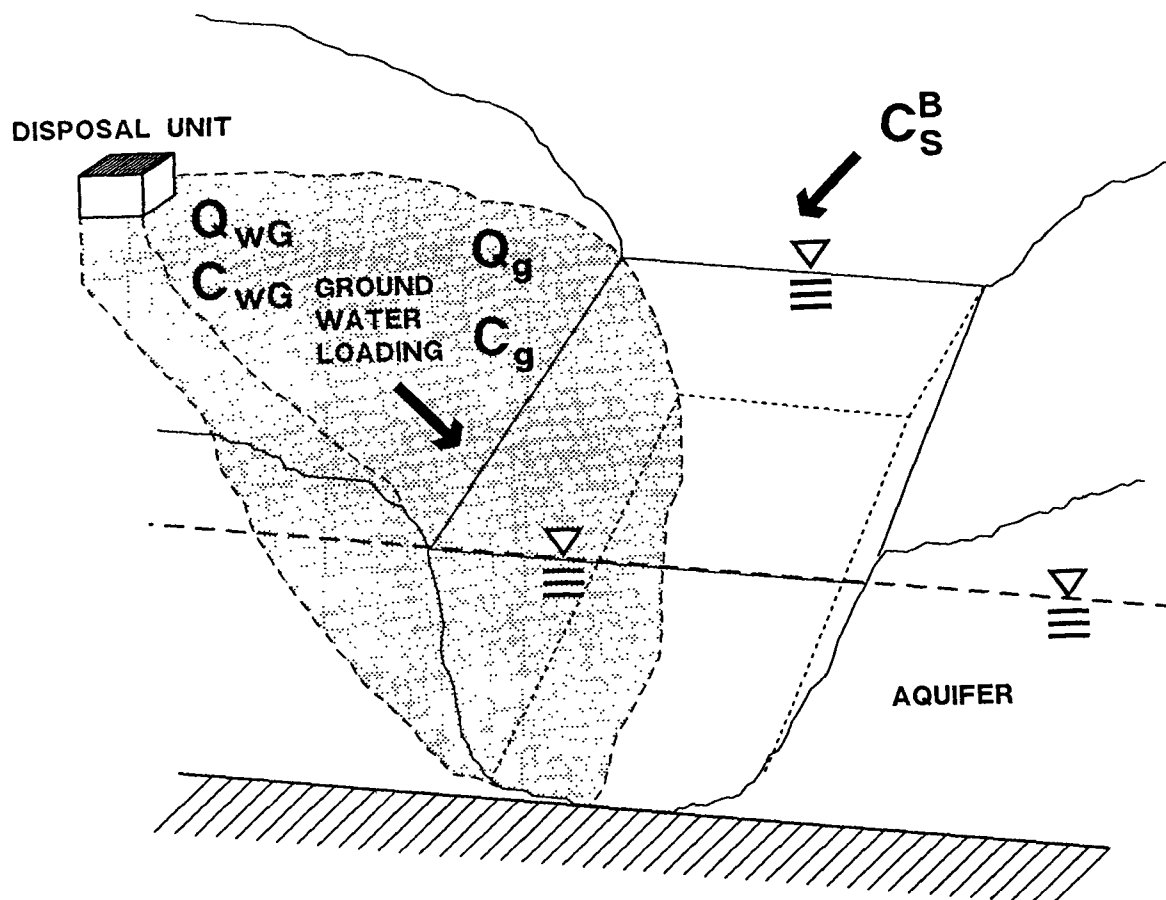


Figure 3.1.2 Ground water Stream Interception

The equations previously developed relate contaminant concentrations in the leachate with concentrations in ground water, and these with concentrations in stream. Combining equations 3.1.18 and 3.1.21 gives:

$$\bar{C}_O = \zeta_{Hg} \cdot \zeta_i \cdot \frac{Q_{wg}}{Q_s} \cdot C_{wg} + \frac{Q_U}{Q_s} \cdot C_U \quad (3.1.22)$$

where:

- C_{wg} = leachate concentration (mg/l)
- Q_{wg} = leachate flow rate (m^3/sec)
- ζ_{Hg} = ground water attenuation factor accounting for the effects of hydrolysis in the aquifer (unitless)
- ζ_i = fraction of ground water flow from the contaminated catchment that is intercepted by the stream (unitless)
- C_U = upstream concentration (mg/l)

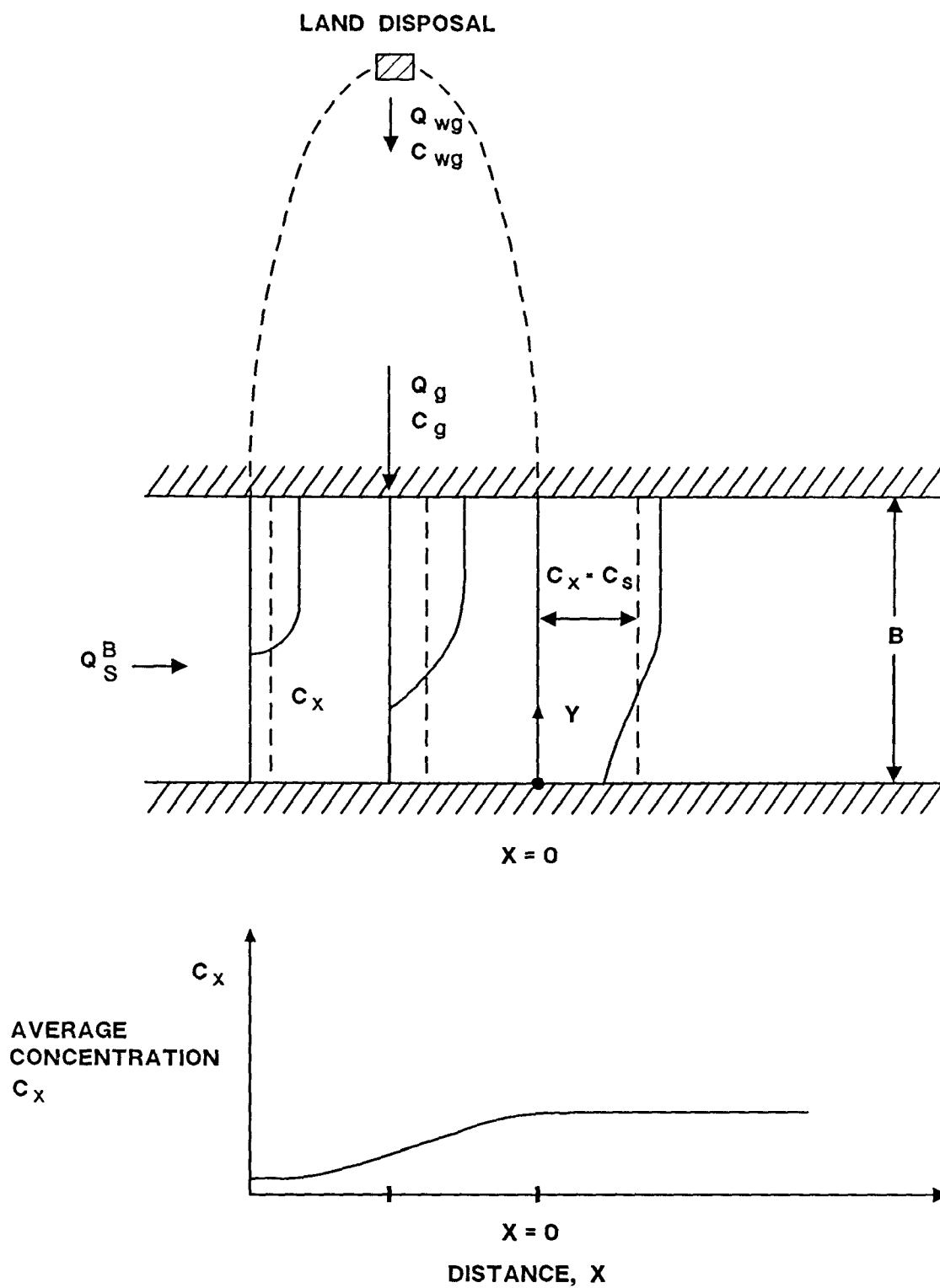


Figure 3.1.3 Ground water loading to the stream showing mass balance and concentration profiles

Q_U = upstream flow (m^3/sec)
 Q_S = total stream flow below the interception point (m^3/sec)

These items are discussed below.

ζ_{Hg} --This attenuation factor is the fraction of the contaminant mass not transformed by hydrolysis during ground water transport to the stream. Assuming a homogenous aquifer, this factor can be calculated by:

$$\zeta_{Hg} = \exp (-K_g \cdot \tau_g) \quad (3.1.23)$$

where K_g is the total effective decay constant in ground water, in $years^{-1}$, and τ_g is the time taken by the contaminant to travel from the land disposal site to the stream entry point, in years. For those chemicals that hydrolyze, K_g is equal to the overall hydrolysis rate constant given by equation A27 and A29 in Appendix A. The travel time of contaminants in ground water is given by:

$$\tau_g = \frac{X_g}{V_g \cdot f_{Dg}} \quad (3.1.24)$$

where X_g is the distance from the site to the stream, in meters, V_g is the ground water seepage velocity, in meters per year, and f_{Dg} is the fraction of the compound that is dissolved in the aquifer, given by equation A20 in Appendix A.

ζ_i --This attenuation factor is the fraction of the ground water flow from the contaminated catchment that is intercepted by the stream. This may vary depending on location in the watershed and time of year. If this factor is unknown for a given site, a conservative analysis is suggested in which ζ_i is set to 1.

Q_s --This is the average stream flow at the downstream edge of the contaminated plume, in cubic meters per second, and may be estimated by:

$$Q_s = \frac{\bar{P} \cdot (1-f_{Rs}) \cdot \bar{\zeta}_i \cdot A_s}{100 \cdot 86400 \cdot (365.25)} \quad (3.1.25)$$

where:

\bar{P} = average annual precipitation rate (cm/year)
 $(1-f_{Rs})$ = fraction of precipitation that leaches through the upper watershed to ground water (unitless)
 $\bar{\zeta}_i$ = average fraction of ground water flow contributing to stream flow in the upper watershed (unitless)
 A_s = surface area of the upper watershed (hydraulically including the contaminated catchment and above) (m^2)

If the average stream flow per unit area, q_s , is known, then Q_s can be approximated by:

$$Q_s = q_s \cdot A_s \quad (3.1.26)$$

where q_s is in units of cubic meters per second per square meter.

Q_U --This is the average stream flow at the upstream edge of the contaminated plume, in cubic meters per second. It may be estimated by:

$$Q_U = Q_s \cdot \frac{A_s - A_c}{A_s} \quad \text{or} \quad Q_U = q_s (A_s - A_c) \quad (3.1.27)$$

where A_c is the surface area of the contaminated catchment, diluting the leachate. If A_c is unknown, it may be conservatively estimated as the surface area leaching through the land disposal unit, A_w , plus the minimum surface area between the facility and the stream.

$$A_c = A_w + X_g \cdot \sqrt{A_w} \quad (3.1.28)$$

Substituting equations 3.1.23, 3.1.6, and 3.1.25 into 3.1.22 and, assuming no upstream contamination, gives the stream concentration resulting from leachate only:

$$\bar{C}_0 = \exp(-K_g \tau_g) \cdot \frac{A_w}{A_s} \cdot \frac{(1-f_{Rw})}{(1-f_{Rs})} \cdot \frac{\zeta_i}{\zeta_i} \cdot C_{wg} \quad (3.1.29)$$

Because clay liners should exhibit lower hydraulic conductivity than natural watersheds, the ratio $(1-f_{Rw})/(1-f_{Rs})$ should be less than 1.0. The ratio ζ_i/ζ_i could be less than or greater than 1.0, depending on the location of the land disposal site. A conservative analysis could be run assuming equal hydraulic conductivities and the fraction of the contaminated plume intercepted = 1:

$$\bar{C}_0 = \exp(-K_g \tau_g) \cdot \frac{A_w}{\zeta_i \cdot A_s} \cdot C_{wg} \quad (3.1.30)$$

3.1.2 SURFACE RUNOFF PATHWAY

Contaminant Concentration and Runoff Transport

Landfills--All RCRA Subtitle C land disposal units (landfills, land treatment facilities, waste piles, and surface impoundments) must be designed such that, at a minimum, runoff from a once-in-25-years, 24-hour storm event is contained (40 CFR Parts 264 and 265). Precipitation events of greater magnitude than the 25-year, 24-hour storm event are assumed to occur at a sufficiently low probability that the protective

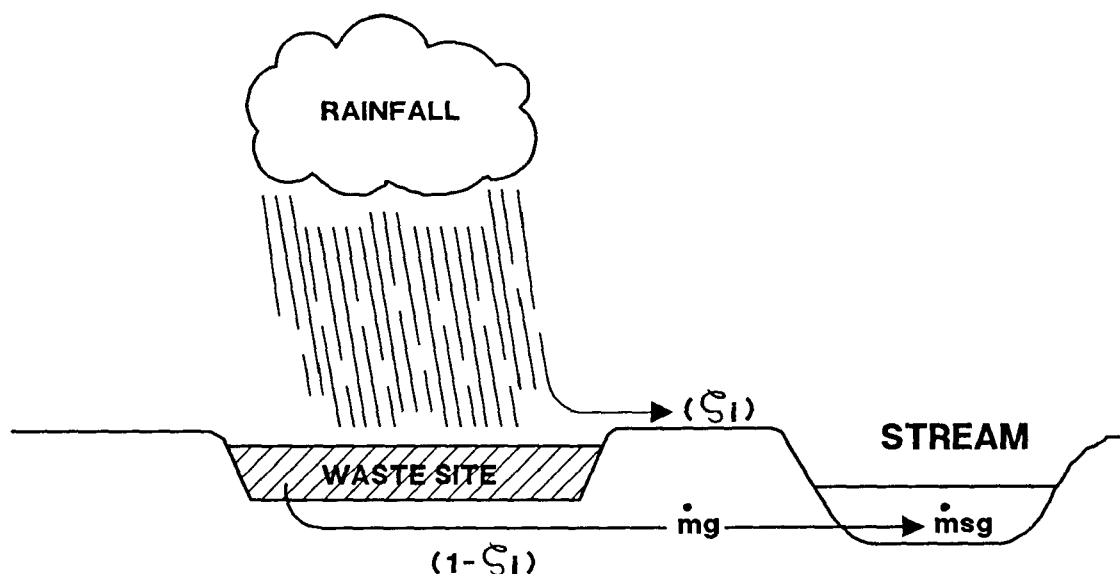


Figure 3.1.4 Ground water/Stream Interception Zone

design can be considered to provide an acceptable level of performance. Other land disposal systems (RCRA Subtitle D) may be designed to contain lesser storm events. "Failure" of a land disposal system, illustrated in Figure 3.1.5, refers to its inability to contain a storm event. Direct surface runoff of leachate plus solids from surface impoundments is assumed to occur from the "failed" containment unit over a time period t_R .

The concentration in the runoff leaving the containment facility is assumed to be equal to the leachate concentration, C_L . This assumption is somewhat conservative: for the case involving surface impoundments, the runoff concentration may be slightly reduced due to dilution from precipitation water that fills the freeboard depth; for the case of landfills and waste piles, not all the precipitation will have contact with the waste and hence, will be at a lower concentration.

Two types of surface runoff loads are considered. The first assumes containment failure that allows leachate from storm runoff to steadily enter a stream throughout the duration of the 24-hour storm. The second assumes sudden containment failure that allows leachate (generated during an entire storm event) to enter the stream as a pulse at the end of the storm. The time over which the steady loading occurs is assumed to be equal to 24-hours (the duration of the storm). The duration of the pulse loading is assumed to be between 10^3 and 10^4 seconds (approximately 15 minutes to 3 hours).

Because runoff leaving the containment facility is assumed to be at the leachate concentration, C_{wR} the runoff mass flux, \dot{m}_{wR} is equal to:

$$\dot{m}_{WR} = C_{WR} \cdot Q_{WR} \quad (3.1.31)$$

where Q_{WR} is the runoff flow rate, in cubic meters per second. The mass flux in runoff entering the stream is assumed equal to that running off the facility, because the short travel times should not allow transformation reactions to significantly occur. Concentrations in the runoff leaving the land disposal facility and entering the stream can be obtained by dividing the mass fluxes by the respective flow rates:

$$C_{WR} = \dot{m}_{WR}/Q_{WR} \quad (3.1.32)$$

$$C_R = \dot{m}_{WR}/Q_R \quad (3.1.33)$$

where Q_R is the runoff flow to the stream from the catchment containing the land disposal facility, in cubic meters per second. Combining the above equations, the average concentration in runoff entering the stream and the leachate concentration may be related by:

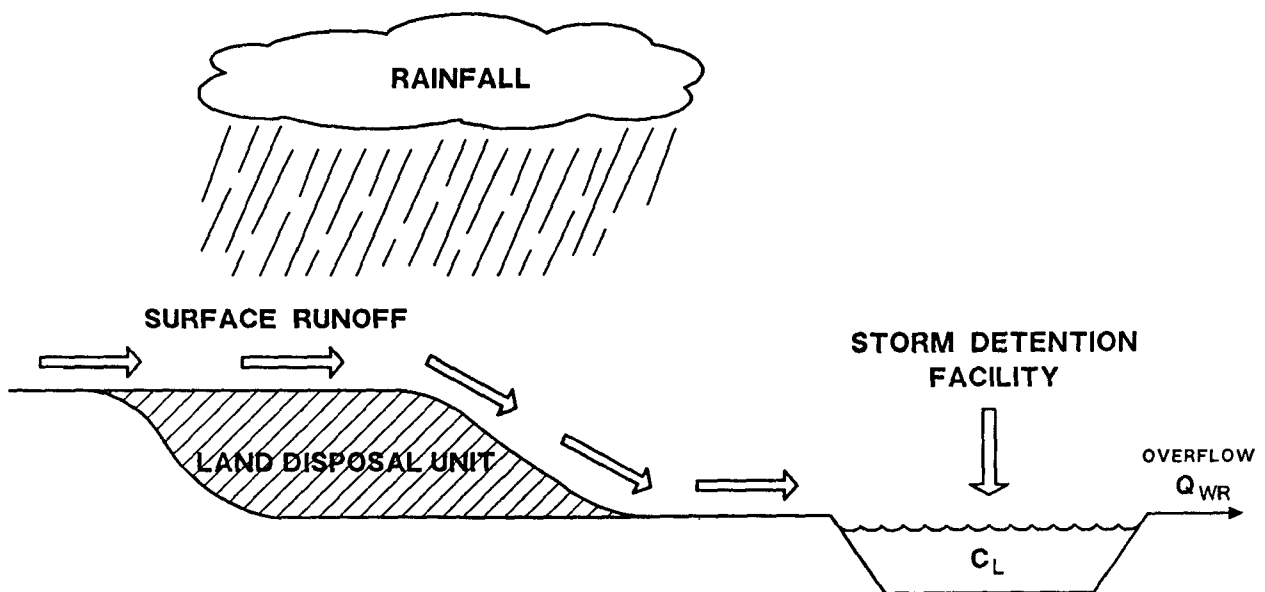


Figure 3.1.5 Surface Runoff from Land Disposal Units

$$C_R = \zeta_R \cdot C_{WR} \quad (3.1.34)$$

where ζ_R is the runoff dilution factor:

$$\zeta_R = Q_{WR}/Q_R \quad (3.1.35)$$

A conservative analysis could assume that the leachate runoff is not mixed with and diluted by runoff from upland areas of the catchment containing the land disposal facility. The runoff mass loading is not affected by this assumption, and stream concentrations below the initial mixing zone should not be very sensitive to this assumption.

Q_R --The leachate flow running off the facility, (in cubic meters per second) may be evaluated from:

$$Q_R = \frac{P_{25} \cdot f_R \cdot A_w}{100 \cdot t_R} \quad (3.1.36)$$

where :

- P_{25} = is the precipitation for the 25-year recurrence, 24-hour duration storm (cm)
- T_R = is the time over which contaminant runoff occurs (sec)
- f_R = is the fraction of the precipitation that runs off the waste site (unitless)
- A_w = is the surface area providing water that leaches through the disposal facility (m^2)

For scenario 2, steady runoff is assumed to occur throughout the storm, and T_R is 86400 seconds (one day). For scenario 3, runoff is assumed to occur over a short period of time following the storm, and t_R is 10^3 to 10^4 seconds.

Lagoon

There are two instances in which surface runoff loading from a lagoon may occur and subsequently contaminate adjacent surface water. Referring to Figure 3.1.6, in the first situation the original depth plus the storm precipitation exceed the free board depth and the lagoon is overloaded. Therefore, the new depth can be calculated by the following equation:

$$D_{new} = D_{old} + P_{25}/100 \quad (3.1.37)$$

where:

- D_{new} = new depth (m)
- D_{old} = old depth before storm (m)
- P_{25} = amount of rainfall (cm)

The volume of runoff to be expected can be calculated by:

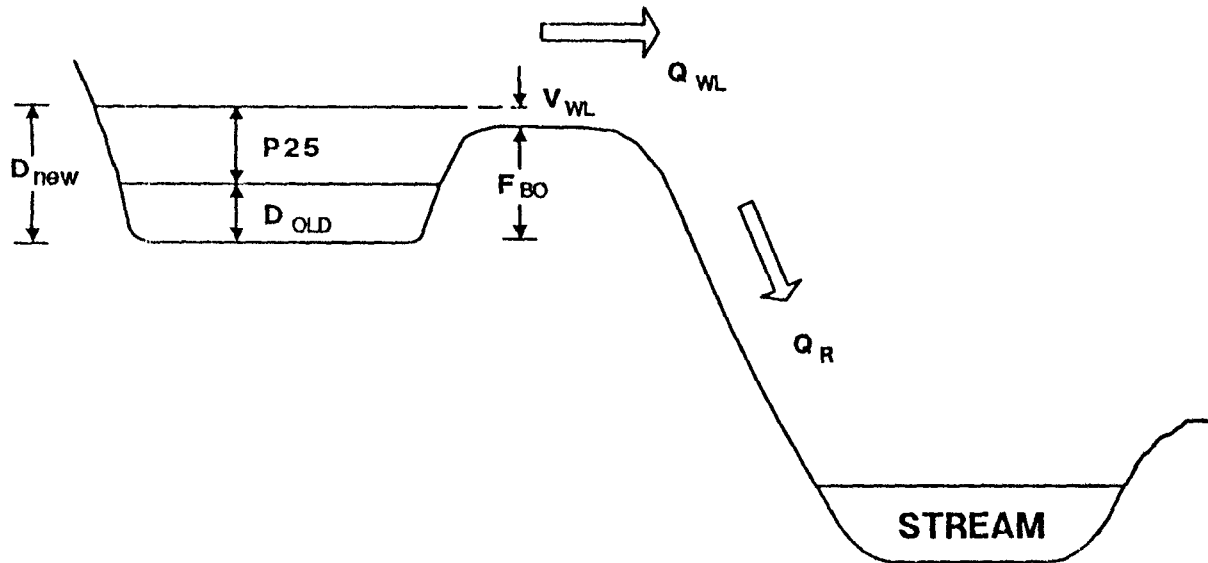


Figure 3.1.6 Lagoon Runoff

$$V_{wl} = (D_{new} - FBD) \cdot A_{la} \quad (3.1.38)$$

where:

V_{wl} = overflow runoff volume (m^3)
 FBD = free board depth (m)
 A_{la} = lagoon surface area (m^2)

The total time runoff occurs, T_R , can be calculated from the following ratio:

$$\frac{T_R}{T_{storm}} = \frac{(D_{old} + (0.01) P_{25} - FBD)}{(0.01) P_{25}} \quad (3.1.39)$$

which gives:

$$T_R = \frac{T_{storm} \cdot (D_{old} + (0.01) P_{25} - FBD)}{(0.01) P_{25}} \quad (3.1.40)$$

The other situation in which runoff from a lagoon may occur is a catastrophic dam failure. In this situation, the volume of runoff is dependent upon where the dam breaks. Referring to Figure 3.1.7, the volume of runoff can be calculated by:

$$V_{wl} = A_{la} \cdot (D_{new} - (FBD - D_B)) \quad (3.1.41)$$

where:

D_B = the distance from the free board depth to the top of the broken dam (m)

and the new depth is still the old depth plus the rainfall. The time of runoff is assumed to be one hour or less.

In both cases, the final runoff flow rate can be calculated by:

$$Q_{wl} = V_{wl}/T_R \quad (3.1.42)$$

where Q_{wl} is in cubic meters per second.

The transport and transformation for contaminants in runoff will remain the same for the lagoon or landfill. Therefore, transport and stream interception will not be analyzed for both cases.

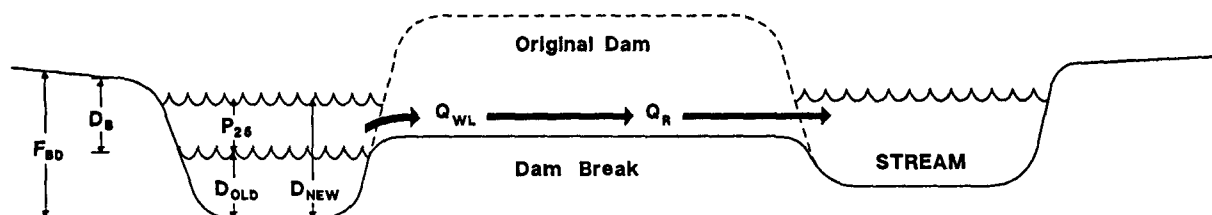


Figure 3.1.7 Lagoon Dam Failure

Runoff Transport and Erosion

The concentration of the runoff at the waste site, C_{WR} , and at the stream interception zone, C_R , can be related by:

$$C_{WR} = \zeta_R \cdot C_R \quad (3.1.43)$$

where:

ζ_R = reduction factor for runoff

therefore:

$$\zeta_R = C_R/C_{WR} \quad (3.1.45)$$

and C_R and C_{WR} can be calculated using the following equations.

