ORNL/TM-12169

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RIVER-RAD: A Computer Code for Simulating the Transport of Radionuclides in Rivers

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MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Date Published - November 1992

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Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ABSTRACT

A screening-level model, RIVER-RAD, has been developed to assess the potential fate of radionuclides released to rivers. The model is simplified in nature and is intended to provide guidance in determining the potential importance of the surface water pathway, relevant transport mechanisms, and key radionuclides in estimating radiological dose to man. The purpose of this report is to provide a description of the model and a user's manual for the FORTRAN computer code.

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1. INTRODUCTION

A screening-level model for simulating the transport of radionuclides in rivers has been developed to assist in determining the importance of this pathway in estimating radiological dose to man. The purpose of the present report is to provide a description of the model RIVER-RAD — a computer program that combines the river portion of the screening-level multimedia model TOX-SCREEN (McDowell-Boyer and Hetrick, 1982; Hetrick and McDowell-Boyer, 1984) and the radioactive decay and daughter buildup algorithms from the MLSOIL model (Sjoreen et al., 1984). In addition, a sediment bed compartment has been included in the model. RIVER-RAD was developed to provide guidance in determining the importance of the surface water pathway, relevant transport mechanisms, and key radionuclides through screening-level calculations.

The RIVER-RAD computer code is written in FORTRAN. The program reads two data files provided by the user — WATER.IN and RADIO.IN — and outputs results in two files — OUTPUT.USR and OUTPUT.RIV (these file names are in OPEN statements in the code and thus can be changed easily). The code is not interactive in that it does not prompt the user for information during execution, but reads all data from the two input files.

A complete description of the model and the assumptions used are given in Sect. 2 of this document. The structure of the program and subprogram descriptions are given in Sect. 3. Section 4 describes how to use RIVER-RAD and gives a complete description of the input data. A description of the code output is given in Sect. 5. A discussion is included in Sect. 6. A listing of the program is given in Appendix A, and Appendix B provides a table of important parameters that are used frequently in the program and their definitions, to allow the user quick access to this information. Example input data are given in Appendix C, and the corresponding output from RIVER-RAD is provided in Appendix D. Appendix E compares model results to analytical calculations.

2. RIVER-RAD — MODEL DESCRIPTION

Radionuclides are transported through a river system in RIVER-RAD via a compartmental linear transfer model (see Fig. 1). The river is divided into reaches (compartments) of equal size, each with a sediment compartment below it. The movement of radionuclides is represented by a series of transfers between the reaches, and between the water and sediment compartments of each reach. Within each reach (for both the water and sediment compartments), the radionuclides are assumed to be uniformly mixed. Upward volatilization is allowed from the water compartment, and the transfer of radionuclides between the reaches is determined by the flow rate of the river. Settling and resuspension velocities determine the transfer of adsorbed radionuclides between the water and sediment compartments. Radioactive decay and decay-product buildup are incorporated into all transport calculations for all radionuclide chains specified by the user. Each nuclide may have unique input and removal rates. Volatilization and radiological decay are considered as linear rate constants in the model.

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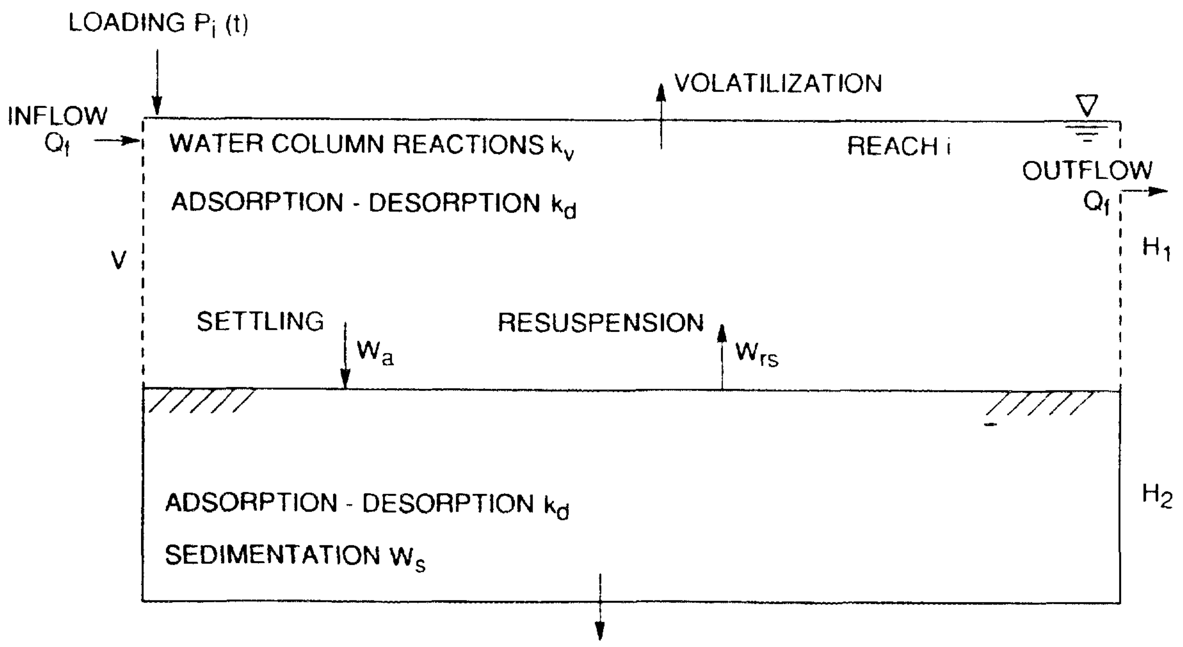

Fig. 1. River system in RIVER-RAD. See page 7 for parameter definitions.

2.1 RADIONUCLIDE TRANSPORT IN A RIVER REACH

The rate of change of activity of radionuclide i (i=1 for parent and i=2,n for daughters) in the water column of a river reach is given by

$$\frac{dA_i}{dt} = P_i(t) - \lambda_i A_i - k_t A_i + \lambda_i \sum_{j=1}^{i-1} b_{ij} A_j - \frac{w_a \alpha_{2w} A_i}{H_1} + \frac{w_{rs} \alpha_{2s} B_i}{H_2} , \tag{1}$$

$$\frac{dB_i}{dt} = -\lambda_i B_i + \lambda_i \sum_{j=1}^{i-1} b_{ij} B_j + \frac{w_a \alpha_{2w} A_i}{H_1} - \frac{w_{rs} \alpha_{2s} B_i}{H_2} - \frac{w_s \alpha_{2s} B_i}{H_2} , \tag{2}$$

where

A_i = activity of nuclide i in the water column (Ci),
A_j = activity of j ($j<i$), a parent of daughter i, in the water column (Ci),
b_{ij} = radioactive branching ratio from nuclide j to nuclide i ($j<i$),
B_i = activity of nuclide i in the sediment column (Ci),
B_j = activity of j ($j<i$), a parent of daughter i, in the sediment column (Ci),
H_1 = depth of the water column (m),
H_2 = depth of the sediment layer (m),
k_t = $Q_f/V + \alpha_{1w} k_v$ (s^{-1}),
k_v = first-order volatilization rate constant (s^{-1}),
$P_i(t)$ = the rate at which radionuclide i enters the reach (Ci/s),
Q_f = river flow rate (m^3/s),
V = volume of reach (m^3),
w_a = settling velocity of adsorbing particles from the water column to the sediment layer (m/s),
w_{rs} = resuspension velocity of the adsorbing particles from the sediment layer to the water column (m/s),
w_s = sedimentation velocity or rate of burial (m/s).
α_{1w} = fraction of radionuclide in dissolved phase in the water column (see Sect. 2.2),
α_{2s} = fraction of radionuclide in particulate phase in the sediment layer (see Sect. 2.2),
α_{2w} = fraction of radionuclide in particulate phase in the water column (see Sect. 2.2),
λ_i = first-order radiological decay constant, nuclide i (s^{-1}).

The activity of all radionuclides in a reach at time t are obtained by solving the set of simultaneous equations represented by Eqs. (1) and (2). In RIVER-RAD the initial activities of the radionuclides are assumed to be zero. In the first reach of the river, a source, $P_i(t)$, can be input for the parent radionuclides only. However, more than one radionuclide chain can be handled in one simulation. Thus, a parent for one chain can be a daughter in another chain that is input to the code. Subsequent river reaches receive input sources for both parent and daughter radionuclides from the preceding reaches.

The system of equations given by Eqs. (1) and (2) can be expressed as a vector-matrix differential equation. The matrix operator method of Lee (1976) is used for solving the system in RIVER-RAD. This method has been described in detail for MLSOIL, a model of radionuclide transport through soil (Sjoreen et al., 1984), and thus will not be discussed here.

2.2 THE DETERMINATION OF DISSOLVED AND SORBED RADIONUCLIDES

Some elements in the lanthanide and actinide series have high distribution coefficients and thus a high affinity for adsorption to sediments. Radionuclide interactions with sediment are modeled by use of the distribution coefficient, K_d, defined as

$$K_d = \frac{\text{atoms of radionuclide adsorbed / g soil}}{\text{atoms of radionuclide dissolved / mL water}} .$$

It follows that the fractions of the radionuclide activity in the dissolved (α_{1w}) and sorbed (α_{2w}) forms of the water column are

$$\alpha_{1w} = \frac{1}{1 + K_d * S} \qquad (3)$$

and

$$\alpha_{2w} = \frac{K_d * S}{1 + K_d * S} , \qquad (4)$$

and in the dissolved (α_{1s}) and sorbed (α_{2s}) forms of the sediment layer, are

$$\alpha_{1s} = \frac{1}{1 + K_d * S_b} \qquad (5)$$

and

$$\alpha_{2s} = \frac{K_d * S_b}{1 + K_d * S_b} , \qquad (6)$$

where

S = suspended sediment concentration in the river (g/mL),
S_b = sediment concentration in the sediment bed (g/mL).

The RIVER-RAD model gives the user the option of either entering or calculating S. The sediment concentration S (g/mL) can be calculated as follows:

$$S = \frac{0.001 * \bar{c}}{\frac{\bar{c}}{\gamma_s} + \frac{100 - \bar{c}}{\gamma}}, \tag{7}$$

where

γ_s = the sediment density (kg/m^3),
γ = water density (1000 kg/m^3),

and the following formula from Laursen (1958) can be used to compute $\bar{c}$:

$$\bar{c} = \sum_i p_i \left(\frac{d_i}{H_1}\right)^{\frac{7}{6}} \left(\frac{\tau_0'}{\tau_c} - 1\right) f\left(\frac{\sqrt{H_1\, s\, g}}{w_a}\right), \tag{8}$$

where

$\bar{c}$ = mean sediment concentration (wt %),
d_i = median sediment particle diameter (m) of size class i,
$f(\,)$ = Laursen's function,
g = acceleration of gravity (m/s^2),
H_1 = water depth (m),
i = sediment size class,
p_i = fraction of bed material of diameter d_i,
s = slope of the river (m/m),
w_a = fall velocity for d_i (m/s),
τ_0' = boundary shear associated with sediment particles (kg/m^2),
τ_c = critical tractive force (kg/m^2).

The boundary shear (τ_0') is estimated from

$$\tau_0' = \frac{\gamma v^2}{590.0928} \left(\frac{d_i}{H_1}\right)^{\frac{1}{3}}, \tag{9}$$

where

v = the flow velocity (m/s).

The constant 590.0928 (m/s^2) is provided in Laursen's work (1958). The critical tractive force τ_c is expressed as

$$\tau_c = \phi(\gamma_s - \gamma) d_i , \tag{10}$$

where

ϕ = the Shields factor (Laursen, 1958).

This latter force represents the limit below which particles of size class i will not move. In RIVER-RAD, values for the parameters w_a and ϕ are computed by use of cubic splines that were fit to curves given in Fields (1976) and Bagnold (1966), respectively. (The user can input an overriding value for w_a if so desired.) Laursen's function f is also computed by use of a cubic spline that was fit to the curve given in Laursen (1958). Only one size sediment class i is allowed by the model. Thus, the only parameters required by RIVER-RAD to use Laursen's formula to calculate sediment concentration are d_i, s, and γ_s. Typical values for these parameters can be found in McDowell-Boyer and Hetrick (1982). All other parameters needed, such as water depth, H_1, and river velocity, v, are always input to RIVER-RAD whether or not Laursen's formula is used.

3. STRUCTURE OF THE RIVER-RAD PROGRAM

This section presents the overall structure of the RIVER-RAD computer program and summarizes each routine in the code. The listing of the program can be found in Appendix A.

3.1 SUBROUTINE STRUCTURE

RIVER-RAD consists of 17 routines in all, 10 that were adapted from the TOX-SCREEN model (Hetrick and McDowell-Boyer, 1984) and 7 that were modified from the MLSOIL model (Sjoreen et al., 1984). The logical structure of RIVER-RAD is diagrammed in Fig. 2. The MAIN program calls subroutine READIN to read the input data, initializes variables needed later, and calls subroutine EXEC to begin execution. If the settling velocity is not known and left as blank or 0.0 in the input data, READIN will call subroutine VFALL to compute it, given the median sediment diameter in the river bed. EXEC first determines if the suspended sediment concentrations for the river are input or calculated using Laursen's formula. If the sediment concentrations have not been input, EXEC calls SEDCON, which in turn calls FUNLAU and SPLEVA, to compute them. Subroutine ALPHA is called by EXEC to compute the dissolved and adsorbed fractions for each radionuclide for both the water column and the sediment layer in the river [see Eqs. (3)-(6)]. EXEC then calls the WATER routine, which passes the source, the initial conditions, the removal rates, and the time step to the DECSRC subroutine, which makes calls to MATACT and its functions (ADDEPS, CPROD, PRODUC, VPRDUC, and CVPRD) to calculate radiologic decay and buildup. These calculations are done for one river reach at a time. Each decay chain is also done separately (i.e., one system of equations). However, results for the same nuclides from different decay chains are added together in the model. The resulting activities of each nuclide in each river reach (for both the water column and sediment layer) are stored in COMMON and the EXEC subroutine calls OUTPUT to write out the results.

The system of equations [Eqs. (1) and (2)] is formulated on a monthly basis, that is, the source terms for the parent radionuclides and the water velocity of the river are input as monthly values. All other input parameters are constant. However, since the equations of the model are written with an explicit time step, a 1-day time step is used in the model to increase accuracy. The output of the model contains end-of-the-month values of radionuclide activities in dissolved, adsorbed, and total form for both the water and sediment compartments for each reach of the river. The monthly results for volatilization represent the summation of results of the 1-day time steps. More details on the output are given in Sect. 5.

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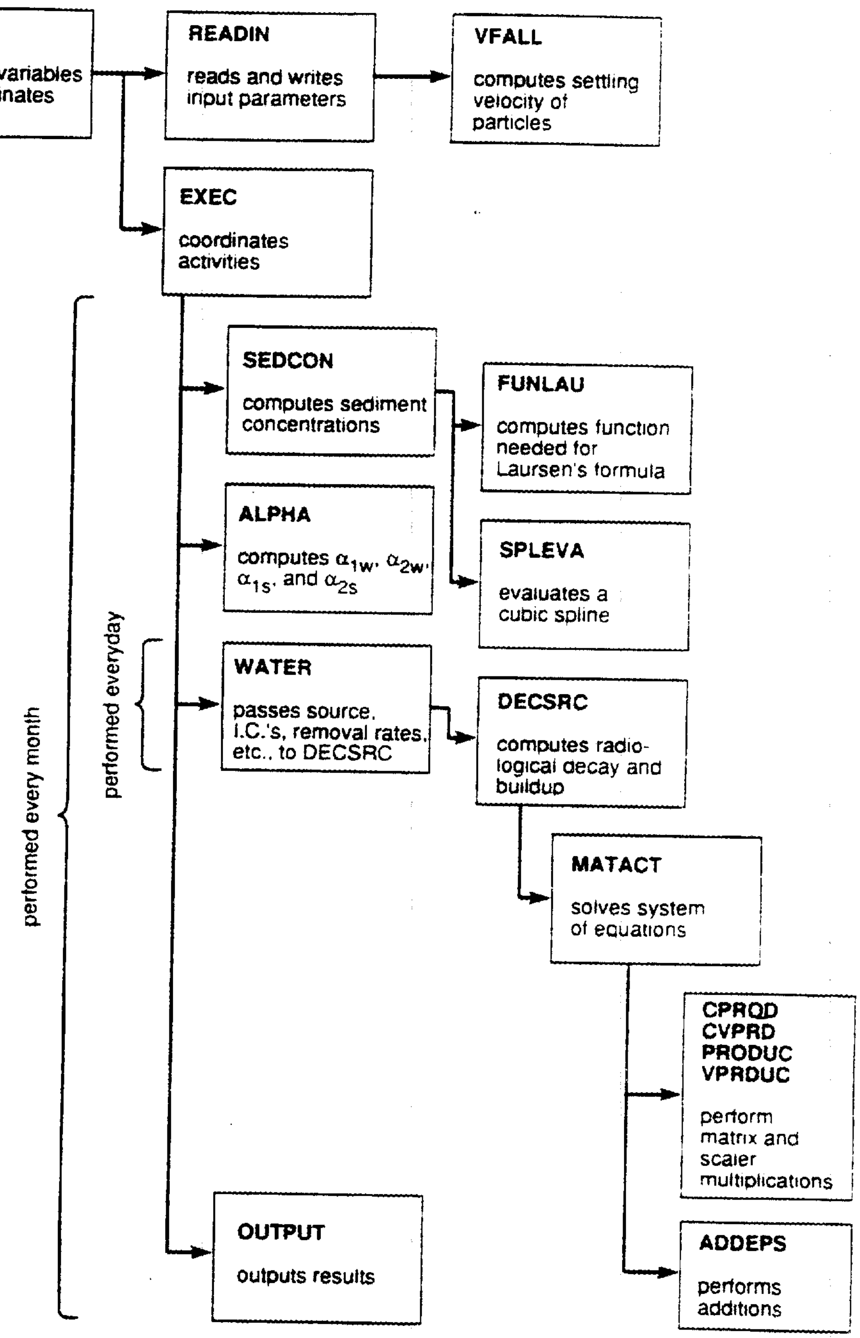

Fig. 2. Structure of RIVER-RAD program.

3.2 SUBPROGRAM DESCRIPTIONS

The RIVER-RAD subroutines are discussed below (in alphabetical order after the MAIN program). If the user desires more details about the code, Appendix B provides a list and description of important parameters in the code, in alphabetical order.

3.2.1 The MAIN Program

The MAIN program of RIVER-RAD calls the subroutine READIN to read the input data. Parameters needed by the model are initialized to 0.0 and stored in COMMON to be passed to other subroutines. Then MAIN calls subroutine EXEC to start the simulation.

3.2.2 Subroutine ALPHA

Subroutine ALPHA computes the fractions in the dissolved (α_{1_w} and α_{1_s}) and sorbed (α_{2_w} and α_{2_s}) forms of each radionuclide [see Eqs. (3)-(6)]. ALPHA computes and stores these fractions separately for each parent radionuclide and its daughters.

3.2.3 Subroutine DECSRC

DECSRC organizes the decay data and removal rates into a matrix array that is passed to subroutine MATACT to solve the system of differential equations described by Eqs. (1) and (2). The resulting activities for all radionuclides and daughters are stored for both the water and sediment compartments. The results are summed by nuclide, regardless of the chains to which they belong. This subroutine was adapted for RIVER-RAD from the MLSOIL computer code (Sjoreen et al., 1984).

