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**The Development of an Aquatic  
Spill Model for the White Oak  
Creek Watershed, Oak  
Ridge National Laboratory,  
Oak Ridge, Tennessee**

R. O. Johnson

MANAGED AND OPERATED BY  
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION  
FOR THE UNITED STATES  
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ORNL-27 (9-89)

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**THE DEVELOPMENT OF AN AQUATIC SPILL MODEL  
FOR THE WHITE OAK CREEK WATERSHED  
OAK RIDGE NATIONAL LABORATORY  
OAK RIDGE, TENNESSEE**

R. O. Johnson

Energy Division

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## ACRONYMS

ANSI	American National Standards Institute
ASCII	American Standard Code for Information Exchange
cfs	cubic feet per second (ft <sup>3</sup> /s)
Ci	radioactivity in curies
CSTR	continuous stirred tank reactor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
HFIR	High Flux Isotope Reactor
LMES	Lockheed Martin Energy Systems, Inc.
NGVD	National Geodetic Vertical Datum of 1929
NPDES	National Pollutant Discharge Elimination System
NRWTF	Non-Radiological Wastewater Treatment Facility
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PFTR	plug flow tubular reactor
SWSA	Solid Waste Storage Area
TPF	Transuranic Processing Facility
TVA	Tennessee Valley Authority
USGS	U.S. Geological Survey
WOC	White Oak Creek
WOCE	White Oak Creek Embayment
WOD	White Oak Dam
WOL	White Oak Lake



## NOMENCLATURE

### Latin Symbols

A	integration constant defined in text
$A_f$	flow area
$C_i$	concentration of effluent entering White Oak Lake
$C_o$	chemical or radiological spill concentration
$C_{out}^{(n)}$	effluent concentration of flow leaving nth gage
$C_{out}^{(wye)}$	effluent concentration of flow leaving wye junction
$C_w$	concentration of effluent passing over White Oak Dam
$C(x,t)$	spill concentration in Clinch River as a function of time and distance downstream
d	mean depth of lake
D	spill duration
$D_x$	downstream longitudinal diffusion/dispersion coefficient
$f(l_M, l_Q)$	unknown function of length scales
$f(t)$	arbitrary function of time
$F_D$	densimetric Froude number
H	Clinch River thermal penetration depth
$H_o$	White Oak Creek Embayment thermal penetration depth
$H(t-t_o)$	Heaviside unit step function with step at $t = t_o$
$I_n$	nth exponential integral defined in text
K	unknown constant multiplier of $f(l_M, l_Q)$
$l_M$	length scale for flux of momentum
$l_Q$	length scale for flux of buoyancy
L	lake length
$L_x$	entrance length
$m_w$	instantaneous mass (having only units of mass) leaving White Oak Lake
$\dot{m}_w$	time-varying mass flux (mass per unit time) leaving White Oak Lake
M	total mass ( $\dot{m}_w$ integrated over time)
n	Manning roughness factor
$P_e$	Peclet number
$P_w$	wetted perimeter
Q	Clinch River discharge
$Q_{baselrun}^{(n)}$	sum of the groundwater seepage and surficial runoff flow contributions between gages n-1 and n
$Q_{gage}^{(n)}$	measured discharge at the nth gage
$Q_{in}^{(n)}$	contaminated flow contribution at wye junction
$Q_{out}^{(n)}$	flow leaving nth gage
$Q_{out}^{(wye)}$	total flow leaving wye junction
$Q_{spill}(t)$	volumetric flow rate of spill as a function of time

$Q_w$	White Oak Lake throughput exclusive of spill
$Q_{wye}$	uncontaminated flow contribution at wye junction
$R$	hydraulic radius
$S$	average Clinch River slope
$t$	temporal coordinate
$t_0$	origin of temporal coordinate usually equal to zero
$t_{1/2}$	half-life of radioactive species
$T_r$	lake residence time (volume/throughput)
$u$	average downstream velocity in Clinch River
$U$	mean axial downstream velocity in lake
$V_w$	effective mixing volume of White Oak Lake
$W$	Clinch River mean width
$W_w$	effective width of White Oak Lake
$x$	axial coordinate in downstream direction
$y$	cross stream coordinate with respect to width
$z$	downward coordinate with respect to depth

### Greek Symbols

$\delta(t - t_0)$	Dirac delta function with infinite spike at $t = t_0$
$\epsilon$	infinitesimally small quantity
$\lambda$	radioactive decay constant
$\xi$	transformation variable $4D_x(t - \tau)/x^2$
$\pi$	irrational number 3.14159 . . .
$\tau$	dummy integration variable in temporal convolution
$v$	volume of spill

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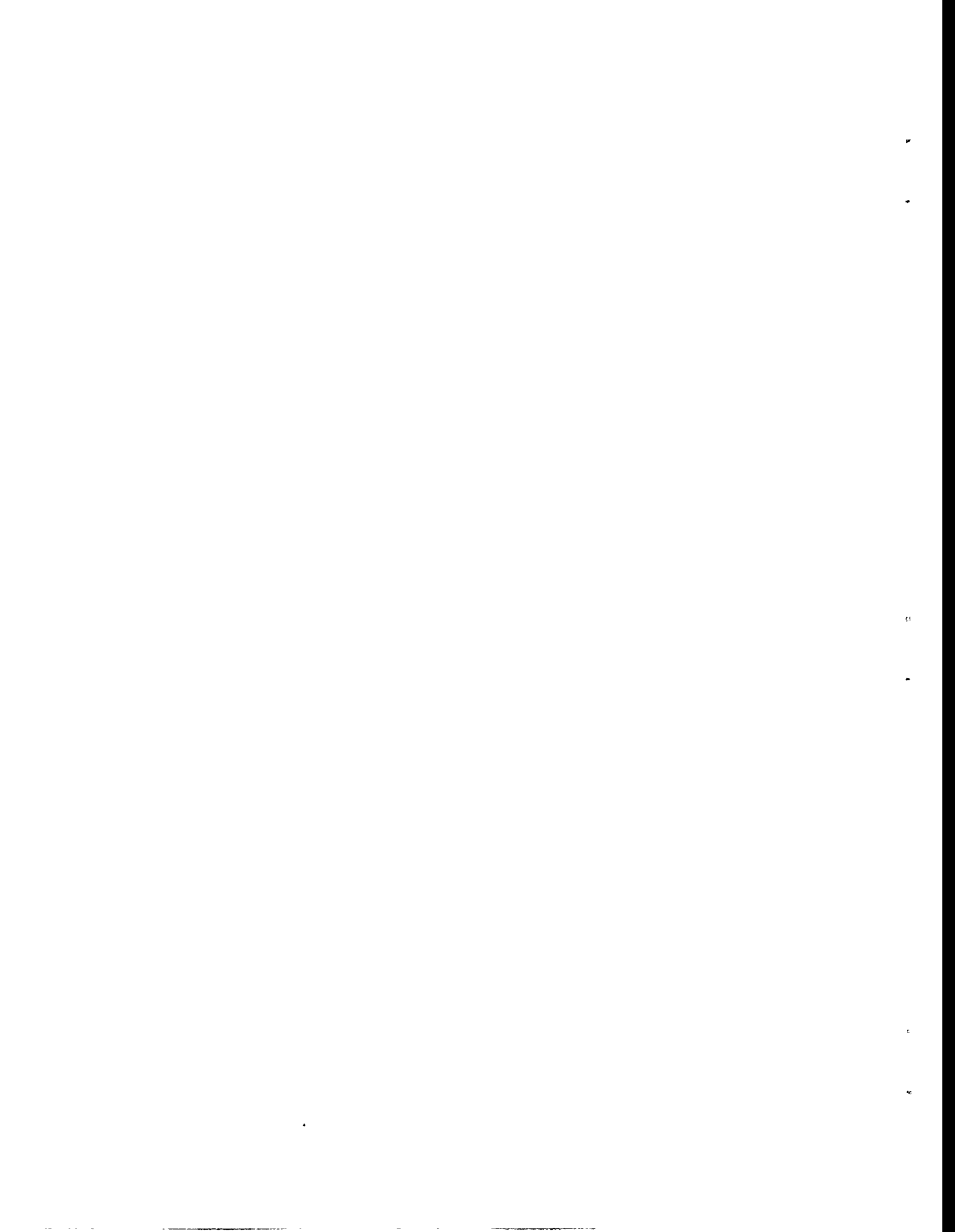
## ABSTRACT

This study develops an aquatic spill model applicable to the White Oak Creek watershed draining the Oak Ridge National Laboratory, Oak Ridge, Tennessee. Hazardous, toxic, and radioactive chemicals are handled and stored on the laboratory reservation. An accidental spill into the White Oak Creek watershed could contaminate downstream water supplies if insufficient dilution did not occur. White Oak Creek empties into the Clinch River, which in turn flows into the Tennessee River. Both rivers serve as municipal water supplies. The aquatic spill model provides estimates of the dilution at sequential downstream locations along White Oak Creek and the Clinch River after an accidental spill of a liquid containing a radioactively decaying constituent. The location of the spill on the laboratory reservation is arbitrary, while hydrologic conditions ranging from drought to extreme flood are simulated. The aquatic spill model provides quantitative estimates with which to assess water quality downstream from the site of the accidental spill, allowing an informed decision to be made whether to perform mitigating measures so that the integrity of affected water supplies is not jeopardized.

The aquatic spill model considers four distinct hydrologic regimes: (1) the White Oak Creek headwaters and tributaries; (2) White Oak Lake formed by White Oak Dam; (3) the White Oak Creek Embayment, whose water level is partially controlled by a sediment retention structure formed by porous rock-filled gabions; and (4) the Clinch River. Discharge statistics published for gaging stations located throughout the White Oak Creek headwaters and tributaries are used as a basis from which to formulate flow and mass balances for conditions ranging from drought to flood. After the accidental spill, the dilution is calculated at each gage located sequentially downstream from the site of the spill.

A mixing-box approach is used to approximate mass transfer in White Oak Lake and to calculate the dilution versus time at White Oak Dam after an accidental spill. The influence of the sediment retention structure on dilution is neglected, resulting in Clinch River plume concentration overestimates (conservative assumption). While the gabions retard the rate at which the spill flows into the Clinch River, all of the spilled liquid eventually enters the river.

Transport in the Clinch River is modeled using a transient, one-dimensional plume model. The efflux of mass from White Oak Dam provides the boundary condition, which varies with time. This point source converts to an areal source in the Clinch River based on an assumed surficial thermal penetration depth and mean river width. The mathematical solution is obtained with convolution. A Clinch River stage-discharge relation is calculated with Manning's formula for open-channel flow. The width of the river is small during droughts and large during floods. Plume concentration overestimates occur at low flows because water level fluctuations in Watts Bar Reservoir are controlled by Melton Hill and Watts Bar dams. The accuracy of the approximation improves when increased flow is released through the dams because the river undergoes partial transition from a reservoir to an open-channel regime. Backwater from Watts Bar Reservoir extends upstream to Melton Hill Dam. The backwater provides additional water to dilute the accidental spill and alters the open-channel regime at low flows by exerting back pressure.



# 1. INTRODUCTION

## 1.1 THE OAK RIDGE NATIONAL LABORATORY

The Oak Ridge National Laboratory (ORNL) is one of three major U.S. Department of Energy (DOE) facilities located on the Oak Ridge Reservation (ORR). The reservation lies within the corporate limits of the City of Oak Ridge in eastern Tennessee, predominantly to the west and south of the population center (see Fig. 1.1). Oak Ridge lies in a valley between the Cumberland and southern Appalachian mountain ranges and is bordered on one side by the Clinch River. The Cumberlands are about 16 km (10 miles) northwest; the Great Smoky Mountains are located 113 km (70 miles) to the southeast.

The ORNL, located toward the west end of Bethel Valley (see Fig. 2.1), is a large, multipurpose research laboratory whose basic mission is to expand knowledge, both basic and applied, in areas related to energy. To accomplish this mission, ORNL conducts research in fields of modern science and technology. Facilities located at ORNL include nuclear reactors, chemical pilot plants, research laboratories, radioisotope production laboratories, accelerators, fusion test devices, and support facilities. The High Flux Isotope Reactor (HFIR), Tower Shielding Facility, and several waste facilities also are managed and operated as part of ORNL.

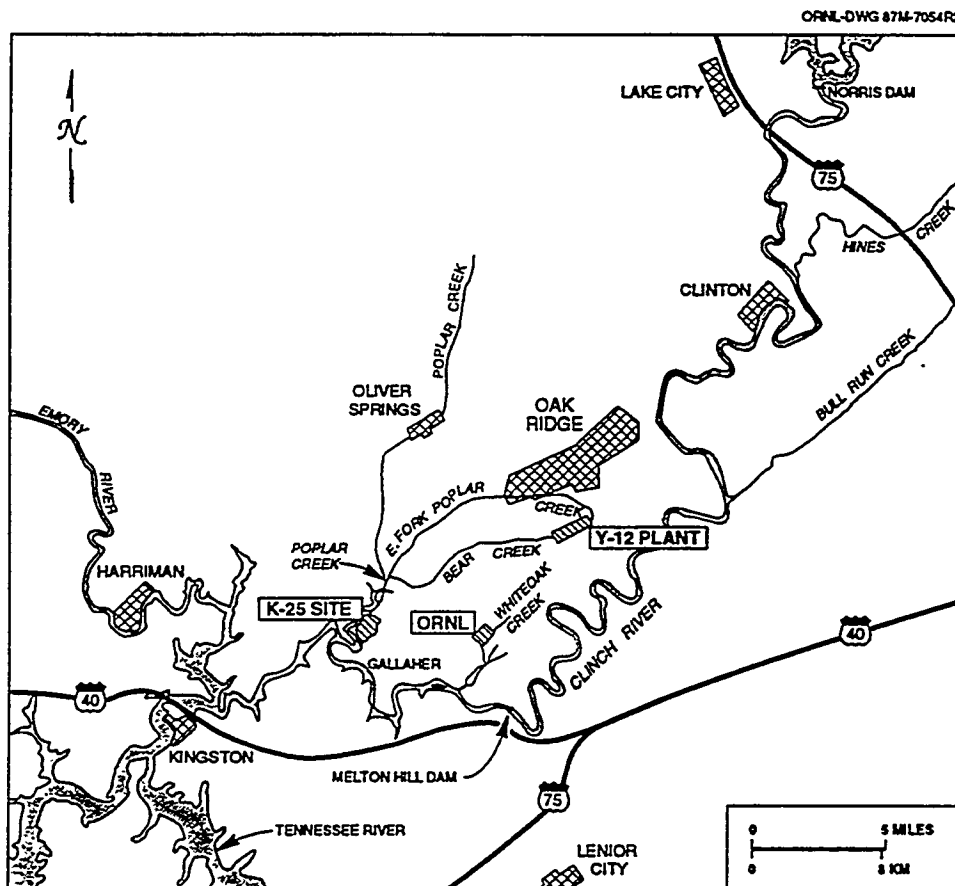


Fig. 1.1. Location map of Oak Ridge National Laboratory in East Tennessee.

## 1.2 HYDROLOGY

The Clinch River (see Fig. 1.2) is the major surface water resource that receives discharges from ORNL. The Clinch River has its headwaters near Tazewell, Virginia, and empties into the Tennessee River near Kingston, Tennessee, at Tennessee River kilometer 914 (river mile 568). The Tennessee River is the seventh largest river in the U.S. The Clinch River watershed constitutes approximately 11% of the Tennessee River watershed. Four dams operated by the Tennessee Valley Authority (TVA) control the flow of the Clinch River. Norris Dam, constructed in 1936, is approximately 50 km (31 miles) upstream from the ORR. Melton Hill Dam, completed in 1963, controls the flow of the river near the ORR. Its primary function is power generation (Boyle et al. 1982). Watts Bar Dam is located on the Tennessee River near the lower end of the Clinch River. Fort Loudon Dam on the Tennessee River upstream from the confluence of the Tennessee and Clinch Rivers also affects the occurrence of backwater downstream from Melton Hill Dam. Watts Bar Reservoir begins immediately below Melton Hill Dam, adjacent to the ORR.

The area on and around the ORR has no streams classified as wild and scenic rivers. Most of the streams on the ORR are classified for fish and aquatic life, irrigation, livestock watering, and wildlife.

Both groundwater and surface water are drained from ORNL by a network of small tributaries of the Clinch River. White Oak Creek (WOC) is the primary Clinch River subbasin that drains ORNL. The WOC empties into the Clinch River (Watts Bar Reservoir) approximately 3.5 km (2.2 miles) downstream from Melton Hill Dam. The Clinch River flows into the Tennessee River at Kingston, Tennessee. Water levels in the Clinch River in the vicinity of ORNL are regulated by the TVA dams. Fluctuations of the Clinch River water level alter the natural flow of WOC.

The WOC splits into several smaller streams on the ORR. First Creek, Fifth Creek, Northwest Tributary, and the WOC headwaters drain ORNL proper. Melton Branch drains the HFIR facility. The confluence of WOC and Melton Branch occurs just upstream from White Oak Lake (WOL), which is formed by White Oak Dam (WOD). Flow in the White Oak Creek Embayment (WOCE) downstream from

ORNL-DWG 87M-B246AR3

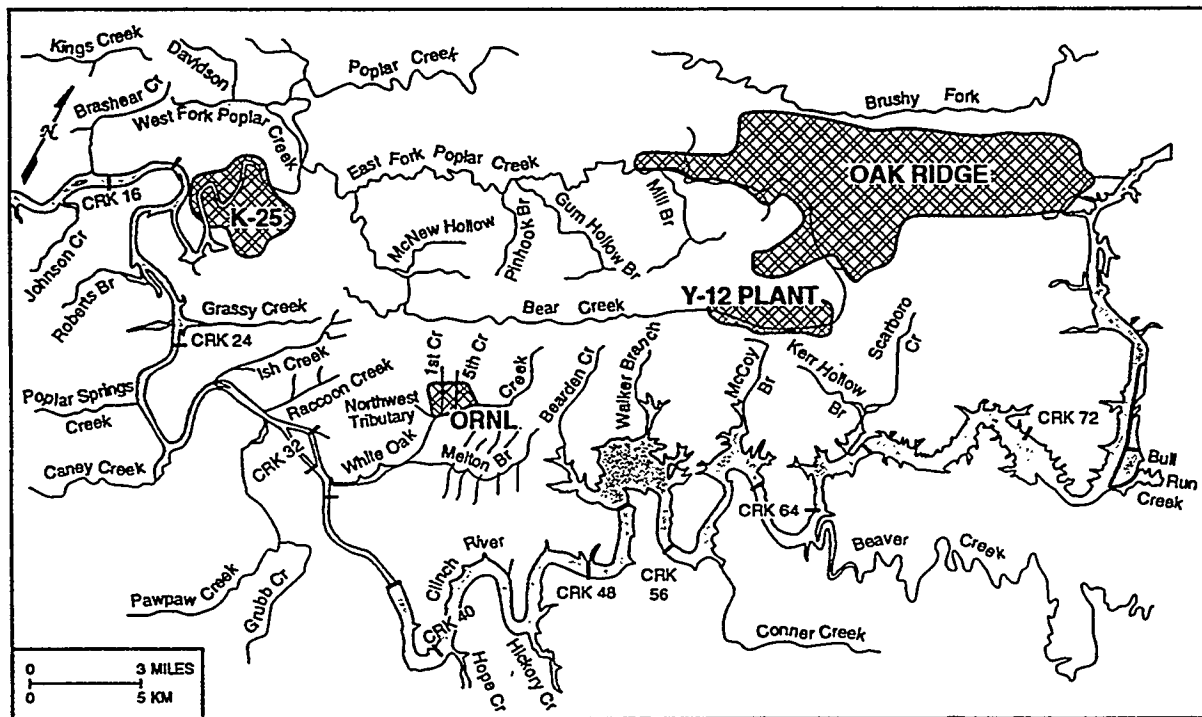


Fig. 1.2. Location map of Oak Ridge Reservation tributaries.

WOD is further controlled by a sediment retention structure located at the mouth of WOC on the Clinch River. The sediment retention structure consists of porous, rock-filled gabions that slow the flow into or out of the WOCE when the Clinch River water level is above or below the embayment water surface, respectively. Daily fluctuations of the water level in Watts Bar Reservoir occur which are caused by the generation of hydroelectric power at Melton Hill Dam.

### 1.3 SCOPE OF STUDY

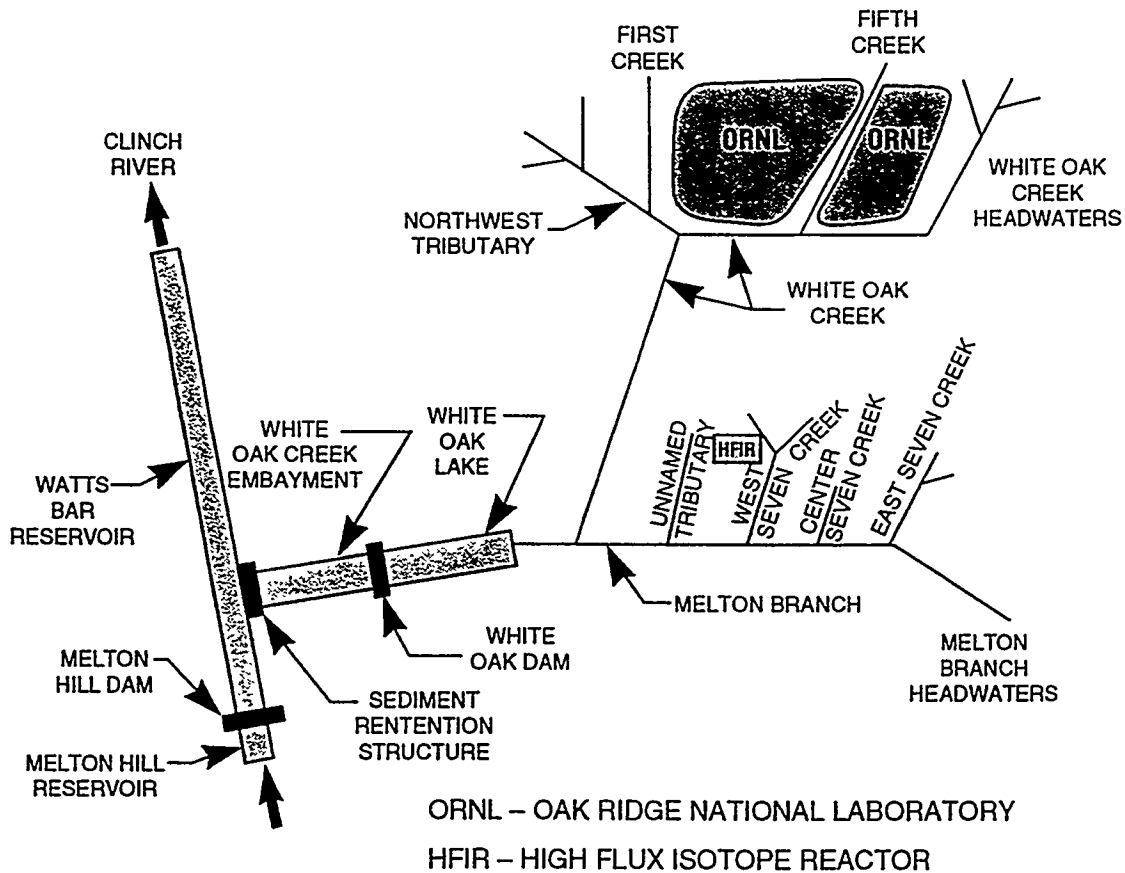
The ORNL handles and stores hazardous, toxic, and radioactive materials. An accidental spill of a chemical classified as hazardous, toxic, or radioactive could affect off-site surface water supplies if dilution to safe levels did not occur prior to migration downstream. The purpose of this study is to develop an ORNL aquatic spill model suitable for estimating the concentrations of a radioactively decaying contaminant (or of a hazardous or toxic material whose decomposition is governed by first-order chemical kinetics) in the waters of WOC and the Clinch River after an accidental spill. The ORNL location where the spill occurs is arbitrary, while conditions ranging from drought to extreme flood are anticipated. The model would be utilized to assess whether mitigating measures are required after an accidental spill so that downstream water supplies are not contaminated and potentially interrupted.

### 1.4 CONCEPTUAL SUMMARY

A schematic diagram of the WOC watershed is shown in Fig. 1.3. The watershed consists of a series of dendritic tributaries, which coalesce into WOL. The discharge over WOD enters the Clinch River after flowing through or over the sediment retention structure. Additional dilution is provided further downstream by the Tennessee River, which receives the flow from the Clinch River. The Emory River, which empties into the Clinch River downstream from WOC, also provides additional dilution. The Tennessee and Emory river flows are neglected in the model formulation.

The WOC tributary streams are monitored by an extensive series of gaging stations, for which discharge statistics are available. Examples of these statistics include the annual average; the lowest and highest daily means; the 10%, 50%, and 90% exceedance flows; and the instantaneous high and low flows recorded at each gaging station. The exceedance flow is the discharge that would be exceeded by 10%, 50%, or 90% of the flow over the designated period of record. The gaging stations are treated as a series of nodes at which steady flow and mass balances (i.e., both quantity and quality) are written based on the measured discharge statistics. The accidental spill could occur at or above any one of the gaging stations. The solution to the flow and mass balances consists of the dilution at each node or gage sequentially downstream from the spill prior to entry into WOL. The dilution is resolvable for flows ranging from drought to extreme flood as represented by the discharge statistics. The accidental spill occurs instantaneously or over a specified finite duration.

The WOL serves as a retention basin that dilutes the spill prior to release into the Clinch River. The WOL mixing chamber is assumed to be a well-stirred region in space having an identifiable effective volume. The accumulation of mass is then equal to the difference between the mass influx and efflux. The removal of mass attributable to radioactive decay also is included in the formulation. The ordinary differential equation describing this continuous stirred-tank reactor (CSTR) is solvable for the dilution versus time leaving WOD after an instantaneous or finite-duration spill. The mass flux entering the WOCE is the product of the original concentration in the spill, the WOD dilution, and the sum of the flows from WOC, Melton Branch, and the spill, which implicitly account for conditions ranging from drought to flood.



**Fig. 1.3. Schematic diagram of the White Oak Creek watershed.**

The sediment retention structure is neglected in the development of the ORNL aquatic spill model. This assumption is conservative, resulting in lower Clinch River dilutions and higher concentrations than actually would occur, because the sediment retention structure slows the rate at which effluent enters the Clinch River as long as the WOCE water surface elevation exceeds that of the river. The model is insensitive to the sediment retention structure flow regime; the spill discharges into the Clinch River irrespective of its path through the porous media (i.e., the gabions), over the top of the structure, or both. Time scales of seepage through the porous media require hours, while flow over the top of the structure, which serves as a broad-crested weir, occurs in seconds. Contaminant transport in the Clinch River is modeled with a time-dependent, one-dimensional species transport equation that accounts for advection, longitudinal dispersion in the downstream direction, and radioactive decay. The mathematical solution is constructed using convolution. The mass efflux leaving WOD provides the time-varying boundary condition; the Clinch River is uncontaminated initially. The plume migrates along the top of the Clinch River because the releases beneath Melton Hill Dam are cooler than the discharge leaving WOD. The vertically downward thermal penetration depth from the river free surface is assumed to be one-tenth of the mean Clinch River depth.

The stage-discharge relation for the Clinch River is calculated with Manning's formula using an average slope, representative areal cross section, and a roughness factor of 0.035. For a specified river flow, defined as the sum of the release through Melton Hill Dam and the discharge from WOD, the river

width is computed from the stage-discharge-area relation. The mean width of the Clinch River must be prescribed before the dilution is resolvable.

The Clinch River plume model is valid at sufficiently large downstream distances where the spill is well-mixed across the active river areal cross section. At low flows this entrance length may extend for several miles, while at higher flows distances measured in only hundreds of feet may be required to achieve complete mixing. Dilutions predicted within the entrance region may exceed dilutions calculated at WOD. The spill model conserves mass in the strictest sense; Fickian transport models of this type have an unremovable singularity at the origin, which is the mouth of WOC. The definition of the entrance length is that distance over which the dilutions from the Clinch River portion of the model exceed dilutions computed at WOD. Models predictions are not valid within the entrance length (a fact that may be significant at low flows).

The Clinch River stage-discharge relation based on Manning's formula is a very conservative estimate of the operation of Watts Bar Reservoir. At very low drought flows, when little or no release occurs at Melton Hill Dam, the model of the river has a depth less than 0.3 m (1 ft) and a width on the order of 30 m (100 ft). Clearly, much more water is available to dilute the spill that is not accounted for by the analysis. Additional dilution would be provided by backwater from Watts Bar Reservoir that extends upstream to Melton Hill Dam.

The applicability of the spill model is limited by the top of the sediment retention structure, whose gabions crest at an elevation of 226.5 m (743 ft). Flood flows in the Clinch River, whose water surface elevations exceed 226.5 m (743 ft), cannot be accommodated because recirculation within WOCE is not included in the model formulation.

## 1.5 PARAMETER SELECTION

The effective mixing volume of WOL is assumed to be one-half of the measured volume. The Clinch River thermal penetration depth is assumed to be one-tenth of the mean river depth under all prescribed flow conditions. The longitudinal mixing coefficient or dispersivity is calculated using a published correlation obtained from the open literature. Measured Clinch River dispersivities exceed values predicted by the correlation. Clinch River plume concentrations rendered by the aquatic spill model are conservative, being higher than actually would occur.

## 1.6 UNITS AND CONVERSION FACTORS

Discharges or flow rates are reported in cubic feet per second [(cfs) or (ft<sup>3</sup>/s)]. Conversion to liters per second (L/s) is accomplished by multiplying cfs by 28.32.

The following list of conversion factors is included for reader convenience:

- (a) 1 m = 100 cm = 3.281 ft = 39.37 in.
- (b) 1 km = 0.621 miles
- (c) 1 acre = 43,560 ft<sup>2</sup> = 4047 m<sup>2</sup> = 0.4047 ha = 0.001563 square miles
- (d) 1 m<sup>3</sup> = 1000 L = 264 U.S. gal = 35.314 ft<sup>3</sup>
- (e) 1 Mgd = 1,000,000 U.S. gal/day = 1.54723 ft<sup>3</sup>/s
- (f) °C = 5/9 (°F - 32)
- (g) 1 Ci = 37,000,000,000 or 3.7 × 10<sup>10</sup> disintegrations/s

## **1.7 CONCENTRATIONS**

Results from the ORNL aquatic spill model are reported as a dimensionless dilution defined as the concentration at an arbitrary prescribed downstream location divided by the contaminant concentration originally in the spilled liquid. Downstream concentrations are obtained by multiplying the original concentration times the predicted dilution. Mass or molar concentrations, mass or molar fractions, or radioactivity per unit volume all are acceptable concentration representations.

## **1.8 DATUM SELECTION**

Elevations are references with respect to the National Geodetic Vertical Datum (NGVD) of 1929 or its assumed equivalent mean sea level. The NGVD of 1929 is based on the geodesy and relationship of planet Earth to the stars, while mean sea level is determined from a time average of tidal motion. Differences between the NGVD of 1929 and mean sea level are negligible.

## 2. WATERSHED DESCRIPTION

White Oak Creek (WOC) drains the watershed in which the Oak Ridge National Laboratory (ORNL) is located and receives radioactive and nonradioactive effluents, both treated and untreated, that are released as a result of normal laboratory operations. Subsurface seepage from underlying geologic formations and leachates from previously buried waste storage areas in use since the early 1940s also drain into the WOC watershed. Hypothetical, unmitigated, accidental spills occurring on the Oak Ridge Reservation (ORR) would run off and/or infiltrate the WOC watershed. This chapter provides an overview of the hydrologic aspects and components composing the WOC watershed and establishes a rational foundation from which to develop the ORNL aquatic spill model. The information and data summarized below have either been taken directly from or are based on the reports by Blaylock et al. (1992, 1993), Borders et al. (1992), Clapp (1992), Cook et al. (1992), and Ford and Wefer (1993). The available open literature on the WOC watershed is extensive; the summary below is an introduction for the sole intent of defining physical parameters and measured data required to develop and synthesize the ORNL aquatic spill model.

### 2.1 WATERSHED LOCATION

The WOC watershed is located primarily in the Roane County portion of the ORR (Borders et al. 1992). The headwaters region of WOC, making up the northeast corner of the watershed, lies partially in Anderson County. The WOC watershed is bounded by Copper Ridge to the south, White Wing Road (State Highway 95) to the west, Chestnut Ridge to the north, and approximately the Roane/Anderson County boundary to the east (see Fig. 2.1). The majority of ORNL facilities, active and inactive waste management areas, and potential sources of contaminants lie within the WOC watershed boundaries. Most waste effluents produced as a result of routine ORNL operations are released into the WOC watershed.

### 2.2 WHITE OAK CREEK

White Oak Creek rises from springs on the southern slopes of Chestnut Ridge and, with its tributaries, drains much of Bethel and Melton valleys (which includes ORNL) to the Clinch River (see Fig. 2.1). The waters of WOC are impounded by White Oak Dam (WOD), constructed 1.0 km (0.6 miles) upstream from the Clinch River in 1943 to form White Oak Lake (WOL), which serves as a holding pond for ORNL waste effluents. The drainage area upstream from the Clinch River and WOD is approximately 16.0 km<sup>2</sup> (6.15 miles<sup>2</sup>) (Martin Marietta Energy Systems, Inc. 1985). Elevations above mean sea level in the watershed range from 226 m (741 ft) at the mouth of WOC to 413 m (1355 ft) at the top of Melton Hill, the highest point on the ORR (McMaster and Waller 1965; McMaster 1967).

Major tributaries within the WOC watershed include Melton Branch (largest), First and Fifth creeks, and the Northwest Tributary (see Fig. 2.1). First and Fifth creeks as well as WOC itself are the primary drainage routes from the industrialized portion of ORNL.

Flow in WOC in the main ORNL plant area is augmented by the discharge of water imported for plant processes, potable supplies, and sanitary use. The flow is complex because of the effects of storm drainage, leakage into and out of an extensive system of underground pipes, and the increased permeability of disturbed subsurface materials along pipe lines and within construction sites. Major regulated effluent discharges that contribute to the WOC flow augmentation include the Sewage Treatment Plant, Coal Yard Runoff Treatment Facility, and the Non-Radiological Wastewater Treatment Facility (NRWTF). Minor

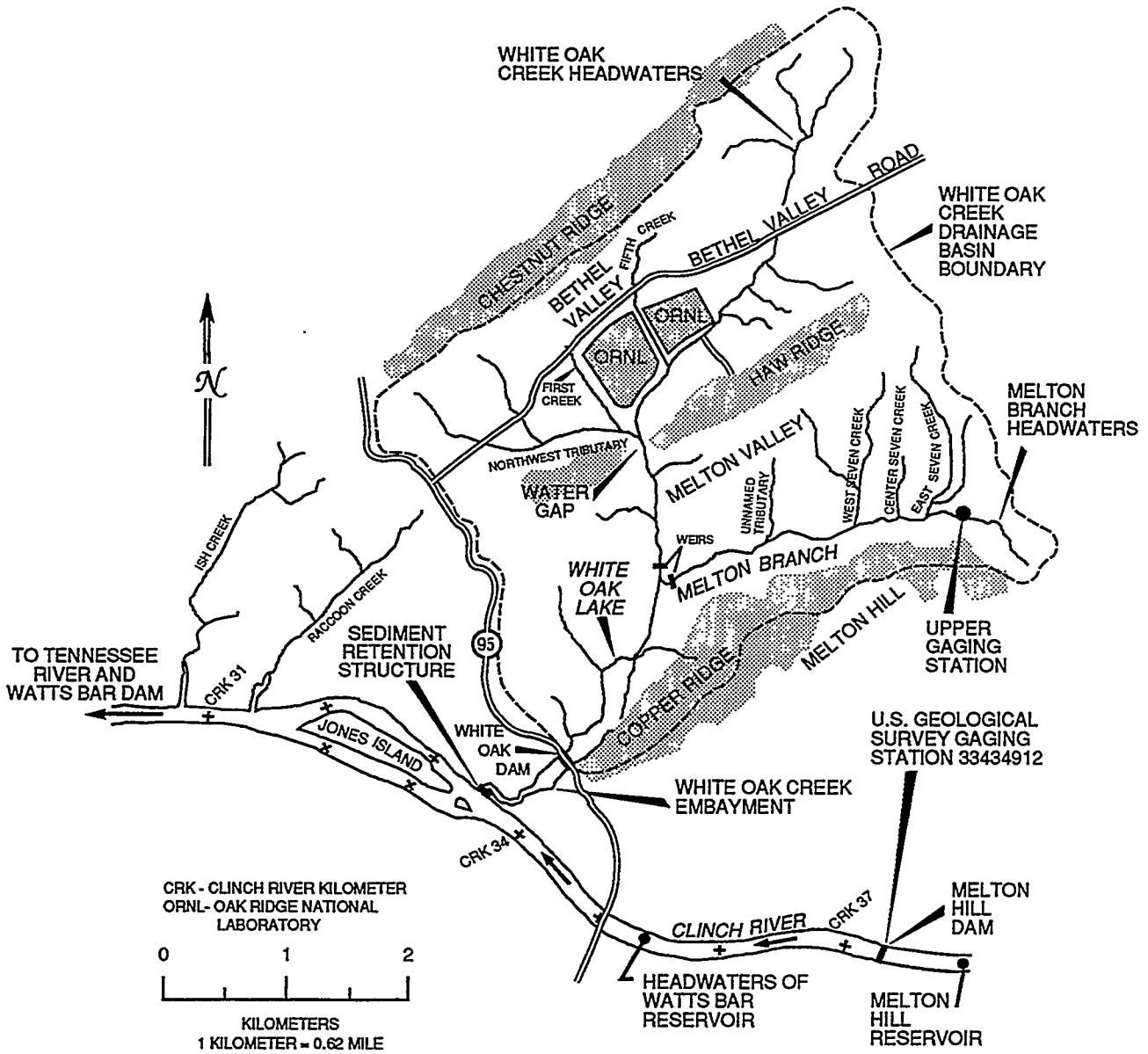


Fig. 2.1. Map of the White Oak Creek watershed.

effluent discharges include flows from various outfalls, cooling water discharges, and miscellaneous source discharges. Measurements indicate that the magnitude of the ORNL flow augmentation is approximately 60 L/s (2 cfs) (Borders et al. 1992, p. 67).

White Oak Creek is a small stream passing through a second growth forest (Blaylock et al. 1992, p. 5). The mean annual flow of WOC at the weir located at km 2.65 (mile 1.65) is approximately 230 L/s (8 cfs). The floodplain upstream from the weir is covered by forest and contains, at WOC km 3.2 (mile 2.0) and km 3.4 (mile 2.1), the former sites of two earthen dikes, which were washed out in 1944. The former ponds, which contained trace quantities of plutonium, americium, and curium, are now a 3-ha (7-acre) contaminated floodplain covered by a second-growth forest. This area is estimated to contain 0.5 Ci of  $^{239,240}\text{Pu}$  in the top 20 cm (8 in.) of soil.

### 2.3 MELTON BRANCH

Melton Branch is the largest WOC tributary. The upper reaches of the Melton Branch headwaters further subdivide into East Seven, Center Seven, and West Seven creeks (see Fig. 2.1). The first unnamed Melton Branch tributary that flows adjacent to the High Flux Isotope Reactor (HFIR) has no formal name.

Melton Branch originates at the eastern end of Melton Valley and joins WOC at km 2.6 (mile 1.6). The annual average flow of this small stream is approximately 60 L/s (2 cfs) at the Melton Branch weir located at km 0.16 (mile 0.1) (Blaylock et al. 1992, p. 5). No flow has been recorded on several occasions during dry periods at the upper gaging station at km 1.93 (mile 1.2). Stream flow in lower Melton Branch is augmented by periodic discharges from several process waste basins and by cooling tower blowdown from the HFIR. Elevated concentrations of the radionuclides  $^{60}\text{Co}$  and tritium ( $^3\text{H}$ ) have been observed in Melton Branch.

Flow in Melton Branch was augmented by effluent discharges of approximately 7 L/s (0.25 cfs) from the HFIR and about 2.3 L/s (0.08 cfs) from the Transuranium Processing Facility (TPF) until November 1986, when HFIR was shut down and discharges were substantially reduced (Borders et al. 1992, p. 67). The reactor began operating again in January 1990 and reached full power in May 1990. However, in February 1990, the NRWTF went on-line to treat dilute ORNL process waste streams. This facility now receives the waste effluents from both the TPF and HFIR facilities, which were previously routed to temporary holding ponds 7908 (TPF), 7909 (TPF), and 7905 (HFIR) before being released to Melton Branch. Currently, Melton Branch receives blowdown from HFIR, an unidentified process water discharge coming from the headwaters region of the Homogeneous Reactor Experiment tributary (see Borders et al. 1991 for further explanation), and rainfall-induced runoff.

### 2.4 WHITE OAK DAM

White Oak Dam is a low-head structure with a normal lake elevation of 227.1 m (745 ft). The reservoir is only 0.9 m (3 ft) above full-pool elevation in the Clinch River, which is 226.6 m (742 ft). Cox et al. (1991) reported that the volume of WOL at normal pool level was 43,787.2 m<sup>3</sup> (1,546,330 ft<sup>3</sup>) in the summer of 1988. Flow from WOL discharges through a weir and concrete-box culvert to the lower reach of WOC. In 1983, the flow system at the dam was modified to increase the flood discharge capacity to approximately 56.6 m<sup>3</sup>/s (2000 cfs). Tschantz (1987) estimated the 100-year flood peak discharge to be approximately 44.6 m<sup>3</sup>/s (1574 cfs).

## 2.5 WHITE OAK LAKE

White Oak Lake was created in 1943 by placing interlocking steel pilings and a sluice gate upstream from a culvert and road fill that was constructed at km 1.0 (mile 0.6) on WOC by the Tennessee Valley Authority (TVA) in 1941. The lake is currently maintained at an elevation of 227.1 m (745 ft), which results in a standing pond behind the dam of approximately 6.9 ha (17 acres); however, the size of the standing pond has changed many times during the past five decades from the original 17.9 ha (44.2 acres) to about 0.4 ha (1 acre) when the lake was drained in 1955 (Oak Ridge National Laboratory 1990; Blaylock et al. 1991).

Numerous studies have been undertaken to determine contaminant sources, quantities of contaminants released into and retained in the lake, and the geology and hydrogeology of WOC/WOL. Table 2.1 summarizes some of the more important studies conducted since 1945. In some instances, the studies referenced in Table 2.1 represent summaries of the information developed; individual investigators have reported in greater detail their efforts in other reports and papers not cited in Table 2.1.

The volume of WOL continues to decrease with time because of the accumulation of sediments. Table 2.2 contains quoted WOL volumes at the normal lake elevation of 227.1 m (745 ft). The original WOL volume has been reduced by approximately fifty percent since 1943. The entire upper lake bed (see Fig. 2.2) has been filled in with the decaying products of organic production and sediment transported mainly by WOC (Cox et al. 1991).

The buildup of sedimentation in WOL also has caused a reduction in water depth. Oakes et al. (1982, p. 49) reported that the depth of WOL varied from less than 0.3 m (1 ft), where WOC empties into WOL, to a maximum of 2.49 m (8.18 ft) behind WOD. Recent WOL size and depth measurements by Cox et al. (1991) (see Table 2.3 and Fig. 2.3) indicate a maximum depth of 1.34 m (4.40 ft) behind WOD and a maximum transect-averaged depth of 0.98 m (3.22 ft) (obtained for Section 3 in Table 2.3). The overall areal variation of the depth also has been reduced by the continual deposition of sediments as indicated by the relatively small average water depth variation between WOL sections quoted in Table 2.3 and the actual discrete measurements shown in Fig. 2.3. The average depth of WOL in 1988 obtained by dividing the total lake volume by the overall surface area was 0.64 m (2.09 ft).

The lake has served as the final settling basin for low-level radioactive effluents from ORNL since 1943. Although low levels of radioactivity have been released over the dam since 1943, current levels are much lower than releases made in previous years (see Table 2.4) (Blaylock et al. 1991). Radionuclides and other contaminants have accumulated in the bottom sediments of WOL (Lomenick and Gardiner 1965; Oakes et al. 1982; Sherwood and Loar 1987; Blaylock et al. 1992). The most recent reported estimate of the total radionuclide inventory in the sediments of WOL is 4.34 Ci (for 1988) (Blaylock et al. 1992, p. 5). The primary radioactive isotopes deposited in the WOL sediments are  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ , and  $^{90}\text{Sr}$ . During periods of heavy precipitation and runoff, some radioactive isotopes are entrained or resuspended and overflow from the lake into the Clinch River.

## 2.6 FLOODPLAIN

The former lake bed and floodplain of WOL and WOC extend from the upper reaches of the standing pond at an elevation of 227.1 m (745 ft) to the WOC and Melton Branch weirs. In 1943, the floodplain area was cleared of trees but is now covered with secondary growth and is being reforested with sycamore, ash, and maple trees. Because WOL is maintained at a lower elevation than when it was first formed, a large portion of the former lake bed is now exposed (Oak Ridge National Laboratory 1990). The former lake bed contains concentrations of radionuclides similar to those present in the submerged sediments of WOL.

**Table 2.1. Historical changes in the surface area of White Oak Lake and major events associated with significant changes to the lake**

Date	Surface area (ha)	Events	References
1941	NA	Highway fill and culvert installed by the Tennessee Valley Authority	Smith (1945) as in Krumholz (1954)
1943	14.5	(a) Sheet piling dam installed with spillway and vertical sliding gate; (b) generation of radioactive waste at Oak Ridge National Laboratory began and lake served as final settling basin (750 ft)	(a) Krumholz (1954a,b); (b) Clinch River Study Steering Committee (1967)
1944	NA	Dikes at White Oak Creek km 3.3 and 3.9 washed out (7.75-in. rainfall, 26-h storm, 3.5-in. runoff)	Setter and Krochitsky (1950)
1945	12.2	Investigation of structural strength of dam (746.5 ft)	Oakes et al. (1982)
1948	10.3	Lake lowered to 745.5 ft to facilitate sediment sampling; normal operation from 1948 to 1955 (level varied from 747 to 749 ft)	Oakes et al. (1982)
1953	NA	Lake partially drained during rotenone survey of fish populations	Oakes et al. (1982)
1955	2.8	Lake drained; radionuclides in lake sediment and water believed to be in equilibrium such that lake served no useful function in retaining radioactivity, but could function as an emergency effluent storage basin	Clinch River Study Steering Committee (1967)
1956	0.4	Significant releases of <sup>137</sup> Cs occurred, probably caused by the erosion of freshly exposed sediment after lake was drained	Lackey (1957)
1959	NA	Gate structure renovated to prevent inflow of backwaters from Clinch River	Clinch River Study Steering Committee (1967)
1960	3.2	Dam closed, surface level raised to 745 ft	Kolehmainen and Nelson (1969)
1963	6	Completion of Melton Hill Dam	Kolehmainen and Nelson (1969)
1967	8.1	None reported	McMaster (1967)
1969	10.5	None reported	Kolehmainen and Nelson (1969)

Table 2.1 (continued)

Date	Surface area (ha)	Events	References
1979	4.6	Lake level gradually dropped from 745 to 742 ft because of potential instability of the dam	Oakes et al. (1982)
1980	6.9	Construction of a berm to stabilize dam was completed	Boyle et al. (1982)
1983	6.9	Discharge channel and weir constructed; roadbed rerouted	General information
1988	6.9	Estimate of surface area and volume 43,787.2 m <sup>3</sup> (1,546,330 ft <sup>3</sup> ) at lake level of 745 ft; sedimentation continues to reduce the lake volume	Cox et al. (1991)
1992	6.9	Sediment retention structure installed at the mouth of White Oak Creek on the Clinch River	Borders et al. (1992)

Notes:

- NA = not available
- 1 ha = 2.471 acres
- 1 m = 3.281 ft
- 1 cm = 0.3937 in.
- 1 m<sup>3</sup> = 35.314 ft<sup>3</sup>

Elevations referenced with respect to mean sea level.

Source: Adapted from Table 1, D. M. Borders et al., *Hydrologic Data Summary for the White Oak Creek Watershed at Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1990–December 1991)*, ORNL/ER-123, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., June 1992, p. 4.

**Table 2.2. White Oak Lake volume during various years**

Year	Volume <sup>a,b</sup> [m <sup>3</sup> (ft <sup>3</sup> )]
Original volume <sup>c</sup>	87,116 (3,076,455) <sup>d</sup>
1950	70,274 (2,481,691) <sup>d</sup>
1979	64,015 (2,260,659) <sup>d</sup>
1988	43,787.2 (1,546,330) <sup>e</sup>

<sup>a</sup>At normal lake water surface elevation of 227.1 m (745 ft) above mean sea level.