As contaminant is transported across land, a certain amount of sediment is eroded and added to the stream in addition to the contaminant. Estimates of the amount of hydrophobic compounds loaded and removed in landfill waste site runoff can be calculated using the Modified Universal Soil Loss Equation, (MUSLE) and sorption partition coefficients derived from the compounds octanol-water partition coefficient. The modified universal soil loss equation (Williams 1975), as presented in Mills et al. (1982) is:

$$SY = (1.18 \times 10^4) (V_R * Q_P)^{0.56} \cdot K \cdot LS \cdot CF \cdot P \quad (3.1.46)$$

where:

SY = sediment yield (kg/event)
 V_R = volume of runoff (m³)
 Q_P = peak flow rate (m³/sec)
 K = soil erodibility factor (commonly expressed in tons per acre per dimensionless rainfall erodibility unit) K can be obtained from the local Soil Conservation Service office
 LS = slope length, and slope steepness factor (unitless)
 CF = cover factor (unitless) (1.0 for bare soils)
 P = erosion control factor (unitless)

Soil erodibility factors are indicators of the erosion potential of given soil types. As such, they are highly site-specific. K values for sites under study can be obtained from the local Soil Conservation Service office. The slope length factor, L , and the slope steepness factor, S , are generally entered into the MUSLE as a combined factor, LS , which is obtained from Figures 3.1.8 through 3.1.10. The cover management factor, CF , is determined by the amount and type of vegetative cover present at the site. Its value is "1" (one) for bare soils. Consult Table 3.1.5 and 3.1.6 to obtain C values for sites with vegetative covers. The factor, P , refers to any erosion control practices used on-site. Because these generally describe the type of agricultural plowing or planting practices, and because it is unlikely that any erosion control would be practiced at an abandoned hazardous waste site, use a worst-case (conservative) P value of 1 (one) for uncontrolled sites.

The sediment yield and consequently the volume of runoff and the peak flow rate must be calculated separately for the three areas in question: (1) the watershed, (2) the waste site, and (3) the contaminated catchments that affect the amount of sorbed chemical. The volume of runoff can be calculated by:

$$V_R = (0.01) (A) (D_R) \quad (3.1.46a)$$

where:

A = area of waste site, contaminated catchment (minus waste site), or watershed (minus contaminated catchment, (m²)
 D_R = depth of runoff (cm)

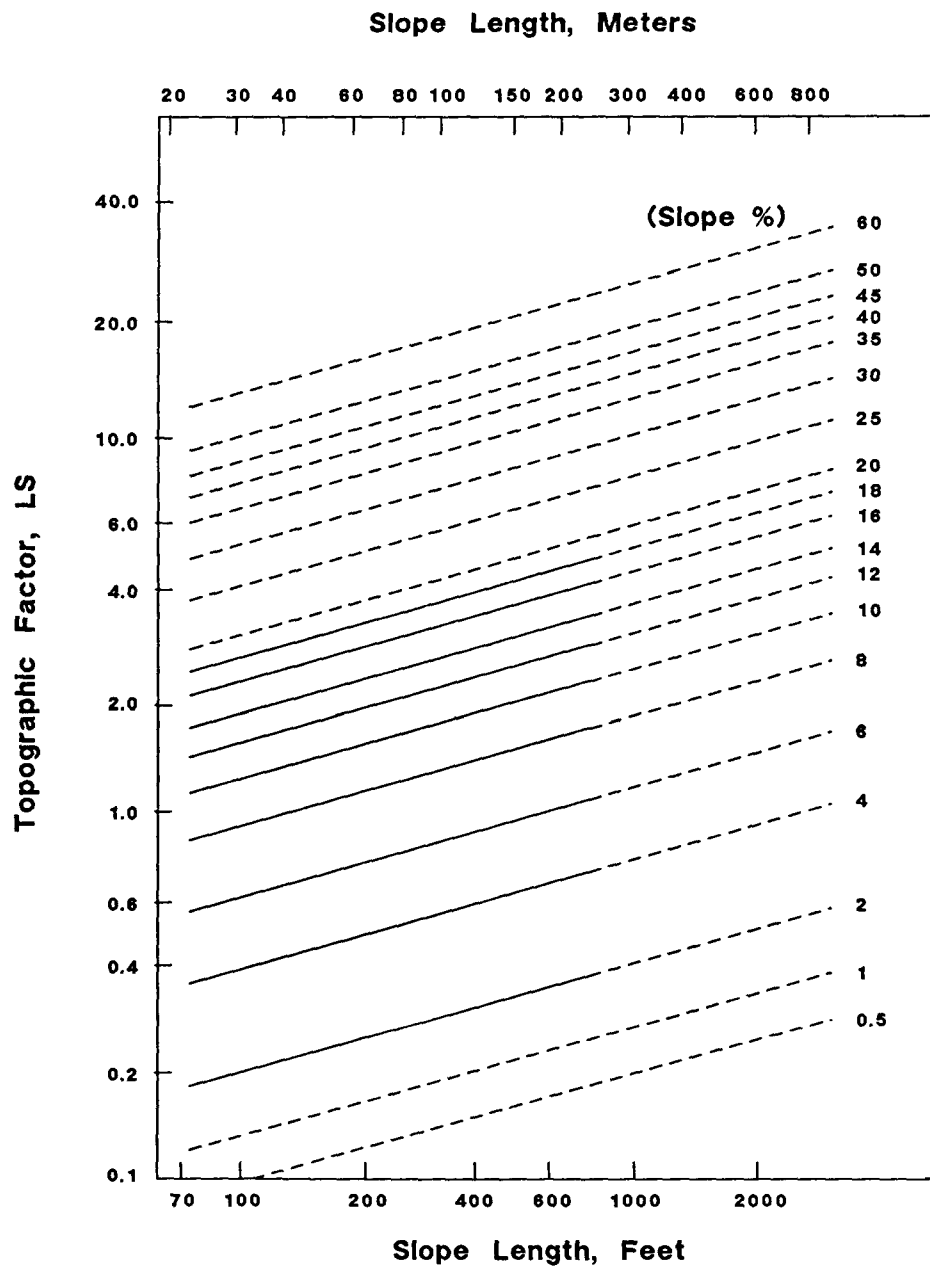


Figure 3.1.8 Slope Effect Chart Applicable to Areas A-1 in Washington, Oregon, and Idaho, and All of A-3: See Figure 3-5 (USDA 1974 as Presented in Mills et al. 1982).

NOTE: Dashed lines are extension of LS formulae beyond values tested in studies.

The peak runoff rate, Q_p , can be calculated by:

$$Q_p = \frac{(2.8 \times 10^{-6}) (A) (P_{25}) (D_R)}{(T_{\text{storm}}) (P_{25} - 0.2 S_w)} \quad (3.1.47)$$

where:

P_{25} = amount of rainfall (cm)
 T_{storm} = duration of storm (sec)
 S_w = water retention factor (cm)

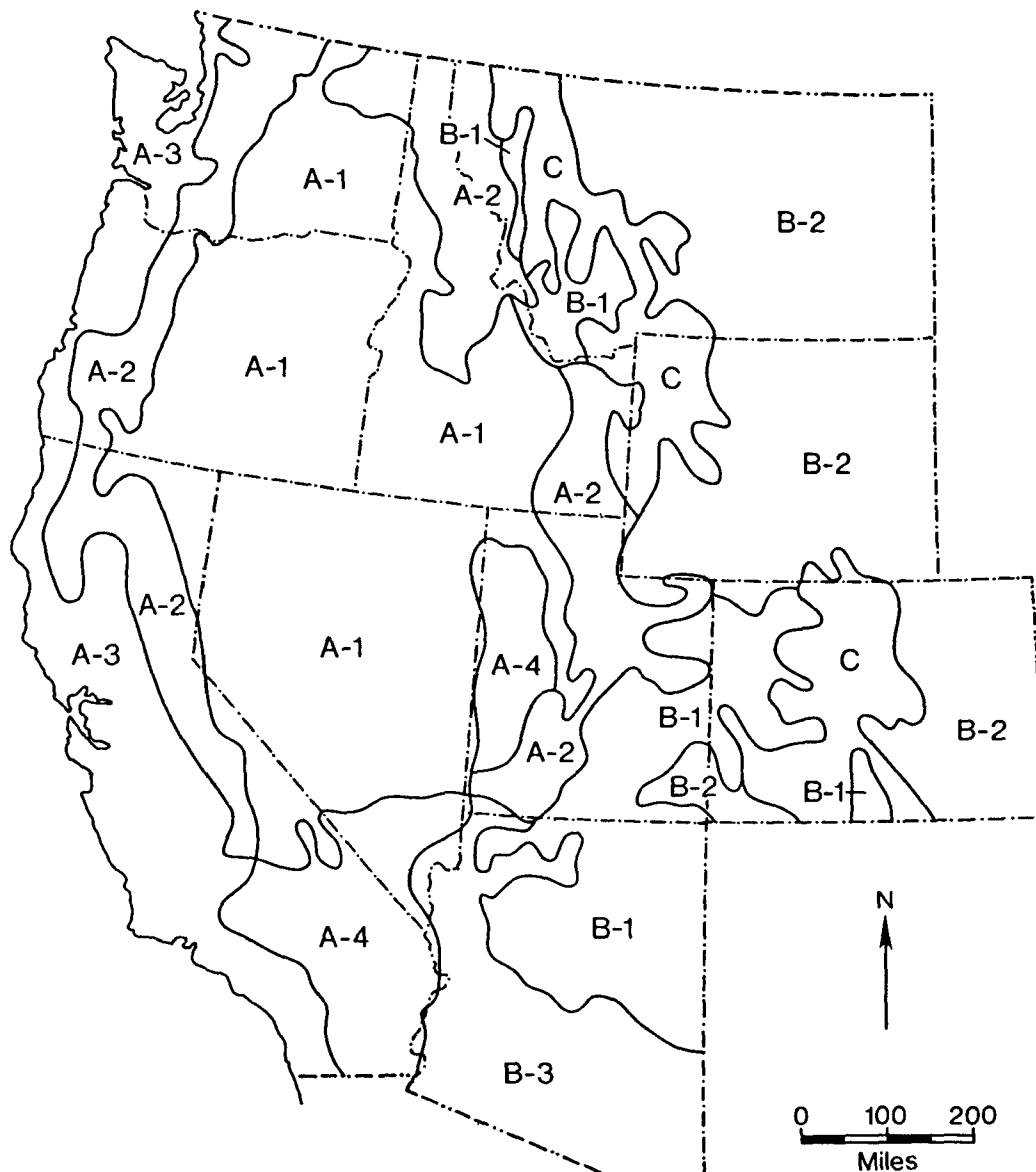


Figure 3.1.9 Soil Moisture - Soil Temperature Regimes of Western United States (USDA 1974)

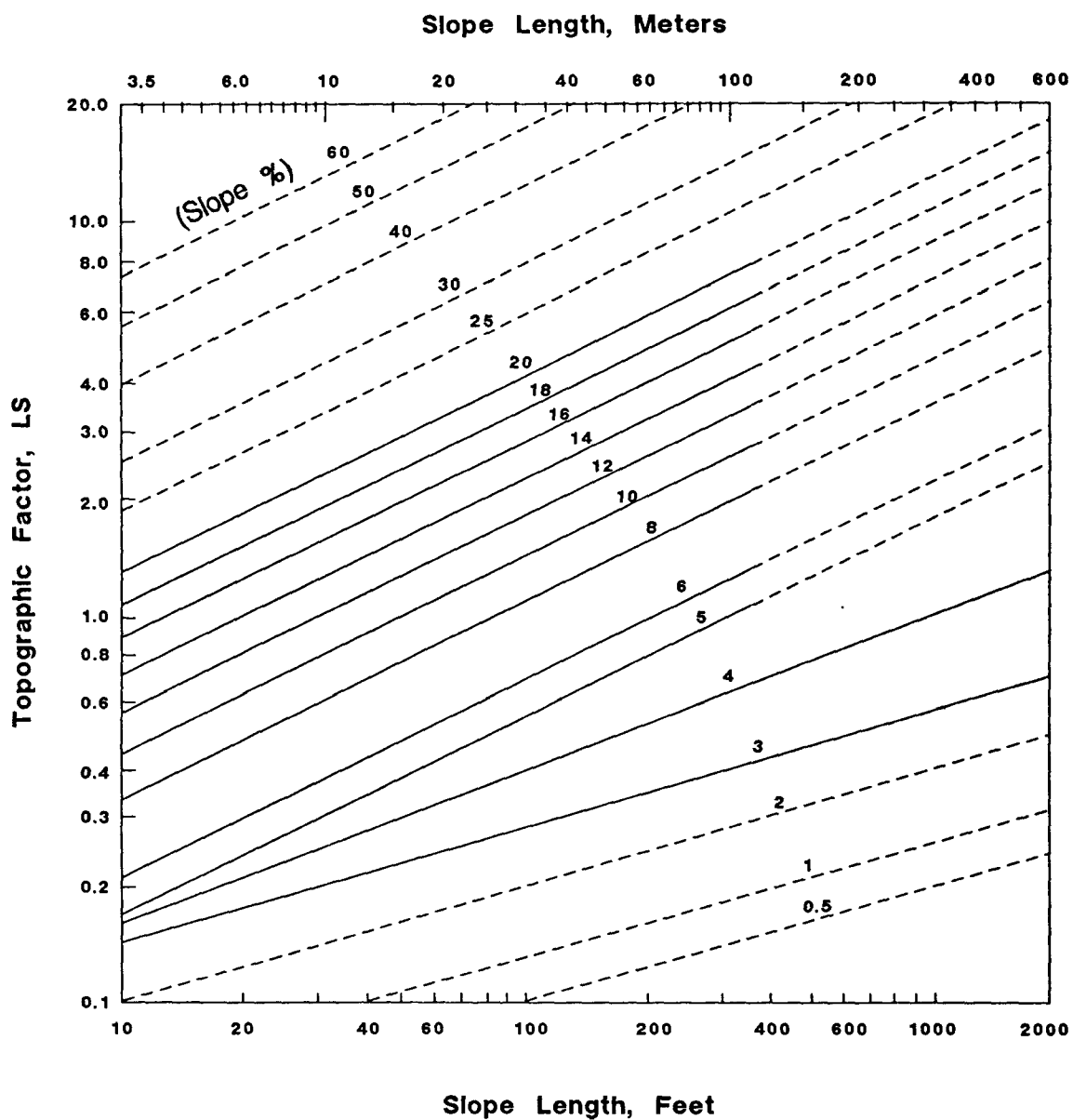


Figure 3.1.10 Slope Effect Chart for Areas Where Figure 3-5 Is Not Applicable (USDA 1974).

NOTE: The dashed lines represent estimates for slope dimensions beyond the range of lengths and steepnesses for which data are available.

TABLE 3.1.5 "C" Values for Permanent Pasture, Rangeland, and Idle Land

Vegetal canopy Type and height of raised canopy	Canopy cover ^c (%)	Cover that contacts the surface						
		Type ^d	Percent groundwater					
			0	20	40	60	80	95-100
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.090	0.043	0.011
Canopy of tall weeds or short bush (0.5 m fall height)	25	G	0.36	0.17	0.09	0.038	0.012	0.003
		W	0.36	0.20	0.13	0.082	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.075	0.039	0.011
	75	G	0.17	0.10	0.06	0.031	0.011	0.003
		W	0.17	0.12	0.09	0.067	0.038	0.011
Appreciable brush or brush (2 m fall height)	25	G	0.40	0.018	0.09	0.040	0.013	0.003
		W	0.40	0.22	0.145	0.085	0.042	0.011
	50	G	0.34	0.16	0.085	0.038	0.012	0.003
		W	0.34	0.19	0.13	0.081	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.077	0.040	0.011
Trees but no appreciable low brush (4 m fall height)	25	G	0.42	0.19	0.10	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.087	0.042	0.011
	50	G	0.39	0.18	0.09	0.040	0.013	0.003
		W	0.39	0.21	0.14	0.085	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.20	0.13	0.083	0.041	0.011

Source: Wischmeier 1972.

^aAll values shown assume: (1) random distribution of mulch or vegetation and (2) mulch of appreciable depth where it exists

^bAverage fall height of waterdrops from canopy to soil surface: m = meters

^cPortion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).

^dG: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 5 cm (2 in) deep.

W: Cover at surface is mostly broadleaf herbaceous plants (as weeds) with little lateral-root network near the surface and/or undecayed residue.

The depth of runoff, D_R , can be calculated by:

$$D_R = \frac{(P_{25} - 0.2 \cdot S_w)^2}{(P_{25} + 0.8 \cdot S_w)} \quad (3.1.48)$$

where:

S_w = the water retention factor (cm). S_w , the water retention factor can be calculated by:

$$S_w = (1000/C_N) - 25.4 \quad (3.1.49)$$

where:

C_N = the SCS runoff curve number, Table 3.1.7, (unitless)

TABLE 3.1.6 "C" Values for Woodland

Standard condition	Tree Canopy percent of area ^a	Forest litter percent of area ^b	Undergrowth ^c	"C" factor
Well stocked	100-75	100-90	Managed ^d Unmanaged ^d	0.001 0.003-0.011
Medium stocked	70-40	85-75	Managed Unmanaged	0.002-0.004 0.01-0.04
Poorly stocked	35-20	70-40	Managed Unmanaged	0.003-0.009 0.02-0.09 ^e

Source: Wischmeir 1972.

^aWhen tree canopy is less than 20 percent, the area will be considered as grass land or corpland for estimating soil loss.

^bForest litter is assumed to be at least 2 in deep over the percent ground surface area covered.

^cUndergrowth is defined as shrubs, weeds, grasses, vines, etc., on the surface area not protected by forest litter. Usually found under canopy openings.

^dManaged - grazing and fires are controlled.

Unmanaged- stands that are overgrazed or subjected to repeated burning.

^eFor unmanaged woodland with litter cover of less than 75 percent, C values should be derived by taking 0.7 of the appropriate values in Table 3-4. The factor of 0.7 adjusts for much higher soil organic matter on permanent woodland.

TABLE 3.1.7 Runoff Curve Numbers

Soil group	Description	Site type			
		Overall site ^a	Road/right of way	Meadow	Woods
A	Lowest runoff potential: Includes deep sands with very little silt and clay, also deep, rapidly permeable loess (infiltration rate = 8-12 mm/h).	59	74	30	45
B	Moderately low runoff potential: Mostly sandy soils loess less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting (infiltration rate = 4-8 mm/h).	74	84	58	66
C	Moderately high runoff potential: Comprises shallow soils and soils containing considerable clay and colloids, through less than those of group D. The group has below-average infiltration after pre-saturation (infiltration rate = 1-4 mm/h).	82	90	71	77
D	Highest runoff potential: Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface (infiltration rate = 0-1 mm/h).	86	92	78	83

Source: Adapted from Schwab et al. 1966.

^aValues taken from farmstead category, which is composite including building, farmyard, road, etc.

To predict the degree of soil/water partitioning expected for given compounds for a storm event use the following equations. First, the amounts of dissolved and adsorbed substances are determined, using equations adapted from Haith (1980):

The total runoff concentration at the stream entry point, C_R , is the sum of sorbed and dissolved concentrations:

$$C_R = C_{LD} + C_{LS} \quad (3.1.50)$$

The sorbed (C_{LS}) and dissolved chemical (C_{LD}) concentrations at the stream entry point can be calculated by:

$$C_{LS} = \frac{(Q_R) (C_{RS}) + (Q_U) (C_U) (1-f_{DS})}{Q_S} \quad (3.1.51)$$

and

$$C_{LD} = \frac{(Q_R) (C_{RD}) + (Q_U) (C_U) (f_{DS})}{Q_S} \quad (3.1.52)$$

where:

C_{RS} = sorbed contaminant concentration in runoff (mg/l)
 C_{RD} = dissolved contaminant concentration in runoff (mg/l)
 Q_R = runoff flowrate (derived in later section) (m^3/sec)
 Q_U = stream flowrate above source (derived in later section) (m^3/sec)
 C_U = chemical concentration above source (mg/l)
 f_{DS} = fraction of dissolved chemical in stream above source
 Q_S = stream flow below source (m^3/sec)

The sorbed and dissolved concentrations can be calculated by converting mass to mass per volume terms for use in estimating contaminant concentration in the receiving waterbody by dividing by the site storm runoff volume (V_R):

$$C_{RS} = \frac{(M_S) (1 \times 10^3)}{(V_{Rw} + V_{Rc} + V_{Rs})} \quad (3.1.53)$$

and

$$C_{RD} = \frac{M_D (1 \times 10^3)}{(V_{Rw} + V_{Rc} + V_{Rs})} \quad (3.1.54)$$

where:

C_{RS} = sorbed contaminant concentration in runoff (mg/l)
 C_{RD} = dissolved contaminant concentration in runoff (mg/l)
 V_{Rw} = volume of runoff from waste site (m^3)

V_{RC} = volume runoff from waste site contaminated catchment (m^3)
 V_s = sorbed substance loss per event (kg)
 M_D = dissolved substance loss per event (kg)
 V_{Rs} = volume of runoff from watershed (m^3)
 M_s = sorbed substance loss per event (kg)

The total loading to the receiving waterbody is calculated as follows (adapted from Haith 1980):

$$M_s = \left[\frac{SY}{100 \cdot \rho_{bw}} \right] \cdot S_s \quad (3.1.55)$$

and

$$M_D = \frac{(D_{Rw}) (D_s)}{P_{25}} \quad (3.1.56)$$

where:

M_s = sorbed substance loss per event (kg)
 SY = sediment yield (metric tons)
 ρ_{bw} = soil bulk density (kg/l)
 S_s = sorbed substance quantity (kg, lb)
 M_D = dissolved substance loss per event (kg)
 D_{Rw} = total storm runoff depth, from waste site (cm)
 P_{25} = total storm rainfall (cm)
 D_s = dissolved substance quantity (kg)

The mass of sorbed and dissolved chemical can be calculated by:

$$S_s = \frac{1 \times 10^{-5}}{(1 + \theta_w / (K_{pw} \cdot \rho_{bw}))} \cdot C_w \cdot A_w \quad (3.1.57)$$

where:

S_s = sorbed chemical mass (kg)
 θ_w = volumetric water content of porous medium
 (difference between wilting point and field capacity)
 (l/l)
 ρ_{bw} = bulk density of porous medium (kg/l)
 K_{pw} = partition coefficient (l/kg)
 C_w = total substance concentration in waste site
 (mg/m^3)
 A_w = area of waste site (m^3) (Actually a volume; assumption is
 contamination in upper 1 cm is available for release.)

and

$$D_s = \frac{0.001}{(1 + K_{pw} \cdot \rho_{bw})} \quad (3.1.58)$$

where: D_s = mass of dissolved chemical (kg)

The bulk density is calculated from the volumetric water content by the relationship:

$$\rho_{bw} = 2.65 \cdot (1 - \theta_w) \quad (3.1.59)$$

The partition coefficient, K_{pw} , can be calculated by:

$$K_{pw} = (0.63 \cdot KOW_w) \cdot FOC_w \quad (3.1.60)$$

where:

KOW_w = octanol-water partition coefficient of the waste constituent (l/kg)

FOC_w = organic carbon fraction of porous medium of the waste site (kg/l)

This model assumes that only the contaminant in the top 1 cm of soil is available for release via runoff.

The soil sorption partition coefficient for a given chemical can be determined from known values of certain other physical/chemical parameters, primarily the chemical's octanol-water partition coefficient, solubility in water, or bioconcentration factor. Lyman et al. (1982) present regression equations that allow the analyst to determine sorption coefficients for specified groups of chemicals (e.g., herbicides, polynuclear aromatics). If parameter values required by the appropriate equations are not available in chemical reference literature, they can be estimated according to procedures described in Lyman et al. (1982). Initially, the octanol-water partition coefficient can be estimated based on the substance's molecular structure. If necessary, this value can be used, in turn, to estimate either solubility in water or bioconcentration factor.