3.2.4 Subroutine EXEC

EXEC is the main connecting link between the major routines SEDCON, ALPHA, WATER, and OUTPUT. The number of time steps (NSTEPS) per month used by the model is set in this subroutine. In the present version, NSTEPS is 30, implying 1-day time steps. If monthly sediment concentrations for the river are not input by the user, subroutine SEDCON is called to compute them. EXEC then calls ALPHA (once per month) to compute the fractions for the dissolved and sorbed forms of each radionuclide for the water and sediment compartments. Subroutine WATER is called every time step to compute the activities for the radionuclides in each reach of the river, again for both the water and sediment compartments. Finally, subroutine OUTPUT is called at the end of EXEC (once per month) to write end of the month results to an output file.

3.2.5 Subroutine FUNLAU

This subprogram is used to compute Laursen's function and other parameters needed for computing sediment concentration in the river by Laursen's formula. The Shields factor, ϕ, is computed based on the sediment particle diameter, *d*. This factor is computed by SPLEVA (see Sect. 3.2.10), which performs a cubic spline interpolation. The curve used for ϕ is from Bagnold (1966). The coefficients of the cubic spline were computed separately for the curve and appear in DATA statements in FUNLAU. In other words, FUNLAU passes

d and the appropriate coefficients to FUNCTION SPLEVA, and ϕ is computed. The critical tractive force [Eq. (10)] is then computed using ϕ, the water density, the sediment density, and d. The independent variable needed for Laursen's function [Eq. (8)] is computed using the settling velocity w_a (see subroutine VFALL below), the acceleration of gravity, and input parameters for water depth and river slope. Finally, Laursen's function is computed by use of a cubic spline that was fit to the curve given by Laursen (1958). These results are passed back to subroutine SEDCON, where the sediment concentration is computed.

3.2.6 Subroutine MATACT

MATACT solves the system of linear ordinary differential equations defined in Eqs. (1) and (2) using matrix methods to obtain the activity of each nuclide. The solution is based on the method described in Sjoreen et al. (1984). Four subroutines, CPROD, PRODUC, VPRDUC, and CVPRD, are called by MATACT to perform matrix and scalar multiplication of matrices and vectors. Function ADDEPS is used to perform additions; an addition is set to zero if it is less than machine epsilon to prevent loss of significance errors.

3.2.7 Subroutine OUTPUT

The sole purpose of subroutine OUTPUT is to write out results from the RIVER-RAD calculations to a file named OUTPUT.RIV. More details about the output are given in Sects. 4 and 5.

3.2.8 Subroutine READIN

The READIN subroutine reads the input data for the RIVER-RAD model from two files: RADIO.IN and WATER.IN. These input data are discussed thoroughly in the next section. After reading the data, READIN outputs the data into the file OUTPUT.USR. This helps the user determine whether the data were input correctly. Where appropriate, various warning messages are written into this file if the program can recognize that the data are incorrect or illogical. See Sect. 5 on output for further discussion of this file.

READIN has the option to call subroutine VFALL if the settling velocity (parameter SETVEL) is not known and is left blank or set to 0.0 by the user in input file WATER.IN. READIN calls VFALL to compute the settling velocity given the median sediment diameter.

3.2.9 Subroutine SEDCON

This subroutine is an optional routine that can be used to compute suspended sediment concentrations for the river if these values are unknown. Values for the median sediment diameter of the river bed, sediment density, water density, average depth, and slope of the river must be input in READIN to use SEDCON. SEDCON will call FUNLAU (see Sect. 3.2.5) to assist in computing the sediment concentration of the river using Laursen's formula (Laursen, 1958).

3.2.10 Function SPLEVA

The sole purpose of SPLEVA is to evaluate a cubic spline function using Horner's rule (Forsythe et al., 1977). SPLEVA is used by both subroutine SEDCON and FUNLAU.

3.2.11 Subroutine VFALL

This subroutine is used to compute the sediment fall or settling velocity, w_a, based on the median sediment diameter d. A cubic spline interpolation is performed by SPLEVA in this computation. The curve used for the fall velocity is from Fields (1976). The coefficients of the cubic spline were computed separately for the curve and appear in DATA statements in VFALL (i.e., VFALL passes d and the cubic spline coefficients for the curve to FUNCTION SPLEVA, and w_a is calculated).

3.2.11 Subroutine WATER

This subprogram passes the radionuclide source term (parent radionuclides into first reach of river only), the removal rates for each radionuclide from one reach to the next plus the volatilization rate, the removal rate of each radionuclide from the water compartment due to settling, the removal rate from the sediment compartment due to resuspension and sedimentation, and the initial activities of the nuclides for each reach (for each time step one reach at a time) to subroutine DECSRC, where the decay and daughter ingrowth are calculated. Upon return from DECSRC, the activities for each reach are stored to be used as the initial activities for the next time step and for flow from reach to reach. Likewise, the activities of the radionuclides in the sediment compartment below each reach are stored. Also, the volatilization from the river is summed from all reaches for each month and stored.

4. RIVER-RAD OPERATION

This section presents the necessary information on how to run the RIVER-RAD computer code. A complete discussion of input data is included. While reading this section, it will be helpful to refer to Appendix C, which contains sample input data.

4.1 MODE OF OPERATION

Before the execution of RIVER-RAD is possible, the user must first prepare two input data files: RADIO.IN and WATER.IN. These files are requested by OPEN statements within the code. RADIO.IN contains the listing of the parent radionuclides and their daughters, as well as their decay matrices (see Appendix C). This file is provided to the user with the code, but instructions will be given here so that the user can modify RADIO.IN if necessary. WATER.IN includes information, such as the number of years the user wants the simulation to run, the names and source terms of the parent nuclides, the river water velocity, the dimensions for the reaches, the volatilization rates and distribution coefficients K_d for the radionuclides, and the sediment parameters (see Appendix C). These files are described in detail below.

During execution, RIVER-RAD writes results into two files: OUTPUT.USR and OUTPUT.RIV (these files are also specified by OPEN statements in the code). These output files are discussed further in Sect. 5.

RIVER-RAD has been run on several different computers, including IBM compatible PC's (286, 386, and 486), an IBM RISC 6000, and a VMS VAX 8600. The following section discusses in detail how the input data should be constructed by the user.

4.2 INPUT DATA

Tables 1 and 2 will aid the user in preparing the input files WATER.IN and RADIO.IN, respectively. Three types of standard FORTRAN format codes appear in Tables 1 and 2: the A, E, and I formats. The A format code is used in transmitting data that are in character format, the E format code is used in transmitting real data, and the I format code is for integer data. For the E and I formats, leading, embedded, and trailing blanks in a field of the input card are interpreted as zeros. In E format, if the decimal point is present, its position overrides the position indicated by the *d* portion of the format field descriptor (Ew.d), and the number of positions specified by the *w* portion of this field must include a place for it. For E formats, the E may be omitted from the exponent if the exponent is signed (i.e., 1.0E+1 may be typed 1.0+1).

Table 1 is used to prepare file WATER.IN. Note that the names of the parent radionuclides (parameter NUC, card set 3, Table 1) in file WATER.IN must be read exactly as they appear in file RADIO.IN (see parameter DAUGHTER, card 2, Table 2). The code reads the parent nuclide name NUC from file WATER.IN, then searches file RADIO.IN for the same name in order to retrieve names of the daughters as well as the decay data. In the example files given in Appendix C, the names of the radionuclides are left justified in the field of character format A8. The nuclide names are given as isotope symbols (e.g., SR-90, Y-90, etc.). Also, in file WATER.IN, the first 20 columns of each line are reserved for comments, such as the name(s) of the parameter(s) that is(are) included on that line (e.g., see the file in Appendix C).

For the volatilization rate, k_v, and the soil-water distribution coefficient, k_d (Table 1, card set 8), the values of the parent are given first, followed by values for each of the daughters given in the order that they are read (see Table 2, card 2). If more than one parent is desired in a simulation, then values for k_v and k_d are given for parent number 1 (see Table 1, card set 3) and its daughters first, followed by parent number 2 and its daughters, etc. Values are always given for each daughter, even if a daughter had appeared previously for another parent. Note that data for k_v and k_d are not given for short-lived daughters.

The user has the option of either entering the settling velocity w_a (Table 1, card set 11) or leaving it blank or 0.0 and the code will compute it via subroutine VFALL. In either case, the parameter (SETVEL) is written to file OUTPUT.RIV.

Table 1. Water parameters input sequence (file WATER.IN)

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
1	(28X,I2)	JYRS	Integer	29-30 (Right justified)	(-)	Number of years to be simulated; limited to 10 due to dimensioning
2	(28X,I2)	NNUC	Integer	29-30 (Right justified)	(-)	Number of parent radionuclides to be simulated; limited to 10 due to dimensioning
Card Set 3 is repeated for each parent nuclide (i.e., enter the name for nuclide I=1 on line 3, I=2 on the next line, etc.)						
3	(20X,A8)	NUC (I) (I=1, NNUC)	Character	21-28	(-)	Radionuclide name of parent nuclide I=1. Enter NNUC lines
Set 4 is repeated for each year and radionuclide. The source for parent I=1 is entered on two lines for year IYR=1, the next two lines for IYR=2, etc. for JYRS. The source for radionuclide I=2 would follow, with data for each year on 2 lines. Repeat for NNUC parents. See Appendix C for examples.						
4 (line 1)	(20X,6E10.3)	WQINR (I,MON,IYR)	Real	21-30 I=1,MON=1,IYR=1 31-40 I=1,MON=2,IYR=1 . . 71-80 I=1,MON=6,IYR=1	Ci/s	Radionuclide source rate into reach 1 of the river for parent I, month MON and year IYR. MON=1 signifies the month October
4 (line 2)	(20X,6E10.3)	WQINR (I,MON,IYR)	Real	21-30 I=1, MON=7,IYR=1 . . 71-80 I=1,MON=12,IYR=1	Ci/s	
5 (line 1)	(20X,6E10.3)	WVELR (MON,IYR)	Real	21-30 for MON=1,IYR=1 31-40 for MON=2,IYR=1 . . 71-80 for MON=6,IYR=1	m/s	The average water velocity of the river for month MON and year IYR. Repeat Set 5 for each year for JYRS years
5 (line 2)	(20X,6E10.3)	WVELR (MON,IYR)	Real	21-30 for MON=7, IYR=1 . . 71-80 for MON=12,IYR=1	m/s	
6	(28X,I2)	NR	Integer	29-30 (Right justified)	(-)	Number of reaches that river is broken into; limited to 20 due to dimensioning

Table 1 (continued)

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
7	(20X,3E10.3)	WLENR	Real	21-30	m	Length of each river reach (all reaches have same dimensions)
		WWIDR	Real	31-40	m	Average width of the river
		WDEPR	Real	41-50	m	Average depth of the river

Repeat set 8 for each parent and its daughters for each chain I. There are SIZE(1)+SIZE(2)+...+SIZE(NNUC) lines in this set.

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
8	(20X,2E10.3)	WKVR (J, I) I=1, NNUC J=1, SIZE (I) (see Table 2 for definition of SIZE)	Real	21-30	s^{-1}	Volatilization rate constant for daughter J of parent I (J=1 is parent and J=2, SIZE (I) are daughters). See Sect. 4.2 for more details
		SWKDR (J,I) I=1, NNUC J=1, SIZE (I)	Real	31-40	(atoms/g) / (atoms/mL)	Soil-water distribution coefficient for parent I, daughter J (see explanation for WKVR)
9	(26X,A4)	SEDRIV	Character	27-30 (Right justified)	(-)	If total suspended sediment concentration in the river is known, type YES in columns 28-30; otherwise, type NO in columns 29-30

If SEDRIV is YES, then card set 10 is:

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
10 (line 1)	(20X,6E10.3)	SEDCR (MON, IYR)	Real	21-30 for MON=1, IYR=1 31-40 for MON=2, IYR=1 . . 71-80 for MON=6, IYR=1	kg/m^3	Average suspended sediment concentration in river for month MON and year IYR. Repeat Set 10 for each year for JYRS years. MON=1 signifies month of October
10 (line 2)	(20X,6E10.3)	SEDCR (MON, IYR)	Real	21-30 for MON=7, IYR=1 . . 71-80 for MON=12, IYR=1		

Table 1 (continued)

If SEDRIV is NO, then card set 10 is as follows (only one line):

Card set	Format	Parameter name	Type	Column postion	Units	Definitions and comments
10	(20X,3E10.3)	DENSDR	Real	21-30	g/cm^3	Sediment density in river
		DENWR	Real	31-40	g/cm^3	Water density
		SLOPER	Real	41-50	(-)	Slope of river bed

For card set 11, typical values can be found in Ditoro et al. (1981).

Card set	Format	Parameter name	Type	Column postion	Units	Definitions and comments
11	(20X,6E10.3)	DIASDR	Real	21-30	mm	Median sediment diameter
		SEDCS	Real	31-40	kg/m^3	Solids concentation in sediment layer
		SDEPR	Real	41-50	m	Depth of sediment layer
		RESVEL	Real	51-60	mm/yr	Sediment resuspension velocity
		SEDVEL	Real	61-70	mm/yr	Sedimentation velocity from bottom of sediment layer
		SETVEL	Real	71-80	m/s	The settling velocity (if left blank or 0.0, VFALL subroutine used to compute it)

Table 2. Nuclides Decay Data Parameters Input Sequence (file RADIO.IN)

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
1	(2I3)	SIZE(I)	Integer	1-3 (Right justified)	(-)	The length of the radionuclide chain. Includes the parent plus the number of daughters. I is the index for the chain
		NEXTRA(I)	Integer	4-6 (Right justified)	(-)	The number of short-lived daughters for chain I
2	(1X,8(A8,2X))	DAUGH-TER (J,I) J=1, SIZE (I)	Character	2-9 for J=1 10-17 for J=2 18-25 for J=3 etc.	(-)	The names of parent and its daughters. I is the index for the chain; J=1 is the index for the parent and J=2 to SIZE (I) are indices for daughters

If NEXTRA (I) is not 0, then the following card is read for each short-lived daughter for chain I just read (if NEXTRA (I) is 0 then skip the next line):

Card set	Format	Parameter name	Type	Column position	Units	Definitions and comments
3	(A8,I3)	EXNAME (J,I) J=1, NEXTRA(I)	Character	1-8	(-)	Name of short-lived daughter for chain I. If NEXTRA > 1, next line would contain name of second short-lived daughter, etc.
		PARNUM (J,I) J=1, NEXTRA (I)	Integer	9-11 (Right justified)	(-)	Number of the index in parameter DAUGHTER that is parent for short-lived daughter EXNAME(J,I)
4	(8E10.3)	DECAY (K,J,I) J=1,SIZE(I) K=1,SIZE(I)	Real	1-10 for J=1,K=1 11-20 for J=1,K=2 etc. for SIZE(I) lines of matrix		Decay matrix for chain I (see Sect. 4.2). There are SIZE(I) lines in this set

The decay matrix (Table 2, card set 4) is defined as follows:

$$a_{ii} = -\lambda_i ,$$

$$a_{ij} = \lambda_i b_{ij} ,$$

where

λ_i = the decay constant for nuclide i in s^{-1}. The decay constant = ln(2)/half-life.
b_{ij} = the branching fraction from nuclide j to nuclide i (unitless).

The matrix is lower triangular. Decay data for short-lived daughters are omitted from the decay matrices because their activity is set equal to that computed for their parent (see card set 3 of Table 2).

5. DESCRIPTION OF CODE OUTPUT

This section gives a detailed description of what is written into the two output files OUTPUT.USR and OUTPUT.RIV. The reader is referred to Appendix D, which contains the RIVER-RAD output that was written during execution of the code using the sample input data from Appendix C.

5.1 RESULTS WRITTEN TO OUTPUT.USR

The input data to RIVER-RAD are written to file OUTPUT.USR so that the user can determine if they were input correctly. The input parameter names, the definitions, the units, and the values for the parameters are listed in this file. The file includes a listing of the daughters for the parent nuclides (the parent names come from file WATER.IN, and the daughters of the parents are read from RADIO.IN). The model flag (SEDRIV) that the user inputs to determine whether the suspended sediment concentrations of the river are either input directly or are calculated in the model is listed, and the option chosen is explained. Following the definitions of the parameters, a table is printed showing the monthly magnitudes of the source terms for each of the parent nuclides.

Where feasible, the RIVER-RAD computer code checks the input data, and if an error (an obviously illogical value or choice) is detected, a message is printed into file OUTPUT.USR and execution stops. For example, if the parameter NUC(I) (Table 1, card set 3) is not input correctly so that it will match the parameter DAUGHTER(1,I) (Table 2, card 2), the following message will appear: "NUCLIDE ______ NOT IN DATABASE - STOP", where ______ is the name that the user typed for parameter NUC in WATER.IN. Numerous other checks such as this one can be found in the computer program. Also, some checks are made during actual execution of RIVER-RAD (i.e., after the input data are read). If errors are detected, messages will be written into this file. Thus, the user should always check file OUTPUT.USR carefully, especially if execution stops prematurely.

5.2 RESULTS WRITTEN TO OUTPUT.RIV

The calculated monthly radionuclide activities and media interaction terms are printed into a file named OUTPUT.RIV. The contaminated surface area of the river is printed first. Thereafter, for each month, the activity (*Ci*) for each radionuclide (in the dissolved or neutral form, the adsorbed form, and the total form) is printed for each river reach for both the water and sediment compartments. Also, the media interaction rates in Ci/mon are printed for each radionuclide. Note that volatilization is the only interaction term considered in the RIVER-RAD model at present. All the other media interaction rates (deposition on water, surface runoff, groundwater runoff, and washload) are assumed to be 0.0 in the present model and are printed as such in OUTPUT.RIV. See Appendix D for examples.

6. DISCUSSION

This report has provided a description and subroutine structure of the RIVER-RAD model, input requirements and format, and description of output from the RIVER-RAD computer code. The RIVER-RAD model is a combination of the river portion of the TOX-SCREEN program (Hetrick and McDowell-Boyer, 1984), modified to include a sediment compartment, and the routines used to compute radioactive decay and buildup from the MLSOIL model (Sjoreen et al., 1984). Thus, proven routines have been used in the development of RIVER-RAD. All the subprograms of RIVER-RAD have been tested by doing preliminary stand-alone computer runs for each routine. For example, the results computed by subroutine SEDCON were checked by writing a driver routine that supplied SEDCON with the appropriate parameters. Where possible, these results were compared with hand computations.

Once the subroutines were assembled to form RIVER-RAD, numerous additional checks were made to ensure the results were correct. For example, the results for RIVER-RAD were compared with TOX-SCREEN results (using the river portion only) for isotopes that had no daughters. The results from the two models matched very closely; note that the solution techniques differ between the two models. To check results for daughters, a "regular" run was performed for an isotope and its daughters, using three river reaches and assuming there was no settling to the sediment compartment (Case 1). The RIVER-RAD program was modified temporarily to take the results for the parent and daughters from Case 1 for the first reach and input these results to the first reach (Case 2). The results for the first reach from Case 2 were found to equal the results from the second reach in Case 1. Also, the model was run to steady state using a constant source term and constant river water velocity. The steady-state results compared closely with the analytical solutions for both the water and sediment compartments. Thus, much effort was put forth in checking and rechecking code calculations.