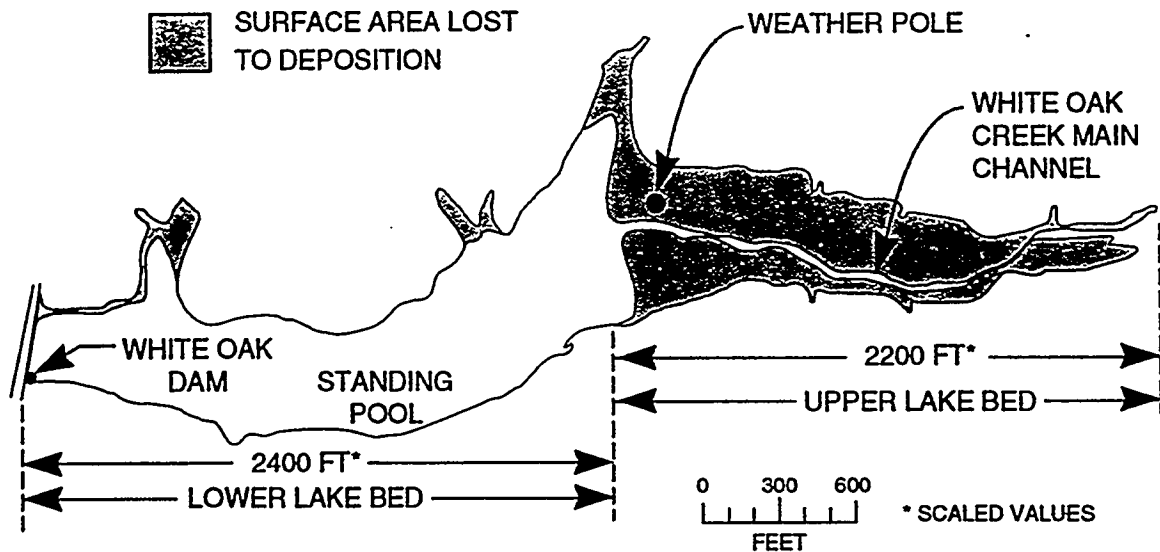
<sup>b</sup>Since 1943, approximately 140,000 m<sup>3</sup> (5,000,000 ft<sup>3</sup>) of contaminated sediment has collected behind White Oak Dam. Source: C. B. Sherwood and J. M. Loar, *Environmental Data for the White Oak Creek/White Oak Lake Watershed*, ORNL/TM-10062, Environmental Sciences Publication No. 2779, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., January 1987, p. 8.

<sup>c</sup>Created in 1943.

<sup>d</sup>Source: Table 4.2, T. W. Oakes et al., *Technical Background Information for the Environmental and Safety Report, Vol. 4: White Oak Lake and Dam*, ORNL-5681, Union Carbide Corporation, Oak Ridge Natl. Lab., March 1982, p. 48.

<sup>e</sup>Source: D. K. Cox, et al., *The New Definitive Map of White Oak Lake*, ORNL/TM-11204, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1991, p. ix.

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**Fig. 2.2. Map of White Oak Lake basin at a water surface elevation of 745 ft showing area lost to deposition.**

**Table 2.3. Physical characteristics of White Oak Lake, April 1988, water surface elevation 745 ft above mean sea level [see Fig. 2.3 for location of sections (dashed lines) and depth measurements (x's)]**

Section number	Average water depth <sup>a</sup>			Water surface area				Lake volume	
	(m)	(ft)	(m <sup>2</sup> )	(ft <sup>2</sup> )	(ha)	(acres)	(m <sup>3</sup> )	(ft <sup>3</sup> )	
Section 1	0.93	3.04	5,366	57,743	0.53	1.33	4,991	175,539	
Section 2	0.86	2.83	8,196	88,184	0.81	2.02	7,048	249,561	
Section 2A	0.55	1.80	2,124	22,849	0.22	0.53	1,168	41,128	
Section 3	0.98	3.22	13,216	142,204	1.32	3.27	12,952	457,897	
Section 4	0.62	2.02	14,742	158,629	1.47	3.64	9,140	320,431	
Section 5	0.51	1.67	13,704	147,460	1.37	3.39	6,989	246,258	
Section 6	0.14	0.45	11,466	123,370	1.15	2.83	1,605	55,517	
Totals	0.64	2.09	68,814	740,439	6.88	17.01	43,893	1,546,330	
BN <sup>b</sup>	0.14	0.45	6,136	66,029	0.62	1.52	859	29,713	
Survey estimate <sup>c</sup>	0.68 <sup>a</sup>	2.23 <sup>a</sup>	63,485	683,098	6.35	15.7	43,147	1,520,526	

<sup>a</sup>Average depths calculated by dividing total volume by total area.

<sup>b</sup>BN—subunit of Section 6, bounded on the upper side by a block net.

<sup>c</sup>Parameters applicable to fish population survey conducted in May 1987.

Source: Table 1, D. K. Cox et al., *The New Definitive Map of White Oak Lake*, ORNL/TM-11204, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1991, p. 4.



**Table 2.4. Estimated routine discharges of selected radionuclides from White Oak Creek into the Clinch River, in curies**

Year	<sup>137</sup> Cs	<sup>106</sup> Ru	<sup>90</sup> Sr	<sup>131</sup> I	<sup>60</sup> Co	<sup>3</sup> H	TRU <sup>a</sup>
1949	77	110	150	77		NA <sup>b</sup>	0.04 <sup>c</sup>
1950	19	23	38	19			0.04
1951	20	18	29	18			0.08
1952	10	15	72	20			0.03
1953	6	26	130	2			0.08
1954	22	11	140	4	NA		0.07
1955	63	31	93	7	7		0.25
1956	170	29	100	4	46		0.28
1957	89	60	83	1	5		0.15
1958	55	42	150	8	9		0.08
1959	76	520	60	1	77		0.68
1960	31	1,900	28	5	72		0.19
1961	15	2,000	22	4	31		0.07
1962	6	1,400	9	0.4	14		0.06
1963	4	430	8	0.4	14		0.17
1964	6	190	7	0.3	15	1,900	0.08
1965	2	69	3	0.2	12	1,200	0.50
1966	2	29	3	0.2	7	3,100	0.16
1967	3	7	5	0.9	3	13,300	1.03
1968	1	5	3	0.3	1	9,700	0.04
1969	1	2	3	0.5	1	12,200	0.20
1970	2	1	4	0.3	1	9,500	0.40
1971	1	0.5	3	0.2	1	8,900	0.05
1972	2	0.5	6	0.3	1	10,600	0.07
1973	2	0.7	7	0.5	1	15,000	0.08
1974	1	0.2	6	0.2	0.6	8,600	0.02

**Table 2.4 (continued)**

Year	<sup>137</sup> Cs	<sup>106</sup> Ru	<sup>90</sup> Sr	<sup>131</sup> I	<sup>60</sup> Co	<sup>3</sup> H	TRU <sup>a</sup>
1975	0.6	0.3	7	0.3	0.5	11,000	0.02
1976	0.2	0.2	5	0.03	0.9	7,400	0.01
1977	0.2	0.2	3	0.03	0.4	6,200	0.03
1978	0.3	0.2	2	0.04	0.4	6,300	0.03
1979	0.2	0.1	2.4	0.04	0.4	7,700	0.03
1980	0.6	0	1.5	0.04	0.4	4,600	0.04
1981	0.2	0.1	1.5	0.04	0.7	2,900	0.04
1982	1.5	0.2	2.7	0.06	1.0	5,400	0.03
1983	1.2	0.2	2.1	0.004	0.3	5,600	0.05
1984	0.6	0.2	2.6	0.05	0.2	6,400	0.03
1985	0.4	0.007	3.0		0.6	3,700	0.008
1986	1.0	0	1.8		0.54	2,600	0.024
1987	0.6	0	1.2		0.12	2,500	0.006
1988	0.4	0	1.1		<0.07	1,700	
1989	1.2	0	2.9		0.13	4,100	
1990	1.1	0	3.1		0.12	3,100	
Total	696.3	6,931.6	1,204.9	175.33	325.26	175,200	5.248

<sup>a</sup>Transuranics.

<sup>b</sup>No analysis performed.

<sup>c</sup>Estimated from measurements made during the last quarter of 1949.

Source: Blaylock et al. 1992.

The operation of the Melton Hill Dam generators further complicated the flow and hydrodynamics in the WOCE. The release of water from the dam increased the depth of water at the mouth of the embayment by over 0.3 m (1 ft) in 2 minutes, and 0.6 m (2 ft) throughout the WOCE in as little as 5 minutes (Kimmel and Ford 1991; Blaylock et al. 1993). Daily water levels at the mouth of the embayment typically varied by ≈0.6–1.2 m (≈2–4 ft), with monthly water-level variations ranging up to 2.5 m (8 ft) or more (Borders et al. 1992). When the generators shut down, the water level dropped almost as quickly. The rapid change in water level and pulsing of flow caused by daily peaking operations at Melton Hill Dam were, until recently

and prior to construction of the sediment retention structure, contributing to the erosion of sediments from the embayment.

A sediment retention structure (see Fig. 2.4) has been constructed (completed mid-April 1992) at the mouth of WOC on the Clinch River. The structure was constructed to reduce the scour of contaminated sediments in WOCE. The spillway of the retention structure consists of sheet pile coffer cells constructed to an elevation of 224.9 m (738 ft) with gabions constructed on top of the cells to elevation 226.5 m (743 ft). This structure limits the winter drawdown in the embayment to an elevation of  $>224.9$  m ( $>738$  ft), resulting in a year-round embayment below WOD. The porous gabions, which consist of rock-filled (i.e., boulder-filled) wire cages, are intended to attenuate the rapid rise and drawdown resulting from the diurnal pulsing of Melton Hill Dam and to reduce the scouring of bottom sediments that has occurred in the past.

## 2.8 GAGING STATIONS AND DATA

Streamflow data for the WOC watershed are collected by the ORNL Environmental Sciences Division, the Lockheed Martin Energy Systems, Inc. (LMES), Environmental Surveillance and Protection Section, and the U.S. Geological Survey (USGS). Gaging station locations are shown in Fig. 2.5 and further described in Table 2.5. The USGS gaging stations located within the WOC watershed begin with the letter G (GS1, for example). Corresponding USGS numbers for these gages are given in Table 2.5. The USGS also monitors the Melton Hill Dam tailwaters along the Clinch River (gage 03535912). The five remaining gages (MS3, MS4, MS5, WOCHW, and WOCCON) displayed in Fig. 2.5 and listed in Table 2.5 are operated by ORNL. The historical measurements available from gage WOCCON are obsolete because a sediment retention structure has been constructed (completed mid-April 1992) at the mouth of WOC on the Clinch River. Drainage areas above selected monitoring gages appearing in Fig. 2.5 are tabulated in Table 2.6.

The USGS publishes annual reports summarizing measured discharges (Lowery et al. 1989, 1990; Flohr et al., 1991, 1993; Mercer et al. 1992). The annual reports contain summary statistics computed for extended periods of record at each gage. Examples of summary statistics are the highest annual mean, the annual seven-day minimum, and the 10%, 50%, and 90% exceedence flows. Summary statistics have not been published for the ORNL discharge records measured at gages MS3, MS4, MS5, WOCHW, and WOCCON. The discharge statistics are pertinent to the spill model development because a variety of hydrologic conditions ranging from drought to flood must be accommodated. The summary statistics provide a convenient way of achieving this requirement.

White Oak Creek splits into two major legs, or tributaries, immediately upstream from WOL. Published discharge statistics for USGS gages upstream from this confluence with Melton Branch are listed in Table 2.7 (gages GS1, GS3, GS4, GS5, and GS6). The flow in Fifth Creek is not monitored. The Fifth Creek discharge statistics are approximated as the differences between the GS5 and GS6 statistics based on continuity of flow. The calculated Fifth Creek discharge statistics appear in the sixth column of Table 2.7. The last column of Table 2.7 presents calculated discharge statistics for ORNL gage MS3 above the Melton Branch confluence. The flows were approximated (assuming statistical uniformity) by forming the product of the published gage GS3 statistics and the drainage area ratio (see Table 2.6).

Table 2.8 contains published discharge statistics for USGS gages (GS2, GS16, GS17, and GS18) located along Melton Branch and its tributaries. The 10%, 50%, and 90% exceedence flows for West Seven Creek not quoted by USGS were estimated from the Center Seven Creek statistics using the drainage area (see Table 2.6) ratio as a formal basis. Similar methodology was employed to calculate the Melton Branch discharge statistics near its confluence with WOC and ORNL gage MS4 based on the combined flows and drainage areas for gages GS2, GS16, GS17, and GS18.

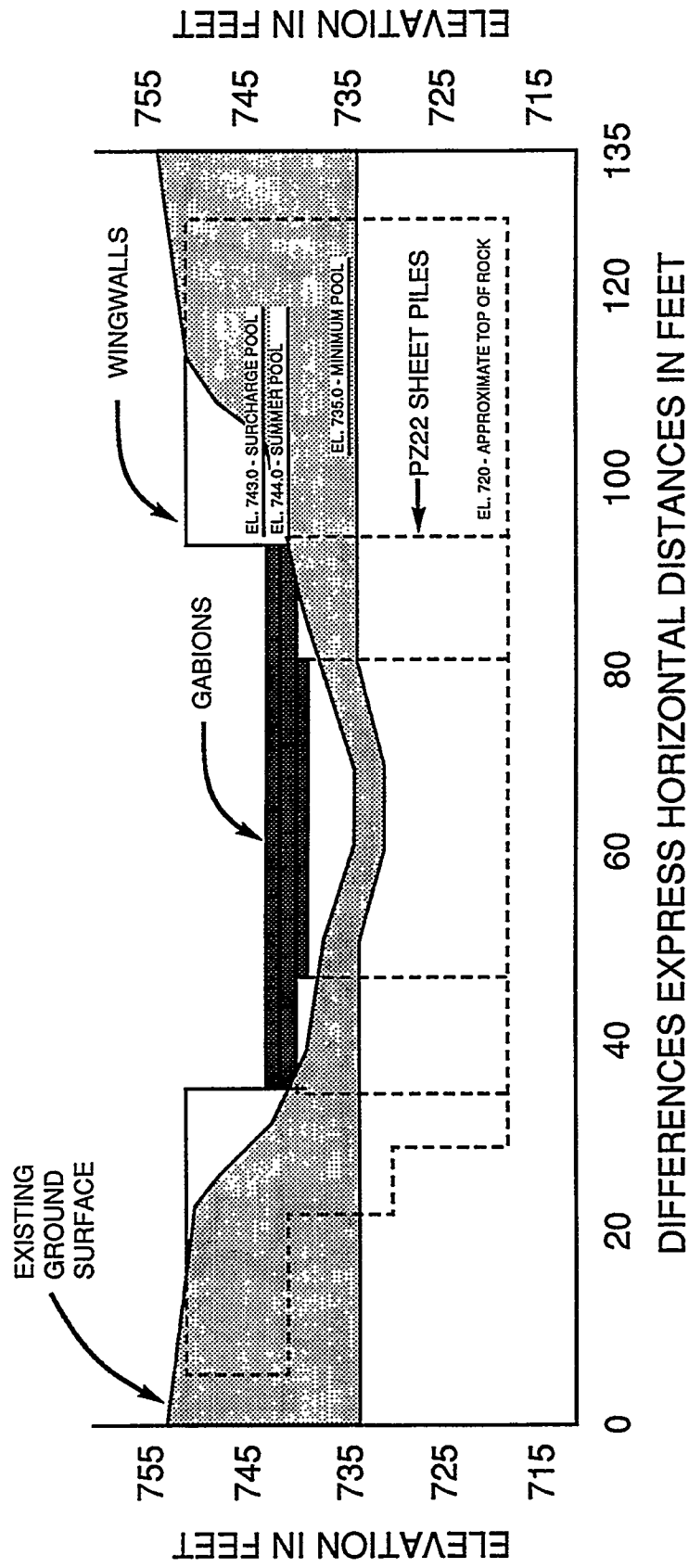


Fig. 2.4. Frontal view looking from the Clinch River side of the sediment control structure located at the mouth of White Oak Creek.

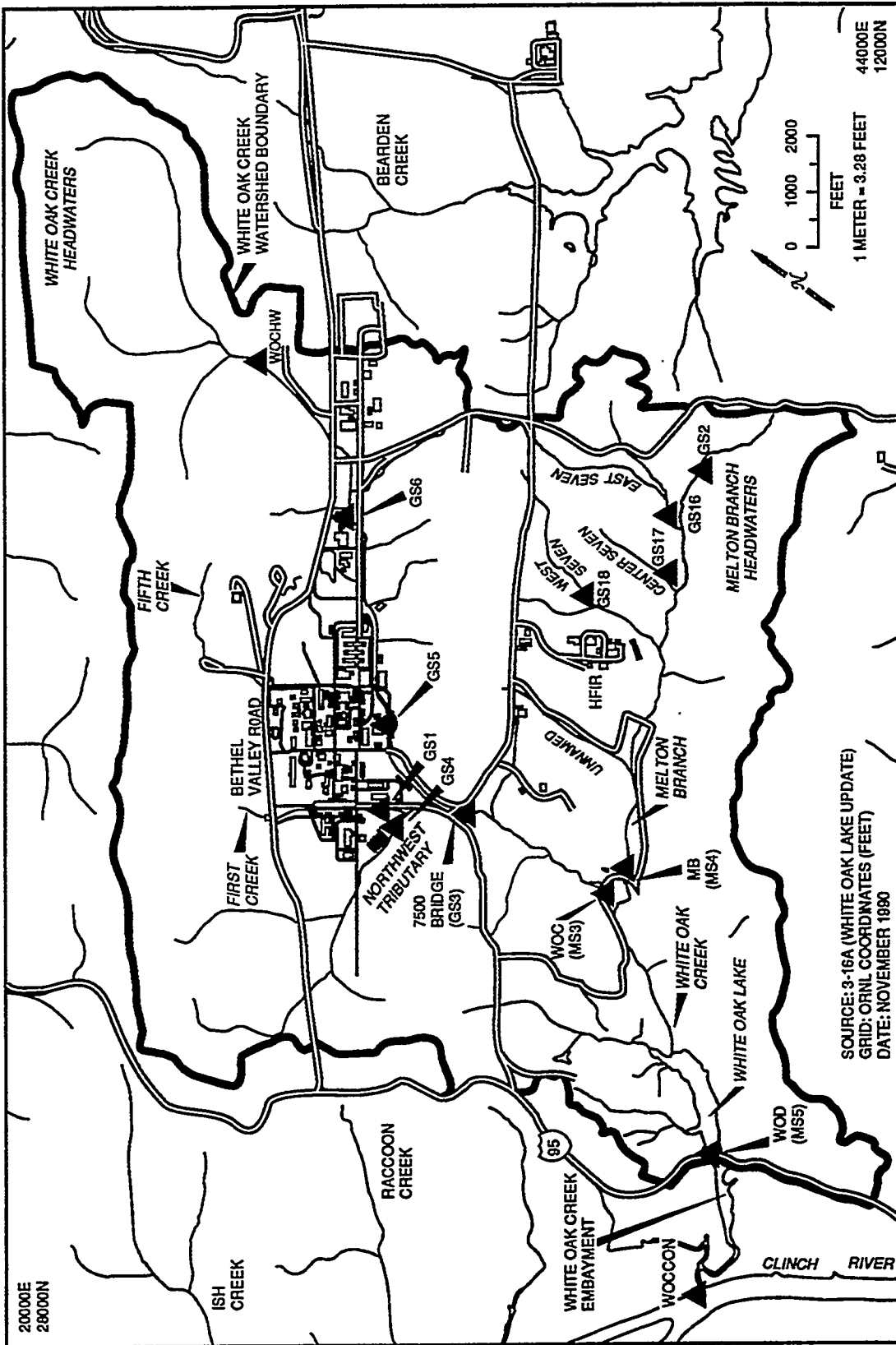


Fig. 2.5. Surface-water gaging stations in the White Oak Creek watershed.

Table 2.5. White Oak Creek watershed gaging station summary

Designator	USGS <sup>a</sup> number	Stream monitored	Location
GS1	03536450	First Creek	Above confluence with Northwest Tributary (mile 0.1)
GS2	03537100	Melton Branch	Upper reaches of Melton Branch upstream from HFIR <sup>b</sup> (mile 1.2)
GS3	03536550	White Oak Creek	Below confluence with First Creek and Northwest Tributary (200 ft downstream of 7500 Bridge) (mile 2.2)
GS4	03536440	Northwest Tributary	Above confluence with First Creek (mile 0.2)
GS5	03536380	White Oak Creek	Downstream from confluence with Fifth Creek (mile 2.7)
GS6	03536320	White Oak Creek	East of east gate outside ORNL <sup>c</sup> main plant area (mile 3.4)
GS16 <sup>d</sup>	03537050	East Seven Creek	Discontinued by USGS in October 1991 (125 ft upstream from mouth)
GS17 <sup>d</sup>	03537200	Center Seven Creek	Near center of three tributaries 300 ft upstream from mouth (discontinued by USGS in October 1991)
GS18 <sup>d</sup>	03537300	West Seven Creek	Discontinued by USGS in October 1989 (1500 ft upstream from mouth)
MS3	NA <sup>e</sup>	White Oak Creek	0.1 mile above confluence with Melton Branch
MS4	NA <sup>e</sup>	Melton Branch	0.1 mile above confluence with White Oak Creek
MS5 (White Oak Dam)	NA <sup>e</sup>	White Oak Creek	Outfall of White Oak Lake where White Oak Creek flows under State Highway 95
WOCHW	NA <sup>e</sup>	White Oak Creek	Upper reaches of White Oak Creek upstream from any ORNL discharges
WOCCON	NA <sup>e</sup>	White Oak Creek	Mouth of White Oak Creek on Clinch River (dismantled January 1991)
Melton Hill Dam	03535912	Clinch River	Downstream side of dam in tailwaters (river mile 23.1) <sup>f</sup>

<sup>a</sup>U.S. Geological Survey.

<sup>b</sup>High Flux Isotope Reactor.

<sup>c</sup>Oak Ridge National Laboratory.

<sup>d</sup>Currently not in operation. Discharge data is available from the USGS for GS16, GS17, and GS18.

<sup>e</sup>Not applicable; ORNL gaging station.

<sup>f</sup>Existing data for WOCCON are obsolete because of construction of sediment retention structure at the mouth of White Oak Creek.

<sup>g</sup>This location is upstream of the area depicted in Fig. 2.5.

Sources: D. M. Borders et al., *Hydrologic Data Summary for the White Oak Creek Watershed at Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1990–December 1991)*, ORNL/ER-123, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., June 1992, pp. 46–55; L. R. Mercer, et al., *Water Resources Data Tennessee Water Year 1991*, U.S. Geological Survey Water-Data Report TN-91-1, National Technical Information Service, Springfield, Va., 1992, pp. 115–26; and J. F. Lowery et al., *Water Resources Data Tennessee Water Year 1989*, U.S. Geological Survey Water-Data Report TN-89-1, National Technical Information Service, Springfield, Va., 1990, p. 124.

**Table 2.6. Drainage areas above selected gages within the White Oak Creek watershed**

Gage	Drainage area [km <sup>2</sup> (mi <sup>2</sup> )]
GS2 <sup>a</sup> (0357100)	1.35 (0.52)
GS3 <sup>a</sup> (03536550)	8.50 (3.28)
GS16 <sup>a</sup> (03537050)	0.62 (0.24)
GS17 <sup>a</sup> (03537200)	0.18 (0.07)
GS18 <sup>a</sup> (03537300)	0.39 (0.15)
MS3 <sup>b</sup>	9.35 (3.61)
MS4 <sup>b</sup>	3.91 (1.51)

<sup>a</sup>U.S. Geological Survey gaging station.

<sup>b</sup>Operated by Oak Ridge National Laboratory.

Sources: J. F. Lowery et al., *Water Resources Data Tennessee Water Year 1988*, U.S. Geological Survey Water-Data Report TN-88-1, National Technical Information Service, Springfield, Va., 1989, and D. M. Borders et al., *Hydrologic Data Summary for the White Oak Creek Watershed at Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1990–December 1991)*, ORNL/ER-123, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., June 1992.

The flow entering WOL is calculated as the gage GS3 discharge corrected for the 0.85 km<sup>2</sup> (0.33 mile<sup>2</sup>) drainage area increase (the calculated gage MS3 statistics in Table 2.7) plus the calculated Melton Branch contribution available from Table 2.8 (gage MS4 contribution). Refer to Table 2.6 for the drainage areas above gages GS3, MS3, and MS4. The resultant discharge statistics quantifying the WOL inflow under various prescribed hydrologic situations are given in Table 2.9.

Summary statistics for USGS monitoring gage 03535912 installed along the tailwaters of Melton Hill Dam are listed in Table 2.10. The USGS does not quote numerical values for the instantaneous peak or instantaneous low flows (Flohr et al. 1993). The instantaneous low flow is zero. Since the completion of Melton Hill Dam in 1963, there has been an average of approximately 13 days per year during which no water was released though the dam (Tennessee Valley Authority no date; Project Management Corporation 1975, 1975a; Boyle et al. 1982). The longest period of no release was 29 consecutive days during February and March 1966. The second-longest period was 11 consecutive days during April and May 1967. Both of these extended periods of no release resulted from operations to control aquatic weed growth in Melton Hill Reservoir and not from periods of extreme drought. Periods of drought since 1963 have caused shorter periods of no release relative to the duration of zero-release periods for control of aquatic weed growth.

**Table 2.7. Summary discharge statistics from monitoring gages on White Oak Creek leg of White Oak Creek watershed, in cfs<sup>a</sup>**

Discharge statistic	Measured						Calculated White Oak Creek Gage, MS3 <sup>c</sup>
	White Oak Creek, GS6 03536320	White Oak Creek, GS5 03536380	White Oak Creek, GS3 03536550	First Creek GS1 03536450	NW Tributary GS4 03536440	Calculated Fifth Creek <sup>b</sup>	
Annual mean	1.51	5.97	10.2	0.93	1.21	4.46	11.2
Highest annual mean	2.19	7.29	12.9	1.15	1.62	5.10	14.2
Lowest annual mean	0.42	3.77	7.47	0.49	0.82	3.35	8.22
Highest daily mean	80	106	150	26	32	26	165
Lowest daily mean	0.01	1.70	4.3	0.14	0.23	1.69	4.73
Annual seven-day minimum	0.02	2	4.5	0.15	0.25	1.98	4.95
Instantaneous peak flow	327	384	711	295	182	57	783
Instantaneous low flow	0.00	1.6	3.8	0.09	0.18	1.6	4.18
10% exceedance flow	3.2	11	17	1.8	2	7.8	18.7
50% exceedance flow	0.20	3.7	7.2	0.48	0.64	3.5	7.92
90% exceedance flow	0.05	2.4	5.4	0.21	0.37	2.35	5.94
Water years of record	1987-1992	1987-1992	1985-1992	1987-1992	1987-1992	NA <sup>d</sup>	NA <sup>d</sup>

<sup>a</sup>1 cfs = 28.32 L/s.

<sup>b</sup>Approximated as the difference between GS5 and GS6 discharge statistics.

<sup>c</sup>Approximated as  $GS3 \times (3.61/3.28)$ ; the quotient in parentheses is the drainage area ratio.

<sup>d</sup>Not applicable.

Source: D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, U.S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va., 1993, pp. 156-65.

**Table 2.8. Summary discharge statistics from monitoring gages on Melton Branch leg of White Oak Creek watershed, in cfs**

Discharge statistic	Measured				Calculated Melton Branch gage MS4 <sup>b</sup>
	Melton Branch Creek, GS2 03537100	East Seven Creek, GS16 03537050	Center Seven Creek, GS17 03537200	West Seven Creek, GS18 03537300	
Annual mean	0.61	0.38	0.13	0.205	2.04
Highest annual mean	0.99	0.49	0.16	0.30	2.99
Lowest annual mean	0.21	0.12	0.044	0.11	0.75
Highest daily mean	28	20	4.6	6.5	91.1
Lowest daily mean	0.00	0.00	0.00	0.00	0.00
Annual seven-day minimum	0.00	0.00	0.00	0.00 <sup>c</sup>	0.00
Instantaneous peak flow	238	51	35	35	553
Instantaneous low flow	0.00	0.00	0.00	0.00	0.00
10% exceedence flow	1.3	0.81	0.24	0.51 <sup>d</sup>	4.41
50% exceedence flow	0.11	0.07	0.04	0.09 <sup>d</sup>	0.48
90% exceedence flow	0.00	0.00	0.00	0.00 <sup>d</sup>	0.00
Water years of record	1985–1992	1987–1991	1987–1991	1988–1989	NA <sup>e</sup>
U.S. Geological Survey Report	TN-92-1	TN-91-1	TN-91-1	TN-89-1	NA <sup>e</sup>

<sup>a</sup>1 cfs = 28.32 L/s.

<sup>b</sup>The Melton Branch gage MS4 discharge statistics in the vicinity of the White Oak Creek confluence are approximated from (GS2 + GS16 + GS17 + GS18) × [1.51/(0.52 + 0.24 + 0.07 + 0.15)], where the latter quantity in brackets is the drainage area ratio (see Table 2.6).

<sup>c</sup>Determined from tabular entries in U.S. Geological Survey Water-Data Report TN-89-1.

<sup>d</sup>GS18 = GS17 × (0.15/0.07); the quotient in parentheses is the drainage area ratio.

<sup>e</sup>Not applicable.

*Sources:* J. F. Lowery et al., *Water Resources Data Tennessee Water Year 1989*, U.S. Geological Survey Water-Data Report TN-89-1, National Technical Information Service, Springfield, Va., 1990, p. 124; L. R. Mercer et al., *Water Resources Data Tennessee Water Year 1991*, U.S. Geological Survey Water-Data Report TN-91-1, National Technical Information Service, Springfield, Va., 1992, pp. 123, 126; and D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, U.S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va., 1993, pp. 166–67.

Since the closure of Norris Dam in 1936, only one flood, that of February 1937, reached bank-full stage at Clinton, Tennessee, located upstream from Melton Hill Dam and downstream from Norris Dam (Tennessee Valley Authority 1959, p. 16). The peak discharge during the 1937 flood at Clinton was 42,000 cfs, which has been entered in Table 2.10 as an estimate of the instantaneous peak flow. Flood discharges along the Clinch River prior to 1936 are chiefly significant from a historical point of view because of the flow regulation provided by Norris Dam. Melton Hill Dam, which was closed in August 1962, also would assist in the regulation of future Clinch River flood flows.

**Table 2.9. Calculated flow into White Oak Lake (MS3 + MS4) from both White Oak Creek (MS3) and Melton Branch (MS4)**

Discharge statistic <sup>a</sup>	MS3 + MS4 discharge (cfs) <sup>b</sup>
Annual mean	13.3
Highest annual mean	17.2
Lowest annual mean	8.97
Highest daily mean	256
Lowest daily mean	4.73
Annual 7-d minimum	4.95
Instantaneous peak flow	1336
Instantaneous low flow	4.18
10% exceedence flow	23.1
50% exceedence flow	8.4
90% exceedence flow	5.94

<sup>a</sup>Approximated as  $GS3 \times (3.61/3.28) + (GS2 + GS16 + GS17 + GS18) \times [1.51/(0.52 + 0.24 + 0.07 + 0.15)]$ . Drainage areas obtained from Table 2.6. MS3 is equal to  $GS3 \times (3.61/3.28)$ , while the remaining part of the expression accounts for MS4.

<sup>b</sup>1 cfs = 28.32 L/s.

Daily temperatures measured by USGS in the tailwaters of Melton Hill Dam and by ORNL below WOD are tabulated in Tables 2.11 and 2.12, respectively. Average temperatures calculated from the data in Tables 2.11 and 2.12 appear in Tables 2.13 and 2.14, as well as the maximum and minimum temperature extremes for the periods of record. The averages reported in Tables 2.12 and 2.13 are based on the approximate same-day temperature in the designated month. The actual date of each measurement is given in Tables 2.11 and 2.12. The average temperatures clearly demonstrate that the Melton Hill Dam tailwaters are cooler than the flow from WOD during much of the year. In the fall when seasonal cooling occurs, the effects of thermal inertia cause the water exiting Melton Hill Dam to exceed WOD effluent water temperatures. The large volume of water in Melton Hill Reservoir requires a longer time to cool relative to the water held in WOL. The shallower water in WOL responds more rapidly to the cooler autumn air temperatures than do the deeper waters of Melton Hill Reservoir.

**Table 2.10. Summary statistics for U.S. Geological Survey gage 03535912 monitoring the tailwaters of Melton Hill Dam**

Discharge statistic	Discharge (cfs) <sup>a</sup>
Annual mean	4853 <sup>b</sup>
Highest annual mean	7056
Lowest annual mean	2235
Highest daily mean	29,000
Lowest daily mean	0.00 <sup>c</sup>
Annual 7-d minimum	3.1
Instantaneous peak flow	42,000 <sup>d</sup>
Instantaneous low flow	0.00 <sup>c</sup>
10% exceedence flow	9080
50% exceedence flow	4100
90% exceedence flow	763
Water years of record	1979-1992

<sup>a</sup>1 cfs = 28.32 L/s.

<sup>b</sup>Unadjusted for change in volumetric contents of Norris and Melton Hill reservoirs.

<sup>c</sup>Multiple no-flow occurrences have taken place since closure of Melton Hill Dam in August 1962.

<sup>d</sup>This is the highest discharge experienced at Clinton, Tennessee, upstream from Melton Hill Dam, since the closure of Norris Dam in 1936. This flow was associated with the flood of February 1937.

*Sources:* Tennessee Valley Authority (TVA), *Hydraulic Data Branch Files*, Knoxville, Tenn.; TVA, *Floods on Clinch River and East Fork Poplar Creek in Vicinity of Oak Ridge, Tennessee*, Report No. 0-5922, Division of Water Control Planning, Knoxville, Tenn., 1959; Project Management Corporation (PMC), *Preliminary Safety Analysis Report, Clinch River Breeder Reactor*, Oak Ridge, Tenn., 1975; PMC, *Clinch River Breeder Reactor Environmental Report*, Vols. I-III, Docket No. 50-537, 1975; and D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, U.S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va., 1993, p. 153.

**Table 2.11. Measured Melton Hill Dam tailwater temperatures**

Temperature [°C(°F)/month-day-year]				
Water year 1988	Water year 1989	Water year 1990	Water year 1991	Water year 1992
15.0(59.0)/10-29-87	16.0(60.8)/10-26-88	17.5(63.5)/10-12-89	19.5(67.1)/10-16-90	17.0(62.6)/10-23-91
12.0(53.6)/12-8-87	9.0(48.2)/12-14-88	10.5(50.9)/12-12-89	14.0(57.2)/12-6-90	13.5(56.3)/12-10-91
8.0(46.4)/2-18-88	8.0(46.4)/2-14-89	8.5(47.3)/2-20-90	9.0(48.2)/2-4-91	8.5(47.3)/2-11-92
14.0(57.2)/4-19-88	15.0(59.0)/4-18-89	12.5(54.5)/4-3-90	13.0(55.4)/4-17-91	12.0(53.6)/4-8-92
20.0(68.0)/6-15-88	17.0(62.6)/6-12-89	18.0(64.4)/6-12-90	20.0(68.0)/6-19-91	21.0(69.8)/6-17-92
20.5(68.9)/8-25-88	21.0(69.8)/8-14-89	20.0(68.0)/8-14-90	19.0(66.2)/8-21-91	Not reported

*Sources:* J. F. Lowery et al., *Water Resources Data Tennessee Water Year 1988*, U.S. Geological Survey (USGS) Water-Data Report TN-88-1, 1989, p. 116; J. F. Lowery et al., *Water Resources Data Tennessee Water Year 1989*, USGS Water-Data Report TN-89-1, 1990, p. 114; D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1990*, USGS Water-Data Report TN-90-1, 1991, p. 112; L. R. Mercer et al., *Water Resources Data Tennessee Water Year 1991*, USGS Water-Data Report TN-91-1, 1992, p. 116; and D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, USGS Water-Data Report TN-92-1, 1993, p. 154; all available from National Technical Information Service, Springfield, Va.

## 2.9 GEOLOGY AND SOILS

Four major geologic units underlie the WOC drainage basin (Borders et al. 1992). The Knox group (Cambrian and Ordovician age), mostly composed of cherty dolomite in which sinkholes and caverns have developed, is the principal water-bearing formation in the watershed. The seeps and springs along the southern slopes of Chestnut Ridge are the principal sources of base flow to the upper portions of WOC (McMaster and Waller 1965).

The Chickamauga group (Ordovician age) underlies Bethel Valley, which includes the ORNL main plant area, and Solid Waste Storage Areas (SWSAs) 1, 2, and 3. This formation consists of limestone, shale, siltstone, and chert. Solution openings and fractures occur in the Chickamauga, although the openings are smaller and more discontinuous than in the Knox group.

The Conasauga group (Cambrian age) underlies Melton Valley, including SWSAs 4, 5, and 6, and the pits and trenches area. The stratigraphic sequence through the Conasauga formation is gradational, from shale at its base to bedded limestone at the top. White Oak Lake and the lower part of WOC reside on limestone or shaley limestone of the Conasauga group.

The Rome formation (Cambrian age) is exposed along Haw Ridge. The formation consists of sandstone, shale, siltstone and, locally, dolomite.

**Table 2.12. Measured temperatures below White Oak Dam**

Temperature [ $^{\circ}$ C( $^{\circ}$ F)/month-day-year]			
Water year 1989	Water year 1990	Water year 1991	Water year 1992
13.1(55.6)/10-25-88	15.9(60.6)/10-10-89	16.7(62.1)/10-16-90	14.6(58.3)/10-22-91
4.9(40.8)/12-13-88	10.4(50.7)/12-12-89	11.0(51.8)/12-4-90	11.8(53.2)/12-10-91
13.9(57.0)/2-14-89	8.9(48.0)/2-21-90	8.8(47.8)/2-5-91	7.4(45.3)/2-11-92
21.1(70.0)/4-18-89	16.3(61.3)/4-3-90	19.9(67.8)/4-16-91	12.9(55.2)/4-7-92
20.2(68.4)/6-13-89	23.6(74.5)/6-12-90	29.3(84.7)/6-18-91	27.9(82.2)/6-16-92
24.1(75.4)/8-15-89	25.4(77.7)/8-14-90	24.6(76.3)/8-20-91	22.4(72.3)/8-18-92

*Source:* M. M. Stevens and P. Y. Goldberg, personal communication to R. O. Johnson, Office of Environmental Compliance, Oak Ridge National Laboratory, Oak Ridge, Tenn., July 1993.

The Knox group and the underlying Maynardville limestone within the Conasauga group form the Knox aquifer (Solomon et al. 1992), which is the source of most natural base flow to streams in the WOC basin. The Rome formation, the Conasauga group, and the Chickamauga group discharge smaller quantities of groundwater to the streams. Groundwater is found in all weathered rock near the land surface.

Forty distinct soil groups have been identified in the WOC watershed (Tschantz and Rghebi 1989). These soils have mostly silty or very fine loamy textures and fall into three major hydrologic groups having moderate, slow, or very slow infiltration rates. The natural soils of the WOC watershed, in both Bethel and Melton Valleys, have relatively slow infiltration rates, which tend to promote relatively high runoff.

## **2.10 NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM**

The ORNL National Pollutant Discharge Elimination System (NPDES) permit (TN0002941) expired March 31, 1991. This permit had authorized ORNL to discharge to receiving waters of WOC, Northwest Tributary, Melton Branch, Fifth Creek, and First Creek on the WOC watershed in compliance with the Clean Water Act and in accordance with effluent limitations, monitoring requirements, and other conditions set forth in the permit. A permit renewal application was submitted in September 1990 (U.S. Department of Energy 1990). The renewal application was filed more than 180 days prior to the expiration of the existing permit. According to regulations, ORNL, having met that filing condition, is qualified to operate under the guidelines of the old permit until the regulatory agency, U.S. Environmental Protection Agency (EPA), acts on the new application. The ORNL continues to operate under the limitations of the original NPDES permit, which had identified at least 176 outfalls (Borders et al. 1992).

**Table 2.13. Average Melton Hill Dam tailwater temperatures  
for water years 1988 to 1992 and tailwater temperature  
extremes for water years 1973 to 1992**

Date <sup>a</sup>	Average temperature [°C(°F)]	Remarks
October day	17.0(62.6)	Five-point average
December day	11.8(53.2)	Five-point average
February day	8.4(47.1)	Five-point average
April day	13.3(55.9)	Five-point average
June day	19.2(66.6)	Five-point average
August day	20.1(68.2)	Four-point average
Maximum <sup>b,c</sup>	23.5(74.3)	May 17, 1982
Minimum <sup>b,c</sup>	4.0(39.2)	January 27, 1983; January 21 and 22, 1984

<sup>a</sup>Approximate same-day average in designated month.

<sup>b</sup>Extreme values; these are not arithmetic averages.

<sup>c</sup>Source: D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, U.S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va., 1993, p. 154.

## 2.11 RELATIONSHIP TO MODEL

The discharge statistics for the WOC gaging stations provide a rational basis from which to construct flow and mass balances (quantity and quality) for WOC and its tributaries above WOL. A mixing-box approach is applied to WOL because the depth is shallow; WOL manifests itself as nothing more than a pipeline bulge. The porous gabions on the sediment retention structure slow the rate at which an accidental spill passes into the Clinch River. The sediment retention structure is neglected because all of the spill still flows into the river (conservative assumption). The measured temperatures demonstrate that a thin plume floats along the surface of the Clinch River. The mass efflux leaving WOD serves as the source that feeds the plume.

**Table 2.14. Average and extreme water temperatures below White Oak Dam for water years 1989 to 1992**

Date <sup>a</sup>	Average temperature [°C(°F)]	Remarks
October day	15.1(59.1)	Four-point average
December day	9.5(49.1)	Four-point average
February day	9.8(49.6)	Four-point average
April day	17.6(63.6)	Four-point average
June day	25.3(77.5)	Four-point average
August day	24.1(75.4)	Four-point average
Maximum <sup>b,c</sup>	31.8(89.2)	August 9, 1988
Minimum <sup>b,c</sup>	3.9(39.0)	December 27, 1989

<sup>a</sup>Approximate same-day average in designated month.

<sup>b</sup>Extreme values; these are not arithmetic averages.

<sup>c</sup>Source: M. M. Stevens and P. Y. Goldberg, personal communication to R. O. Johnson, Office of Environmental Compliance, Oak Ridge National Laboratory, Oak Ridge, Tenn., July 1993.

### 3. MATHEMATICAL FORMULATION

The Oak Ridge National Laboratory (ORNL) aquatic spill model is developed from first principles using conservation of mass. Analytical solutions to the governing equations are obtained with the intent of implementing them on a digital computer. Flow measurements reported along White Oak Creek (WOC) above White Oak Lake (WOL) are used as a formal basis to construct mass balances at gaging stations located throughout the upper portions of the watershed. Mixing in WOL is approximated with continuous stirred tank reactor methodology to derive mathematical expressions for the mass efflux of spilled contaminant exiting White Oak Dam (WOD) as a function of time. A transient, one-dimensional plume model that utilizes the WOD efflux as an imposed boundary condition is then employed to predict contaminant concentrations in the Clinch River downstream from the mouth of WOC and Melton Hill Dam.

#### 3.1 PHYSICAL BASIS

The development of the ORNL aquatic spill model is based on the principle of conservation of mass, which states that the rate of mass accumulation within a clearly defined region of space is equal to the net rate of mass efflux plus or minus the rate of mass generation or depletion, respectively. Both quantity and quality must be conserved. Quantity is concerned with volumes of fluid, while quality deals with the type and concentration of constituents in these volumes. Mathematical expressions for quantity and quality applicable to the ORNL aquatic spill model must suitably account for the implicit temporal dependence of an accidental release into the WOC watershed. Radioactive decay is included in the formulation of the model as a first-order depletion process.

#### 3.2 SPILL DYNAMICS

The spill of total volume  $v$  and concentration  $C_0$  occurs instantaneously or over duration  $D$ . The mathematical description of the instantaneous spill is accomplished using the Dirac delta function, while the finite-duration spill is represented with Heaviside unit step functions.

##### Dirac Delta Function

The Dirac delta function  $\delta(t - t_0)$  is an infinitely high, infinitely thin spike having dimensions of reciprocal time. The spike is located at  $t = t_0$  and has the following mathematical properties (Lighthill 1962):

$$\delta(t - t_0) = \begin{cases} \infty & \text{for } t = t_0 \\ 0 & \text{for } t - t_0 \neq 0 \end{cases} , \quad (3.1)$$

$$\int_{-\infty}^{+\infty} \delta(t - t_0) \cdot dt = 1 , \quad (3.2)$$

and

$$\int_{-\infty}^{+\infty} f(t) \cdot \delta(t - t_0) \cdot dt = f(t_0) \quad (3.3)$$

### Heaviside Unit Step Function

The Heaviside unit step function  $H(t - t_0)$  is equal to zero or one, and has a step discontinuity at  $t = t_0$  (Kreyszig 1968):

$$H(t - t_0) = \begin{cases} 1 & \text{for } t > t_0 \\ 0 & \text{for } t < t_0 \end{cases} \quad (3.4)$$

The Dirac delta and Heaviside unit step functions are used to express mathematically the temporal variation of the flow of contaminant spilled at a prescribed location into the WOC watershed. Denote the volumetric flow of the spill by  $Q_{spill}(t)$ , which varies with time. The corresponding flux of mass is  $C_0 Q_{spill}(t)$ . The origin of the temporal coordinate is zero such that  $t_0 = 0$ . Mathematical representations of the instantaneous and finite-duration spills are written as follows:

#### Instantaneous Spill

$$Q_{spill}(t) = v\delta(t) = \begin{cases} \infty & \text{for } t = 0 \\ 0 & \text{for } t \neq 0 \end{cases} \quad (3.5)$$

and

$$\int_{-\infty}^{+\infty} Q_{spill}(t) \cdot dt = v \int_{-\infty}^{+\infty} \delta(t) \cdot dt = v \quad (3.6)$$

#### Finite-Duration Spill

$$Q_{spill}(t) = \frac{v}{D} [H(t) - H(t - D)] \quad (3.7)$$

where

$$H(t) - H(t - D) = \begin{cases} 1 & \text{for } 0 < t < D \\ 0 & \text{for } t > D \end{cases} \quad (3.8)$$

and

$$\int_{-\infty}^{+\infty} Q_{spill}(t) \cdot dt = \left. \frac{vt}{D} \right|_0^D = v \quad (3.9)$$

Graphical representations of the volumetric flow variation with respect to time during the instantaneous and finite-duration spills appear in Fig. 3.1. The flux of spilled mass exhibits similar temporal variation although the scale along the vertical axis or ordinate is multiplied by the concentration  $C_0$ .

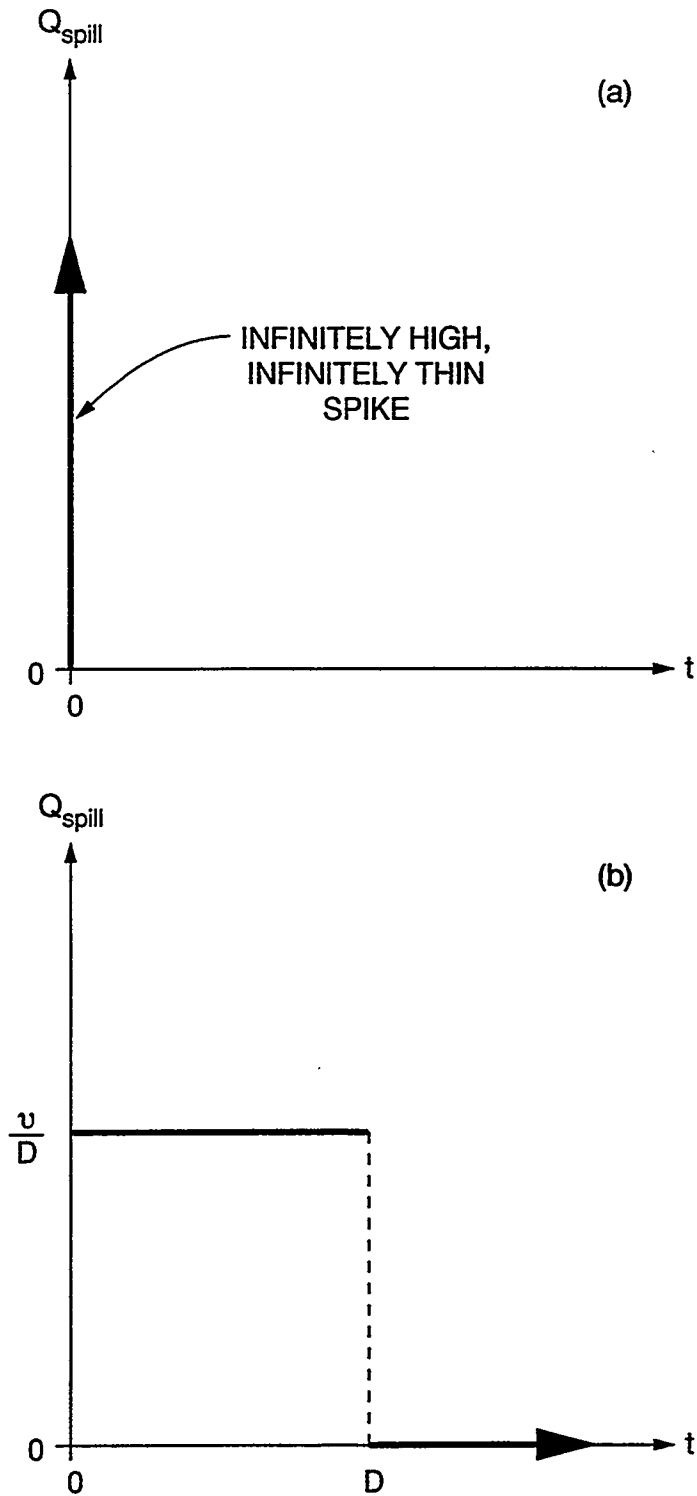


Fig. 3.1. Temporal variation of volumetric flow during instantaneous (a) and finite-duration (b) spills.