Runoff Mixing

An initial mixing zone in the stream is developed over the contaminant discharge area. For upland watersheds where the stream is shallow, complete vertical mixing of the contaminant occurs within this mixing zone. As indicated in Figure 3.1.11, however, lateral mixing may be incomplete. In cases of runoff loading and direct discharge, where lateral mixing is likely to be incomplete, there is a finite plume

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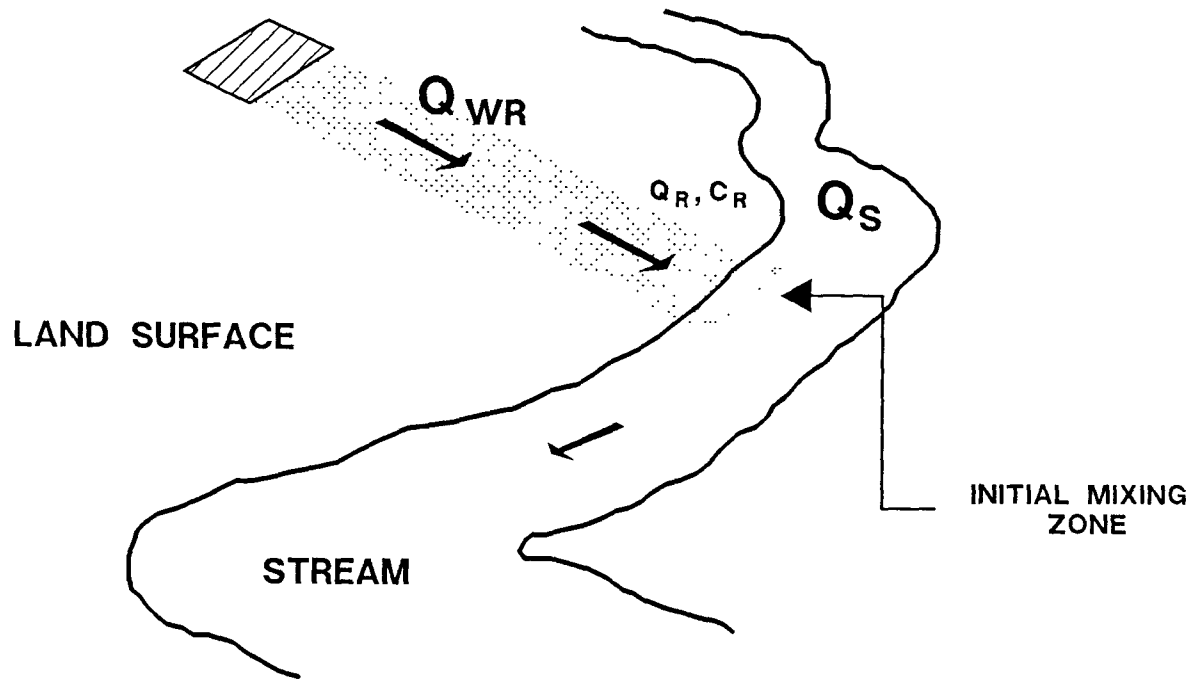


Figure 3.1.11 Runoff/Stream Mixing

width over which a Gaussian concentration distribution $C_{0,y}$ is assumed. The maximum contaminant concentration and the standard deviation of the Gaussian distribution are denoted by C_R (runoff), C_D (discharge), σ_R (runoff), and σ_D (discharge). The standard deviation, σ , is a measure of the plume width at the edge of mixing zone.

The contaminant mass flux loaded into the stream from surface runoff, m_R , is assumed equal to the runoff mass flux at the edge of the stream, m_{WR} . The total mass flux at the downstream edge of the mixing zone is the sum of the upstream mass flux, assumed equally distributed across the stream, and the runoff mass flux, distributed along the near bank:

$$m_0 = m_R + m_U \quad (3.1.61)$$

The concentration distribution across the mixing zone can be obtained by dividing the mass fluxes by the stream flow:

$$C_{0,y} = \zeta_{x,y} \cdot C_R + \zeta_{SU} \cdot C_U \quad (3.1.62)$$

where ζ_{SU} is a dilution factor for upstream concentrations:

$$\zeta_{SU} = Q_U/Q_S \quad (3.1.63)$$

and $\zeta_{x,y}$ is a dilution factor for runoff concentration describing a lateral, Gaussian distribution across the stream. This dilution factor

declines from 1 at $y = 0$ to 0 for large values of y . Q_s is the downstream flow rate, or the sum of Q_R and Q_U .

Contaminants reaching a stream via runoff are assumed to enter the stream as a steady load throughout release duration t_R (Figure 3.1.12). For scenario 2 and 7, the time over which the contaminant loading occurs is assumed to be the 1-day duration of the storm. For scenario 3 and 8, contaminant loading is assumed to occur for a short duration following the storm. During the loading event, an initial mixing zone is developed over the runoff discharge area. Within this mixing zone, dilution of the loading concentration occurs but is somewhat limited by the magnitude of the release flow compared with the stream flow. At the edge of the initial mixing zone ($x = 0$), it is assumed that the transverse concentration distribution is a Gaussian distribution.

The equations developed in Sections 2.1.1 and 2.1.2 relate contaminant concentrations in the leachate running off the facility with concentrations in runoff at the stream bank, and these with concentrations in stream. Combining equations 3.1.34, 3.1.35, 3.1.62, and 3.1.63 gives:

$$C_{O,y} = \zeta_{x,y} \cdot \frac{Q_{wR}}{Q_R} \cdot C_{wR} + \frac{Q_U}{Q_s} \cdot C_U \quad (3.1.64)$$

where:

- C_{wR} = the runoff concentration (mg/l)
- Q_{wR} = the runoff flow running off the facility (m^3/sec)
- Q_R = the runoff flow from the contaminated catchment (m^3/sec)
- Q_U = the upstream flow, C_U the upstream concentration (m^3/sec)
- Q_s = the total down stream flow (m^3/sec)
- $\zeta_{x,y}$ = a dilution factor for runoff concentrations describing a lateral, Gaussian distribution across the stream (unitless).

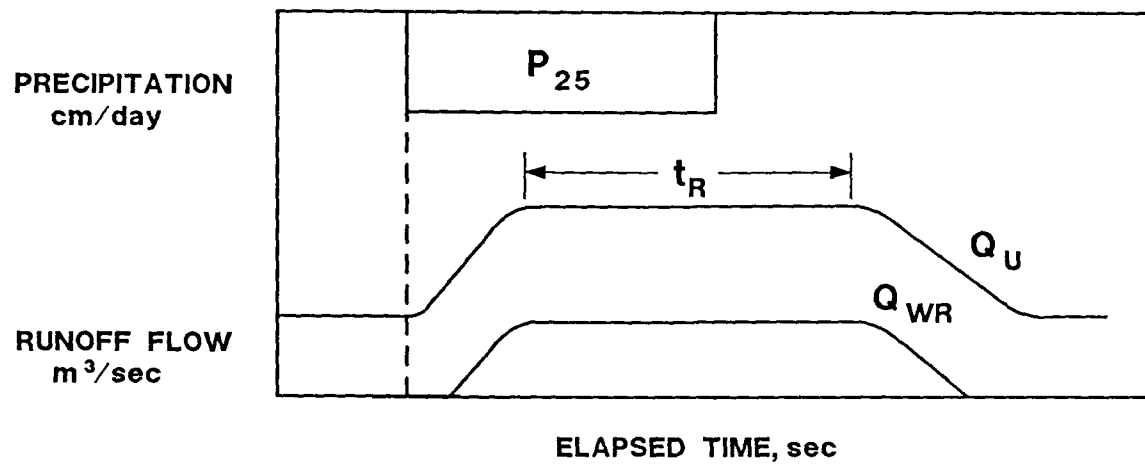
These terms are discussed below.

$\zeta_{x,y}$ -- Runoff entering a stream adds to the stream flow along the bank. It is assumed that stream flow at the bank in the mixing zone is at the runoff concentration, which is diluted laterally according to the Gaussian distribution:

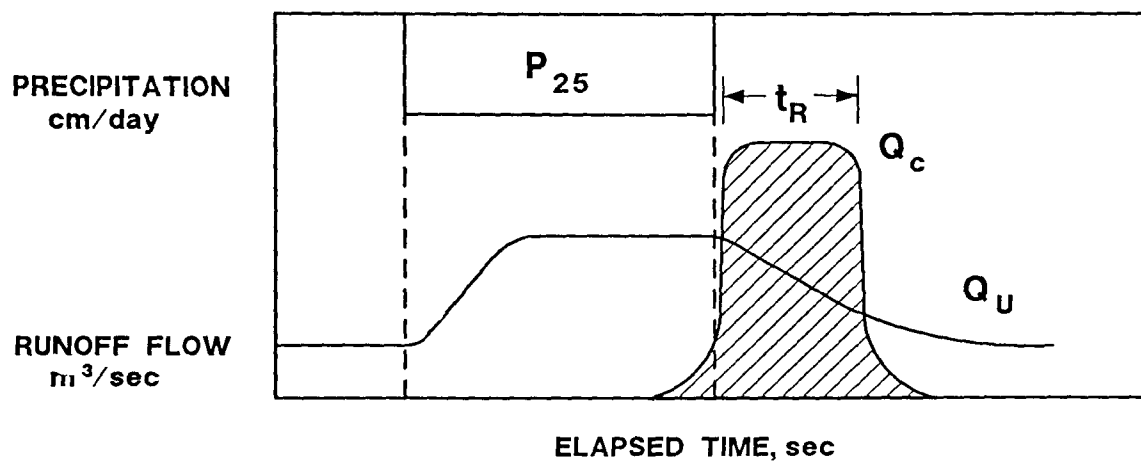
$$\zeta_{x,y} = \exp(-y^2/2\sigma^2) \quad (3.1.65)$$

where y is the lateral distance across the stream and σ is the standard deviation of the distribution, which can be derived from mass balance principles as follows. For the case of no upstream concentrations, the mass flux in the stream at the edge of the mixing zone is equal to the mass flux entering the stream runoff:

$$m_R = m_0 \quad (3.1.66)$$



(a)



(b)

Figure 3.1.12 Precipitation and runoff flows: (a) runoff due to 24-hour precipitation, (b) catastrophic pulse runoff at the end of the 24-hour storm.

The runoff mass flux is its flow multiplied by its concentration:

$$m_R = Q_R \cdot C_R \quad (3.1.67)$$

The instream mass flux can be obtained by integrating the lateral concentration distribution width:

$$m_0 = U \cdot d \cdot \int_0^B (C_R \cdot \exp(-y^2/2\sigma^2)) dy \quad (3.1.68)$$

where U is average stream velocity in meters per second, d is average stream depth in meters, and B is stream width in meters. Integrating equation 3.1.68 and equating it to 3.1.67 gives:

$$Q_R \cdot C_R = \sqrt{\pi/2} \cdot U \cdot d \cdot \sigma \cdot C_R \cdot \text{erf}(B/\sigma\sqrt{2}) \quad (3.1.69)$$

where erf is the error function, which is equal to 1.0 for $B \gg \sigma$. Noting that stream flow Q_S is the product of the mean depth, velocity, and width ($Q_S = UdB$), equation 3.1.69 can be solved for σ :

$$\sigma = \frac{B}{\sqrt{\pi/2}} \cdot \frac{Q_R}{Q_S} = 0.798 \cdot B \cdot \frac{Q_R}{Q_S} \quad (3.1.70)$$

Q_R --The runoff flow from the contaminated catchment, in cubic meters per second, may be estimated by:

$$Q_R = \frac{P_{25} \cdot f_{Rc} \cdot (A_c - A_w)}{100 \cdot t_s} + \frac{P_{25} \cdot f_{Rw} \cdot A_w}{100 \cdot t_R} \quad (3.1.71)$$

where:

- P_{25} = precipitation for the design storm event (cm)
- f_{Rc} = average fraction of precipitation that runs off of the contaminated catchment (unitless)
- f_{Rw} = fraction of precipitation that runs off waste site (unitless)
- A_c = area of contaminated catchment (m^2)
- A_w = area of waste site (m^2)
- t_s = total time of design storm event (sec)
- t_R = total time runoff occurs (sec)

where t_s is the duration of the storm, or 86400 sec, and A_c is the land area of the contaminated catchment, in square meters, which includes the surface area of the facility A_w plus the surface area between the facility and the stream. Note that for steady runoff throughout the storm, $t_R = t_s$ and equation 3.1.70 reduces to:

$$Q_R = \frac{P_{25} \cdot f_{Rc} \cdot A_c}{100 \cdot t_s} \quad (3.1.72)$$

For the case of no dilution in overland flow, $A_c = A_w$ and equation 3.1.72 reduces to:

$$Q_R = \frac{P_{25} \cdot f_{Rw} \cdot A_w}{100 \cdot t_s} = Q_{wR} \quad (3.1.73)$$

Q_U --The stream flow at the upstream edge of the contaminated runoff, in cubic meters per second, may be estimated by:

$$Q_U = Q_0 + \frac{P_{25} \cdot f_{RS} \cdot f_R^* \cdot (A_s - A_w)}{100 \cdot t_s} \quad (3.1.74)$$

where f_{RS} is the average fraction of the precipitation that runs off the upper watershed, f_R^* is a stream flow recession parameter (0-1) for scenario 3 runoff events that follow a storm (input value describing whether the stream flow is at full storm conditions $f_R^* = 1$; or at before storm conditions, $f_R^* = 0$.), and Q_0 is the base flow of the upper watershed, in cubic meters per second.

Q_S --The total stream flow at the downstream edge of the mixing zone is the sum of the upstream flow and the runoff flow:

$$Q_S = Q_U + Q_R \quad (3.1.75)$$

3.1.1.3 DIRECT DISCHARGE PATHWAY

Direct Loading From a Treatment Facility

All treatment facilities discharging into a stream must comply with EPA rules and regulations. Waste load allocations are based upon the detrimental effects to humans or aquatic species and must specify the maximum loading rate and concentration of direct discharge into a stream, m_D and C_D . In this analysis, maximum loading rates and concentrations in both the industrial waste stream and in the wastewater effluent may be estimated from maximum allowable stream concentrations by the back calculation procedure.

Two types of contaminant discharge are considered. The first is a constant loading over a long period of time. The second type of contaminant discharge is a pulse loading over a short period of time, t_D . The waste water flow rates, and contaminant concentrations for both types of discharge are assumed to be constant during the time of discharge.

The mass flux in the industrial waste stream, m_W , and the mass flux in the treated wastewater effluent, m_D , may be related by:

$$\dot{m}_D = \zeta_{wD} \cdot \dot{m}_{wD} \quad (3.1.76)$$

where ζ_{wD} is the treatment plant attenuation factor (1-fractional removal) accounting for the effects of sorption and settling, volatilization, and bacterial degradation. No general equation is developed in this model for calculating ζ_{wD} . If no measured (or independently estimated) value is specified by the user, ζ_{wD} defaults to 1 and mass is conserved through the treatment plant. The concentrations in industrial waste and the wastewater effluent can be obtained by dividing the mass fluxes by the flow rates:

$$C_{wD} = \dot{m}_{wD}/Q_{wD} \quad (3.1.77)$$

$$C_D = \dot{m}_D/Q_D \quad (3.1.78)$$

Combining the above equations, the concentrations in the wastewater effluent and in the industrial waste may be related by:

$$C_D = \zeta_D \cdot C_{wD} \quad (3.1.79)$$

where ζ_D is the wastewater treatment plant reduction factor accounting for both dilution and mass reduction due to treatment efficiency e_{wD} :

$$\zeta_D = \zeta_{wD} \cdot Q_{wD}/Q_D = (1 - e_{wD}) \frac{Q_{wD}}{Q_D} \quad (3.1.80)$$

Lagoon

The only type of discharge considered for the lagoon scenario is a constant loading over a long period of time. The mass flux entering the lagoon, \dot{m}_{wL} , and the mass flux leaving the lagoon, \dot{m}_L , can be related by:

$$\dot{m}_L = \zeta_{wL} \cdot \dot{m}_{wL} \quad (3.1.81)$$

where ζ_{wL} is the attenuation factor accounting for the effects of sorption and settling, volatilization, and bacterial degradation. No general equation is developed in this model for calculating ζ_{wL} . If no measured (or independently estimated) value is specified by the user, ζ_{wL} defaults to one and mass is conserved through the lagoon. The concentrations in industrial waste and the wastewater effluent can be obtained by dividing the mass fluxes by the flow rates:

$$C_{wL} = \dot{m}_{wL}/Q_{wL} \quad (3.1.82)$$

$$C_D = \dot{m}_D/Q_D \quad (3.1.83)$$

Combining the above equations, the concentrations in the wastewater effluent and in the industrial waste may be related by:

$$C_D = \zeta_1 \cdot C_{w1} \quad (3.1.84)$$

where ζ_1 is the wastewater treatment plant reduction factor accounting for both dilution and mass reduction due to treatment efficiency e_{WL} :

$$\zeta_1 = \zeta_{w1} \cdot Q_{w1}/Q_D \quad (3.1.85)$$

$$= (1 - e_{w1}) \frac{Q_{w1}}{Q_D} \quad (3.1.86)$$

Direct discharge mixing--The contaminant mass flux loaded into the stream from wastewater effluent, m_{SD} , is assumed equal to the effluent mass flux, m_D (Figure 3.1.13). The total mass flux at the downstream edge of the mixing zone is the sum of the upstream mass flux, assumed equally distributed across the stream, and the effluent mass flux distributed along near the bank:

$$\dot{m}_O = \dot{m}_{SD} + \dot{m}_U \quad (3.1.87)$$

The concentration distribution across the mixing zone can be obtained by dividing the mass fluxes by the stream flow:

$$C_{O,y} = \zeta_{x,y} \cdot C_D + \zeta_{SU} \cdot C_U \quad (3.1.88)$$

where ζ_{SU} is a dilution factor for upstream concentrations:

$$\zeta_{SU} = Q_U/Q_S \quad (3.1.89)$$

and $\zeta_{x,y}$ is a dilution describing a lateral, Gaussian distribution for effluent concentrations. This dilution factor, developed in the runoff section, declines from 1 at $y = 0$ to 0 for large values of y . Q_S is the downstream flow rate, or the sum of Q_D and Q_U .

Contaminants reaching a stream via wastewater discharge or lagoon releases are assumed to enter the stream as steady load of duration t_D . For scenarios 4 and 7, the time over which the contaminant loading occurs is assumed to be indefinite. For scenario 5, contaminant loading is assumed to occur for a short duration on a regular basis.

During wastewater discharge, an initial mixing zone is developed over the discharge area. Within this mixing zone, dilution of the discharge concentration occurs but is somewhat limited by the magnitude of the discharge flow compared with the stream flow. At the edge of the

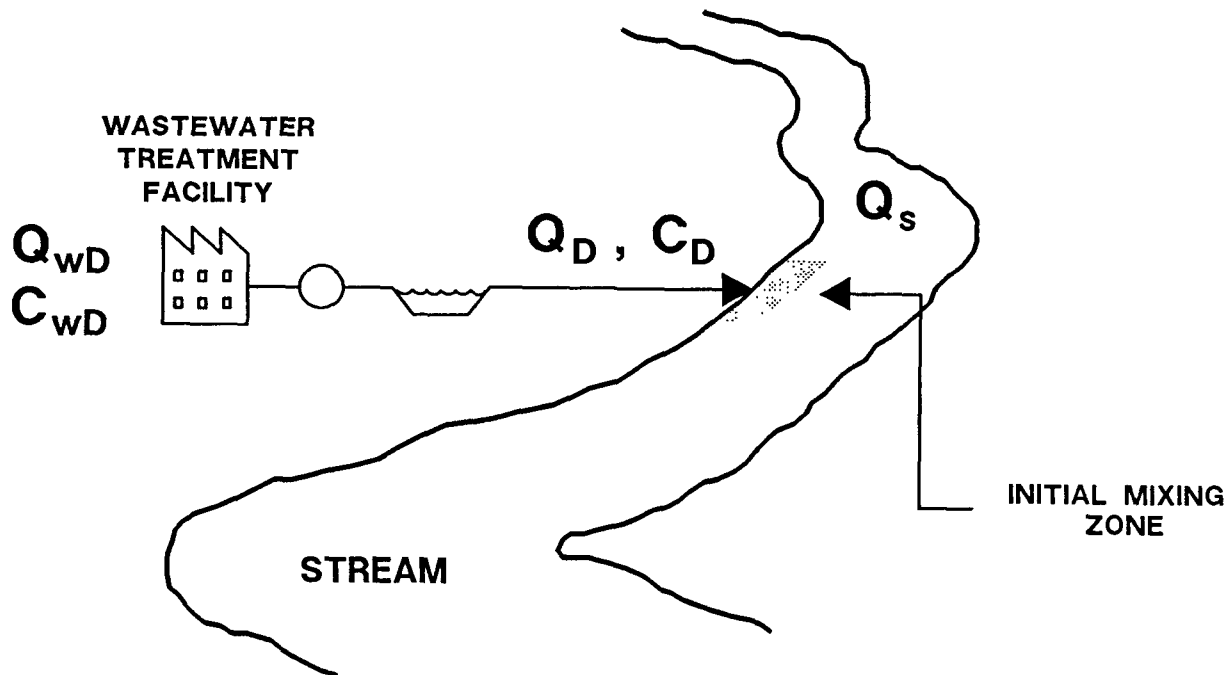


Figure 3.1.13 Direct Discharge Mixing

initial mixing zone ($x = 0$), it is assumed that the transverse concentration distribution is a Gaussian distribution.

The equations relate contaminant concentrations in the industrial waste stream with concentrations in the wastewater effluent, and these with concentrations in stream. Combining equations 3.1.79, 3.1.80, 3.1.88 and 3.1.89 gives:

$$C_{O,y} = \zeta_{x,y} \cdot \zeta_{wD} \cdot \frac{Q_{wD}}{Q_D} \cdot C_{wD} + \frac{Q_U}{Q_s} \cdot C_U \quad (3.1.90)$$

where:

- C_{wD} = the industrial waste concentration (mg/l)
- Q_{wD} = the industrial waste flow, Q (m^3/sec)
- Q_D = the wastewater effluent flow (m^3/sec)
- ζ_{wD} = is the treatment plant mass attenuation factor (unitless)
- Q_U = the upstream flow (m^3/sec)
- C_U = the upstream concentration, Q_s is the total downstream flow (m^3/sec)
- $\zeta_{x,y}$ = a dilution factor for effluent concentrations describing a lateral, Gaussian distribution across the stream (unitless)
- Q_s = stream flow downstream source (m^3/sec)

These terms are discussed below.

$\zeta_{x,y}$ --Wastewater effluent entering a stream adds to the stream flow at a point near the bank. It is assumed that stream flow at the bank in the mixing zone is at the effluent concentration, which is diluted laterally according to the Gaussian distribution:

$$\zeta_{x,y} = \exp(-y^2/2\sigma^2) \quad (3.1.91)$$

where y is the lateral distance across the stream and σ is the standard deviation of the distribution. This parameter can be derived by following equation 3.1.66-3.1.70, substituting m_D for m_{SR} and Q_D for Q_{SR} to give:

$$\sigma = \frac{B}{\sqrt{\pi/2}} \cdot \frac{Q_D}{Q_S} = 0.798 \cdot B \cdot \frac{Q_D}{Q_S} \quad (3.1.92)$$

ζ_{WD} --The treatment plant mass attenuation factor accounts for the effects of sorption and settling, volatilization, and bacterial degradation. No general equation is developed here for calculating ζ_W . If no measured or independently estimated value is specified by the user, ζ_{WD} defaults to 1 and mass is conserved through the treatment plant.

Q_{WD} --The flow rate for the industrial waste stream, in cubic meters per second, must be specified by the user. If total loading m_{WD} and concentration C_{WD} are known, then Q_{WD} can be calculated by:

$$Q_{WD} = \frac{m_{WD}}{C_{WD} \cdot t_D} \quad (3.1.93)$$

where m_{WD} is expressed in grams, C_{WD} is expressed in mg/L (or grams per cubic meter), and t_D is expressed in seconds.

Q_D --The flow rate of the wastewater treatment effluent, in cubic meters per second, must be specified by the user.

Q_U --The stream flow, in cubic meters per second, can be specified by the user. If known, an average flow condition can be calculated:

$$Q_U = q_S \cdot A_S \quad (3.1.94)$$

where q_S is the average stream flow per unit drainage area, in cubic meters per second per square meter, and A_S is the surface area of the watershed above the discharge, in square meters.

Q_S --The stream flow at the point of mixing is the sum of the upstream flow and the effluent flow:

$$Q_S = Q_U + Q_D \quad (3.1.95)$$

3.2 Transport of Contaminants Downstream

Following initial dilution in the stream, the contaminant is transported downstream from the edge of the initial mixing zone. In the cases of runoff loading and direct discharge, the initial boundary condition assumes a Gaussian distribution of $C_{0,y}$. In the case of ground water loading, the initial boundary condition is the laterally averaged C_0 . At a specified downstream measurement point, x , (Figure 3.2.1) the contaminant concentration, C_x , is expressed as:

$$\bar{C}_x = \zeta_x \cdot \bar{C}_0 \quad \text{for ground water loading} \quad (3.2.1)$$

$$C_{x,y} = \zeta_{x,y} \cdot C_{0,y} \quad \text{for surface and effluent discharge} \quad (3.2.2)$$

where ζ_x and $\zeta_{x,y}$ are concentration reduction factors accounting for the combined influence of advection, longitudinal and lateral dispersion, degradation and sorption occurring during downstream transport. Note that in the case of ground water loading, lateral mixing is probably almost complete at $x = 0$, because of a fairly extensive contaminant discharge area as compared to the cases of runoff loading.

Following initial dilution in the stream, contaminants at peak concentration, C_0 , are routed downstream under the combined influence of advection, longitudinal and lateral dispersion, degradation and sorption. The concentration at downstream distance x from the edge of the initial mixing zone is C_x and is related to C_0 via equations 3.2.1 and 3.2.2, in which ζ_x is the attenuation factor for transport in surface water. The expressions for ζ_x can be obtained from analytical solutions of the transient two-dimensional transport equation. Two cases corresponding to continuous loading and pulse loading of contaminants are considered.