RIVER-RAD results from the first reach of a river are compared with an analytical equation for ingrowth of activity of a radioactive daughter in Appendix E. The code was temporarily modified not to allow any settling to the sediment compartment for these results.

The equation cannot be compared with model results for downstream reaches below the first reach because these reaches receive daughters.

At present, RIVER-RAD does not include media interaction rates, such as deposition on water, surface runoff, groundwater runoff, and washload. Thus, the only way to input such rates is to include them in the input source term. RIVER-RAD has the capability to easily add media interaction terms if needed.

The input data in Appendix C used for the sample computer runs that produced the output in Appendix D were hypothetical. It was the authors' intent to show the capabilities of the model through use of these examples, not to show an actual application. It is hoped that RIVER-RAD can be used as a screening device in identifying radionuclides that are highly unlikely to pose a problem even under conservative assumptions.

REFERENCES

1. R. A. Bagnold, *An Approach to the Sediment Transport Problem from General Physics*, Geological Survey Professional Paper 422-I, U.S. Government Printing Office (1966).

2. D. M. DiToro, D. J. O'Connor, R. V. Thomann, and J. P. St. John, *Analysis of Fate of Chemicals in Receiving Waters - Phase I*, HydroQual, Inc., Mahwah, NJ (1981).

3. D. E. Fields, *CHNSED: Simulation of Sediment and Trace Contaminant Transport with Sediment/Contaminant Interaction*, ORNL/NSF/EATC-19, Oak Ridge National Laboratory (1976).

4. G. E. Forsythe, M. A. Malcolm, and C. B. Moler, *Computer Methods for Mathematical Computations*, Prentice-Hall, Inc. (1977).

5. D. M. Hetrick and L. M. McDowell-Boyer, *User's Manual for TOX-SCREEN: A Multimedia Screening-Level Program for Assessing the Potential Fate of Chemicals Released to the Environment*, ORNL-6041, EPA-560/5-83-024, Oak Ridge National Laboratory (1984).

6. E. M. Laursen, *The Total Sediment Load of Streams*, Paper #1530 in Proceedings of ASCE 84, HY1 (1958).

7. C. E. Lee, *The Calculation of Isotopic Mass and Energy Production by a Matrix Operator Method*, LA-6483-MS (1976).

8. L. M. McDowell-Boyer and D. M. Hetrick, *A Multimedia Screening-Level Model for Assessing the Potential Fate of Chemicals Released to the Environment*, ORNL/TM-8334, Oak Ridge National Laboratory (1982)

9. A. L. Sjoreen, D. C. Kocher, G. G. Killough, and C. W. Miller, *MLSOIL and DFSOIL — Computer Codes to Estimate Effective Ground Surface Concentrations for Dose Computations*, ORNL-5974, Oak Ridge National Laboratory (1984).