### 3.3 HEADWATERS

Upstream from WOL, the WOC watershed consists of a dendritic system of tributaries flowing over relatively steep slopes. The confluence of Melton Branch and WOC occurs slightly upstream from WOL. The time interval for the spill to flow from the accident site on the ORNL reservation into WOL is short relative to the retention time in WOL. Gaging stations that measure the stream flow are available at various locations throughout the watershed. Discharge statistics are calculated and published for many of these gaging stations (see Mercer et al. 1992, for example). Assuming no accumulation of mass and instantaneous complete mixing, the data recorded at each gage are used to estimate the concentration of spilled contaminant sequentially through the watershed down to WOL. The analysis must consider the spill site itself, each sequential downstream gage (or node), and wyes (i.e., confluences) where tributaries join together. Radioactive decay (which typically requires months or years) is neglected in this portion of the aquatic spill model because of the relatively short transit time (i.e., several days) in the WOC headwaters.

#### 3.3.1 Stream Element

Consider the first (1) gaging station below the spill site. A pictorial representation of the flow and mass balances is shown in Fig. 3.2(a). The measured flow  $Q_{gage}^{(1)}$  is uncontaminated initially. After the spill, the flow  $Q_{out}^{(1)}$  leaving the gage is  $Q_{out}^{(1)} = Q_{gage}^{(1)} + Q_{spill}$ , while the contaminant concentration of the effluent is  $C_{out}^{(1)} = C_0 \left[1 + Q_{gage}^{(1)}/Q_{spill}\right]^{-1}$ . The magnitudes of  $Q_{out}^{(1)}$  and  $C_{out}^{(1)}$  depend on the temporal variation of the spill flow rate:

##### Instantaneous Spill

$$Q_{out}^{(1)} = Q_{gage}^{(1)} + v\delta(t) = \begin{cases} \infty & \text{for } t = 0 \\ Q_{gage}^{(1)} & \text{for } t \neq 0 \end{cases} \quad (3.10)$$

$$C_{out}^{(1)} = C_0 \left[1 + Q_{gage}^{(1)}/v\delta(t)\right]^{-1} = \begin{cases} C_0 & \text{for } t = 0 \\ 0 & \text{for } t \neq 0 \end{cases} \quad (3.11)$$

##### Finite-Duration Spill

$$Q_{out}^{(1)} = Q_{gage}^{(1)} + v[H(t) - H(t - D)]/D \quad (3.12a)$$

$$= \begin{cases} Q_{gage}^{(1)} + v/D & \text{for } 0 < t < D \\ Q_{gage}^{(1)} & \text{for } t > D \end{cases} \quad (3.12b)$$

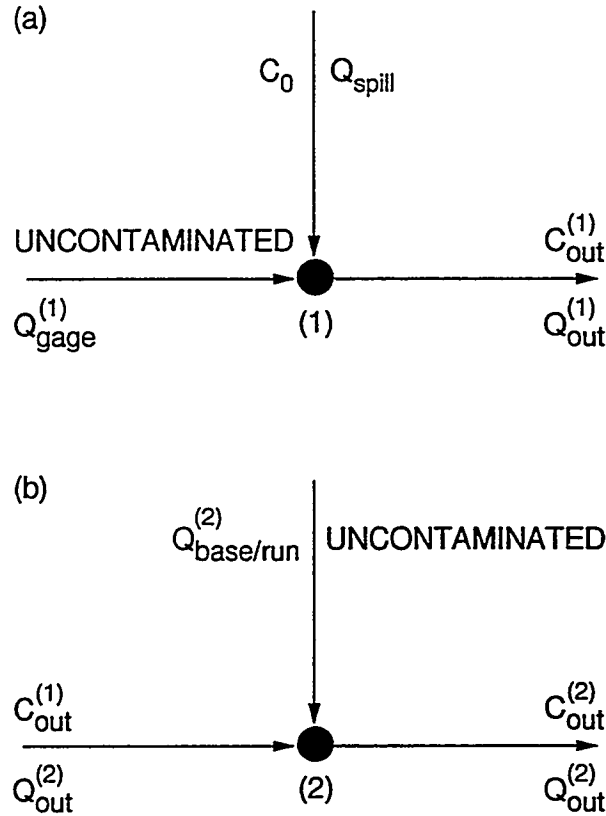


Fig. 3.2. Flow and mass balances at the first (a) and second (b) gaging stations downstream from the spill.

$$C_{out}^{(1)} = C_0 \left\{ 1 + Q_{gage}^{(1)} D/v [H(t) - H(t - D)] \right\}^{-1} , \quad (3.13a)$$

$$= \begin{cases} C_0 \left[ 1 + Q_{gage}^{(1)} D/v \right]^{-1} & \text{for } 0 < t < D \\ 0 & \text{for } t > D \end{cases} . \quad (3.13b)$$

### 3.3.2 Downstream Element

At the second (2) gage downstream from the first, the inflow consists of the contaminated flow from the first gage plus the groundwater seepage (or base flow) and runoff contributions entering the stream between the two gages [see Fig. 3.2(b)]. The seepage/runoff flow  $Q_{baselrun}^{(2)}$  is the difference between the flows recorded at the two gaging stations:

$$Q_{baselrun}^{(2)} = Q_{gage}^{(2)} - Q_{gage}^{(1)} . \quad (3.14)$$

The seepage and runoff are assumed to be uncontaminated prior to reaching the second gage. Flow and mass balances at the second gage are written as follows:

$$Q_{out}^{(2)} = Q_{out}^{(1)} + Q_{baselrun}^{(2)} \quad , \quad (3.15a)$$

$$= [Q_{gage}^{(1)} + Q_{spill}] + [Q_{gage}^{(2)} - Q_{gage}^{(1)}] \quad , \quad (3.15b)$$

$$= Q_{gage}^{(2)} + Q_{spill} \quad . \quad (3.15c)$$

$$C_{out}^{(2)} = C_{out}^{(1)} Q_{out}^{(1)} / Q_{out}^{(2)} \quad , \quad (3.16a)$$

$$= \frac{C_0 Q_{spill}}{[Q_{gage}^{(1)} + Q_{spill}]} \cdot \frac{[Q_{gage}^{(1)} + Q_{spill}]}{[Q_{gage}^{(2)} + Q_{spill}]} \quad , \quad (3.16b)$$

$$= C_0 [1 + Q_{gage}^{(2)} / Q_{spill}]^{-1} \quad . \quad (3.16c)$$

Invoking mathematical induction, expressions for the flow and concentration at the  $n$ th downstream gage immediately follow:

$$Q_{out}^{(n)} = Q_{gage}^{(n)} + Q_{spill} \quad , \quad (3.17)$$

$$C_{out}^{(n)} = C_0 [1 + Q_{gage}^{(n)} / Q_{spill}]^{-1} \quad . \quad (3.18)$$

Mathematical expressions for  $Q_{out}^{(n)}$  and  $C_{out}^{(n)}$  applicable to the instantaneous and finite-duration spills follow.

### Instantaneous Spill

$$Q_{out}^{(n)} = Q_{gage}^{(n)} + v\delta(t) \quad , \quad (3.19a)$$

$$= \begin{cases} \infty & \text{for } t = 0 \\ Q_{gage}^{(n)} & \text{for } t \neq 0 \end{cases} \quad . \quad (3.19b)$$

$$C_{out}^{(n)} = C_0 \left[ 1 + Q_{gage}^{(n)} / v \delta(t) \right]^{-1} , \quad (3.20a)$$

$$= \begin{cases} C_0 & \text{for } t = 0 \\ 0 & \text{for } t \neq 0 \end{cases} . \quad (3.20b)$$

### Finite-Duration Spill

$$Q_{out}^{(n)} = Q_{gage}^{(n)} + v[H(t) - H(t - D)]/D , \quad (3.21a)$$

$$= \begin{cases} Q_{gage}^{(n)} + v/D & \text{for } 0 < t < D \\ Q_{gage}^{(n)} & \text{for } t > D \end{cases} . \quad (3.21b)$$

$$C_{out}^{(n)} = C_0 \{ 1 + Q_{gage}^{(n)} D / v [H(t) - H(t-D)] \}^{-1} , \quad (3.22a)$$

$$= \begin{cases} C_0 [1 + Q_{gage}^{(n)} D / v]^{-1} & \text{for } 0 < t < D \\ 0 & \text{for } t > D \end{cases} . \quad (3.22b)$$

### 3.3.3 Wye Confluence

The confluence of Melton Branch and WOC is an example of a wye junction where two tributaries coalesce. The spill occurs in one leg and then flows to the junction, where additional dilution is provided by the remaining tributary (see Fig. 3.3). Simultaneous spills in both legs are not considered; one of the tributaries is contaminated by the spill, while the second is uncontaminated above the wye. The relevant flow and mass balances are

$$Q_{out}^{(wye)} = Q_{in}^{(n)} + Q_{wye} , \quad (3.23a)$$

$$= Q_{gage}^{(n)} + Q_{spill} + Q_{wye} , \quad (3.23b)$$

and

$$C_{out}^{(wye)} = C_{in}^{(n)} Q_{in}^{(n)} / Q_{out}^{(wye)} , \quad (3.24a)$$

$$= \frac{C_0 Q_{spill}}{[Q_{gage}^{(n)} + Q_{spill}]} \cdot \frac{[Q_{gage}^{(n)} + Q_{spill}]}{[Q_{gage}^{(n)} + Q_{spill} + Q_{wye}]} , \quad (3.24b)$$

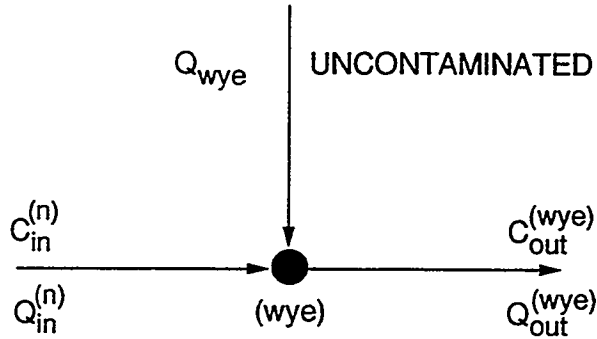


Fig. 3.3. Flow and mass balances at the confluence of two tributaries downstream from the spill.

$$= C_0 \left[ 1 + \frac{Q_{gage}^{(n)} + Q_{wye}}{Q_{spill}} \right]^{-1} \quad (3.24c)$$

Equations applicable to the instantaneous and finite-duration spills follow:

#### Instantaneous Spill

$$Q_{out}^{(wye)} = Q_{gage}^{(n)} + Q_{wye} + v\delta(t) \quad (3.25a)$$

$$= \begin{cases} \infty & \text{for } t = 0 \\ Q_{gage}^{(n)} + Q_{wye} & \text{for } t \neq 0 \end{cases} \quad (3.25b)$$

$$C_{out}^{(wye)} = C_0 \left[ 1 + \frac{Q_{gage}^{(n)} + Q_{wye}}{v\delta(t)} \right]^{-1} \quad (3.26a)$$

$$= \begin{cases} C_0 & \text{for } t = 0 \\ 0 & \text{for } t \neq 0 \end{cases} \quad (3.26b)$$

#### Finite-Duration Spill

$$Q_{out}^{(wye)} = Q_{gage}^{(n)} + Q_{wye} + v[H(t) - H(t - D)]/D \quad (3.27a)$$

$$= \begin{cases} Q_{gage}^{(n)} + Q_{wye} + v/D & \text{for } 0 < t < D \\ Q_{gage}^{(n)} + Q_{wye} & \text{for } t > D \end{cases} \quad (3.27b)$$

$$C_{out}^{(wye)} = C_0 \left[ 1 + \frac{Q_{gage}^{(n)} + Q_{wye}}{(v/D)[H(t) - H(t - D)]} \right]^{-1}, \quad (3.28a)$$

$$= \begin{cases} C_0 [1 + D(Q_{gage}^{(n)} + Q_{wye})/v]^{-1} & \text{for } 0 < t < D \\ 0 & \text{for } t > D \end{cases} \quad (3.28b)$$

### 3.3.4 Remarks

In all of the above cases, the concentration at the node depends only on the total exit flow or efflux. This is a direct consequence of treating the region of space under consideration as well stirred and uniform in contaminant concentration with no accumulation of mass. The only imposed restriction is the flow of an incompressible fluid that may be steady or unsteady (Fox and McDonald 1973). The size of the control volume is fixed, the density of the fluid is constant (dilute mixture theory), and the imposed temporal variation is retained throughout the mixing process. The WOC headwaters analysis is of limited utility in the case of an instantaneous spill because no dilution is predicted. Clearly, a finite duration should, if possible, be established for the accidental release to avoid such conservative dilution overestimates.

## 3.4 WHITE OAK LAKE

Two issues require careful consideration before performing a contaminant transport analysis of WOL. The first question deals with whether or not thermal stratification strongly influences vertical mixing; while the second must assess whether the transport analysis should assume complete mixing [continuous stirred tank reactor (CSTR)] or unmixed plug flow [plug flow tubular reactor (PFTR)] in which advection is dominant.

### 3.4.1 Thermal Effects

The relative importance of thermal stratification depends on the interplay of the momentum of the WOL throughput and the gravitational forces attributable to the buoyancy of water. The densimetric Froude number  $F_D$  quantifies the interplay of momentum and buoyancy. For a lake (Chapra and Reckhow 1983),  $F_D$  is approximated by

$$F_D \approx 10^{-5} \frac{L}{d \cdot T_R}, \quad (3.29)$$

where

$L$  = lake length in meters,

$d$  = mean depth in meters,

$T_R$  = water residence or retention time in years,

which is equal to the quotient of the lake volume and throughput. If  $F_D \gg 0.32$ , the lake is completely mixed vertically. Strong vertical stratification occurs when  $F_D \ll 0.32$ . For intermediate values of  $F_D$  in the vicinity of 0.32, weak stratification could influence mass, momentum, and energy transport processes.

The discharge at WOD has equaled or exceeded  $0.048 \text{ m}^3/\text{s}$  (1.7 cfs) 99.9% of the time (Sherwood and Loar 1987, p. A-10); the estimated peak flood discharge was  $42.25 \text{ m}^3/\text{s}$  (1492 cfs), which occurred November 27–28, 1973 ( $\approx$  25-year recurrence interval) (Oakes et al. 1982, p. 57). The average WOD flow for the 5-year period of record 1953–55 and 1960–63 was  $0.382 \text{ m}^3/\text{s}$  (13.5 cfs) (Sherwood and Loar 1987, p. A-9). Releases from WOD are occasionally halted. Because releases are eventually resumed, this situation does not imply an infinite retention time although periods of no release could be envisioned that extend over weeks or even months, depending on the availability of unfilled storage volume behind WOD and the influx of water entering WOL.

The normal water level elevation of WOL is 227 m (745 ft) above mean sea level (Boyle et al. 1982, p. 3-16). In 1979, the volume of WOL at this elevation was  $64,016 \text{ m}^3$  ( $2,260,660 \text{ ft}^3$ ) (Oakes et al. 1982, p. 48), which created a pool surface area of approximately 9.7 ha (24 acres) (Boyle et al. 1982, p. 3-16). The estimated length of WOL was 1372 m (4500 ft), which included both the upper and lower lake beds (Sherwood and Loar 1987, Fig. A.11, p. A-37). The mean depth of WOL obtained by dividing the normal lake volume by the pool surface area was 0.66 m (2.16 ft). The actual depth reported in 1979 varied from less than 0.3 m (1 ft) where WOC empties into WOL to a maximum of 2.49 m (8.18 ft) reported behind the dam (Oakes et al. 1982, p. 49).

Sedimentation has caused marked reductions in the volume of WOL. The entire upper lake bed has been filled in with decaying products of organic production and sediment transported by WOC and Melton Branch. The upper lake bed is now a marshy area that extends half the distance from the back of the original lake basin to WOD. The lower lake bed has an approximate length of 731 m (2400 ft) (Cox et al. Fig. 2, p. 6). In April 1988, Cox et al. (1991) measured the total area and volume of WOL at a water surface elevation of 227 m (745 ft) above mean sea level and reported estimates of 6.88 ha (17.0 acres) and  $43,787.2 \text{ m}^3$  ( $1,546,330 \text{ ft}^3$ ), respectively. The mean depth calculated from these values of area and depth was 0.64 m (2.09 ft). The measured depth varied from a minimum of 0.18 m (7.1 in.) where WOC empties into WOL, to a maximum of 1.34 m (4.40 ft) behind WOD. Based on the measured 1988 WOL volume, the retention time ranges from 10.5 d corresponding to the 99.9% exceedence flow, to 0.29 h during the estimated 25-year flood flow.

Table 3.1 presents values of  $F_D$  for the anticipated range of flows and depths in WOL. The influence of thermal stratification on mixing in WOL is characterized as weak when the magnitude of  $F_D$  is near 0.32. This occurs less than 0.1% of the time. At throughputs greater than the 99.9% exceedence flow,  $F_D \gg 0.32$ , indicating a condition of complete vertical mixing. The results appearing in Table 3.1 demonstrate that the effects of thermal stratification on mixing in WOL are secondary and can be neglected as a first approximation in the ORNL spill model. Clearly, thermal stratification would influence vertical mixing directly behind the dam during prolonged periods of no release, a condition that occurs rarely. During such times, wind-induced waves and the diurnal variation of solar heating and nocturnal thermal cooling would promote mixing such that a relatively homogeneous WOL concentration would be achieved in a finite length of time. The  $F_D$  values quoted in Table 3.1 were calculated using only the lower WOL bed length of 731 m (2400 ft) because the upper bed is a marshy area rather than a body of water having lake-like characteristics. The values of  $F_D$  would be increased proportionately if the total length (i.e., the sum of the upper and lower bed lengths) were used to obtain the  $F_D$  estimates. Such results would add further credence to the arguments presented here.

The notion of weak thermal stratification in WOL also implies that a well-defined thermocline seldom exists. The metalimnion is a relatively thin layer of diabatic water whose temperature rapidly decreases with depth that separates the warmer surface mixed layer (epilimnion) from the deeper, cooler layer (hypolimnion). The thermocline is the horizontal plane within the metalimnion passing through the point of maximum water temperature decrease with depth (Thibodeaux 1979, p. 359). The depth of thermocline formation in the early spring is shallow, being from 2 to 3 m (6.5 to 9.8 ft) below the water surface

**Table 3.1. Densimetric Froude number<sup>a</sup> of White Oak Lake as a function of flow and depth**

Depth <sup>c</sup> [m(ft)]	White Oak Dam flow [m <sup>3</sup> /s (cfs)]/ White Oak Lake retention time <sup>b</sup> (year)			
	42.25 <sup>d</sup> (1492)/ 0.000033	0.382 <sup>e</sup> (13.5)/ 0.0036	0.048 <sup>f</sup> (1.7)/ 0.029	0 <sup>g</sup> (0)/∞
0.18 (0.59)	1231	11.3	1.4	0
0.64 (2.09)	346	3.2	0.39	0
1.34 (4.40)	165	1.5	0.19	0

<sup>a</sup>Based on the lower lake bed length of 731 m (2400 ft).

<sup>b</sup>Obtained by dividing the measured 1988 White Oak Lake volume [43,787.2 m<sup>3</sup> (1,546,330 ft<sup>3</sup>) by the White Oak Dam flow.

<sup>c</sup>Minimum, average, and maximum depths reported for 1988.

<sup>d</sup>Estimated 25-year flood flow; thorough mixing.

<sup>e</sup>Average flow for 5-year period of record (1953–55, 1960–63); 50% exceedence flow; weak stratification.

<sup>f</sup>99.9% exceedence flow, which occurs 0.1% of the time; strong stratification.

<sup>g</sup>Extreme condition that rarely occurs.

(Ragotzkie 1978, p. 5). Wind-induced mixing and agitation cause the thermocline to descend. The depth of WOL is insufficient to allow thermocline formation.

### 3.4.2 Complete Mix Versus Plug Flow Theory

Two general approaches are available to predict the transport of dissolved species in contaminated water bodies (Perlmutter 1972; Chapra and Reckhow 1983): (1) the CSTR, in which the contents are well mixed and uniformly distributed and (2) the PFTR, or unmixed model, in which all variation of species concentration occurs in a single spatial direction as if the reacting mixture moves like an identifiable plug from the inlet to the outlet of the water body. Mixing in the CSTR is dominated by diffusion; advection is the primary transport mechanism in the PFTR.

Between the idealizations of complete mixing (CSTR) and plug flow (PFTR) are those water bodies in which advection and diffusion both influence species transport. Such river-run lakes, as depicted in Fig. 3.4(a), typically are long and narrow, with a major tributary at one end and an outlet at the other (Chapra and Reckhow 1983, pp. 94–99). A plug of dye injected or spilled at the inlet of a river-run lake advects and diffuses simultaneously as it transverses through the lake [see Fig. 3.4(b)]. The cloud of dye is spread over the spatial domain that reduces peak concentrations in the downstream direction.

Consider an idealized lake of constant cross-sectional area, completely mixed both laterally and vertically, but subject to longitudinal advection and turbulent mixing in the downstream direction. Normalized, dimensionless, steady-state solutions to the one-dimensional species transport equation that describes this problem mathematically [see Fig. 3.4(c)] are expressed as a function of the Peclet number  $P_e$ , defined as the dimensionless group  $LU/D_x$ . The parameter  $L$  is the lake length,  $U$  is the mean velocity in

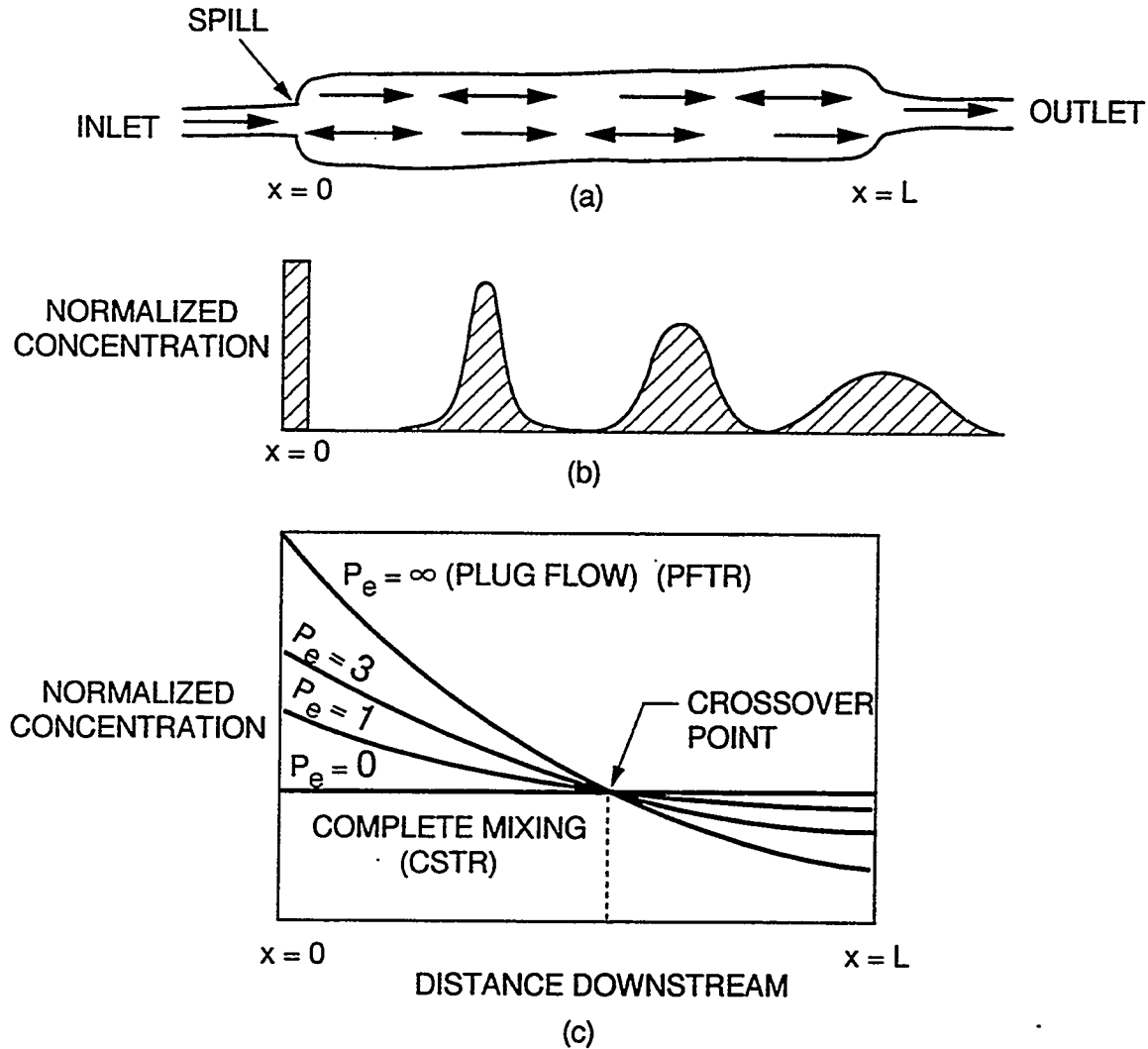


Fig. 3.4. A river-run lake: (a) overhead view, (b) movement of a plug of dye through the lake, and (c) steady-state concentration profiles for varying Peclet numbers ( $P_e$ ).

the downstream direction, and  $D_x$  is a transport coefficient that accounts for both molecular diffusion and mechanical mixing or agitation (i.e., turbulent dispersion).

The Peclet number  $P_e$  characterizes the relative importance of advection and diffusion within the lake. If  $P_e \ll 1$ , diffusion predominates (high levels of turbulent mixing). If  $P_e \gg 1$ , transport is controlled by advection (low levels of turbulent mixing). At intermediate levels,  $0.1 < P_e < 10$ , both advection and diffusion are important. Complete mixing (CSTR) occurs in the limit as  $P_e$  goes to zero;  $P_e$  increases indefinitely in the unmixed situation (PFTR).

The normalized concentrations shown graphically in Fig. 3.4(c) decrease with distance downstream for nonzero  $P_e$ , decreasing from a high at the inlet to a low at the outlet. The normalized concentration remains constant with respect to distance downstream when  $P_e$  is zero (CSTR). At some intermediate downstream distance above the outlet located at  $x=L$ , the nonzero  $P_e$  concentration profiles decrease below the constant-value concentration profile obtained with CSTR theory ( $P_e = 0$ ). At the outlet  $x=L$ ,

concentrations predicted with CSTR theory are conservative (predicting higher concentrations than actually would occur) relative to concentrations based on a steady-state, one-dimensional, longitudinal, advection-diffusion equation (nonzero  $P_e$ ).

The Fig. 3.4(c) results allow considerable simplification of the WOL transport analysis after an accidental spill. The  $P_e$  of WOL clearly is finite and nonzero. White Oak Lake is assumed to be sufficiently long such that the outlet is located downstream from the crossover point illustrated in Fig. 3.4(c). Outlet concentrations at WOD based on CSTR methodology are then conservative estimates of the effluent concentration released at the dam. The CSTR methodology is used to approximate the flux of spilled contaminant released at WOD.

The results presented in Fig. 3.4 demonstrate that a river-run lake is a more efficient settling basin than a completely mixed water body. First-order reactions in which the rate of removal is based on direct proportionality with concentration characterize different transformations in natural waters such as sedimentation, radioactive and bacterial decay, and biochemical oxidation of organic matter. In the completely-mixed lake or CSTR, the removal rate is uniform because the concentration is constant. The rate of removal is higher near the inlet to the river-run system, where concentrations are higher. Removal rates are proportionately higher near the inlet than reduced losses near the outlet, where concentrations are lower such that the net removal exceeds that of the CSTR.

### 3.4.3 Analysis

The analysis of WOL (see Fig. 3.5) using CSTR principles is based on the premise that accumulation equals the input minus both the output and removal by first-order reactions. Only losses attributable to radioactive decay are considered. The accumulation is the WOL volume  $V_w$  multiplied by the time rate of concentration change  $dC_w/dt$ . The WOL volume is assumed to remain constant throughout the temporal domain of the accidental spill. The input is the mass flux from the spill  $C_0 Q_{spill}(t)$ . The output after the spill is  $Q_w + Q_{spill}(t)$ , where  $Q_w$  is the specified throughput in WOL normally released at the dam. The mass flux  $\dot{m}_w$  passing over the dam is the product of the unknown concentration  $C_w$  and the flow  $Q_w + Q_{spill}(t)$ . The removal rate is  $\lambda V_w C_w$ , where  $\lambda$  is the radioactive decay constant [equal to  $\ln(2)$  divided by the half-life  $t_{1/2}$  (Arya 1966)]. The ordinary differential equation describing mass transport in WOL during and after the spill is

$$V_w \frac{dC_w}{dt} = C_0 Q_{spill}(t) - C_w [Q_w + Q_{spill}(t)] - \lambda V_w C_w \quad , \quad (3.30)$$

where

$$\lambda = \ln(2)/t_{1/2} \quad . \quad (3.31)$$

The concentration of contaminant in WOL prior to the spill is zero such that

$$C_w |_{t=0} = 0 \quad . \quad (3.32)$$

The mass flux  $C_0 Q_{spill}(t)$  entering WOL is equal to  $C_i [Q_w + Q_{spill}(t)]$ , where  $C_i$  is the concentration of contaminant in the WOC inlet prior to lake dilution. Solving for  $C_i$ , obtain

$$C_i = C_0 [1 + Q_w/Q_{spill}(t)]^{-1} \quad . \quad (3.33)$$

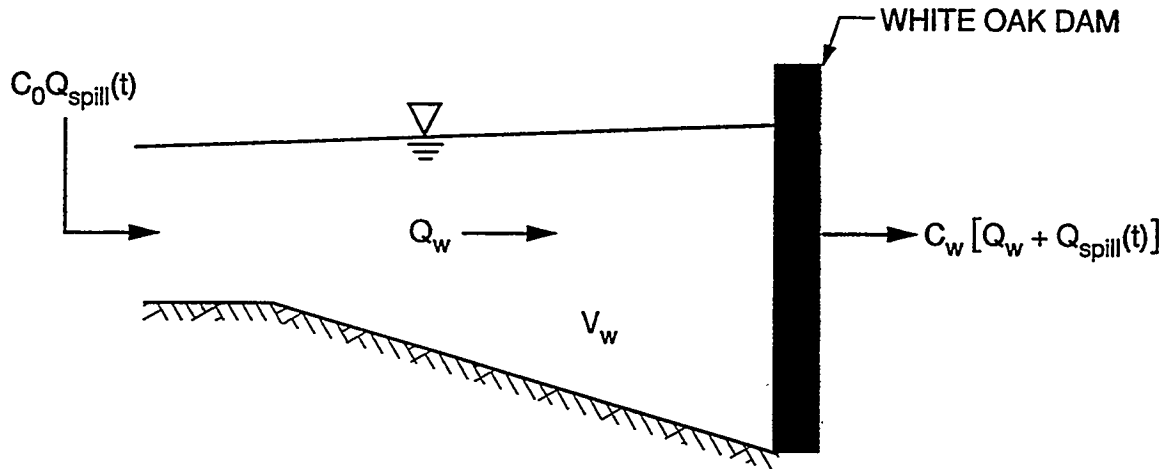


Fig. 3.5. White Oak Lake mass balance.

Specification of the initial value problem is complete once  $Q_{spill}(t)$  is defined. Closed form solutions for the WOL concentration time history at the WOD outlet are possible for the instantaneous and finite-duration spills.

#### Instantaneous Spill

$$\frac{dC_w}{dt} + \left[ \frac{v}{V_w} \delta(t) + \frac{Q_w}{V_w} + \lambda \right] C_w = \frac{C_0 v}{V_w} \delta(t) \quad (3.34)$$

For nonzero  $t$ , the solution (obtained by separating variables) to this equation is

$$C_w = A \exp \left[ - \left( \frac{Q_w}{V_w} + \lambda \right) t \right] \quad (3.35)$$

The solution exhibits an instantaneous rise from zero to some finite value at  $t = 0$ , followed by an exponential decay to zero over an infinite temporal domain. The integration constant  $A$  is determined by integrating the parent ordinary differential equation from  $0 - \epsilon$  to  $0 + \epsilon$ , where  $\epsilon$  is an infinitesimally small quantity that goes to zero in the limit. Integration across the discontinuity at  $t = 0$  is accomplished as follows:

$$\int_{0-\epsilon}^{0+\epsilon} \frac{dC_w}{dt} \cdot dt + \left( \frac{Q_w}{V_w} + \lambda \right) \int_{0-\epsilon}^{0+\epsilon} C_w \cdot dt \quad (3.36)$$

$$+ \int_{0-\epsilon}^{0+\epsilon} \frac{v}{V_w} \delta(t) C_w \cdot dt = \int_{0-\epsilon}^{0+\epsilon} \frac{C_0 v}{V_w} \delta(t) \cdot dt \quad .$$

The second integral vanishes because  $C_w$  is a finite, piecewise continuous function. Hence,

$$C_w \Big|_{0-\epsilon}^{0+\epsilon} + \frac{v}{V_w} \int_{0-\epsilon}^{0+\epsilon} \delta(t) C_w \cdot dt = \frac{C_0 v}{V_w} . \quad (3.37)$$

Using the zero boundary condition for  $C_w$  to evaluate the lower limit, and the value  $A$  for the upper limit obtain

$$[A - 0] + \frac{v}{V_w} [A - 0] = \frac{C_0 v}{V_w} , \quad (3.38)$$

or

$$A = \frac{C_0 v}{V_w} \left[ 1 + \frac{v}{V_w} \right]^{-1} . \quad (3.39)$$

The complete solution for  $C_w$  is

$$C_w = \frac{C_0 v}{V_w} \left[ 1 + \frac{v}{V_w} \right]^{-1} \exp \left[ - \left( \frac{Q_w}{V_w} + \lambda \right) t \right] . \quad (3.40)$$

The flux of mass is  $\dot{m}_w = C_w [Q_w + v\delta(t)]$ , where the total spilled mass  $M$  is

$$M = \int_0^{\infty} \dot{m}_w \cdot dt = C_0 v , \quad \text{where } \lambda = 0 . \quad (3.41)$$

The expression for  $\dot{m}_w$  satisfies this relationship. The mass flux  $\dot{m}_w$  has a discontinuity at  $t = 0$ , where its magnitude is infinitely high (see Fig. 3.6). The concentration  $C_w$  is, however, finite at  $t = 0$ .

The WOL concentration of the WOC influent  $C_i$  is

$$C_i = C_0 [1 + Q_w/v\delta(t)]^{-1} , \quad (3.42a)$$

or

$$= \begin{cases} C_0 & \text{for } t = 0 \\ 0 & \text{for } t \neq 0 \end{cases} . \quad (3.42b)$$

In the case of an instantaneous spill, dilution does not occur until after entry into WOL.

### Finite-Duration Spill

$$\frac{dC_w}{dt} + \left\{ \frac{v}{V_w D} [H(t) - H(t - D)] + \frac{Q_w}{V_w} + \lambda \right\} C_w = \frac{C_0 v}{V_w D} [H(t) - H(t - D)] , \quad (3.43)$$

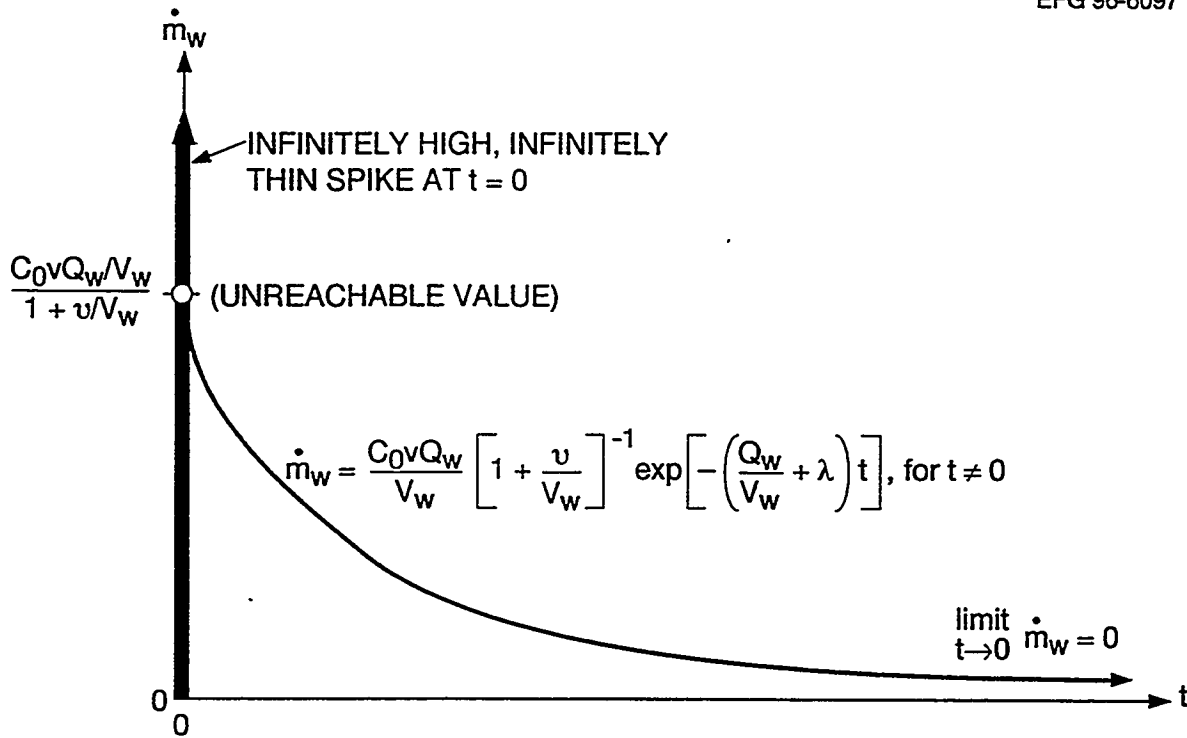


Fig. 3.6. Mass efflux leaving White Oak Dam after an instantaneous spill.

or

$$\frac{dC_w}{dt} + \left[ \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right] C_w = \frac{C_0 v}{V_w D} \quad \text{for } 0 < t < D, \quad (3.44)$$

and

$$\frac{dC_w}{dt} + \left[ \frac{Q_w}{V_w} + \lambda \right] C_w = 0 \quad \text{for } t > D. \quad (3.45)$$

Both of these equations are solvable using an integrating factor. The solutions are continuous at  $t = D$ . The integration constant (again denoted by A) implicit in the second ordinary differential equation is determined by equating the two solutions for  $C_w$  at  $t = D$ .

The complete solution for  $C_w$  is

$$C_w = \frac{C_0 v}{V_w D} \left[ \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right]^{-1} \times \left\{ 1 - \exp \left[ - \left( \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right) t \right] \right\} \quad \text{for } 0 < t < D, \quad (3.46)$$

and

$$C_w = A \exp\left[-\left(\frac{Q_w}{V_w} + \lambda\right)t\right] \text{ for } t > D, \quad (3.47)$$

where

$$A = \frac{C_0 v}{V_w D} \left[ \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right]^{-1} \times \exp\left[\left(\frac{Q_w}{V_w} + \lambda\right)D\right] \left\{ 1 - \exp\left[-\left(\frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda\right)D\right] \right\}. \quad (3.48)$$

The WOD mass flux  $\dot{m}_w$  and WOL influent concentration  $C_i$  are

$$\dot{m}_w = C_w \left\{ Q_w + \frac{v}{D} [H(t) - H(t - D)] \right\}, \quad (3.49a)$$

$$= \begin{cases} C_w \left( Q_w + \frac{v}{D} \right) & \text{for } 0 < t < D, \\ C_w Q_w & \text{for } t > D \end{cases}, \quad (3.49b)$$

and

$$C_i = C_0 \{ 1 + Q_w D / v [H(t) - H(t - D)] \}^{-1}, \quad (3.50a)$$

$$= \begin{cases} C_0 [1 + Q_w D / v]^{-1} & \text{for } 0 < t < D, \\ 0 & \text{for } t > D \end{cases}. \quad (3.50b)$$

The expression for  $\dot{m}_w$  reduces to  $C_0 v$  when integrated temporally from zero to infinity with  $\lambda = 0$ , which is an expected result. The mass flux  $\dot{m}_w$  has a discontinuity at  $t = D$  (see Fig. 3.7) where the continuous, single-valued concentration exhibits a maximum.

### 3.5 WHITE OAK CREEK EMBAYMENT

The mass flux  $\dot{m}_w$  leaving WOD is a time-varying point source undergoing radioactive decay. The spilled contaminant discharges into the White Oak Creek Embayment (WOCE), passes either through or over the sediment control structure located at the mouth of WOC, and then flows into the Clinch River. The point source disperses into a line source extending over either a portion of or the entire WOCE

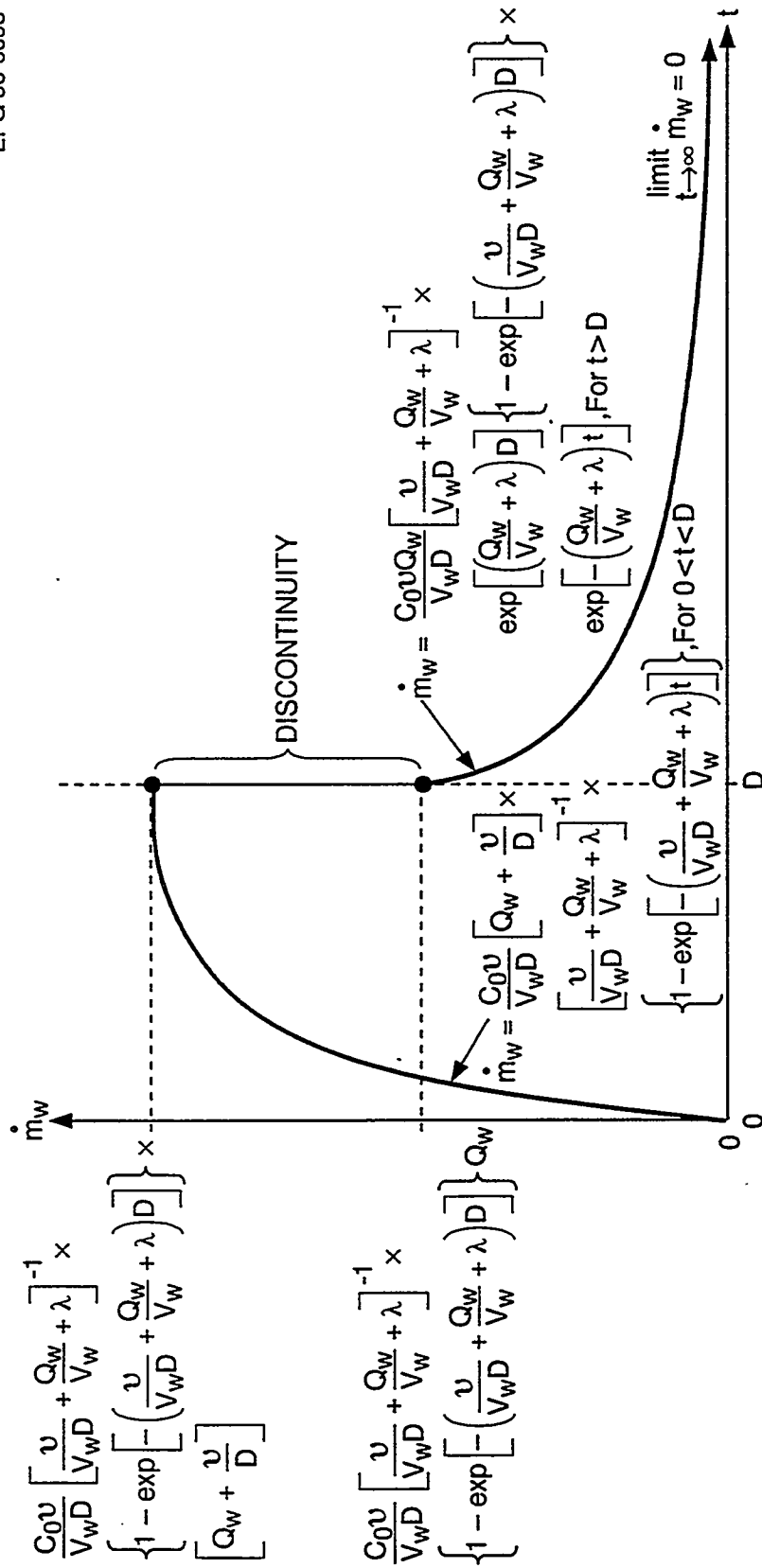


Fig. 3.7. Mass flux leaving White Oak Dam after a finite-duration spill.

depth of flow  $H_0$ . A line source of  $\dot{m}_w$  units flowing over depth  $H_0$  is equivalent to a point source of strength  $\dot{m}_w/H_0$ .

Upon entering the Clinch River, the flow from the WOCE becomes a buoyant surface jet because of the relatively cold discharge released beneath Melton Hill Dam. The physical situation is depicted in Fig. 3.8. The surface jet remains attached to the bottom of the Clinch River for some distance out into the channel and then springs clear from the riverbed because of the buoyancy. The precise location of the lift-off point depends on the magnitude of the WOCE and Clinch River flow rates, the temperature difference between the two flows, the relative geometric arrangement, the presence of the sediment control structure, and the water levels in the WOCE and Clinch River. Additional dilution occurs in the Clinch River because  $H > H_0$  where  $H$  is the water depth at which lift off occurs along the riverbed. The equivalent point source strength realized by the Clinch River is  $\dot{m}_w/H$  (line source of  $\dot{m}_w/H$  units flowing over depth  $H$ ).

Studies (Safaie 1978; Fischer et al. 1979, p. 382) have shown that the penetration depths  $H_0$  and  $H$  appearing in Fig. 3.8 are related by  $H = KH_0 f(\ell_M, \ell_Q)$ . The parameter  $K$  is a constant, while  $f(\ell_M, \ell_Q)$  is a function whose value depends on the characteristic length scales  $\ell_M$  and  $\ell_Q$  which account for the fluxes of momentum and buoyancy, respectively. The presence of the sediment control structure has a dramatic effect on the momentum flux. When the WOCE flow seeps through the rock-filled gabions (see Fig. 2.4), the flux of momentum is low and possibly negligible. Conversely, when the WOCE discharge overtops the gabions, open-channel flow occurs that is controlled by the sediment control structure, which serves as a broad-crested weir. In this situation, the momentum flux is relatively high and cannot be neglected.

Precise values of  $K$  and  $f(\ell_M, \ell_Q)$  are not available to characterize the hydrodynamics of the sediment control structure. As a first approximation, the Clinch River effective thermal penetration depth  $H$  is set equal to a prescribed fraction of the mean Clinch River depth. The magnitude of this fraction is greater than zero and less than or equal to one.