Stream transport below continuous ground water loading--The laterally averaged concentration at the downstream edge of the ground water plume ($x = 0$) is C_0 (see Figure 3.2.1). At a given measurement point located at distance x from the edge of the mixing zone (see Figure 3.2.1a), the concentration will quickly reach a steady-state value under base flow conditions. The steady-state, laterally averaged solution for concentrations at the measurement point is given by:

$$\zeta_x = e^{-K \cdot \tau} \quad (3.2.3)$$

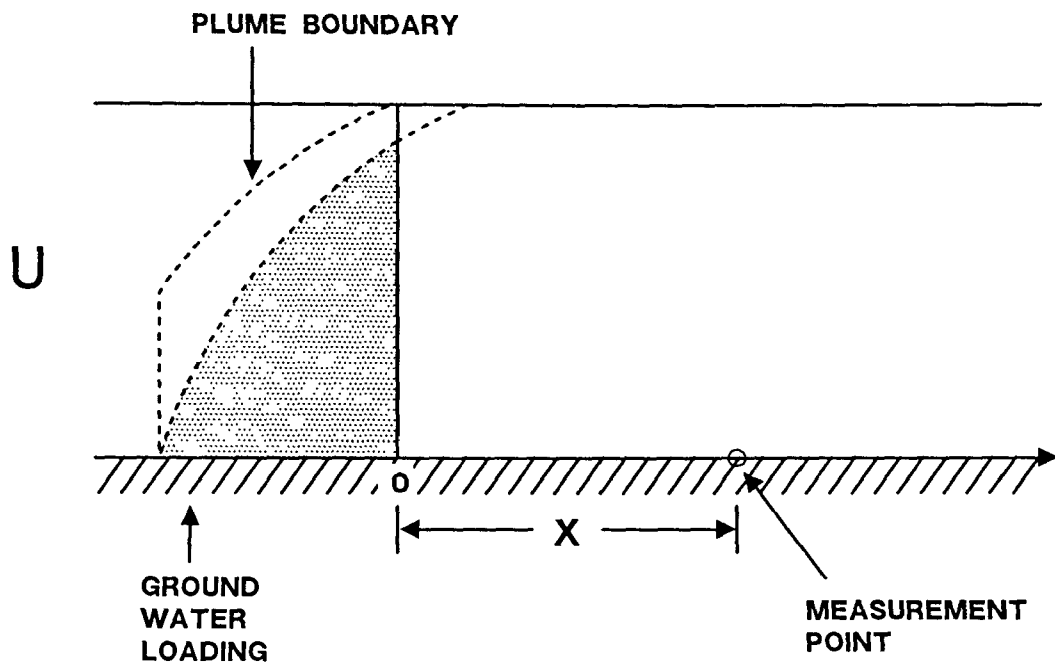
$$\tau = x/U \quad (3.2.4)$$

where:

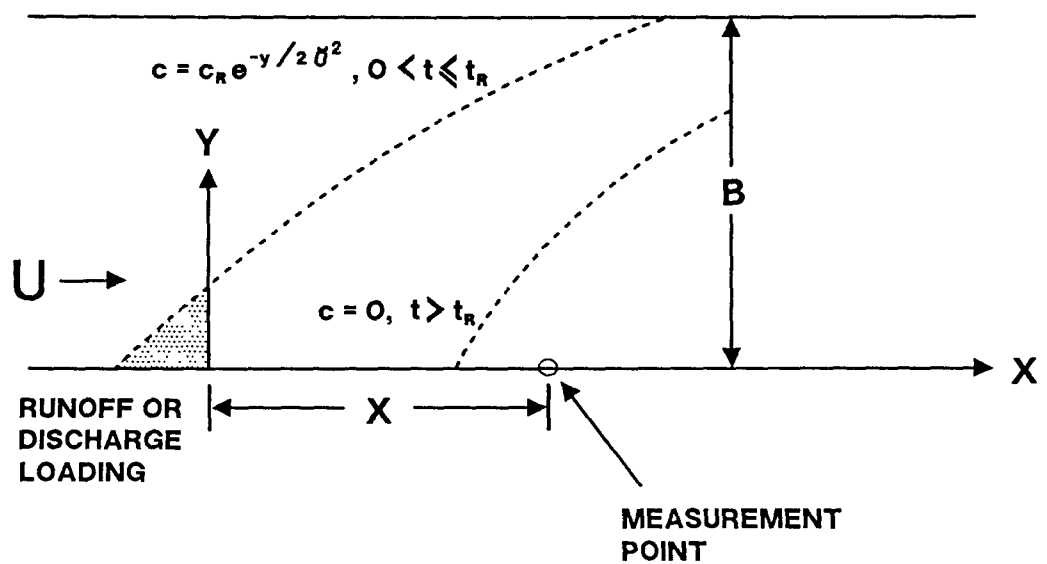
K = decay rate constant (sec⁻¹)

U = mean downstream velocity (m/sec)

For calculating bioconcentration in scenario 1B or chronic toxicity in scenario 1C, we assume that the fish reside continuously in the upstream



(a) Continuous Ground Water Loading



(b) Pulse Runoff Loading

Figure 3.2.1 Downstream Contaminant Transport from the Edge of Initial Mixing Zone

area where the effect of degradation is insignificant ($x = 0$). Therefore in this case ζ_x is 1, and C_x becomes C_0 .

Stream transport below pulse runoff loading--Pulse runoff loading produces a lateral concentration profile that is a Gaussian distribution characterized (at $x = 0$) by a minimum C_R and a standard deviation of σ over the contaminant loading period t_R (see Figure 3.2.1b). Downstream transport will be accompanied by lateral mixing until the contaminants are evenly dispersed across the stream. The concentrations at a given measurement point located at distance point, x , will increase from zero to a relatively steady value between times (x/U) and $x/U + t_R$. At subsequent times, the concentrations will decrease gradually and become zero as the contaminant slug passes through the measurement point. The general analytical solution for transient, two-dimensional transport from a Gaussian pulse source is presented in Appendix B. This solution may be written as:

$$\zeta_{x,y} = [C^*_{f}(x,y,t) + \sum_{i=1}^{\infty} C^*_{fi}(x,y,t) - C^*_{f}(x,y,t-t_R) - \sum_{i=1}^{\infty} C^*_{fi}(x,y,t-t_R)] \quad (3.2.5)$$

where:

$$C^*_{f}(x,y,t) = \frac{\sigma x \exp(U/2E_x)}{(2\pi E_x)^{1/2}} \cdot I \quad (3.2.6)$$

$$I = \int_0^t \frac{\exp\left(-\frac{x^2}{4E_x \tau} - \frac{y^2}{4E_y \tau + 2\sigma^2} - \frac{U^2 \tau}{4E_x} - K\tau\right) d\tau}{\tau^{3/2} (2\sigma^2 + 4E_y \tau)^{1/2}} \quad (3.2.7)$$

$$C^*_{fi} = C^*_{f}(x, 2Bi + 6 \cos(i\pi), t) \quad (3.2.8)$$

E_x = longitudinal dispersion coefficient (m^2/sec)

E_y = lateral dispersion coefficient (m^2/sec)

The infinite series in equation 3.2.5 is evaluated in a computer subroutine using finite sums of N terms, where N corresponds to the number of image sources described in Appendix B. Good convergence is obtained with $N < 10$. The integral I is evaluated numerically using Gaussian quadrature.

Stream transport below pulse discharge loading--Pulse discharge loading produces a lateral concentration profile that is a Gaussian distribution characterized (at $x = 0$) by a maximum C_0 and a standard deviation of σ over the contaminant loading period t_D . Downstream transport will be accompanied by lateral mixing until the contaminants are evenly dispersed across the stream. The concentrations at a given measurement point, x , will increase from zero to a relatively steady value between times (x/U) and $(x/U + t_D)$. At subsequent times, the concentrations will decrease gradually and become zero as the contaminant slug passes through the measurement point. The general analytical solution for transient, two-dimensional transport from a Gaussian pulse source is presented in Appendix B. This solution is given by equations 3.2.5 - 3.2.8 (with t_D substituted for t_R in equation 3.2.5).

3.3 EXPOSURE AND EFFECTS

At a distance x downstream, contaminants at concentration C_x may be taken into a drinking water plant or exposed to aquatic organisms, including fish. The drinking water concentration C_{DW} , the aquatic exposure concentration C_{EXP} , and the fish body concentration C_F must be calculated from C_x .

Human exposure to contaminants through drinking water--Humans are exposed to dissolved chemicals through the consumption of water obtained from a treatment plant that is located in the zone of contamination downstream from the initial mixing zone. The plant takes in water from the stream, with a contaminant concentration, $C_{x,y}$. The water is assumed to be treated by a primary settling process allowing suspended solids and adsorbed chemicals to settle out. As a result of this treatment, the contaminant concentration is reduced from $C_{x,y}$ to C_{DW} . The relationship of C_{DW} and $C_{x,y}$ is expressed as:

$$C_{DW} = \zeta_{DW} \cdot C_{x,y} \quad (3.3.1)$$

where ζ_{DW} is the factor accounting for the reduction in contaminant concentration achieved through the treatment process, i.e., the pollutant removal efficiency.

Drinking water plants take in raw water at a distance x downstream from the point of discharge. As a minimum requirement, it is assumed that in any drinking water plant, the raw water having contaminant concentration C_x is treated by allowing suspended solids and adsorbed chemicals to settle out. This leads to a reduction of concentration from C_x to C_{DW} . The relationship between C_{DW} and C_x is given by equation 3.1.77 with ζ_{DW} being the dilution factor corresponding to the fraction of the compound that is dissolved, f_D . The expression for f_D is developed in Appendix A. This may be written as:

$$\zeta_{DW} = f_D = \frac{1}{1 + 0.41 K_{OW} \cdot f_{oc} \cdot S \cdot 10^{-6}} \quad (3.3.2)$$

where:

K_{OW} = octanol-water partition coefficient ($^{1}_{oct}/^{1}_{water}$)
 f_{oc} = organic carbon fraction of sediment (unitless)
 S = sediment concentration (mg/l)

Human exposure to contaminants through consumption of fish--Another route resulting in human exposure to chemicals in leachate and discharge is the consumption of contaminated fish. To be conservative, it is assumed that these fish reside continuously within the most polluted reach of the stream where concentrations are not reduced by dilution or chemical transformation. The allowable daily intake adopted here is based on an average 70-year consumption of contaminated fish.

For the case of runoff loading, the infrequency of runoff events (2 or 3 occurrences in 70 years) and the length of time required for food fish to attain high body burdens (weeks to months) should prevent significant contaminant doses to humans. For the case of ground water direct discharge and lagoon loading the continuous nature of discharge and ground water seepage into streams may cause fish to attain high body burdens which result in significant contaminant doses to humans over a lifetime. Delivery of contaminants through consumption of fish allows for the fact that a fish population can be quite mobile over the length and width of a contaminated stream. Furthermore, a single fish may be exposed to a wide range of concentrations during its lifetime. The typical fish will be exposed to the average concentration denoted by \bar{C}_0 in the case of ground water loading (given by equation 3.1.27) and $C_{x,y}$ in the case of direct discharge.

Chemicals enter a fish through biochemical exchanges across its gill and gut membranes and through its skin. When these exchange processes have reached equilibrium, the average concentration in the whole body of the fish becomes C_F , which is related to the exposure concentration by:

$$C_F = \zeta_F \cdot \bar{C}_0 \quad (\text{for ground water loading}) \quad (3.3.3)$$

$$C_F = \zeta_F \cdot C_{x,y} \quad (\text{for direct discharge}) \quad (3.3.4)$$

where ζ_F is a bioaccumulation factor depending on both the nature of the chemical and the species of fish.

Conceptually, one more step is required in calculating average chemical dose through fish consumption. Most fish are cleaned, with much of the fat removed before consumption. Because organic chemicals are concentrated in fat, another reduction factor could be used to

derive fillet concentrations from whole fish concentrations. To be conservative, however, it is assumed that there is no reduction in chemical concentration due to the preparation of fish for consumption.

Delivery of contaminants through fish to humans--Dissolved neutral organic compounds in the water can be taken up by fish through exchange across the gill and gut membranes and through the skin. Contaminated food can be ingested, resulting in further exchange of compounds across the gut membrane. Concentration levels in the fish will rise until the activity of the compound in the blood equals the activity of the compound in the water. This condition represents chemical equilibrium. Further uptake of the compound resulting in higher blood concentrations will lead to net exchange out of the fish through the gill, gut, kidney, and skin. Consequently, any chemical buildup above the equilibrium level is controlled by the relative rates of ingestion, metabolism, and exchange. There is some evidence that active transport across the gut can cause the equilibrium concentration to be exceeded:

$$C_B = K_{FC} f_D C_x \quad (3.3.5)$$

where C_B is the dissolved concentration in the blood, mg/L, f_D is the fraction of chemical dissolved, K_{FC} is the food chain bioaccumulation factor, expected to range from 2 to 3 and C_x is the stream concentration.

If the fish is exposed to steady aqueous concentrations over a long period of time, the distribution of the compound within the various fish tissues will equilibrate, so that:

$$C_l = K_l \cdot C_B \quad (3.3.6)$$

and

$$C_{nl} = K_{nl} \cdot C_B \quad (3.3.7)$$

where:

C_l = lipid (or fat) biomass concentration (mg/kg)

K_l = lipid phase partition coefficient (l/kg)

C_{nl} = non-lipid (blood-muscle) biomass concentration (mg/kg)

K_{nl} = non-lipid partition coefficient (l/kg)

The average whole fish concentration C_F (mg/kg) is the weighted sum of the tissue concentrations:

$$C_F = f_l \cdot c_l + (1-f_l) C_{nl} \quad (3.3.8)$$

where f_l = fraction of biomass that is lipid. Substituting equation 3.3.8 and 3.3.6 into 3.3.7 gives:

$$C_F = K_{FC} \cdot K_F f_D C_X \quad (3.3.9)$$

where K_F is the entire fish partition coefficient, or bioconcentration factor given by:

$$K_F = K_1 f_1 + K_{n1} (1-f_1) \quad (3.3.10)$$

Equation 3.3.9 reduces to equation 3.3.4 provided that the parameter ζ_F is defined as:

$$\zeta_F = K_{FC} \cdot K_F \cdot f_D \quad (3.3.11)$$

Note that unlike the dilution factors, ζ_F is not dimensionless. The unit for ζ_F is l/kg. For strongly hydrophobic compounds, lipid storage dominates K_F . The lipid phase partition coefficient can be replaced by the octanol-water partition coefficient, so that, approximately:

$$K_F = K_{ow} \cdot f_1 \quad (3.3.12)$$

For less hydrophobic compounds, K_{n1} may contribute significantly to K_F . Non-lipid tissue is composed primarily of water, along with protein and carbohydrates. Assuming that partitioning to non-lipids is always less than or equal to 1% of the partitioning to lipids, a conservative estimate of K_F is approximately (R.R. Lassiter, USEPA, personal communication):

$$K_F = K_{ow} \cdot (f_1 + 0.01) \quad (3.3.13)$$

For highly polar compounds and metals, the bioconcentration factor K_F can not be estimated from the octanol-water partition coefficient and lipid fraction. In this case, observed field or experimental values of K_F must be used directly.

Delivery of contaminants to aquatic organisms--Aquatic organisms are exposed to contaminants at a distance x downstream from the point of discharge. Only dissolved species of a compound cross fish membranes and cause internal exposure. There is some evidence, however, that suspended solids with sorbed species can enhance the rate of uptake and thus internal exposure of a compound. The CCC set to protect against chronic toxic effect is generally referenced to the total concentration of a compound. Therefore, ζ_{EXP} is set to 1 and C_{EXP} is equated to C_X .

If contaminant concentrations are high enough, aquatic organisms may suffer chronic or acute toxic effects. Water quality criteria have been established by EPA to protect against these effects. These criteria specify acceptable concentrations, durations of averaging periods, and frequency of allowed excursions. To prevent a potential hazard to aquatic life, the average contaminant concentration in the surface water is directly equated to the Criterion Continuous Concentration (CCC) Water Quality Criteria. The duration of the averaging period is set at

4 nonconsecutive days, and the frequency of allowed excursions is no more than once in 3 years. To be conservative, it is assumed that the fish reside continuously within the most polluted reach of the stream where concentrations are not reduced by degradation.

For the case of runoff loading, the infrequency of runoff events (2 or 3 occurrences in 70 years) and their duration (approximately 1 day) should prevent chronic toxic effects in aquatic organisms. For the case of ground water loading and direct discharge, the continuous nature of seepage into streams may result in chronic toxic effects. Because ground water loading is expected to be relatively steady, highest stream concentrations should occur when the stream reaches low, base flow conditions, providing the least dilution water. For these conditions, both loading and dilution are driven by ground water flow. The dilution factor should be steady for a wide range of base flows, as illustrated by Figure 3.3. The model allows for the fact that a fish population can be mobile over the width of a contaminated stream during a 4 day period. Thus, the typical fish in the most contaminated stream reach will be exposed to the averaged concentration \bar{C}_{EXP} :

$$\bar{C}_{EXP} = \zeta_{EXP} \cdot \bar{C}_0 \quad (3.3.14)$$

or

$$\bar{C}_{EXP} = \zeta_{EXP} \cdot \bar{C}_{x,y} \quad (3.3.15)$$

where ζ_{EXP} is an aquatic exposure factor, equal to 1 for ground water and discharge loading, respectively.

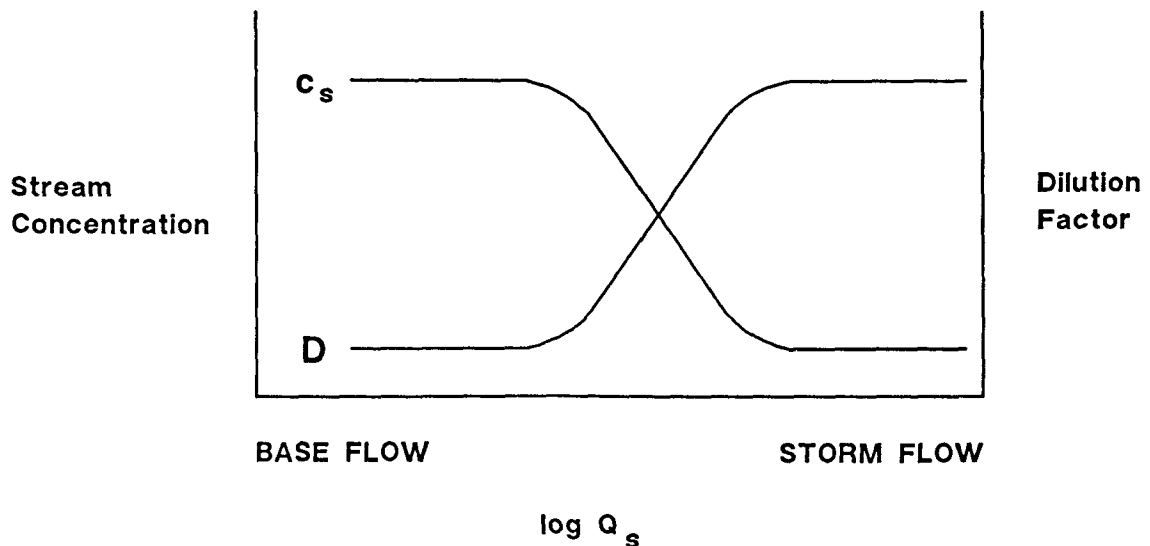


Figure 3.3 Variation of dilution factor with stream flow for steady ground water loading.

SECTION 4

USER'S MANUAL

SARAH2 is a full-screen interactive model. The computer program, through a series of menus and questions, can build and save a user-specific data file from a pre-existing default data set. This section describes all interactive screens, explains the function keys, presents an example run, describes all variables, and lists all default values.

4.1 EXPLANATION OF MENUS

SARAH2 interactively allows the user to select the chemical release pathway and exposure effect scenario. Subsequent menus include: the listing or nonlisting of intermediate calculations, forward or backward calculations, a lined or unlined lagoon (in case of a lagoon scenario), inclusion of erosion calculations (in the case of landfill runoff or lagoon overflow), exiting the program, editing the data set, or executing the program. The following is a description of all menus illustrated in Figure 4.

The first menu allows the user to specify one of nine possible loading scenarios:

MENU: Potential Contaminant Sources

1. Steady groundwater loading from landfill
2. Steady storm runoff from landfill
3. Catastrophic storm runoff from landfill
4. Continuous industrial discharge loading
5. Batch industrial discharge loading
6. Lagoon loading through groundwater
7. Lagoon loading through steady runoff
8. Lagoon loading through catastrophic dam failure
9. Lagoon loading by steady direct discharge

The second menu allows the user to specify one of three possible exposure scenarios:

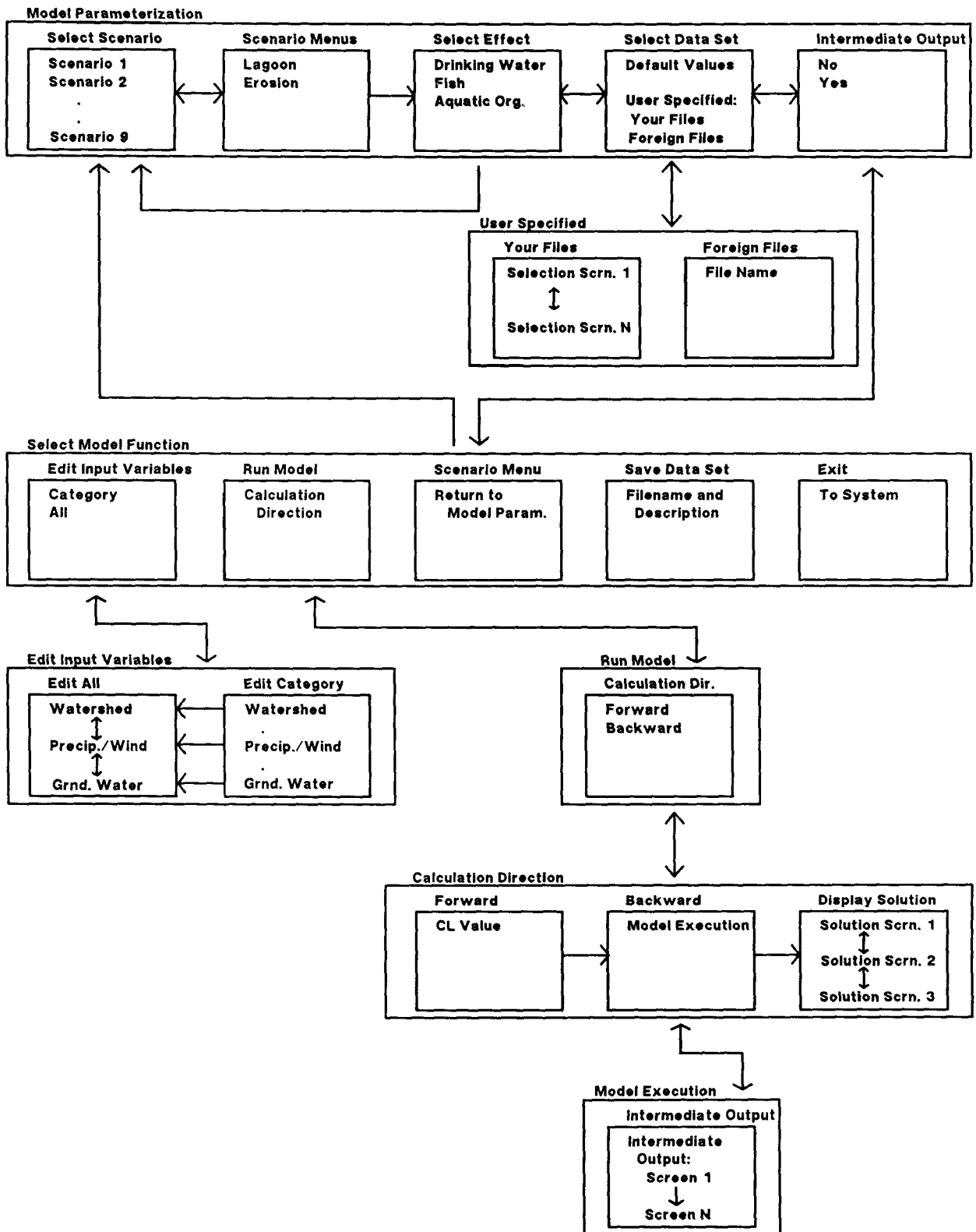


Figure 4. Menus available in SARAH2.

MENU: Potential Effect of Release

1. Human exposure through drinking water
2. Human exposure through fish consumption
3. Toxicity to aquatic organisms

If the user selects scenario 6, he/she needs to specify whether the lagoon is lined or unlined:

MENU: Is the lagoon lined or unlined?

1. Unlined
2. Lined

If the runoff or overflow pathway (scenarios 2, 3, 7, or 8) is selected, whether to include erosion calculations needs to be specified:

MENU: Erosion Equations Included?

1. No erosion
2. Erosion

The following combination of loading and exposure scenarios can not be specified due to the unsubstantial amount of time to create an exposure problem.

<u>Source</u>	<u>Effect</u>	
2	2	Steady Landfull Runoff/Fish Consumption
3	2	Catastrophic Landfill Runoff/Fish Consumption
7	2	Steady Lagoon Overflow/Fish Consumption
8	2	Catastrophic Lagoon Failure/Fish Consumption

The user specifies his data set in the third menu:

```
MENU: Select Data Set

1.  Default Values
2.  User Specified: Your Files
3.  User Specified: Foreign Files
```

The default data set is a pre-existing data set describing a small, flat watershed containing a large land disposal facility and a slow, shallow stream. To create his own, the user should choose the default data set and alter or edit the numbers to represent his scenario. If the user has already created and saved his data set, he may select #2, a user specified file. If a user specified file is chosen, the next screen lists all available files:

```
MENU: User Specified

1.  Data Set #1
2.  Data Set #2
3.  Data Set #3
```

The "foreign files" refers to an external file that has not previously been a part of the model. If the user selects a foreign file he must give the name in the following menu.

```
MENU: User Specified

Enter file name for user-specified
foreign data file.
```

The fourth menu allows the user to view all intermediate calculations:

```
MENU: Do you wish to see the model's intermediate output?

1.  No
2.  Yes
```

The fifth menu is the main operational menu

```
MENU:  SARAH2 model EDIT/RUN/RETURN/HELP/QUIT
```

1. Edit Input Values
2. Run SARAH2
3. Return to Scenario Menu
4. Save Current Dataset Values
5. Exit to System

If the user selects to "edit input values," the model allows two methods of editing:

```
MENU:  Edit Ground water Input Values by Category
```

1. Edit All Scenario Input Values by Category
2. Edit All Scenario Input Values

The quickest editing procedure would be by category, which allows the choice of the following categories.

```
MENU: Edit Groundwater Input Values by Category
```

1. Edit Watershed and Landfill Values
2. Edit Precipitation and Wind Values
3. Edit Stream Environment Values
4. Edit Chemical Values
5. Edit Loading/Exposure Values
6. Edit Groundwater Values

For example, if the user should need to alter the size of the watershed, he should select the "watershed and landfill" category. Entering a "1" results in the following screen.