APPENDIX A

LISTING OF RIVER-RAD

The MAIN program is given first, followed by the subprograms in alphabetical order.

```
C
C                                  RIVER-RAD
C                 RIVER SCREENING-LEVEL MODEL FOR RADIONUCLIDES
C                D.M. HETRICK, L.M. MCDOWELL-BOYER, A.L. SJOREEN,
C                       D.J. THORNE, AND  M.R. PATTERSON
C                         OAK RIDGE NATIONAL LABORATORY
C.                                JUNE, 1992
C   DEVELOPED TO ASSESS THE POTENTIAL FOR ENVIRONMENTAL ACCUMULATION OF
C   RADIONUCLIDES RELEASED TO SURFACE WATER (RIVERS).
C
      PARAMETER (NDAU=10,NDAU2=20,NNUCL=10,NUCALL=200,NYRS=10,NREACH=20)
      COMMON/MEDIA/AWQINR,WAQOUR(NUCALL,NREACH),
     $             SWQINR,SWQOUR,SURROF,GRWROF
      COMMON/WPARR/WVELR(12,NYRS),WQINR(NNUCL,12,NYRS),
     $             CONRIV(NDAU2,NNUCL,NREACH),CONOLD(NDAU,NNUCL),
     $             NR,WWIDR,WLENR,WDEPR,WVOLR,AREAR
      REAL*8 CONOLD,CONRIV
C
C --- READ DATA
C
      CALL READIN
C
C --- INITIALIZE VARIABLES (VOLATILIZATION TERMS,
C --- RUNOFF TERMS, ETC.)
C
      DO 30 K=1,NR
      DO 20 J=1,NNUCL
      DO 20 I=1,NDAU
      CONOLD(I,J)=0.0
      CONRIV(I,J,K)=0.0
20    CONRIV(I+NDAU,J,K)=0.0
30    CONTINUE
      SURROF=0.0
      GRWROF=0.0
C
C --- CALL ROUTINES  FOR EXECUTION LEVEL
C
      CALL EXEC
C
C --- END OF EXECUTION -STOP
C
      STOP
      END
```

```
      SUBROUTINE ALPHA
      PARAMETER (NDAU=10,NNUCL=10,NYRS=10)
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $              SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      COMMON/EQUIL/SWKDR(NDAU,NNUCL)
      COMMON/FLAGS/SEDRIV
      COMMON/ALPHAS/A1R(NDAU,NNUCL),A2R(NDAU,NNUCL),A1S(NDAU,NNUCL),
     $              A2S(NDAU,NNUCL)
      COMMON/NUM/NNUC,NNEW,SIZE(NNUCL),NEXTRA(NNUCL),PARNUM(2,NNUCL)
      INTEGER SIZE,PARNUM
      DATA EPS/1.0E-5/
      IWP=12
C
C
C CONSDR IS IN KG/M**3, NEED G/ML, SO MULTIPLY BY .001
C COMPUTE ADSORPTION TERM (ADSORB) AND DENOMINATOR (DENOM)
C
      DO 20 I=1,NNUC
      DO 20 J=1,SIZE(I)
      ADSORB=SWKDR(J,I)*CONSDR*.001
      DENOM=1.0+ADSORB
      ADSORBS=SWKDR(J,I)*SEDCS*.001
      DENOMS=1.0+ADSORBS
C
C COMPUTE ALPHA 1 & 2 FOR RIVER (WATER & SEDIMENT).
C
      A1R(J,I)=1.0/DENOM
      A2R(J,I)=ADSORB/DENOM
      A1S(J,I)=1.0/DENOMS
      A2S(J,I)=ADSORBS/DENOMS
      IF((A1R(J,I)+A2R(J,I)-1.0).LT.EPS.AND.
     $   (A1S(J,I)+A2S(J,I)-1.0).LT.EPS)GO TO 20
C
C WRITE ERROR MESSAGE
C
      WRITE(IWP,10)
 10   FORMAT(1X,'ERROR IN ALPHA ROUTINE, ALPHAS FOR RIVER DO NOT ADD UP
     $TO 1.0')
      STOP
 20   CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE CPROD(A,B,C,M,N)
      REAL*8 A(M,M),B,C(M,M)
      DO 10 I=1,N
        DO 10 J=1,N
  10      A(I,J)=B*C(I,J)
      RETURN
      END
```

```
      SUBROUTINE CVPRD(A,B,C,M,N)
      REAL*8 A(M),C(M),B
      DO 10 I=1,N
  10    A(I)=B*C(I)
      RETURN
      END
```

```
      subroutine DECSRC(i,k,A0,P,TIME,LAMR,ISTEP,NSTEPS,A)
C***********************************************************************
C
C     DECSRC
C     Computes decay of source term; uses GG Killough's algorithm
C     for Lee's method for solving the decay matrices
C
C     AL Sjoreen
C
C     Oak Ridge National Laboratory
C     P.O. Box 2008
C     Oak Ridge, TN 37831
C
C     Created: October, 1989
C     Updated: 3/15/90
C     MODIFIED: 4/14/92 BY D.M. HETRICK FOR USE IN RIVER-RAD
C
C     Makes calls to: MATACT and its functions
c
c  NOTE!!  this subroutine assumes that all source nuclide names will be
c  found in the data base.
C
C***********************************************************************
      PARAMETER (NNUCL=10,NDAU=10,NDAU2=20,NUCALL=200,NREACH=20)
      COMMON/ALPHAS/A1R(NDAU,NNUCL),A2R(NDAU,NNUCL),A1S(NDAU,NNUCL),
     $              A2S(NDAU,NNUCL)
      COMMON/WRATES/WKVR(NDAU,NNUCL)
      COMMON/NUM/NNUC,NNEW,SIZE(NNUCL),NEXTRA(NNUCL),PARNUM(2,NNUCL)
      COMMON/DEC/DECAY(NDAU,NDAU,NNUCL),DECAYSRC(NUCALL)
      COMMON/CHAR/NUC(NUCALL),DAUGHTER(NDAU,NNUCL),EXNAME(2,NNUCL)
      COMMON/OUT/WVOLAR(NUCALL),ACTR1(NUCALL,NREACH),
     $           ACTR2(NUCALL,NREACH),TOTACR(NUCALL,NREACH)
      COMMON/MEDIA/AWQINR,WAQOUR(NUCALL,NREACH),
     $             SWQINR,SWQOUR,SURROF,GRWROF
      CHARACTER*8 NUC,DAUGHTER,EXNAME
      REAL*8 LAMR(NDAU2),TIME
C      REAL intdecsr(NUCALL)
      REAL*8 C(NDAU2,NDAU2),A0(NDAU2),P(NDAU2),A(NDAU2),AI(NDAU2)
      integer size,actout(NUCALL),parnum
c time is in seconds
c
c  i is the index of the source nuclide
c  nnew is the total number of source nuclides plus daughters
c
      actout(1) = i
c
c  check if any members of this chain are already present in another chain
      do 40 mm=2,size(i)
        do 35 n=1,nnew
          if(nuc(n).eq.daughter(mm,i)) then
            actout(mm) = n
            go to 40
          endif
  35      continue
        nnew = nnew+1
        nuc(nnew) = daughter(mm,i)
        actout(mm) = nnew
  40    continue
      if(nextra(i).le.0)go to 52
c
c nextra(i) is the number of short-lived daughters for chain i
c
      do 50 mm=1,nextra(i)
        do 45 n=1,nnew
          if(nuc(n).eq.exname(mm,i)) then
            actout(mm+size(i)) = n
            go to 50
          endif
  45      continue
```

```
        nnew = nnew+1
        nuc(nnew) = exname(mm,i)
        actout(mm+size(i)) = nnew
   50   continue
   52   continue
c
c set data for solution subroutine call
c
        do 60 mm=1,size(i)
          mmpsiz=mm+size(i)
          a(mm) = 0.d0
          ai(mm) = 0.d0
          a(mmpsiz)=0.0d0
          ai(mmpsiz)=0.0d0
          do 55 n=1,size(i)
            c(n+size(i),mmpsiz)=decay(mm,n,i)
   55       c(n,mm) = decay(mm,n,i)
            c(mmpsiz,mmpsiz)=c(mmpsiz,mmpsiz)-lamr(mmpsiz)
   60       c(mm,mm) = c(mm,mm) - lamr(mm)
        nsiz2=size(i)*2
        call matact(C,A0,P,ndau2,nsiz2,time,A,AI)
c  integrated result is in Ci(or Bq)-yr
        do 65 n=1,size(i)
c          intdecsr(actout(n)) = intdecsr(actout(n)) + ai(n)/secyr
           decaysrc(actout(n)) = decaysrc(actout(n)) + a(n)
           decaysrc(actout(n)+nnew) = decaysrc(actout(n)+nnew) +
     >                                a(n+size(i))
           waqour(actout(n),k)=waqour(actout(n),k)+
     >                         a(n)*wkvr(n,i)*alr(n,i)
           if(istep.lt.nsteps)go to 65
           actr1(actout(n),k)=actr1(actout(n),k)+a(n)*alr(n,i)
           actr2(actout(n),k)=actr2(actout(n),k)+a(n)*a2r(n,i)
           actr1(actout(n)+nnew,k)=actr1(actout(n)+nnew,k)+
     >                             a(n+size(i))*als(n,i)
           actr2(actout(n)+nnew,k)=actr2(actout(n)+nnew,k)+
     >                             a(n+size(i))*a2s(n,i)
           totacr(actout(n),k)=decaysrc(actout(n))
           totacr(actout(n)+nnew,k)=decaysrc(actout(n)+nnew)
   65   continue
c  store results for short-lived daughters
        if(nextra(i).le.0)return
        do 70 n=1,nextra(i)
        nn = n+size(i)
c          intdecsr(actout(nn)) = intdecsr(actout(nn)) +
c     -      ai(parnum(n))/secyr
        decaysrc(actout(nn)) = decaysrc(actout(nn)) + a(parnum(n,i))
        decaysrc(actout(nn)+nnew)=decaysrc(actout(nn)+nnew)+
     >                          a(parnum(n,i)+size(i))
        waqour(actout(nn),k)=waqour(actout(nn),k)+a(parnum(n,i))*
     >                     wkvr(parnum(n,i),i)*alr(parnum(n,i),i)
        if(istep.lt.nsteps)go to 70
        actr1(actout(nn),k)=actr1(actout(nn),k)+a(parnum(n,i))*
     >                     alr(parnum(n,i),i)
        actr2(actout(nn),k)=actr2(actout(nn),k)+a(parnum(n,i))*
     >                     a2r(parnum(n,i),i)
        totacr(actout(nn),k)=decaysrc(actout(nn))
        actr1(actout(nn)+nnew,k)=actr1(actout(nn)+nnew,k)+
     >         a(parnum(n,i)+size(i))*als(parnum(n,i),i)
        actr2(actout(nn)+nnew,k)=actr2(actout(nn)+nnew,k)+
     >         a(parnum(n,i)+size(i))*a2s(parnum(n,i),i)
        totacr(actout(nn)+nnew,k)=decaysrc(actout(nn)+nnew)
   70   continue
      return
      end
```

```
      SUBROUTINE EXEC
C     ========================
C
      PARAMETER (NUCALL=200,NYRS=10,NREACH=20)
      COMMON /EX/ JYRS
      COMMON/MEDIA/AWQINR,WAQOUR(NUCALL,NREACH),
     $             SWQINR,SWQOUR,SURROF,GRWROF
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $             SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      COMMON/FLAGS/SEDRIV
      REAL NO
      DATA NO/4H  NO/,YES/4H YES/
C
C --- RUN FOR JYRS
C
C
C --- TIME STEP IS 1 DAY, NSTEPS IS NUMBER OF STEPS PER MONTH
C
      DT=1.0*24.0*3600.0
      NSTEPS=30
      DO 20 I=1,JYRS
C
      DO 20 IMO=1,12
C
C --- FIND SEDIMENT CONCENTRATION
C
      IF(SEDRIV.EQ.YES) CONSDR=SEDCR(IMO,I)
      IF(SEDRIV.EQ.NO) CALL SEDCON(IMO,I)
      CALL ALPHA
C
C
C --- DO MONTHLY RADIONUCLIDE CYCLE SIMULATION
C
      DO 10 ISTEP=1,NSTEPS
C
C
      AWQINR=0.0
      SWQINR=SWQOUR
C
C CALCULATE SOIL TO WATER RATE
C
      SWQOUR=(SURROF+GRWROF)
C
C
C CALL WATER SUBROUTINE FOR CALCULATION OF WATER ACTIVITIES
C & INTERACTION TERMS BETWEEN WATER & AIR
C
      CALL WATER(IMO,I,DT,ISTEP,NSTEPS)
 10   CONTINUE
C
C
C OUTPUT RESULTS
C
      CALL OUTPUT(IMO,I)
 20   CONTINUE
C
C --- RETURN TO MAIN PROGRAM
C
      RETURN
      END
```

```
      SUBROUTINE FUNLAU(DIASED,DENSED,DENWAT,WDEPTH,SLOPE,TCRIT,
     $                  FUNC,TOPFAC,RATIO)
      PARAMETER (NYRS=10)
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $              SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      DIMENSION SVFL(26),F(26),BFUNC(26),CFUNC(26),DFUNC(26),DIATHE(22),
     $ SHIELD(22),BTHETA(22),CTHETA(22),DTHETA(22)
C
C DIATHE, SHIELD, BTHETA, CTHETA, & DTHETA ARE PARAMETERS
C NEEDED IN SPLINE CALCULATION OF SHIELDS FACTOR (THETA) BELOW.
C
      DATA DIATHE/.01,.015,.02,.03,.04,.06,.08,.1,.15,.2,.3,.4,.6,.8,
     $ 1.0,1.5,2.0,3.0,4.0,6.0,8.0,10.0/
      DATA SHIELD/1.0,.60,.43,.275,.20,.17,.12,.085,.06,.05,.038,.034,
     $ .032,.033,.034,.04,.045,.053,.056,.059,.06,.06/
      DATA BTHETA/-112.5423,-51.66603,-22.79358,-10.40648,-4.580516,
     $ -1.203952,-2.603676,-1.131346,-.1963915,-.1830883,
     $ -.06868714,-.02216312,.0003529924,.005751148,.006642417,
     $ .01262521,.008856734,.005609170,.001706586,.001042143,
     $ .0001248412,-.00004150783/
      DATA CTHETA/7350.127,4825.127,949.3631,289.3469,293.2492,
     $ -124.421,54.43484,19.18166,-.4825736,.7486376,.3953741,
     $ .06986621,.04271434,-.01572356,.02017991,-.008214317,
     $ .0006773615,-.003924926,.00002234224,-.0003545637,
     $-.0001040873,.00002091275/
      DATA DTHETA/-168333.3,-258384.3,-22000.54,130.0753,-6961.17,
     $ 2980.931,-587.553,-131.0949,8.208074,-1.177545,
     $ -1.085026,-.04525312,-.0973965,.05983912,-.01892948,
     $ .005927786,-.001534096,.001315756,-.00006281766,
     $ .00004174608,.00002083333,.00002083333/

C
C SVFL, F, BFUNC, CFUNC, DFUNC ARE PARAMETERS NEEDED IN SPLINE CALCULATION
C OF LAURSEN'S FUNCTION (FUNC) BELOW.
C
      DATA SVFL/-4.60517,-3.91202,-3.21887,-2.81341,-2.52573,-2.30258,
     $ -1.60944,-.91629,-.51083,-.22314,0.,.69315,1.38629,1.79176,
     $ 2.07944,2.30258,2.99573,3.68888,4.09434,4.38203,4.60517,5.29832,
     $ 5.99146,6.39693,6.68461,6.90776/
      DATA F/1.253,1.411,1.569,1.668,1.758,1.792,1.960,2.197,2.398,
     $ 2.565,2.773,3.496,4.867,5.768,6.397,6.867,8.455,9.245,9.904,
     $ 10.127,10.275,10.545,10.692,10.799,10.878,10.933/
      DATA BFUNC/.2288849,.2309644,.2149268,.3161113,.2249758,.1409309,
     $ .2907453,.4489659,.4939646,.7892218,.9613132,1.469371,2.224274,
     $ 2.227120,2.096494,2.233934,1.642620,1.487729,1.199183,.6293903,
     $ .6281968,.2352389,.2356600,.2792161,.2636840,.2254239/
      DATA CFUNC/-.007068473,.01006856,-.03320577,.2827604,-.5995552,
     $ .2229258,-.006787031,.2350501,-.1240681,1.150371,-.3791451,
     $ 1.112114,-.02300823,.03002671,-.4840906,1.100025,-1.953107,
     $ 1.729647,-2.441297,.4607183,-.466067,-.1008493,.1014569,
     $ .005964327,-.05995511,-.1114997/
      DATA DFUNC/.008241137,-.02081047,.2597594,-1.022335,1.228592,
     $ -.1104696,.1162986,-.2952353,1.476635,-2.284838,.7171412,
     $ -.5458842,.04359956,-.5957051,2.366401,-1.46824,1.771023,
     $ -3.428981,3.362434,-1.384460,.1756319,.09728969,-.07850358,
     $ -.07638051,-.0769955,-.0769955/
      IWP=12
C
C DIASED IS SEDIMENT MEDIAN DIAMETER IN MM.
C
      DIA=DIASED
      IF(DIASED.GE.DIATHE(1).AND.DIASED.LE.DIATHE(22))GO TO 20
      IF(DIASED.LT.DIATHE(1))DIA=DIATHE(1)
      IF(DIASED.GT.DIATHE(22))DIA=DIATHE(22)
      WRITE(IWP,10)
 10   FORMAT(1X,'WARNING IN FUNLAU: THE SEDIMENT DIAMETER IS OUTSIDE THE
     $ BOUNDS OF THE ',/,1X,'SHIELDS FACTOR CURVE; CODE USED ENDPOINT')
 20   THETA=SPLEVA(22,DIA,DIATHE,SHIELD,BTHETA,CTHETA,DTHETA)
C
```

```
C DIASDM IS SEDIMENT MEDIAN DIAMETER IN M.
C
      DIASDM=0.001*DIASED
C
C CONVERT DENSITY OF SEDIMENT (DENSED) AND DENSITY OF WATER
C (DENWAT) FROM G/CM**3 TO KG/M**3.
C
      DENSED=DENSED*1000.0
      DENWAT=DENWAT*1000.0
C
C CALCULATE CRITICAL TRACTIVE FORCE FOR BEGINNING OF
C SEDIMENT TRANSPORT.
C
      TCRIT=THETA*(DENSED-DENWAT)*DIASDM
      DIADTH=DIASDM/WDEPTH
C
C COMPUTE FACTOR (TOPFAC) USED IN BOUNDARY SHEAR EQUATION IN SEDCON.
C
      TOPFAC=DENWAT*(DIADTH)**(1./3.)/590.0928
C
C CALCULATE RATIO OF SEDIMENT DIAMETER TO WATER DEPTH RAISED
C TO THE 7/6 POWER (TO BE USED IN LAURSEN'S FORMULA BELOW).
C
      RATIO=DIADTH**(7.0/6.0)
C
C CALCULATE SQ. ROOT OF BOUNDARY SHEAR (SHEAR) USED IN LAURSEN'S
C FORMULA BELOW.
C
      SHEAR=SQRT(WDEPTH*SLOPE*9.80665)
C
C CALCULATE FUNCTION NEEDED IN LAURSEN'S FORMULA. LOG'S USED FOR ACCURACY.
C
      SHEVFL=ALOG(SHEAR/SETVEL)
      IF(SHEVFL.GE.SVFL(1).AND.SHEVFL.LE.SVFL(26))GO TO 60
      IF(SHEVFL.LT.SVFL(1))SHEVFL=SVFL(1)
      IF(SHEVFL.GT.SVFL(26))SHEVFL=SVFL(26)
      WRITE(IWP,50)
 50   FORMAT(1X,'WARNING IN FUNLAU: THE BOTTOM SHEAR VELOCITY DIVIDED BY
     $ THE FALL VELOCITY IN',/,1X,'LAURSENS FUNCTION IS OUTSIDE THE BOUN
     $DS OF LAURSENS CURVE; CODE USED ENDPOINT')
 60   FUNC=SPLEVA(26,SHEVFL,SVFL,F,BFUNC,CFUNC,DFUNC)
      FUNC=EXP(FUNC)
      RETURN
      END
```

```
      SUBROUTINE MATACT(C,A0,P,M,N,DT,A,AI)
      PARAMETER (MTEST=14,M1=20)
      REAL*8 C(M,M),A0(M),P(M),H(M1,M1),D(M1,M1),TMAT1(M1,M1),DT,
     -  TMAT2(M1,M1),A(M),AI(M),CSUM,Q2,TVEC1(M1),TVEC2(M1),DUM,ADDEPS
      INTEGER Q
      CSUM=0.D0
      DO 20 I=1,N
        DO 10 J=1,N
          C(I,J)=DT*C(I,J)
          DUM = C(I,J)*C(I,J)
          CSUM=ADDEPS(CSUM,DUM)
   10     D(I,J)=0.D0
   20   D(I,I)=1.D0
      Q = 2.D0 + ( DLOG(DSQRT(CSUM)) / DLOG(2.D0) )
      IF (Q.LT.0.D0) THEN
        Q = 0.D0
        Q2 = 1.D0
      ELSE
        Q = Q+1
        Q2 = 1.D0/(2.D0**Q)
      ENDIF
C
      CALL CPROD(H,Q2,C,M,N)
      DO 30 K1=1,MTEST
        K=MTEST+2-K1
        CALL PRODUC(TMAT1,H,D,M,N)
        Q2=1.D0/K
        CALL CPROD(D,Q2,TMAT1,M,N)
        DO 30 I=1,N
   30     D(I,I)=ADDEPS(D(I,I),1.D0)
      CALL CPROD(H,.5D0,H,M,N)
      DO 50 K=1,Q
        CALL CPROD(H,2.D0,H,M,N)
        CALL PRODUC(TMAT1,H,D,M,N)
        CALL CPROD(TMAT1,.5D0,TMAT1,M,N)
        DO 40 I=1,N
   40     TMAT1(I,I)=ADDEPS(TMAT1(I,I),1.D0)
        CALL PRODUC(TMAT2,D,TMAT1,M,N)
        DO 50 I=1,N
          DO 50 J=1,N
   50       D(I,J)=TMAT2(I,J)
C
      CALL PRODUC(TMAT2,C,D,M,N)
      DO 60 I=1,N
   60   TMAT2(I,I)=ADDEPS(TMAT2(I,I),1.D0)
      CALL VPRDUC(AI,TMAT2,A0,M,N)
      CALL VPRDUC(TVEC1,D,P,M,N)
      CALL CVPRD(TVEC1,DT,TVEC1,M,N)
      DO 70 I=1,N
   70   A(I)=ADDEPS(AI(I),TVEC1(I))
C      DO 80 I=1,N
C  80    TMAT1(I,I)=ADDEPS(D(I,I),-1.D0)
C      CALL VPRDUC(TVEC1,TMAT1,P,M,N)
C      CALL VPRDUC(TVEC2,C,TVEC1,M,N)
C      CALL VPRDUC(TVEC1,D,A0,M,N)
C      CALL CVPRD(TVEC1,DT,TVEC1,M,N)
C      DO 90 I=1,N
C  90    AI(I)=ADDEPS(AI(I), ADDEPS(TVEC2(I),TVEC1(I)) )
      RETURN
      END
```

```
      SUBROUTINE OUTPUT(MON,IYR)
      PARAMETER (NUCALL=200,NNUCL=10,NDAU=10,NDAU2=20,NREACH=20,NYRS=10)
      CHARACTER*4 AMO(12)
      COMMON/WPARR/WVELR(12,NYRS),WQINR(NNUCL,12,NYRS),
     $              CONRIV(NDAU2,NNUCL,NREACH),CONOLD(NDAU,NNUCL),
     $              NR,WWIDR,WLENR,WDEPR,WVOLR,AREAR
      COMMON/FLAGS/SEDRIV
      COMMON/NUM/NNUC,NNEW,SIZE(NNUCL),NEXTRA(NNUCL),PARNUM(2,NNUCL)
      COMMON/CHAR/NUC(NUCALL),DAUGHTER(NDAU,NNUCL),EXNAME(2,NNUCL)
      COMMON/OUT/WVOLAR(NUCALL),ACTR1(NUCALL,NREACH),
     $           ACTR2(NUCALL,NREACH),TOTACR(NUCALL,NREACH)
      REAL*8 CONOLD,CONRIV
      CHARACTER*8 NUC,DAUGHTER,EXNAME
      INTEGER SIZE,PARNUM
      DATA AMO/' OCT',' NOV',' DEC',' JAN',' FEB',' MAR',
     $' APR',' MAY',' JUN',' JUL',' AUG',' SEP'/
C
C RIVER RESULTS ARE WRITTEN WITH UNIT # IWR
C
      IWR=13
      OPEN(IWR,FILE='OUTPUT.RIV',STATUS='UNKNOWN')
C
      IF(MON.GT.1)GO TO 60
C
C
      WRITE(IWR,10)
 10   FORMAT(19X,'MONTHLY ACTIVITY AND INTERACTION TERMS')
      WRITE(IWR,20)
 20   FORMAT(28X,'WATER BODY IS A RIVER')
      WRITE(IWR,30)
 30   FORMAT(28X,'IR IS THE REACH NUMBER')
      WRITE(IWR,40)AREAR
 40   FORMAT(11X,'CONTAMINATED WATER (SURFACE AREA) IN M**2 = ',
     $1PE10.3)
      WRITE(IWR,50)IYR
 50   FORMAT(34X,'YEAR ',I2)
C
C
 60   CONTINUE
C
C
      WRITE(IWR,70)AMO(MON)
 70   FORMAT(//,1X,3X,A4)
      WRITE(IWR,75)
 75   FORMAT(22X,'WATER COMPARTMENT',14X,'SEDIMENT COMPARTMENT')
      WRITE(IWR,80)
 80   FORMAT(1X,'ACTIVITY',5X,2('DISSOLVED',3X,'ADSORBED',4X,
     $'TOTAL',4X))
      DO 120 IR=1,NR
      WRITE(IWR,90)IR
 90   FORMAT(1X,'  (CI)  ','IR=',I2)
      DO 110 N=1,NNEW
      NPNNEW=N+NNEW
      WRITE(IWR,100)NUC(N),ACTR1(N,IR),ACTR2(N,IR),TOTACR(N,IR),
     $              ACTR1(NPNNEW,IR),ACTR2(NPNNEW,IR),TOTACR(NPNNEW,IR)
 100  FORMAT(4X,A8,1X,6(1PE10.3,1X))
 110  CONTINUE
 120  CONTINUE
      WRITE(IWR,130)
 130  FORMAT(/,1X,'  RATES   ','DEP ON WATER',3X,
     $'VOLAT WATER ',2X,'SURF RUNOFF'
     $,3X,'GRWTR RUNOFF',3X,'WASHLOAD')
      AWDEPR=0.
      SWSURR=0.
      SWGRWR=0.
      WASHR=0.
      WRITE(IWR,140)
 140  FORMAT(1X,'(CI/MON)')
```

```
      DO 160 N=1,NNEW
      WRITE(IWR,150)NUC(N),AWDEPR,WVOLAR(N),SWSURR,
     $              SWGRWR,WASHR
 150  FORMAT(4X,A8,4(1PE10.3,4X),1PE10.3)
 160  CONTINUE
C
C
      RETURN
C
C
      END
```

```
      SUBROUTINE PRODUC(A,B,C,M,N)
      REAL*8 A(M,M),B(M,M),C(M,M),DUM,ADDEPS
      DO 10 I=1,N
        DO 10 J=1,N
          A(I,J) = 0.D0
          DO 10 K=1,N
            DUM = B(I,K)*C(K,J)
  10        A(I,J) = ADDEPS(A(I,J),DUM)
      RETURN
      END
```

```
      SUBROUTINE READIN
      PARAMETER (NDAU=10,NDAU2=20,NNUCL=10,NUCALL=200,NREACH=20,NYRS=10)
      COMMON /EX/ JYRS
      COMMON/MEDIA/AWQINR,WAQOUR(NUCALL,NREACH),
     $             SWQINR,SWQOUR,SURROF,GRWROF
      COMMON/WPARR/WVELR(12,NYRS),WQINR(NNUCL,12,NYRS),
     $             CONRIV(NDAU2,NNUCL,NREACH),CONOLD(NDAU,NNUCL),
     $             NR,WWIDR,WLENR,WDEPR,WVOLR,AREAR
      COMMON/FLAGS/SEDRIV
      COMMON/ALPHAS/A1R(NDAU,NNUCL),A2R(NDAU,NNUCL),A1S(NDAU,NNUCL),
     $              A2S(NDAU,NNUCL)
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $              SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      COMMON/EQUIL/SWKDR(NDAU,NNUCL)
      COMMON/WRATES/WKVR(NDAU,NNUCL)
      COMMON/NUM/NNUC,NNEW,SIZE(NNUCL),NEXTRA(NNUCL),PARNUM(2,NNUCL)
      COMMON/DEC/DECAY(NDAU,NDAU,NNUCL),DECAYSRC(NUCALL)
      COMMON/CHAR/NUC(NUCALL),DAUGHTER(NDAU,NNUCL),EXNAME(2,NNUCL)
      CHARACTER*8 NUC,DAUGHTER,EXNAME
      CHARACTER*4 AMO(12)
      INTEGER SIZE,PARNUM
      REAL*8 CONOLD,CONRIV
      REAL NO
      DATA AMO/' OCT',' NOV',' DEC',' JAN',' FEB',' MAR',
     $' APR',' MAY',' JUN',' JUL',' AUG',' SEP'/
      DATA YES/4H YES/,NO/4H  NO/
C
C IRW UNIT # FOR FILE READING IN WATER PARAMETERS
C
      IRW=10
C
C IRD UNIT # FOR READING THE RADIOLOGICAL MATRICES
C
      IRD=11
CC
C IWP UNIT # FOR OUTPUT MESSAGES (ALSO, OUTPUTS INPUT DATA)
C
      IWP=12
C
C IWG UNIT # FOR GENERAL OUTPUT FILE
C
      IWG=IWP
C
C
```

```
      OPEN(IRW,FILE='WATER.IN',STATUS='OLD')
      OPEN(IRD,FILE='RADIO.IN',STATUS='OLD')
      OPEN(IWP,FILE='OUTPUT.USR',STATUS='UNKNOWN')
C
C
      WRITE(IWP,10)
 10   FORMAT(//14X,'INPUT DATA FOR AND MESSAGES FROM THE RIVER-RAD MODEL
     >',/)
      WRITE(IWP,20)
 20   FORMAT(15X,'DEFINITION',20X,'NAME',9X,'UNIT',6X,'VALUE(S)',/)
      READ(IRW,30)JYRS
 30   FORMAT(28X,I2)
      WRITE(IWP,40)JYRS
 40   FORMAT(25X,'NUMBER OF YEARS',6X,'JYRS',9X,'(-)',12X,I3)
      READ(IRW,30)NNUC
      WRITE(IWP,50)NNUC
 50   FORMAT(22X,'NUMBER OF NUCLIDES',6X,'NNUC',9X,'(-)',12X,I3,/)
      DO 220 I=1,NNUC
      READ(IRW,60)NUC(I)
 60   FORMAT(20X,A8)
C
 70   READ(IRD,80,END=750)SIZE(I),NEXTRA(I)
 80   FORMAT(2I3)
      READ(IRD,90)(DAUGHTER(J,I),J=1,SIZE(I))
 90   FORMAT(1X,8(A8,2X))
      IF(NEXTRA(I) GT.0)THEN
         DO 100 J=1,NEXTRA(I)
 100     READ(IRD,110)EXNAME(J,I),PARNUM(J,I)
 110     FORMAT(A8,I3)
      ENDIF
      DO 120 J=1,SIZE(I)
 120  READ(IRD,130)(DECAY(K,J,I),K=1,SIZE(I))
 130  FORMAT(8E10.2)
C
      IF(NUC(I).EQ.DAUGHTER(1,I))GO TO 140
      GO TO 70
 140  CONTINUE
      WRITE(IWP,150)I
 150  FORMAT(/,1X,'NUCLIDE # ',I2,' AND ITS DAUGHTERS:')
      DO 160 J=1,SIZE(I)
 160  WRITE(IWP,170)DAUGHTER(J,I)
 170  FORMAT(45X,A8)
      IF(NEXTRA(I).GT.0)THEN
         WRITE(IWP,180)
 180     FORMAT(1X,'SHORT-LIVED DAUGHTERS:')
         DO 190 J=1,NEXTRA(I)
 190     WRITE(IWP,170)EXNAME(J,I)
      ENDIF
      WRITE(IWP,200)
 200  FORMAT(1X,'DECAY MATRIX:')
      DO 210 J=1,SIZE(I)
 210  WRITE(IWP,130)(DECAY(K,J,I),K=1,SIZE(I))
 220  CONTINUE
      DO 270 I=1,NNUC
      DO 250 IYR=1,JYRS
      READ(IRW,230) (WQINR(I,MON,IYR),MON=1,6)
 230  FORMAT(20X,6E10.3)
      WRITE(IWP,240)I,IYR,(WQINR(I,MON,IYR),MON=1,6)
 240  FORMAT(/,2X,'SOURCE, NUCLIDE I=',I2,' MON=1, 6 IYR=',I2,1X,'WQINR(
     $I,MON,IYR)',2X,'CI/S',/,10X,6(1PE10.3,1X))
      READ(IRW,230) (WQINR(I,MON,IYR),MON=7,12)
 250  WRITE(IWP,260)IYR,(WQINR(I,MON,IYR),MON=7,12)
 260  FORMAT(23X,'MON=7,12 IYR=',I2,/,10X,6(1PE10.3,1X),/)
 270  CONTINUE
      DO 290 IYR=1,JYRS
      READ(IRW,230) (WVELR(MON,IYR),MON=1,6)
      WRITE(IWP,280)IYR,(WVELR(MON,IYR),MON=1,6)
 280  FORMAT(4X,'RIVER WATER VELOCITY MON=1, 6 IYR=',I2,2X,'WVELR(MON,IY
     $R)',3X,'M/S',/,10X,6(1PE10.3,1X))
```

```
      READ(IRW,230) (WVELR(MON,IYR),MON=7,12)
 290  WRITE(IWP,260)IYR,(WVELR(MON,IYR),MON=7,12)
      READ(IRW,30) NR
      WRITE(IWP,300)NR
 300  FORMAT(23X,'NUMBER OF REACHES',7X,'NR',10X,'(-)',12X,I3)
      READ(IRW,230) WLENR,WWIDR,WDEPR
      WRITE(IWP,310)WLENR
 310  FORMAT(19X,'LENGTH OF RIVER REACH',6X,'WLENR',9X,'M',6X,1PE10.3)
      WRITE(IWP,320)WWIDR
 320  FORMAT(20X,'WIDTH OF RIVER REACH',6X,'WWIDR',9X,'M',6X,1PE10.3)
      WRITE(IWP,330)WDEPR
 330  FORMAT(20X,'DEPTH OF RIVER REACH',6X,'WDEPR',9X,'M',6X,1PE10.3,/)
      WVOLR=WLENR*WWIDR*WDEPR
      AREAR=WWIDR*WLENR*FLOAT(NR)
      DO 420 I=1,NNUC
      DO 420 J=1,SIZE(I)
      READ(IRW,230) WKVR(J,I),SWKDR(J,I)
C
C WRITE VOLATILIZATION AND KD ONLY ONCE FOR EACH RADIONUCLIDE (I.E.,
C IF TWO PARENTS HAVE THE SAME DAUGHTERS, WRITE THE INFORMATION ONCE).
C
      IF(I.EQ.1)GO TO 360
      IM1=I-1
      DO 350 L=1,IM1
      DO 340 K=1,SIZE(L)
      LL=L
      KK=K
      IF(DAUGHTER(J,I).EQ.DAUGHTER(K,L))GO TO 390
340   CONTINUE
350   CONTINUE
360   CONTINUE
      WRITE(IWP,370)DAUGHTER(J,I),WKVR(J,I)
370   FORMAT(8X,'VOLATILIZATION RATE FOR ',A8,6X,'WKVR',8X,'S**-1',4X,
     $1PE10.3)
      WRITE(IWP,380)DAUGHTER(J,I),SWKDR(J,I)
380   FORMAT(5X,'DISTRIBUTION COEFF. KD FOR ',A8,6X,'SWKDR'
     $,4X,'ATM/G/ATM/ML',1PE10.3)
      GO TO 420
390   CONTINUE
      IF(WKVR(J,I).NE.WKVR(KK,LL))THEN
      WRITE(IWP,400)I,J,LL,KK
400   FORMAT(/,1X,'ERROR - VOLATILIZATION FOR NUCLIDE ',I2,' DAUGHTER ',
     >I2,' SHOULD BE BUT IS NOT THE',/,1X,'SAME AS FOR NUCLIDE ',I2,' DA
     >UGHTER ',I2)
      STOP
      ENDIF
      IF(SWKDR(J,I).NE.SWKDR(KK,LL))THEN
      WRITE(IWP,410)I,J,LL,KK
 410  FORMAT(/,1X,'ERROR - KD FOR NUCLIDE ',I2,' DAUGHTER ',I2,' SHOULD
     >BE BUT IS NOT THE SAME AS FOR',/,1X,'NUCLIDE ',I2,' DAUGHTER ',I2)
      STOP
      ENDIF
 420  CONTINUE
C
C
 430  FORMAT(26X,A4)
      READ(IRW,430)SEDRIV
      WRITE(IWP,440)
 440  FORMAT(//18X,'MODEL FLAG THAT DETERMINES WHAT USER INPUTS',/)
      WRITE(IWP,450)
 450  FORMAT(2X,'OPTION CHOSEN',6X,'NAME',21X,'MEANING',/)
C
C
      IF(SEDRIV.EQ.YES.OR.SEDRIV.EQ.NO)GO TO 470
      WRITE(IWP,460)SEDRIV
 460  FORMAT(1X,'ERROR IN DATA: SEDRIV DOES NOT EQUAL YES OR NO, BUT = '
     $, A4)
      STOP
 470  CONTINUE
```

```
      IF(SEDRIV.EQ.NO)GO TO 500
      WRITE(IWP,480)
 480  FORMAT(12X,'YES',5X,'SEDRIV',5X,'SIGNIFIES THAT SEDIMENT CONCENTRA
     $TIONS FOR THE')
      WRITE(IWP,490)
 490  FORMAT(32X,'RIVER ARE INPUT (SEE BELOW)',/)
      GO TO 530
 500  WRITE(IWP,510)
 510  FORMAT(13X,'NO',5X,'SEDRIV',5X,'SIGNIFIES THAT SEDIMENT PARAMETERS
     $ (FOR LAURSENS')
      WRITE(IWP,520)
 520  FORMAT(32X,'FORMULA) FOR THE RIVER ARE INPUT (SEE BELOW)',/)
 530  CONTINUE
      IF(SEDRIV.EQ.YES) GO TO 580
      READ(IRW,230)DENSDR,DENWR,SLOPER
      WRITE(IWP,550)DENSDR
 550  FORMAT(15X,'SEDIMENT DENSITY IN RIVER',5X,'DENSDR',7X,'G/CM**3',
     $2X,1PE10.3)
      WRITE(IWP,560)DENWR
 560  FORMAT(18X,'WATER DENSITY IN RIVER',6X,'DENWR',7X,'G/CM**3',2X,
     $1PE10.3)
      WRITE(IWP,570)SLOPER
 570  FORMAT(26X,'SLOPE OF RIVER',5X,'SLOPER',8X,'(-)',5X,1PE10.3)
      GO TO 610
 580  DO 600 IYR=1,JYRS
      READ(IRW,230) (SEDCR(MON,IYR),MON=1,6)
      WRITE(IWP,590)IYR,(SEDCR(MON,IYR),MON=1,6)
 590  FORMAT(2X,'SEDIMENT CONC. (RIVER) MON=1, 6 IYR=',I2,2X,
     $'SEDCR(MON,IYR)',2X,'KG/M**3',/,10X,6(1PE10.3,1X))
      READ(IRW,230) (SEDCR(MON,IYR),MON=7,12)
 600  WRITE(IWP,260)IYR,(SEDCR(MON,IYR),MON=7,12)
 610  CONTINUE
      READ(IRW,230)DIASDR,SEDCS,SDEPR,RESVEL,SEDVEL,SETVEL
      WRITE(IWP,611)DIASDR
 611  FORMAT(7X,'MEDIAN SEDIMENT DIAMETER IN RIVER',5X,'DIASDR',9X,'MM',
     $5X,1PE10.3)
      WRITE(IWP,612)SEDCS
 612  FORMAT(2X,'SOLIDS CONCENTRATION IN SEDIMENT LAYER',6X,'SEDCS',7X,
     $'KG/M**3',2X,1PE10.3)
      WRITE(IWP,613)SDEPR
 613  FORMAT(17X,'DEPTH OF SEDIMENT LAYER',6X,'SDEPR',10X,'M',5X,
     $1PE10.3)
      IF(SETVEL.NE.0.)GO TO 614
C
C  CALL VFALL HERE TO COMPUTE THE SETTLING VELOCITY OF SEDIMENT PARTICLES
C  IN THE STREAM (WRITE OUT THE RESULTS - SETVEL)
C
      CALL VFALL(DIASDR)
 614  WRITE(IWP,615)SETVEL
 615  FORMAT(14X,'SEDIMENT SETTLING VELOCITY',5X,'SETVEL',9X,'M/S',4X,
     $1PE10.3)
      WRITE(IWP,617)RESVEL
 617  FORMAT(10X,'SEDIMENT RESUSPENSION VELOCITY',5X,'RESVEL',8X,'MM/YR'
     $,3X,1PE10.3)
      WRITE(IWP,619)SEDVEL
 619  FORMAT(18X,'SEDIMENTATION VELOCITY',5X,'SEDVEL',8X,'MM/YR',3X,
     $1PE10.3)
C
C CONVERT RESVEL & SEDVEL TO M/S (FROM MM/YR)
C
      RESVEL=RESVEL/3.1536E10
      SEDVEL=SEDVEL/3.1536E10
C
C
      WRITE(IWG,620)
 620  FORMAT(///,36X,'SCENARIO',//)
      DO 630 I=1,NNUC
      DO 630 IYR=1,JYRS
      DO 630 MON=1,12
```

```
 630  IF(WQINR(I,MON,IYR).NE.0.0)GO TO 650
      WRITE(IWG,640)
 640  FORMAT(1X,31X,'RIVER (NO SOURCE)')
      GO TO 670
 650  IRIV=1
      WRITE(IWG,660)
 660  FORMAT(1X,31X,'RIVER (HAS SOURCE)')
 670  CONTINUE
C
C
      WRITE(IWG,680)
 680  FORMAT(//,29X,'MAGNITUDE OF SOURCE(S)',/)
      WRITE(IWG,690)(AMO(I),I=1,12)
 690  FORMAT(1X,6X,6(6X,A4),/,7X,6(6X,A4),/)
      IF(IRIV.NE.1)RETURN
      WRITE(IWG,700)
 700  FORMAT(/,1X,'RIVER')
      WRITE(IWG,710)
 710  FORMAT(1X,'(CI/SEC)')
      DO 730 I=1,NNUC
      WRITE(IWG,720)I
 720  FORMAT(1X,'NUCLIDE # ',I2)
      DO 730 IYR=1,JYRS
 730  WRITE(IWG,740)IYR,(WQINR(I,MON,IYR),MON=1,12)
 740  FORMAT(2X,'YEAR ',I2,2X,6(1PE9.2,1X),/,11X,6(1PE9.2,1X))
      RETURN
 750  WRITE(IWP,760)NUC(I)
 760  FORMAT(1X,'NUCLIDE ',A8,' NOT IN DATABASE - STOP')
      STOP
      END
```

```
      SUBROUTINE SEDCON(IMON,IYR)
      PARAMETER (NDAU=10,NDAU2=20,NNUCL=10,NREACH=20,NYRS=10)
      COMMON/WPARR/WVELR(12,NYRS),WQINR(NNUCL,12,NYRS),
     $              CONRIV(NDAU2,NNUCL,NREACH),CONOLD(NDAU,NNUCL),
     $              NR,WWIDR,WLENR,WDEPR,WVOLR,AREAR
      COMMON/FLAGS/SEDRIV
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $               SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      REAL*8 CONOLD,CONRIV
      DATA IWP/12/
      MON=IMON
      IF(MON.GT.1.OR.IYR.GT.1)GO TO 20
C
C THE FOLLOWING COMPUTES THE SEDIMENT CONCENTRATION FOR A
C RIVER OR STREAM. 1ST, COMPUTE LAURSENS FUNCTION.
C
      CALL FUNLAU(DIASDR,DENSDR,DENWR,WDEPR,SLOPER,
     $            TCRITR,FUNCR,TOPFCR,RATIOR)
 20   TOPRIM=TOPFCR*(WVELR(MON,IYR)**2)
      IF((TOPRIM/TCRITR).GT.1.0)GO TO 40
      WRITE(IWP,30)
 30   FORMAT(1X,'STOP IN SEDCON (IN RIVER CALCULATION): TOPRIM/TCRITR IS
     $ < 1.0 CAUSING SEDIMENT',/,1X,'CONCENTRATION TO BE NEGATIVE. USER
     $SHOULD CHECK INPUT DATA FOR ERRORS. IF NO',/,1X,'ERRORS, USER SHOU
     $LD SET SEDRIV TO YES AND INPUT EMPIRICAL (GENERIC) DATA',/,1X,'(PA
     $RAMETER SEDCR(MON,IYR))')
      STOP
C
C HERE CONSDR IS SEDIMENT CONCENTRATION (% BY WEIGHT) (LAURSENS FORMULA)
C
 40   CONSDR=RATIOR*((TOPRIM/TCRITR)-1.0)*FUNCR
C
C CALCULATE CONSDR IN KG/M**3
C
      CONSDR=CONSDR/((CONSDR/DENSDR)+((100.0-CONSDR)/DENWR))
C
      RETURN
      END
```

```
      FUNCTION SPLEVA(NPTS,U,X,Y,B,C,D)
      DIMENSION X(NPTS),Y(NPTS),B(NPTS),C(NPTS),D(NPTS)
      DATA I/1/
C
C THIS SUBROUTINE EVALUATES A CUBIC SPLINE FUNCTION USING
C HORNER'S RULE.
C
C NPTS=# OF DATA POINTS
C U=ABSCISSA AT WHICH SPLINE IS TO BE EVALUATED
C X,Y=ARRAYS OF DATA ABSCISSAA & ORDINATES
C B,C,D=ARRAYS OF SPLINE COEFFICIENTS
C
      IF(I.GE.NPTS)I=1
      IF(U.LT.X(I))GO TO 10
      IF(U.LE.X(I+1))GO TO 30
 10   I=1
      J=NPTS+1
 20   K=(I+J)/2
      IF(U.LT.X(K))J=K
      IF(U.GE.X(K))I=K
      IF(J.GT.I+1)GO TO 20
C
C EVALUATE SPLINE
C
 30   DX=U-X(I)
      SPLEVA=Y(I)+DX*(B(I)+DX*(C(I)+DX*D(I)))
      RETURN
      END
```

```
      SUBROUTINE VFALL(DIASED)
      PARAMETER (NYRS=10)
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $              SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      DIMENSION DIAVFL(12),VFL(12),BVFALL(12),CVFALL(12),DVFALL(12)
C
C DIAVFL, VFL, BVFALL, CVFALL, DVFALL ARE PARAMETERS NEEDED IN SPLINE
C CALCULATION OF FALL VELOCITY (SETVEL) BELOW.
C
      DATA DIAVFL/.035,.05,.08,.1,.2,.5,.8,1.,2.,5.,8.,10./
      DATA VFL/.001,.0021,.0053,.0084,.028,.062,.082,.094,.130,
     $ .20,.245,.270/
      DATA BVFALL/.06516542,.0822833,.1359694,.1702466,.1901943,
     $ .07170594,.06298195,.05558953,.02601584,.01910471,
     $ .01256532,.01287912/
      DATA CVFALL/.4923909,.6488011,1.140735,.5731256,-.3736484,
     $ -.02131277,-.00776719,-.0291949,-.0003787943,-.001924914,
     $ -.0002548826,.0004117841/
      DATA DVFALL/3.475783,5.465927,-9.460148,-3.155913,.3914841,
     $ .01505064,-.03571286,.00960537,-.0001717911,.0001855591,
     $ .0001111111,.0001111111/
C
C COMPUTE FALL VELOCITY (M/S).
C
      DIA=DIASED
      IF(DIASED.GE.DIAVFL(1).AND.DIASED.LE.DIAVFL(12))GO TO 40
      IF(DIASED.LT.DIAVFL(1))DIA=DIAVFL(1)
      IF(DIASED.GT.DIAVFL(12))DIA=DIAVFL(12)
      WRITE(IWP,30)
 30   FORMAT(1X,'WARNING IN FUNLAU: THE SEDIMENT DIAMETER IS OUTSIDE THE
     $ BOUNDS OF THE FALL',/,1X,'VELOCITY CURVE; CODE USED ENDPOINT')
 40   SETVEL=SPLEVA(12,DIA,DIAVFL,VFL,BVFALL,CVFALL,DVFALL)
      RETURN
      END
      SUBROUTINE VPRDUC(A,B,C,M,N)
      REAL*8 A(M),B(M,M),C(M),DUM,ADDEPS
        DO 10 I=1,N
          A(I) = 0.D0
          DO 10 J=1,N
            DUM  = B(I,J)*C(J)
 10         A(I) = ADDEPS(A(I),DUM)
      RETURN
      END
```

```
      SUBROUTINE WATER(IMON,IYR,DT,ISTEP,NSTEPS)
      PARAMETER (NNUCL=10,NDAU=10,NDAU2=20,NUCALL=200,NREACH=20,NYRS=10)
      COMMON/MEDIA/AWQINR,WAQOUR(NUCALL,NREACH),
     $             SWQINR,SWQOUR,SURROF,GRWROF
      COMMON/WPARR/WVELR(12,NYRS),WQINR(NNUCL,12,NYRS),
     $             CONRIV(NDAU2,NNUCL,NREACH),CONOLD(NDAU,NNUCL),
     $             NR,WWIDR,WLENR,WDEPR,WVOLR,AREAR
      COMMON/FLAGS/SEDRIV
      COMMON/SDPARR/SEDCR(12,NYRS),DIASDR,DENSDR,DENWR,SLOPER,
     $              SEDCS,SDEPR,SETVEL,RESVEL,SEDVEL,CONSDR
      COMMON/ALPHAS/A1R(NDAU,NNUCL),A2R(NDAU,NNUCL),A1S(NDAU,NNUCL),
     $              A2S(NDAU,NNUCL)
      COMMON/WRATES/WKVR(NDAU,NNUCL)
      COMMON/NUM/NNUC,NNEW,SIZE(NNUCL),NEXTRA(NNUCL),PARNUM(2,NNUCL)
      COMMON/DEC/DECAY(NDAU,NDAU,NNUCL),DECAYSRC(NUCALL)
      COMMON/CHAR/NUC(NUCALL),DAUGHTER(NDAU,NNUCL),EXNAME(2,NNUCL)
      COMMON/OUT/WVOLAR(NUCALL),ACTR1(NUCALL,NREACH),
     $           ACTR2(NUCALL,NREACH),TOTACR(NUCALL,NREACH)
      CHARACTER*8 NUC,DAUGHTER,EXNAME
      INTEGER SIZE,PARNUM
      REAL*8 CONOLD,CONRIV,LAMR(NDAU2),P(NDAU2),A0(NDAU2),TIME,
     $       A(NDAU2)
      MON=IMON
C
```

```
C
C WATER BODY IS RIVER
C
C
      WKDR=WVELR(MON,IYR)/WLENR
C
C K IS NUMBER OF RIVER REACH
C
      DO 100 K=1,NR
      DO 10 I=1,NUCALL
      ACTR1(I,K)=0.0
      ACTR2(I,K)=0.0
      WAQOUR(I,K)=0.0
10    DECAYSRC(I)=0.0
      NNEW=NNUC
C
C I IS NUMBER OF THE NUCLIDE
C
      DO 60 I=1,NNUC
C
C P IS CONTINUOUS SOURCE IN CI/S (DOES NOT INCLUDE ANY AIR OR SOIL SOURCE)
C
      IF(K.EQ.1)THEN
         P(1)=WQINR(I,MON,IYR)
C
C J IS # OF DAUGHTER (J=1 IS PARENT)
C
         DO 20 J=2,SIZE(I)
 20      P(J)=0.0
      ENDIF
      IF(K.GT.1)THEN
         DO 30 J=1,SIZE(I)
 30      P(J)=WKDR*CONOLD(J,I)
      ENDIF
      DO 40 J=1,SIZE(I)
C
C LAMR(J) IS REMOVAL RATE FROM ONE REACH TO THE NEXT PLUS VOLATILIZATION -
C IT ALSO INCLUDES REMOVAL IN REACH DUE TO SETTLING OF SEDIMENT.
C LAMR(J+SIZE(I)) IS REMOVAL RATE FROM SEDIMENT COMPARTMENT DUE TO
C RESUSPENSION AND SEDIMENTATION.
C
      LAMR(J)=WKDR+A1R(J,I)*WKVR(J,I)+SETVEL*A2R(J,I)/WDEPR
      LAMR(J+SIZE(I))=(RESVEL+SEDVEL)*A2S(J,I)/SDEPR
C
C P(J) IS INPUT TO REACH FROM SEDIMENT RESUSPENSION; P(J+SIZE(I)) IS
C INPUT TO SEDIMENT COMPARTMENT FROM SETTLING OF SEDIMENT.
C
      P(J)=P(J)+RESVEL*A2S(J,I)*CONRIV(J+SIZE(I),I,K)/SDEPR
      P(J+SIZE(I))=SETVEL*A2R(J,I)*CONRIV(J,I,K)/WDEPR
C
C SAVE ACTIVITY FOR NUCLIDE (J=1) AND DAUGHTERS (J=2,SIZE(I)) FOR NUCLIDE
C I AND RIVER REACH K FOR NEXT TIME STEP FOR FLOW INTO REACH K+1
C
      CONOLD(J,I)=CONRIV(J,I,K)
C
C A0 IS INITIAL ACTIVITY AT BEGINNING OF TIME STEP
C
      A0(J+SIZE(I))=CONRIV(J+SIZE(I),I,K)
 40   A0(J)=CONOLD(J,I)
C
C CALL DECSRC TO COMPUTE DECAY OF SOURCE TERM; TIME IS TIME STEP (S)
C
      TIME=DT
      CALL DECSRC(I,K,A0,P,TIME,LAMR,ISTEP,NSTEPS,A)
C
C A(J) IS ARRAY CONTAINING RESULTING ACTIVITY (CI) FOR J=1,SIZE(I) WHERE
C I IS NUCLIDE, J IS DAUGHTERS (J=1 IS PARENT), FOR RIVER REACH K.
C A(J+SIZE(I)) IS RESULTING ACTIVITY IN SEDIMENT COMPARTMENT BELOW THE REACH.
C STORE THESE RESULTS FOR USE IN INITIAL ACTIVITY FOR NEXT TIME STEP
```

```
C (SEE A0 ABOVE) AND FOR FLOW FROM REACH TO REACH (SEE CONOLD ABOVE).
C
      DO 50 J=1,SIZE(I)
      CONRIV(J+SIZE(I),I,K)=A(J+SIZE(I))
 50   CONRIV(J,I,K)=A(J)
 60   CONTINUE
C
C COMPUTE TOTAL MONTHLY VOLATILIZATION
C
      IF(ISTEP.GT.1.OR.K.GT.1)GO TO 80
      DO 70 N=1,NNEW
 70   WVOLAR(N)=0.0
 80   DO 90 N=1,NNEW
 90   WVOLAR(N)=WVOLAR(N)+WAQOUR(N,K)*DT
C
 100  CONTINUE
C
      RETURN
      END
```