### 3.6 CLINCH RIVER

Contaminant transport in the Clinch River is approximated using a time-dependent, one-dimensional, aerially uniform, radioactively decaying plume model as shown in Fig. 3.9. Mixing in the depthwise or downward direction is assumed to be instantaneous as well as complete such that the concentration is uniform and no vertical gradients exist. The spilled contaminant floats along the top of the Clinch River. The appropriate time-varying point source strength at the mouth of WOC is  $\dot{m}_w/H$ . The plume spreads in both the spanwise (cross-stream) and downstream directions after entering the Clinch River. Intersection with the opposite side of the river occurs after the plume has traversed some longitudinal distance  $L_x$  known as the entrance length. Beyond  $x = L_x$ , the contaminant is completely mixed over the areal cross

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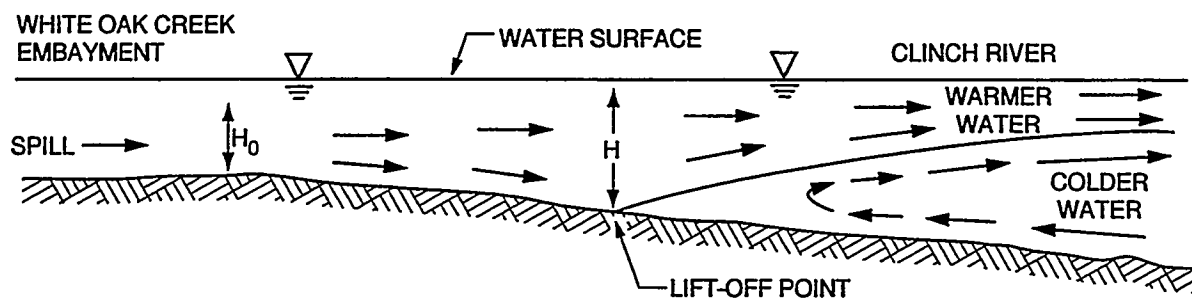


Fig. 3.8. Buoyant discharge from the White Oak Creek embayment into the Clinch River.

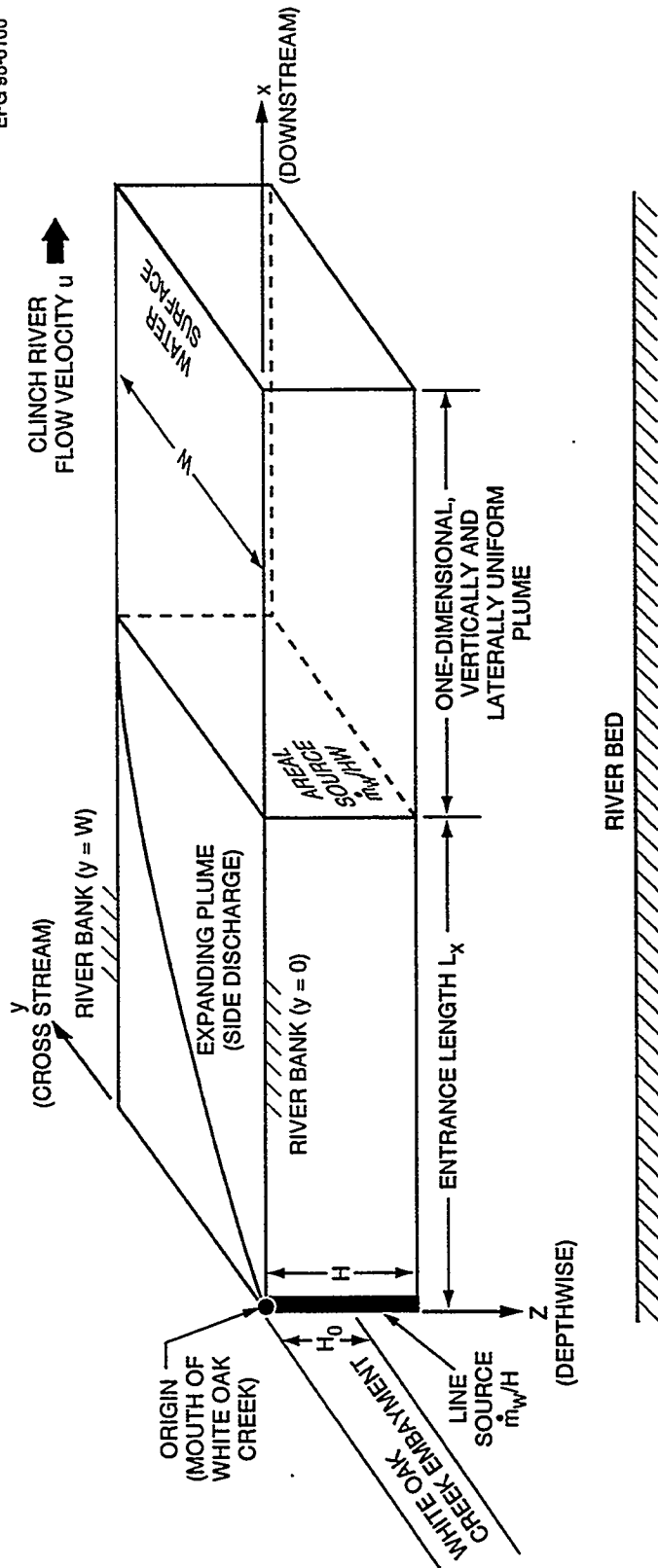


Fig. 3.9. One-dimensional Clinch River plume model.

section *HW*. Fischer et al. (1979, p. 114) formally defines complete mixing to mean that the concentration is within 5% of its average value everywhere on the cross section. The areal source strength at  $x = L_x$  is  $\dot{m}_w/HW$ . The one-dimensional transport model is intended for use at relatively large downstream distances. The model cannot predict species concentrations within the entrance region where mixing is multidimensional and strongly influenced by Melton Hill Dam and the sediment control structure.

The governing species transport equation is (Crank 1956 and 1975)

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} - \lambda C \quad , \quad (3.51)$$

where  $C$  is the contaminant concentration in the Clinch River. The average velocity  $u$  in the downstream direction  $x$  is equal to the measured discharge divided by the entire river cross-sectional area.

The solution to Eq. (3.51) for an instantaneous areal source (or puff) of strength  $\dot{m}_w/HW$  (mass per unit area) is (Sutton 1953; Glover 1964; Fischer et al. 1979; Neely and Lutz 1985)

$$C(x,t) = \frac{\dot{m}_w}{2HW\sqrt{\pi D_x t}} \cdot \exp\left[-\frac{(x - ut)^2}{4D_x t} - \lambda t\right] \quad . \quad (3.52)$$

The numerical factor of 2 appearing in the denominator of Eq. (3.52) would increase to 8 if the advecting/dispersing puff diffused radially in all directions into the infinite sphere (solid angle of  $4\pi$  steradians) (Sutton 1953, pp. 134–35). The concentrations double (numerical factor of 4 in the denominator) when the diffusion is constrained to the upper infinite hemisphere (solid angle of  $2\pi$  steradians) (U.S. Department of Energy 1989, p. F-12), which is equivalent to a discharge in the middle or center of the river. The concentrations again double (numerical factor of 2 in the denominator) when the discharge occurs near the bank of the river (Neely and Lutz 1985, p. 34), which is the appropriate mathematical description for the WOD/WOCE/Clinch River confluence.

The solution for a time-varying, continuously discharging areal source  $\dot{m}_w/HW$  (mass per unit area and per unit time) is obtained by applying a variant of Duhamel's principle (Clough and Penzien 1975; Farlow 1982; U.S. Department of Energy 1989, Appendix F). The solution is evaluated by performing the following integration (or convolution):

$$C(x,t) = \frac{1}{2HW\sqrt{\pi D_x}} \int_0^t \frac{\dot{m}_w(\tau)}{\sqrt{t - \tau}} \cdot \exp\left\{-\frac{[x - u(t - \tau)]^2}{4D_x(t - \tau)} - \lambda(t - \tau)\right\} \cdot d\tau \quad . \quad (3.53)$$

Integration along the time line in terms of the dummy variable  $\tau$  does not require two distinct steps because conversion of the point source at WOD to an areal source at the WOD/WOCE/Clinch River confluence is instantaneous. Radioactive decay within WOL and subsequent radioactive decay in the Clinch River are both implicit in the integral formulation for the solution  $C(x,t)$  obtained using convolution.

Integral expressions for the concentration after instantaneous and finite-duration spills ( $t > 0$ ) are developed by substituting the derived expressions for  $\dot{m}_w$  (which are written in terms of the independent variable  $t$ ) with  $t$  replaced by  $\tau$  into the convoluted equation for  $C(x,t)$ , Eq. (3.53).

## Instantaneous Spill

The solution for the concentration is

$$C(x,t) = \frac{C_0 v}{V_w} \left[ 1 + \frac{v}{V_w} \right]^{-1} \frac{e^{-\lambda t}}{2HW\sqrt{\pi D_x}} \left\{ \frac{v}{\sqrt{t}} \exp \left[ -\frac{(x-ut)^2}{4D_x t} \right] + \int_{\tau=0}^{\tau=t} \frac{Q_w}{\sqrt{t-\tau}} \exp \left[ -\frac{[x-u(t-\tau)]^2}{4D_x(t-\tau)} - \frac{Q_w}{V_w} \tau \right] \cdot d\tau \right\}, \quad (3.54)$$

or

$$C(x,t) = \frac{C_0 v}{V_w} \left[ 1 + \frac{v}{V_w} \right]^{-1} \frac{e^{-\lambda t}}{2HW\sqrt{\pi D_x}} \left\{ \frac{v}{\sqrt{t}} \exp \left[ -\frac{(x-ut)^2}{4D_x t} \right] + \frac{xQ_w}{2\sqrt{D_x}} \exp \left[ -\frac{Q_w t}{V_w} \right] \int_{\xi=0}^{\xi=4D_x u x^2} \frac{1}{\sqrt{\xi}} \exp \left[ -\frac{1}{\xi} + \frac{ux}{2D_x} - \frac{x^2 \xi}{4D_x} \left( \frac{u^2}{4D_x} - \frac{Q_w}{V_w} \right) \right] \cdot d\xi \right\}. \quad (3.55)$$

The transformation  $\xi = 4D_x(t-\tau)/x^2$  has been invoked to develop Eq. (3.55) from Eq. (3.54).

## Finite-Duration Spill

For  $t > D$ , the solution for the concentration is

$$C(x,t) = \frac{C_0 v}{V_w D} \left[ \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right]^{-1} \frac{1}{2HW\sqrt{\pi D_x}} \left\{ \left( Q_w + \frac{v}{D} \right) I_1 + Q_w I_2 \right\}, \quad (3.56)$$

where

$$I_1 = \int_{\tau=0}^{\tau=D} \frac{1}{\sqrt{t-\tau}} \left\{ 1 - \exp \left[ -\left( \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right) \tau \right] \right\} \cdot \exp \left\{ -\frac{[x-u(t-\tau)]^2}{4D_x(t-\tau)} - \lambda(t-\tau) \right\} \cdot d\tau, \quad (3.57)$$

and

$$I_2 = \left\{ 1 - \exp \left[ - \left( \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right) D \right] \right\} \cdot \int_{\tau=D}^{\tau=t} \frac{1}{\sqrt{t-\tau}} \cdot \exp \left\{ - \left( \frac{Q_w}{V_w} + \lambda \right) (\tau-D) \right\} \exp \left\{ - \frac{[x - u(t-\tau)]^2}{4D_x(t-\tau)} - \lambda(t-\tau) \right\} \cdot d\tau \quad (3.58)$$

The solution manifests itself as the sum of two integrals because of the discontinuity that occurs in the temporal history of the mass flux entering the Clinch River (see Fig. 3.7). For  $t \leq D$ , the second integral  $I_2$  is zero. The solution  $C(x,t)$  for  $t \leq D$  is obtained using Eq. (3.56) with  $I_2 = 0$  and with the upper integration limit  $\tau = D$  on  $I_1$  in Eq. (3.57) replaced by  $\tau = t$ .

Invoking the transformation variable  $\xi = 4D_x(t-\tau)/x^2$  once again, the solution for the contaminant concentration in the Clinch River after a finite-duration spill can be recast for  $t > D$  as follows:

$$C(x,t) = \frac{C_0 v}{V_w D} \left[ \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right]^{-1} \left[ \frac{x}{4HWD_x \sqrt{\pi}} \right] \left\{ \left( \frac{Q_w}{V_w} + \frac{v}{D} \right) (I_3 - I_4) + Q_w I_5 \right\} \quad (3.59)$$

where

$$I_3 = \int_{\xi = 4D_x(t-D)/x^2}^{\xi = 4D_x t/x^2} \frac{1}{\sqrt{\xi}} \exp \left[ - \frac{1}{\xi} + \frac{xu}{2D_x} - \frac{x^2 \xi}{4D_x} \left( \frac{u^2}{4D_x} + \lambda \right) \right] \cdot d\xi \quad (3.60)$$

$$I_4 = \exp \left[ - \left( \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right) t \right] \cdot \int_{\xi = 4D_x(t-D)/x^2}^{\xi = 4D_x t/x^2} \frac{1}{\sqrt{\xi}} \exp \left[ - \frac{1}{\xi} + \frac{xu}{2D_x} - \frac{x^2 \xi}{4D_x} \left( \frac{u^2}{4D_x} - \frac{v}{V_w D} - \frac{Q_w}{V_w} \right) \right] \cdot d\xi \quad (3.61)$$

and

$$I_5 = \left\{ 1 - \exp \left[ - \left( \frac{v}{V_w D} + \frac{Q_w}{V_w} + \lambda \right) D \right] \right\} \exp \left[ - \left( \frac{Q_w}{V_w} + \lambda \right) (t-D) \right] \cdot \int_{\xi=0}^{\xi=4D_x(t-D)/x^2} \frac{1}{\sqrt{\xi}} \exp \left[ - \frac{1}{\xi} + \frac{xu}{2D_x} - \frac{x^2 \xi}{4D_x} \left( \frac{u^2}{4D_x} - \frac{Q_w}{V_w} \right) \right] \cdot d\xi \quad (3.62)$$

For  $t \leq D$ , the solution  $C(x,t)$  is obtained by setting  $I_5 = 0$ , and changing the lower integration limits on the integrals  $I_3$  and  $I_4$ , Eqs. (3.60) and (3.61), respectively, to zero ( $\xi = 0$ ).

The integrals appearing in the solutions for  $C(x,y,t)$  after instantaneous and finite-duration spills are variants of the exponential integral. The exponential integral cannot be expressed in terms of a finite number of elementary functions. Recourse to numerical techniques such as Gauss-Legendre quadrature (Carnahan, Luther, and Wilkes 1969) is necessary to perform the integrations. An open-ended integration formula must be used to perform the computations because  $C(x,t)$  is unbounded as  $x \rightarrow 0$ . Such behavior is typical of Fickian transport models, which conserve mass. Concentrations exceeding  $C_0$  are predicted in the entrance region  $L_x$ , which are physically impossible.

### 3.7 DEGENERATE CASES

The cases of no WOL throughput ( $Q_w = 0$ ) and/or no radioactive decay ( $\lambda = 0$ ) are limiting solutions of the analyses that have been presented. Each portion of the WOC watershed is considered separately to evaluate the solutions that are appropriate to these degenerate cases.

#### 3.7.1 Headwaters

Radioactive decay is not accounted for in the analysis of the WOC headwaters. Specification of  $\lambda = 0$  has no effect on the flow and mass balances. The expressions for quantity and quality are valid when the gaged flows are set equal to zero. No dilution occurs when the gaged flows are zero.

#### 3.7.2 White Oak Lake

Several cases require individual consideration.

##### Instantaneous Spill—No Outflow With Decay ( $Q_w = 0, \lambda \neq 0$ )

$$C_w = \left[ \frac{C_0 v}{V_w} \right] \exp(-\lambda t) \quad . \quad (3.63)$$

##### Instantaneous Spill—No Outflow Without Decay ( $Q_w = \lambda = 0$ )

$$C_w = \frac{C_0 v}{V_w} \quad . \quad (3.64)$$

The term  $[1 + v/V_w]^{-1}$  disappears from both of these solutions because the spill does not exit the impoundment.

##### Finite-Duration Spill—No Outflow With Decay ( $Q_w = 0, \lambda \neq 0$ )

$$C_w = \left[ \frac{C_0 v}{V_w D \lambda} \right] \cdot [1 - \exp(-\lambda t)] \quad \text{for } 0 < t < D \quad , \quad (3.65a)$$

$$C_w = \frac{C_0 v}{V_w D \lambda} [e^{-\lambda(t-D)} - e^{-\lambda t}] \quad \text{for } t > D \quad . \quad (3.65b)$$

These two expressions for  $C_w$  are equal at  $t = D$ .

### Finite-Duration Spill—No Outflow Without Decay ( $Q_w = \lambda = 0$ )

$$C_w = \frac{C_0 v}{V_w} \left( \frac{t}{D} \right) \quad \text{for } 0 < t < D \quad , \quad (3.66a)$$

$$C_w = \frac{C_0 v}{V_w} \quad \text{for } t > D \quad . \quad (3.66b)$$

These two expressions for  $C_w$  are equal at  $t = D$ .

The two degenerate finite-duration spill solutions [Eqs. (3.65) and (3.66)] are not implicit in the preceding analysis (Sect. 3.4.3) because no flows leave WOL.

### 3.7.3 Clinch River

The case of zero Clinch River flow velocity ( $u = 0$ ) is not admissible. The plume would disperse directly towards the opposite bank and require a solution applicable to the entrance region. The minimum flow in the Clinch River is the minimum nonzero WOC flow that occurs when the release at Melton Hill Dam is zero. The Clinch River solutions presented in Sect. 3.6 predict suitable results for nonzero flows with ( $\lambda \neq 0$ ) or without ( $\lambda = 0$ ) radioactive decay. If the WOL throughput is zero ( $Q_w = 0$ ), no spilled contaminant reaches the Clinch River and  $C(x,t) = 0$ .

## 3.8 ANCILLARY TOPICS

### 3.8.1 Origin Along Temporal Axis

The travel time for the spill to flow from either WOC or Melton Branch into the headwaters of WOL is not accounted for in the development of the aquatic spill model. Likewise, the time delay in WOCE between WOD and the sediment retention structure is neglected. The travel time in WOC or Melton Branch ranges from several hours to several days, depending on antecedent moisture and precipitation (i.e., conditions of flood or drought). The spill model is insensitive to the WOCE, which is equivalent to assuming that WOD is located on the bank of the Clinch River at the edge of the water. The delay period in WOCE is approximately equal to the WOC or Melton Branch travel time and would range from several hours to several days as long as the water level in the Clinch River remained below the WOCE water surface. The aquatic spill model cannot consider reverse flow from the Clinch River into the WOCE.

Time begins at the instant the spill starts to flow over WOD. Clearly, there is a delay between the time when the spill enters the marshy area at the upper part of the lake bed and the time when it reaches WOD. Dye studies reported by Borders et al. (1987, 1988) have demonstrated that the travel time from just below ORNL WOC gage MS3 (and above the confluence of WOC and Melton Branch) to WOD is approximately 60 h. In the aquatic spill model, the contaminant immediately flows into and down the Clinch River after being released through WOD.

There is a certain inevitable degree of abstraction associated with the aquatic spill model that manifests itself in the physical interpretation of the temporal coordinate. The entire WOC watershed has been reduced to an equivalent point source located on the bank of the Clinch River. Errors introduced by ignoring travel times in WOC, Melton Branch, WOL, and WOCE are secondary to the overall

development of the model. Time durations ranging from approximately 10 to 20 days are required for the contaminant concentration of the original spill to be reduced by six orders of magnitude in WOL prior to reaching WOD. This time duration increases proportionately if further reductions are required to achieve a sufficiently low concentration at WOD.

The use of the aquatic spill model is restricted to radioactively decaying species whose half-lives are measured in months or years. The half-life under consideration must substantially exceed the WOL retention time (see Table 3.1) and the travel times in WOC, Melton Branch, and WOCE. Concentrations of short-lived radionuclides would decay below detection limits before passing through WOD and ultimately entering the Clinch River.

### 3.8.2 Model Complexity

The time-dependent, one-dimensional, advection-dispersion equation [Eq. (3.51)] used to mathematically describe transport in the Clinch River is adequate to scope and assess the effects of accidental spills downstream from the entrance region. An accuracy of plus or minus one order of magnitude is expected and would be considered excellent if obtained.

The entrance length required for complete mixing in the Clinch River could extend 10 to 15 km (6 to 9 miles) downstream from the mouth of WOC, depending on hydrologic conditions and external control exerted by the TVA dams on the watershed (D. Borders, ORNL, personal communication; from Ford and Wefer 1993, p. 12). A multidimensional mathematical description would be required to model mass, momentum, and energy transport within the entrance region. Such a numerical model utilizing computational fluid dynamics would have to include operational aspects of the TVA dams, would require very detailed geometry of the Clinch River streambed, and would need results from dye experiments to obtain dispersivities. The simpler model developed in this study offers an alternative to the more sophisticated models. Results in the Clinch River that would be obtained from the aquatic spill model should be conservative, predicting concentrations higher than actually would occur, because backwater that extends upstream from Watts Bar Dam to Melton Hill Dam has been neglected. At lower flows, much more water would be available in Watts Bar Reservoir to dilute an accidental spill. The influence of the backwater is less at higher flows.

### 3.8.3 CSTR/PFTR Relationship

Consider the flow of an identifiable plug of contaminant spilled into the upper shallow marshy part of WOL. A PFTR, or unmixed model, would utilize an advective/dispersion equation similar to Eq. (3.51) to predict concentrations in the downstream direction towards WOD. The longitudinal flow velocity  $u$  towards the dam is the WOL throughput  $Q_w + Q_{spill}(t)$  divided by an unknown effective area of WOL that is representative of ongoing mixing processes.

In turn, the unknown flow area is expressible as the quotient of the WOL volume  $V_w$  and an effective width  $W_w$ . The velocity  $u$  in Eq. (3.51) becomes

$$u = \frac{[Q_w + Q_{spill}(t)]}{(V_w / W_w)} \quad (3.67)$$

If the actual volume of WOL is utilized in Eq. (3.67)—as opposed to an effective volume—the effective width  $W_w$  is a free parameter that is available to fit the model to experiment.

Equation (3.67) demonstrates that the CSTR and PFTR approaches to modeling WOL are comparable. The CSTR utilizes an effective volume to match experiment, while the PFTR obtains similar

results with an effective width of the lake. CSTR/PFTR equivalency allows the seeming dependency of the CSTR analysis on a sufficiently long lake (see Sect. 3.4.2) to be relaxed, or at least delegated to a secondary status, because modeled concentrations ultimately must be matched with experimental measurements. The CSTR is mathematically concise and amenable to the development of a closed-form solution. The PFTR probably would utilize numerical methods based on computational fluid dynamics and require much of the detailed information already discussed in Sect. 3.8.2. If dispersion is neglected totally, a spill model development for WOL analogous to that presented in this study may be feasible. Chapra and Reckhow (1983, pp. 93–4) present a simple steady-plug flow model that could serve as a starting point.

### 3.8.4 Model Extension

The presence of the entrance region over which the contaminant becomes fully mixed over the areal cross section of the river could be accounted for in the aquatic spill model by adding a spanwise (cross-stream) second-order diffusion/dispersion term to Eq. (3.51). The resultant contaminant concentration distribution predicted by the two-dimensional transport model would decrease gradually and continuously from the concentration of the effluent leaving the WOL/WOD/WOCE complex. The concentration distribution of the plume would not be singular (i.e., increase without bound) near the origin as  $x \rightarrow 0$ .

The mathematical solution to the two-dimensional transport equation is obtainable using the method of images (Fischer et al. 1979, pp. 47–48 and 112–20). The solution is cast as a Laurent series whose summation limits extend from  $-\infty$  to  $\infty$ . Convolution then produces integral expressions similar to those shown in Eqs. (3.54) to (3.62) that are positioned under the summation sign and that cannot be factored out. The one-dimensional transport model was pursued because of computational problems encountered with the evaluation of the integrals in Eqs. (3.54) to (3.62). Extension to two dimensions is natural after these difficulties with numerical integration are overcome.



## 4. MODEL IMPLEMENTATION

### 4.1 SPILL MODEL PARAMETERS

#### 4.1.1 Specification of $V_w$

The solutions for the White Oak Lake (WOL) contaminant concentration are inversely proportional to the lake volume  $V_w$ . This quantity is the effective volume of the mixing chamber, which intuitively depends on the throughput  $Q_w$ . The volume of water in which mixing occurs is less than the actual volume of the entire lake. As a first approximation, the effective volume  $V_w$  is set equal to one-half of the quoted WOL volume of 43,787.2 m<sup>3</sup> (1,546,330 ft<sup>3</sup>) so that dilution by the lake is not overstated. More refined model calibration is possible by adjusting  $V_w$  so that predicted concentrations match measured ones.

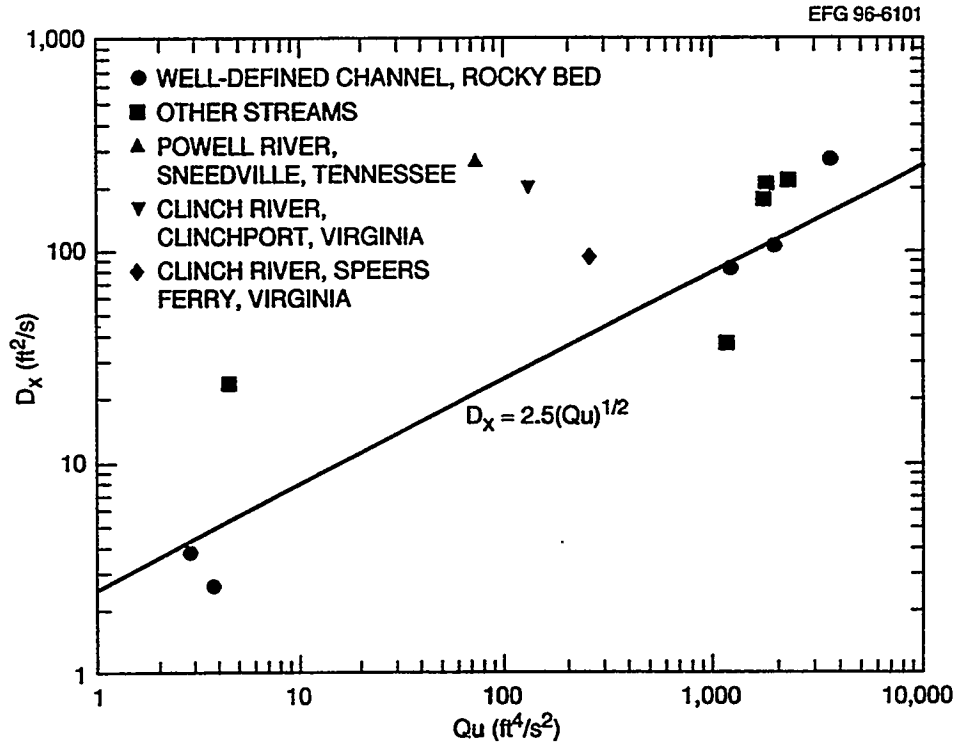
#### 4.1.2 Longitudinal Dispersion Coefficient

Spilled contaminant spreads out in the upstream-downstream direction of the Clinch River because of velocity differences and turbulent diffusion (McQuivey and Keefer 1976). Velocity differences are caused by the shear imparted to the fluid by the streambed and its associated roughness as well as superimposed random motions of the fluid that are turbulent. Hull (1962) developed an empirical correlation for the longitudinal dispersion coefficient  $D_x$  based on experimental measurements made in the South Fork of the American River and results obtained from earlier tests (Hull and Macomber 1958). The American River runs through a deep, rocky northern California gorge in which water is churned by rapids located several hundreds of meters (yards) apart. The correlation is

$$D_x = 2.5\sqrt{Qu} \quad , \quad (4.1)$$

where  $D_x$  is the longitudinal dispersion coefficient (ft<sup>2</sup>/s),  $Q$  is the river discharge (cfs), and  $u$  is the average downstream velocity (ft/s). The value of  $D_x$  increases with stream size and is greater where the average velocity is faster. Hence,  $D_x$  correlates with the product  $Qu$ .

The correlation developed by Hull et al. (1958, 1962) is shown in Fig. 4.1 as well as the measured values on which it is based. Dispersivity values reported by Godfrey and Frederick (1970) for the Clinch River and its Powell River tributary also are plotted in Fig. 4.1. The three measured longitudinal dispersion coefficients observed in the Clinch River headwaters of northeastern Tennessee and southwestern Virginia vary from 98 to 450 ft<sup>2</sup>/s. Dispersivities predicted by Eq. (4.1) are below the three values measured in Clinch River headwaters above Norris Dam. Results based on Eq. (4.1) could actually exhibit better agreement with dispersivities that would be representative of the Clinch River below Melton Hill Dam. Verification of this statement by experiment would be required. Improved agreement could occur because rivers are considerably steeper in their headwaters, becoming relatively level near their mouths (COE 1966, p. 6 and Table 2). Slopes of stream reaches in headwaters tend to exceed average slopes for the stream as a whole and slopes near the mouth. The decrease in slope reduces mixing and, in turn, the dispersivity. The operation of Melton Hill and Watts Bar dams also affects the longitudinal dispersivity downstream from the mouth of White Oak Creek (WOC). Equation (4.1) offers a conservative approximation (resulting in



**Fig. 4.1. Longitudinal dispersion coefficient versus discharge-velocity product.** Sources: R. G. Godfrey and B. J. Frederick, *Stream Dispersion at Selected Sites*, U.S. Geological Survey Professional Paper 433-K, U.S. Government Printing Office, Washington, D.C., 1970, and D. E. Hull, "Dispersion and Persistence of Tracer in River Flow Measurements," *Int. J. Appl. Radiat. Isot.* **13**, 63-73 (February 1962).

lower longitudinal dispersivities and higher concentrations than actually would occur) for the Clinch River longitudinal dispersion coefficient over the measured range of  $\sqrt{Qu}$ .

Estimated peak concentrations are reduced by corresponding increases in the longitudinal dispersion coefficient. Equations similar to Eq. (4.1) have been applied successfully by the U.S. Army (1988, Vol. 3, Appendix N) to the prediction of maximum concentrations attributable to the spill of dangerous chemicals into major rivers. Alternative mixing coefficient correlations are discussed in the monograph by Fischer et al. (1979). The dimensionless constant of proportionality 2.5 in Eq. (4.1) could be adjusted to better match actual dispersivities after experimental results become available for the Clinch River below Melton Hill Dam and the mouth of WOC.

#### 4.1.3 Distance for Complete Mixing

Hull (1962) reported the following correlation for the entrance length  $L_x$  (ft) required for complete mixing from a side discharge (as opposed to a discharge entering at mid-stream):

$$L_x = 200^3 \sqrt{Q} \quad (4.2)$$

The river discharge  $Q$  is expressed in cfs while the constant of proportionality 200 has the dimension  $s^{1/3}$ . Equation (4.2) offers a rough estimate of the distance required for complete mixing. The plume must migrate far enough downstream such that Clinch River concentrations, as predicted by the model, are below concentrations of the effluent being released at White Oak Dam (WOD). Results based on Eq. (4.2) tend to underpredict actual entrance lengths. The distance required to achieve complete mixing downstream from the mouth of WOC has, at times, extended downstream from 10 to 15 km (6 to 9 miles) (D. Borders, ORNL, personal communication; from Ford and Wefer 1993, p. 12). The  $200 s^{1/3}$  constant of proportionality could be readjusted after further information is obtained.

#### 4.1.4 Clinch River Hydraulics

Manning's formula is used to approximate the stage-discharge relation for the Clinch River below Melton Hill Dam:

$$Q = uA_f = \frac{1.49}{n} A_f R^{2/3} \sqrt{S} \quad , \quad (4.3)$$

in which the hydraulic radius  $R$  is defined as

$$R \equiv A_f / P_w \quad , \quad (4.4)$$

and where

- $n$  = Manning roughness factor or coefficient (ft)<sup>1/6</sup>,
- $A_f$  = flow area (ft<sup>2</sup>),
- $P_w$  = wetted perimeter (ft),
- $u$  = average velocity (ft/s) over the cross section,
- $Q$  = volumetric flow rate (cfs),
- $S$  = dimensionless slope (ft/ft) of the channel.

The wetted perimeter  $P_w$  does not include free surface lengths. If metric units are utilized in Eqs. (4.3) and (4.4), the constant 1.49 should be replaced by unity (ASCE & WPCF 1991, p. 80). Under these conditions, the Manning roughness factor  $n$  is a specified constant whose magnitude does not depend on the system of units (Chow 1959, f.n. 1, pp. 98–99).

The location of the streambed contour required to perform the Eq. (4.3) calculation is shown in Fig. 4.2 (Project Management Corporation 1975). Digital values read from Fig. 4.2 are listed in Table 4.1. The Manning roughness factor  $n$  is approximately 0.035, which applies to natural channels described by Chow [1959, Fig. 5-5 (15), p. 120] as follows: (1) somewhat irregular side slopes; (2) fairly even, clean, and regular bottom; (3) erosional surface cut into light gray silty clay to light tan silt loam; and (4) very little variation in cross-sectional flow area. The Manning roughness factor  $n$  accounts for and depends on the roughness of the streambed, but also is a function of the size and shape of the channel cross section (Streeter 1971, p. 278). The slope of the Clinch River from Norris Dam to mile 7 averages 1.5 ft/mile ( $S = 0.00028$ ) (Tennessee Valley Authority 1959, p. 5).

Table 4.2 presents the stage-discharge-area relation for the Clinch River obtained with Manning's formula. Given a prescribed discharge, the data in Table 4.2 are sufficient to resolve a mean depth, average velocity, and river width. Manning's formula assumes an open-channel flow regime with no external control (i.e., no dams).

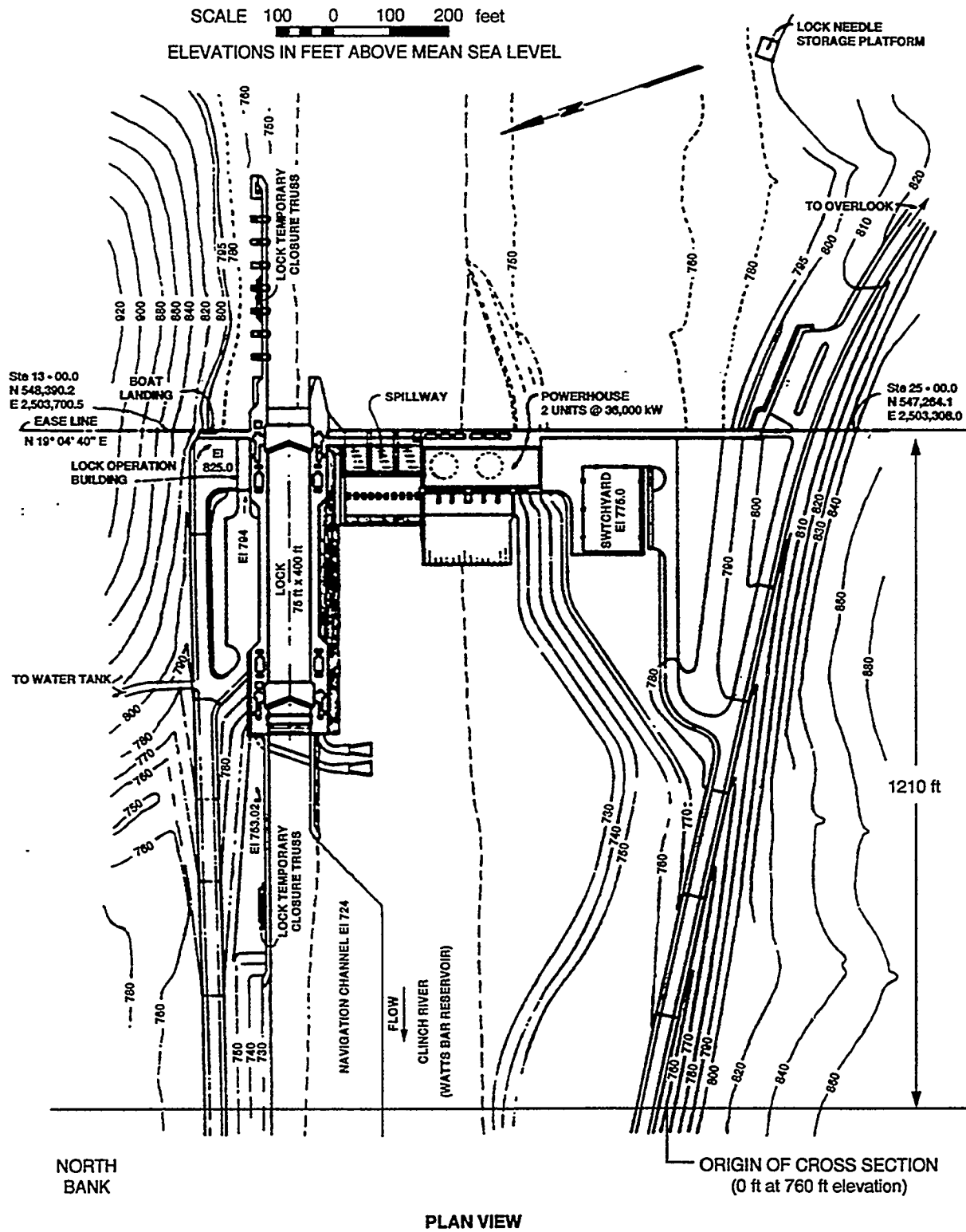


Fig. 4.2. Streambed cross section downstream from Melton Hill Dam. Source: Project Management Corporation, *Preliminary Safety Analysis Report, Clinch River Breeder Reactor*, Oak Ridge, Tenn., 1975, adapted from Fig. 2.4-32, p. 2.4-152.

**Table 4.1. Clinch River streambed contour<sup>a</sup>**

Cross-stream coordinate (ft)	Elevation (ft)
0.0	760 <sup>b</sup>
264.9	750
286.5	740
302.7	730
324.3	725
497.3	724
637.8	725
713.5	730
740.5	740
756.8	750
897.3	760 <sup>c</sup>

<sup>a</sup>See Fig. 4.2 for location of channel cross section along Clinch River.

<sup>b</sup>South bank (origin).

<sup>c</sup>North bank (terminus).

#### **4.1.5 Thermal Penetration Depth**

The Clinch River thermal penetration depth  $H$  accounts for thermal stratification and attendant density differences, and is assumed to be one-tenth of the average river depth over the entire range of flows extending from drought to flood. The value of  $H$  partially controls the dilution that occurs between WOD and downstream locations along the river. Smaller thermal penetration depths should not be used until results are available from comparisons between model predictions and measurements and a consensus has been reached that the magnitude of  $H$  is acceptable.

## **4.2 FORTRAN PROGRAM DEVELOPMENT**

### **4.2.1 Program Description**

A listing of the FORTRAN computer program that implements the mathematical development in the preceding chapter is contained in Appendix A. A 5¼-in. diskette is appended to this document that stores both the FORTRAN (FORmula TRANslation) source code (file SPILL.FOR) and a compiled code version as an executable load module (file SPILL.EXE). Both files are written in ASCII (American Standard Code

**Table 4.2. Calculated Clinch River stage-discharge-area relation**

Discharge (cfs)	Stage elevation <sup>a</sup> (ft)	Flow area <sup>b</sup> (ft <sup>2</sup> )
0	724	0
1	724.20	6.42
5	724.37	21.46
10	724.48	36.09
30	724.72	82.28
50	724.88	120.7
70	725.00	155.3
100	725.12	193.3
300	725.69	379.0
500	726.12	520.2
700	726.48	641.8
1000	726.95	803.4
3000	729.15	1627
5000	730.70	2254
7000	731.94	2775
10,000	733.57	3462
15,000	735.89	4461
20,000	737.90	5347
25,000	739.71	6160
30,000	741.37	6916
35,000	742.91	7629
40,000	744.36	8309
45,000	745.74	8961
50,000	747.06	9590

<sup>a</sup>Computed with Manning's formula with a roughness factor  $n$  of 0.035.

<sup>b</sup>See Fig. 4.2 and Table 4.1 for the streambed contour on which these flow areas are based.

for Information Exchange). The program is self-contained. All hydrologic data pertinent to the WOC watershed description are written in digital form using DATA statements. All input and output appear on the monitor screen. By way of internal dialog and menu-driven questionnaires that appear on the monitor, the user supplies the additional information necessary to define and simulate the accidental spill into the WOC watershed above WOD. The inputs consist of the spill volume, duration, location, and half-life. The flow conditions in the WOC watershed that are described by discharge statistics also must be selected. The computer offers a menu of available discharge statistic types for this purpose.

All prompts that appear on the monitor are answered by typing in a numerical value or the word TRUE or FALSE, which can be abbreviated T or F, respectively. The TRUE (T) or FALSE (F) responses set LOGICAL variables internal to the program that direct internal logic. Internal checks are carried out by the program to ensure the accuracy of inputs; in many cases, the program will continue to prompt the user until the proper type of input has been entered.

The first prompt that appears on the screen asks the user if all hydrologic data internal to the program should be listed. By using the Ctrl-S (freeze screen command) and Ctrl-Q (delete freeze screen command), or alternatively, the Ctrl-Num Lock (halt electronic transmission command) followed by Enter, the user can scroll all data internal to the program. A second TRUE/FALSE prompt after completion of the listing requests whether or not the internal data should be listed again. On many computers, any key on the keyboard (except, of course, the Ctrl-Num Lock key itself) can serve as the response to Ctrl-Num Lock that resumes electronic transmission.

The output from the program consists of three major blocks separated by PAUSE(s). The first block contains the dilution at each gage downstream from the spill, but upstream from WOL. The second block is the dilution versus time history at WOD, while the third is the dilution versus time history at a prescribed distance (input in feet) downstream from the mouth of WOC in the Clinch River. Time begins at the instant the spill leaves WOD. The dilution at WOD is reduced sequentially by integral powers of 10, and the elapsed time back-calculated. These dilutions and corresponding times appear on the screen. The elapsed times quoted for Clinch River dilutions correspond approximately to the times at WOD for the spill to be slowly released plus the travel time to the downstream river location (downstream distance  $x$  divided by the mean river flow velocity  $u$ ). The dilution in the Clinch River is calculated for each value of the elapsed time at WOD plus the plume travel time from the mouth of WOC to the chosen downstream river location.

The flows at WOD and in the Clinch River can be user specified. Prompts appear on the monitor that allow the internal discharge statistics to be overridden. The discharge statistics cannot be superseded in the dilution analysis of the WOC headwaters and tributaries. If the WOD and/or Clinch River flows are changed, the output for the WOC headwaters and tributaries is distinct from the results predicted for WOD and the Clinch River. The dilutions calculated for the WOC watershed above WOL would still correspond to the selected discharge statistic (mean, minimum, maximum, exceedence, and etc.), while the dilutions computed for the WOL/WOD/Clinch River complex would reflect the WOD and Clinch River flows specified by the user.

After each PAUSE the information appearing on the screen can be printed by typing Shift-Print Screen. If the Enter key is depressed after PAUSE, the program will continue execution. All output generated during the session can be dumped to a printer by typing Ctrl-Print Screen prior to program execution. A second Ctrl-Print Screen should be entered after the session to halt the screen dump to the printer.

#### 4.2.2 Numerical Methods

Piecewise linear interpolation is used to construct a continuous function from digitized data. The function STLNIN invokes a binary search routine to repeatedly subdivide the abscissa on which the data

are defined to determine the appropriate interval in which to interpolate. Interpolation within the interval is then accomplished with two-point form of a straight line. Extrapolation at either endpoint of the data set is performed using the first or last two data points. The data points that are input to STLNIN do not have to be equally spaced. The abscissas must, however, be monotonically increasing.

Numerical evaluation of the exponential integrals required for the Clinch River plume calculation is performed with four-point, Gauss-Legendre quadrature (Carnahan, Luther, and Wilkes 1969, pp. 109–10). The FUNCTION GAUSSQ applies the four-point open integration formula over the single interval from A to B. The integrand is not evaluated at the endpoints A and B. The integrand has an unremovable singularity at  $t = 0$  that is avoided by this numerical procedure. The EXTERNAL FUNCTION SPILL contains the exponential integrands.

The SUBROUTINE INTGRT applies the four-point, Gauss-Legendre quadrature procedure in a composite manner. The integration interval is repeatedly subdivided in an iterative manner until convergence is attained to a prescribed tolerance level. The relative error tolerance is set equal to 0.001. If, on the first pass when the quadrature formula is applied over the entire interval with no subdivision (producing the approximation to the integral A1), the quantity DABS(A1) is returned less than  $10^{-30}$ , the integral is returned as the computed value of A1. A relative error test cannot be performed for a zero condition. The maximum number of subdivisions is 250. A warning message appears on the monitor screen when convergence is not attained with 250 subdivisions. Each successive composite integration is performed with ten more subdivisions than the last; the results from the two most recent computations are compared with 0.001 based on the absolute value of their quotient expressed as a relative error.

The entire computer program is written in DOUBLE PRECISION.

#### 4.2.3 Output Interpretation

The plume that disperses downstream in the Clinch River undergoes an initial dilution caused by the discharge from Melton Hill Dam. This dilution occurs primarily within the entrance region. Farther downstream, longitudinal dispersion causes spreading that would further dilute an instantaneous slug because the contaminant is being mixed into a larger and larger fluid volume. The efflux from WOD requires a relatively long elapsed time before the source is extinguished. In this sense, the source is maintained. If the source were maintained indefinitely, a constant concentration equal to that of the source eventually would be realized at a downstream location. The time history of the dilution predicted by the ORNL spill model in the Clinch River exhibits portions of both of these behaviors. The dilution exhibits a peak that dilutes very slowly as the plume migrates downstream in the Clinch River. The plume is maintained by the WOD efflux; hence significant dilution does not occur downstream until the source undergoes dilution. In this sense, a very long plume is produced by the spill, which extends down the river and whose manifestation as an absolute concentration depends to a great extent on the mixing action occurring in WOL.

#### 4.3 MATHCAD PROGRAM VERSION

A less robust version of the ORNL aquatic spill model has been programmed with the computer software known as Mathcad (MathSoft, Inc. 1995). Appendix B contains a listing of the Mathcad version of the code that was prepared with the Mathcad PLUS 6.0 Professional Edition. Mathcad combines text, graphics, and equations into a single worksheet. Mathcad utilizes the language of mathematics as it appears explicitly in textbooks rather than a more cryptic programming language. Mathcad is privately owned, copyrighted software that must be purchased and used in accordance with a license agreement. Mathcad is a registered trademark of MathSoft, Inc. The file SPILL.MCD on the diskette included in the pocket on the

back cover is the Mathcad version of the ORNL aquatic spill model. The file SPILL.MCD must be read by Mathcad before program execution can commence. If Mathcad is not available, computational results cannot be calculated with SPILL.MCD.

The Mathcad version of the spill model does not contain as much WOC watershed information and corresponding dialogue as the FORTRAN version does. The Mathcad version was written to confirm the calculation of the exponential integrals appearing in Sect. 3.6. The graphics produced by the Mathcad version were used to verify anticipated trends that should and have been observable in the results. The output of the Clinch River portion of the FORTRAN code version is digital, and interpretation is sometimes difficult. The graphics provided by the Mathcad version of the code allow this problem to be resolved. Both the FORTRAN and Mathcad codes have produced similar (i.e., equal) computational results for WOL and the Clinch River.

#### 4.4 COMPARISON WITH EXPERIMENT

Predictions from the ORNL aquatic spill model are compared against experimental measurements obtained from dye studies in WOC and WOL, and total  $^{137}\text{Cs}$  radioactivities recorded in the Clinch River during construction of the White Oak Creek Embayment (WOCE) sediment retention structure. The agreement between calculated and measured quantities demonstrates the viability of the ORNL aquatic spill model. More detailed model calibration that would specify  $V_w$ ,  $D_x$ ,  $L_x$ ,  $H$ , and the Clinch River stage-discharge-area relation is beyond the scope of this study. Ultimate selection and specification of these quantities could require constrained optimization, additional experiments, and a suitable consensus between interested parties and cooperating agencies.

##### 4.4.1 White Oak Lake

Two dye studies were conducted in 1987 and 1988 that evaluated the dilution occurring in WOL (Borders et al. 1987, 1988). The results of these two experiments have provided a formal basis from which to develop a methodology for the determination of peak contaminant concentrations at WOD resulting from releases into WOC (Green 1992). Both experiments were performed during conditions of base flow when the WOD discharge was 142 L/s (5 cfs). This flow corresponds to the annual 7-d minimum quoted in Table 2.9.

The first dye study (Borders et al. 1987) in late September 1987 involved an instantaneous release of approximately 4.73 L (1.25 gal) of dye solution into WOC just below gage MS3 and above the confluence of WOC with Melton Branch. The second dye study (Borders et al. 1988) in June 1988 involved a 4-h release of dye solution into WOC in the ORNL main plant area near Building 4500S. Based on the results of the first dye study, the ratio of the peak contaminant concentration measured at the first sampling location just downstream of gage MS3 to the peak concentration of the contaminant measured at WOD was 207 for a slug or instantaneous release. The slug release had an approximate duration of a 20-min release into WOC during passage through the first sampling location. Although the entire plume passed by the sampling location in 1 h, the highest concentrations within the plume dissipated in 20 min. Thus, the factor of 207 is equivalent to a 20-min release. Based on the results of the second dye study, the ratio of the peak contaminant concentration measured at gage MS3 to the peak contaminant concentration measured at WOD was 15.8 for a 4-h release into WOC.