MENU: Groundwater Input Values

Watershed and Landfill

AS: Surface area of the upper watershed	> 0.1000E+08	m**2
AW: Surface area that provides water	> 1000000.	m**2
AC: Surface area of contaminated catchment	> 0	m**2
DIST: Distance from land disposal site to stream	> 150.	meters
FRS: Avg frac of precip runs off upper watershed	> 0.2	unitless
FRW: The frac of precip runs off waste site	> 0.4	unitless
FRC: Avg frac of precip runs off contam. catchment	> 0	unitless

After the new value has been entered, the model returns to the editing menu:

MENU: SARA2 model EDIT VARIABLE MENU

1. Edit All Scenario Input Values by Category
2. Edit All Scenario Input Values

To return to the fifth menu (or the main "operational menu"), the user should press the F5 function key (end).

If the user elects to edit all scenario input values, the program will step the user through all subject categories. To exit a category use the "enter" key (F3). To exit the editing process use the "end" key (F5) which will return the user to the main operational menu:

MENU: SARA2 Model EDIT/RUN/RETURN/HELP/QUIT

1. Edit Input Values
2. Run SARA2 Model
3. Return to Scenario Menu
4. Save Current Dataset Values
5. Exit System

The user may return to menu 1 (scenario menu) by entering choice 3, or exit the program by entering choice 5. If the user has altered the data set, he should select number 4, "save current data set values," at

this point. If he chooses to save his new data set, the next screen will ask him to name the data set:

MENU: User Specified Save File Name and Description	
Enter file name for user supplied data file	_____.
Enter any user comments on the data file:	_____

The file name entered will appear on the list of optional files and the comment lines, which should be a brief description of the scenario, should appear any time the user requests help on that data file.

When the user elects to run the program, the next screen will ask for the direction of calculations direction:

MENU: Backward and Forward Calculations
1. Backward Calculations
2. Forward Calculations

If the user selects "backwards," then he must know the stream standards and want to determine the maximum leachate concentration. On the other hand, if he chooses "forward" calculations, the program needs C_L (the leachate concentration) and calculates the stream concentration profile. Therefore, if C_L is zero the screen will request a nonzero number:

MENU: Leachate Concentration
To do forward calculations the Leachate Concentration must be nonzero.
CL: Maximum allowable leachate concentration > 1.0 mg/L

The default value is one, but the user may enter any reasonable concentration representative of his scenario.

At this point, the model will continue and calculate leachate or instream concentrations. The next few screens will be the intermediate output or the final results. To progress through the screens, the user should press the space bar.

4.2 EXPLANATION OF FUNCTION KEYS

There are six function keys:

F1 - Help
F2 - CMDS
F3 - Next
F4 - Back
F5 - End
F6 - Exit

F1 allows the user to obtain vital information pertaining to the highlighted field contained in the current screen. Help information is available for every input variable (definition, mode, format, units, and range), every output variable (definition, mode, format, units and range), every scenario (description of source and pathway), and data set (user supplied information). Help can be accessed anytime during the model run.

F2 lists the function keys and their functions:

List of function key commands

F1 Display help information about the highlighted menu item
F2 Display a list of function key command descriptions
F3 Complete current operation and return control to calling program
F4 Suspend current operation and return to previous program
F5 Abort program execution and return control to previous program
F6 exit from the current job and return control to previous program

To exit this screen press F2 again.

F3 is basically an "enter" key. Any editing must be saved by this key. F3 also proceeds to the next logical screen.

F4 returns the user to the previous screen. This is useful if the user realizes a mistake was made on any one of the previous screens.

F5 is best used to end an editing session. This key returns the user to the operational menu. The user must use caution in that this key does not save any entered values. The user should use the following sequence when editing: enter the input variable value, press F3 to save, and then press F5 to exit editing mode.

F6 allows the user to exit the program. Exiting is allowed any time during the program execution. The user must use this key cautiously if data set storage is desired.

4.3 EXAMPLE PROBLEM

This section describes in detail the execution, results, and conclusion of an example problem. The overall approach is to demonstrate the difference in forward and backward calculations:

- 1) Given the maximum leachate concentration (from a landfill) in the groundwater, forward-calculate the instream concentration.
- 2) Using this calculated instream concentration as the drinking water standard (C_{RFD}), back-calculate the maximum leachate concentration. In this situation, the maximum leachate concentration should be equal to the concentration given in part 1 (C_L).

4.3.1. Problem

Description

Source: Landfill
Pathway: Groundwater
Effect: Drinking Water
Problem 1: Calculate in-stream concentration ($C_{x,y}$) given that the leachate concentration, C_L , is equal to 1 mg/L.
Problem 2: Calculate maximum leachate concentration (C_L) given that the drinking water standard, C_{RFD} , is equal to $C_{x,y}$.
Purpose: To check forward against backward calculations.

4.3.2. Forward

Execution

To determine the in-stream concentration, $C_{x,y}$, perform the following steps:

Menu 1

MENU: Potential Contaminant Sources

1. Steady Groundwater Loading from Landfill
2. Steady Storm Runoff from Landfill
3. Catastrophic Storm Runoff from Landfill
4. Continuous Industrial Discharge Loading
5. Batch Industrial Discharge Loading
6. Lagoon loading through groundwater
7. Lagoon loading through steady runoff
8. Lagoon loading through catastrophic dam failure
9. Lagoon loading by steady direct discharge

Select 1 (Steady ground water loading from landfill). Press F3.

Menu 2

```
MENU: Potential Effect of Release

1. Human Exposure Through Drinking Water
2. Human Exposure Through Fish Consumption
3. Toxicity to Aquatic Organisms
```

Select 1 (Human exposure through drinking water). Press F3.

Menu 3

```
MENU: Select Data Set

1. Default Values
2. User Specified: your files
3. User Specified: foreign files
```

Select 1 (Default Values). Press F3.

Menu 4

```
MENU: Do you wish to see the model's intermediate output?

1. No
2. Yes
```

Select 1 (No). Press F3.

Menu 5

```
MENU: SARAH2 model EDIT/RUN/RETURN/HELP/QUIT

1. Edit Input Values
2. Run SARAH2 Model
3. Return to Scenario Menu
4. Help for SARAH2 variables
5. Exit to System
```

Select 2 (Run SARAH2 Model). Press F3.

Menu 6

MENU: Backward or Forward Calculations

1. Backward Calculations
2. Forward Calculations

Select 2 (Forward Calculations). Press F3.

Menu 7

MENU: Leachate Concentration

To do forward calculations the Leachate
Concentration must be nonzero.

CL: Maximum allowable concentration > 1.0 mg/L

Enter 1.0 (C_L concentration). Press F3.

4.3.3. Results

At this point, the model computes the in-stream concentrations and the results are contained in the next three screens.

Screen 1

CU = 0.00000 mg/L

Forward calculations for chemical concentrations across
stream, mg/L

Distance across stream is (0 - 15.68098) meters

Press Space bar to continue

Screen 2

X	0.000	3.920	7.840	11.761	15.681
20.00	0.038	0.038	0.038	0.038	0.038
20.00	0.038	0.038	0.038	0.038	0.038
20.00	0.038	0.038	0.038	0.038	0.038
20.00	0.038	0.038	0.038	0.038	0.038
20.00	0.038	0.038	0.038	0.038	0.038
Press space bar to continue					

Screen 3

For a Leachate Concentration of 0.10000E+02 the
Predicted Drinking Water Concentration is mg/L
0.38018E-01

Press space bar to continue

4.3.4 Backward

Execution

The data set must be altered to compute the maximum leachate concentration (backward calculations) from stream standards ($C_{RFD} = 0.038$ mg/L)

Menu 1:

```
MENU:  SARAH2 model EDIT/RUN/RETURN/HELP/QUIT

1.  Edit Input Values
2.  Run SARAH2 Model
3.  Return to Scenario Menu
4.  Help for SARAH2 variables
5.  Exit to System
```

Select 1 (Edit Input Values). Press F3.

Menu 2:

```
MENU:  SARAH2 model EDIT VARIABLE MENU

1.  Edit All Scenario Input Values by Category
2.  Edit All Scenario Input Values
```

Select 1 (Edit by category). Press F3.

Menu 3:

```
MENU:  Edit Groundwater Input Values by Category

1.  Edit Watershed and Landfill Values
2.  Edit Precipitation and Wind Values
3.  Edit Stream Environment Values
4.  Edit Chemical Values
5.  Edit Loading/Exposure Values
6.  Edit Groundwater Values
```

Select 5 (Edit loading/exposure values). Press F3.

Menu 4:

```
MENU:  Groundwater Input Values

      Loading/Exposure

X:  Dist of interest downstream of source    > 100.      M
Y:  Horizontal distance                      > 15.68098    M
CRFD: Specified acceptable daily intake conc  > 0.038      mg/L
CPRFD: Specif acceptable daily bioaccumulation > 1.          mg/L
CCC:  Water quality std for aquatic organism  > 1.          mg/L
CL:   Max allowable leachate concentration    > 10.         mg/L
FL:   Fraction of biomass that is lipid in fish > 0.3         Unitless
KFC:  Food chain bioaccumulation factor       > 3.          3 mg/L
KF:   Entire fish partition coefficient       > 0           L/Kg
```

Change CRFD = 1 mg/L to CRFD = 0.038 mg/L. Press F3.

Menu 5:

```
MENU:  SARAH2 model EDIT VARIABLE MENU

1.  Edit All Scenario Input Values by Category
2.  Edit All Scenario Input Values
```

Press F5 to exit editing process.

Menu 6:

```
MENU:  SARAH2 model EDIT/RUN/RETURN/HELP/QUIT

1.  Edit Input Values
2.  Run SARAH2 Model
3.  Return to Scenario Menu
4.  Help for SARAH2 variables
5.  Exit to System
```

Select 2 (Run SARAH2 Model). Press F3.

Menu 7:

```
MENU:  Backward or Forward Calculations

1.  Backward Calculations
2.  Forward Calculations
```

Select 1 (Backward Calculations). Press F3.

4.3.5 Results

```
For a Drinking Water Concentration of
0.3800E-01 the Allowable Leachate
Concentration is 0.99953E+01 mg/L

Press space bar to continue
```

4.3.6 Conclusion

The forward calculations calculate an instream concentration of 0.038 mg/L when the leachate concentration was 1 mg/L. By running in the backwards mode,

the model calculated an allowable leachate concentration approximately equal to 1 mg/L when the stream standard was set equal to the answer given in the forward model (CRFD = 0.038).

4.4 SCENARIO VARIABLES

Numerous equations have been presented. Together they describe leachate loading, dilution, instream transport and transformation, and exposure to humans through drinking water and fish consumption. The many variables are categorized by scenarios. Then they are grouped into those scenarios describing:

- 1) watershed hydrology
- 2) stream and ground water environments
- 3) compound properties
- 4) loading/exposure scenarios
- 5) wind
- 6) dispersion
- 7) lagoon
- 8) runoff

The number of potential input variables may appear to make the practical application of these analyses difficult. Fortunately, many of these inputs can be estimated from other more readily available variables. Furthermore, many terms in the equations can be ignored for more conservative analyses.

The input variables for each scenario are listed in the following tables. These tables are designed to give the user the choice of 1) conservative analyses with a minimum set of data, 2) more complete analyses with a recommended set of data, and 3) "full equation" analyses with an optional data set.

The steps for calculating an allowable leachate concentration for Scenario 1 are summarized in Table 4.4.1. Input variables are given in Table 4.4.2. The calculations and input data for Scenarios 2 and 3 are summarized in Tables 4.4.3 and 4.4.4. Calculations and input data for Scenario 4 and 5 are summarized in Tables 4.4.5 and 4.4.6., etc.

4.5 DEFAULT VALUES

SARAH2 contains a default data file. A user may use this data set as is, or build a totally new data set. This data set represents a small, flat watershed containing a large land disposal facility and a slow, shallow stream for each variable are listed in Table 4.5.

TABLE 4.4.1 CALCULATIONS FOR SCENARIO 1

Step	Calculate	Explanation (and Equations)
1	$\tau_g(\text{TAUG})$	Travel time of contaminant from land disposal facility to stream, years (A17, A16, 3.1.18)
2	$K_g(\text{KHG})$	First-order rate coefficient for hydrolysis in ground water, years ⁻¹ (A23, A25).
3	$\zeta_H(\text{ZH})$	Mass attenuation factor in ground water (3.1.17).
4	$\zeta_{Sg}(\text{ZSG})$	Concentration dilution factor in ground water and stream (3.1.6, 3.1.19, 3.1.20).
5	$\zeta_{SU}(\text{ZSU})$	Concentration dilution factor for upstream contaminants (3.1.22, 3.1.21, Q_U/Q_S).
6	$\zeta(\text{TAU})$	Travel time of contaminant downstream, seconds (A4, 3.2.4).
7	$K(\text{KK})$	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
8	$\zeta_x(\text{ZX})$	Concentration reduction factor for downstream transformations (3.2.3).
9	$\zeta_{DW}(\text{ZDW})$	Drinking water treatment reduction factor (A15, 3.3.2).
10	$\zeta_F(\text{ZF})$	Fish bioaccumulation factor (3.1.13, A15, 3.3.6).
11	$\zeta_F(\text{ZG})$	Concentration dilution factor due to transport in ground water ($=\zeta_H \zeta_i Q_L/Q_S$) (3.1.17, 3.1.6, 3.1.19).
12	$C_L(\text{CL})$	Acceptable leachate concentration, mg/L (Drinking Water: ζ_{SU} , 3.2.3, 3.3.2, ζ_g , 67; 3.1.20, Aquatic Organisms: ζ_{SU} , ζ_g , 3.1.20 Fish Accumulation: ζ_{SU} , 3.3.6, ζ_g , 3.1.20).

TABLE 4.4.2 INPUT VARIABLES FOR SCENARIO 1

Variable	Input Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_w	m^2	$10^4 - 10^6$	AW	Conservative
A_c	m^2	$10^4 - 10^6$	AC	Optional
A_s	m^2	$10^7 - 10^9$	AS	Conservative
D_{ist}	m	$10 - 10^3$	DIST	Recommended
f_{Rs}	--	0.1 - 0.5	FRS	Recommended
f_{Rc}	--	0.1 - 0.5	FRC	Recommended
f_{Rw}	--	0.1 - 0.5	FRW	Recommended
Precipitation				
\bar{P}	cm/year	10-200	PBAR	Recommended
Ground water				
f_{ocg}	--	0.001-0.10	FOCG	Recommended
pH_g	--	5 - 8	PHG	Recommended
T_g	$^{\circ}C$	10 - 20	TG	Recommended
θ_g	l/l	0.3 - 0.5	THETAG	Recommended
T	$^{\circ}C$	10 - 20	TREF	Recommended
V_g	m/sec	$1 - 10^5$	VG	Recommended
ζ_i	--	0.1 - 1.0	ZI	Recommended
$\bar{\zeta}_i$	--	0.1 - 1.0	ZIBAR	Recommended

TABLE 4.4.2 INPUT VARIABLES FOR SCENARIO 1 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Stream Env.				
C_U	mg/l	--	CU	Optional
d_o	m	0.1 - 3	DO	Recommended
f_{oc}	--	0.01 - 0.10	FOC	Recommended
n	sec/m ^{1/3}	0.02 - 0.08	NN	Optional
Q_0	m ³ /sec	10 ⁻² - 10	QQS	Optional
q_s	m ³ /sec/m ²	10 ⁻⁹ - 10 ⁻⁸	QS	Optional
S_{slope}	m/m	10 - 50	SLOPE	Recommended
S	mg/l	10 ⁻⁴ - 10 ⁻²	SS	Optional
T_s	°C	5 - 30	TSTREAM	Recommended
U_0	m/sec	0.1 - 2	UO	Recommended
pH	--	5 - 8	PH	Optional
Wind				
W_z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional
Chemical				
H	atm - m ³ ----- mole	10 ⁻⁷ - 10 ⁻¹	HENRY	Optional
k_{HA}	l/mole/sec	0 - 10 ⁻¹	KHA	Recommended
k_{HB}	l/mole/sec	0 - 10 ⁻¹	KHB	Recommended
k_{HN}	sec ⁻¹	0 - 10 ⁻⁵	KHN	Recommended
K_{ow}	l/l	10 - 10 ⁷	KOW	Conservative
MW	--	10 - 10 ³	MW	Optional

TABLE 4.4.2 INPUT VARIABLES FOR SCENARIO 1 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
K	l/mole/sec	0 - 10 ⁻¹	KK	Optional
Exposure				
C _{RFD} '	mg/l	--	CPRFD	Conservative
C _{RFD}	mg/l	--	CRFD	Conservative
K _{FC}	mg/l	1 - 3	KFC	Recommended
f ₁	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Optional
CCC	mg/l	--	CCC	Conservative
C _L	mg/l	--	CL	Optional

TABLE 4.4.3 CALCULATIONS FOR SCENARIOS 2, 3

Step	Calculate	Explanation (and Equations)
With Erosion		
1	SY	Sediment yield (3.1.49, 3.1.48, 3.1.47, 3.1.46a, 3.1.46)
Without Erosion		
1	ζ _R (ZRU)	Concentration dilution factor in surface runoff (3.1.35, 3.1.70, 3.1.34).
2	ζ _{x,y} (ZXY)	Concentration dilution factor across stream at point of mixing (A3, 3.1.73, 3.1.74, A4, A5, A7, 3.1.69, 3.1.64).
3	ζ _{SU} (ZSU)	Concentration dilution factor for upstream contaminants (3.1.88).

TABLE 4.4.3 CALCULATIONS FOR SCENARIOS 2, 3 (Continued)

Step	Calculate	Explanation (and Equations)
4	$\tau(\text{TAU})$	Travel time of contaminant downstream, seconds (A4, 3.2.4).
5	$K(\text{KK})$	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A31, A27, A28, A26, A19).
6	$\zeta_{x,y}(\text{ZXY})$	Concentration reduction factor for downstream transformation (A8, A9, A10, 3.2.7, 3.2.6, 3.2.8, 3.2.5).
7	$\zeta_{\text{DW}}(\text{ZDW})$	Drinking water treatment reduction factor (A15, 3.3.2).
8	$C_L(\text{CL})$	Acceptable leachate concentration, mg/L (3.1.88, 3.1.34, 3.1.64, 3.3.2, 3.2.5, 2.2.3).
With Erosion		
9	C_R	Sediment concentration at stream entry point, sorbed and dissolved (3.1.57, 3.1.58, 3.1.54, 3.1.60, 3.1.55, 3.1.56, 3.1.53, 3.1.54, 3.1.51, 3.1.52, 3.1.60)

TABLE 4.4.4 INPUT VARIABLES FOR SCENARIOS 2, 3

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_w	m	$10^4 - 10^6$	AW	Conservative
A_c	m	$10^4 - 10^6$	AC	Optional
A_s	m	$10^7 - 10^9$	AS	Conservative
f_{Rc}	--	0.1 - 0.5	FRC	Recommended
f_{Rs}	--	0.1 - 0.5	FRS	Recommended
f_{Rw}	--	0.1 - 0.5	FRW	Recommended
f_R^*	--	0 - 1	FRSTAR	Recommended
D_{ist}	m	$10 - 10^3$	DIST	Recommended
Precipitation				
\bar{P}	cm/year	10 - 200	PBAR	Recommended
P_{25}	cm	10 - 15	P25	Recommended
t_{storm}	sec	$10^3 - 10^6$	TSTORM	Recommended
Stream Environment				
C_U	mg/l	--	CU	Optional
d_o	m	0.1 - 3	DO	Conservative
Q_0	m^3/sec	$10^{-2} - 10$	QQ0	Optional
q_s	$m^3/sec/m^2$	$10^{-9} - 10^{-8}$	QS	Conservative
S	mg/l	$10^{-4} - 10^{-2}$	SS	Recommended

TABLE 4.4.4 INPUT VARIABLES FOR SCENARIOS 2, 3 (Continued)

Input Variable	Units	Value Range	Computer Code Variables	Recommendation
n	sec/m ^{1/3}	0.02 - 0.08	NN	Recommended
T _S	°C	5 - 20	TSTREAM	Recommended
b	--	0.02 - 0.5	BEXP	Recommended
T _R	°C	5 - 20	TREF	Recommended
f	--	0.2 - 0.7	FEXP	Recommended
f _{oc}	--	0.01 - 0.10	FOC	Recommended
S _{slope}	m/m	10 ⁻⁴ - 10 ⁻²	SLOPE	Recommended
U _O	m/sec	--	UO	Optional
pH	--	5 - 8	PH	Optional
Q _s	m ³ /sec	10 ⁻² - 20	QQS	Optional
Dispersion				
E _x	m ² /sec	1 - 10	EX	Optional
E _y	m ² /sec	10 ⁻² - 10 ⁻¹	EY	Optional
Wind				
W _Z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional
Chemical				
K _{ow}	l/l	10 - 10 ⁷	KOW	Conservative
k _{HA}	l/mole/sec	0 - 10 ⁻¹	KHA	Optional
k _{HN}	sec ⁻¹	0 - 10 ⁻⁵	KHN	Optional
k _{HB}	l/mole/sec	0 - 10 ⁻¹	KHB	Optional
MW	--	10 - 10 ³	MW	Optional

TABLE 4.4.4 INPUT VARIABLES FOR SCENARIOS 2, 3 (Continued)

Input Variable	Units	Value Range	Computer Code Variables	Recommendation
H	atm - m ³ ----- mole	10 ⁻⁷ - 10 ⁻¹	HENRY	Optional
K	l/mole/sec	0 - 10 ⁻¹	KK	Optional
Exposure				
C _{RFD} '	mg/l	--	CPRFD	Conservative
C _{RFD}	mg/l	--	CRFD	Conservative
K _{FC}	mg/l	1 - 3	KFC	Recommended
f ₁	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Conservative
y	m	0 - B	Y	Recommended
CCC	mg/l	--	CCC	Conservative
C _R	mg/l	--	CR	Optional
Groundwater				
$\bar{\zeta}_i$	--	0.1 - 1.0	ZIBAR	Recommended
Dispersion				
E _X	m ² /sec	1 - 10	ELONG	Optional
E _y	m ²	10 ⁻² - 10 ⁻¹	ELAT	Optional
Runoff				
C _{FW}	--	0.01 - 1.0	CFW	Recommended
K _w	tons/acre	0.1 - 0.5	KW	Recommended
L _{SW}	--	0.1 - 40.0	LSW	Recommended
C _{NW}	--	30 - 100	CNW	Recommended

TABLE 4.4.4 INPUT VARIABLES FOR SCENARIOS 2, 3 (Concluded)

Input Variable	Units	Value Range	Computer Code Variables	Recommendation
P_W	--	1.0	PW	Conservative
C_{FS}	--	0.01 - 1.0	CFS	Recommended
K_S	tons/acres	0.1 - 0.5	KS	Recommended
L_{SS}	--	0.1 - 40.0	LSS	Recommended
C_{NS}	--	30 - 100	CNS	Recommended
P_S	--	1.0	PS	Conservative
C_{FC}	--	0.01 - 1.0	CFC	Recommended
K_C	tons/acres	0.1 - 0.5	KC	Recommended
L_{SC}	--	0.1 - 40.0	LSC	Recommended
C_{NC}	--	30 - 100	CNC	Recommended
P_c	--	1.0	PC	Conservative
θ_w	1/1	0.3 - 0.5	THETA _W	Recommended
K_{OWW}	1/1	10 - 10 ⁷	KOWW	Recommended
F_{OCW}	--	0.01 - 0.10	FOCW	Recommended

TABLE 4.4.5 CALCULATIONS FOR SCENARIOS 4, 5

Step	Calculate	Explanation (and Equations)
1	$\zeta_D(\text{ZWD})$	Concentration reduction factor in wastewater treatment (3.1.92, 3.1.79).
2	$\zeta_x(\text{ZX})$	Concentration dilution factor across stream at point of mixing (3.1.93, 3.1.94, A4, A5, A7, 3.1.91, 3.1.64).
3	$\zeta_{\text{SU}}(\text{ZSU})$	Concentration reduction factor for upstream contaminants (3.1.88).
4	$r(\text{TAU})$	Travel time of contaminant downstream, seconds (A4, 3.2.4).
5	$K(\text{KK})$	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
6	$\zeta_{x,y}(\text{ZXY})$	Concentration reduction factor for downstream transformation (A8, A9, A10, 3.2.7, 3.2.6, 3.2.8, 3.2.5).
7	$\zeta_{\text{DW}}(\text{ZDW})$	Drinking water treatment reduction factor (A15, 3.3.2).
8	$\zeta_F(\text{ZF})$	Fish bioaccumulation factor (3.3.13, A15, 3.3.6), 1/kg.
9	$C_W(\text{CW})$	Acceptable industrial waste concentration, mg/L (2.4.3, 2.5.1, 2.9.6, or 2.9.9).