APPENDIX B

IMPORTANT PARAMETERS AND THEIR DEFINITIONS

Parameter	Definition	Location
A(J)	Resulting activity (Ci) of radionuclide J in a decay chain in a river reach (water compartment) that is computed at end of a time step	SUBROUTINES WATER, DECSRC, and MATACT
A(J+SIZE(I))	Same as A(J) only for the sediment compartment	SUBROUTINES WATER, DECSRC, and MATACT
A0(J)	Initial activity (Ci) of radionuclide J in a decay chain in a river reach (water compartment) at the beginning of a time step	SUBROUTINES WATER, DECSRC, and MATACT
A0(J+SIZE(I))	Same as A0(J) only for the sediment compartment	SUBROUTINES WATER, DECSRC, and MATACT
A1R(J,I)	Fraction of daughter J (J=1 is parent) of radionuclide chain I that is in dissolved phase in water compartment	COMMON/ALPHAS/
A2R(J,I)	Fraction of daughter J (J=1 is parent) of radionuclide chain I that is in adsorbed phase in water compartment	COMMON/ALPHAS/
A1S(J,I)	Same as A1R(J,I) only for the sediment compartment	COMMON/ALPHAS/
A2S(J,I)	Same as A2R(J,I) only for the sediment compartment	COMMON/ALPHAS/