For the September 1987 dye experiment [4.73-L (1.25-gal), 20-min release at gage MS3, annual 7-d minimum flows], the ORNL aquatic spill model predicted a dilution of  $2.81 \times 10^{-5}$  at gage MS3, and a peak dilution at WOD of  $2.15 \times 10^{-7}$ . The ratio of these two dilutions (the concentration of dye in the

original release divides out) is 131, which is approximately one-half of the measured value of 207. If the duration of the release is decreased to 12.6 min, the calculated and measured peak concentration ratios are equivalent.

Using the June 1988 dye experiment [4.73-L (1.25-gal) (inferred), 4-h release, annual 7-d minimum flows] as a basis, the ORNL aquatic spill model predicted dilutions of  $2.58 \times 10^{-6}$  and  $2.06 \times 10^{-7}$  at gage MS3 and WOD, respectively. The dye release in the model calculation occurred at gage GS6, which is slightly upstream from Building 4500S. The ratio of these two dilutions is 12.5, which compares favorably with the value of 15.8 reported for the ratio of measured peak concentrations at gage MS3 and WOD. Improved agreement with either of the dye experiments could be obtained by refining the estimated effective WOL mixing volume  $V_w$ .

#### 4.4.2 Clinch River

The dilution afforded to the effluent exiting the mouth of WOC typically varies between 0.02 and 0.002 within the Clinch River (Ford and Wefer 1993, p. 12). The precise dilution is determined primarily by the river discharge. The distance required for complete mixing in the Clinch River from the mouth of WOC may extend downstream from 10 to 15 km (6 to 9 miles) depending on hydrologic conditions and external controls such as the Tennessee Valley Authority (TVA) dams (D. Borders, ORNL, personal communication; from Ford and Wefer 1993, p. 12).

Table 4.3 presents measured Clinch River dilutions as a function of Melton Hill Dam discharges. Activities (pCi/L) of total  $^{137}\text{Cs}$  (30-year half-life) in 24-h composite samples were measured at the mouth of WOC [Clinch River km 33.5 (mile 20.8)] and downstream at the K-1513 intake structure [Clinch River km 23.3 (mile 14.5)], where drinking water is obtained for the Oak Ridge K-25 Site (Ford and Wefer 1993, Appendix A, Table A.1, pp. A-3 to A-9). The daily discharges measured at Melton Hill Dam were reported by Flohr et al. (1993, p. 152). The dilution quoted in Table 4.3 is calculated as the quotient of the downstream and upstream activities. These measurements were taken during construction of the WOCE sediment retention structure to ensure that resuspended radioactive sediments did not compromise the K-25 Site water supply. The nature of the source producing the radioactivity is not well understood but obviously has components from both WOD releases and construction activities associated with the sediment retention structure. The set of measurements reported by Ford and Wefer (1993) is more extensive than the subset exhibited in Table 4.3. Pairs of activity values in which the downstream magnitude exceed that of the upstream and those containing negative activities were not used to compute dilutions.

The set of dilutions in Table 4.3 vary from a maximum of 0.97 (essentially no dilution) to a minimum of 0.024 with an average of 0.25. The discharge from Melton Hill Dam varies from 10,140 to 480,000 L/s (358 to 17,000 cfs) with a mean flow of 123,400 L/s (4,357 cfs). The higher discharge correlates with the smaller dilution (0.024) and vice versa. The average Melton Hill Dam discharge in Table 4.3 approximates closely the 50% exceedence flow of 116,000 L/s (4100 cfs) given in Table 2.10. The data reported in Table 4.3 seem to corroborate the statement by Borders (Ford and Wefer 1993, p. 12) with regard to the distance required for complete mixing and dilution in the Clinch River.

Dilutions predicted by the ORNL aquatic spill model are comparable with the measured values in Table 4.3. An instantaneous, zero-duration spill having a volume of 3.8 L (1 gal) receives peak dilutions of  $1.73 \times 10^{-7}$  and  $3.37 \times 10^{-9}$  at WOD and 10.1 km [6.3 miles (33,264 ft)] downstream from the mouth of WOC at the K-1513 intake structure, respectively, at 50% exceedence flows in the WOC and Clinch River watersheds. If the 3.8-L (1-gal) spill is released over a finite duration of 10 d, peak dilutions at WOD and the K-1513 facility are  $1.84 \times 10^{-8}$  and  $3.30 \times 10^{-10}$ , respectively. Treating these model predictions as concentrations/activities and forming the quotient of the downstream and upstream values, the instantaneous spill is diluted by a factor of 0.0195 in the Clinch River. The corresponding finite-duration

**Table 4.3. Measured Clinch River dilutions**

Measurement date	White Oak <sup>a,b</sup> Creek mouth	K-1513 water intake structure <sup>a,c</sup>	Melton Hill Dam discharge <sup>d</sup> (cfs)	Dilution
10-3-91	1.89	1.08	5840	0.57
10-29-91	1.89	1.62	4800	0.86
12-2-91	54.06	1.89	15,800	0.035
12-6-91	2.97	0.54	17,000	0.18
1-6-92	10.27	0.81	16,300	0.079
2-19-92	21.08	3.78	3580	0.18
2-21-92	29.73	0.81	466	0.027
3-3-92	37.84	1.35	1450	0.036
3-6-92	19.73	2.16	2010	0.11
3-10-92	32.44	7.30	4680	0.23
3-18-92	29.73	2.16	358	0.073
3-20-92	59.47	3.24	4600	0.054
3-25-92	22.16	0.54	4120	0.024
3-26-92	64.87	3.51	1860	0.054
3-27-92	170.29	10.81	1520	0.063
3-31-92	19.46	1.89	2770	0.097
4-2-92	62.17	7.84	2200	0.13
4-3-92	7.84	7.57	2670	0.97
4-8-92	37.84	7.03	2180	0.19
4-15-92	59.47	5.95	2500	0.10
5-13-92	7.57	4.87	1570	0.64
5-20-92	2.43	1.89	1240	0.78
6-17-92	18.65	7.30	2560	0.39
7-8-92	26.22	7.84	4030	0.30
7-15-92	25.14	1.35	2830	0.054
	Maximum		17,000	0.97
	Average		4357	0.25
	Minimum		358	0.024

<sup>a</sup>Total <sup>137</sup>Cs radioactivities (pCi/L) (30-year half-life) measured from 24-h composite samples.

<sup>b</sup>Clinch River mile 20.8.

<sup>c</sup>Clinch River mile 14.5 (K-25 Site water supply intake).

<sup>d</sup>Clinch River mile 23.1.

Source: D. F. Flohr et al., *Water Resources Data Tennessee Water Year 1992*, U.S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va., 1993, and C. J. Ford and M. T. Wefer, *Water Quality Monitoring Report for the White Oak Creek Embayment*, Report ORNL/ER-150, Environmental Sciences Division Publication 4039, Oak Ridge Natl. Lab., Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn., January 1993, Table A.1, pp. A-3 to A-9.

spill is released more slowly and receives an expected lower Clinch River dilution of 0.0018. These model predictions correlate with the lower range of measured values appearing in Table 4.3. The Clinch River dilutions predicted by the spill model are slightly lower than recent measured values, but certainly not out of the reported range. Further reduction of the thermal penetration depth  $H$  probably would reduce the difference between the calculated and measured dilutions.

#### 4.5 LIMITATIONS

The digital output produced by the FORTRAN version of the spill model for the Clinch River analysis is shown in Figs. 4.3 and 4.4, while corresponding Mathcad calculations appear as graphs in Figs. 4.5 and 4.6, respectively. The spill is nonradioactive, has a volume of 3.8 L (1 gal), enters WOL directly, and assumes 50% exceedence flows in the WOC and Clinch River watersheds. The dilution is calculated that would be realized by an observer standing 20.3 km [12.6 miles (66,528 ft)] downstream from the mouth of WOC on the bank of the Clinch River. Figures 4.3 and 4.5 portray an instantaneous spill, while Figs. 4.4 and 4.6 consider a 10-d finite-duration spill. The tabular values in the two rightmost columns of Figs. 4.3 and 4.4 are either proportional to, or are, the exponential integrals that arise in the  $C(x,t)$  mathematical solutions for the instantaneous and finite-duration spills. In Fig. 4.3, the rightmost column (CONTINUOUS PORTION) is the integral or second term in Eq. (3.55), while the adjacent column (INSTANT PORTION) is the first or exponential term. The rightmost column (CONTINUOUS PORTION) in Fig. 4.4 is  $I_5$  [refer to Eq. (3.62)], while the adjacent column (FINITE DURATION PORTION) is the difference  $I_3 - I_4$  [see Eqs. (3.60) and (3.61)]. Figures 4.3 through 4.6 depict the dilution versus time history of the spill at the prescribed downstream location along the Clinch River.

Portions of the dilution-time history shown in Figs. 4.5 and 4.6 suddenly decrease to zero over finite segments of the temporal domain. Similar behavior is exhibited in the digital solutions in Figs. 4.3 and 4.4. The dilution of  $2.9026 \times 10^{-39}$  in Fig. 4.3, and the  $1.1804 \times 10^{-45}$  and  $7.7419 \times 10^{-27}$  values in Fig. 4.4 are analogous to the zero segments that appear in Figs. 4.5 and 4.6. The numerical integration routines do not converge when this behavior occurs. The cause of this phenomenon is unknown. The nonconvergences appear without warning, are nonuniform in appearance and location along the temporal domain, and occur more frequently when the spill has a finite duration than when the spill is instantaneous. The utility of the predictions is not compromised because simple trend analysis allows erroneous portions of the solutions to be identified and deleted from consideration. The digital output in Figs. 4.3 and 4.4 requires more experience with the operation of the FORTRAN version of the spill model to detect nonconvergences. In extreme cases, or if there is doubt as to whether or not nonconvergences have occurred, the Mathcad version of the spill model should be used to obtain graphical output that is much easier to interpret.

Both the FORTRAN and Mathcad versions of the spill model repeatedly subdivide the integration interval until the sequence of computations converges within the limits of a prespecified tolerance test. Numerical integration in the FORTRAN version utilizes Gauss-Legendre quadrature (Carnahan, Luther, and Wilkes 1969, pp. 109–10). The Mathcad version applies the trapezoidal rule at the midpoints of subintervals in open-ended applications, followed by extrapolation of a sequence of midpoint estimates to obtain a Romberg estimate (i.e., Romberg integration) (MathSoft, Inc. 1995, pp. 633–35). The methodologies are analogous in principle and exhibit similar symptoms when convergence is not attained. Both algorithms yield equivalent results when applied to the exponential integral variants that require computation in the spill model. Because source code probably would be required to maintain a stand-alone FORTRAN program, other potential integration methods commercially available in the IMSL (Microsoft Corporation 1994) or NAG (Numerical Algorithms Group, Inc. 1984) libraries, for example, have not been investigated to ameliorate the convergence problem.

CLINCH RIVER DISTANCE FROM WHITE OAK CREEK MOUTH: 66528.0 FT ( 12.6 MILES)

```

*****ELAPSED TIME*****
SECONDS HOURS DAYS WEEKS CLINCH RIVER INSTANT CONTINUOUS
          PORTION PORTION PORTION PORTION
3.2334D+04 8.9816D+00 3.7423D-01 5.3462D-02 1.7008D-09 7.4343D-04 1.0556D+02
3.5524D+04 9.8679D+00 4.1116D-01 5.8737D-02 3.2231D-09 1.8955D-04 2.0005D+02
3.8715D+04 1.0754D+01 4.4809D-01 6.4013D-02 3.3000D-09 5.3541D-06 2.0482D+02
4.1906D+04 1.1641D+01 4.8502D-01 6.9289D-02 3.1910D-09 2.7704D-08 1.9806D+02
4.5097D+04 1.2527D+01 5.2195D-01 7.4564D-02 3.0823D-09 3.7656D-11 1.9131D+02
4.8287D+04 1.3413D+01 5.5888D-01 7.9840D-02 2.9773D-09 1.7528D-14 1.8479D+02
5.1478D+04 1.4299D+01 5.9581D-01 8.5116D-02 2.8758D-09 3.4105D-18 1.7849D+02
5.4669D+04 1.5186D+01 6.3274D-01 9.0391D-02 2.778D-09 3.2322D-22 1.7241D+02
5.7859D+04 1.6072D+01 6.6967D-01 9.5667D-02 2.6831D-09 1.6807D-26 1.6653D+02
6.1050D+04 1.6958D+01 7.0660D-01 1.0094D-01 2.5917D-09 5.2687D-31 1.6086D+02
1.9215D+05 5.3374D+01 2.2239D+00 3.1770D-01 2.9026D-39 4.7481-270 1.8016D-28
2.9091D+05 8.0809D+01 3.3670D+00 4.8101D-01 2.1530D-10 .0000D+00 1.3363D+01
3.8968D+05 1.0824D+02 4.5101D+00 6.4431D-01 7.2904D-11 .0000D+00 4.5249D+00
4.8844D+05 1.3568D+02 5.6532D+00 8.0761D-01 2.4923D-11 .0000D+00 1.5469D+00
5.8720D+05 1.6311D+02 6.7963D+00 9.7091D-01 8.5225D-12 .0000D+00 5.2896D-01

```

PERFORM ANOTHER DILUTION CALCULATION AT DIFFERENT DOWNSTREAM CLINCH RIVER LOCATION (ENTER TRUE), OR END COMPUTING SESSION (ENTER FALSE)?

Fig. 4.3. Instantaneous 3.8-L (1-gal) spill (into White Oak Lake) calculation performed with FORTRAN program (nonradioactive, 50% exceedence flows).

CLINCH RIVER DISTANCE FROM WHITE OAK CREEK MOUTH: 66528.0 FT ( 12.6 MILES)

```

*****ELAPSED TIME*****
SECONDS HOURS DAYS WEEKS CLINCH RIVER DILUTION FINITE DURATION CONTINUOUS
      8.0993D+05 2.2498D+02 9.3742D+00 1.3392D+00 3.8626D-10 1.2211D-02 .0000D+00
      8.2228D+05 2.2841D+02 9.5171D+00 1.3596D+00 3.7652D-10 1.1903D-02 .0000D+00
      8.3462D+05 2.3184D+02 9.6599D+00 1.3800D+00 3.7729D-10 1.1927D-02 .0000D+00
      8.4696D+05 2.3527D+02 9.8028D+00 1.4004D+00 3.7656D-10 1.1904D-02 .0000D+00
      8.5931D+05 2.3870D+02 9.9457D+00 1.4208D+00 3.7659D-10 1.1905D-02 .0000D+00
      8.7165D+05 2.4212D+02 1.0089D+01 1.4412D+00 1.1804D-45 3.7316D-38 1.5195-181
      8.8399D+05 2.4555D+02 1.0231D+01 1.4616D+00 7.7419D-27 4.1996D-58 2.4473D-19
      8.9633D+05 2.4898D+02 1.0374D+01 1.4820D+00 1.8112D-10 2.5368D-79 5.7257D-03
      9.0868D+05 2.5241D+02 1.0517D+01 1.5024D+00 3.2976D-10 2.3177-101 1.0424D-02
      9.2102D+05 2.5584D+02 1.0660D+01 1.5228D+00 2.8837D-10 5.8272-124 9.1158D-03
      9.3336D+05 2.5927D+02 1.0803D+01 1.5433D+00 2.5217D-10 5.8369-147 7.9716D-03
      9.4571D+05 2.6270D+02 1.0946D+01 1.5637D+00 2.2052D-10 2.9639-170 6.9709D-03
      9.5805D+05 2.6612D+02 1.1089D+01 1.5841D+00 1.9284D-10 8.9860-194 6.0959D-03
      9.7039D+05 2.6955D+02 1.1231D+01 1.6045D+00 1.6863D-10 1.8250-217 5.3308D-03
? Error: REAL math overflow
Error Code 2101

```

PC = 0940: 000A; SS = 3361, FP = 30C0, SP = 8082

Fig. 4.4. Finite-duration [10-d, 3.8-L (1-gal)] spill (into White Oak Lake) calculation performed with FORTRAN program (nonradioactive, 50% exceedence flows).

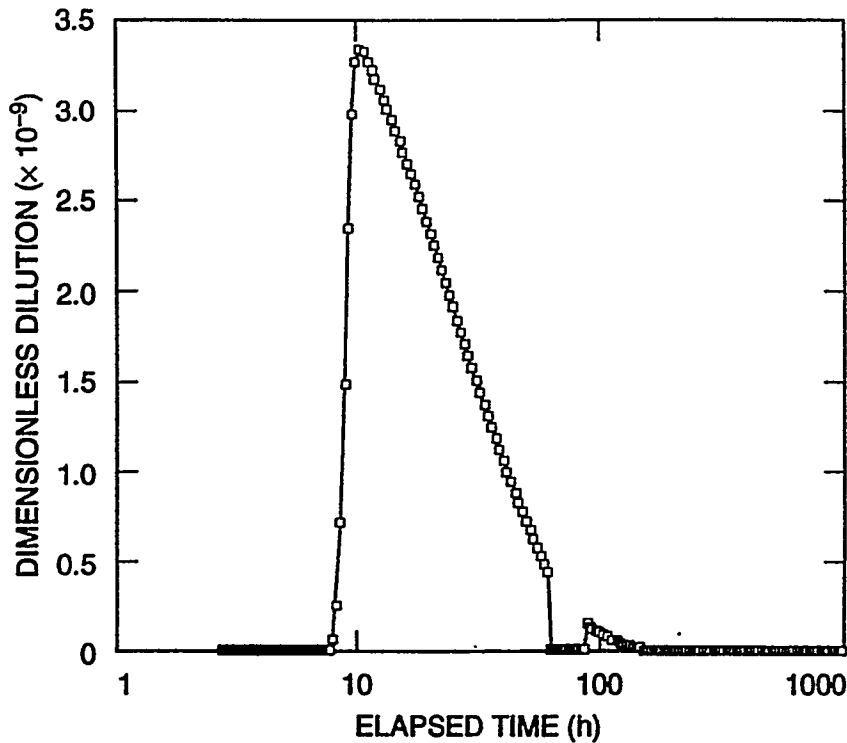


Fig. 4.5. Instantaneous 3.8-L (1-gal) spill (into White Oak Lake) calculation performed with Mathcad program [nonradioactive, 50% exceedence flows, 20.3 km (12.6 miles)].

The digital output in Figs. 4.3 and 4.4 is arranged to appear near the location where the dilution exhibits a maximum value. For the instantaneous spill, this location is approximated as  $x/u$ , while being  $x/u + D$  when the spill has a finite duration. In Figs. 4.3 and 4.5,  $x/u$  is equal to 8.9 h, while the value of  $x/u + D$  is 248.9 h in Figs. 4.4 and 4.6. The digital output is limited by the number of data points that can be shown on the monitor screen. If increased resolution is required, consideration should be given to using the Mathcad version to perform the computations. A large number of points along the temporal coordinate, on the order of 250, sometimes is required to obtain an accurate estimate of the maximum dilution. The digital output of the FORTRAN program currently is limited to 15 points.

Table 4.4 presents the maximum Clinch River dilution as a function of downriver distance from the mouth of WOC for the spill depicted in Figs. 4.3–4.6. The Mathcad version of the aquatic spill model was used to calculate these results. The dilution of the instantaneous spill exhibits an expected monotonic decrease in the downstream direction. The Romberg integration algorithm successfully converges and produces dilution estimates as far downstream as the confluence of the Tennessee and Ohio rivers [947.6 km (588.8 miles) from the mouth of WOC]. Once the instantaneous spill passes beyond the entrance length  $L_x$ , longitudinal mixing provides only minimal dilution of the peak contaminant concentration. Additional flow must enter the Clinch River watershed to further dilute the spill.

The calculated results for the 10-d finite-duration spill in Table 4.4 do not converge for downriver distances beyond approximately 40.6 km (25.2 miles). The problem has been traced to the numerical integration of  $I_5$  [see Eq. (3.62)]. For large downriver distances, asymptotic methods (de Bruijn 1981) may be required to obtain accurate estimates of  $I_5$ . Useful predictions for the dilution of a finite-duration spill from the end of the entrance length to the confluence of the Clinch and Tennessee rivers are provided by the spill model. The finite-duration spill is diluted more than the instantaneous spills. Until an improved

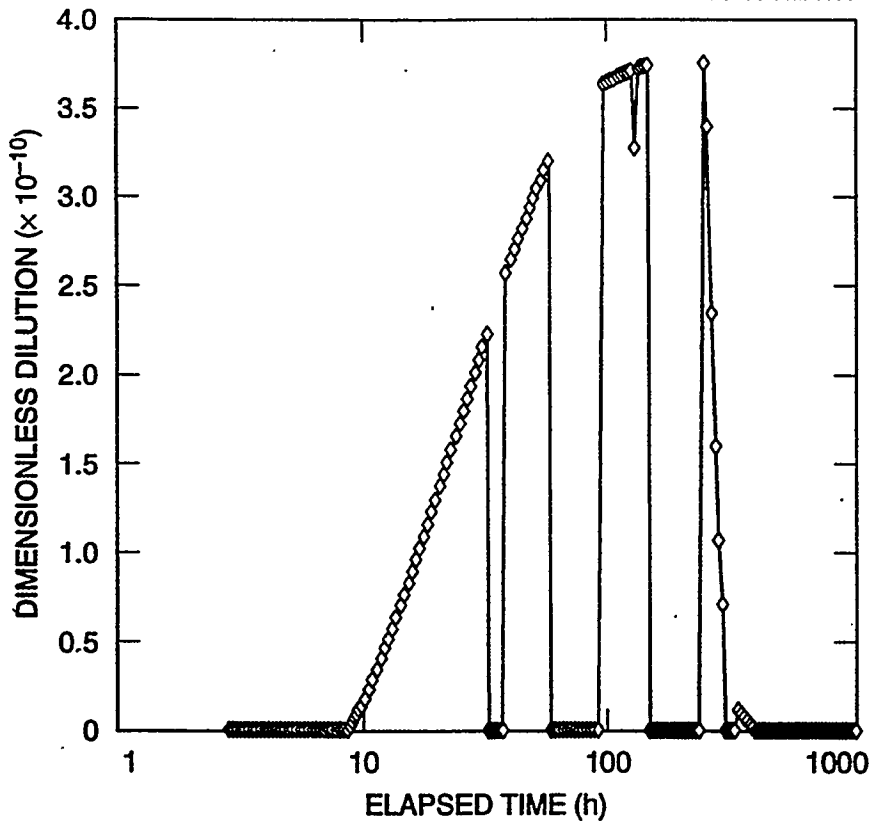


Fig. 4.6. Finite-duration [10-d, 3.8-L (1-gal)] spill (into White Oak Lake) calculation performed with Mathcad program [nonradioactive, 50% exceedence flows, 20.3 km (12.6 miles)].

method is found to compute  $I_5$ , no more than one or two significant digits should be attached to the accuracy of the finite-duration spill calculations. The solution for the instantaneous spill offers an overestimate of the dilution of a finite-duration spill at larger downriver distances past the confluence of the Clinch and Tennessee rivers.

**Table 4.4. Maximum Clinch River dilution<sup>a</sup>**

Downriver location <sup>b</sup> [km (miles)]	Instantaneous spill ( $\times 10^{-9}$ )	10-d finite-duration spill ( $\times 10^{-10}$ )
10.1 (6.3) <sup>c</sup>	3.37952	3.76322
20.3 (12.6)	3.33097	3.76560
30.4 (18.9)	3.28976	3.76424
33.5 (20.8) <sup>d</sup>	3.28536	3.76588
40.6 (25.2)	3.26379	3.76557
50.7 (31.5)	3.21807	NC <sup>e</sup>
60.8 (37.8)	3.20541	NC
71.0 (44.1)	3.19836	NC
80.5 (50.0)	3.18323	NC
160.9 (100.0)	2.95270	NC
321.9 (200.0)	2.93757	NC
947.6 (588.8) <sup>f</sup>	2.26551	NC

<sup>a</sup>Based on a presumed 3.8-L (1-gal) nonradioactive spill directly into White Oak Lake with 50% exceedence flows. Computed with Mathcad version of Oak Ridge National Laboratory aquatic spill model.

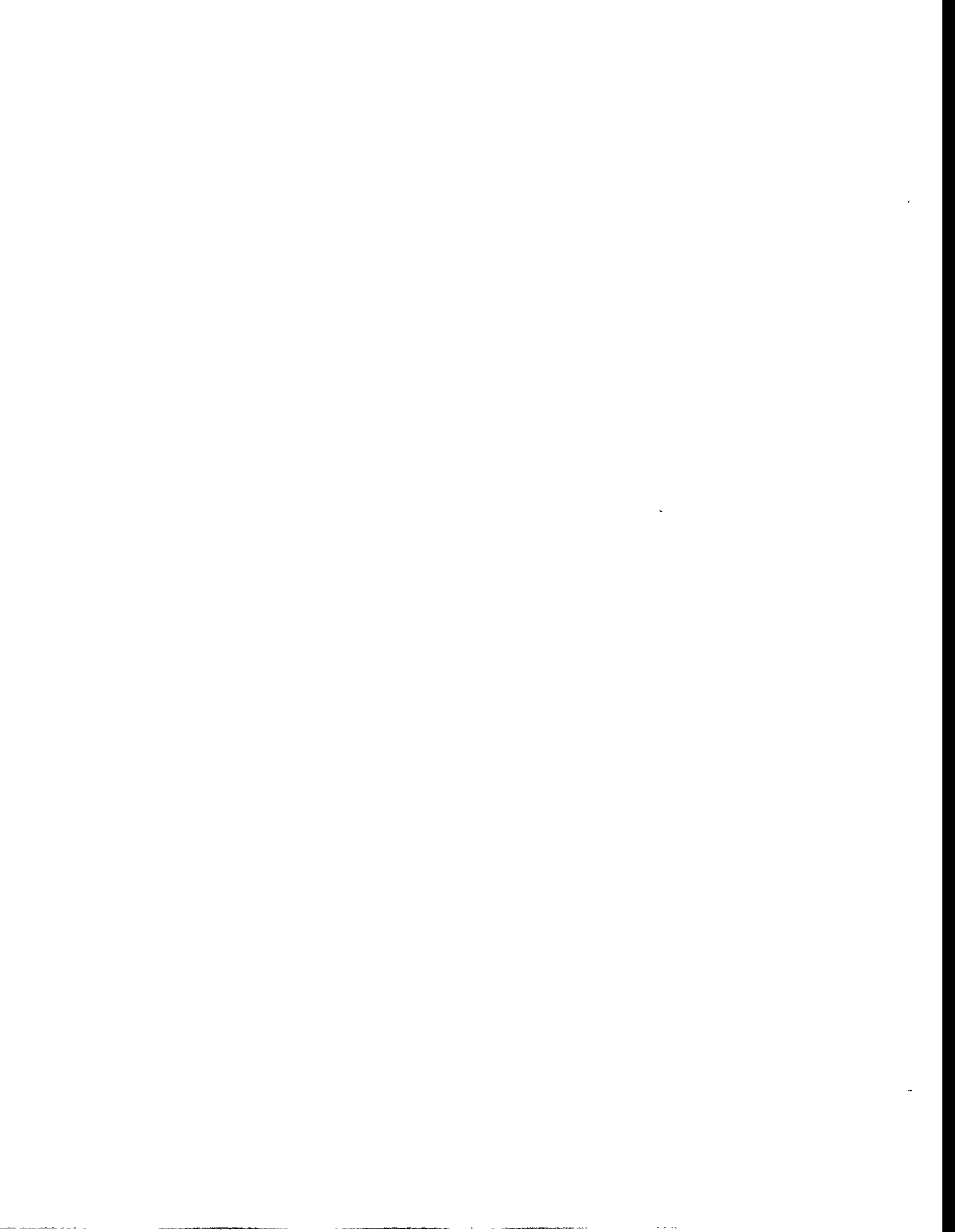
<sup>b</sup>Measured from the mouth of White Oak Creek.

<sup>c</sup>Clinch River mile 14.5 (K-25 Site water supply intake).

<sup>d</sup>The confluence of the Clinch and Tennessee rivers occurs 33.5 km (20.8 miles) downstream from the mouth of White Oak Creek. The Tennessee River would provide additional dilution at this downriver location that is not accounted for in the spill model.

<sup>e</sup>The algorithm using Romberg integration to calculate  $I_5$  as given by Eq. (3.62) did not converge.

<sup>f</sup>The confluence of the Tennessee and Ohio rivers is located 947.6 km (588.8 miles) downriver from the mouth of White Oak Creek. The Ohio River would provide additional dilution that the spill model does not consider.



## 5. SUMMARY

This study has derived the Oak Ridge National Laboratory (ORNL) liquid pathways aquatic spill model from first principles using conservation of mass. Mathematical statements are written which govern the interrelationship between quantity and quality. Quantity accounts for the volumes of fluid while quality deals with the concentrations of constituents dissolved in the volumes of fluid. The hypothetical accidental spill into the White Oak Creek (WOC) watershed (1) occurs at an arbitrary location, (2) has a known volume and dissolved solute concentration, and (3) could involve a radioactive substance or reactive compound that undergoes a first-order decay or depletion/removal process, respectively. The spill could occur instantaneously or over a finite duration of time.

The aquatic spill model divides the WOC watershed into three distinct subregions: (1) the tributary system above White Oak Lake (WOL), consisting of WOC, First and Fifth creeks, Northwest Tributary, Melton Branch, and West Seven, Center Seven, and East Seven creeks; (2) WOL itself; and (3) the Clinch River below White Oak Dam (WOD) and Melton Hill Dam.

The WOC tributaries are monitored by a series of gaging stations. The data recorded at these gaging stations are used to compute discharge statistics that are publicly available. Examples of these discharge statistics include (1) the annual average; (2) the lowest and highest daily means; (3) the 10%, 50%, and 90% exceedance flows; and (4) the instantaneous high and low flows. The gaging stations were treated as nodes at which flow and mass balances (i.e., both quantity and quality) were constructed using the discharge statistics as a rational basis. The accidental spill could occur at or above any of the gaging stations. The mathematical solution to the flow and mass balances consisted of the dilution at each gage sequentially downstream from the spill prior to entry into WOL. The dilution is resolvable for flows ranging from drought to extreme flood as represented by the discharge statistics.

The WOL was analyzed as a well-stirred region in space having an identifiable effective volume that is representative of ongoing mixing processes. Treatment as a continuous stirred tank reactor (CSTR) is feasible because (1) the depth of WOL is insufficient to allow formation of a thermocline that separates a surficial layer of warmer water mixed by wind shear from a deeper, more stagnant, cooler layer, and (2) an analysis that utilizes an advection-dispersion transport equation [plug flow tubular reactor (PFTR)] must relate the measured volumetric discharge through WOL to the flow velocity. The flow velocity would be obtained by dividing the volumetric discharge by an effective area that is representative of mixing that occurs in WOL. The empiricism introduced into either the CSTR or PFTR that is required to calibrate the aquatic spill model with measurements causes the two approaches to be analogous. Both the CSTR and PFTR approaches have the capability to predict the concentration versus time history at WOD as a hypothetical accidental spill passes through WOL.

The analysis of WOL was formulated from CSTR principles and based on the statement that accumulation is equal to the inflow minus (1) the outflow and (2) removal/depletion by first-order reactions or radioactive decay. The effective mixing volume of WOL is time invariant and attributable to the assumed negligible variation of the elevation of the WOL water surface. The ordinary differential equation governing the concentration versus time history in WOL is solvable using separation of variables when the instantaneous spill is represented with the Dirac delta function, and by introduction of an integrating factor when the finite-duration spill is described with Heaviside unit step functions. The mass flux leaving WOD is a time-varying point source undergoing first-order decay, whose magnitude is equal to the product of the volumetric flow through WOL (gaged flow plus spill) and the concentration obtained with CSTR principles.

The presence of the sediment control structure located at the mouth of WOC was neglected in the formulation of the aquatic spill model. The sediment control structure consists of an array of porous gabions which are rock-filled wire cages. The gabions attenuate the rapid rise and drawdown of the White

Oak Creek Embayment (WOCE) water surface that is caused by the diurnal pulsing of the flow through Melton Hill Dam during periods of hydroelectric power production. While the gabions slow the rate at which the flow from WOD enters the Clinch River, the gabions do not stop the movement of water from WOCE into the river. In turn, dilutions predicted by the aquatic spill model are underestimated. Contaminant concentrations are higher than actually would occur because of the conservative assumption that the sediment retention structure is absent.

Contaminated flow emanates from the WOL/WOD/WOCE complex that has been impacted by the accidental spill. At the confluence of WOC and the Clinch River, the discharge converts into a buoyant surface jet because relatively cold water is released from beneath Melton Hill Dam. The surface jet remains attached to the bottom of the Clinch River for some distance out into the channel and then springs clear from the riverbed because of buoyancy. The point source that describes the mass flux leaving WOD converts into a line source at the mouth of WOC. The line source extends downward from the water surface of the Clinch River to approximately the depth of the lift-off point where the plume becomes detached from the riverbed. The depth of thermal penetration is dependent on the degree of thermal stratification and attendant density differences, and was approximated as a fraction or percentage of the average Clinch River depth.

Contaminant transport in the Clinch River was approximated as a time-dependent, one-dimensional, areally uniform, radioactively decaying plume that dispersed longitudinally in the downstream direction. Vertical and lateral mixing are instantaneous as well as complete, such that the concentration is uniform and no downward or spanwise concentration gradients exist. The contaminant plume floats along the top of the Clinch River and has a thickness equal to the thermal penetration depth. The width of the plume extends completely across the Clinch River. The transport analysis is applicable to relatively large downstream distances beyond the entrance region and where the contaminant is completely mixed over the areal cross section.

The solution to the partial differential equation governing species transport was obtained with convolution. The boundary condition is provided by the time-varying, continuously discharging, equivalent point source that describes the flux of mass exiting the WOL/WOD/WOCE complex and entering the Clinch River. The river is uncontaminated initially. The concentration as a function of time and downriver location is written in terms of variants of the exponential integral. A numerical technique with an open-ended formula is required to compute the concentration, which is unbounded as the downriver location approaches the origin within the entrance region and at the mouth of WOC. Fickian transport models that utilize a boundary condition based on the mass or flux of mass entering the system rather than a specified concentration exhibit this type of behavior.

Manning's formula was used to approximate a stage-discharge-area relationship for the Clinch River after the streambed contour, Manning roughness factor, and average slope of the channel were specified. The average Clinch River velocity in the downstream direction is equal to the discharge divided by entire river cross-sectional area. Discharge statistics are available for a gage that monitors the discharge in the tailwaters of Melton Hill Dam. Given a prescribed discharge statistic, the average depth, width, and flow velocity of the Clinch River are calculated from the stage-discharge-area relationship developed with Manning's formula.

The accuracy of the Clinch River hydraulics that was based on the stage-discharge-area relationship calculated with Manning's formula improves with increased flow through Melton Hill Dam. At low flows, the river width and depth decrease substantially as required by the mathematical description based on the assumption of open-channel flow. The aquatic spill model predicts relatively high concentrations at low flows because insufficient water is available to provide for dilution. These results are conservative, being higher concentrations than actually would occur, because a minimum water level elevation would be maintained in Watts Bar Reservoir by the system of Tennessee Valley Authority dams farther upstream and downstream from the mouth of WOC. The aquatic spill model does not account for this additional water in

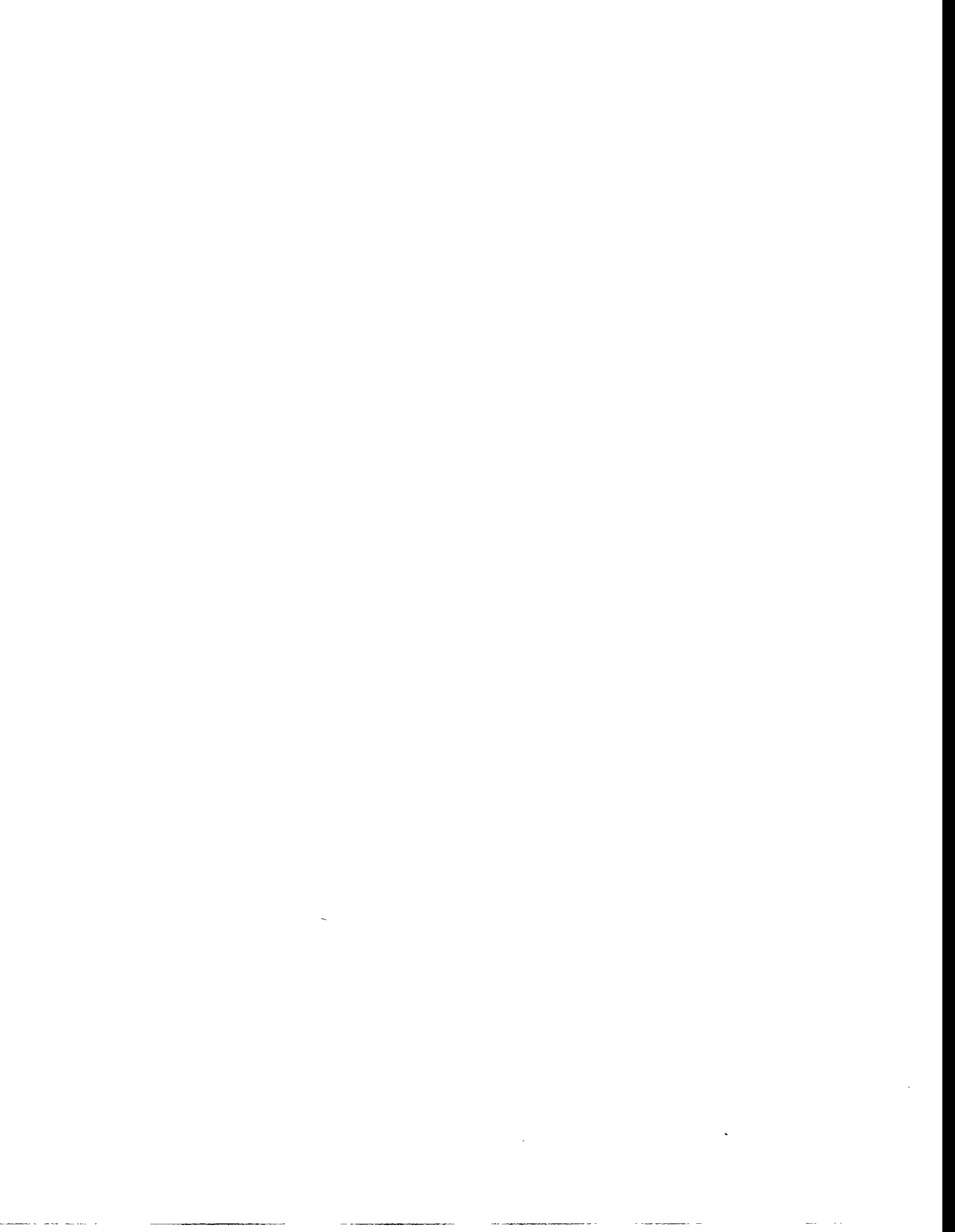
Watts Bar Reservoir that would increase the available dilution. The accuracy of the open-channel flow hypothesis improves as the discharge through Melton Hill Dam is increased, and the flow in the headwaters of Watts Bar Reservoir undergoes partial transition from a reservoir to an open-channel flow regime.

The longitudinal dispersion coefficient and downstream distance for complete mixing were obtained from published empirical correlations that have been developed from measurements. The correlation for the longitudinal dispersion coefficient predicts values that are below and in reasonable agreement with three measured longitudinal dispersivities reported for the Clinch and Powell rivers above Norris Dam and Reservoir.

Two computer programs have been written to implement the aquatic spill model on a digital computer: (1) a stand-alone, menu-driven FORTRAN program whose load module requires only an IBM-compatible personal computer supervised under the MS-DOS operating system; and (2) a Mathcad version that utilizes commercially available software to evaluate the variants of the exponential integral. The Mathcad software must be installed and available before execution of the Mathcad version of the spill model is possible. Both programs (1) employ a form of repeated subdivision of the integration interval until a sequence of calculations converges to a preset error tolerance, (2) do not converge for all possible conditions, and (3) have produced identical answers to the same test problems. The nonconvergences are nonfatal because trend analysis of the computed results allows erroneous results to be identified and deleted from further consideration. The Mathcad version produces graphical output that facilitates identification of nonconvergences. Results calculated by the FORTRAN program require more experience to interpret because only digital output is produced. At this time, the ease of operation provided by the menus available in the FORTRAN version of the aquatic spill model have not been built into the Mathcad program version.

The effective mixing volume of WOL and the thermal penetration depth were used to calibrate the aquatic spill model with experimental measurements. The effective mixing volume was set equal to one-half of the actual WOL volume, while the thermal penetration depth was approximated as one-tenth of the mean river depth obtained using the stage-discharge-area relationship computed with Manning's formula. The dilution occurring in WOL predicted by the aquatic spill model agreed with results reported from two dye experiments. Predictions from the spill model for the Clinch River were slightly lower than measurements recorded during construction of the WOCE sediment retention structure. Improved correlation would be obtained by reducing the thermal penetration depth presently used by the model.

The ORNL liquid pathways aquatic spill model offers a viable method to predict contaminant concentrations in the WOC watershed, at WOD, and in the Clinch River at relatively large downstream distances beyond the entrance length required for complete mixing. Hydrologic conditions ranging from drought to flood are simulated by the model. The spill model provides a continuous trace of the dilution from the location where the accidental spill occurred, to downriver distances as far as the confluence of the Tennessee and Ohio rivers (instantaneous spill), and the confluence of the Clinch and Tennessee rivers (finite-duration spill). The aquatic spill model does not account for additional flows that would increase dilution such as the Emory, Tennessee, and Ohio rivers. Provision of an improved numerical integration method whose source code is available would relieve the present limitations imposed on downriver distances and make interpretation of the calculated results more routine.



## 6. REFERENCES

- Arya, A. P. 1966. *Fundamentals of Nuclear Physics*, Allyn and Bacon, Boston.
- ASCE & WPCF (American Society of Civil Engineers and the Water Pollution Control Federation) 1991. *Design and Construction of Sanitary and Storm Sewers*, Sixth Printing, ASCE Manual on Engineering Practice No. 37 and WPCF Manual of Practice No. 9, New York.
- Blaylock, B. G., et al. 1991. *Interim Site Characterization and Contaminant Screening Report on the White Oak Creek Embayment*, ORNL/ER-81, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Blaylock, B. G., et al. 1992. *Screening of Contaminants in Waste Area Grouping 2 at Oak Ridge National Laboratory, Oak Ridge, Tennessee*, ORNL/ER-62/R1, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Blaylock, B. G., et al. 1993. *White Oak Creek Embayment Site Characterization and Contaminant Screening Analysis*, ORNL/ER-81, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Borders, D. M., et al. 1987. *Discharge Forecast Modeling Project FY87 Progress Report*, ORNL/RAP/LTR-88/2, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Borders, D. M., et al. 1988. *Discharge Forecast Modeling Project FY 1988*, ORNL/RAP/LTR-89/2, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Borders, D. M., et al. 1991. *Annual Hydrologic Data Summary for the Whiteoak Creek Watershed, Water Year 1990 (October 1989–September 1990)*, ORNL/ER-55, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Borders, D. M., et al. 1992. *Hydrologic Data Summary for the White Oak Creek Watershed at Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1990–December 1991)*, ORNL/ER-123, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Borders, D. M., et al. 1993. *Hydrologic Data Summary for the White Oak Creek Watershed at Oak Ridge National Laboratory, Oak Ridge, Tennessee (January–December 1992)*, ORNL/ER-166, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Boyle, J. W., et al. 1982. *Environmental Analysis of the Operation of Oak Ridge National Laboratory (X-10 Site)*, ORNL-5870, Union Carbide Corp., Oak Ridge Natl. Lab.
- Carnahan, B., H. A. Luther, and J. O. Wilkes 1969. *Applied Numerical Methods*, Wiley, New York.
- Chapra, S. C., and K. H. Reckhow 1983. *Engineering Approaches for Lake Management Volume 2: Mechanistic Modeling*, Butterworth Publishers, Boston.
- Chow, V. T. 1959. *Open-Channel Hydraulics*, McGraw, New York.

- Clapp, R. B., ed. 1992. *Annual Report of the Environmental Restoration Monitoring and Assessment Program at Oak Ridge National Laboratory for FY 1992*, ORNL/ER-124, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Clinch River Study Steering Committee 1967. *Comprehensive Report of the Clinch River Study*, ORNL-4035, Union Carbide Corp., Oak Ridge Natl. Lab.
- Clough, R. W., and J. Penzien 1975. *Dynamics of Structures*, McGraw, New York.
- COE (The Corps of Engineers, U.S. Army Engineer Division, Ohio River) 1966. *Hydrology of the Ohio River Basin, Appendix C, Ohio River Basin Comprehensive Survey*, Vol. IV, Cincinnati.
- Cook, R. B., et al. 1992. *Phase I Data Summary Report for the Clinch River Remedial Investigation: Health Risk and Ecological Risk Screening Assessment*, ORNL/ER-155, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Cox, D. K., et al. 1991. *The New Definitive Map of White Oak Lake*, ORNL/TM-11204, Environmental Sciences Division Publication No. 3319, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Crank, J. 1956. *The Mathematics of Diffusion*, Oxford University Press (Clarendon), London and New York.
- Crank, J. 1975. *The Mathematics of Diffusion*, Second Edition, Oxford University Press (Clarendon), London and New York.
- de Bruijn, N. G. 1981. *Asymptotic Methods in Analysis*, Dover Publications, New York.
- Farlow, S. J. 1982. *Partial Differential Equations for Scientists and Engineers*, Wiley, New York.
- Fischer, H. B., et al. 1979. *Mixing in Inland and Coastal Waters*, Academic Press, New York.
- Flohr, D. F., et al. 1991. *Water Resources Data Tennessee Water Year 1990*, U. S. Geological Survey Water-Data Report TN-90-1, National Technical Information Service, Springfield, Va.
- Flohr, D. F., et al. 1993. *Water Resources Data Tennessee Water Year 1992*, U. S. Geological Survey Water-Data Report TN-92-1, National Technical Information Service, Springfield, Va.
- Ford, C. J., and M. T. Wefer 1993. *Water Quality Monitoring Report for the White Oak Creek Embayment*, ORNL/ER-150, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Fox, R. W., and A. T. McDonald 1973. *Introduction to Fluid Mechanics*, Wiley, New York.
- Glover, R. E. 1964. *Dispersion of Dissolved or Suspended Materials in Flowing Streams*, U.S. Geological Survey Professional Paper 433-B, U.S. Government Printing Office, Washington, D.C.
- Godfrey, R. G., and B. J. Frederick 1970. *Stream Dispersion at Selected Sites*, U.S. Geological Survey Professional Paper 433-K, U.S. Government Printing Office, Washington, D.C.

- Green, M. A. 1992. *Methodology for Determination of the Peak Concentrations of Contaminants at the White Oak Dam Outflow During Base Flow Conditions Resulting from Release into White Oak Creek*, internal correspondence dated March 18 to D. G. Renfro, Martin Marietta Energy Systems, Inc., Oak Ridge. Natl. Lab.
- Hull, D. E. 1962. "Dispersion and Persistence of Tracer in River Flow Measurements," *Int. J. Appl. Radiat. Isot.* **13**, 63–72 (February).
- Hull, D. E., and M. Macomber 1958. *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva*, Vol. 19, United Nations, New York, p. 324.
- Kimmel, B. L., and C. J. Ford 1991. *White Oak Creek Embayment, Time-Critical CERCLA Removal Action Water Quality Monitoring Plan*, Off-Site Environmental Restoration Program, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee.
- Kolehmainen, S. E., and D. J. Nelson 1969. *The Balances of <sup>137</sup>Cs, Stable Cesium, and Feeding Rates of Bluegill (Lepomis Macrochirus Raf.) in White Oak Lake*, ORNL-4445, Union Carbide Corp., Oak Ridge Natl. Lab.
- Kornegay, F. C., et al. 1991. *Oak Ridge Reservation Environmental Report for 1990, Volume 1: Narrative, Summary, and Conclusions, and Volume 2: Data Presentation*, ES/ESH-18/V1 and V2, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Kornegay, F. C., et al. 1992. *Oak Ridge Reservation Environmental Report for 1991, Volume 1: Narrative, Summary, and Conclusions, and Volume 2: Data Presentation*, Reports ES/ESH-22/V1 and V2, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Kreyszig, E. 1968. *Advanced Engineering Mathematics*, 2nd corrected printing, Wiley, New York.
- Krumholz, L. A. 1954. *An Ecological Survey of White Oak Creek, 1950-1953*, ORO-587, Vol. 1, U.S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, Tenn.
- Krumholz, L. A. 1954a. *An Ecological Survey of the Limnology of White Oak Creek and Lake*, ORO-587, Vol. 2, U. S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, Tenn.
- Krumholz, L. A. 1954b. *An Ecological Survey of the Vertebrate Fauna of White Oak Lake and Environs*, ORO-587, Vol. 3, U. S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, Tenn.
- Lackey, J. B. 1957. *The Suspended Microbiota of the Clinch River and Adjacent Waters in Relation to Radioactivity in the Summer of 1956*, ORNL-2410, Union Carbide Corp., Oak Ridge Natl. Lab.
- Lighthill, M. J. 1962. *Introduction to Fourier Analysis and Generalized Functions*, Cambridge University Press, London.
- Lomenick, T. F., and D. A. Gardiner 1965. "The Occurrence and Retention of Radionuclides in Sediments of White Oak Lake," *Health Phys.* **11**, 567–77.