TABLE 4.4.6 INPUT VARIABLES FOR SCENARIOS 4, 5

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_s	m^2	$10^7 - 10^9$	AS	Conservative
F_{Rs}	--	0.1 - 0.5	FRS	Recommended
Precipitation				
\bar{P}	cm/year	10 - 200	PBAR	Recommended
Stream Environment				
q_s	$m^3/sec/m^2$	$10^{-9} - 10^{-8}$	QS	Conservative
Q_0	m^3/sec	$10^{-2} - 10$	QQO	Optional
C_U	mg/l	--	CU	Optional
t_R	sec	$10^3 - 10^6$	TR	Optional
d_o	m	0.1 - 3	DO	Conservative
S_{lope}	m/m	$10^{-4} - 10^{-2}$	SLOPE	Recommended
n	$sec/m^{1/3}$	0.02 - 0.08	NN	Recommended
b	--	0.02 - 0.5	BEXP	Recommended
f	--	0.2 - 0.7	FEXP	Recommended
f_{oc}	--	0.01 - 0.10	FOC	Conservative
S	mg/l	$10^{-4} - 10^{-2}$	SS	Conservative
U_0	mg/l	--	UO	Optional
pH	--	5 - 8	PH	Optional
T_s	°C	5 - 30	TSTREAM	Optional
Wind				
W_z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional

TABLE 4.4.6 INPUT VARIABLES FOR SCENARIOS 4, 5 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Dispersion				
E_x	m^2/sec	1 - 10	ELONG	Optional
E_y	m^2/sec	10^{-2} - 10^{-1}	ELAT	Optional
Chemical				
K_{ow}	l/l	10 - 10^7	KOW	Conservative
k_{HA}	l/mole/sec	0 - 10^{-1}	KHA	Optional
k_{HN}	sec^{-1}	0 - 10^{-1}	KHN	Optional
k_{HB}	l/mole/sec	0 - 10^{-1}	KHB	Optional
MW	--	10 - 10^3	MW	Optional
H	atm - m^3 ----- mole	10^{-7} - 10^{-1}	HENRY	Optional
K	l/mole/sec	0 - 10^{-1}	KK	Optional
Loading and Exposure				
T_R	sec	15 - 25	TR	Optional
C'_{RFD}	mg/l	--	CPRFD	Conservative
C_{RFD}	mg/l	--	CRFD	Conservative
K_{FC}	mg/l	1 - 3	KFC	Recommended

TABLE 4.4.6 INPUT VARIABLES FOR SCENARIOS 4, 5 (Concluded)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
f_1	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Conservative
Y	m	0 - B	Y	Recommended
CCC	mg/l	--	CCC	Conservative
Q_{WD}	m ³ /sec	--	QWD	Recommended
C_1	mg/l	--	CL	Recommended
KFC	mg/l	0 - 4	KFC	Optional
T_D	sec	60 - 86400	TD	Recommended
W_{mass}	g	--	WMASS	Conservative
ζ_{wD}	--	0 - 1	ζW	Conservative
Q_D	m ³ /sec	--	QD	Conservative

TABLE 4.4.7 CALCULATIONS FOR SCENARIO 6

Step	Calculate	Explanation (and Equations)
Lined Lagoon		
1	P_g (PS)	Permeation rate (3.1.14).
2	Q_{wl} (QWL)	Contaminant loading rate (3.1.15).
Unlined Lagoon		
1	K_c (KC)	Corrected hydraulic conductivity term (3.1.13).
2	Q_{wl} (QWL)	Contaminant loading rate (3.1.12).
3	τ_g (TAUG)	Travel time of contaminant from land disposal facility to stream, years (A17, A16, 3.1.18)
4	K_g (KHG)	First-order rate coefficient for hydrolysis in ground water, years ⁻¹ (A23, A25).
5	ζ_H (ZH)	Mass attenuation factor in ground water (3.1.17).
6	ζ_{Sg} (ZSG)	Concentration dilution factor in ground water and stream (3.1.6, 3.1.19, 3.1.20).
7	ζ_{SU} (ZSU)	Concentration dilution factor for upstream contaminants (3.1.22, 3.1.21, Q_U/Q_S).
8	ζ (TAU)	Travel time of contaminant downstream, seconds (A4, 3.2.4).
9	K (KK)	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
10	ζ_x (ZX)	Concentration reduction factor for downstream transformations (3.2.3).
11	ζ_{DW} (ZDW)	Drinking water treatment reduction factor (A15, 3.3.2).
12	ζ_F (ZF)	Fish bioaccumulation factor (3.1.13, A15, 3.3.6).
13	ζ_F (ZG)	Concentration dilution factor due to transport in ground water ($=\zeta_H \zeta_i Q_L/Q_S$) (3.1.17, 3.1.6, 3.1.19).
14	C_L (CL)	Acceptable leachate concentration, mg/L (Drinking Water: ζ_{SU} , 3.2.3, 3.3.2, ζ_g , 67; 3.1.20, Aquatic Organisms: ζ_{SU} , ζ_g , 3.1.20 Fish Accumulation: ζ_{SU} , 3.3.6, ζ_g , 3.1.20).

TABLE 4.4.8 INPUT VARIABLES FOR SCENARIO 6

Variable	Input Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_w	m^2	$10^4 - 10^6$	AW	Conservative
A_c	m^2	$10^4 - 10^6$	AC	Optional
A_s	m^2	$10^7 - 10^9$	AS	Conservative
D_{ist}	m	$10 - 10^3$	DIST	Recommended
f_{Rs}	--	0.1 - 0.5	FRS	Recommended
f_{Rc}	--	0.1 - 0.5	FRC	Recommended
f_{Rw}	--	0.1 - 0.5	FRW	Recommended
Precipitation				
\bar{P}	cm/year	10-200	PBAR	Recommended
Ground water				
f_{ocg}	--	0.001-0.10	FOCG	Recommended
pH_g	--	5 - 8	PHG	Recommended
T_g	$^{\circ}C$	10 - 20	TG	Recommended
θ_g	1/1	0.3 - 0.5	THETAG	Recommended
T	$^{\circ}C$	10 - 20	TREF	Recommended
V_g	m/sec	$1 - 10^5$	VG	Recommended
ζ_i	--	0.1 - 1.0	ZI	Recommended
$\bar{\zeta}_i$	--	0.1 - 1.0	ZIBAR	Recommended

TABLE 4.4.8 INPUT VARIABLES FOR SCENARIO 6 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Stream Env.				
C_U	mg/l	--	CU	Optional
d_o	m	0.1 - 3	DO	Recommended
f_{oc}	--	0.01 - 0.10	FOC	Recommended
n	$\text{sec}/\text{m}^{1/3}$	0.02 - 0.08	NN	Optional
Q_0	m^3/sec	10^{-2} - 10	QQS	Optional
q_s	$\text{m}^3/\text{sec}/\text{m}^2$	10^{-9} - 10^{-8}	QS	Optional
S_{slope}	m/m	10 - 50	SLOPE	Recommended
S	mg/l	10^{-4} - 10^{-2}	SS	Optional
T	°C	5 - 30	TSTREAM	Recommended
U_0	m/sec	0.1 - 2	UO	Recommended
pH	--	5 - 8	PH	Optional
Wind				
W_z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional
Chemical				
H	$\frac{\text{atm} \cdot \text{m}^3}{\text{mole}}$	10^{-7} - 10^{-1}	HENRY	Optional
k_{HA}	1/mole/sec	0 - 10^{-1}	KHA	Recommended
k_{HB}	1/mole/sec	0 - 10^{-1}	KHB	Recommended
k_{HN}	sec^{-1}	0 - 10^{-5}	KHN	Recommended
K_{ow}	1/1	10 - 10^7	KOW	Conservative
MW	--	10 - 10^3	MW	Optional

TABLE 4.4.8 INPUT VARIABLES FOR SCENARIO 6 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
K	l/mole/sec	0 - 10^{-1}	KK	Optional
Exposure				
C'_{RFD}	mg/l	--	CPRFD	Conservative
C_{RFD}	mg/l	--	CRFD	Conservative
K_{FC}	mg/l	1 - 3	KFC	Recommended
f_1	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Optional
CCC	mg/l	--	CCC	Conservative
C_L	mg/l	--	CL	Optional
Lined Lagoon				
A_p	g - mil ----- 100 in ² · day · CmHg	10 - 1000	AP	Recommended
S_H	cc/cal	0.1 - 0.6	SH	Recommended
ϕ	cal/cc	1.0 - 160	PHI	Recommended
A_{LI}	m ²	1000 - 8000	ALI	Recommended
V_p	cmHg	.1 - 5	VP	Recommended
D_{LI}	mils	1 - 5	DLI	Recommended
D_c	kg/m ³	700 - 14,000	DC	Recommended
Unlined Lagoon				
D_c	kg/m ³	700 - 14,000	DC	Recommended
D_w	kg/m ³	990 - 1000	DW	Recommended
U_w	kg/m·sec	0.1 - 0.7	UW	Recommended
U_c	kg/m·sec	0.1 - 4.0	UC	Recommended

TABLE 4.4.8 INPUT VARIABLES FOR SCENARIO 6 (Concluded)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
K_{GW}	cm/hr	0.01 - 30.0	KGW	Recommended
A_{LA}	m ²	1000 - 8000	ALA	Recommended

TABLE 4.4.9 CALCULATIONS FOR SCENARIOS 7, 8

Step	Calculate	Explanation (and Equations)
1	D_{NEW}	The new lagoon depth after the storm or after the dam failure (3.1.37).
2	T_R	Total time of runoff (3.1.40).
3	V_{w1}	Volume of runoff (3.1.38 for no dam failure, and 3.1.41 for dam failure).
4	Q_{w1}	Runoff flow rate (3.1.42).
With Erosion		
5	SY	Sediment yield (3.1.49, 3.1.48, 3.1.47, 3.1.46a, 3.1.46).
Without Erosion		
5	$\zeta_R(ZR)$	Concentration dilution factor in surface runoff (3.1.35, 3.1.70, 3.1.34).
6	$\zeta_{x,y}(ZXY)$	Concentration dilution factor across stream at point of mixing (A3, 3.1.73, 3.1.74, A4, A5, A7, 3.1.69, 3.1.64).
7	$\zeta_{SU}(ZSU)$	Concentration dilution factor for upstream contaminants (3.1.88).

TABLE 4.4.9 CALCULATIONS FOR SCENARIOS 7, 8 (Concluded)

Step	Calculate	Explanation (and Equations)
8	τ (TAU)	Travel time of contaminant downstream, seconds (A4, 3.2.4).
9	K(KK)	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A31, A27, A28, A26, A19).
10	$\zeta_{x,y}$ (ZXY)	Concentration reduction factor for downstream transformation (A8, A9, A10, 3.2.7, 3.2.6, 3.2.8, 3.2.5).
11	ζ_{DW} (ZDW)	Drinking water treatment reduction factor (A15, 3.3.2).
12	C_L (CL)	Acceptable leachate concentration, mg/L (3.1.88, 3.1.34, 3.1.64, 3.3.2, 3.2.5, 2.2.3).
With Erosion		
13	C_R	Sediment concentration at stream entry point, sorbed and dissolved (3.1.57, 3.1.58, 3.1.54, 3.1.60, 3.1.55, 3.1.55, 3.1.56, 3.1.53, 3.1.54, 3.1.51, 3.1.52, 3.1.50).

TABLE 4.4.10 INPUT VARIABLES FOR SCENARIOS 7, 8

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_w	m	$10^4 - 10^6$	AW	Conservative
A_c	m	$10^4 - 10^6$	AC	Optional
A_s	m	$10^7 - 10^9$	AS	Conservative
f_{Rc}	--	0.1 - 0.5	FRC	Recommended
f_{Rs}	--	0.1 - 0.5	FRS	Recommended
f_{Rw}	--	0.1 - 0.5	FRW	Recommended
f_R^*	--	0 - 1	FRSTAR	Recommended
D_{ist}	m	$10 - 10^{-3}$	DIST	Recommended
Precipitation				
\bar{P}	cm/year	10 - 200	PBAR	Recommended
P_{25}	cm	10 - 15	P25	Recommended
t_{storm}	sec	$10^3 - 10^6$	TSTORM	Recommended
Stream Environment				
C_U	mg/l	--	CU	Optional
d_o	m	0.1 - 3	DO	Conservative
Q_0	m^3/sec	$10^2 - 10$	QQ0	Optional
q_s	$m^3/sec/m^2$	$10^{-9} - 10^{-8}$	QS	Conservative
S	mg/l	$10^{-4} - 10^{-2}$	SS	Recommended
n	$sec/m^{1/3}$	0.02 - 0.08	NN	Recommended
T_s	°C	5 - 20	TSTREAM	Recommended
b	--	0.02 - 0.5	BEXP	Recommended

TABLE 4.4.10 INPUT VARIABLES FOR SCENARIOS 7, 8 (Continued)

Input Variable	Units	Value Range	Computer Code Variables	Recommendation
T_R	$^{\circ}\text{C}$	5 - 20	TREF	Recommended
f	--	0.2 - 0.7	FEXP	Recommended
f_{oc}	--	0.01 - 0.10	FOC	Recommended
S_{lope}	m/m	10^{-4} - 10^{-2}	SLOPE	Recommended
U_0	m/sec	--	UO	Optional
pH	--	5 - 8	PH	Optional
Dispersion				
E_x	m^2/sec	1 - 10	EX	Optional
E_y	m^2/sec	10^{-2} - 10^{-1}	EY	Optional
Wind				
W_z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional
Chemical				
K_{ow}	l/l	10 - 10^7	KOW	Conservative
k_{HA}	l/mole/sec	0 - 10^{-1}	KHA	Optional
k_{HN}	sec^{-1}	0 - 10^{-5}	KHN	Optional
k_{HB}	l/mole/sec	0 - 10^{-1}	KHB	Optional
MW	--	10 - 10^3	MW	Optional
H	atm - m^3 ----- mole	10^{-7} - 10^{-1}	HENRY	Optional
K	l/mole/sec	0 - 10^{-1}	KK	Optional
Exposure				
C'_{RFD}	mg/l	--	CPRFD	Conservative

TABLE 4.4.10 INPUT VARIABLES FOR SCENARIOS 7, 8 (Concluded)

Input Variable	Units	Value Range	Computer Code Variables	Recommendation
C_{RFD}	mg/l	--	CRFD	Conservative
K_{FC}	mg/l	1 - 3	KFC	Recommended
f_1	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Conservative
y	m	0 - B	Y	Recommended
CCC	mg/l	--	CCC	Conservative
C_R	mg/l	--	CR	Optional
Groundwater				
$\bar{\zeta}_i$	--	0.1 - 1.0	ZIBAR	Recommended
Dispersion				
E_X	m ² /sec	1 - 10	ELONG	Optional
E_y	m ²	10 ⁻² - 10 ⁻¹	ELAT	Optional
Runoff				
C_{FW}	--	0.01 - 1.0	CFW	Recommended
K_w	tons/acre	0.1 - 0.5	KW	Recommended
L_{SW}	--	0.1 - 40.0	LSW	Recommended
C_{NW}	--	30 - 100	CNW	Recommended
Lagoon				
D_B	m	0 - 5	DB	Recommended
F_{BD}	m	0.5 - 10.0	FBD	Recommended
D_{OLD}	m	0.5 - 5.0	DOLD	Recommended
A_{LA}	m ²	1000 - 8000	ALA	Recommended
θ_w	1/1	0.3 - 0.5	THETAW	Recommended
K_{oww}	1/1	10 - 10 ⁷	KOWW	Recommended

TABLE 4.4.11 CALCULATIONS FOR SCENARIO 9

Step	Calculate	Explanation (and Equations)
1	$\zeta_D(ZD)$	Concentration reduction factor in wastewater treatment (3.1.92, 3.1.79).
2	$\zeta_{SR,y}(ZSRY)$	Concentration dilution factor across stream at point of mixing (3.1.93, 3.1.94, A4, A5, A7, 3.1.91, 3.1.64).
3	$\zeta_{SU}(ZSU)$	Concentration reduction factor for upstream contaminants (3.1.88).
4	$\tau(TAU)$	Travel time of contaminant downstream, seconds (A4, 3.2.4).
5	$K(KK)$	First order rate coefficient for hydrolysis and volatilization in stream, seconds ⁻¹ (A15, A22, A24, A30, A29, A34, (A32, A33, or A35), A27, A28, A26, A19).
6	$\zeta_{x,y}(ZXY)$	Concentration reduction factor for downstream transformation (A8, A9, A10, 3.2.7, 3.2.6, 3.2.8, 3.2.5).
7	$\zeta_{DW}(ZDW)$	Drinking water treatment reduction factor (A15, 3.3.2).
8	$\zeta_F(ZF)$	Fish bioaccumulation factor (3.3.13, A15, 3.3.6), 1/kg.
9	$C_W(CW)$	Acceptable industrial waste concentration, mg/L (2.4.3, 2.5.1, 2.9.6, or 2.9.9).

TABLE 4.4.12 INPUT VARIABLES FOR SCENARIO 9

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Watershed and Landfill				
A_s	m^2	$10^7 - 10^9$	AS	Conservative
F_{Rs}	--	0.1 - 0.5	FRS	Recommended
Precipitation				
\bar{P}	cm/year	10 - 200	FBAR	Recommended
Stream Environment				
q_s	$m^3/sec/m^2$	$10^{-9} - 10^{-8}$	QS	Conservative
Q_0	m^3/sec	$10^{-2} - 10$	QQ0	Optional
C_U	mg/l	--	CU	Optional
t_R	sec	$10^3 - 10^6$	TR	Optional
d_o	m	0.1 - 3	DO	Conservative
S_{lope}	m/m	$10^{-4} - 10^{-2}$	SLOPE	Recommended
n	$sec/m^{1/3}$	0.02 - 0.08	NN	Recommended
b	--	0.02 - 0.5	BEXP	Recommended
f	--	0.2 - 0.7	FEXP	Recommended
f_{oc}	--	0.01 - 0.10	FOC	Conservative
S	mg/l	$10^{-4} - 10^{-2}$	SS	Conservative
U_0	mg/l	--	UO	Optional
pH	--	5 - 8	PH	Optional
T_s	°C	5 - 30	TSTREAM	Optional
Wind				
W_z	m/sec	0 - 10	WZ	Optional
Z	m	0 - 10	Z	Optional

TABLE 4.4.12 INPUT VARIABLES FOR SCENARIO 9 (Continued)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
Dispersion				
E_x	m^2/sec	1 - 10	ELONG	Optional
E_y	m^2/sec	10^{-2} - 10^{-1}	ELAT	Optional
Chemical				
K_{ow}	l/l	10 - 10^7	KOW	Conservative
k_{HA}	l/mole/sec	0 - 10^{-1}	KHA	Optional
k_{HN}	sec^{-1}	0 - 10^{-1}	KHN	Optional
k_{HB}	l/mole/sec	0 - 10^{-1}	KHB	Optional
MW	--	10 - 10^3	MW	Optional
H	atm - m^3 ----- mole	10^{-7} - 10^{-1}	HENRY	Optional
K	l/mole/sec	0 - 10^{-1}	KK	Optional
Loading and Exposure				
T_R	sec	15 - 25	TR	Optional
C'_{RFD}	mg/l	--	CPRFD	Conservative
C_{RFD}	mg/l	--	CRFD	Conservative
K_{FC}	mg/l	1 - 3	KFC	Recommended
f_1	--	0.01 - 0.25	FL	Conservative
X	m	0 - 5000	X	Conservative
Y	m	0 - B	Y	Recommended
CCC	mg/l	--	CCC	Conservative
Q_{WD}	m^3/sec	--	QWD	Recommended

TABLE 4.4.12 INPUT VARIABLES FOR SCENARIO 9 (Concluded)

Input Variable	Units	Value Range	Computer Code Variable	Recommendation
C ₁	mg/l	--	CL	Recommended
KFC	mg/l	0 - 4	KFC	Optional
T _D	sec	60 - 86400	TD	Recommended
W _{mass}	g	--	WMASS	Conservative
ζ _{wD}	--	0 - 1	ζW	Conservative
Q _D	m ³ /sec	--	QD	Conservative

TABLE 4.5. DEFAULT VALUES

			#1
Watershed and Landfill			
AS			1.0E9
AW			1.0E6
AC			0.0E0
EIST			150.0E0
FRS			0.20E0
FRSTAR	(SCEN.EQ. 3)		1.0E0
FRSTAR	(SCEN.EQ. 2)		1.0E0
FRW			0.4E0
FRW	(SCEN.EQ. 2)		1.0E0
FRW	(SCEN.EQ. 3)		0.60E0
FRC			0.0E0
Precipitation			
P25			30.0E0
PBAR			10.0E0
TSTORM			86400.0E0
Stream Environment			
BEXP			0.23E0
FEXP			0.42E0
QS			0.5E-8
Stream Environment (cont.)			
SLOPE			9.0E-5
EO			0.1E0
NN			0.04E0
QQO			0.0E0
UO			0.0E0
TSTREAM			20.0E0
SS			10.0E0
PH			7.0E0
FOC			0.05E0
CU			0.0E0
TREF			25.0E0

*Note E5 = 10⁵

TABLE 4.5. DEFAULT VALUES (Cont.)

Wind		
Z		10.0E0
WZ		1.4E0
Chemical		
KK		0.0E0
KHA		0.0E0
KHB		0.0E0
KHN		0.0E0
HENRY		1.0E-7
MW		1.0E3
KOW		1.0E3
Loading/Exposure		
X		1.0E3
Y		0.0E0
CRFD		1.0E0
CPRFD		1.0E0
CCC		1.0E0
CL		0.0E0
FL		0.3E0
KFC		3.0E0
TR	(SCEN.EQ. 2)	8.64E4
TR	(SCEN.EQ. 3)	7.20E3
Loading/Exposure		
TE	(SCEN.EQ. 4)	8.64E4
TE	(SCEN.EQ. 5)	7200.0E0
WMASS		0.0E0
ZW		1.0E0
QWE		4.0E-3
QE		4.0E-3
Ground water		
VG		10.0E0
THETAG		0.5E0

TABLE 4.5. DEFAULT VALUES (Cont.)

TG	20.0E0
FOCG	0.01E0
TREF	25.0E0
ZIBAR	0.5E0
ZI	1.0E0
PHG	5.0E0

Dispersion	
ELAT	0.0E0
ELONG	0.0E0

Lagoon	
EC	1500.0E0
EW	998.2E0
KGW	0.2E0
UW	1.002E0
UC	0.5E0
ALA	1.0E2
AP	1.0E4
SH	0.23E0
PHI	44.0E0
TR	0.0E0
FBE	4.0E0
EOLE	4.0E0
EB	0.0E0
QWL	4.0E-3
QE	0.0E0
LMASS	0.0E0
CWL	0.0E0
ZL	0.0E0

REFERENCES

1. Ambrose, R.A., Mulkey, L.A., and Huyakorn, P.S. 1985. A methodology for assessing surface water contamination due to land disposal. EPA draft report.
2. Ambrose, R.A., Vandergrift, S.B. 1986. SARAH, A surface water assessment model for back calculating reductions in abiotic hazardous wastes. U.S. Environmental Protection Agency, Athens, GA. EPA-600-3-86-058.
3. Burns, L.A., Cline, D.M., and Lassiter, R.R. 1982. Exposure analysis modeling system (EXAMS): User manual and system documentation. U.S. Environmental Protection Agency, Athens, GA. EPA-600/3-82-023.
4. Carsel, R.F. and R.S. Parrish. 1988. Developing joint probability distributions of soil-water retention characteristics. Water Resources Research (in press).
5. Covar, A.P. 1976. Selecting the proper reaeration coefficient for use in water quality models. Presented at the U.S. EPA Conference on Environmental Simulation and Modeling, Cincinnati, OH, April 19-22, 1976.
6. Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J., and Brooks, N.H. 1979. Mixing in inland and coastal waters. Academic Press, New York.
7. Haith DA. 1980. A mathematical model for estimating pesticide losses in runoff. Journal of Environmental Quality. 9(3):428-433.
8. Israelsen, O.W. and Hansen, V.E. 1962. Irrigation principles and practices. John Wiley and Sons, Inc., New York. 447 pp.
9. Karickhoff, S.W. 1981. Semi-empirical estimation of sorption of hydrophobic pollutants on natural sediments and soils. Chemosphere. 10(8):833-846.
10. Karickhoff, S.W., Brown, D.S., and Scott, T.A. 1979. Sorption of hydrophobic pollutants on natural sediments. Water Res. 13:241-248.
11. Leopold, L.B. and Maddock, T. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey, Washington, DC. Professional Paper No. 252.
12. Liss, P.S. 1973. Processes of gas exchange across an air-water interface. Deep-Sea Res. 20:221-23B.