Parameter	Definition	Location
ACTOUT(MM)	An array that keeps track of which members of each radionuclide chain are the same (the results for members are added together)	SUBROUTINE DECSRC
ACTR1(N,IR)	Dissolved activity (Ci) of radionuclide N in reach IR in the water compartment	COMMON/OUT/
ACTR1(N+NNEW,IR)	Same as ACTR1(N,IR) only in the sediment compartment	COMMON/OUT/
ACTR2(N,IR)	Adsorbed activity (Ci) of radionuclide N in reach IR in the water compartment	COMMON/OUT/
ACTR2 (N+NNEW,IR)	Same as ACTR2(N,IR) only in the sediment compartment	COMMON/OUT/
AREAR	The surface area of the river in m^2	COMMON/WPARR/
AWQINR	Air-to-water deposition rate (assumed to be 0.0)	COMMON/MEDIA/
BFUNC	Array used to store cubic coefficients b_i (Forsythe et al., 1977) needed in spline fit of Laursen's function (Laursen, 1958)	SUBROUTINE FUNLAU
BTHETA	Array used to store cubic coefficients b_i (Forsythe et al., 1977) needed in spline fit of Shields factor (Bagnold, 1966)	SUBROUTINE FUNLAU
BVFALL	Array used to store cubic coefficients b_i (Forsythe et al., 1977) needed in spline fit of the fall velocity (Fields, 1976)	SUBROUTINE VFALL

Parameter	Definition	Location
C(MM,MM)	Radiological decay matrix	SUBROUTINES DECSRC and MATACT
CFUNC	Array used to store cubic coefficients c_i (Forsythe et al., 1977) needed in spline fit of Laursen's function (Laursen, 1958)	SUBROUTINE FUNLAU
CONOLD(J,I)	Activity in Ci for daughter J (J=1 is parent) of nuclide chain I that is saved for the next time step in computing flow from one reach to the next	COMMON/WPARR/
CONRIV(J,I,K)	Activity in Ci for daughter J (J=1 is parent) of nuclide chain I in river reach K (water compartment)	COMMON/WPARR/
CONRIV(J+SIZE(I), I,K)	Same as CONRIV(J,I,K) only for the sediment compartment	COMMON/WPARR/
CONSDR	The average suspended sediment concentration in kg/m^3 for the river	COMMON/SDPARR/
CTHETA	Array used to store cubic coefficients c_i (Forsythe et al., 1977) needed in spline fit of Shields factor (Bagnold, 1966)	SUBROUTINE FUNLAU
CVFALL	Array used to store cubic coefficients c_i (Forsythe et al., 1977) needed in spline fit of the fall velocity (Fields, 1976)	SUBROUTINE VFALL
DAUGHTER(J,I)	The names of the parents and their daughters. I is index for the chain, J=1 is index for the parent, and J=2,SIZE(I) are indices for the daughters	COMMON/CHAR/

Parameter	Definition	Location
DECAY(K,J,I)	Decay matrix for chain I; K and J are indices for length of the chain	COMMON/DEC/
DECAYSRC(N)	Total resulting activity (Ci) for nuclide N in the water compartment, where N=1,NNEW	COMMON/DEC/
DECAYSRC(N+NNEW)	Same as DECAYSRC(N) only for the sediment compartment	COMMON/DEC/
DENSDR	The sediment density in the river in g/cm^3	COMMON/SDPARR/
DENWR	The density of the water in the river in g/cm^3	COMMON/SDPARR/
DFUNC	Array used to store cubic coefficients d_i (Forsythe et al., 1977) needed in spline fit of Laursen's function (Laursen, 1958)	SUBROUTINE FUNLAU
DIASDR	The median sediment diameter in the river bed in mm	COMMON/SDPARR/
DIATHE	Array containing values of median sediment diameter in mm that were used in the spline fit to the Shields factor curve (Bagnold, 1966); see parameter SHIELD below	SUBROUTINE FUNLAU
DIAVFL	Array containing values of median sediment diameter in mm that were used in the spline fit to the fall velocity curve (Fields, 1976); see parameter VFL below	SUBROUTINE VFALL
DT	Duration of time step in s	SUBROUTINES EXEC, WATER, and MATACT

Parameter	Definition	Location
DTHETA	Array used to store cubic coefficients d_i (Forsythe et al., 1977) needed in spline fit of Shields factor (Bagnold, 1966)	SUBROUTINE FUNLAU
DVFALL	Array used to store cubic coefficients d_i (Forsythe et al., 1977) needed in spline fit of the fall velocity (Fields, 1976)	SUBROUTINE VFALL
EXNAME(J,I)	The names of short-lived daughters for chain I. J=1,NEXTRA(I), where NEXTRA(I) is the number of short-lived daughters for chain I	COMMON/CHAR/
F	Array used to store values of Laursen's function taken from Laursen's curve (Laursen, 1958) at points SVFL (see below); this array contains the natural log of the actual points from the curve in order to increase accuracy	SUBROUTINE FUNLAU
FUNC	Function needed in Laursen's formula (Laursen, 1958)	SUBROUTINE FUNLAU
FUNCR	Same as FUNC	SUBROUTINE SEDCON
GRWROF	Radionuclides in groundwater runoff to river in Ci/s (assumed to be 0.0)	COMMON/MEDIA/
IMO or IMON	Index signifying month of the year; 1 = October	Numerous subroutines
IR	Number of the current reach in the river	SUBROUTINE OUTPUT

Parameter	Definition	Location
IRD	Logical input device number used for reading radiological decay matrices from file RADIO.IN	SUBROUTINE READIN
IRW	Logical input device number used for reading water parameters from file WATER.IN	SUBROUTINE READIN
ISTEP	The index of the current time step within the current month	SUBROUTINES DECSRC, EXEC, and WATER
IWG	Logical output device number used for writing a table of the radionuclide sources in file OUTPUT.USR	SUBROUTINE READIN
IWP	Logical output device number used for writing the input data and other messages (such as warnings or errors) in file OUTPUT.USR	SUBROUTINE READIN
IYR	The index of the current year	Numerous Subroutines
JYRS	The number of years to be simulated (input)	COMMON/EX/
LAMR(J)	Removal rate from one reach to the next plus volatilization for radionuclide J	SUBROUTINES WATER and DECSRC
LAMR(J+SIZE(I))	Removal rate from sediment compartment due to resuspension and sedimentation	SUBROUTINES WATER DECSRC
MON	Index signifying month of the year; 1 = October	Numerous subroutines
NDAU	The number of members allowed in a radionuclide chain (set to 10)	PARAMETER statement in several subroutines

Parameter	Definition	Location
NDAU2	Twice the number of members allowed in a radionuclide chain (set to 20)	PARAMETER statement in several subroutines
NEXTRA(I)	The number of short-lived daughters for chain I	COMMON/NUM/
NNEW	The total number of source nuclides plus daughters	COMMON/NUM/
NNUC	The number of source radionuclides to be simulated (input by the user)	COMMON/NUM/
NNUCL	The number of parent nuclides allowed in a simulation (set to 10)	PARAMETER statement in some subroutines
NR	The number of reaches that the river is broken into (input)	COMMON/WPARR/
NREACH	The number of river reaches allowed (set to 20)	PARAMETER statement in some subroutines
NSTEPS	The number of time steps taken each month (currently is set to 30)	SUBROUTINES DECSRC, EXEC, and WATER
NUC(I)	The radionuclide name of parent nuclide I input by the user	COMMON/CHAR/
NUCALL	Twice the total number of parent (source) nuclides plus daughters (set to 200)	PARAMETER statement in some subroutines
NYRS	The number of years allowed in the simulation (set to 10)	PARAMETER statement in some subroutines
P(J)	Source in Ci/s for radionuclide J in water compartment; J=1 is parent and J=2,SIZE(I) are daughters	SUBROUTINES WATER, DECSRC, and MATACT

Parameter	Definition	Location
P(J+SIZE(I))	Source in Ci/s for radionuclide J to sediment due to settling of sediment from the water compartment; J=1 is parent and J=2, SIZE(I) are daughters	SUBROUTINES WATER, DECSRC, and MATACT
PARNUM(J,I)	The index of the parent for the short-lived daughter EXNAME(J,I) for index J in chain I in array DAUGHTER	COMMON/NUM/
RATIO	Parameter needed in Laursen's formula to compute sediment concentration; RATIO is the ratio of the sediment diameter to water depth raised to the 7/6 power	SUBROUTINE FUNLAU
RESVEL	Sediment resuspension velocity (input as mm/year and converted to m/s)	COMMON/SDPARR/
SDEPR	The depth of the sediment layer (m)	COMMON/SDPARR/
SEDCR(MON,IYR)	The average suspended sediment concentration in the river for month MON and year IYR (kg/m^3)	COMMON/SDPARR/
SEDCS	The solids concentration in sediment layer (kg/m^3)	COMMON/SDPARR/
SEDRIV	SEDRIV is a flag; if YES the suspended sediment concentration in the river is known, if NO it is not	COMMON/FLAGS/
SEDVEL	The sedimentation velocity or rate of burial (input as mm/year and converted to m/s)	COMMON/SDPARR/

Parameter	Definition	Location
SETVEL	The sediment settling velocity in m/s. User can input SETVEL or the code will compute it (subroutine VFALL)	COMMON/SDPARR/
SHEAR	Used in Laursen's formula for sediment concentration, SHEAR is the square root of the boundary shear	SUBROUTINE FUNLAU
SHIELD	Array containing values of Shield's factor at sediment diameters DIATHE (see above) from the curve given in Bagnold (1966)	SUBROUTINE FUNLAU
SIZE(I)	The length of the radio-nuclide chain I; the parent plus the number of daughters	COMMON/NUM/
SLOPER	The slope of the river bed	COMMON/SDPARR/
SURROF	Radionuclides in surface runoff to river in Ci/s (assumed to be 0.0)	COMMON/MEDIA/
SVFL	Array used to store values of $\sqrt{\tau_o/\rho}/w_a$ from Laursen's curve (Laursen, 1958); this array contains the natural log of the actual points from the curve in order to increase accuracy (see parameter F above)	SUBROUTINE FUNLAU
SWKDR(J,I)	Soil-water distribution coefficient in (atoms/g)/(atoms/mL) for daughter J (J=1 is parent) of radionuclide chain I	COMMON/EQUIL/

Parameter	Definition	Location
SWQINR	Surface runoff plus groundwater runoff in Ci/s into the river at beginning of time step (assumed to be 0.0)	COMMON/MEDIA/
SWQOUR	Surface runoff plus groundwater runoff in Ci/s into the river at end of time step (assumed to be 0.0)	COMMON/MEDIA/
TCRIT	Critical tractive force for beginning of sediment transport in kg/m^2	SUBROUTINE FUNLAU
TCRITR	Same as TCRIT	SUBROUTINE SEDCON
THETA	Shields factor used in calculation of TCRIT (Laursen, 1958 and Bagnold, 1966)	SUBROUTINE FUNLAU
TIME	Time step in s	SUBROUTINES WATER and DECSRC
T0PRIM	Boundary shear τ_0' associated with sediment particles in kg/m^2	SUBROUTINE SEDCON
TOTACR(N,IR)	Total activity (Ci) for radionuclide N in reach IR (water compartment)	COMMON/OUT/
TOTACR(N+NNEW,IR)	Same as TOTACR(N,IR) only for the sediment compartment	COMMON/OUT/
VFL	Array containing sediment fall velocity values in m/s taken from velocity curve given in Fields, 1976 (see parameter DIAVFL above)	SUBROUTINE VFALL
WAQOUR(N,K)	Volatilization rate (Ci/s) for nuclide N from reach K	COMMON/MEDIA/

Parameter	Definition	Location
WDEPR	The average depth of the river in m	COMMON/WPARR/
WKDR	Rate at which water flows out of the river in s^{-1}	SUBROUTINE WATER
WKVR(J,I)	The volatilization rate constant in s^{-1} for daughter J (J=1 is parent) of radionuclide chain I	COMMON/WRATES/
WLENR	The length of each river reach in m (all reaches have the same length)	COMMON/WPARR/
WQINR(I,MON,IYR)	Radionuclide source rate into reach 1 of the river for parent I, month MON, and year IYR in Ci/s	COMMON/WPARR/
WVELR(MON,IYR)	Current velocity of the river for month MON and year IYR in m/s	COMMON/WPARR/
WVOLAR(N)	Total monthly volatilization from river	COMMON/OUT/
WVOLR	The water volume of each reach in m^3	COMMON/WPARR/
WWIDR	The average width of the river in m that is input by the user	COMMON/WPARR/

APPENDIX C

EXAMPLES OF INPUT FILES FOR RIVER-RAD

The first file given is RADIO.IN (see Table 2 in the text). Three different examples of the file WATER.IN follow (see Table 1 in the text).

This is file RADIO.IN. Additional radionuclides can be added to this file by following the instructions given in Table 2. Note that an example using short-lived daughters is given for U-233 (see below).

```
  1
 C-14
-3.830e-12
  1
 K-40
-1.729e-17
  1
 MN-54
-2.570E-08
  1
 FE-55
-8.140e-09
  1
 CO-60
-4.167E-09
  1
 NI-63
-2.190E-10
  1
 ZN-65
-3.280e-08
  2
 SR-90      Y-90
-7.680E-10 0.000E+00
 3.004E-06-3.004E-06
  1
 Y-90
-3.004E-06
  1
 ZR-95
-1.253e-08
  1
 TC-99
-1.031E-13
  2
 TC-99M     TC-99
-3.198E-05 0.000E+00
 1.031E-13-1.031E-13
  2
 RU-103     RH-103
-2.039E-07 0.000E+00
 2.053E-04-2.059E-04
  2
 RU-106     RH-106
-2.179E-08 0.000E+00
 2.317E-02-2.317E-02
  1
 RH-106
-2.317E-02
```

```
  1
 I-125
-1.334E-07
  1
 I-131
-9.978E-07
  1
 I-132
-8.371E-05
  1
 I-133
-9.257E-06
  1
 I-134
-2.196E-04
  1
 I-135
-2.913E-05
  1
 CS-134
-1.065E-08
  2
 CS-137     BA-137M
-7.280E-10 0.000E+00
 4.282E-03-4.527E-03
  1
 BA-137M
-4.527E-03
  1
 EU-152
-1.615e-09
  1
 EU-154
-2.500e-09
  2
 TH-228     RA-224
-1.148E-08 0.000E+00
 2.216E-06-2.216E-06
  2
 TH-230     RA-226
-2.853E-13 0.000E+00
 1.373E-11-1.373E-11
  5
 TH-232     RA-228     AC-228     TH-228     RA-224
-1.563E-18 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 3.820E-09-3.820E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 3.141E-05-3.141E-05 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 1.148E-08-1.148E-08 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 2.216E-06-2.216E-06
  8  2
 U-233      TH-229     RA-225     AC-225     FR-221     PO-213     TH-209     PB-209
AT-217     5
BI-213     5
-1.380E-13 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 2.992E-12-2.992E-12 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 5.421E-07-5.421E-07 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 8.023E-07-8.023E-07 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 2.407E-03-2.407E-03 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.531E-04-2.531E-04 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 1.134E-04-5.251E-03 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 5.791E-05 5.919E-05-5.919E-05
```

```
 3
 U-234      TH-230     RA-226
-8.983E-14 0.000E+00 0.000E+00
 2.853E-13-2.853E-13 0.000E+00
 0.000E+00 1.373E-11-1.373E-11
 7
 U-235      TH-231     PA-231     AC-227     TH-227     FR-223     RA-223
-3.121E-17 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 7.545E-06-7.545E-06 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 5.895E-13-5.895E-13 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 1.009E-09-1.009E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 4.227E-07-4.286E-07 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 7.313E-06 0.000E+00-5.299E-04 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 7.016E-07 7.016E-07-7.016E-07
 6
 U-236      TH-232     RA-228     AC-228     TH-228     RA-224
-9.381E-16 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.563E-18-1.563E-18 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 3.820E-09-3.820E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 3.141E-05-3.141E-05 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 1.148E-08-1.148E-08 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.216E-06-2.216E-06
 7
 U-238      TH-234     PA-234M    PA-234     U-234      TH-230     RA-226
-4.916E-18 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 3.329E-07-3.329E-07 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 9.874E-03-9.874E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 4.598E-08-2.874E-05 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 8.969E-14 8.983E-14-8.983E-14 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.853E-13-2.853E-13 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 1.373E-11-1.373E-11
 4
 PU-238     U-234      TH-230     RA-226
-2.503E-10 0.000E+00 0.000E+00 0.000E+00
 8.983E-14-8.983E-14 0.000E+00 0.000E+00
 0.000E+00 2.853E-13-2.853E-13 0.000E+00
 0.000E+00 0.000E+00 1.373E-11-1.373E-11
 8
 PU-239     U-235      TH-231     PA-231     AC-227     TH-227     FR-223     RA-223
-9.102E-13 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 3.121E-17-3.121E-17 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 7.545E-06-7.545E-06 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 5.895E-13-5.895E-13 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 1.009E-09-1.009E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.227E-07-4.286E-07 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 7.313E-06 0.000E+00-5.299E-04 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 7.016E-07 7.016E-07-7.016E-07
 7
 PU-240     U-236      TH-232     RA-228     AC-228     TH-228     RA-224
-3.344E-12 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 9.381E-16-9.381E-16 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 1.563E-18-1.563E-18 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 3.820E-09-3.820E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 3.141E-05-3.141E-05 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 1.148E-08-1.148E-08 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.216E-06-2.216E-06
 3
 AM-241     NP-237     PA-233
-5.082E-11 0.000E+00 0.000E+00
 1.026E-14-1.026E-14 0.000E+00
 0.000E+00 2.971E-07-2.971E-07
 8
 CM-244     PU-240     U-236      TH-232     RA-228     AC-228     TH-228     RA-224
-1.213E-09 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 3.344E-12-3.344E-12 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 9.381E-16-9.381E-16 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 1.563E-18-1.563E-18 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 3.820E-09-3.820E-09 0.000E+00 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 3.141E-05-3.141E-05 0.000E+00 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 1.148E-08-1.148E-08 0.000E+00
 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.216E-06-2.216E-06
```