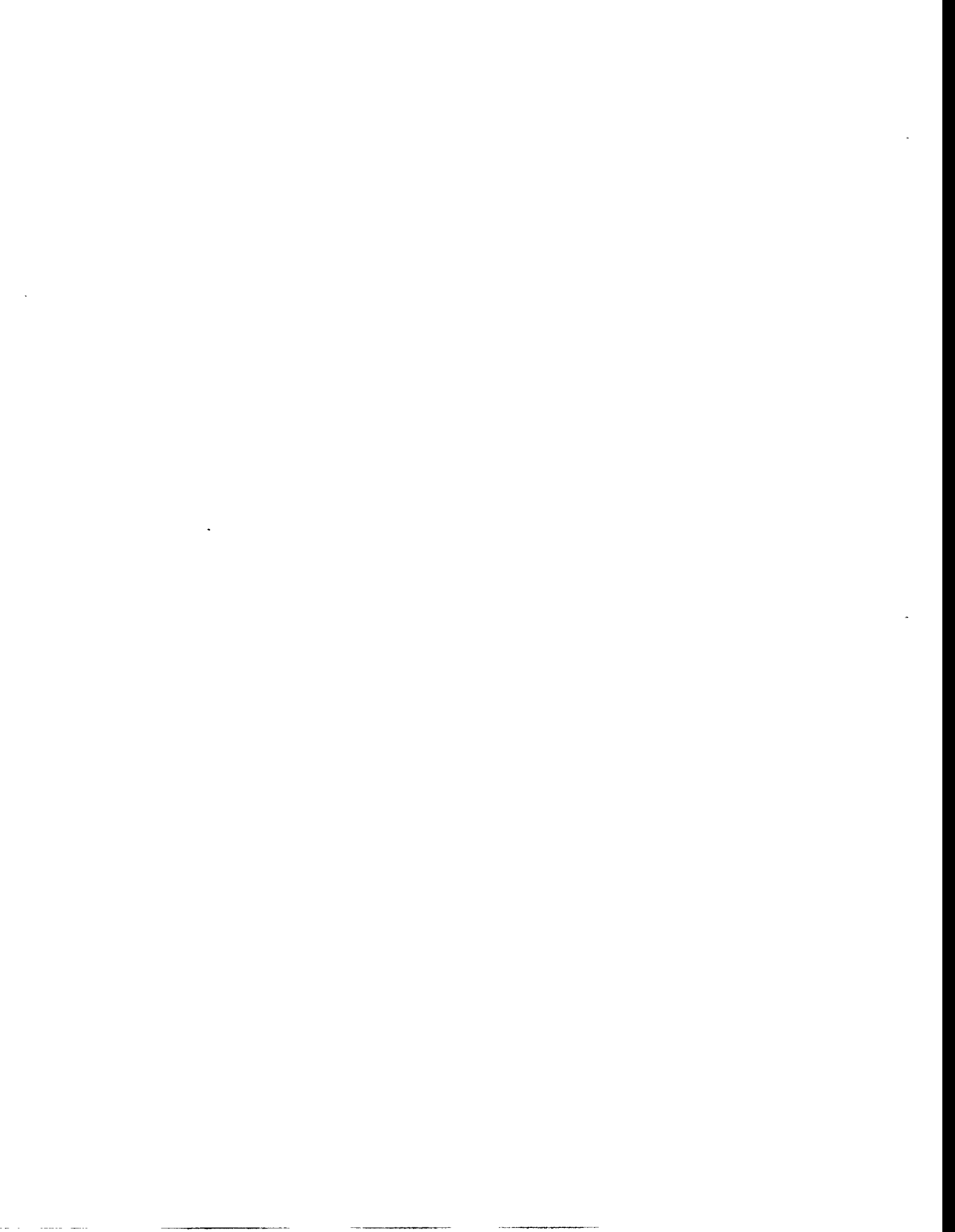
- Lowery, J. F., et al. 1989. *Water Resources Data Tennessee Water Year 1988*, U.S. Geological Survey Water-Data Report TN-88-1, National Technical Information Service, Springfield, Va.
- Lowery, J. F., et al. 1990. *Water Resources Data Tennessee Water Year 1989*, U.S. Geological Survey Water-Data Report TN-89-1, National Technical Information Service, Springfield, Va.
- Martin Marietta Energy Systems, Inc. 1985. *Environmental Monitoring Report, United States Department of Energy Oak Ridge Facilities, Calendar Year 1984*, ORNL-6209, Oak Ridge Natl. Lab.
- MathSoft, Inc. 1995. *Mathcad User's Guide, Mathcad 6.0, Mathcad PLUS 6.0*, Cambridge, Mass.
- McMaster, W. M. 1967. *Hydrologic Data for the Oak Ridge Area, Tennessee*, USGS Water Supply Paper No. 1839-N, U.S. Geological Survey, Washington, D.C.
- McMaster, W. M., and H. D. Waller 1965. *Geology and Soils of White Oak Creek Basin, Tennessee*, ORNL/TM-1108, Union Carbide Corp., Oak Ridge Natl. Lab.
- McQuivey, R. S., and T. N. Keefer 1976. "Convective Model of Longitudinal Dispersion," *J. Hydraul. Div.* 102 (HY10), 1409-24 (October).
- Meissner, L. P., and E. I. Organick 1980. *FORTRAN 77 Featuring Structured Programming*, reprint with corrections, Addison-Wesley, Reading, Mass., April 1982.
- Mercer, L. R., et al. 1992. *Water Resources Data Tennessee Water Year 1991*, U.S. Geological Survey Water-Data Report TN-91-1 (USGS/WRD/HD-92/235), National Technical Information Service, Springfield, Va.
- Microsoft Corporation 1994. *User's Guide Microsoft IMSL Mathematical and Statistical Libraries, FORTRAN Subroutines Version 2.0, for the MS-DOS and Windows Operating Systems*, DB58206-0694, Redmond, Wash.
- Neely, W. B., and R. W. Lutz 1985. "Estimating Exposure from a Chemical Spilled into a River," *J. Hazardous Mater.* 10(1), 33-41 (February).
- Numerical Algorithms Group, Inc. 1984. *NAG FORTRAN Mini Manual Mark 11, An Introductory Guide to the NAG FORTRAN Manual*, Downers Grove, Ill.
- Oak Ridge National Laboratory 1990. *Remedial Investigation Plan for Waste Area Grouping 2 at Oak Ridge National Laboratory*, ES/ER-14&D1, Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn.
- Oakes, T. W., et al. 1982. *Technical Background Information for the Environmental and Safety Report, Vol. 4: White Oak Lake and Dam*, ORNL-5681, Union Carbide Corp., Oak Ridge Natl. Lab.
- Perlmutter, D. D. 1972. *Stability of Chemical Reactors*, Prentice-Hall, Englewood Cliffs, N.J.
- Project Management Corporation 1975. *Preliminary Safety Analysis Report, Clinch River Breeder Reactor*, Oak Ridge, Tenn.

- Project Management Corporation 1975a. *Clinch River Breeder Reactor Environmental Report*, Vols. I–III, Docket No. 50-537, Oak Ridge, Tenn.
- Ragotzkie, R. A. 1978. "Heat Budgets of Lakes," pp. 1–19 in *Lakes—Chemistry, Geology, Physics*, ed. A. Lerman, Springer-Verlag, New York.
- Safaie, B. 1978. *Mixing of Horizontal Buoyant Surface Jet Over Sloping Bottom*, HEL-27-4, Hydraulic Engineering Laboratory, University of California, Berkeley.
- Setter, L. R., and O. W. Kochtitzky 1950. *Studies of the White Oak Creek Drainage System: 1. Drainage Area of the Creek and Capacity of White Oak Lake*, ORNL-562, Union Carbide Corp., Oak Ridge Natl. Lab.
- Sherwood, C. B., and J. M. Loar 1987. *Environmental Data for the White Oak Creek/White Oak Lake Watershed*, ORNL/TM-10062, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Smith, M. S. 1945. *Report on White Oak Creek Dam Structure and Flood Operation*, CL-455, Nuclear Div., Union Carbide Corp., Oak Ridge, Tenn.
- Solomon, D. K., et al. 1992. *A Hydrologic Framework for the Oak Ridge Reservation*, ORNL/TM-12026, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Streeter, V. L. 1971. *Fluid Mechanics*, 5th ed., McGraw, New York.
- Sutton, O. G. 1953. *Micrometeorology: A Study of Physical Processes in the Lowest Layers of the Earth's Atmosphere*, McGraw, New York.
- Tennessee Valley Authority 1959. *Floods on Clinch River and East Fork Poplar Creek in Vicinity of Oak Ridge, Tennessee*, Report 0-5922, Division of Water Control Planning, Knoxville, Tenn.
- Tennessee Valley Authority n.d. *Hydraulic Data Branch Files*, Knoxville, Tenn.
- Thibodeaux, L. J. 1979. *Chemodynamics—Environmental Movement of Chemicals in Air, Water, and Soil*, Wiley-Interscience (Wiley), New York.
- Tschantz, B. A. 1987. *White Oak Creek Hydrologic and Spillway Adequacy Analysis*, ORNL/SUB/87-32-CT 213V-1, University of Tennessee, Knoxville.
- Tschantz, B. A., and W. A. Rghebi 1989. *Hydrologic and Hydraulic Sensitivity Analysis for Supporting White Oak Dam Emergency Plan*, Civil Engineering Dept., University of Tennessee, Knoxville.
- U.S. Army 1988. *Chemical Stockpile Disposal Program Final Programmatic Environmental Impact Statement*, Vols. 1, 2, and 3, Program Executive Officer—Program Manager for Chemical Demilitarization, Aberdeen Proving Ground, Md.
- U.S. Department of Energy 1989. *Feed Materials Production Center Renovation and Site Evaluation*, DOE/EIS-0142 D, Green Cover Review, Draft 4, Environmental Impact Statement, DOE Feed Materials Production Center Site Office, Cincinnati.

U.S. Department of Energy 1990. *Department of Energy Oak Ridge National Laboratory NPDES Permit Application*, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab. and International Technology Corp.

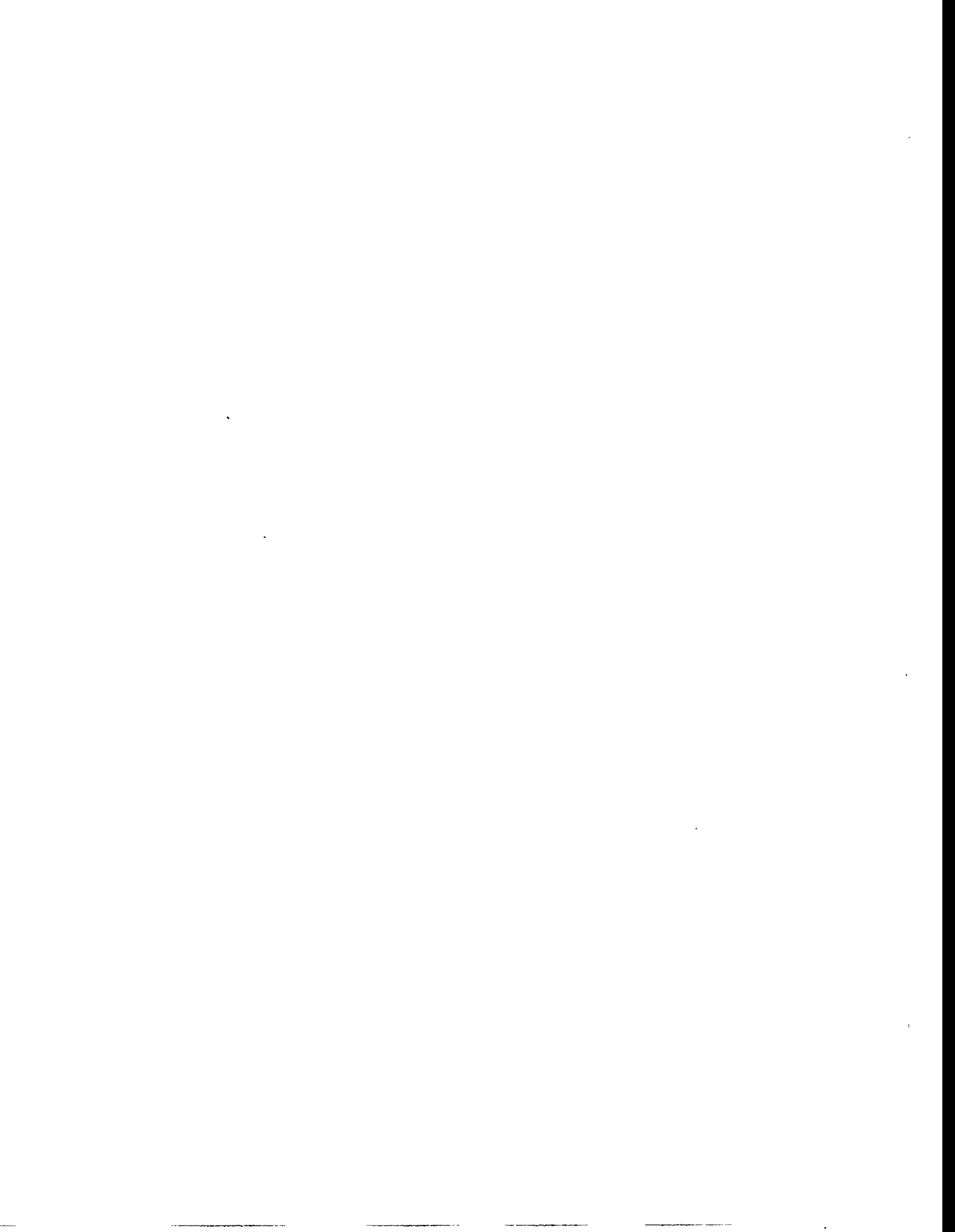
Westaway, C. R., and A. W. Loomis, eds. 1977. *Cameron Hydraulic Data*, 15th ed., Ingersoll-Rand, Woodcliff Lake, N.J.

**Appendix A. LISTING OF FORTRAN COMPUTER PROGRAM**



This appendix contains a listing of the computer program that simulates an accidental aquatic spill into the Oak Ridge National Laboratory (ORNL) White Oak Creek (WOC) watershed. The program is written in the FORTRAN 77 language (Meissner and Organick 1980) and is compatible with older FORTRAN IV conventions as well as FORTRAN language standards adopted by the American National Standards Institute (ANSI). The code is fully commented for user convenience; comment statements begin with a C in the first column. A relatively large number of FORMAT statements were required to develop the interactive, menu-driven program, which requires minimal effort on the part of the user. Alteration of these FORMAT statements should be carried out only if absolutely necessary. Each screen position on the monitor has been assigned a unique location. Alteration of one FORMAT statement could affect another.

A 5¼-in., double-sided, high-density diskette is included in the pocket on the back cover of this document. The diskette contains the FORTRAN source code in file SPILL.FOR written in the American Standard Code for Information Exchange (ASCII) character set. The file named SPILL.EXE on the diskette is an executable load module suitable for use on an IBM-compatible personal computer supporting the MS-DOS operating system. File SPILL.EXE is the output of Microsoft FORTRAN copiler, Version 3.31, supervised under MS-DOS 3.20, and prepared using an IBM Personal Computer AT. The ORNL aquatic spill model is invoked by typing X:SPILL from the keyboard, and then following the menus and interactive dialogue that appear on the monitor. The X appearing in the command X:SPILL is the drive identifier (usually A, B, C, or D) onto which the diskette has been loaded on the IBM-compatible personal computer. If file SPILL.EXE resides on the default drive, the drive identifier and colon do not have to be entered. The aquatic spill model is then prompted by simply typing SPILL.







```

C
DATA NPCLRV / 80 /

C
C   AVERAGE CLINCH RIVER SLOPE (1.5 FT/MILE = 0.0002840909...)
C   (APPEARS ON OUTPUT; NOT USED INTERNALLY BY COMPUTER PROGRAM)
C

DATA CRSLPE / 0.0002840909D0 /

C
C   NUMBER OF DATA POINTS WRITTEN TO CONSOLE IN DILUTION VERSUS TIME
C   HISTORY CALCULATED AT WHITE OAK LAKE/DAM FACILITY (THE VARIABLES
C   SECWOL, HRSWOL, DAYWOL, WKSWOL, AND DILWOL MUST BE DIMENSIONED
C   AT LEAST NWOLPT)
C

DATA NWOLPT / 13 /

C
C   NUMBER OF DATA POINTS WRITTEN TO CONSOLE IN DILUTION VERSUS TIME
C   HISTORY COMPUTED FOR THE CLINCH RIVER (THE VARIABLES SECCR, HRSCR,
C   DAYCR, WKSCR, AND DILCR MUST BE DIMENSIONED AT LEAST NCRPTS)
C   (NCRPTS MUST ALSO BE EQUAL TO OR GREATER THAN INTMED + 1)
C
C
C   DATA NCRPTS / 15 /
C
C *****
C *           D I S C H A R G E   S T A T I S T I C S           *
C *****
C *   ARRAY LOCATION           *           STATISTIC           *
C *****
C *           1           *           ANNUAL MEAN           *
C *           2           *           HIGHEST ANNUAL MEAN   *
C *           3           *           LOWEST ANNUAL MEAN    *
C *           4           *           HIGHEST DAILY MEAN    *
C *           5           *           LOWEST DAILY MEAN     *
C *           6           *           ANNUAL SEVEN-DAY MINIMUM *
C *           7           *           INSTANTANEOUS PEAK FLOW *
C *           8           *           INSTANTANEOUS LOW FLOW *
C *           9           *           10% EXCEEDANCE FLOW   *
C *           10          *           50% EXCEEDANCE FLOW   *
C *           11          *           90% EXCEEDANCE FLOW   *
C *****
C * GAGE/ARRAY NAME * USGS NUMBER *           LOCATION           *
C *****
C *   GS1 / GS1 * 03536450 *   FIRST CREEK (MILE 0.1) *
C *   GS2 / GS2 * 03537100 * MELTON BRANCH HEADWATERS (MILE 1.2) *
C *   GS3 / GS3 * 03536550 *   WHITE OAK CREEK (7500 BRIDGE) *
C *   GS4 / GS4 * 03536440 * NORTHWEST TRIBUTARY (MILE 0.2) *
C *   GS5 / GS5 * 03536380 *   WHITE OAK CREEK (MILE 2.7) *
C *   GS6 / GS6 * 03536320 *   WHITE OAK CREEK (MILE 3.4) *
C *   GS16 / GS16 * 03537050 * EAST SEVEN CREEK (MILE 0.024) *
C *   GS17 / GS17 * 03537200 * CENTER SEVEN CREEK (MILE 0.057) *
C *   GS18 / GS18 * 03537300 * WEST SEVEN CREEK (MILE 0.28) *
C *CLINCH R./HMELTN * 03535912 *MELTON HILL DM TAILWATER (MILE 23.1) *
C *****
C *   DATA SOURCES: USGS WATER-REPORTS TN-89-1, TN-91-1, AND TN-92-1 *
C *****

```

C \* UNITS: ALL DISCHARGES QUOTED IN CUBIC FEET PER SECOND \*

C \*\*\*\*\*

C DATA GS1 / 0.93D0, 1.15D0, 0.49D0, 26.0D0, 0.14D0, 0.15D0,  
 A 295.0D0, 0.09D0, 1.8D0, 0.48D0, 0.21D0 /

C DATA GS2 / 0.61D0, 0.99D0, 0.21D0, 28.0D0, 0.00D0, 0.00D0,  
 A 238.0D0, 0.00D0, 1.3D0, 0.11D0, 0.00D0 /

C DATA GS3 / 10.2D0, 12.9D0, 7.47D0, 150.0D0, 4.3D0, 4.5D0,  
 A 711.0D0, 3.8D0, 17.0D0, 7.2D0, 5.4D0 /

C DATA GS4 / 1.21D0, 1.62D0, 0.82D0, 32.0D0, 0.23D0, 0.25D0,  
 A 182.0D0, 0.18D0, 2.0D0, 0.64D0, 0.37D0 /

C DATA GS5 / 5.97D0, 7.29D0, 3.77D0, 106.0D0, 1.7D0, 2.0D0,  
 A 384.0D0, 1.6D0, 11.0D0, 3.7D0, 2.4D0 /

C DATA GS6 / 1.51D0, 2.19D0, 0.42D0, 80.0D0, 0.01D0, 0.02D0,  
 A 327.0D0, 0.00D0, 3.2D0, 0.20D0, 0.05D0 /

C DATA GS16 / 0.38D0, 0.49D0, 0.12D0, 20.0D0, 0.00D0, 0.00D0,  
 A 51.0D0, 0.00D0, 0.81D0, 0.07D0, 0.00D0 /

C DATA GS17 / 0.13D0, 0.16D0, 0.044D0, 4.6D0, 0.00D0, 0.00D0,  
 A 35.0D0, 0.00D0, 0.24D0, 0.04D0, 0.00D0 /

C DATA GS18 / 0.205D0, 0.30D0, 0.11D0, 6.5D0, 0.00D0, 0.00D0,  
 A 35.00D0, 0.00D0, 0.51D0, 0.09D0, 0.00D0 /

C DATA HMELTN / 4853.0D0, 7056.0D0, 2235.0D0, 29900.0D0,  
 A 0.00D0, 3.1D0, 42000.0D0, 0.00D0,  
 B 9080.0D0, 4100.0D0, 763.0D0 /

C DRAINAGE AREAS (IN SQUARE MILES) ABOVE SELECTED GAGES

C DATA DAGS02 / 0.520D0 /, DAGS03 / 3.280D0 /, DAGS16 / 0.240D0 /  
 C DATA DAGS17 / 0.070D0 /, DAGS18 / 0.150D0 /, DAGMS3 / 3.610D0 /  
 C DATA DAGMS4 / 1.510D0 /

C CLINCH RIVER RATING CURVE

C THE WATER LEVEL ELEVATION ABOVE MEAN SEA LEVEL AND CROSS-SECTIONAL  
 C AREA OF THE CLINCH RIVER NORMAL TO THE DOWNSTREAM FLOW DIRECTION  
 C WERE CALCULATED AS A FUNCTION OF THE PRESCRIBED DISCHARGE. THE  
 C FOLLOWING RIVER CROSS SECTION WAS USED AS A FORMAL BASIS TO CARRY  
 C OUT THE REQUIRED COMPUTATION:

C \*\*\*\*\*

* NUMBER OF INCHES	* DISTANCE (FEET)	* ELEVATION (FEET)	*
* SCALED FROM DRAWING	* (37/64 = 200 FEET)	* ABOVE MEAN SEA LEVEL*	
*****			
* 0	* 0	* 760 (SOUTH BANK)	*
* 49/64	* 264.86	* 750	*

C \*\*\*\*\*

C	*	53/64	*	286.49	*	740	*
C	*	7/8	*	302.70	*	730	*
C	*	15/16	*	324.32	*	725	*
C	*	1 - 7/16	*	497.30	*	724	*
C	*	1 - 27/32	*	637.84	*	725	*
C	*	2 - 1/16	*	713.51	*	730	*
C	*	2 - 9/64	*	740.54	*	740	*
C	*	2 - 3/16	*	756.76	*	750	*
C	*	2 - 19/32	*	897.30	*	760 (NORTH BANK)	*

\*\*\*\*\*

THE AREAL CROSS SECTION WAS OBTAINED FROM FIGURE 2.4-32 (MELTON HILL DAM - GENERAL PLAN, ELEVATION, AND SECTIONS) OF THE CLINCH RIVER BREEDER REACTOR SAFETY ANALYSIS REPORT, AMENDMENT 33, JANUARY 1977 (SECTION 2.4 - HYDROLOGIC ENGINEERING). SEE: PROJECT MANAGEMENT CORPORATION, PRELIMINARY SAFETY ANALYSIS REPORT, CLINCH RIVER BREEDER REACTOR, OAK RIDGE, TENNESSEE, 1975. THE CROSS SECTION IS LOCATED APPROXIMATELY 1200 FEET DOWNSTREAM FROM MELTON HILL DAM (SCALED 3-1/2 INCHES = 1210.81 FEET). THE AREA AT A PRESCRIBED ELEVATION WAS CALCULATED BY SUMMING INDIVIDUAL TRAPEZOIDAL CONTRIBUTIONS TO OBTAIN COMPOSITE AREAS.

THE WATER LEVEL ELEVATION CORRESPONDING TO A PRESCRIBED DISCHARGE WAS CALCULATED USING THE MANNING FORMULA FOR OPEN-CHANNEL FLOW. MANNING'S N WAS SET EQUAL TO 0.035 WHICH APPLIES TO A NATURAL CHANNEL, SOMEWHAT IRREGULAR SIDE SLOPES; FAIRLY EVEN, CLEAN AND REGULAR BOTTOM; IN LIGHT GRAY SILTY CLAY TO LIGHT TAN SILT LOAM; VERY LITTLE VARIATION IN CROSS SECTION. SEE: VEN TE CHOW, OPEN-CHANNEL HYDRAULICS, MCGRAW-HILL BOOK COMPANY, INC., NEW YORK, 1959, FIGURE 5-5 (15), P. 120. THE SLOPE OF THE CLINCH RIVER FROM NORRIS DAM TO MILE 7 AVERAGES APPROXIMATELY 1.5 FEET PER MILE, OR 0.0002840909... REFER TO TENNESSEE VALLEY AUTHORITY, DIVISION OF WATER CONTROL PLANNING, FLOODS ON CLINCH RIVER & EAST FORK POPLAR CREEK IN VICINITY OF OAK RIDGE, TENNESSEE, REPORT NO. 0-5922, KNOXVILLE, TENNESSEE, SEPTEMBER, 1959, P. 5.

	DATA CLRVOQ /	0.0D0,	0.5D0,	1.0D0,	2.0D0,
A	3.0D0,	4.0D0,	5.0D0,	6.0D0,	7.0D0,
B	8.0D0,	9.0D0,	10.0D0,	20.0D0,	30.0D0,
C	40.0D0,	50.0D0,	60.0D0,	70.0D0,	80.0D0,
D	90.0D0,	100.0D0,	200.0D0,	300.0D0,	400.0D0,
E	500.0D0,	600.0D0,	700.0D0,	800.0D0,	900.0D0,
F	1000.0D0,	2000.0D0,	3000.0D0,	4000.0D0,	5000.0D0,
G	6000.0D0,	7000.0D0,	8000.0D0,	9000.0D0,	10000.0D0,
H	11000.0D0,	12000.0D0,	13000.0D0,	14000.0D0,	15000.0D0,
I	16000.0D0,	17000.0D0,	18000.0D0,	19000.0D0,	20000.0D0,
J	21000.0D0,	22000.0D0,	23000.0D0,	24000.0D0,	25000.0D0,
K	26000.0D0,	27000.0D0,	28000.0D0,	29000.0D0,	30000.0D0,
L	31000.0D0,	32000.0D0,	33000.0D0,	34000.0D0,	35000.0D0,
M	36000.0D0,	37000.0D0,	38000.0D0,	39000.0D0,	40000.0D0,
N	41000.0D0,	42000.0D0,	43000.0D0,	44000.0D0,	45000.0D0,
O	46000.0D0,	47000.0D0,	48000.0D0,	49000.0D0,	50000.0D0,
P	51000.0D0 /				

DATA CLRVEL / 724.0000D0, 724.1560D0, 724.2023D0, 724.2624D0,  
 A 724.3055D0, 724.3403D0, 724.3700D0, 724.3962D0, 724.4198D0,  
 B 724.4413D0, 724.4612D0, 724.4799D0, 724.6223D0, 724.7245D0,  
 C 724.8070D0, 724.8774D0, 724.9395D0, 724.9954D0, 725.0382D0,  
 D 725.0781D0, 725.1161D0, 725.4360D0, 725.6940D0, 725.9182D0,  
 E 726.1202D0, 726.3060D0, 726.4793D0, 726.6425D0, 726.7974D0,  
 F 726.9452D0, 728.1757D0, 729.1540D0, 729.9947D0, 730.6958D0,  
 G 731.3415D0, 731.9446D0, 732.5136D0, 733.0541D0, 733.5707D0,  
 H 734.0665D0, 734.5441D0, 735.0056D0, 735.4527D0, 735.8868D0,  
 I 736.3092D0, 736.7208D0, 737.1224D0, 737.5150D0, 737.8990D0,  
 J 738.2751D0, 738.6439D0, 739.0057D0, 739.3610D0, 739.7102D0,  
 K 740.0532D0, 740.3890D0, 740.7197D0, 741.0455D0, 741.3666D0,  
 L 741.6833D0, 741.9958D0, 742.3043D0, 742.6089D0, 742.9097D0,  
 M 743.2070D0, 743.5009D0, 743.7914D0, 743.0787D0, 744.3630D0,  
 N 744.6443D0, 744.9228D0, 745.1984D0, 745.4714D0, 745.7418D0,  
 O 746.0096D0, 746.2750D0, 746.5380D0, 746.7988D0, 747.0573D0,  
 P 747.3135D0 /

C

DATA CLRVA / 0.0D0, 3.816546D0, 6.418640D0, 10.79484D0,  
 A 14.63134D0, 18.15467D0, 21.46201D0, 24.60687D0, 27.62273D0,  
 B 30.53240D0, 33.35223D0, 36.09467D0, 60.70375D0, 82.27805D0,  
 C 102.0911D0, 120.6897D0, 138.3746D0, 155.3340D0, 168.7603D0,  
 D 181.2980D0, 193.3120D0, 295.3199D0, 379.0125D0, 452.8305D0,  
 E 520.1691D0, 582.8134D0, 641.8438D0, 697.9750D0, 751.7100D0,  
 F 803.4184D0, 1250.506D0, 1627.004D0, 1965.414D0, 2254.467D0,  
 G 2522.563D0, 2774.635D0, 3013.850D0, 3242.433D0, 3462.027D0,  
 H 3673.882D0, 3878.978D0, 4078.101D0, 4271.894D0, 4460.887D0,  
 I 4645.531D0, 4826.204D0, 5003.235D0, 5176.908D0, 5347.471D0,  
 J 5515.141D0, 5680.113D0, 5842.558D0, 6002.632D0, 6160.473D0,  
 K 6316.052D0, 6468.793D0, 6619.624D0, 6768.637D0, 6915.923D0,  
 L 7061.563D0, 7205.630D0, 7348.196D0, 7489.322D0, 7629.070D0,  
 M 7767.495D0, 7904.648D0, 8040.579D0, 8175.332D0, 8308.949D0,  
 N 8441.472D0, 8572.938D0, 8703.381D0, 8832.836D0, 8961.335D0,  
 O 9088.906D0, 9215.580D0, 9341.382D0, 9466.339D0, 9590.474D0,  
 P 9713.811D0 /

C

MANNING'S N FOR CLINCH RIVER (APPEARS ON OUTPUT; NOT  
 USED INTERNALLY BY COMPUTER PROGRAM)

C

DATA RMNNNN / 0.035D0 /

C

SPECIFY STREAMBED CONTOUR ALONG SOUTH CLINCH RIVER BANK  
 (ARRAYS SBANKW AND SBANKE MUST BE DIMENSIONED LSBANK)

C

DATA LSBANK / 6 /

C

DATA SBANKW / 497.30D0, 324.32D0, 302.70D0, 286.49D0,  
 A 264.86D0, 0.0D0 /

C

DATA SBANKE / 724.0D0, 725.0D0, 730.0D0, 740.0D0,  
 A 750.0D0, 760.0D0 /

C

SPECIFY STREAMBED CONTOUR ALONG NORTH CLINCH RIVER BANK  
 (ARRAYS RNBANKW AND RNBANKE MUST BE DIMENSIONED NBANK)

C

C  
 DATA NBANK / 6 /

C  
 DATA RNBANKW / 497.30D0, 637.84D0, 713.51D0, 740.54D0,  
 A 756.76D0, 897.30D0 /

C  
 DATA RNBANK E / 724.0D0, 725.0D0, 730.0D0, 740.0D0,  
 A 750.0D0, 760.0D0 /

C  
 C VOLUME (FT\*\*3) OF WHITE OAK LAKE (ORNL/TM-11204)

C  
 DATA VOLUME / 1546330.0D0 /

C  
 C FRACTION OF WHITE OAK LAKE THAT PARTICIPATES IN DILUTION PROCESS

C  
 DATA FRACTN / 0.50D0 /

C  
 C FRACTION OF CLINCH RIVER MEAN DEPTH THAT PARTICIPATES IN MIXING;  
 C THIS QUANTITY IS A MEASURE OF THE DEPTH TO WHICH THE PLUME  
 C DESCENDS IN THE RIVER. BUOYANCY CAUSES THE PLUME TO FLOAT ALONG  
 C THE WATER SURFACE.

C  
 DATA FCLNCH / 0.10D0 /

C  
 C CONSTANT IN DISPERSION COEFFICIENT CORRELATION (DISPCN). REFER  
 C TO D. E. HULL, 'DISPERSION AND PERSISTENCE OF TRACER IN RIVER FLOW  
 C MEASUREMENTS,' INTERNATIONAL JOURNAL OF APPLIED RADIATION AND  
 C ISOTOPES, 1962, VOLUME 13, PP. 63-73. DISPERSION  
 C COEFFICIENT (FT\*\*2/S) = DISPCN \* SQUARE ROOT OF ( DISCHARGE  
 C (FT\*\*3/S)\*MEAN STREAM VELOCITY (FT/S) ). SEE FIG. 5 ON P. 70.

C  
 DATA DISPCN / 2.50D0 /

C  
 C CONSTANT IN CORRELATION FOR DOWNSTREAM DISTANCE REQUIRED FOR  
 C COMPLETE MIXING FROM A SIDE DISCHARGE (DSMIXC).  
 C DISTANCE (FT) = DSMIXC \* CUBE ROOT OF DISCHARGE (FT\*\*3/S)  
 C REFER TO PAPER BY D. E. HULL REFERENCED ABOVE DATA DISPCN.

C  
 DATA DSMIXC / 200.0D0 /

C  
 C COMPUTE IRRATIONAL NUMBER PI (3.14159...) AND ITS SQUARE ROOT

C  
 PI = 4.0D0 \* DATAN( 1.0D0 )

C  
 PISQRT = DSQRT( PI )

C  
 C COMPUTE EFFECTIVE VOLUME OF WHITE OAK LAKE

C  
 EFFVOL = FRACTN \* VOLUME

C  
 C APPROXIMATE CALCULATED SUMMARY DISCHARGE STATISTICS FOR FIFTH  
 C CREEK (UNGAGED) (ARRAY FIFTHC), WHITE OAK CREEK ABOVE MELTON  
 C BRANCH CONFLUENCE (ORNL GAGE MS3) (ARRAY WOCMS3), MELTON BRANCH  
 C ABOVE WHITE OAK CREEK CONFLUENCE (ORNL GAGE MS4) (ARRAY BRMMS4),

```

C      AND THE TOTAL WHITE OAK LAKE INFLOW (UNGAGED) (ARRAY WOLAKE)
C
      DO 10 J = 1, 11
      FIFTHC(J) = GS5(J) - GS6(J)
      WOCMS3(J) = GS3(J) * DAGMS3 / DAGS03
      DAFRAC = DAGMS4 / ( DAGS02 + DAGS16 + DAGS17 + DAGS18 )
      BRMMS4(J) = ( GS2(J) + GS16(J) + GS17(J) + GS18(J) ) * DAFRAC
      WOLAKE(J) = WOCMS3(J) + BRMMS4(J)
10 CONTINUE
C
      WRITE (*, 10000) IVERSN
10000 FORMAT ( 1H0, 10X, 'O A K R I D G E N A T I O N A L', 2X,
A          'L A B O R A T O R Y', /, 13X, 'A Q U A T I C', 2X,
B          'S P I L L M O D E L', 3X, '(VERSION', 1X, I2, ')', //,
C          10X, 'NOTE: THE TRUE OR FALSE RESPONSE TO PROMPTS CAN BE',
D          1X, 'ABBRE-', /, 16X, 'VIATED WITH THE SINGLE LETTER',
E          1X, 'T O R F, RESPECTIVELY.' )
C
      WRITE (*, 10001)
10001 FORMAT ( 1H0, 'OUTPUT DATA INTERNAL TO PROGRAM (ENTER', 1X,
A          'TRUE OR FALSE)?' )
      7 READ (*, *, ERR=8) QUEST1
      IF ( QUEST1 .AND. .TRUE. ) GO TO 20
      GO TO 30
      8 WRITE (*, 10036)
10036 FORMAT ( 1H0, 'TRUE (T) OR FALSE (F) MUST BE ENTERED!' )
      GO TO 7
C
C      OUTPUT DATA INTERNAL TO PROGRAM
C
      20 CONTINUE
C
      WRITE (*, 10004)
10004 FORMAT ( 1H0, 26X, 'DISCHARGE STATISTICS (CFS)' )
      WRITE (*, 10005)
10005 FORMAT ( 1H0, 'ORNL GAGE ID', 18X, 'GS1', 8X, 'GS2', 8X, 'GS3',
A          8X, 'GS4', 8X, 'GS5' )
      WRITE (*, 10006)
10006 FORMAT ( 1H , 'USGS GAGE NUMBER', 11X, '03536450', 2X,
A          '03537100', 4X, '03536550', 3X, '03536440', 3X,
B          '03536380' )
      WRITE (*, 10007) GS1(1), GS2(1), GS3(1), GS4(1), GS5(1)
10007 FORMAT ( 1H , 'ANNUAL MEAN', 13X, 5(2X, F9.3) )
      WRITE (*, 10008) GS1(2), GS2(2), GS3(2), GS4(2), GS5(2)
10008 FORMAT ( 1H , 'HIGHEST ANNUAL MEAN', 5X, 5(2X, F9.3) )
      WRITE (*, 10009) GS1(3), GS2(3), GS3(3), GS4(3), GS5(3)
10009 FORMAT ( 1H , 'LOWEST ANNUAL MEAN', 6X, 5(2X, F9.3) )
      WRITE (*, 10010) GS1(4), GS2(4), GS3(4), GS4(4), GS5(4)
10010 FORMAT ( 1H , 'HIGHEST DAILY MEAN', 6X, 5(2X, F9.3) )
      WRITE (*, 10011) GS1(5), GS2(5), GS3(5), GS4(5), GS5(5)
10011 FORMAT ( 1H , 'LOWEST DAILY MEAN', 7X, 5(2X, F9.3) )
      WRITE (*, 10012) GS1(6), GS2(6), GS3(6), GS4(6), GS5(6)
10012 FORMAT ( 1H , 'ANNUAL SEVEN-DAY MINIMUM', 5(2X, F9.3) )
      WRITE (*, 10013) GS1(7), GS2(7), GS3(7), GS4(7), GS5(7)

```

```

10013 FORMAT ( 1H , 'INSTANTANEOUS PEAK FLOW', 1X, 5(2X, F9.3) )
      WRITE (*, 10014) GS1(8), GS2(8), GS3(8), GS4(8), GS5(8)
10014 FORMAT ( 1H , 'INSTANTANEOUS LOW FLOW', 2X, 5(2X, F9.3) )
      WRITE (*, 10015) GS1(9), GS2(9), GS3(9), GS4(9), GS5(9)
10015 FORMAT ( 1H , '10% EXCEEDANCE FLOW', 5X, 5(2X, F9.3) )
      WRITE (*, 10016) GS1(10), GS2(10), GS3(10), GS4(10), GS5(10)
10016 FORMAT ( 1H , '50% EXCEEDANCE FLOW', 5X, 5(2X, F9.3) )
      WRITE (*, 10017) GS1(11), GS2(11), GS3(11), GS4(11), GS5(11)
10017 FORMAT ( 1H , '90% EXCEEDANCE FLOW', 5X, 5(2X, F9.3) )
C
      WRITE (*, 10018)
10018 FORMAT ( 1H0, 72X, 'MELTON' )
      WRITE (*, 10019)
10019 FORMAT ( 1H , 'ORNL GAGE ID', 18X, 'GS6', 8X, 'GS16', 7X, 'GS17',
A          7X, 'GS18', 4X, 'HILL DAM' )
      WRITE (*, 10020)
10020 FORMAT ( 1H , 'USGS GAGE NUMBER', 11X, '03536320', 3X,
A          '03537050', 3X, '03537200', 3X, '03537300', 3X,
B          '03535912' )
      WRITE (*, 10007) GS6(1), GS16(1), GS17(1), GS18(1), HMELTN(1)
      WRITE (*, 10008) GS6(2), GS16(2), GS17(2), GS18(2), HMELTN(2)
      WRITE (*, 10009) GS6(3), GS16(3), GS17(3), GS18(3), HMELTN(3)
      WRITE (*, 10010) GS6(4), GS16(4), GS17(4), GS18(4), HMELTN(4)
      WRITE (*, 10011) GS6(5), GS16(5), GS17(5), GS18(5), HMELTN(5)
      WRITE (*, 10012) GS6(6), GS16(6), GS17(6), GS18(6), HMELTN(6)
      WRITE (*, 10013) GS6(7), GS16(7), GS17(7), GS18(7), HMELTN(7)
      WRITE (*, 10014) GS6(8), GS16(8), GS17(8), GS18(8), HMELTN(8)
      WRITE (*, 10015) GS6(9), GS16(9), GS17(9), GS18(9), HMELTN(9)
      WRITE (*, 10016) GS6(10), GS16(10), GS17(10), GS18(10), HMELTN(10)
      WRITE (*, 10017) GS6(11), GS16(11), GS17(11), GS18(11), HMELTN(11)
C
      WRITE (*, 10021)
10021 FORMAT (1H0, 21X, 'CALCULATED DISCHARGES (CFS)', //, 30X, 'FIFTH',
A          4X, 'WHITE OAK', 4X, 'MELTON', 3X, 'WHITE OAK', /, 1H ,
B          29X, 'CREEK', 6X, 'CREEK', 6X, 'BRANCH', 5X, 'LAKE', /,
C          1H , 27X, '(UNGAGED)', 4X, '(MS3)', 7X, '(MS4)', 3X,
D          '(MS3+MS4)' )
      WRITE (*, 10007) FIFTHC(1), WOCMS3(1), BRMMS4(1), WOLAKE(1)
      WRITE (*, 10008) FIFTHC(2), WOCMS3(2), BRMMS4(2), WOLAKE(2)
      WRITE (*, 10009) FIFTHC(3), WOCMS3(3), BRMMS4(3), WOLAKE(3)
      WRITE (*, 10010) FIFTHC(4), WOCMS3(4), BRMMS4(4), WOLAKE(4)
      WRITE (*, 10011) FIFTHC(5), WOCMS3(5), BRMMS4(5), WOLAKE(5)
      WRITE (*, 10012) FIFTHC(6), WOCMS3(6), BRMMS4(6), WOLAKE(6)
      WRITE (*, 10013) FIFTHC(7), WOCMS3(7), BRMMS4(7), WOLAKE(7)
      WRITE (*, 10014) FIFTHC(8), WOCMS3(8), BRMMS4(8), WOLAKE(8)
      WRITE (*, 10015) FIFTHC(9), WOCMS3(9), BRMMS4(9), WOLAKE(9)
      WRITE (*, 10016) FIFTHC(10), WOCMS3(10), BRMMS4(10), WOLAKE(10)
      WRITE (*, 10017) FIFTHC(11), WOCMS3(11), BRMMS4(11), WOLAKE(11)
C
      WRITE (*, 10040) DAGS02, DAGS03, DAGS16, DAGS17, DAGS18,
A          DAGMS3, DAGMS4
10040 FORMAT ( 1H0, 22X, 'DRAINAGE AREA', /, 1H , 5X, 'SELECTED GAGE',
A          4X, '(SQUARE MILES)', /, 1H , 4X, 'GS2 (03537100)',
B          6X, F6.3, /, 1H , 4X, 'GS3 (03536550)', 6X, F6.3, /,

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C      1H , 4X, 'GS16 (03537050)', 6X, F6.3, /, 1H , 4X,
D      'GS17 (03537200)', 6X, F6.3, /, 1H , 4X, 'GS18 ',
E      '(03537300)', 6X, F6.3, /, 1H , 4X, 'MS3 (ORNL GAGE)',
F      5X, F6.3, /, 1H , 4X, 'MS4 (ORNL GAGE)', 5X, F6.3 )

```

C

```

      WRITE (*, 10031) VOLUME, FRACTN, EFFVOL
10031 FORMAT ( 1H0, ' VOLUME OF WHITE OAK LAKE (CUBIC FT) = ', F11.2,
A          /, 1H , 2X, ' EFFECTIVE WHITE OAK LAKE FRACTION = ', F4.2,
B          /, 1H , 3X, ' EFFECTIVE LAKE VOLUME (CUBIC FT) = ', F11.2)

```

C

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      WRITE (*, 37565) CRSLPE, RMNNNN, FCLNCH, DISPCN, DSMIXC
37565 FORMAT ( 1H , ' CLINCH RIVER SLOPE (DIMENSIONLESS) = ', F11.9,
A          /, 1H , 11X, ' CLINCH RIVER MANNING',
B          1H', 'S N = ', F8.5, 1X, '(ENGLISH UNITS)', /, 1H ,
C          ' CLINCH RIVER MEAN DEPTH FRACTION = ', F4.2, 1X,
D          '(VERTICAL PENETRATION)', /, 1H ,
E          ' DISPERSION CORRELATION CONSTANT = ', F6.4,
F          1X, '(DIMENSIONLESS)', /, 1H ,
G          ' MIXING DISTANCE CORRELATION CONSTANT = ', F6.4 )

```

C

```

      WRITE (*, 37566)
37566 FORMAT ( 1H0, 'CLINCH RIVER', 3X, 'WATER SURFACE', /, 1H ,
A          ' DISCHARGE ', 3X, ' ELEVATION ', 5X, 'FLOW AREA',
B          /, 1H , 3X, '(CFS)', 8X, '(FT - AMSL)', 5X, '(SQUARE FT)' )
      DO 543 LXT = 1, NPCLRV
      543 WRITE (*, 37567) CLRVQQ(LXT), CLRVEL(LXT), CLRVAA(LXT)
37567 FORMAT ( 1H , 1X, F10.2, 5X, F10.5, 4X, F12.7 )

```

C

```

      JLIMIT = LSBANK
      IF ( NBANK .GT. LSBANK ) JLIMIT = NBANK
      WRITE (*, 37568)
37568 FORMAT ( 1H0, 16X, 'CLINCH RIVER STREAMBED CONTOUR', /,
A          1H0, 9X, 'SOUTH BANK', 25X, 'NORTH BANK', /,
B          1H0, 1X, 'ELEVATION', 4X, 'CROSS CHANNEL', 9X,
C          'ELEVATION', 4X, 'CROSS CHANNEL', /, 1H ,
D          '(FT - AMSL)', 2X, 'COORDINATE (FT)', 7X, '(FT - AMSL)',
E          2X, 'COORDINATE (FT)' )
      DO 553 KLQ = 1, JLIMIT
      IF ( KLQ .LE. LSBANK .AND. KLQ .LE. NBANK )
      A WRITE (*, 37569) SBANKE(KLQ), SBANKW(KLQ), RNBANKE(KLQ), RNBANKW(KLQ)
37569 FORMAT( 1H , 1X, F8.3, 7X, F8.3, 12X, F8.3, 7X, F8.3 )
      IF ( KLQ .GT. LSBANK .AND. KLQ .LE. NBANK )
      A WRITE (*, 37570) RNBANKE(KLQ), RNBANKW(KLQ)
37570 FORMAT ( 1H , 36X, F8.3, 7X, F8.3 )
      IF ( KLQ .LE. LSBANK .AND. KLQ .GT. NBANK )
      A WRITE (*, 37571) SBANKE(KLQ), SBANKW(KLQ)
37571 FORMAT ( 1H , 1X, F8.3, 7X, F8.3 )
      553 CONTINUE

```

C

```

      WRITE (*, 10001)
      3 READ (*, *, ERR=2) QUEST2
      IF ( QUEST2 .AND. .TRUE. ) GO TO 20
      GO TO 30
      2 WRITE (*, 10036)

```