13. Lyman, W.J., Reehl W.F., Rosenblatt DH. 1982. Handbook of chemical property estimation methods. New York. McGraw-Hill.
14. Marin, Carlos. 1988. Personal communication.
15. Mills, W.B., Dean, J.D., Porcella, D.B., et al. 1982. Water quality assessment: a screening procedure for toxic and conventional pollutants: parts 1, 2, and 3. U.S. Environmental Protection Agency, Athens, GA. EPA/600/6-85/002 a, b, c.
16. Park, C.C. 1977. World-wide variations in hydraulic geometry exponents of stream channels: an analysis and some observations. Journal of Hydrology, 33 (1977):133-146.
17. Salame, M. (no date) Permeability-structure relationships of high polymers. Obtained by private communication. Monsanto Co., Bloomfield, CT.
18. Salame, M. 1961. The prediction of liquid permeation in polyethylene and related polymers. SPE Trans. 1(4):153.
19. Salame, M. 1973. Transport properties of nitrile polymers. J. Polymer Sci. 41:1-15.
20. Salame, M. 1985. Private communication. Monsanto Co., Bloomfield, CT.
21. Schwab, G.O., Frevert, R.K., Edminster, T.W., Barnes, K.K. 1966. Soil and water conservation engineering. 2nd edn. John Wiley and Sons, New York, NY.
22. Steingiser, S., Nemphos, S.P., Salame, M. 1978. Barrier polymers. In: Kirk-Othmer encyclopedia of chemical technology, 3rd ed. John Wiley and Sons, New York, NY.
23. Versar, Inco 1983. Theoretical evaluation of sites located in the zone of saturation. Draft final report. Versar, Inc., Chicago IL. U.S. Environmental Protection Agency. Contract No. 68-01-6438.
24. Versar, Inc. 1987. Superfund Exposure Assessment Manual. U.S. EPA draft report. OSWER Directive 9285.5-1. pp 2-33 - 2-42; 2-46- 2-55.
25. Whitman, R.G. 1923. A preliminary experimental confirmation of the two-film theory of gas absorption. Chem. Metallurg. Eng. 29:146-148.
26. Williams, J.R. 1975. Sediment-yield prediction with the universal equation using runoff energy factor. In: present and prospective technology for predicting sediment yields and sources. U.S. Department of Agriculture, Washington, DC. ARS-S-40.
27. Wischmeier W.H. 1972. Estimating the cover and management factor on undisturbed areas. U.S. Department of Agriculture, Oxford, MS: Proceedings of the USDA Sediment Yield Workshop.

APPENDIX A

ADVECTION, DISPERSION AND CHEMICAL TRANSFORMATION IN STREAM

This appendix describes procedures and formulas for estimating the physical parameters of advection, dispersion and chemical transformation in surface water.

A.1. ADVECTION

A compound introduced to a water body will be advected downstream with the bulk water at mean velocity U such that

$$U = Q / (B \cdot d) \quad (A1)$$

where Q = stream flow, m^3/sec

For a given flow in a specific stream reach, width, depth, and velocity are related empirically by the following equations (Leopold and Maddock, 1953).

$$B = aQ^b \quad (A2)$$

$$d = cQ^f \quad (A3)$$

$$U = kQ^m \quad (A4)$$

where the sum of the exponents ($b+f+m$) and the product of the constants ($a \cdot c \cdot k$) must equal 1.0. Although theoretical considerations predict that $b = 0.23$, $f = 0.42$, and $m = 0.35$, considerable variations have been observed among sites. Figure A.1 presents the exponents observed at 139 sites, as analyzed by Park (1977).

The upstream base flow for subwatersheds can be calculated from the relationship where:

$$Q\phi = A_s \cdot q_s \quad (A5)$$

where q_s = average flow per unit area $\frac{m^3/sec}{m^2}$

A_s = area of the watershed (m^2)

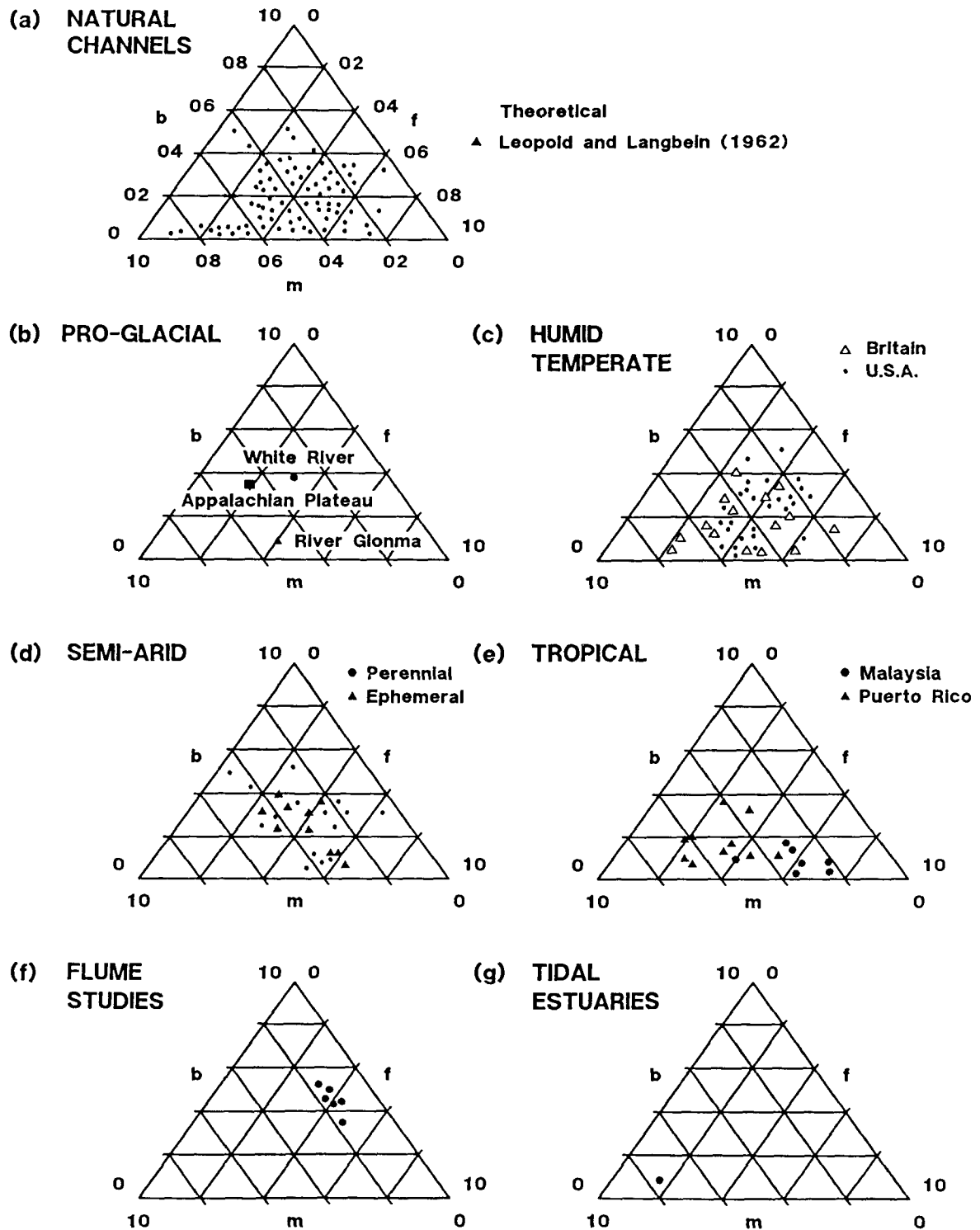


Figure A. Tri-axial Graphs of At-a-Station Hydraulic Geometry Exponesnts

Velocity at baseflow, U_o can be calculated by Manning's equation:

$$U_o = d_o^{2/3} \cdot s^{1/2}/n \quad (A6)$$

where: d_o = depth baseflow (m)

s = channel slope (m/m)

n = Manning's roughness coefficient ($\text{sec}/\text{m}^{1/3}$)

The width at baseflow B_o , can be calculated from U_o , d_o , and the baseflow Q_o using equation A1 rearranged:

$$B_o = Q_o/(U_o \cdot d_o) \quad (A7)$$

The upstream flow during a storm includes both baseflow and runoff, as given by equation A6:

$$Q_U = Q_o + A_U P_{25} \bar{f}_R/(100 \cdot t_s) \quad (A8)$$

Given the baseflow values B_o , d_o , U_o , and Q_o and the stormflow value Q , the widths, depths, and velocities for stormflow conditions can be calculated as:

$$B = B_o (Q_U/Q_o)^b \quad (A9)$$

$$d = d_o (Q_U/Q_o)^f \quad (A10)$$

$$U = U_o (Q_U/Q_o)^{1-b-f} \quad (A11)$$

When the theoretical values for b and f hold, U increases with Q to the $1/3$ power. A ten-fold increase in flow, results in a doubling of velocity.

Streamflows and the associated hydraulic variables, can be synthesized from: 1) distributions of watershed areas, A_s 2) areal flows, q 3) channel slopes, slope 4) channel roughness factors n , precipitation totals p_{25} , 5) runoff coefficients, f_R 6) hydraulic geometry exponents b and f .

A.2. DISPERSION

A compound advected through a water body will be mixed vertically, laterally, and longitudinally from areas of high concentration to areas of low concentration. The rate of mixing is proportional to the concentration gradient and either a turbulent mixing coefficient or a dispersion coefficient. A turbulent mixing coefficient in rivers is proportional to the length scaled and the intensity of turbulence (which is represented by the shear velocity):

$$U_{sv} = \sqrt{g \cdot d \cdot s} \quad (A12)$$

where: U_{sv} = shear velocity (m/sec)

s = channel slope (m/m)

d = mean depth (m)

g = acceleration of gravity (m/sec²)

Because vertical mixing in streams occurs very quickly, we assume completion during the initial dilution stage. Lateral mixing is most important in the near field. It is smallest for uniform straight channels, and increases with curves and irregularities. Fischer et al. (1979) suggest calculating the lateral diffusion coefficient as:

$$E_y = 0.6 \cdot d \cdot U_{sv}, \pm 50\% \quad (A13)$$

The proportionality factor can vary evenly between 0.4 and 0.8.

Longitudinal turbulent mixing is generally much smaller than shear flow dispersion (which is caused by velocity gradients). Fischer and coworkers, suggest calculating the longitudinal dispersion coefficient with the approximate relationship:

$$E_x = 0.011 U^2 \cdot B^2 / d \cdot U_{sv} \quad (A14)$$

Here, again, the proportionality factor can vary $\pm 50\%$.

A.3. CHEMICAL TRANSFORMATION

A compound transported through a water body can undergo several physical and chemical transformations. Fast reactions are treated by assuming local equilibrium conditions. Sorption is considered to be in equilibrium with desorption:

$$SS + C_w = C_s \quad (A15)$$

where: SS = sediment concentration (kg/l)

C_w = dissolved aqueous concentration (mg/l)

C_s = sorbed concentration (mg/l)

The local equilibrium concentrations C_w and C_s are governed by the equilibrium distribution coefficient K_p (l/kg):

$$K_p = \frac{C_s}{S' \cdot C_w} \quad (A16)$$

Karickhoff et al., 1979, have shown that for sorption of hydrophobic organic compounds:

$$K_p = K_{oc} \cdot f_{oc} \quad (A17)$$

where: K_{oc} = organic carbon partition coefficient (l/kg)

f_{oc} = organic carbon fraction of sediment (unitless)

Karickhoff et al. (1979) further correlated K_{oc} with K_{ow} for organic sediments. Subsequent work by Karickhoff (1981) suggested the proportionality factor for mixed sediments of 0.4:

$$K_{oc} = 0.41 \cdot K_{ow} \quad (A18)$$

Combining equations A16 - A18 and rearranging terms gives an expression for the fraction of the compound that is dissolved:

$$f_D = \frac{1}{1 + 0.41 \cdot K_{ow} \cdot f_{oc} \cdot SS \cdot 10^{-6}} \quad (A19)$$

The sorbed chemical fraction f_s is equal to $1 - f_D$.

The fraction of the compound that is dissolved in ground water can be calculated from an equivalent expression:

$$f_{Dg} = \frac{\theta_g}{\theta_g + 0.41 \cdot K_{ow} \cdot f_{ocg} \cdot \rho_{bg}} \quad (A20)$$

where: θ_g = volumetric water content of porous medium, l^3/l^3

f_{ocg} = organic carbon fraction of porous medium (unitless)

ρ_{bg} = bulk density of porous medium (kg/l)

$$\text{and } \rho_{bg} = 2.65 \cdot (1 - \theta_g) \quad (A21)$$

The sorbed chemical fraction f_{sg} is equal to $1 - f_{Dg}$.

Slower chemical transformation reactions can be treated generally by using mixed second order kinetics (Burns et al., 1982):



where: $[E]_i$ = environmental property for process "i"

P = transformation product (mg/l)

The reaction rate R_i (mg/l-sec) for process "i" is:

$$R_i = k_i \cdot Y_i \cdot f_D \cdot C \quad (A23)$$

where: k_i = second order rate constant for process "i"

Y_i = yield coefficient for process "i"

C = total concentration of compound (mg/l)

Given a local value for $[E]_i$, a pseudo-first order rate constant K_i (sec^{-1}) can be calculated:

$$K_i = k_i \cdot [E]_i \cdot Y_i \cdot f_D \quad (A24)$$

For a compound undergoing several competing reactions, the overall pseudo-first order rate constant K (sec^{-1}) is:

$$K = \sum_i K_i \quad (A25)$$

This general second order reaction method can be used to predict reaction rates for photolysis, hydrolysis, oxidation, and bacterial degradation. For short reaches of rivers with travel times of hours, these reactions are not likely to significantly reduce instream concentrations. For transient loads during storms, darkness should further reduce photolysis and, indirectly, oxidation. Bacterial communities are unlikely to acclimate in hours to the transient loads. Of these transformation reactions, then, only hydrolysis will be considered for those few compounds with large rate constants. The nominal hydrolysis rate constant is calculated from the acid-catalyzed, neutral, and base-catalyzed pathways (Burns et al., 1982):

$$K_{Ho} = (k_{HA}[H^+] (\alpha \cdot f_s + f_D) + k_{HN} + k_{HB}[OH^-] \cdot (f_D)) / 3600. \quad (A26)$$

where: k_{HA} = second-order acid-catalysis hydrolysis rate constant (l/mole-hour)

$[H^+]$ = hydrogen ion concentration = 10^{-pH} (mole/l)

pH = stream pH

α = acid-catalysis hydrolysis rate enhancement factor for sorbed compound = 10

k_{HN} = neutral hydrolysis rate constant (hr^{-1})

k_{HB} = second-order base-catalysis hydrolysis rate constant, (l/mole-hr)

$[OH^-]$ = hydronium ion concentration = 10^{-pOH} (mole/l)

pOH = stream pOH = 14 - pH.

For ground water, the nominal hydrolysis rate constant (in years⁻¹) is calculated from an equivalent expression:

$$K_{go} = (k_{HA}[H^+]_g(\alpha \cdot f_{sg} + f_{Dg}) + k_{HN} + k_{HB}[OH^-]_g \cdot f_{Dg}) \cdot (24) \cdot (365.25)$$

where: $[H^+]_g$ = hydrogen ion concentration = 10^{-pH_g} (mole/l)

pH_g = ground water pH

$[OH^-]_g$ = hydronium ion concentration = 10^{-pOH_g} (mole/l)

pOH_g = ground water pOH = $14 - pH_g$

The nominal hydrolysis rate constants K_{Ho} and K_{go} apply to a reference temperature, T_R (usually 25 °C). These can be corrected to ambient surface or ground water temperatures (T or T_g) with the following Arrhenius expressions.

$$K_H = K_{Ho} \cdot \exp[10^4 \cdot (\frac{1}{T_R + 273} - \frac{1}{T + 273})] \quad (A28)$$

$$K_g = K_{go} \cdot \exp[10^4 \cdot (\frac{1}{T_R + 273} - \frac{1}{T_g + 273})] \quad (A29)$$

A final transformation pathway to consider is volatilization. The volatilization rate constant K_v (sec⁻¹) can be calculated from the Whitman, or two-resistance model (Whitman, 1923; Burns et al., 1982):

$$K_v = \frac{1}{d} \cdot \frac{1}{R_L + R_G} \cdot f_D \quad (A30)$$

where: d = mean stream depth (m)

R_L = liquid phase resistance (sec/m)

R_G = gas phase resistance (sec/m)

The second term in equation A30 represents the conductivity of the compound through a liquid and a gas boundary layer at the water surface. The liquid phase resistance to the compound is assumed to be proportional to the transfer rate of oxygen (which is limited by the liquid phase only):

$$R_L = \frac{1}{K_{O2} \cdot d \cdot \sqrt{32/MW}} \quad (A31)$$

where: K_{O2} = reaeration rate constant (sec^{-1})

MW = molecular weight of the compound

32 = molecular weight of oxygen.

The gas phase resistance to the compound is assumed to be proportional to the transfer rate of water vapor (which is limited by the gas phase only):

$$R_G = \frac{1}{\frac{H}{RT'} \cdot WAT \cdot \sqrt{18/MW}} \quad (\text{A32})$$

where: WAT = water vapor exchange constant (m/sec)

18 = molecular weight of water

H = Henry's law constant ($\text{atm} \cdot \text{m}^3/\text{mole}$)

R = ideal gas constant = $8.206 \times 10^{-5} \text{ m}^3 \cdot \text{atm}/\text{mol} \cdot ^\circ\text{K}$

T' = water temperature ($^\circ\text{K}$) = $273 + T$

The reaeration and water vapor exchange constants will vary with stream reach and time of year. They can be calculated using one of several empirical formulations. The water vapor exchange constant will be calculated using wind speed and a regression proposed by Liss (1973):

$$WAT = 5.16 \times 10^{-5} + 3.156 \times 10^{-3} \cdot W \quad (\text{A33})$$

where: W = wind speed at 10 cm above surface (m/sec)

Wind speed measured above 10 cm can be adjusted to the 10 cm height assuming a logarithmic velocity profile and a roughness height of 1 mm (Israelsen and Hanson, 1962):

$$W = W_z \cdot \log(0.1/0.001)/\log(z/0.001) \quad (\text{A34})$$

where: W_z = wind speed at height z (m/sec)

Z = wind measurement height (m)

The reaeration rate constant will be calculated by the Covar method using stream velocity U and depth d, then corrected for temperature (Covar, 1976).

$$K_{O2} = K_{20} \cdot 1.024^{T-20} \quad (\text{A35})$$

where: K_{20} = reaeration rate at 20°C

For shallow streams where depth is less than 0.61 m, the Covar method uses the Owens formula:

$$K_{20} = 6.194 \cdot 10^{-5} \cdot U^{0.67} \cdot d^{-1.85} \quad (A36)$$

For deeper, slower streams ($d > 0.61$, $U < 0.518$), the formula selected depends upon the transition depth:

$$K_{20} = 4.555 \cdot 10^{-5} \cdot U^{0.5} \cdot d^{-1.5} \quad (A37)$$

For deeper, faster streams ($d > 0.61$, $U > 0.518$), the formula selected depends upon the transition depth:

$$d_T = 4.1404 \cdot U^{2.9135} \quad (A38)$$

When $d > d_T > 0.61$, the O'Connor-Dobbins formula is used. When $d_T > d > 0.61$, the Churchill formula is used:

$$K_{20} = 5.825 \cdot 10^{-5} \cdot U^{0.969} \cdot d^{-1.673} \quad (A39)$$

In summary, three transformation processes are considered in this analysis: sorption, hydrolysis, and volatilization. Sorption of hydrophobic organic compounds is calculated by equation A19 using data for K_{ow} , f_{ow} , and s . Hydrolysis is calculated by equations A26 and A28 using data for pH, k_{HA} , k_{HN} , and k_{HB} . Volatilization is calculated by equations A22 through A34 using data for U , d , W , T , MW , and H . When insufficient data are available, ignoring any of these processes is acceptable in order to complete conservative analyses.

APPENDIX B

ANALYTICAL SOLUTION FOR TWO-DIMENSIONAL FLOW DUE TO PULSE LOADING

The stream transport model described in the main body of this report, is based on our analytical solution for two-dimensional transport from a distributed vertical plane source in uniform flow (Figure B.1). The case involving pulse release of contaminant is considered. The analytical solution for this case is developed in this appendix.

Consider the region with the Gaussian distributed source shown in Figure B.1. The advective-dispersive equation for transport of a nonconservative contaminant in uniform stream flow can be written as:

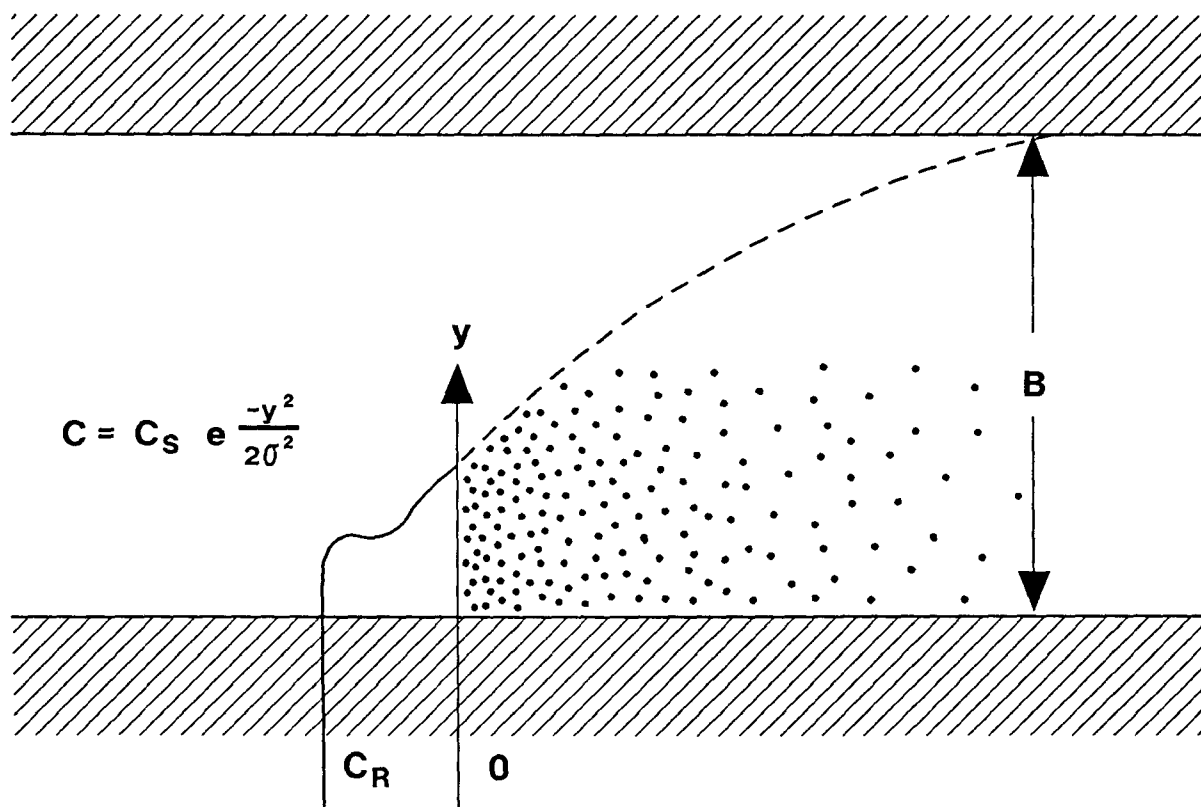


Figure B.1. Schematic Description of Two-Dimensional Transport in Uniform Flow

$$U \frac{\partial c}{\partial x} - E_x \frac{\partial^2 c}{\partial x^2} - E_y \frac{\partial^2 c}{\partial y^2} + Kc + \frac{\partial c}{\partial t} = 0 \quad (B1)$$

where: E_x = longitudinal dispersion coefficients
 E_y = transverse dispersion coefficients
 U = the main flow velocity in the x-direction
 C = the solute concentration
 K = the first-order decay constant
 T = the elapsed time

The initial and boundary conditions associated with equation B1 may be expressed as:

$$c(x, y, 0) = 0 \quad (B2)$$

$$c(\infty, y, t) = 0 \quad (B3)$$

$$\frac{\partial c}{\partial y}(x, 0, t) = 0 \quad (B4)$$

$$\frac{\partial c}{\partial y}(x, B, t) = 0 \quad (B5)$$

$$c(0, y, t) = C_s \exp(-y^2/2\sigma^2), \quad t \leq t_R \quad (B6)$$

$$c(0, y, t) = 0, \quad t > t_R$$

where C_s and σ are the peak concentration and standard deviation of the Gaussian source assumed to be located at $x = 0$.