This is file WATER.IN (example 1). There is one parent (SR-90) with a source of 0.01 Ci/s each month for 1 year. The water velocity varies each month, there are 3 reaches with length of 5000.0 m, width of 300.0 m, and depth of 5.0 m, the volatilization rates for the parent and daughter (Y-90) are assumed to be 0.0, the distribution coefficient Kd (SWKDR) is given for each, and sediment parameters for Laursen's formula are given. Sediment compartment parameters are given on the last line - note that the settling velocity is 0.0, so the code calculates it via subroutine VFALL. The output from RIVER-RAD corresponding to this input is given in Appendix D.

```
# OF YEARS JYRS              1
NNUC                         1
NUCLIDE NAME NUC    SR-90
WQINR(MN,IY),MN=1,6       0.01       0.01       0.01       0.01       0.01       0.01
             MN=7,12      0.01       0.01       0.01       0.01       0.01       0.01
WVELR(MN,IY),MN=1,6        1.0        1.0        0.9        0.8        0.7        1.1
             MN=7,12       1.0        0.9        1.5        1.4        1.3        1.5
NR                           3
WLENR,WWIDR,WDEPR       5000.0       300.         5.
WKVR,SWKDR  SR-90      0.00E-0     3.5E+1
            Y-90                   5.0E+2
FLAG SEDRIV                 NO
LAURSEN'S PARAMETERS      2.65        1.0     7.5E-5
SEDIMENT COMPARTMENT       .05       100.       0.01     1000.0        0.0       0.00
```

This is file WATER.IN (example 2). There are two parents (TH-232 and U-236), each with a source of 0.01 Ci/s every month for 1 year. The water velocity is constant at 1.5 m/s each month, there are 3 reaches with length of 500.0 m, width of 300.0 m, and depth of 10.0 m, the volatilization rates for the parents and daughters are assumed to be 0.0, the distribution coefficients Kd (SWKDR) are given for each, and sediment parameters for Laursen's formula are given. Note that TH-232 must be first in this file because it appears before U-236 in file RADIO.IN . Also, the parameters WKVR and SWKDR are given for the TH-232 chain first (TH-232, RA-228, AC-228, TH-228, and RA-224), followed by the U-236 chain. They must be given in the same order that they appear in file RADIO.IN. The output from RIVER-RAD corresponding to this input is given in Appendix D.

```
# OF YEARS JYRS              1
NNUC                         2
NUCLIDE NAME NUC     TH-232
                    U-236
WQINR,TH-232 FOR MON      0.01      0.01      0.01      0.01      0.01      0.01
              = 1,12      0.01      0.01      0.01      0.01      0.01      0.01
WQINR, U-236 FOR MON      0.01      0.01      0.01      0.01      0.01      0.01
              = 1,12      0.01      0.01      0.01      0.01      0.01      0.01
WVELR(MN,IY),MN=1,6        1.5       1.5       1.5       1.5       1.5       1.5
             MN=7,12       1.5       1.5       1.5       1.5       1.5       1.5
NR                           3
WLENR,WWIDR,WDEPR         500.      300.       10.
WKVR,SWKDR  TH-232    0.00E+0   1.5E+5
            RA-228    0.00E+0   4.5E+2
            AC-228    0.00E+0   1.5E+3
            TH-228    0.00E+0   1.5E+5
            RA-224    0.00E+0   4.5E+2
            U-236     0.00E+0   4.5E+2
            TH-232    0.00E+0   1.5E+5
            RA-228    0.00E+0   4.5E+2
            AC-228    0.00E+0   1.5E+3
            TH-228    0.00E+0   1.5E+5
            RA-224    0.00E+0   4.5E+2
FLAG SEDRIV                 NO
LAURSEN'S PARAMETERS      2.65       1.0    7.5E-5
SEDIMENT COMPARTMENT       .05      100.       .01    2500.0       0.0
```

This is WATER.IN (example 3). There are ten parents, each with a source of 0.01 Ci/s every month for 1 year. The water velocity is constant at 1.5 m/s each month, there are 5 reaches with length of 500.0 m, width of 300.0 m, and depth of 10.0 m, the volatilization rates are all assumed to be 0.0, the distribution coefficients Kd (SWKDR) are given for each, and sediment concentrations are given for each month. Note that the radionuclides must be given in the order shown since they are in this order in file RADIO.IN (the same holds for the parameters WKVR and SWKDR). The output from RIVER-RAD corresponding to this input is given in Appendix D.

```
# OF YEARS JYRS              1
NNUC                        10
NUCLIDE NAME NUC      MN-54
NUCLIDE NAME NUC      Y-90
                      RH-106
                      I-132
                      I-133
                      I-134
                      I-135
                      CS-134
                      BA-137M
                      EU-154
WQINR, MN-54 FOR          0.01      0.01      0.01      0.01      0.01      0.01
          MONTH=1,12      0.01      0.01      0.01      0.01      0.01      0.01
WQINR, Y-90               0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, RH-106             0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, I-132              0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, I-133              0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, I-134              0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, I-135              0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, CS-134             0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, BA-137M            0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WQINR, EU-154             0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
WVELR(MN,IY),MN=1,6        1.5       1.5       1.5       1.5       1.5       1.5
             MN=7,12       1.5       1.5       1.5       1.5       1.5       1.5
NR                           5
WLENR,WWIDR,WDEPR         500.      300.       10.
WKVR,SWKDR  MN-54      0.00E+0    6.5E+1
            Y-90       0.00E+0    5.0E+2
            RH-106     0.00E+0    6.0E+1
            I-132      0.00E+0    6.0E+1
            I-133      0.00E+0    6.0E+1
            I-134      0.00E+0    6.0E+1
            I-135      0.00E+0    6.0E+1
            CS-134     0.00E+0    1.0E+3
            BA-137M    0.00E+0    6.0E+1
            EU-154     0.00E+0    6.5E+2
FLAG SEDRIV                YES
SEDIMENT CONC.'S          0.01      0.01      0.01      0.01      0.01      0.01
                          0.01      0.01      0.01      0.01      0.01      0.01
SEDIMENT PARAMETERS        .05      100.       .01    2500.0      0.00      .002
```

APPENDIX D

RESULTS FROM THE RIVER-RAD MODEL

These results correspond to the input data (examples 1, 2, and 3) given in Appendix C.

This is the file OUTPUT.USR that resulted from running RIVER-RAD using the input file WATER.IN (example 1) from Appendix C. The user should always check this file to make sure that all data were input correctly and for any warning or error messages.

```
                    INPUT DATA FOR AND MESSAGES FROM THE RIVER-RAD MODEL

                     DEFINITION                    NAME        UNIT       VALUE(S)

                               NUMBER OF YEARS     JYRS        (-)              1
                            NUMBER OF NUCLIDES     NNUC        (-)              1


NUCLIDE #  1 AND ITS DAUGHTERS:
                                                   SR-90
                                                   Y-90
DECAY MATRIX:
-0.77E-09  0.00E+00
 0.30E-05 -0.30E-05

 SOURCE, NUCLIDE I= 1 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                    MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02

   RIVER WATER VELOCITY MON=1, 6 IYR= 1  WVELR(MON,IYR)   M/S
         1.000E+00  1.000E+00  9.000E-01  8.000E-01  7.000E-01  1.100E+00
                    MON=7,12 IYR= 1
         1.000E+00  9.000E-01  1.500E+00  1.400E+00  1.300E+00  1.500E+00

                    NUMBER OF REACHES              NR          (-)              3
                 LENGTH OF RIVER REACH             WLENR       M        5.000E+03
                  WIDTH OF RIVER REACH             WWIDR       M        3.000E+02
                  DEPTH OF RIVER REACH             WDEPR       M        5.000E+00

       VOLATILIZATION RATE FOR SR-90               WKVR        S**-1    0.000E-01
    DISTRIBUTION COEFF. KD FOR SR-90               SWKDR   ATM/G/ATM/ML 3.500E+01
       VOLATILIZATION RATE FOR Y-90                WKVR        S**-1    0.000E-01
    DISTRIBUTION COEFF. KD FOR Y-90                SWKDR   ATM/G/ATM/ML 5.000E+02


                MODEL FLAG THAT DETERMINES WHAT USER INPUTS

OPTION CHOSEN       NAME                        MEANING

           NO      SEDRIV      SIGNIFIES THAT SEDIMENT PARAMETERS (FOR LAURSENS
                                FORMULA) FOR THE RIVER ARE INPUT (SEE BELOW)

              SEDIMENT DENSITY IN RIVER            DENSDR      G/CM**3  2.650E+00
                 WATER DENSITY IN RIVER            DENWR       G/CM**3  1.000E+00
                         SLOPE OF RIVER            SLOPER      (-)      7.500E-05
        MEDIAN SEDIMENT DIAMETER IN RIVER          DIASDR      MM       5.000E-02
SOLIDS CONCENTRATION IN SEDIMENT LAYER             SEDCS       KG/M**3  1.000E+02
                 DEPTH OF SEDIMENT LAYER           SDEPR       M        1.000E-02
             SEDIMENT SETTLING VELOCITY            SETVEL      M/S      2.100E-03
```

SEDIMENT RESUSPENSION VELOCITY	RESVEL	MM/YR	1.000E+03
SEDIMENTATION VELOCITY	SEDVEL	MM/YR	0.000E-01

SCENARIO

RIVER (HAS SOURCE)

MAGNITUDE OF SOURCE(S)

	OCT	NOV	DEC	JAN	FEB	MAR
	APR	MAY	JUN	JUL	AUG	SEP
RIVER						
(CI/SEC)						
NUCLIDE # 1						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02

This is the file OUTPUT.RIV that resulted from running RIVER-RAD using the input file WATER.IN (example 1) from Appendix C. To conserve space, results from only the first and last months of the simulation are given.

MONTHLY ACTIVITY AND INTERACTION TERMS
WATER BODY IS A RIVER
IR IS THE REACH NUMBER
CONTAMINATED WATER (SURFACE AREA) IN M**2 = 4.500E+06
YEAR 1

OCT

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
SR-90	4.972E+01	2.773E-01	5.000E+01	1.047E+01	3.664E+01	4.710E+01
Y-90	9.420E-01	7.505E-02	1.017E+00	5.542E-01	2.771E+01	2.826E+01
(CI) IR= 2						
SR-90	4.972E+01	2.773E-01	5.000E+01	1.046E+01	3.661E+01	4.707E+01
Y-90	1.804E+00	1.437E-01	1.948E+00	6.459E-01	3.230E+01	3.294E+01
(CI) IR= 3						
SR-90	4.971E+01	2.773E-01	4.999E+01	1.045E+01	3.657E+01	4.702E+01
Y-90	2.593E+00	2.066E-01	2.799E+00	7.295E-01	3.647E+01	3.720E+01

RATES	DEP ON WATER	VOLAT WATER	SURF RUNOFF	GRWTR RUNOFF	WASHLOAD
(CI/MON)					
SR-90	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
Y-90	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

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SEP

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
SR-90	3.277E+01	5.630E-01	3.333E+01	2.129E+01	7.452E+01	9.581E+01
Y-90	5.758E-01	1.413E-01	7.171E-01	1.113E+00	5.567E+01	5.678E+01
(CI) IR= 2						
SR-90	3.277E+01	5.630E-01	3.333E+01	2.129E+01	7.452E+01	9.582E+01
Y-90	1.078E+00	2.646E-01	1.343E+00	1.279E+00	6.397E+01	6.525E+01
(CI) IR= 3						
SR-90	3.277E+01	5.630E-01	3.333E+01	2.129E+01	7.453E+01	9.582E+01

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Y-90      1.517E+00  3.723E-01  1.889E+00  1.424E+00  7.122E+01  7.265E+01