```

GO TO 3
C
30 CONTINUE
C
C INPUT INTEGER TO SPECIFY FLOWS IN WATERSHED
C

WRITE (*, 10032)
10032 FORMAT (1H0, 'SELECT THE TYPE OF DISCHARGE STATISTICS ACCORDING',
A 1X, 'TO THE FOLLOWING TABLE:', /, 1H0, 18X, 'ANNUAL MEAN',
B 'S (1)', /, 1H, 10X, 'HIGHEST ANNUAL MEANS (2)', /,
C 1H, 11X, 'LOWEST ANNUAL MEANS (3)', /, 1H, 11X,
D 'HIGHEST DAILY MEANS (4)', /, 1H, 12X, 'LOWEST DAILY ',
E 'MEANS (5)', /, 6X, 'ANNUAL SEVEN-DAY MINIMUMS (6)',
F /, 1H, 6X, 'INSTANTANEOUS PEAK FLOWS (7)', /, 1H, 7X,
G 'INSTANTANEOUS LOW FLOWS (8)', /, 1H, 10X, '10% ',
H 'EXCEEDANCE FLOWS (9)', /, 1H, 10X, '50% EXCEEDANCE ',
I 'FLOWS (10)', /, 1H, 10X, '90% EXCEEDANCE FLOWS (11)',
J /, 1H0, 'INPUT AN INTEGER FROM 1 TO 11 FOR THE DESIRED',
K 1X, 'DISCHARGE STATISTICS?' )
18 READ (*, *, ERR=17) NFLOW
IF ( NFLOW .GE. 1 .AND. NFLOW .LE. 11 ) GO TO 19
17 WRITE (*, 10033)
10033 FORMAT ( 1H0, 'AN INTEGER FROM 1 TO 11 MUST BE ENTERED!' )
GO TO 18
19 CONTINUE
C
C INPUT INTEGER TO SPECIFY SPILL LOCATION
C

WRITE (*, 10037)
10037 FORMAT (1H0, 'SELECT SPILL LOCATION FROM THE FOLLOWING TABLE:', /,
A 1H0, 16X, 'WHITE OAK CREEK', /, 1H0, '(1) EAST ',
B 'OF EAST ORNL GATE (WOC MI 3.4) GS6 (03536320)', /, 1H,
C '(2) DOWNSTREAM OF FIFTH CREEK CONFLUENCE (WOC MI 2.7) ',
D 'GS5 (03536380)', /, 1H, '(3) 200 FT BELOW 7500 BRIDGE',
E 1X, '(WOC MI 2.2) GS3 (03536550)', /, 1H,
F '(4) 0.1 MI ABOVE MELTON BRANCH CONFLUENCE ',
G '(ORNL GAGE MS3)', /, 1H, '(5) BELOW ',
H 'MELTON BRANCH CONFLUENCE (AND ABOVE WHITE OAK LAKE)',
I /, 1H, '(6) FIFTH CREEK', /, 1H, '(7) FIRST CREEK (MI ',
J '0.2) GS1 (03536450)', /, 1H, '(8) NORTHWEST TRIBUTARY ',
K '(MI 0.1) GS4 (03536440) ABOVE FIRST CREEK CONFLUENCE', /,
L 1H, '(9) DIRECTLY INTO WHITE OAK LAKE' )
WRITE (*, 10038)
10038 FORMAT ( 1H0, 17X, 'MELTON BRANCH', /, 1H0, '(10) MELTON BRANCH ',
A 'HEADWATERS (MI 1.2) GS2 (03537100)', /, 1H, '(11) ',
B 'EAST SEVEN CREEK (125 FT UPSTREAM FROM MOUTH) GS16 ',
C '(03537050)', /, 1H, '(12) CENTER SEVEN CREEK (300 FT ',
D 'UPSTREAM FROM MOUTH) GS17 (03537200)', /, 1H, '(13) ',
E 'WEST SEVEN CREEK (1500 FT UPSTREAM FROM MOUTH) GS18 ',
F '(03537300)', /, 1H, '(14) 0.1 MI ABOVE WHITE OAK ',
G 'CREEK CONFLUENCE (ORNL GAGE MS4) ',
H '(BELOW HFIR)', /, 1H0, 'INPUT AN ',
I 'INTEGER FROM 1 TO 14 FOR THE DESIRED SPILL SITE?' )

```

```

33 READ (*, *, ERR=31) NSPILL
   IF ( NSPILL .GE. 1 .AND. NSPILL .LE. 14 ) GO TO 32
31 WRITE (*, 10039)
10039 FORMAT ( 1H0, 'AN INTEGER FROM 1 TO 14 MUST BE ENTERED!' )
      GO TO 33
32 CONTINUE

C
C   WRITE INFORMATIVE MESSAGES TO SCREEN
C
      WRITE (*, 10050)
10050 FORMAT ( 1H0, 'THIS AQUATIC SPILL MODEL PREDICTS THE DILUTION ',
A      ' THAT WOULD OCCUR IN VARIOUS', /, 1H , ' PARTS OF THE ',
B      ' WHITE OAK CREEK WATERSHED. THE DILUTION IS DEFINED ',
C      ' AS THE ', /, 1H , ' CONCENTRATION AT THE DOWNSTREAM ',
D      ' LOCATION DIVIDED BY THE CONCENTRATION OF', /, 1H ,
E      ' CONTAMINANT ORIGINALLY IN THE SPILLED LIQUID. ',
G      ' CONCENTRATIONS AT VARIOUS', /, 1H ,
H      ' DOWNSTREAM LOCATIONS ARE OBTAINED BY MULTIPLYING ',
I      ' THE ORIGINAL CONCENTRATION', /, 1H , ' TIMES THE ',
J      ' PREDICTED DILUTION. DILUTION IS A DIMENSIONLESS ',
K      ' QUANTITY. MASS OR ', /, 1H , ' MOLAR CONCENTRATIONS, ',
L      ' MASS OR MOLAR FRACTIONS, OR RADIOACTIVITY PER UNIT',
M      /, 1H , ' VOLUME ALL ARE ACCEPTABLE ',
N      ' CONCENTRATION REPRESENTATIONS.' )
      WRITE (*, 10053)
10053 FORMAT ( 1H0, 'THE SPILL MODEL CAN ACCOMMODATE EITHER ',
A      ' INSTANTANEOUS OR FINITE', /, 1H , ' DURATION SPILLS. ',
B      ' THE TEMPORAL DURATION OF AN INSTANTANEOUS SPILL', /, 1H ,
C      ' IS ZERO. INSTANTANEOUS SPILLS ARE NOT DILUTED UNTIL',
D      ' 1X, 'AFTER', /, 1H ,
E      ' FLOW INTO WHITE OAK LAKE HAS OCCURRED ',
F      ' (MATHEMATICAL PECULIARITY).' )

C
C   SPECIFY TYPE OF SPILL INTO ORNL WOC WATERSHED. THE INTEGER
C   VARIABLE NTYPE HAS TWO PERMISSIBLE VALUES: (1) NTYPE = 1 FOR
C   AN INSTANTANEOUS SPILL, AND (2) NTYPE = 2 FOR A FINITE DURATION
C   SPILL.
C
      WRITE (*, 10052)
10052 FORMAT ( 1H0, 'SELECT THE TYPE OF SPILL: (1) INSTANTANEOUS, OR ',
A      ' (2) FINITE DURATION.', /, 1H0, 'INPUT THE INTEGER 1 ',
B      ' OR 2 FOR THE DESIRED TYPE OF SPILL?' )
80 READ (*, *, ERR=81) NTYPE
   IF ( NTYPE .GE. 1 .AND. NTYPE .LE. 2 ) GO TO 82
81 WRITE (*, 10051)
10051 FORMAT ( 1H0, 'THE INTEGER 1 OR 2 MUST BE ENTERED!' )
      GO TO 80
82 CONTINUE

C
C   SELECT UNITS FOR SIZE OF SPILL, INPUT SIZE OF SPILL, AND
C   PERFORM INTERNAL UNIT CONVERSION INTO CUBIC FEET
C
      WRITE (*, 10060)
10060 FORMAT ( 1H0, 'SELECT UNITS FOR VOLUME OF SPILL: (1) LITERS,' /,

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      A      1H , ' (2) GALLONS, OR (3) CUBIC FEET.' , / , 1H0 ,
      B      ' INPUT THE INTEGER 1, 2, OR 3 FOR THE DESIRED UNITS?' )
94 READ (*, *, ERR=95) IVUNIT
      IF ( IVUNIT .GE. 1 .AND. IVUNIT .LE. 3 ) GO TO 97
95 WRITE (*, 10061)
10061 FORMAT ( 1H0, 'THE INTEGER 1, 2, OR 3 MUST BE ENTERED!' )
      GO TO 94
97 CONTINUE
C
      WRITE (*, 10062)
10062 FORMAT ( 1H0, 'SPECIFY THE VOLUME OF THE SPILL IN THE CHOSEN ' ,
      A      ' UNITS.' )
92 READ (*, *, ERR=98) VOLDMY
      IF ( VOLDMY .GT. 0.0D0 ) GO TO 99
98 WRITE (*, 10063)
10063 FORMAT ( 1H0, 'A POSITIVE, NONZERO, NUMERICAL VALUE MUST BE ' ,
      A      ' ENTERED!' )
      GO TO 92
99 CONTINUE
C
      GO TO ( 101, 102, 103 ), IVUNIT
101 VSPILL = VOLDMY * 0.03531566D0
      GO TO 104
102 VSPILL = VOLDMY * 0.133680555D0
      GO TO 104
103 VSPILL = VOLDMY
104 CONTINUE
C
C      FOR A FINITE DURATION SPILL, SELECT UNITS IN WHICH DURATION
C      IS SPECIFIED, INPUT THE NUMERICAL VALUE IN THE SELECTED UNITS,
C      AND CONVERT TO SECONDS WHEN NECESSARY. FOR AN INSTANTANEOUS
C      SPILL, BYPASS INPUT SECTION AND SET DURATION EQUAL TO ZERO.
C
      GO TO ( 230, 240 ), NTYPE
C
230 DSPILL = 0.0D0
      GO TO 216
C
240 WRITE (*, 10100)
10100 FORMAT (1H0, 'SELECT UNITS FOR DURATION OF SPILL: (1) SECONDS,' / ,
      A      1H , ' (2) MINUTES, (3) HOURS, (4) DAYS, OR (5) WEEKS.' / ,
      B      1H0, 'INPUT AN INTEGER BETWEEN 1 AND 5 FOR THE ' ,
      C      ' DESIRED UNITS?' )
204 READ (*, *, ERR=205) IDUNIT
      IF ( IDUNIT .GE. 1 .AND. IDUNIT .LE. 5 ) GO TO 207
205 WRITE (*, 10101)
10101 FORMAT ( 1H0, 'AN INTEGER BETWEEN 1 AND 5 MUST BE ENTERED!' )
      GO TO 204
207 CONTINUE
C
      WRITE (*, 10102)
10102 FORMAT ( 1H0, 'SPECIFY THE DURATION OF THE SPILL IN THE CHOSEN ' ,
      A      ' UNITS.' )
202 READ (*, *, ERR=208) DURDMY

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      IF ( DURDMY .GT. 0.0D0 ) GO TO 209
208 WRITE (*, 10103)
10103 FORMAT ( 1H0, 'A POSITIVE, NONZERO, NUMERICAL VALUE MUST BE ',
      A      'ENTERED!' )
      GO TO 202
209 CONTINUE
C
      GO TO ( 211, 212, 213, 214, 215 ), IDUNIT
211 DSPILL = DURDMY
      GO TO 216
212 DSPILL = DURDMY * 60.0D0
      GO TO 216
213 DSPILL = DURDMY * 3600.0D0
      GO TO 216
214 DSPILL = DURDMY * 86400.0D0
      GO TO 216
215 DSPILL = DURDMY * 604800.0D0
216 CONTINUE
C
C      A N A L Y S I S   O F   W O C   H E A D W A T E R S
C
C      COMPUTE AND PRINT DILUTION IN EACH HEADWATER STREAM FOR EACH CASE
C
      CALL TITLE ( NTYPE, NSPILL, NFLOW, IVUNIT,
      A      IDUNIT, VOLDMY, DURDMY )
C
      GO TO ( 9201, 9202, 9203, 9204, 9205, 9206, 9207, 9208,
      A      9209, 9210, 9211, 9212, 9213, 9214 ), NSPILL
C
C      SPILL EAST OF EAST ORNL GATE ABOVE (WOC MI 3.4) GS6 (03536320)
C
9201 CONTINUE
      DILUT1 = 1.0D0 / ( 1.0D0 + GS6(NFLOW) * DSPILL / VSPILL )
      DILUT2 = 1.0D0 / ( 1.0D0 + GS5(NFLOW) * DSPILL / VSPILL )
      DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )
      DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
      DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
      WRITE (*, 19201) DILUT1, GS6(NFLOW), DILUT2, GS5(NFLOW),
      A      DILUT3, GS3(NFLOW), DILUT4, WOCMS3(NFLOW),
      B      DILUT5, WOLAKE(NFLOW)
19201 FORMAT ( 1H , 6X, 'WOC MI 3.4 GS6 (03536320)', 8X, 1PD13.5, 2X,
      A 0PF9.3, /, 1H , 6X, 'WOC MI 2.7 GS5 (03536380)', 8X, 1PD13.5, 2X,
      B 0PF9.3, /, 1H , 6X, 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
      C 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
      D 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
      E 7X, 1PD13.5, 2X, 0PF9.3, / )
      GO TO 9215
C
C      SPILL DOWNSTREAM OF FIFTH CREEK CONFLUENCE (WOC MI 2.7) BUT
C      ABOVE USGS GAGE GS5 (03536380)
C
9202 CONTINUE
      DILUT2 = 1.0D0 / ( 1.0D0 + GS5(NFLOW) * DSPILL / VSPILL )
      DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )

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DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19202) DILUT2, GS5(NFLOW), DILUT3, GS3(NFLOW),
A          DILUT4, WOCMS3(NFLOW), DILUT5, WOLAKE(NFLOW)
19202 FORMAT ( 1H , 6X, 'WOC MI 2.7 GS5 (03536380)', 8X, 1PD13.5, 2X,
A 0PF9.3, /, 1H , 6X, 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
B 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
C 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
D 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

C
C SPILL ABOVE USGS GAGE GS3 (03536550) (WOC MI 2.2) LOCATED
C 200 FT BELOW 7500 BRIDGE
C
9203 CONTINUE
DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )
DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19203) DILUT3, GS3(NFLOW), DILUT4, WOCMS3(NFLOW),
A          DILUT5, WOLAKE(NFLOW)
19203 FORMAT ( 1H , 6X, 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
A 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
B 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
C 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

C
C SPILL 0.1 MI ABOVE MELTON BRANCH CONFLUENCE ABOVE ORNL GAGE MS3
C
9204 CONTINUE
DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19204) DILUT4, WOCMS3(NFLOW), DILUT5, WOLAKE(NFLOW)
19204 FORMAT ( 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
A 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
B 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

C
C SPILL BELOW WHITE OAK CREEK / MELTON BRANCH CONFLUENCE
C BUT ABOVE WHITE OAK LAKE
C
9205 CONTINUE
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19205) DILUT5, WOLAKE(NFLOW)
19205 FORMAT ( 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
A          7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

C
C SPILL INTO FIFTH CREEK WHICH IS AN UNGAGED WOC TRIBUTARY
C
9206 CONTINUE
DILUT1 = 1.0D0 / ( 1.0D0 + FIFTHC(NFLOW) * DSPILL / VSPILL )
DILUT2 = 1.0D0 / ( 1.0D0 + GS5(NFLOW) * DSPILL / VSPILL )
DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )
DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )

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DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19206) DILUT1, FIFTHC(NFLOW), DILUT2, GS5(NFLOW),
A          DILUT3, GS3(NFLOW), DILUT4, WOCMS3(NFLOW),
B          DILUT5, WOLAKE(NFLOW)
19206 FORMAT ( 1H , 12X, 'FIFTH CREEK', 16X, 1PD13.5, 2X,
A 0PF9.3, /, 1H , 6X, 'WOC MI 2.7 GS5 (03536380)', 8X, 1PD13.5, 2X,
B 0PF9.3, /, 1H , 6X, 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
C 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
D 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
E 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

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C
C FIRST CREEK ABOVE MILE 0.2 AND USGS GAGE GS1 (03536450)
C

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9207 CONTINUE

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DILUT1 = 1.0D0 / ( 1.0D0 + GS1(NFLOW) * DSPILL / VSPILL )
WNFLOW = GS1(NFLOW) + GS4(NFLOW)
DILUT2 = 1.0D0 / ( 1.0D0 + WNFLOW * DSPILL / VSPILL )
DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )
DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19207) DILUT1, FIFTHC(NFLOW), DILUT2, WNFLOW,
A          DILUT3, GS3(NFLOW), DILUT4, WOCMS3(NFLOW),
B          DILUT5, WOLAKE(NFLOW)
19207 FORMAT ( 1H , ' FIRST CREEK MI 0.2 GS1 (03536450)', 5X, 1PD13.5,
A 2X, 0PF9.3, /, 1H , ' NORTHWEST TRIB BELOW GS4 (03536440)',
B 3X, 1PD13.5, 2X, 0PF9.3, /, 1H , 6X,
C 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
D 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
E 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
F 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

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C
C SPILL INTO NORTHWEST TRIBUTARY ABOVE MI 0.1 GS4 (03536440) AND
C ABOVE FIRST CREEK CONFLUENCE
C

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9208 CONTINUE

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DILUT1 = 1.0D0 / ( 1.0D0 + GS4(NFLOW) * DSPILL / VSPILL )
WNFLOW = GS1(NFLOW) + GS4(NFLOW)
DILUT2 = 1.0D0 / ( 1.0D0 + WNFLOW * DSPILL / VSPILL )
DILUT3 = 1.0D0 / ( 1.0D0 + GS3(NFLOW) * DSPILL / VSPILL )
DILUT4 = 1.0D0 / ( 1.0D0 + WOCMS3(NFLOW) * DSPILL / VSPILL )
DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
WRITE (*, 19208) DILUT1, GS4(NFLOW), DILUT2, WNFLOW,
A          DILUT3, GS3(NFLOW), DILUT4, WOCMS3(NFLOW),
B          DILUT5, WOLAKE(NFLOW)
19208 FORMAT ( 1H , ' NORTHWEST TRIBUTARY GS4 (03536440)', 4X, 1PD13.5,
A 2X, 0PF9.3, /, 1H , 'BELOW FIRST CRK CONFLUENCE ABOVE WOC',
B 3X, 1PD13.5, 2X, 0PF9.3, /, 1H , 6X,
C 'WOC MI 2.2 GS3 (03536550)', 8X, 1PD13.5, 2X,
D 0PF9.3, /, 1H , 2X, '0.1 MI ABOVE MELTON BRANCH AT MS3', 4X,
E 1PD13.5, 2X, 0PF9.3, /, 1H , 3X, 'BELOW MELTON BRANCH ABOVE WOL',
F 7X, 1PD13.5, 2X, 0PF9.3, / )
GO TO 9215

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C
C     SPILL DIRECTLY INTO WHITE OAK LAKE
C     (NO HEADWATER CALCULATIONS PERFORMED)
C
9209 CONTINUE
     GO TO 9215
C
C     SPILL INTO MELTON BRANCH HEADWATERS (MI 1.2) GS2 (03537100)
C
9210 CONTINUE
     DILUT3 = 1.0D0 / ( 1.0D0 + GS2(NFLOW) * DSPILL / VSPILL )
     DILUT4 = 1.0D0 / ( 1.0D0 + BRMMS4(NFLOW) * DSPILL / VSPILL )
     DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
     WRITE (*, 19210) DILUT3, GS2(NFLOW), DILUT4, BRMMS4(NFLOW),
A           DILUT5, WOLAKE(NFLOW)
9210 FORMAT ( 1H , 1X, 'MELTON BRANCH MI 1.2 GS2 (03537100)',
A 4X, 1PD13.5, 2X, 0PF9.3, /, 1H ,
B 1X, '0.1 MI ABOVE WHITE OAK CREEK AT MS4', 4X, 1PD13.5, 2X,
C 0PF9.3, /, 1H , 3X, 'BELOW WOC CONFLUENCE ABOVE WOL',
D 7X, 1PD13.5, 2X, 0PF9.3, / )
     GO TO 9215
C
C     SPILL INTO EAST SEVEN CREEK (125 FT UPSTREAM FROM MELTON BRANCH
C     CONFLUENCE) ABOVE USGS GAGE GS16 (03537050)
C
9211 CONTINUE
     DILUT3 = 1.0D0 / ( 1.0D0 + GS16(NFLOW) * DSPILL / VSPILL )
     DILUT4 = 1.0D0 / ( 1.0D0 + BRMMS4(NFLOW) * DSPILL / VSPILL )
     DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
     WRITE (*, 19211) DILUT3, GS16(NFLOW), DILUT4, BRMMS4(NFLOW),
A           DILUT5, WOLAKE(NFLOW)
9211 FORMAT ( 1H , 2X, 'EAST SEVEN CREEK GS16 (03537050)',
A 6X, 1PD13.5, 2X, 0PF9.3, /, 1H ,
B 1X, '0.1 MI ABOVE WHITE OAK CREEK AT MS4', 4X, 1PD13.5, 2X,
C 0PF9.3, /, 1H , 3X, 'BELOW WOC CONFLUENCE ABOVE WOL',
D 7X, 1PD13.5, 2X, 0PF9.3, / )
     GO TO 9215
C
C     SPILL INTO CENTER SEVEN CREEK (300 FT UPSTREAM FROM MELTON BRANCH
C     CONFLUENCE) ABOVE USGS GAGE GS17 (03537200)
C
9212 CONTINUE
     DILUT3 = 1.0D0 / ( 1.0D0 + GS17(NFLOW) * DSPILL / VSPILL )
     DILUT4 = 1.0D0 / ( 1.0D0 + BRMMS4(NFLOW) * DSPILL / VSPILL )
     DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
     WRITE (*, 19212) DILUT3, GS17(NFLOW), DILUT4, BRMMS4(NFLOW),
A           DILUT5, WOLAKE(NFLOW)
9212 FORMAT ( 1H , 1X, 'CENTER SEVEN CREEK GS17 (03537200)',
A 5X, 1PD13.5, 2X, 0PF9.3, /, 1H ,
B 1X, '0.1 MI ABOVE WHITE OAK CREEK AT MS4', 4X, 1PD13.5, 2X,
C 0PF9.3, /, 1H , 3X, 'BELOW WOC CONFLUENCE ABOVE WOL',
D 7X, 1PD13.5, 2X, 0PF9.3, / )
     GO TO 9215
C

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C      SPILL INTO WEST SEVEN CREEK (1500 FT UPSTREAM FROM MELTON BRANCH
C      CONFLUENCE) ABOVE USGS GAGE GS18 (03537300)
C
9213 CONTINUE
      DILUT3 = 1.0D0 / ( 1.0D0 + GS18(NFLOW) * DSPILL / VSPILL )
      DILUT4 = 1.0D0 / ( 1.0D0 + BRMMS4(NFLOW) * DSPILL / VSPILL )
      DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
      WRITE (*, 19213) DILUT3, GS18(NFLOW), DILUT4, BRMMS4(NFLOW),
A      DILUT5, WOLAKE(NFLOW)
19213 FORMAT ( 1H , 2X, 'WEST SEVEN CREEK GS17 (03537300)',
A 6X, 1PD13.5, 2X, 0PF9.3, /, 1H ,
B 1X, '0.1 MI ABOVE WHITE OAK CREEK AT MS4', 4X, 1PD13.5, 2X,
C 0PF9.3, /, 1H , 3X, 'BELOW WOC CONFLUENCE ABOVE WOL',
D 7X, 1PD13.5, 2X, 0PF9.3, / )
      GO TO 9215

C
C      SPILL INTO MELTON BRANCH 0.1 MI ABOVE CONFLUENCE WITH WHITE
C      OAK CREEK (BELOW HIGH FLUX ISOTOPE REACTOR -- HFIR) AND
C      ABOVE ORNL GAGE MS4
C
9214 CONTINUE
      DILUT4 = 1.0D0 / ( 1.0D0 + BRMMS4(NFLOW) * DSPILL / VSPILL )
      DILUT5 = 1.0D0 / ( 1.0D0 + WOLAKE(NFLOW) * DSPILL / VSPILL )
      WRITE (*, 19214) DILUT4, BRMMS4(NFLOW), DILUT5, WOLAKE(NFLOW)
19214 FORMAT ( 1H , 1X, '0.1 MI ABOVE WHITE ',
A 'OAK CREEK AT MS4', 4X, 1PD13.5, 2X,
B 0PF9.3, /, 1H , 3X, 'BELOW WOC CONFLUENCE ABOVE WOL',
C 7X, 1PD13.5, 2X, 0PF9.3, / )

C
9215 CONTINUE
C
      PAUSE

C
C      INPUT THE RADIOACTIVE DECAY CONSTANT OR HALF LIFE; SELECT UNITS.
C      THE RADIOACTIVE DECAY CONSTANT IS EQUAL TO THE NATURAL LOGARITHM
C      OF THE INTEGER TWO DIVIDED BY THE HALF LIFE OF THE RADIONUCLIDE.
C      RADIOACTIVE DECAY IS NOT CONSIDERED IN THE HEADWATERS ANALYSIS.
C      SHORT-LIVED RADIONUCLIDES WHOSE HALF LIVES ARE MEASURED IN SECONDS
C      OR MINUTES ARE EXCLUDED FROM CONSIDERATION. HALF LIVES ARE
C      MEASURED IN HOURS, DAYS, OR YEARS; DECAY CONSTANTS IN (1/SECONDS).
C
      WRITE (*, 13981)
13981 FORMAT ( 1H0, 'DO YOU WISH TO CONSIDER RADIOACTIVE DECAY', 1X,
A      '(ENTER TRUE OR FALSE)?' )
8347 READ (*, *, ERR=8348) QUEST3
      IF ( QUEST3 .AND. .TRUE. ) GO TO 2348
      RLAMDA = 0.0D0
      GO TO 3519
8348 WRITE (*, 10036)
      GO TO 8347

C
2348 WRITE (*, 13982)
13982 FORMAT ( 1H0, 'SELECT (1) RADIOACTIVE DECAY CONSTANT, OR (2)', 1X,
A      'HALF LIFE (ENTER 1 OR 2)?' )

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8377 READ (*, *, ERR=8349) JRAD
      IF ( JRAD .GE. 1 .AND. JRAD .LE. 2 ) GO TO ( 8363, 8364 ), JRAD
8349 WRITE (*, 18349)
18349 FORMAT ( 1H0, 'THE INTEGER 1 OR 2 MUST BE ENTERED!' )
      GO TO 8377
C
8363 WRITE (*, 18363)
18363 FORMAT ( 1H0, 'INPUT RADIOACTIVE DECAY CONSTANT (1/SECONDS)?' )
8396 READ (*, *, ERR=8395) RLAMDA
      IF ( RLAMDA ) 8395, 3519, 7378
7378 HALFLF = DLOG( 2.0D0 ) / RLAMDA
      WRITE (*, 13519) RLAMDA
      WRITE (*, 14456) HALFLF
14456 FORMAT ( 1H , 'HALF LIFE (SECONDS) = ', 1PD13.5 )
      GO TO 3390
8395 WRITE (*, 18395)
18395 FORMAT ( 1H0, 'A NUMERICAL VALUE EQUAL TO GREATER OR THAN ZERO ',
      A      'MUST BE ENTERED!' )
      GO TO 8396
C
8364 WRITE (*, 18364)
18364 FORMAT ( 1H0, 'SELECT HALF-LIFE UNITS (1) HOURS, (2) DAYS, OR ',
      A      '(3) YEARS (ENTER 1, 2, OR 3)?' )
8312 READ (*, *, ERR=8311) LLUNIT
      IF ( LLUNIT .GE. 1 .AND. LLUNIT .LE. 3 ) GO TO 8313
8311 WRITE (*, 18312)
18312 FORMAT ( 1H0, 'THE INTEGER 1, 2, OR 3 MUST BE ENTERED!' )
      GO TO 8312
8313 WRITE (*, 18313)
18313 FORMAT ( 1H0, 'INPUT HALF LIFE IN CHOSEN UNITS?' )
8315 READ (*, *, ERR=8314) HALDMY
      IF ( HALDMY .GT. 0.0D0 ) GO TO ( 8317, 8318, 8319 ), LLUNIT
8314 WRITE (*, 18314)
18314 FORMAT ( 1H0, 'A NUMERICAL VALUE GREATER THAN ZERO MUST BE ',
      A      'ENTERED?' )
      GO TO 8315
8317 HALFLF = HALDMY * 3600.0D0
      GO TO 8320
8318 HALFLF = HALDMY * 3600.0 * 24.0D0
      GO TO 8320
8319 HALFLF = HALDMY * 3600.0D0 * 24.0D0 * 365.0D0
8320 RLAMDA = DLOG( 2.0D0 ) / HALFLF
C
3519 WRITE (*, 13519) RLAMDA
13519 FORMAT ( 1H0, 'DECAY CONSTANT (1/SECONDS) = ', 1PD13.5 )
      IF ( RLAMDA .NE. 0.0D0 ) GO TO ( 3387, 3388, 3389 ), LLUNIT
      IF ( RLAMDA .EQ. 0.0D0 ) WRITE (*, 13520)
13520 FORMAT ( 1H , 'INFINITE HALF LIFE (NO RADIOACTIVE DECAY)' )
      GO TO 3390
3387 WRITE (*, 13387) HALDMY
13387 FORMAT ( 1H , 'HALF LIFE (HOURS) = ', 1PD13.5 )
      GO TO 3390
3388 WRITE (*, 13388) HALDMY
13388 FORMAT ( 1H , 'HALF LIFE (DAYS) = ', 1PD13.5 )

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GO TO 3390
3389 WRITE (*, 13389) HALDMY
13389 FORMAT ( 1H , 'HALF LIFE (YEARS) = ', 1PD13.5 )
3390 CONTINUE
C
C      A N A L Y S I S   O F   W H I T E   O A K   L A K E   /   D A M
C
C      S P E C I F Y   F L O W   O V E R   W H I T E   O A K   D A M   ( I . E . ,   W H I T E   O A K   L A K E   T H R O U G H P U T )
C
      WRITE (*, 15670) WOLAKE(NFLOW)
15670 FORMAT ( 1H0, 'THE FLOW OVER WHITE OAK DAM IS ', F9.3, 1X,
A          'CFS.', /, 1H , 'DO YOU WISH TO CHANGE THIS VALUE ',
B          '(ENTER TRUE OF FALSE)?' )
5671 READ (*, *, ERR=5672) QUEST4
      IF ( QUEST4 .AND. .TRUE. ) GO TO 5674
      WODFLW = WOLAKE(NFLOW)
      GO TO 5673
5672 WRITE (*, 10036)
      GO TO 5671
C
5674 WRITE (*, 15674)
15674 FORMAT ( 1H0, 'INPUT THE REVISED FLOW OVER WHITE OAK DAM IN ',
A          'CUBIC FEET PER SECOND.' )
5677 READ (*, *, ERR=5675) WODFLW
      IF ( WODFLW .GE. 0.0D0 ) GO TO 5678
5675 WRITE (*, 15675)
15675 FORMAT ( 1H0, 'A NUMERICAL VALUE EQUAL TO OR GREATER THAN ',
A          'ZERO MUST BE ENTERED?' )
      GO TO 5677
5678 WRITE (*, 15678) WODFLW
15678 FORMAT ( 1H0, 'THE FLOW OVER WHITE OAK DAM HAS BEEN CHANGED TO ',
A          F9.3, 1X, 'CFS.' )
5673 CONTINUE
C
C      C O M P U T E   D I L U T I O N   A T   W H I T E   O A K   L A K E   /   W H I T E   O A K   D A M   V E R S U S   T I M E
C
C          ( T H E R E   A R E   S I X   D I S T I N C T   C O M P U T A T I O N A L
C          F O R M S   D E P E N D I N G   O N   E X T E R N A L   C O N D I T I O N S )
C
C      T H E S E   E Q U A T I O N S   H A V E   B E E N   P R O G R A M M E D   S U C H   T H A T   A L L   E X P O N E N T I A L
C      T E R M S   H A V E   N E G A T I V E   E X P O N E N T S ,   A N D   S U C H   T H A T   A L L   Q U A N T I T I E S
C      W H O S E   N A T U R A L   L O G A R I T H M   I S   R E Q U I R E D   A R E   W E L L   D E F I N E D   ( I . E . ,
C      C A N N O T   B E C O M E   N E G A T I V E .   T H E   M A X I M U M   D I L U T I O N   I S   F I R S T   C A L C U L A T E D .
C      T H E   M A X I M U M   D I L U T I O N   I S   T H E N   R E D U C E D   B Y   S U C C E S S I V E   P O W E R S   O F   T E N .
C      T H E   T I M E   I S   T H E N   C A L C U L A T E D   C O R R E S P O N D I N G   T O   E A C H   V A L U E   O F   R E D U C E D
C      D I L U T I O N   T O   P R O D U C E   T H E   D E S I R E D   D I L U T I O N - V E R S U S - T I M E   H I S T O R Y .
C
      IF ( WODFLW .EQ. 0.0D0 .AND. RLAMDA .EQ. 0.0D0 ) GO TO 4894
C
      IF ( WODFLW .EQ. 0.0D0 .AND. RLAMDA .NE. 0.0D0 ) GO TO 4444
C
      GO TO ( 7231, 7232 ), NTYPE
C
C      I N S T A N T A N E O U S   S P I L L   ( N O N Z E R O   T H R O U G H P U T   W I T H   O R   W I T H O U T

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C   RADIOACTIVE DECAY)
C
7231 SECWOL(1) = 0.0D0
    HRSWOL(1) = 0.0D0
    DAYWOL(1) = 0.0D0
    WKSWOL(1) = 0.0D0
    TCONST = - RLAMDA - WODFLW / EFFVOL
    DILWOL(1) = VSPILL / EFFVOL / ( 1.0D0 + VSPILL / EFFVOL )
    DO 7233 JV = 2, NWOLPT
    SECWOL(JV) = - DBLE( JV-1 ) * DLOG( 10.0D0 ) / TCONST
    HRSWOL(JV) = SECWOL(JV) / 3600.0D0
    DAYWOL(JV) = HRSWOL(JV) / 24.0D0
    WKSWOL(JV) = DAYWOL(JV) / 7.0D0
7233 DILWOL(JV) = DILWOL(1) * DEXP( - DBLE( JV-1 ) * DLOG( 10.0D0 ) )
    GO TO 5624

C
C   FINITE DURATION SPILL (NONZERO THROUGHPUT WITH OR WITHOUT
C   RADIOACTIVE DECAY)
C
7232 RABC = VSPILL / EFFVOL / DSPILL
    TC = RABC + WODFLW / EFFVOL + RLAMDA
    DILWOL(1) = 0.0D0
    SECWOL(1) = 0.0D0
    HRSWOL(1) = 0.0D0
    DAYWOL(1) = 0.0D0
    WKSWOL(1) = 0.0D0
    DILWOL(2) = RABC * ( 1.0D0 - DEXP( - TC * DSPILL / 2.0D0 ) ) / TC
    SECWOL(2) = DSPILL / 2.0D0
    HRSWOL(2) = SECWOL(2) / 3600.0D0
    DAYWOL(2) = HRSWOL(2) / 24.0D0
    WKSWOL(2) = DAYWOL(2) / 7.0D0
    DILWOL(3) = RABC * ( 1.0D0 - DEXP( - TC * DSPILL ) ) / TC
    SECWOL(3) = DSPILL
    HRSWOL(3) = SECWOL(3) / 3600.0D0
    DAYWOL(3) = HRSWOL(3) / 24.0D0
    WKSWOL(3) = DAYWOL(3) / 7.0D0
    TC2 = RLAMDA + WODFLW / EFFVOL
    APART = RABC * ( 1.0D0 - DEXP( - TC * DSPILL ) ) / TC
    DO 7234 JV = 4, NWOLPT
    SECWOL(JV) = DBLE( JV-3 ) * DLOG( 10.0D0 ) / TC2 + DSPILL
    HRSWOL(JV) = SECWOL(JV) / 3600.0D0
    DAYWOL(JV) = HRSWOL(JV) / 24.0D0
    WKSWOL(JV) = DAYWOL(JV) / 7.0D0

C
C   NOTE: THE DIFFERENCE (DSPILL - SECWOL(JV)) IS ALWAYS NEGATIVE
C
7234 DILWOL(JV) = APART * DEXP( TC2 * ( DSPILL - SECWOL(JV) ) )

C
C   WRITE RESULTS TO CONSOLE SCREEN (NONZERO THROUGHPUT WITH
C   OR WITHOUT RADIOACTIVE DECAY)
C
5624 WRITE (*, 15624)
15624 FORMAT ( 1H0, 23(1H*), 'ELAPSED TIME', 23(1H*) , 3X, 'DILUTION',
A          1X, 'AT', /, 1H , 3X, 'SECONDS', 9X, 'HOURS', 11X,

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      B          'DAYS', 10X, 'WEEKS', 6X, 'WHITE OAK DAM' )
      IF ( NTYPE .EQ. 1 ) WRITE (*, 29682) SECWOL(1), HRSWOL(1),
      A          DAYWOL(1), WKSWOL(1), DILWOL(1)
29682 FORMAT ( 1H , 1PD13.5, 4(2X, 1PD13.5), 1H& )
      IF ( NTYPE .EQ. 2 ) WRITE (*, 17235) SECWOL(1), HRSWOL(1),
      A          DAYWOL(1), WKSWOL(1), DILWOL(1)
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29678) SECWOL(2), HRSWOL(2),
      A          DAYWOL(2), WKSWOL(2), DILWOL(2)
29678 FORMAT ( 1H , 1PD13.5, 1H#, 1X, 1PD13.5, 3(2X, 1PD13.5) )
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29679) SECWOL(3), HRSWOL(3),
      A          DAYWOL(3), WKSWOL(3), DILWOL(3)
29679 FORMAT ( 1H , 1PD13.5, 1H$, 1X, 1PD13.5, 3(2X, 1PD13.5), 1H& )
      IF ( NTYPE .EQ. 1 ) NWILPT = 2
      IF ( NTYPE .EQ. 2 ) NWILPT = 4
      DO 7235 JV = NWILPT, NWOLPT
      7235 WRITE (*, 17235) SECWOL(JV), HRSWOL(JV), DAYWOL(JV),
      A          WKSWOL(JV), DILWOL(JV)
17235 FORMAT ( 1H , 1PD13.5, 4(2X, 1PD13.5) )
      IF ( NTYPE .EQ. 1 ) WRITE (*, 29681)
29681 FORMAT ( 1H0, 59X, '& MAXIMUM' )
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29680)
29680 FORMAT ( 1H0, 5X, '# SPILL DURATION/2', 10X, '$ SPILL DURATION',
      A          10X, '& MAXIMUM' )
      GO TO 99998

C
C      ZERO FLOW AT WHITE OAK DAM AND NO RADIOACTIVE DECAY
C      (FINAL DILUTION IDENTICAL FOR INSTANTANEOUS AND
C      FINITE DURATION SPILLS ALTHOUGH TIME HISTORIES
C      ARE DIFFERENT)
C
4894 DWHITE = VSPILL / EFFVOL
      IF ( NTYPE .EQ. 1 ) WRITE (*, 14894) DWHITE
14894 FORMAT ( 1H0, 'THE SPILL WILL BE DILUTED INSTANTANEOUSLY BY A ',
      A          /, 1H , 'FACTOR OF ', 1PD13.5, 1X, 'IN WHITE OAK LAKE.',
      B          /, 1H , 'THE CONCENTRATION IN WHITE OAK LAKE ',
      C          /, 1H , 'WILL REMAIN CONSTANT AT THIS VALUE UNTIL ',
      D          /, 1H , 'THE FLOW AT WHITE OAK DAM IS RESUMED.' )
      IF ( NTYPE .EQ. 2 ) WRITE (*, 14895) DWHITE, DSPILL
14895 FORMAT (1H0, 'THE DILUTION OF THE SPILL WILL RISE LINEARLY FROM ',
      A          /, 1H , 'ZERO TO ', 1PD13.5, 1X, 'OVER THE SPILL TIME ',
      B          'DURATION OF', /, 1H , 1PD13.5, 1X,
      C          'SECONDS. THE CONCENTRATION IN WHITE ',
      D          /, 1H , 'OAK LAKE WILL THEN REMAIN CONSTANT AT THIS VALUE ',
      E          /, 1H , 'UNTIL THE FLOW AT WHITE OAK DAM IS RESUMED.' )
      WRITE (*, 14896)
14896 FORMAT ( 1H0, 'NO PORTION OF THE SPILL REACHES THE CLINCH RIVER.',
      A          /, 1H , 'TRANSPORT CALCULATIONS ARE NOT PERFORMED IN THE',
      B          /, 1H , 'CLINCH RIVER TO EVALUATE CONCENTRATIONS OF SPILLED',
      C          /, 1H , 'CONTAMINANT DOWNSTREAM FROM WHITE OAK LAKE/DAM.' )
      GO TO 99999

C
C      NO OUTFLOW FROM WHITE OAK LAKE/DAM WITH RADIOACTIVE DECAY
C
4444 GO TO ( 4445, 4446 ), NTYPE

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C
C   INSTANTANEOUS SPILL, NO OUTFLOW, WITH RADIOACTIVE DECAY
C
4445 SECWOL(1) = 0.0D0
    HRSWOL(1) = 0.0D0
    DAYWOL(1) = 0.0D0
    WKSWOL(1) = 0.0D0
    DILWOL(1) = VSPILL / EFFVOL
    DO 4451 JV = 2, NWOLPT
    SECWOL(JV) = DBLE( JV-1 ) * DLOG( 10.0D0 ) / RLAMDA
    HRSWOL(JV) = SECWOL(JV) / 3600.0D0
    DAYWOL(JV) = HRSWOL(JV) / 24.0D0
    WKSWOL(JV) = DAYWOL(JV) / 7.0D0
4451 DILWOL(JV) = DILWOL(1) * DEXP( - DBLE( JV-1 ) * DLOG( 10.0D0 ) )
    GO TO 4447

C
C   FINITE DURATION SPILL, NO OUTFLOW, WITH RADIOACTIVE DECAY
C
4446 A123A = VSPILL / EFFVOL / DSPILL / RLAMDA
    DILWOL(1) = 0.0D0
    SECWOL(1) = 0.0D0
    HRSWOL(1) = 0.0D0
    DAYWOL(1) = 0.0D0
    WKSWOL(1) = 0.0D0
    DILWOL(2) = A123A * ( 1.0D0 - DEXP( - RLAMDA * DSPILL / 2.0D0 ) )
    SECWOL(2) = DSPILL / 2.0D0
    HRSWOL(2) = SECWOL(2) / 3600.0D0
    DAYWOL(2) = HRSWOL(2) / 24.0D0
    WKSWOL(2) = DAYWOL(2) / 7.0D0
    DILWOL(3) = A123A * ( 1.0D0 - DEXP( - RLAMDA * DSPILL ) )
    SECWOL(3) = DSPILL
    HRSWOL(3) = SECWOL(3) / 3600.0D0
    DAYWOL(3) = HRSWOL(3) / 24.0D0
    WKSWOL(3) = DAYWOL(3) / 7.0D0
    DO 4456 JV =4, NWOLPT
    SECWOL(JV) = DBLE( JV-3 ) * DLOG( 10.0D0 ) / RLAMDA + DSPILL
    HRSWOL(JV) = SECWOL(JV) / 3600.0D0
    DAYWOL(JV) = HRSWOL(JV) / 24.0D0
    WKSWOL(JV) = DAYWOL(JV) / 7.0D0

C
C   NOTE: THE DIFFERENCE (DSPILL - SECWOL(JV)) IS ALWAYS NEGATIVE
C
    TIMEXA = DEXP( RLAMDA * ( DSPILL - SECWOL(JV) ) )
    TIMEXB = DEXP( - RLAMDA * SECWOL(JV) )
4456 DILWOL(JV) = A123A * ( TIMEXA - TIMEXB )

C
C   OUTPUT RESULTS FOR THE NO FLOW CASE WITH RADIOACTIVE DECAY
C
4447 WRITE (*, 14447)
14447 FORMAT ( 1H0, 23(1H*), 'ELAPSED TIME', 23(1H*) , 3X, 'DILUTION',
A      1X, 'AT', /, 1H , 3X, 'SECONDS', 9X, 'HOURS', 11X,
B      'DAYS', 10X, 'WEEKS', 6X, 'WHITE OAK LAKE' )
    IF ( NTYPE .EQ. 1 ) WRITE (*, 29682) SECWOL(1), HRSWOL(1),
A      DAYWOL(1), WKSWOL(1), DILWOL(1)

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      IF ( NTYPE .EQ. 2 ) WRITE (*, 17235) SECWOL(1), HRSWOL(1),
A      DAYWOL(1), WKSWOL(1), DILWOL(1)
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29678) SECWOL(2), HRSWOL(2),
A      DAYWOL(2), WKSWOL(2), DILWOL(2)
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29679) SECWOL(3), HRSWOL(3),
A      DAYWOL(3), WKSWOL(3), DILWOL(3)
      IF ( NTYPE .EQ. 1 ) NWILPT = 2
      IF ( NTYPE .EQ. 2 ) NWILPT = 4
      DO 4467 JV = NWILPT, NWOLPT
4467 WRITE (*, 17235) SECWOL(JV), HRSWOL(JV), DAYWOL(JV),
A      WKSWOL(JV), DILWOL(JV)
      IF ( NTYPE .EQ. 1 ) WRITE (*, 29681)
      IF ( NTYPE .EQ. 2 ) WRITE (*, 29680)
      WRITE (*, 14896)
      PAUSE
      GO TO 99999

C
C      C L I N C H   R I V E R   A N A L Y S I S
C
99998 CONTINUE
      PAUSE

C
C      COMPUTE TOTAL FLOW AT WHITE OAK CREEK / CLINCH RIVER CONFLUENCE
C
      TFLOW = WOLAKE(NFLOW) + HMELTN(NFLOW)

C
C      RESET CLINCH RIVER DISCHARGE TO USER-SPECIFIED VALUE IF DESIRED
C
      WRITE (*, 49571) TFLOW
49571 FORMAT ( 1H0, 'THE CLINCH RIVER FLOW BELOW THE MOUTH OF WHITE ',
A      'OAK CREEK IS SET INTERNALLY', /, 1H, 'TO THE SUM OF ',
B      'THE FLOWS FROM BOTH WHITE OAK AND MELTON HILL DAMS',
C      /, 1H, 'THE MAGNITUDE OF THIS DISCHARGE ',
D      'PRESENTLY IS ', F11.5, 1X, 'CFS.', /, 1H, 'DO YOU ',
E      'DESIRE TO CHANGE THIS VALUE (ENTER TRUE OF FALSE)?' )
74571 READ (*, *, ERR=83492) QUEST5
      IF ( QUEST5 .AND. .TRUE. ) GO TO 20999
      GO TO 30999
83492 WRITE (*, 10036)
      GO TO 74571

C
20999 WRITE (*, 19914)
19914 FORMAT ( 1H0, 'INPUT THE REVISED CLINCH RIVER DISCHARGE IN ',
A      'CUBIC FEET PER SECOND.' )
75922 READ (*, *, ERR=35922) TFLOW
      IF ( TFLOW .GT. 0.0D0 ) GO TO 65678
35922 WRITE (*, 10063)
      GO TO 75922
65678 WRITE (*, 95678) TFLOW
95678 FORMAT ( 1H0, 'THE CLINCH RIVER DISCHARGE HAS BEEN CHANGED TO ',
A      F11.5, 1X, 'CFS.' )