The analytical solution for the above case can be derived in two steps. The first step involves an application of the image source theory to the fundamental solution of the corresponding case. In this case the stream is of infinite width and the contaminant is continuously released from the source. Let C_f^* denote the fundamental solutions. The expression for C_f^* has been derived in the report dealing with ground water screening procedures. It may be written as:

$$C_f^*(x, y, t) = \left[\frac{\sigma x \exp(U_x/2E_x)}{(2\pi E_x)^{1/2}} \cdot I \right] C_s \quad (B7)$$

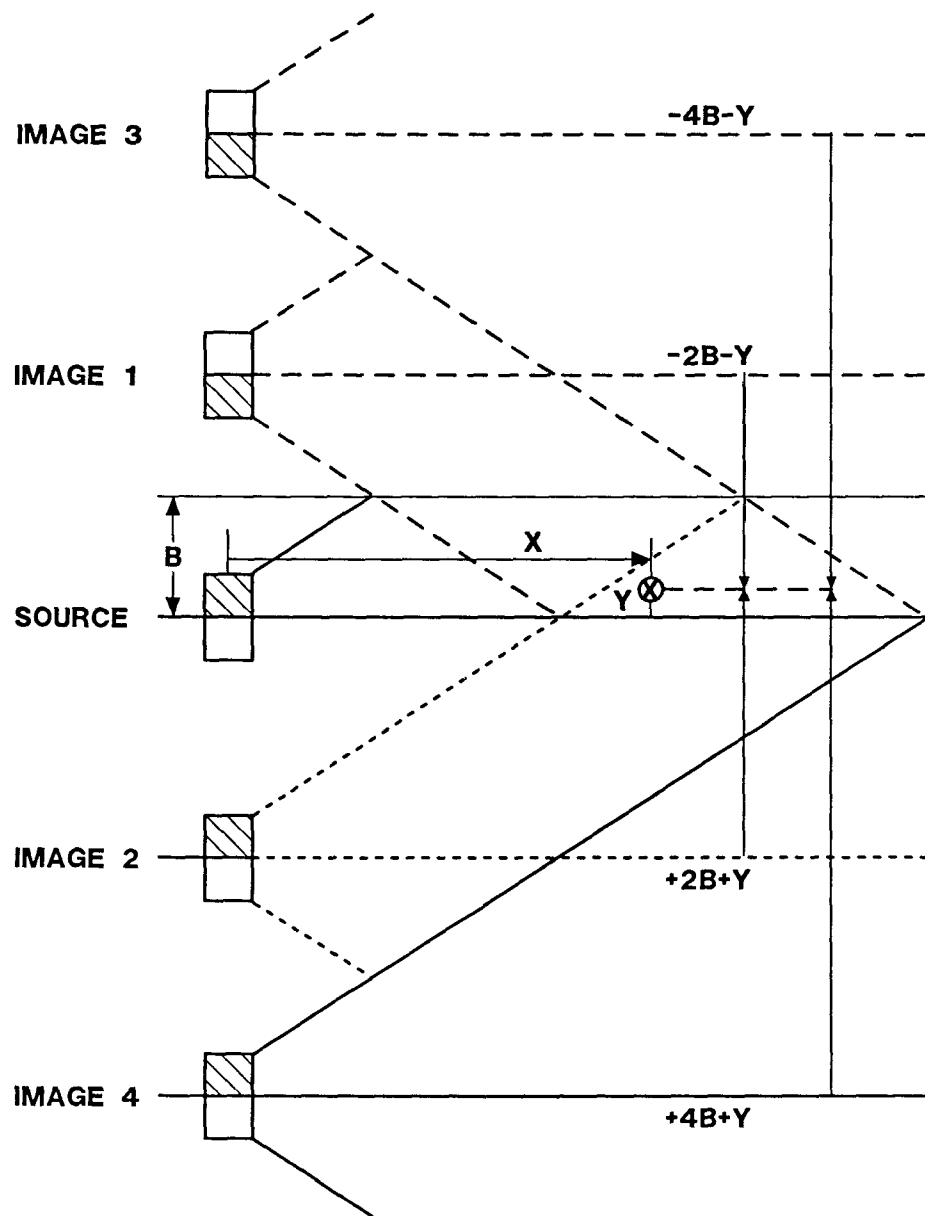


Figure B2 Treatment of Lateral Boundary Conditions Using Image Sources

where

$$I = \int_0^t \frac{\exp \left(- \frac{x^2}{4E_x \tau} - \frac{y^2}{4E_y \tau + 2\sigma^2} - \frac{U^2 \tau}{4E_x} - K\tau \right) d\tau}{\tau^{3/2} (2\sigma^2 + 4E_y \tau)^{1/2}} \quad (B8)$$

Image sources must be applied and their effects must be added to the fundamental solution to satisfy the zero normal gradient, lateral boundary conditions. (Figure B.2 the actual source plus the first four image sources.) In general, an infinite number of image sources are required to precisely reproduce the lateral boundary effect. The resulting solution becomes:

$$C^*(c, y, t) = C_s [C_f^*(x, y, t) + \sum_{i=1}^{\infty} C_{fi}^*(x, y, t)] \quad (B9)$$

where

$$C_{fi}^* = C_f^*(x, 2Bi + y \cos(i\pi), t) \quad (B10)$$

The second step in the derivation involves an application of Duhamel's theorem of superposition in the time domain in order to satisfy the pulse source boundary condition (B6). The pulse load condition is obtained by superimposing two continuous loads staggered over time interval t_R .

The combined response is the required analytical solution and is given by:

$$\begin{aligned} C_{x,y,t} = C_s [& C_f^*(x, y, t) + \sum_{i=1}^{\infty} C_{fi}^*(x, y, t) \\ & - C_f^*(x, y, t-t_R) + \sum_{i=1}^{\infty} C_{fi}^*(x, y, t-t_R)] \end{aligned} \quad (B11)$$

APPENDIX C: LIST OF SYMBOLS

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
A_c (AC)	The surface area of the contaminated catchment, diluting the leachate	m^2	Input or calculated	GRND2A, GRND2B, STM1, USEDf1, USEDf2, USEDf3
A_{1a} (ALA)	The lagoon surface area	m^2	Input	UNLINED
A_{1i} (ALI)	Surface area of lagoon liner	m^2	Input	LINED
α (ALPHA)	Acid-catalysis hydrolysis rate enhancement factor for the sorbed compound	Unitless	Constant = 0	GRND1, GRND3, STM4, DISCH4
A_p (AP)	Constant solely dependent on the type of liner	$\frac{G-Mil}{(100 \text{ in}^2 \text{ day cmHg})}$	Input	LINED
A_s (AS)	Surface area of the upper watershed (hydraulically including the contaminated catchment and above)	Unitless	Input	GRND2A, GRND2B, STM1, STM4, USEDf1, USEDf2, USEDf3
A_w (AW)	Surface water that provides water which leaches through the disposal facility	m^2	Input	GRND2A, GRND2B, STM1, CERF, USEDf1, USEDf2, USEDf3
B (BB)	Stream width below contaminated source	M	Calculated	STM1, STM2, STM3, DISCH1, DISCH2, DISCH3, GAUSS
b (BEXP)	Width exponent for stream hydraulic geometry	Unitless	Input	STM1, DISCH1, LARF1, LADD1
B_0 (BBO)	Stream width before storm	m	Calculated	STM1, DISCH1
CCC (CCC)	Specified Criterion Continous Concentration Water Standard for aquatic organisms	mg/l	Input	AQUTIC, CERF, USEDf1, USEDf2, USEDf3

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
C_l (CL)	Maximum allowable leachate concentration	mg/l	Calculated	DISCH1, DWATER, FISH, AQUATIC, GAUSS, USED1, USED2, USED3
C_{fw} (CFW)	Cover factor for waste site	Unitless	Input	RUNOFF
C_{fs} (CFS)	Cover factor for watershed	Unitless	Input	RUNOFF
C_{fc} (CFC)	Cover factor for contaminated catchment	Unitless	Input	RUNOFF
C_{nc} (CNC)	The SCS runoff curve number for the contaminated catchment (Table 3.1.7)	Unitless	Input	RUNOFF
C_{ns} (CNS)	The SCS runoff curve number for the watershed (Table 3.1.7)	Unitless	Input	RUNOFF
C_{nw} (CNW)	The SCS runoff curve number for the waste site (Table 3.1.7)	Unitless	Input	RUNOFF
C'_{RFD} (C'RFD)	Reference dose pertaining to fish consumption	mg/l	Calculated	FISH, USED1, USED2, USED3
C_{RFD} (CRFD)	Reference dose pertaining to drinking	mg/l	Input	DWATER, USED1, USED2, USED3
C_u (CU)	Chemical concentration upstream	mg/l	Input	USED1, USED2, USED3
C_{wl} (CWL)	Concentration in lagoon discharge stream	mg/l	Input or Calculated	LADD1
DO (DO)	Depth of baseflow	m	Input	GRND2B, STM1, DISCH1, USED1, USED2, USED3
D_B (DB)	Distance from the lagoon free board depth to the top of the broken dam	m	Input	LARF1
D_c (DC)	Density of contaminant	kg/m ³	Input	UNLINED

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
D (DEPTH)	Mean stream depth below contaminated source after storm	m	Calculated	GRND2B, GRND3, STM1, STM3, STM4, DISCH1, DISCH2, DISCH3
D _f (DF)	Dilution factor	Unitless	Constant = 1	STM2, DISCH2
D (DIST)	Distance from land disposal site to stream	m	Input	USEDf1, USEDf2, USEDf3
D _{LI} (DLI)	Lagoon liner thickness	mils	Input	LINED
D _{NEW} (DNEW)	The new depth of a lagoon after the addition of precipitation	m	Calculated	LARF1
D _{OLD} (DOLD)	Original depth of lagoon before storm or dam break	m	Input	LARF1
D _T (DT)	Transition stream depth	m	Calculated	GRND3
D _w (DW)	Density of water	kg/m ³	Input	UNLINED
E _x (ELONG)	Longitudinal dispersion coefficient	m ² /sec	Input or Calculated	STM3, DISCH3, GAUSS, CERF
E _y (ELAT)	Lateral dispersion coefficient	m ² /sec	Input or Calculated	STM3, DISCH3
E _x (EX)	Longitudinal dispersion coefficient	m ² /sec	Calculated	STM3, DISCH3, GAUSS, CERF
E _y (EY)	Lateral dispersion coefficient	m ² /sec	Calculated	STM3, DISCH3
F _{BD} (FBD)	Lagoon free board depth	m	Input	LARF1
F _D (FD)	Fraction of dissolved compound in stream	Unitless	Calculated	GRND3, STM4, DISCH4, EFFECT
F _{DG} (FDG)	Fraction of dissolved compound in ground water	Unitless	Calculated	GRND1

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
F_1 (FL)	Fraction of biomass that is lipid in fish	Unitless	Calculated	USED1, USED2, USED3
F_{OC} (FOC)	Organic carbon fraction of suspended sediment	Unitless	Input	GRND3, STM4, DISCH4, USED1, USED2, USED3
F_{OCW} (FOCW)	Organic carbon fraction of suspended sediment in the waste	Unitless	Input	RUNOFF
F_{OCG} (FOCG)	Fraction of organic carbon of porous medium through which ground water flows	Unitless	Input	GRND1, USED1, USED2, USED3
F_{RC} (FRC)	Average fraction of precipitation that runs off the contaminated catchment area (defaults to f_{RS} if not input)	Unitless	Input	GRND2A, STM1, DISCH1, USED1, USED2, USED3
F_{RS} (FRS)	Average fraction of the precipitation that runs off upper watershed	Unitless	Input	GRND2A, STM1, DISCH1, USED1, USED2, USED3
F_R^* (FRSTAR)	Stream flow recession parameter (0-1) for scenario #3 runoff events that follow a storm	Unitless	Input	STM1, USED1, USED2, USED3
F_{RW}	Fraction of precipitation that runs off of wastesite	Unitless	Input	STM1, USED1, USED2, USED3
F_S (FS)	Sorbed chemical fraction	Unitless	Calculated	GRND3, STM4, DISCH4
F_{SG} (FSG)	Sorbed chemical fraction in ground water	Unitless	Calculated	GRND1
g (GRAV)	Acceleration due to gravity	m/sec ²	Constant = 9.81	STM3, DISCH3
H (HENRY)	Henry's law constant, chemical specific	Atm-m ³ /Mole	Input	GRND3, STM4, DISCH4, USED1, USED2, USED3
H_C (HC)	Corrected hydraulic conductivity for contaminants with viscosity different than water	m/sec	Calculated	UNLINE

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
H_G (HG)	Hydrogen ion concentration	mole/l	Calculated	GRND1
K_{2O} (K2O)	Reaeration rate at 20 Degrees C	sec ⁻¹	Calculated	GRND3, STM4, DISCH4
K_c (KC)	Soil erodibility factor for contaminated catchment	ton/acre	Input	RUNOFF
K_F (KF)	Entire fish partition coefficient, or bio-concentration factor	l/kg	Calculated	EFFECT
K_{FC} (KFC)	Food chain bio-accumulation factor	Constant = 3 mg/l	Input	USED1, USED2, USED3
K_G (KG)	Hydrolysis rate constant at ground water temperature TG	1/years	Calculated	GRND1
K_{GO} (KGO)	Nominal hydrolysis rate constant at a reference temperature (Usually 25 C)	1/year	Calculated	GRND1
K_{GW} (KGW)	Hydraulic conductivity of ground water in natural soils	cm/hr	Input	UNLINE
K_H (KH)	Hydrolysis rate constant at ambient surface temperature	yr ⁻¹	Calculated	GRND3
K_{HO} (KHO)	Nominal hydrolysis rate constant	sec ⁻¹	Calculated	GRND3
K_{HA} (KHA)	Second-order acid-catalysis hydrolysis rate constant	l/(mole-hr)	Input	GRND1, GRND3, STM4, DISCH4, USED1, USED2, USED3
K_{HB} (KHB)	Second-order base-catalysis hydrolysis rate constant	l/mole-hr	Input	GRND1, GRND3, STM4, DISCH4, USED1, USED2, USED3
K_{HN} (KHN)	Neutral hydrolysis rate constant	hr ⁻¹	Input	GRND1, GRND3, STM4, DISCH4, USED1, USED2,

USED3

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
K (KK)	Overall pseudo-first order rate constant	sec ⁻¹	Calculated	GRND3, STM4, DISCH4
K ₀₂ (K02)	Reaeration rate constant	sec ⁻¹	Calculated	GRND3, STM4, DISCH4
K _s (KS)	Soil erodibility factor for watershed	ton/acre	Input	RUNOFF
K _{OW} (KOW)	Octanol water partition coefficient for stream	loct/ lwater	Input	GRND1, GRND3, STM4, DISCH4, EFFECT, USED3, USED3, USED3
K _{oww} (KOWW)	Octanol water partition coefficient for waste-site	loct/ lwater	Input	RUNOFF
K _w	Soil erodibility factor for wastesite	ton/acre	Input	RUNOFF
K _v (KV)	Volatilization rate constant	sec ⁻¹	Calculated	GRND3, STM4, DISCH4
L _{MASS} (LMASS)	Total mass loading from a lagoon directly discharging into a stream	G	Input	LADD1
L _{sc} (LSC)	Slope length and slope steepness factor for contaminated catchment		Unitless	RUNOFF
L _{ss} (LSS)	Slope length and slope steepness factor for watershed		Unitless	RUNOFF
L _{sw} (LSW)	Slope length and slope steepness factor for watershed		Unitless	RUNOFF
(MAX)	Maximum number of iterations allowed before the series is assumed to have failed to converge	Unitless	Constant	GAUSS

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
MW (MW)	Molecular weight of the compound	Unitless	Calculated	GRND3, STM4, DISCH4, USEDf1, USEDf2, USEDf3
n (NN)	Manning's roughness coefficient	sec/ m ^{1/3}	Input	GRND2B, STM1, DISCH1, USEDf1, USEDf2, USEDf3
OH (OH)	Hydronium ion concentration	mole/l	Calculated	GRND3
OHG (OHG)	Hydronium ion concentration in ground water	mole/l	Calculated	GRND1
P ₂₅ (P25)	Precipitation for the 25-year re-occurrence, 24 hour deviation storm	cm	Input	STM1, USEDf1, USEDf2, USEDf3
\bar{P} (PBAR)	Average annual precipitation rate	cm/yr	Input	GRND2A, STM1, DISCH1, USEDf1, USEDf2, USEDf3
P _c (PC)	Erosion control practice factor for contaminated catchment	Unitless	Input	RUNOFF
pH (PH)	Stream hydrogen ion concentration	g-Atoms/ l	Input	USEDf1, USEDf2, USEDf3
pHg (PHG)	Ground water pH	g-Atoms/ l	Calculated	GRND1, USEDf1, USEDf2, USEDf3
ϕ (PHI)	The polymer "permachor" calculated for each polymer-permeant pair (lagoon)	Cal/CC	Input	LINED
pOH (POH)	Hydroxyl ion concentration	g*Atoms/ l	Calculated	GRND3, STM4, DISCH4
pOHg (POHG)	Ground water hydroxyl ion concentration	g*Atoms/ l	Calculated	GRND1

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
P_s (PS)	Erosion control factor for watershed	Unitless	Input	RUNOFF
P_w (PW)	Erosion control factor for wastesite	Unitless	Input	RUNOFF
Q_D (QD)	Flow rate of wastewater treatment effluent at stream interception	m^3/sec	Input	DISCH1, DISCH2, USED1, USED2, USED3
Q_g (QG)	Contaminated ground water discharge flow rate at stream interception site	m^3/sec	Calculated	GRND2A
Q_{wg} (QWG)	Average volumetric rate of percolation through the land disposal site	m^3/sec	Calculated	GRND2A
Q_{wl} (QWL)	Flow rate leaving the contaminated lagoon	m^3/sec	Calculated or Input	LINED, UNLINED, LAGW2, LARF1, LADD1, USED1, USED2, USED3
Q_s^B (QQO)	Stream baseflow before storm	m^3/Sec	Input	STM1, DISCH1, USED1, USED2, USED3
Q_s (QQS)	The stream flow downstream of source	m^3/sec	Input or Calculated	GRND2A, GRND2B, STM1, STM2, DISCH1, DISCH2
Q_R (QR)	Contaminated runoff flow rate at stream interception site	m^3/Sec	Calculated	STM1, STM2
q_s (QS)	The average stream flow at the downstream edge of the contaminated plume	$m^3/sec/m^2$	Calculated or Input	GRND2A, STM1, DISCH1, USED1, USED2, USED3
Q_U (QU)	The average stream flow at the upstream edge of the contaminated plume	m^3/sec	Calculated	GRND2B, STM1, DISCH1, USED1, USED2, USED3

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
Q_{wD} (QWD)	Flow rate for industrial waste stream	m^3	Calculated	DISCH1, DISCH2, USED F1, USED F2, USED F3
R_g (RG)	Gas phase resistance to the compound	sec/m	Calculated	GRND3, STM4, DISH4
R (RGAS)	Ideal gas constant	m^3 -Atm/ Mol H	Constant = 8.206 * 10^{-5}	GAUSS, EXERF
ρ_{bg} (RHOBG)	Bulk density of porous medium	kg/l	Calculated	GRND1
R_l (RL)	Liquid phase resistance	sec/m	Calculated	GRND3, STM4, DISCH4
S_H (SH)	Constant dependent upon the type of polymer liner	Cal/CC	Input	LINED
(SIGMA)	Standard deviation of Gaussian source	m	Calculated	STM2, DISCH2, GAUSS
S (SLOPE)	Channel slope	m/m	Input	GRND2B, STM1, STM3, DISCH1, DISCH3, USED F1, USED F2, USED F3
S (SS)	Stream sediment concentration	mg/l	Input	USED F1, USED F2, USED F3
τ (TAU)	Travel time of pollutants in stream	sec	Input	GRND3
τ_g (TAUG)	The time taken by the contaminant to travel from the land disposal site to the stream entry point	Yr	Calculated	GRND1
T_D (TD)	Total time of discharge into stream (Scenario 4 and 5)	sec	Input	DISCH1, GAUSS, USED F1, USED F2, USED F3
T_g (TG)	Ground water temperature	Degrees C	Input	GRND1, USED F1, USED F2, USED F3

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
θ_g (THETAG)	Volumetric water content of porous medium	l^3/l^3	Input	GRND1, USEDf1, USEDf2, USEDf3
θ_w (THETAW)	Volumetric water content of waste site (top 1 cm)	l^3/l^3	Input	RUNOFF
T_K (TK)	Water temperature	Degrees	Calculated	STM4, DISCH4
T_l (TL)	Total time of waste loading (TD or TR)	sec	Input as TD or TR	GAUSS
T_R (TR)	Total time of runoff loading to the stream (Scenario 2 and 3)	sec	Input	STM1, GAUSS, USEDf1, USEDf2, USEDf3
T (TREF)	Reference temperature (Usually 25 C)	Degrees C	Input	GRND2, GRND3, STM4, DISCH4, USEDf1, USEDf2, USEDf3
T_{SD} (TSD)	Time since discharge	sec	Input	GAUSS
T_s (TSTREAM)	Water temperature	Degrees C	Input	GRND3, STM4, DISCH4, USEDf1, USEDf2, USEDf3
U (U)	Mean downstream velocity	m/sec	Calculated	GRND2B, GRND3, STM1, DISCH1
U_0 (UO)	Stream velocity at base flow (Calculated by Manning's equation)	m/sec	Calculated	GRND2B, STM1, DISCH1
U_c (UC)	Dynamic viscosity of contaminant	kg/m·sec	Input	UNLINE
U_{SV} (USV)	Shear velocity	M/sec	Calculated	STM3, DISCH3
U_w (UW)	Dynamic viscosity of water	kg/m·sec	Input	UNLINE
V_g (VG)	Ground water seepage velocity	m/yr	Input	USEDf1, USEDf2, USEDf3

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
V_p (VP)	Vapor pressure of contaminant	cmHg	Input	LINED
V_{wl} (VWL)	Volume of runoff from the waste lagoon	m ³	Calculated	LINED
WAT (WAT)	Water vapor exchange constant	m/sec	Calculated	GRND3, STM4, DISCH4
WM (WMASS)	Total mass loading from an industrial site	g	Input	GRND3, DISCH1, USEDf1, USEDf2, USEDf3
W_z (WZ)	Wind speed at height Z	m/sec	Input	GRND3, STM4, DISCH4, USEDf1, USEDf2, USEDf3
z (Z)	Wind measurement height	m	Input	GRND3, USEDf1, USEDf2, USEDf3
-- (Z1)	See ZD	See ZD	See ZD	DWATER, FISH, AQTIC
-- (Z2)	See ZT	See ZT	See ZT	DWATER, FISH, AQTIC
-- (Z3)	See ZXY	See ZXY	See ZXY	DWATER, FISH, AQTIC
-- (Z4)	See ZSU	See ZSU	See ZSU	DWATER, FISH, AQTIC
-- (Z5)	See ZDW or ZF or ZEXP	See ZDW or ZF or ZEXP	See ZDW or ZF or ZEXP	DWATER, FISH AQTIC
ζ_D (ZD)	Reduction factor for direct discharge (dilution plus reaction)	Unitless	Calculated	DISCHARGE,
ζ_{DW} (ZDW)	The dilution factor corresponding to the fraction of the compound that is dissolved	Unitless	Calculated	STORM, DISCHARGE, EFFECT

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
ζ_{EXP} (ZEXP)	Aquatic exposure factor	Unitless	Calculated	STORM, DISCHARGE, EFFECT
ζ_F (ZF)	Bioaccumulation factor in fish due to the biochemical exchange process with the fish	l/kg	Calculated	STORM, DISCHARGE, EFFECT
ζ_g (ZG)	Reduction factor due to transport in ground water	Unitless	Calculated	GRND2A
ζ_{HG} (ZHG)	Attenuation factor for the fraction of contaminant of mass not transformed by hydrolysis during ground water transport to the stream	Unitless	Calculated	GRND1, GRND2A
ζ_i (ZI)	Attenuation factor for interception of stream and ground water	Unitless	Calculated	GRND2A, USEDf1, USEDf2, USEDf3
ζ_i (ZIBAR)	Average fraction of ground water flow contributing to stream flow in the upper watershed	Unitless	Input	GRND2A, STM1, USEDf1, USEDf2, USEDf3
ζ_L (ZL)	Reduction factor for lagoon direct discharge (dilution plus reaction)	Unitless	Input	LADD1
ζ_R (ZR)	Runoff dilution factor	Unitless	Calculated	STORM, STM1
ζ_{sg} (ZSG)	Reduction factor due to mixing at area leachate entry into stream	Unitless	Calculated	GRND2A
ζ_{su} (ZSU)	Reduction factor due to transport in stream	Unitless	Calculated	GRND2B, STORM, STM1, DISCHARGE, DISCH1

<u>Variable</u>	<u>Definition</u>	<u>Units</u>	<u>Type</u>	<u>Found in Subroutines</u>
ζ_w (ZW)	The treatment plant mass attenuation factor accounting for the effects of sorption and settling, volatilization and bacterial degradation	Unitless	Input	DISCH1, USEDf1, USEDf2, USEDf3
ζ_x (ZX)	The steady-state laterally averaged solution for concentrations at the measurement point	Unitless	Calculated	STM3, DISCH3
ζ_{xy} (ZXY)	Concentration reduction factor for downstream transformation	Unitless	Calculated	STORM, DISCHARGE, DISCH1
-- (18)	Molecular weight of water			
-- (32)	Molecular weight of oxygen			

APPENDIX D
SAMPLE OUTPUTS

Sample Output:

D.1 Scenario 1B (Ground Water/Fish Consumption), Default Values #1

SARAH Model Scenario 1C

Scenario 1 Steady Ground Water Loading Run Program

KHG(/YR) = 0.00000E + 00
TAUG = 0.17797E + 03
RG = 0.10000E + 01

D' = 0.10000E + 00
C<L = 0.10000E + 02

Sample Output:

D.2 Scenario 1C (Ground Water/Aquatic Toxicity), Default Values #1

SARAH Model Scenario 1B

Scenario 1 Steady Ground Water Loading Run Program

KHG(/YR) = 0.00000E + 00
TAUG = 0.17797E + 03
RG = 0.10000E + 01

D' = 0.10000E + 00
f<D = 0.99980E + 00
K<F = 0.31000E + 03
C<L = 0.32265E - 01

Sample Output:

D.3 Scenario 2A (Steady Storm/Drinking Water), Default Values #1, Gaussian Solution

Drinking Water Model

Scenario 2A Storm Runoff Loading Run Program

QQ0 = 0.50000E - 01
QQ = 0.59817E + 01
D0 = 0.30000E + 00
D = 0.22378E + 01
BB0 = 0.15687E + 01
BB = 0.47147E + 01
U0 = 0.10624E + 00
U = 0.56696E + 00

QW = 0.72338E + 00
DF = 0.12093E + 00
DD = 0.10000E + 01
B = 0.57016E + 00
SIGMA = 0.45492E + 00

USV = 0.44449E - 01
EY = 0.59681E - 01
EX = 0.79016E - 00

FD = 0.99980E + 00
POH = 0.70000E + 01
ALPHA = 0.10000E + 02
FS = 0.20496E - 03
KH = 0.00000E + 00
W10 = 0.10000E + 01
WAT = 0.32076E - 02
TK = 0.29300E + 03
RG = 0.55871E + 09
RL = 0.24382E + 06
KV = 0.79932E - 09
KK = 0.79932E - 09