 RATES   DEP ON WATER   VOLAT WATER   SURF RUNOFF   GRWTR RUNOFF   WASHLOAD
(CI/MON)
  SR-90    0.000E-01     0.000E-01     0.000E-01     0.000E-01     0.000E-01
  Y-90     0.000E-01     0.000E-01     0.000E-01     0.000E-01     0.000E-01
```

This is the file OUTPUT.USR that resulted from running RIVER-RAD using the input file WATER.IN (example 2) from Appendix C. The user should always check this file to make sure that all data were input correctly and for any warning or error messages.

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                  INPUT DATA FOR AND MESSAGES FROM THE RIVER-RAD MODEL

                   DEFINITION                     NAME         UNIT        VALUE(S)

                              NUMBER OF YEARS     JYRS         (-)                1
                           NUMBER OF NUCLIDES     NNUC         (-)                2


NUCLIDE #  1 AND ITS DAUGHTERS:
                                                 TH-232
                                                 RA-228
                                                 AC-228
                                                 TH-228
                                                 RA-224
DECAY MATRIX:
-0.16E-17  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.38E-08 -0.38E-08  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.31E-04 -0.31E-04  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.11E-07 -0.11E-07  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.22E-05 -0.22E-05

NUCLIDE #  2 AND ITS DAUGHTERS:
                                                 U-236
                                                 TH-232
                                                 RA-228
                                                 AC-228
                                                 TH-228
                                                 RA-224
DECAY MATRIX:
-0.94E-15  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.16E-17 -0.16E-17  0.00E+00  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.38E-08 -0.38E-08  0.00E+00  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.31E-04 -0.31E-04  0.00E+00  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.11E-07 -0.11E-07  0.00E+00
 0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.22E-05 -0.22E-05

 SOURCE, NUCLIDE I= 1 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                   MON=7,12 IYR= 1
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 2 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                   MON=7,12 IYR= 1
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02

   RIVER WATER VELOCITY MON=1, 6 IYR= 1  WVELR(MON,IYR)    M/S
        1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00
                   MON=7,12 IYR= 1
        1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00
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NUMBER OF REACHES	NR	(-)	3
LENGTH OF RIVER REACH	WLENR	M	5.000E+02
WIDTH OF RIVER REACH	WWIDR	M	3.000E+02
DEPTH OF RIVER REACH	WDEPR	M	1.000E+01

VOLATILIZATION RATE FOR TH-232	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR TH-232	SWKDR	ATM/G/ATM/ML	1.500E+05
VOLATILIZATION RATE FOR RA-228	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR RA-228	SWKDR	ATM/G/ATM/ML	4.500E+02
VOLATILIZATION RATE FOR AC-228	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR AC-228	SWKDR	ATM/G/ATM/ML	1.500E+03
VOLATILIZATION RATE FOR TH-228	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR TH-228	SWKDR	ATM/G/ATM/ML	1.500E+05
VOLATILIZATION RATE FOR RA-224	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR RA-224	SWKDR	ATM/G/ATM/ML	4.500E+02
VOLATILIZATION RATE FOR U-236	WKVR	S**-1	0.000E-01
DISTRIBUTION COEFF. KD FOR U-236	SWKDR	ATM/G/ATM/ML	4.500E+02

MODEL FLAG THAT DETERMINES WHAT USER INPUTS

OPTION CHOSEN	NAME	MEANING
NO	SEDRIV	SIGNIFIES THAT SEDIMENT PARAMETERS (FOR LAURSENS FORMULA) FOR THE RIVER ARE INPUT (SEE BELOW)

SEDIMENT DENSITY IN RIVER	DENSDR	G/CM**3	2.650E+00
WATER DENSITY IN RIVER	DENWR	G/CM**3	1.000E+00
SLOPE OF RIVER	SLOPER	(-)	7.500E-05
MEDIAN SEDIMENT DIAMETER IN RIVER	DIASDR	MM	5.000E-02
SOLIDS CONCENTRATION IN SEDIMENT LAYER	SEDCS	KG/M**3	1.000E+02
DEPTH OF SEDIMENT LAYER	SDEPR	M	1.000E-02
SEDIMENT SETTLING VELOCITY	SETVEL	M/S	2.100E-03
SEDIMENT RESUSPENSION VELOCITY	RESVEL	MM/YR	2.500E+03
SEDIMENTATION VELOCITY	SEDVEL	MM/YR	0.000E-01

SCENARIO

RIVER (HAS SOURCE)

MAGNITUDE OF SOURCE(S)

	OCT APR	NOV MAY	DEC JUN	JAN JUL	FEB AUG	MAR SEP
RIVER						
(CI/SEC)						
NUCLIDE # 1						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 2						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02

This is the file OUTPUT.RIV that resulted from running RIVER-RAD using the input file WATER.IN (example 2) from Appendix C. To conserve space, results from only the first and last months of the simulation are given. Note that in RIVER-RAD the results are summed by nuclide, regardless of the chains to which they belong.

MONTHLY ACTIVITY AND INTERACTION TERMS
WATER BODY IS A RIVER
IR IS THE REACH NUMBER
CONTAMINATED WATER (SURFACE AREA) IN M**2 = 4.500E+05
YEAR 1

OCT

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	1.024E-04	1.120E-05	1.136E-04	9.265E-04	4.169E-02	4.262E-02
AC-228	6.479E-05	2.360E-05	8.839E-05	2.265E-04	3.397E-02	3.420E-02
TH-228	3.500E-09	1.275E-07	1.310E-07	3.522E-09	5.283E-05	5.283E-05
RA-224	2.739E-08	2.993E-09	3.038E-08	2.566E-07	1.155E-05	1.180E-05
(CI) IR= 2						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	2.049E-04	2.239E-05	2.273E-04	9.331E-04	4.199E-02	4.292E-02
AC-228	1.293E-04	4.710E-05	1.764E-04	2.289E-04	3.434E-02	3.457E-02
TH-228	7.046E-09	2.567E-07	2.637E-07	3.785E-09	5.678E-05	5.678E-05
RA-224	5.684E-08	6.212E-09	6.305E-08	2.772E-07	1.247E-05	1.275E-05
(CI) IR= 3						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	3.073E-04	3.359E-05	3.409E-04	9.397E-04	4.229E-02	4.323E-02
AC-228	1.935E-04	7.049E-05	2.640E-04	2.314E-04	3.471E-02	3.494E-02
TH-228	1.064E-08	3.876E-07	3.982E-07	4.051E-09	6.077E-05	6.077E-05
RA-224	8.837E-08	9.659E-09	9.803E-08	2.980E-07	1.341E-05	1.371E-05

RATES (CI/MON)	DEP ON WATER	VOLAT WATER	SURF RUNOFF	GRWTR RUNOFF	WASHLOAD
TH-232	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
U-236	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RA-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
AC-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
TH-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RA-224	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

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SEP

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	1.024E-04	1.120E-05	1.136E-04	9.265E-04	4.169E-02	4.262E-02
AC-228	6.479E-05	2.360E-05	8.839E-05	2.265E-04	3.398E-02	3.420E-02
TH-228	3.500E-09	1.275E-07	1.310E-07	3.522E-09	5.283E-05	5.283E-05
RA-224	2.739E-08	2.993E-09	3.038E-08	2.566E-07	1.155E-05	1.180E-05

(CI) IR= 2						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	2.049E-04	2.239E-05	2.273E-04	9.331E-04	4.199E-02	4.292E-02
AC-228	1.293E-04	4.710E-05	1.764E-04	2.289E-04	3.434E-02	3.457E-02
TH-228	7.046E-09	2.567E-07	2.638E-07	3.785E-09	5.678E-05	5.678E-05
RA-224	5.684E-08	6.213E-09	6.305E-08	2.772E-07	1.247E-05	1.275E-05
(CI) IR= 3						
TH-232	8.905E-02	3.244E+00	3.333E+00	5.730E-03	8.594E+01	8.595E+01
U-236	3.005E+00	3.284E-01	3.333E+00	1.933E-01	8.700E+00	8.894E+00
RA-228	3.073E-04	3.359E-05	3.409E-04	9.397E-04	4.229E-02	4.323E-02
AC-228	1.935E-04	7.049E-05	2.640E-04	2.314E-04	3.471E-02	3.494E-02
TH-228	1.064E-08	3.876E-07	3.982E-07	4.052E-09	6.077E-05	6.078E-05
RA-224	8.838E-08	9.660E-09	9.804E-08	2.981E-07	1.341E-05	1.371E-05

RATES (CI/MON)	DEP ON WATER	VOLAT WATER	SURF RUNOFF	GRWTR RUNOFF	WASHLOAD
TH-232	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
U-236	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RA-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
AC-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
TH-228	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RA-224	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

This is the file OUTPUT.USR that resulted from running RIVER-RAD using the input file WATER.IN (example 3) from Appendix C. The user should always check this file to make sure that all data were input correctly and for any warning or error messages.

INPUT DATA FOR AND MESSAGES FROM THE RIVER-RAD MODEL

DEFINITION	NAME	UNIT	VALUE(S)
NUMBER OF YEARS	JYRS	(-)	1
NUMBER OF NUCLIDES	NNUC	(-)	10

NUCLIDE # 1 AND ITS DAUGHTERS: MN-54

DECAY MATRIX:
-0.26E-07

NUCLIDE # 2 AND ITS DAUGHTERS: Y-90

DECAY MATRIX:
-0.30E-05

NUCLIDE # 3 AND ITS DAUGHTERS: RH-106

DECAY MATRIX:
-0.23E-01

NUCLIDE # 4 AND ITS DAUGHTERS: I-132

DECAY MATRIX:
-0.84E-04

NUCLIDE # 5 AND ITS DAUGHTERS: I-133

DECAY MATRIX:
-0.93E-05

NUCLIDE # 6 AND ITS DAUGHTERS: I-134

DECAY MATRIX:

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-0.22E-03

NUCLIDE #  7 AND ITS DAUGHTERS:
                                              I-135
DECAY MATRIX:
-0.29E-04

NUCLIDE #  8 AND ITS DAUGHTERS:
                                              CS-134
DECAY MATRIX:
-0.11E-07

NUCLIDE #  9 AND ITS DAUGHTERS:
                                              BA-137M
DECAY MATRIX:
-0.45E-02

NUCLIDE # 10 AND ITS DAUGHTERS:
                                              EU-154
DECAY MATRIX:
-0.25E-08

 SOURCE, NUCLIDE I= 1 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 2 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 3 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 4 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 5 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 6 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 7 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


 SOURCE, NUCLIDE I= 8 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                     MON=7,12 IYR= 1
         1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
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SOURCE, NUCLIDE I= 9 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                   MON=7,12 IYR= 1
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02


SOURCE, NUCLIDE I=10 MON=1, 6 IYR= 1 WQINR(I,MON,IYR)  CI/S
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                   MON=7,12 IYR= 1
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02

  RIVER WATER VELOCITY MON=1, 6 IYR= 1  WVELR(MON,IYR)   M/S
        1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00
                   MON=7,12 IYR= 1
        1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00  1.500E+00

                   NUMBER OF REACHES      NR         (-)              5
               LENGTH OF RIVER REACH      WLENR       M       5.000E+02
                WIDTH OF RIVER REACH      WWIDR       M       3.000E+02
                DEPTH OF RIVER REACH      WDEPR       M       1.000E+01

     VOLATILIZATION RATE FOR MN-54        WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR MN-54        SWKDR   ATM/G/ATM/ML  6.500E+01
     VOLATILIZATION RATE FOR Y-90         WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR Y-90         SWKDR   ATM/G/ATM/ML  5.000E+02
     VOLATILIZATION RATE FOR RH-106       WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR RH-106       SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR I-132        WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR I-132        SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR I-133        WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR I-133        SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR I-134        WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR I-134        SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR I-135        WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR I-135        SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR CS-134       WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR CS-134       SWKDR   ATM/G/ATM/ML  1.000E+03
     VOLATILIZATION RATE FOR BA-137M      WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR BA-137M      SWKDR   ATM/G/ATM/ML  6.000E+01
     VOLATILIZATION RATE FOR EU-154       WKVR       S**-1      0.000E-01
  DISTRIBUTION COEFF. KD FOR EU-154       SWKDR   ATM/G/ATM/ML  6.500E+02


                MODEL FLAG THAT DETERMINES WHAT USER INPUTS

OPTION CHOSEN       NAME                     MEANING

         YES       SEDRIV       SIGNIFIES THAT SEDIMENT CONCENTRATIONS FOR THE
                                 RIVER ARE INPUT (SEE BELOW)

SEDIMENT CONC. (RIVER) MON=1, 6 IYR= 1  SEDCR(MON,IYR)  KG/M**3
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02
                   MON=7,12 IYR= 1
        1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02  1.000E-02

    MEDIAN SEDIMENT DIAMETER IN RIVER     DIASDR          MM      5.000E-02
SOLIDS CONCENTRATION IN SEDIMENT LAYER    SEDCS       KG/M**3     1.000E+02
              DEPTH OF SEDIMENT LAYER     SDEPR           M       1.000E-02
           SEDIMENT SETTLING VELOCITY     SETVEL         M/S      2.000E-03
       SEDIMENT RESUSPENSION VELOCITY     RESVEL        MM/YR     2.500E+03
              SEDIMENTATION VELOCITY      SEDVEL        MM/YR     0.000E-01
```

SCENARIO

RIVER (HAS SOURCE)

MAGNITUDE OF SOURCE(S)

	OCT APR	NOV MAY	DEC JUN	JAN JUL	FEB AUG	MAR SEP
RIVER						
(CI/SEC)						
NUCLIDE # 1						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 2						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 3						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 4						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 5						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 6						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 7						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 8						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 9						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
NUCLIDE # 10						
YEAR 1	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02

This is the file OUTPUT.RIV that resulted from running RIVER-RAD using the input file WATER.IN (example 3) from Appendix C. To conserve space, results from only the first and last months of the simulation are given.

MONTHLY ACTIVITY AND INTERACTION TERMS
WATER BODY IS A RIVER
IR IS THE REACH NUMBER
CONTAMINATED WATER (SURFACE AREA) IN M**2 = 7.500E+05
YEAR 1

OCT

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.280E-02
Y-90	3.313E+00	1.657E-02	3.330E+00	6.029E-03	3.014E-01	3.075E-01
RH-106	3.819E-01	2.291E-04	3.821E-01	2.825E-07	1.695E-06	1.977E-06
I-132	3.241E+00	1.944E-03	3.243E+00	6.138E-04	3.683E-03	4.297E-03
I-133	3.321E+00	1.993E-03	3.323E+00	3.547E-03	2.128E-02	2.483E-02
I-134	3.104E+00	1.862E-03	3.106E+00	2.350E-04	1.410E-03	1.645E-03
I-135	3.299E+00	1.980E-03	3.301E+00	1.574E-03	9.446E-03	1.102E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	1.328E+00	7.966E-04	1.329E+00	5.020E-06	3.012E-05	3.514E-05
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 2						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.280E-02
Y-90	3.310E+00	1.655E-02	3.326E+00	6.022E-03	3.011E-01	3.071E-01
RH-106	4.378E-02	2.627E-05	4.380E-02	3.238E-08	1.943E-07	2.267E-07
I-132	3.153E+00	1.892E-03	3.155E+00	5.972E-04	3.583E-03	4.180E-03
I-133	3.311E+00	1.986E-03	3.313E+00	3.536E-03	2.121E-02	2.475E-02
I-134	2.892E+00	1.735E-03	2.894E+00	2.190E-04	1.314E-03	1.533E-03
I-135	3.267E+00	1.960E-03	3.269E+00	1.559E-03	9.355E-03	1.091E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	5.292E-01	3.175E-04	5.295E-01	2.001E-06	1.201E-05	1.401E-05
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 3						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.279E-02
Y-90	3.306E+00	1.653E-02	3.322E+00	6.015E-03	3.008E-01	3.068E-01
RH-106	5.018E-03	3.011E-06	5.021E-03	3.712E-09	2.227E-08	2.598E-08
I-132	3.067E+00	1.840E-03	3.069E+00	5.809E-04	3.486E-03	4.067E-03
I-133	3.300E+00	1.980E-03	3.302E+00	3.525E-03	2.115E-02	2.467E-02
I-134	2.695E+00	1.617E-03	2.696E+00	2.041E-04	1.224E-03	1.428E-03
I-135	3.236E+00	1.942E-03	3.238E+00	1.544E-03	9.265E-03	1.081E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	2.109E-01	1.265E-04	2.110E-01	7.975E-07	4.785E-06	5.582E-06
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 4						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.279E-02
Y-90	3.302E+00	1.651E-02	3.319E+00	6.009E-03	3.004E-01	3.064E-01
RH-106	5.753E-04	3.452E-07	5.756E-04	4.255E-10	2.553E-09	2.979E-09
I-132	2.984E+00	1.790E-03	2.985E+00	5.651E-04	3.391E-03	3.956E-03
I-133	3.290E+00	1.974E-03	3.292E+00	3.514E-03	2.108E-02	2.460E-02
I-134	2.511E+00	1.507E-03	2.512E+00	1.901E-04	1.141E-03	1.331E-03
I-135	3.205E+00	1.923E-03	3.207E+00	1.529E-03	9.175E-03	1.070E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	8.406E-02	5.044E-05	8.411E-02	3.178E-07	1.907E-06	2.225E-06
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 5						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.372E-03	5.442E-02	6.279E-02
Y-90	3.299E+00	1.649E-02	3.315E+00	6.002E-03	3.001E-01	3.061E-01
RH-106	6.595E-05	3.957E-08	6.599E-05	4.878E-11	2.927E-10	3.414E-10
I-132	2.903E+00	1.742E-03	2.904E+00	5.498E-04	3.299E-03	3.848E-03
I-133	3.280E+00	1.968E-03	3.282E+00	3.503E-03	2.102E-02	2.452E-02
I-134	2.340E+00	1.404E-03	2.341E+00	1.772E-04	1.063E-03	1.240E-03

I-135	3.174E+00	1.904E-03	3.176E+00	1.514E-03	9.087E-03	1.060E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	3.350E-02	2.010E-05	3.352E-02	1.267E-07	7.601E-07	8.867E-07
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01

RATES (CI/MON)	DEP ON WATER	VOLAT WATER	SURF RUNOFF	GRWTR RUNOFF	WASHLOAD
MN-54	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
Y-90	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RH-106	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-132	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-133	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-134	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-135	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
CS-134	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
BA-137M	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
EU-154	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

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SEP

	WATER COMPARTMENT			SEDIMENT COMPARTMENT		
ACTIVITY	DISSOLVED	ADSORBED	TOTAL	DISSOLVED	ADSORBED	TOTAL
(CI) IR= 1						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.280E-02
Y-90	3.313E+00	1.657E-02	3.330E+00	6.029E-03	3.014E-01	3.075E-01
RH-106	3.819E-01	2.291E-04	3.821E-01	2.825E-07	1.695E-06	1.977E-06
I-132	3.241E+00	1.944E-03	3.243E+00	6.138E-04	3.683E-03	4.297E-03
I-133	3.321E+00	1.993E-03	3.323E+00	3.547E-03	2.128E-02	2.483E-02
I-134	3.104E+00	1.862E-03	3.106E+00	2.350E-04	1.410E-03	1.645E-03
I-135	3.299E+00	1.980E-03	3.301E+00	1.574E-03	9.446E-03	1.102E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	1.328E+00	7.966E-04	1.329E+00	5.020E-06	3.012E-05	3.514E-05
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 2						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.280E-02
Y-90	3.310E+00	1.655E-02	3.326E+00	6.022E-03	3.011E-01	3.071E-01
RH-106	4.378E-02	2.627E-05	4.380E-02	3.238E-08	1.943E-07	2.267E-07
I-132	3.153E+00	1.892E-03	3.155E+00	5.972E-04	3.583E-03	4.180E-03
I-133	3.311E+00	1.986E-03	3.313E+00	3.536E-03	2.121E-02	2.475E-02
I-134	2.892E+00	1.735E-03	2.894E+00	2.190E-04	1.314E-03	1.533E-03
I-135	3.267E+00	1.960E-03	3.269E+00	1.559E-03	9.355E-03	1.091E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	5.292E-01	3.175E-04	5.295E-01	2.001E-06	1.201E-05	1.401E-05
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 3						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.279E-02
Y-90	3.306E+00	1.653E-02	3.322E+00	6.015E-03	3.008E-01	3.068E-01
RH-106	5.018E-03	3.011E-06	5.021E-03	3.712E-09	2.227E-08	2.598E-08
I-132	3.067E+00	1.840E-03	3.069E+00	5.809E-04	3.486E-03	4.067E-03
I-133	3.300E+00	1.980E-03	3.302E+00	3.525E-03	2.115E-02	2.467E-02
I-134	2.695E+00	1.617E-03	2.696E+00	2.041E-04	1.224E-03	1.428E-03
I-135	3.236E+00	1.942E-03	3.238E+00	1.544E-03	9.265E-03	1.081E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	2.109E-01	1.265E-04	2.110E-01	7.975E-07	4.785E-06	5.582E-06
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 4						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.373E-03	5.442E-02	6.279E-02
Y-90	3.302E+00	1.651E-02	3.319E+00	6.009E-03	3.004E-01	3.064E-01
RH-106	5.753E-04	3.452E-07	5.756E-04	4.255E-10	2.553E-09	2.979E-09
I-132	2.984E+00	1.790E-03	2.985E+00	5.651E-04	3.391E-03	3.956E-03
I-133	3.290E+00	1.974E-03	3.292E+00	3.514E-03	2.108E-02	2.460E-02
I-134	2.511E+00	1.507E-03	2.512E+00	1.901E-04	1.141E-03	1.331E-03
I-135	3.205E+00	1.923E-03	3.207E+00	1.529E-03	9.175E-03	1.070E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	8.406E-02	5.044E-05	8.411E-02	3.178E-07	1.907E-06	2.225E-06
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01
(CI) IR= 5						
MN-54	3.331E+00	2.165E-03	3.333E+00	8.372E-03	5.442E-02	6.279E-02

Y-90	3.299E+00	1.649E-02	3.315E+00	6.002E-03	3.001E-01	3.061E-01
RH-106	6.595E-05	3.957E-08	6.599E-05	4.878E-11	2.927E-10	3.414E-10
I-132	2.903E+00	1.742E-03	2.904E+00	5.498E-04	3.299E-03	3.848E-03
I-133	3.280E+00	1.968E-03	3.282E+00	3.503E-03	2.102E-02	2.452E-02
I-134	2.340E+00	1.404E-03	2.341E+00	1.772E-04	1.063E-03	1.240E-03
I-135	3.174E+00	1.904E-03	3.176E+00	1.514E-03	9.087E-03	1.060E-02
CS-134	3.300E+00	3.300E-02	3.333E+00	8.315E-03	8.315E-01	8.398E-01
BA-137M	3.350E-02	2.010E-05	3.352E-02	1.267E-07	7.601E-07	8.867E-07
EU-154	3.312E+00	2.153E-02	3.333E+00	8.353E-03	5.429E-01	5.513E-01

RATES (CI/MON)	DEP ON WATER	VOLAT WATER	SURF RUNOFF	GRWTR RUNOFF	WASHLOAD
MN-54	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
Y-90	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
RH-106	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-132	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-133	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-134	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
I-135	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
CS-134	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
BA-137M	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
EU-154	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

APPENDIX E

MODEL RESULTS COMPARED WITH ANALYTICAL CALCULATIONS

RIVER-RAD results from the first reach of a river can be compared with the following equation for ingrowth of activity of a radioactive daughter (J. E. Turner, 1986).[1] The code was temporarily modified to prevent settling of radionuclides adsorbed to the sediment to go to the sediment compartment. This approximation cannot be compared with model results from downstream reaches below the first reach since these reaches receive daughters.

$$\frac{A_d}{A_p} = \frac{\lambda_d (e^{-\lambda_p t} - e^{-\lambda_d t})}{\lambda_d - \lambda_p} , \qquad (1)$$

where A_d is the activity of the daughter, A_p is the activity of the parent, λ_p and λ_d are the decay constants for the parent and daughter, respectively. The following table shows results for several chains. The residence time is the length of the reach divided by the water velocity, both of which were used in the model simulations.

Table E.1. RIVER-RAD Results Compared to Analytical Calculations from Eq. (1)

Parent/Daughter	Residence Time (s)	Eq. (1) A_d/A_p	RIVER-RAD A_d/A_p
Sr-90/Y-90	333.33	1.0E-3	1.0E-3
Sr-90/Y-90	3333.3	9.963E-3	9.916E-3
Sr-90/Y-90	5000.0	1.491E-2	1.480E-2
Sr-90/Y-90	33333.3	9.528E-2	9.100E-2
Ra-225/Ac-225	333.33	2.674E-4	2.674E-4
Th-228/Ra-224	333.33	7.384E-4	7.380E-4
Ra-228/Ac-228	333.33	1.042E-6	1.036E-2
Th-232/Ra-228	333.33	1.273E-6	1.273E-6
Ru-106/Rh-106	333.33	9.996E-1	8.850E-1
Am-241/Np-237	333.33	0.000E+0	- 3.42E-12
Np-237/Pa-233	333.33	9.902E-5	9.904E-5
Tc-99m/Tc-99	333.33	3.42E-11	3.44E-11

It is clear from the table that the longer the residence time, the greater the difference in the results from RIVER-RAD and Eq. (1). Rh-106 is a short-lived daughter of Ru-106 and results of the model are not as accurate in these cases. However, results for short-lived daughters can be set equal to the parent in RIVER-RAD (see Sect. 4.2 and Table 2, card 3).

[1]Turner, J. E., *Atoms, Radiation, and Radiation Protection*, Pergamon Press, Inc. (1986).

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