C
C      COMPUTE CLINCH RIVER WATER LEVEL ELEVATION AND FLOW AREA
C

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30999 ZLEVEL = STLIN ( NPCLRV, TFLOW, CLRVQQ, CLRVEL )
      FLAREA = STLIN ( NPCLRV, TFLOW, CLRVQQ, CLRVAA )
C
C   COMPUTE CLINCH RIVER WIDTH, MEAN DEPTH, AND EFFECTIVE MIXING DEPTH
C
      COSOTH = STLIN ( LSBANK, ZLEVEL, SBANKE, SBANKW )
      CONRTH = STLIN ( NBANK, ZLEVEL, RNBANKE, RNBANKW )
      RWIDTH = CONRTH - COSOTH
      DEPTHM = FLAREA / RWIDTH
      EFDPTH = FCLNCH * DEPTHM
C
C   COMPUTE MEAN VELOCITY, MIXING COEFFICIENT, AND MIXING DISTANCE
C
      AVEVEL = TFLOW / FLAREA
      DSTAR  = DISPCN * DSQRT( TFLOW * AVEVEL )
      DISMIX = DSMIXC * TFLOW ** (1.0D0/3.0D0)
C
C   WRITE INPUT PARAMETERS TO CONSOLE SCREEN
C
      WRITE (*, 77883) TFLOW, ZLEVEL, FLAREA, RWIDTH, DEPTHM,
A          EFDPTH, AVEVEL, DISMIX, DSTAR
77883 FORMAT (1H0, 'CLINCH RIVER FLOW BELOW WHITE OAK CREEK (CFS) = ',
A F11.4, /, 1H, ' CLINCH RIVER WATER LEVEL ELEVATION (FT-AMSL) = ',
B F10.5, /, 1H, ' CLINCH RIVER FLOW AREA (SQUARE FT) = ',
C F12.5, /, 1H, ' WIDTH OF CLINCH RIVER (FT) = ',
D F11.5, /, 1H, ' AVERAGE CLINCH RIVER DEPTH (FT) = ',
E F10.5, /, 1H, ' DOWNWARD PLUME PENETRATION DEPTH (FT) = ',
F F10.5, /, 1H, ' AVERAGE CLINCH RIVER FLOW VELOCITY (FT/S) = ',
G F10.5, /, 1H, ' REQUIRED DISTANCE FOR COMPLETE MIXING (FT) = ',
H F10.5, /, 1H, ' MECHANICAL MIXING COEFFICIENT (SQUARE FT/S) = ',
I F10.5)
C
C   COMPUTE CONCENTRATION PROFILE
C
C   INPUT DOWNSTREAM COORDINATE X -- XPOSTN
C
      5216 WRITE (*, 38422)
      38422 FORMAT ( 1H0, 'INPUT CLINCH RIVER DISTANCE (FT) ',
A          'DOWNSTREAM FROM WHITE OAK CREEK MOUTH?' )
      38421 READ (*, *, ERR=38423) XPOSTN
      IF ( XPOSTN .GT. 0.0D0 ) GO TO 38424
      38423 WRITE (*, 10063)
      GO TO 38421
C
      38424 GO TO ( 4891, 4892 ), NTYPE
C
C   INSTANTANEOUS SPILL
C
      4891 CONTINUE
C
      TMAX = XPOSTN / AVEVEL
      XMILES = XPOSTN / 5280.0D0
C
      WRITE (*, 75194) XPOSTN, XMILES

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75194 FORMAT ( 1H0, 'CLINCH RIVER DISTANCE FROM WHITE OAK CREEK', 1X,
A      'MOUTH:', 1X, F8.1, 1X, 'FT', 1X, '(', F5.1, 1X,
B      'MILES)', /, 1H0, 47X, 'CLINCH', /, 1H , 16(1H*),
C      'ELAPSED TIME', 16(1H*), 4X, 'RIVER', 4X, 'INSTANT',
D      3X, 'CONTINUOUS', /, 1H , 2X, 'SECONDS', 5X, 'HOURS',
E      7X, 'DAYS', 6X, 'WEEKS', 5X, 'DILUTION', 3X, 'PORTION',
F      4X, 'PORTION' )

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C
      INTMED = 10
      SIIMAX = ( 1.0D0 - 0.10D0 ) / ( 5000.0D0 - 500000.0D0 )
      XMAXIN = 1.0D0 - ( SIIMAX * ( 5000.0D0 - XPOSTN ) )
      IF ( XPOSTN .LT. 5000.0D0 ) XMAXIN = 1.0D0
      IF ( XPOSTN .GT. 500000.0D0 ) XMAXIN = 0.10D0
      DTCLI1 = ( XMAXIN * TMAX ) / DBLE ( INTMED - 1 )
      DO 21151 JK = 1, INTMED
      SECCR(JK) = TMAX + DTCLI1 * DBLE( JK - 1 )
      HRSCR(JK) = SECCR(JK) / 3600.0D0
      DAYCR(JK) = HRSCR(JK) / 24.0D0
21151 WKSCR(JK) = DAYCR(JK) / 7.0D0

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C
      INTOUT = NCRPTS - INTMED
      DTCLI2= ( SECWOL(3) + TMAX - SECCR(INTMED) ) / DBLE( INTOUT - 1 )
      IPLUS1 = INTMED + 1
      DO 21154 JX = IPLUS1, NCRPTS
      SECCR(JX) = SECCR(INTMED) + TMAX + DTCLI2* DBLE( JX - INTMED )
      HRSCR(JX) = SECCR(JX) / 3600.0D0
      DAYCR(JX) = HRSCR(JX) / 24.0D0
21154 WKSCR(JX) = DAYCR(JX) / 7.0D0

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C
      QQ1 = VSPILL / EFFVOL
      QQ2 = 1.0D0 / ( 1.0D0 + VSPILL / EFFVOL )
      QQ3 = 2.0D0 * RWIDTH * EFDPTH * PISQRT * DSQRT( DSTAR )
      QQ4 = QQ1 * QQ2 / QQ3
      QQ5 = XPOSTN * WODFLW / 2.0D0 / DSQRT( DSTAR )

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C
      AAAAAA = AVEVEL * XPOSTN / 2.0D0 / DSTAR
      DUMMY1 = XPOSTN * XPOSTN / 4.0D0 / DSTAR
      BBBBBB = DUMMY1 * ( AVEVEL * AVEVEL / 4.0D0 / DSTAR
A      - WODFLW / EFFVOL )

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C
      DO 72167 KT = 1, NCRPTS
C
      TIME = SECCR(KT)
C
      CON = QQ4 * DEXP( - RLAMDA * TIME )
      FGH1 = ( XPOSTN - AVEVEL * TIME )**2
      TRM1 = VSPILL * DEXP( - FGH1 / 4.0D0 / DSTAR / TIME )
A      / DSQRT( TIME )
      PGH = QQ5 * DEXP( - WODFLW * TIME / EFFVOL )

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C
      UPLIM = 4.0D0 * DSTAR * TIME / XPOSTN / XPOSTN
      CALL INTGRT ( 0.0D0, UPLIM, SPILL, VALUE )
      TRM2 = PGH * VALUE
      DILUTI = CON * ( TRM1 + TRM2 )

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74 FORMAT ( 1H , 'DURATION (HOURS) =' , 1PD13.5 )
   GO TO 40
65 WRITE (*, 75) DURDMY
75 FORMAT ( 1H , 'DURATION (DAYS) =' , 1PD13.5 )
   GO TO 40
66 WRITE (*, 76) DURDMY
76 FORMAT ( 1H , 'DURATION (WEEKS) =' , 1PD13.5 )
40 CONTINUE

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C

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   GO TO ( 80, 90, 95 ), IVUNIT
80 WRITE (*, 81) VOLDMY
81 FORMAT ( 1H , 'VOLUME (LITERS) =' , 1PD13.5 )
   GO TO 99
90 WRITE (*, 91) VOLDMY
91 FORMAT ( 1H , 'VOLUME (GALLONS) =' , 1PD13.5 )
   GO TO 99
95 WRITE (*, 96) VOLDMY
96 FORMAT ( 1H , 'VOLUME (CUBIC FT) =' , 1PD13.5 )
99 CONTINUE

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C

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   GO TO ( 101, 102, 103, 104, 105, 106, 107, 108,
   A      109, 110, 111, 112, 113, 114 ), NSPILL
101 WRITE (*, 201)
201 FORMAT ( 1H , 'SPILL LOCATION: EAST OF EAST ORNL GATE ABOVE GS6 ' ,
   A      '(03536320) (WOC MI 3.4)' )
   GO TO 115
102 WRITE (*, 202)
202 FORMAT ( 1H , 'SPILL LOCATION: BELOW FIFTH CREEK CONFLUENCE ' ,
   A      '(GS5) (03536380) (WOC MI 2.7)' )
   GO TO 115
103 WRITE (*, 203)
203 FORMAT (1H , 'SPILL LOCATION: NEAR 7500 BRIDGE (GS3) (03536550) ' ,
   A      '(WOC MI 2.2)' )
   GO TO 115
104 WRITE (*, 204)
204 FORMAT ( 1H , 'SPILL LOCATION: WOC 0.1 MI ABOVE MELTON BRANCH ' ,
   A      'CONFLUENCE (MS3)' )
   GO TO 115
105 WRITE (*, 205)
205 FORMAT ( 1H , 'SPILL LOCATION: BELOW MELTON BRANCH CONFLUENCE ' ,
   A      'AND ABOVE WHITE OAK LAKE' )
   GO TO 115
106 WRITE (*, 206)
206 FORMAT ( 1H , 'SPILL LOCATION: FIFTH CREEK' )
   GO TO 115
107 WRITE (*, 207)
207 FORMAT ( 1H , 'SPILL LOCATION: FIRST CREEK ABOVE GS1 (03536450) ' ,
   A      '(MI 0.2)' )
   GO TO 115
108 WRITE (*, 208)
208 FORMAT ( 1H , 'SPILL LOCATION: NORTHWEST TRIBUTARY ABOVE ' ,
   A      'GS4 (03536440), MI 0.1, AND FIRST CRK' )
   GO TO 115
109 WRITE (*, 209)

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209 FORMAT ( 1H , 'SPILL LOCATION: DIRECTLY INTO WHITE OAK LAKE' )
    GO TO 115
110 WRITE (*, 210)
210 FORMAT ( 1H , 'SPILL LOCATION: MELTON BRANCH HEADWATERS ABOVE ',
    A      'GS2 (03537100) (MI 1.2)' )
    GO TO 115
111 WRITE (*, 211)
211 FORMAT ( 1H , 'SPILL LOCATION: EAST SEVEN CREEK ABOVE GS16 ',
    A      '(03537050)' )
    GO TO 115
112 WRITE (*, 212)
212 FORMAT ( 1H , 'SPILL LOCATION: CENTER SEVEN CREEK ABOVE GS17 ',
    A      '(03537200)' )
    GO TO 115
113 WRITE (*, 213)
213 FORMAT ( 1H , 'SPILL LOCATION: WEST SEVEN CREEK ABOVE GS18 ',
    A      '(03537300)' )
    GO TO 115
114 WRITE (*, 214)
214 FORMAT ( 1H , 'SPILL LOCATION: MELTON BRANCH 0.1 MI ABOVE WOC ',
    A      'CONFLUENCE (MS4) (BELOW HFIR)' )
115 CONTINUE

```

C

```

    GO TO ( 501, 502, 503, 504, 505, 506, 507,
    A      508, 509, 510, 511 ), NFLOW
501 WRITE (*, 601)
601 FORMAT ( 1H , 'DISCHARGE STATISTICS: ANNUAL MEANS' )
    GO TO 512
502 WRITE (*, 602)
602 FORMAT ( 1H , 'DISCHARGE STATISTICS: HIGHEST ANNUAL MEANS' )
    GO TO 512
503 WRITE (*, 603)
603 FORMAT ( 1H , 'DISCHARGE STATISTICS: LOWEST ANNUAL MEANS' )
    GO TO 512
504 WRITE (*, 604)
604 FORMAT ( 1H , 'DISCHARGE STATISTICS: HIGHEST DAILY MEANS' )
    GO TO 512
505 WRITE (*, 605)
605 FORMAT ( 1H , 'DISCHARGE STATISTICS: LOWEST DAILY MEANS' )
    GO TO 512
506 WRITE (*, 606)
606 FORMAT ( 1H , 'DISCHARGE STATISTICS: ANNUAL SEVEN-DAY MINIMUMS' )
    GO TO 512
507 WRITE (*, 607)
607 FORMAT ( 1H , 'DISCHARGE STATISTICS: INSTANTANEOUS PEAK FLOWS' )
    GO TO 512
508 WRITE (*, 608)
608 FORMAT ( 1H , 'DISCHARGE STATISTICS: INSTANTANEOUS LOW FLOWS' )
    GO TO 512
509 WRITE (*, 609)
609 FORMAT ( 1H , 'DISCHARGE STATISTICS: 10% EXCEEDANCE FLOWS' )
    GO TO 512
510 WRITE (*, 610)
610 FORMAT ( 1H , 'DISCHARGE STATISTICS: 50% EXCEEDANCE FLOWS' )

```

```

GO TO 512
511 WRITE (*, 611)
611 FORMAT ( 1H , 'DISCHARGE STATISTICS: 90% EXCEEDANCE FLOWS' )
512 CONTINUE
C
IF ( NSPILL .EQ. 9 ) GO TO 9876
C
WRITE (*, 999)
999 FORMAT ( 1H0, 9X, 'WATERSHED LOCATION', 15X,
A          'DILUTION', 4X, 'FLOW(CFS)' )
C
9876 CONTINUE
C
RETURN
C
END

```

```

FUNCTION STLIN ( NPTS, XVALUE, X, Y )

```

```

C
C           P I E C E W I S E   S T R A I G H T
C           L I N E   I N T E R P O L A T I O N
C
C   GIVEN NPTS ORDERED DATA POINT PAIRS OF Y VERSUS X, THIS FUNCTION
C   USES LINEAR INTERPOLATION TO INTERPOLATE OR EXTRAPOLATE A VALUE OF
C   Y (CALLED STLIN) CORRESPONDING TO XVALUE.  THE X'S MUST BE
C   SINGLE-VALUED AND MONOTONICALLY INCREASING.  THE X'S DO NOT HAVE
C   TO BE EQUALLY-SPACED.
C
C           NPTS = NUMBER OF DATA POINT PAIRS
C           XVALUE = ABSCISSA AT WHICH LINEAR INTERPOLATION IS REQUIRED
C           X,Y = ARRAYS OF DATA ABSCISSAS (X'S) AND ORDINATES (Y'S)
C           STLIN = LINEARLY INTERPOLATED VALUE CORRESPONDING TO XVALUE
C
C   NOTES:
C
C   1. IF XVALUE .LT. X(1), THEN I = 1 IS USED.
C   2. IF XVALUE .GE. X(NPTS), THEN I=NPTS-1 IS USED (RESET).
C   3. ADJUSTABLE DIMENSIONS MUST BE SET TO LARGEST APPLICABLE
C       ARRAY SIZE IN CALLING PROGAM THAT WILL BE INPUT TO STLIN.
C
C   PRECISION: DOUBLE
C
C   IMPLICIT REAL*8 ( A-H, O-Z ), INTEGER ( I-N )
C
C   VARIABLE (ADJUSTABLE) DIMENSION STATEMENT
C
C   DIMENSION X(NPTS), Y(NPTS)
C
C   BINARY SEARCH ROUTINE
C
C   I = 1
C   J = NPTS + 1

```

```

200 K = ( I+J ) / 2
   IF ( XVALUE .LT. X(K) ) J = K
   IF ( XVALUE .GE. X(K) ) I = K
   IF ( J .GT. I+1 ) GO TO 200
C
C   COUNTER RESET FOR EXTRAPOLATION AT RIGHT-HAND SIDE OF INTERVAL
C
   IF ( XVALUE .GE. X(NPTS) ) I = NPTS - 1
C
C   TWO-POINT FORM OF A STRAIGHT LINE
C
   SLOPE = ( Y(I+1) - Y(I) ) / ( X(I+1) - X(I) )
   DX = XVALUE - X(I)
   STLININ = Y(I) + DX * SLOPE
C
   RETURN
C
   END

```

```

FUNCTION GAUSSQ ( A, B, FUNCT )
C
C   G A U S S - L E G E N D R E   Q U A D R A T U R E
C
C   THIS FUNCTION USES THE 4-POINT GAUSS-LEGENDRE
C   QUADRATURE FORMULA TO COMPUTE THE INTEGRAL OF
C   FUNCTN(X)*DX BETWEEN INTEGRATION LIMITS A AND B.
C   THE ROOTS OF THE LEGENDRE POLYNOMIAL AND THE
C   WEIGHT FACTORS FOR THE QUADRATURE PROCEDURE
C   ARE STORED IN THE Z AND WEIGHT ARRAYS, RESPECTIVELY.
C
C   NOTE: THIS IS AN OPEN INTEGRATION FORMULA THAT DOES NOT
C   REQUIRE INFORMATION ABOUT THE INTEGRAND AT THE
C   LIMITS OF INTEGRATION. THE INTEGRALS COMPUTED
C   IN THIS CODE CANNOT BE CALCULATED USING CLOSED
C   INTEGRATION FORMULAS BECAUSE THE INTEGRAND RISES
C   WITHOUT BOUND TOWARDS INFINITY AT THE LOWER LIMIT.
C
C   REFERENCE: "APPLIED NUMERICAL METHODS," BY BRICE
C   CARNAHAN, H. A. LUTHER, AND JAMES O.
C   WILKES, JOHN WILEY & SONS, INC., NEW
C   YORK, 1969, PP. 109-110.
C
C   PRECISION: DOUBLE           USER-DEFINED EXTERNAL: FUNCT
C
C   DOUBLE PRECISION A, B, C, D, FUNCT, GAUSSQ, SUM, WEIGHT, Z
C
C   DIMENSION Z(2), WEIGHT(2)
C
C   PRESET Z AND WEIGHT ARRAYS
C
C   DATA      Z / 0.339981043584856D0, 0.861136311594053D0 /
C

```

```

DATA WEIGHT / 0.652145154862546D0, 0.347854845137454D0 /
C
C TRANSFORM INTEGRATION VARIABLE FROM A TO B OVER TO -1 TO 1
C
C = ( B - A ) / 2.0D0
D = ( B + A ) / 2.0D0
C
C ACCUMULATE THE SUM IN THE 4-POINT FORMULA
C
SUM = WEIGHT(1) * ( FUNCT( Z(1)*C + D ) + FUNCT( - Z(1)*C + D ) )
A + WEIGHT(2) * ( FUNCT( Z(2)*C + D ) + FUNCT( - Z(2)*C + D ) )
C
C MAKE INTERVAL CORRECTION AND RETURN
C
GAUSSQ = C * SUM
C
RETURN
C
END

```

```

SUBROUTINE INTGRT ( A, B, FUNCT, V )
C
C COMPOSITE INTEGRATION ROUTINE
C
C NUMERICAL INTEGRATION USING INTERVAL HALVING TO
C ACHIEVE A PRESCRIBED RELATIVE ERROR TOLERANCE
C
C IMPLICIT REAL*8 ( A-H, O-Z ), INTEGER ( I-N )
C
DATA RERR / 0.001D0 /, MAX / 250 /, ZERO / 1.0D-30 /, ICT / 10 /
C
A1 = GAUSSQ ( A, B, FUNCT )
C
C CHECK FOR ZERO CONDITION (RELATIVE ERROR CANNOT BE TESTED)
C
IF ( DABS( A1 ) .LT. ZERO ) GO TO 3
C
C PERFORM INTERVAL HALVING PROCEDURE (COMPOSITE INTEGRATION)
C
N = ICT
C
2 V = 0.0D0
DX = ( B - A ) / DBLE( N )
C
DO 1 J = 1, N
X1 = A + DBLE( J-1 ) * DX
X2 = A + DBLE( J ) * DX
1 V = V + GAUSSQ ( X1, X2, FUNCT )
C
ERR = DABS ( ( A1 - V ) / A1 )
IF ( ERR .LT. RERR ) RETURN
C

```

```

N = N + ICT
A1 = V
IF ( N .GT. MAX ) GO TO 4
GO TO 2
C
4 WRITE (*, 100) MAX
100 FORMAT ( 1H0, 'WARNING: COMPOSITE INTEGRATION ROUTINE DID NOT ',
A          'CONVERGE WITH', I4, 1X, 'SUBDIVISIONS.' )
RETURN
C
3 V = A1
RETURN
C
END

FUNCTION SPILL ( ETA )
C
C          I N T E G R A N D
C
C  INTEGRAND FOR INSTANTANEOUS AND FINITE DURATION AQUATIC SPILL MODEL
C
C          1          1      UX      X**2      U**2
C  F(ETA) = ***** DEXP ( - *** + ** - ***** (***** - ETC ) ETA )
C          DSQRT(ETA)      ETA      2D      4D      4D
C
C  DOUBLE PRECISION SPILL, ETA, AAAAAA, BBBBBB, FACTOR, DEXP, DSQRT
C
C  PASS INTERNAL PROGRAM CONSTANTS TO INTEGRAND USING UNLABELED COMMON:
C
C          UX      AVEVEL*XPOSTN
C  AAAAAA = ***** = ***** .
C          2D      2.0D0*DSTAR
C
C          X**2      U**2
C  BBBBBB = ***** ( ***** - ETC ) ,
C          4D      4D
C
C          XPOSTN*XPOSTN      AVEVEL*AVEVEL
C  = ***** (***** - ETC ) .
C          4.0D0*DSTAR      4.0D0*DSTAR
C
C  THE FACTOR ETC TAKES ON FOUR DIFFERENT VALUES:
C
C  1. INSTANANEOUS SPILL: ETC = QW / VW = WODFLW / EFFVOL .
C
C  2. FINITE DURATION SPILL (THREE POSSIBILITIES):
C
C  A. T .LE. D      OR      TIME .LE. DSPILL :
C
C          (1) ETC = - LAMDA = - RLAMDA (FIRST INTEGRAL) .
C
C          (2) ETC = V / VW / D + QW / VW (SECOND INTEGRAL) ,

```

```

C
C           = VSPILL / EFFVOL / DSPILL + WODFLW / EFFVOL .
C
C
C      B.  T .GT. D    OR    TIME .GT. DSPILL :
C
C           ETC = QW / VW = WODFLW / EFFVOL .
C
C  THE FACTOR ETC IS COMPUTED IN MAIN AND PASSED IMPLICITLY VIA BBBBBB.
C
C      COMMON      AAAAAA,      BBBBBB
C
C      FACTOR = - 1.0D0 / ETA + AAAAAA - BBBBBB * ETA
C
C      SPILL = DEXP( FACTOR ) / DSQRT( ETA )
C
C      RETURN
C
C      END

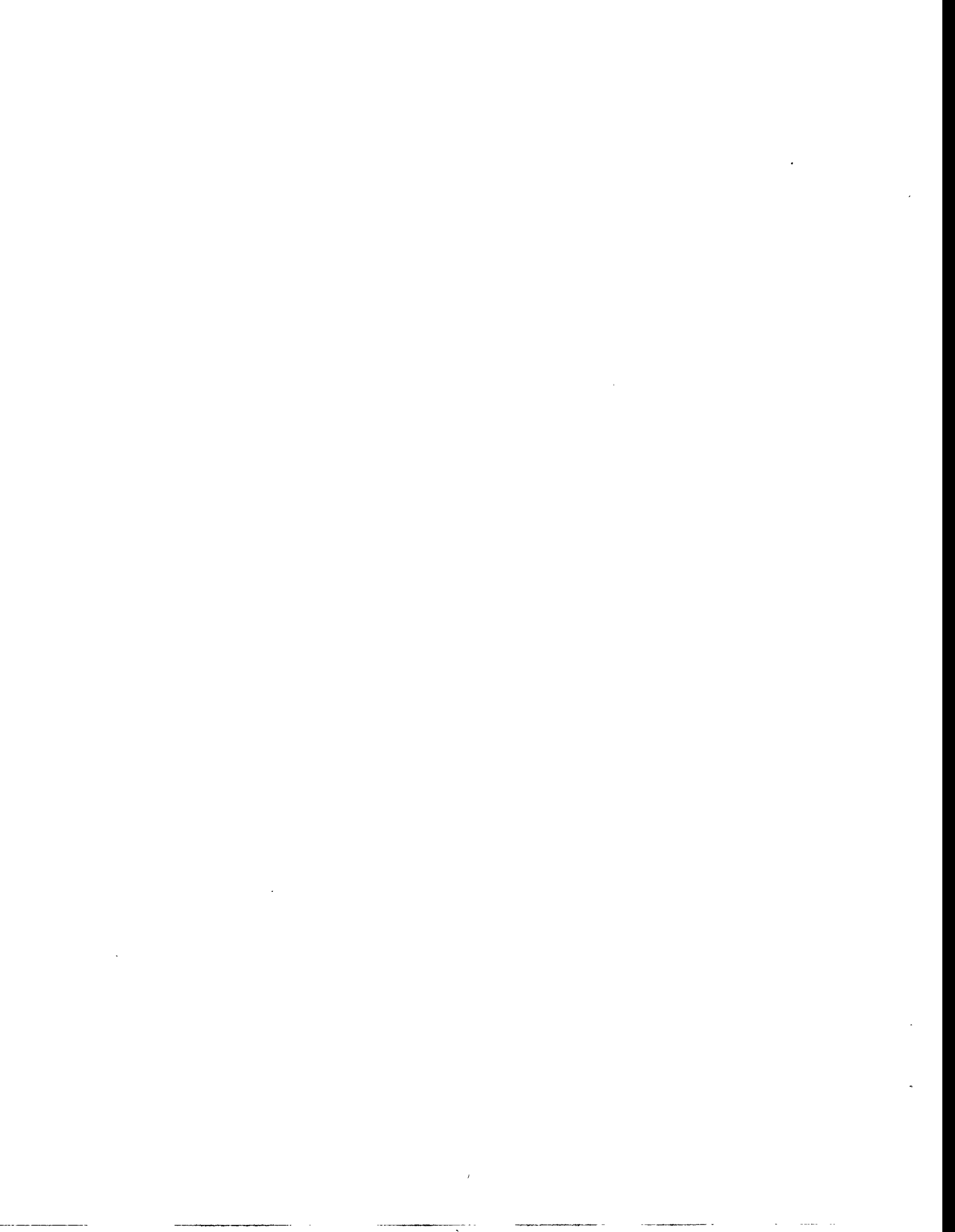
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**Appendix B. MATHCAD PROGRAM LISTING**



A listing of the Mathcad (MathSoft, Inc. 1995) version of the ORNL aquatic spill model is included in this appendix. The program was prepared with the Mathcad PLUS 6.0 Professional Edition. The symbol := is deployed by Mathcad to define variables and functions. The variables with units are unknown quantities/free parameters or inputs that must be specified by the user. The mathematical functions defined in the program appear explicitly as they do in Sect. 3 of this report and require the user-specified variables to compute the dilution-time history of the spill throughout the White Oak Creek (WOC) and Clinch River watersheds. Calculated results produced by the program are separated by an equal (=) sign. File SPILL.MCD is the Mathcad version of the spill model and resides on the 5¼-in., double-sided, high-density diskette included in the pocket on the back cover.

Problems occasionally arise during the calculation of the integral  $I_5$  [ $I_5$ ; see Eq. (3.62)]. Mathcad returns an error message when the Romberg integration algorithm fails to converge. The built-in Mathcad variable TOL affects the accuracy of the integral calculations. The Mathcad default value for TOL is  $10^{-3}$ . For the instantaneous spill, a relatively tight tolerance of  $10^{-10}$  works quite well. Conversely, the calculation of  $I_5$  for the finite-duration spill is sensitive to TOL. The default value of  $10^{-3}$  admits solutions for downriver distances less than approximately 40.6 km (25.2 miles) (above the confluence of the Clinch and Tennessee rivers). If divergence occurs, the values of downriver distance and TOL can be adjusted using trial-and-error methodology, such that converged solutions are sometimes still computed. Trend analysis based on the graphical output should be used to confirm the validity of the calculated result.



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Input the volume  $v$  of the spill in gallons:  $v := 1 \cdot \text{gal}$

$$v = 0.133680558 \cdot \text{ft}^3 \quad v = 0.003785412 \cdot \text{m}^3$$

$$v = 3.78541184 \cdot \text{liter} \quad v = 128 \cdot \text{fl\_oz}$$

Input the duration of the spill  $D$  in minutes:  $D := 10 \cdot \text{day}$

$$D = 8.64 \cdot 10^5 \cdot \text{sec} \quad D = 240 \cdot \text{hr}$$

$$D = 10 \cdot \text{day} \quad D = 0.02738 \cdot \text{yr}$$

Input flow at White Oak Dam  $Q_w$  in cubic feet per second:  $Q_w := 8.402 \cdot \frac{\text{ft}^3}{\text{sec}}$

$$Q_w = 3771.07942 \cdot \frac{\text{gal}}{\text{min}} \quad Q_w = 0.23792 \cdot \frac{\text{m}^3}{\text{sec}} \quad Q_w = 14275.0887 \cdot \frac{\text{liter}}{\text{min}}$$

Input Clinch River flow at Melton Hill Dam  $Q_{cr}$  in cubic feet per second:  $Q_{cr} := 4100 \cdot \frac{\text{ft}^3}{\text{sec}}$

$$Q_{cr} = 1.84021 \cdot 10^6 \cdot \frac{\text{gal}}{\text{min}} \quad Q_{cr} = 116.09907 \cdot \frac{\text{m}^3}{\text{sec}} \quad Q_{cr} = 6.96594 \cdot 10^6 \cdot \frac{\text{liter}}{\text{min}}$$

Input half-life of radioactive isotope  $t_{\text{half}}$  in years:  $t_{\text{half}} := 10000000000000 \cdot \text{yr}$

$$t_{\text{half}} = 3.15569 \cdot 10^{20} \cdot \text{sec} \quad t_{\text{half}} = 8.76581 \cdot 10^{16} \cdot \text{hr} \quad t_{\text{half}} = 3.65242 \cdot 10^{15} \cdot \text{day}$$

Radioactive decay constant  $\lambda$ :  $\lambda := \frac{\ln(2)}{t_{\text{half}}} \quad \lambda = 0 \cdot \text{sec}^{-1}$

One-half of the volume of White Oak Lake is assumed to participate in the dilution processes that occur behind White Oak Dam.

White Oak Lake volume  $V_w$ :  $V_w := 1546330 \cdot 0.5 \cdot \text{ft}^3$

$$V_w = 7.73165 \cdot 10^5 \cdot \text{ft}^3 \quad V_w = 5.78368 \cdot 10^6 \cdot \text{gal} \quad V_w = 2.18936 \cdot 10^7 \cdot \text{liter}$$

Input Clinch River downstream location  $x$  in feet at which dilution calculation is to be performed:  $x := 66528 \cdot \text{ft}$

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$x = 12.6 \cdot \text{mi}$      $x = 22176 \cdot \text{yd}$      $x = 20.27773 \cdot \text{km}$      $x = 20277.7344 \cdot \text{m}$

Clinch River discharge-stage-area relationship calculated using Manning's formula:

Number of data-point entries:     $j := 0..13$

$Q_j :=$	$S_j :=$	$A_j :=$
0	724	0
1	724.20	6.42
5	724.37	21.46
10	724.48	36.09
30	724.72	82.28
50	724.88	120.7
70	725	155.3
100	725.12	193.3
300	725.69	379.0
500	726.12	520.2
700	726.48	641.8
1000	726.95	803.4
3000	729.15	1627
5000	730.70	2254
7000	731.94	2775
10000	733.57	3462
15000	735.89	4461
20000	737.90	5347
25000	739.71	6160
30000	741.37	6916
35000	742.91	7629
40000	744.36	8309
45000	745.74	8961
50000	747.06	9590

Add units to Clinch River discharge-stage-area relationship data-point entries:

$$Q := Q \cdot \frac{\text{ft}^3}{\text{sec}} \quad S := S \cdot \text{ft} \quad A := A \cdot \text{ft}^2$$

Interpolate linearly to obtain the Clinch River water surface elevation (stage) and flow area (flowarea) corresponding the user-specified Melton Hill plus White Oak dams flow rate  $Q_{cr} + Q_w$ :

$$\text{stage} := \text{linterp}(Q, S, Q_{cr} + Q_w)$$

$$\text{stage} = 730.0090115 \cdot \text{ft}$$

$$\text{flowarea} := \text{linterp}(Q, A, Q_{cr} + Q_w)$$

$$\text{flowarea} = 1974.484027 \cdot \text{ft}^2$$

Number of data-points in Clinch

River streambed contour:     $k := 0..5$

<u>South Bank</u>		<u>North Bank</u>	
$\text{sbel}_k :=$	$\text{sbco}_k :=$	$\text{nbel}_k :=$	$\text{nbco}_k :=$
724	479.3	724	479.3
725	324.3	725	637.8
730	302.7	730	713.5
740	286.5	740	740.5
750	264.9	750	756.8
760	0.0	760	897.3

Add units to north & south Clinch River streambed contours:

$$\text{sbel} := \text{sbel} \cdot \text{ft} \quad \text{sbco} := \text{sbco} \cdot \text{ft} \quad \text{nbel} := \text{nbel} \cdot \text{ft} \quad \text{nbco} := \text{nbco} \cdot \text{ft}$$

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The width  $W$  of the Clinch River is calculated from the value of stage corresponding to  $Q_{cr}$ . Linear interpolation is used to obtain the north & south bank cross-stream coordinates from the north & south streambed contours.

$$W := \text{linterp}(\text{nbcl}, \text{nbco}, \text{stage}) - \text{linterp}(\text{sbel}, \text{sbco}, \text{stage}) \quad W = 410.83893 \cdot \text{ft}$$

Clinch River flow velocity  $u$  (volumetric flow rate divided by flow area):

$$u := \frac{Q_{cr} + Q_w}{\text{flowarea}} \quad u = 2.08075 \cdot \text{ft} \cdot \text{sec}^{-1} \quad u = 34.04859 \cdot \frac{\text{mi}}{\text{day}} \quad u = 0.63421 \cdot \frac{\text{m}}{\text{sec}}$$

Clinch River longitudinal dispersion coefficient  $D_x$  (empirical correlation):

$$D_x := 2.5 \cdot \sqrt{(Q_{cr} + Q_w)} \cdot u \quad D_x = 231.1458648 \cdot \text{ft}^2 \cdot \text{sec}^{-1} \quad D_x = 21.47415 \cdot \frac{\text{m}^2}{\text{sec}}$$

Clinch River entrance length  $L_x$  required for complete mixing across channel cross section (based on 1962 empirical correlation developed by Hull):

$$L_x := 200 \cdot \text{sec}^{\frac{1}{3}} \cdot (Q_{cr} + Q_w)^{\frac{1}{3}} \quad L_x = 3203.226 \cdot \text{ft} \quad L_x = 0.97634 \cdot \text{km}$$

$$L_x = 1067.74214 \cdot \text{yd} \quad L_x = 0.60667 \cdot \text{mi} \quad L_x = 976.343 \cdot \text{m}$$

Mean depth of Clinch River ( $d_{\text{mean}}$ ) calculated as the flow area divided by the width:

$$d_{\text{mean}} := \frac{\text{flowarea}}{W} \quad d_{\text{mean}} = 4.8059808 \cdot \text{ft} \quad d_{\text{mean}} = 1.46486 \cdot \text{m}$$

The thermal penetration depth  $H$  of contaminant dispersion in the Clinch River is assumed to be 1/10 of the mean depth (cold water is released at Melton Hill Dam):

$$H := \left(\frac{1}{10}\right) \cdot d_{\text{mean}} \quad H = 0.4805981 \cdot \text{ft} \quad H = 0.14649 \cdot \text{m}$$

Calculate elapsed time  $x_{\text{overu}}$  for contaminant plume to reach downstream location  $x$ :

$$x_{\text{overu}} := \frac{x}{u} \quad x_{\text{overu}} = 31973.13051 \cdot \text{sec} \quad x_{\text{overu}} = 532.88551 \cdot \text{min}$$

$$x_{\text{overu}} = 8.88143 \cdot \text{hr} \quad x_{\text{overu}} = 0.37006 \cdot \text{day} \quad x_{\text{overu}} = 0.001013189 \cdot \text{yr}$$

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INTEGRATION SETUP

npts := 250      i := 0, 1.. npts

$$\text{power}_i := -0.5 + \frac{4.0}{\text{npts}} \cdot i \qquad t_i := 10^{\text{power}_i} \cdot \text{xoveru}$$

INSTANTANEOUS SPILL

TOL := 0.0000000001

$$C_i := \frac{v}{V_w} \cdot \left(1 + \frac{v}{V_w}\right)^{-1} \cdot \frac{\exp(-\lambda \cdot t_i)}{2 \cdot H \cdot W \cdot \sqrt{\pi \cdot D_x}}$$

$$\text{dilution}_i := C_i \cdot \left[ \frac{v}{\sqrt{t_i}} \cdot \exp\left[-\frac{(x - u \cdot t_i)^2}{4 \cdot D_x \cdot t_i}\right] \dots \right. \\ \left. + Q_w \cdot \int_{0 \cdot \text{sec}}^{t_i} \frac{1}{\sqrt{t_i - \tau}} \cdot \exp\left[-\frac{[x - u \cdot (t_i - \tau)]^2}{4 \cdot D_x \cdot (t_i - \tau)} - \frac{Q_w}{V_w} \cdot \tau\right] d\tau \right]$$

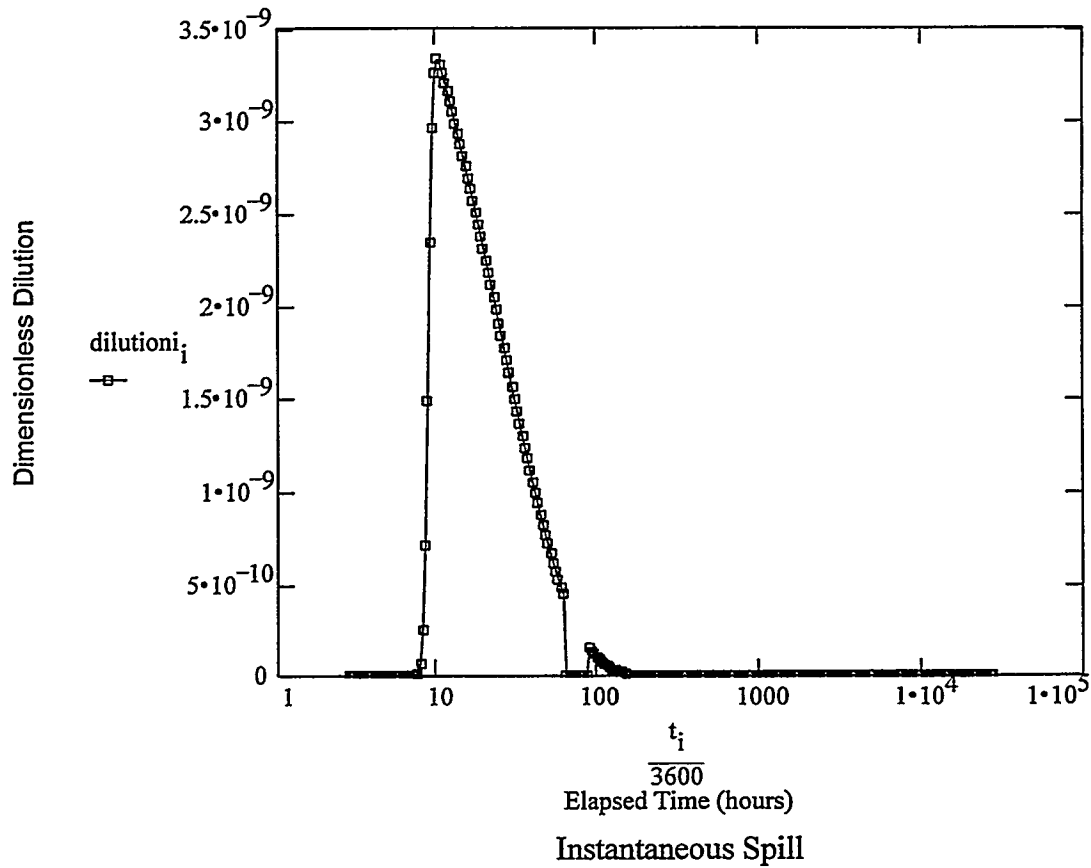
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$$\max(\text{dilution}_i) = 3.3309652 \cdot 10^{-9}$$

$$x = 12.6 \cdot \text{mi}$$

$$\frac{x}{u} = 8.88143 \cdot \text{hr}$$



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FINITE DURATION SPILL

TOL := 0.001

$$g3(\xi) := \frac{1}{\sqrt{\xi}} \cdot \exp \left[ -\frac{1}{\xi} + \frac{x \cdot u}{2 \cdot D_x} - \frac{x^2 \cdot \xi}{4 \cdot D_x} \cdot \left( \frac{u^2}{4 \cdot D_x} + \lambda \right) \right]$$

$$g4(\xi) := \frac{1}{\sqrt{\xi}} \cdot \exp \left[ -\frac{1}{\xi} + \frac{x \cdot u}{2 \cdot D_x} - \frac{x^2 \cdot \xi}{4 \cdot D_x} \cdot \left( \frac{u^2}{4 \cdot D_x} - \frac{v}{V_w \cdot D} - \frac{Q_w}{V_w} \right) \right]$$

$$g5(\xi) := \frac{1}{\sqrt{\xi}} \cdot \exp \left[ -\frac{1}{\xi} + \frac{x \cdot u}{2 \cdot D_x} - \frac{x^2 \cdot \xi}{4 \cdot D_x} \cdot \left( \frac{u^2}{4 \cdot D_x} - \frac{Q_w}{V_w} \right) \right]$$

$$c1 := \frac{v}{V_w \cdot D} \cdot \left( \frac{v}{V_w \cdot D} + \frac{Q_w}{V_w} + \lambda \right)^{-1} \cdot \left( \frac{x}{4 \cdot H \cdot W \cdot D_x \cdot \sqrt{\pi}} \right)$$

$$c2_i := \exp \left[ - \left( \frac{v}{V_w \cdot D} + \frac{Q_w}{V_w} + \lambda \right) \cdot t_i \right]$$

$$c3_i := \left[ 1 - \exp \left[ - \left( \frac{v}{V_w \cdot D} + \frac{Q_w}{V_w} + \lambda \right) \cdot D \right] \right] \cdot \exp \left[ - \left( \frac{Q_w}{V_w} + \lambda \right) \cdot (t_i - D) \right]$$

$$alim_i := \frac{4 \cdot D_x \cdot t_i}{x^2}$$

$$blim_i := \frac{4 \cdot D_x \cdot (t_i - D)}{x^2}$$

$$I3_i := \begin{cases} \int_{blim_i}^{alim_i} g3(\xi) d\xi & \text{if } t_i > D \\ \int_0^{alim_i} g3(\xi) d\xi & \text{if } t_i \leq D \end{cases}$$

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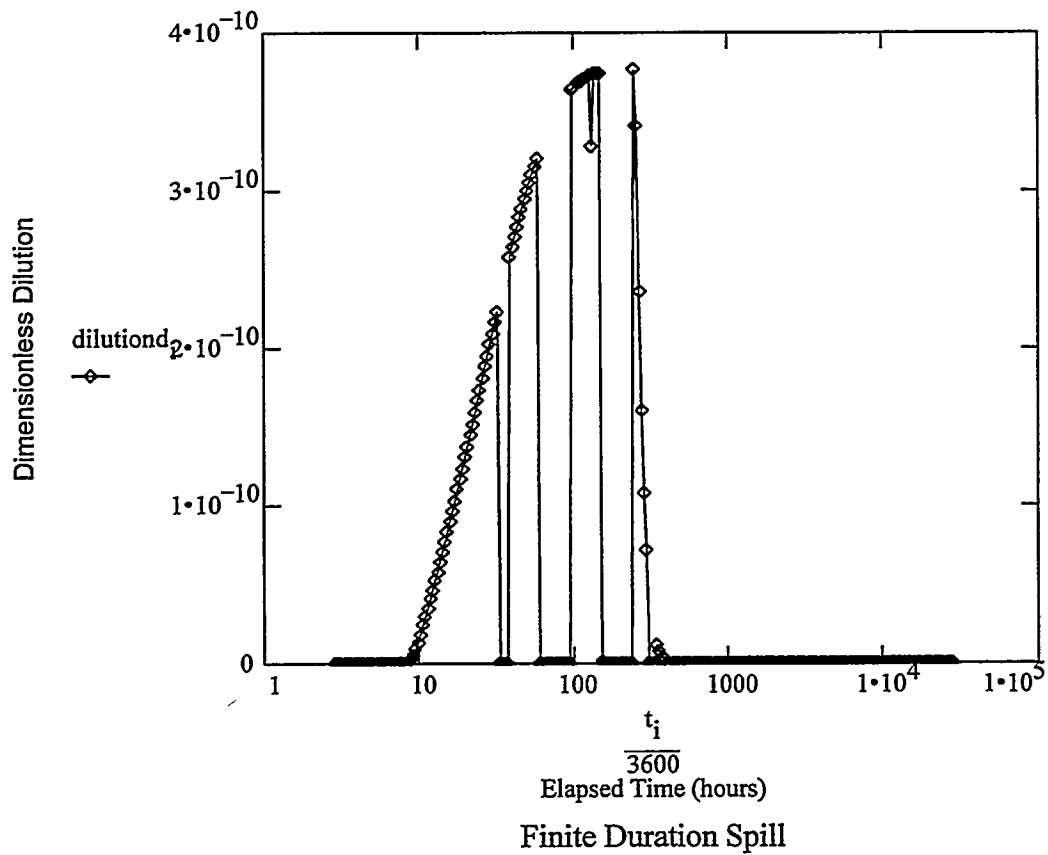
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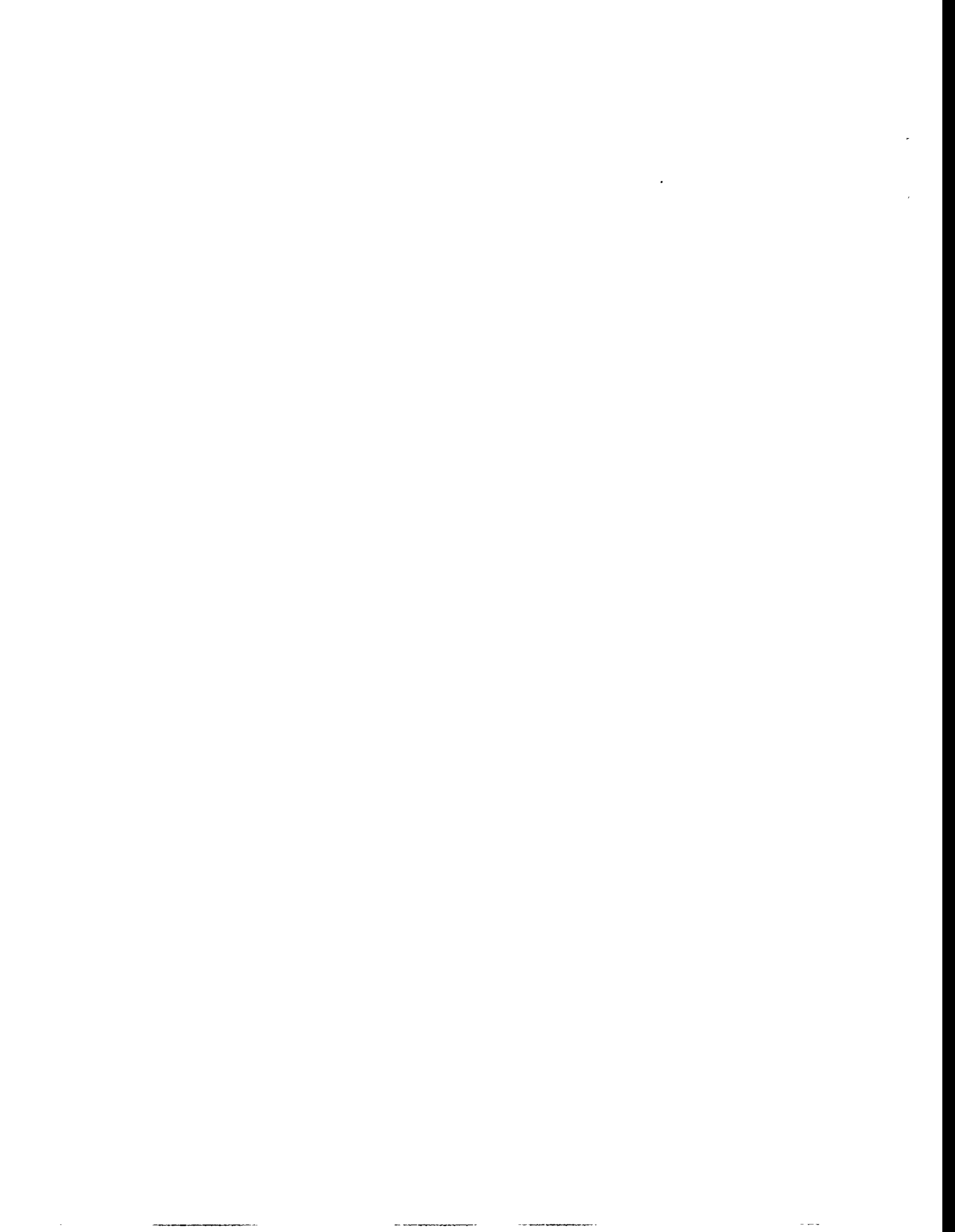
$$I4_i := \begin{cases} c2_i \cdot \int_{blim_i}^{alim_i} g4(\xi) d\xi & \text{if } t_i > D \\ c2_i \cdot \int_0^{alim_i} g4(\xi) d\xi & \text{if } t_i \leq D \end{cases} \quad I5_i := \begin{cases} c3_i \cdot \int_0^{blim_i} g5(\xi) d\xi & \text{if } t_i > D \\ 0 & \text{if } t_i \leq D \end{cases}$$

$$sumint_i := \left( Q_w + \frac{v}{D} \right) \cdot (I3_i - I4_i) + Q_w \cdot I5_i \quad dilutiond_i := c1 \cdot sumint_i$$

$$\max(dilutiond) = 3.7655968 \cdot 10^{-10}$$

$$x = 66528 \cdot \text{ft} \quad \frac{x}{u} = 8.88143 \cdot \text{hr}$$





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