WATERSHED MODULE

BACKGROUND AND IMPLEMENTATION FOR THE MULTIMEDIA, MULTIPATHWAY, AND MULTIRECEPTOR RISK ASSESSMENT (3MRA) FOR HWIR99

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DISCLAIMER

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1.0 Introduction

Chemical mass released from the WMU in the form of volatile or particulate emissions can be deposited onto the soils of nearby land areas as wet or dry deposition. This chemical is then subject to fate and transport processes within the watershed and is available either for direct exposure to human or ecological receptors or indirect exposure through a food chain. Fate and transport processes simulated by the Watershed Module are volatilization, leaching, runoff, erosion, and biological and/or chemical degradation. Transport of chemical by runoff and erosion is into adjacent waterbodies. Because the surface transport processes are hydrologically related, the land areas surrounding the waste management unit (WMU) are disaggregated on a watershed basis. A watershed can vary in size from a sheet-flow-only “hillside,” similar to the “local watershed” construct of the land application unit (LAU) and wastepile (WP) (see U.S. EPA, 1999), to much larger areas encompassing regional stream or river networks. In all cases, a watershed is modeled as a single, homogeneous area with respect to soil characteristics, runoff and erosion characteristics, and chemical concentrations in soil. No spatial disaggregation below the watershed level is made; that is, no spatial chemical concentration gradients are simulated within a given watershed.

In addition to the above chemical-related outputs, the Watershed Module also develops streamflow and solids loading estimates for subsequent use by the Waterbody Module and regional infiltration (recharge) estimates for the Vadose Module. In summary, the Watershed Module addresses the following specific objectives:

- Simulate the time series of annual average chemical concentrations in surficial soil (top 1 cm) soil resulting from aerial deposition throughout the area of interest (AOI) surrounding the WMU. (Note that, although chemical mass losses due to volatilization and leaching from the soil column are evaluated, these losses are simulated only for the purpose of estimating soil concentrations and waterbody loads; that is, these losses are not subsequently received as inputs by the Air or Vadose modules because they are secondary sources.)

- Simulate the time series of annual average chemical loadings in surface runoff and erosion that will enter individual waterbody reaches throughout the AOI.

- Simulate the time series of annual average runoff that will enter waterbodies throughout the AOI.

- Simulate the time series of annual average stream baseflow (dry weather streamflow) in waterbodies throughout the AOI. (Runoff plus baseflow represents total streamflow.)

Simulate the time series of annual average eroded solids loads that will enter waterbodies throughout the AOI.

Simulate the time series of annual average infiltration (recharge) rates for each watershed in the AOI.

It is emphasized that the chemical loads to the waterbody simulated by the Watershed Module are indirect loads only; that is, the sole source of chemical is aerial deposition. Chemical loads to the waterbody resulting from **direct** runoff and erosion from a WMU are simulated by the appropriate source module (LAU or WP). Similarly, if a receptor is located in a buffer area between a WMU and the downslope waterbody (i.e., in the WMU's local watershed), the **total** surficial soil concentration that the receptor is exposed to is the aerial deposition-related concentration simulated by the Watershed Module **plus** the WMU runoff/erosion-related concentration simulated by the relevant source module.

The Watershed Module is based on conceptual and mathematical models that are very similar to those already described for the LAU and WP sources — the combined "local watershed/soil column" algorithm described in Section 3.4 of the Source Modules for Nonwastewater Waste Management Units documentation (U.S. EPA, 1999). This algorithm is essentially a dynamic, two-dimensional, fate and transport model that also includes hydrological functionality. There are two general differences between the way the algorithm is implemented in the LAU/WP Modules and the Watershed Module. First, in the Watershed Module, the algorithm is applied to each watershed constituting the AOI with no further disaggregation – watersheds are not disaggregated into "subareas" as were the local watersheds containing either the LAU or WP, although that functionality is available in the Watershed Module software should it ever be needed. (With no lateral disaggregation, the algorithm as applied in the Watershed Module is one-dimensional [vertical] only. It is a lumped model on the surface.) Each watershed is independent of other watersheds and is simulated individually.

The other difference involves the size of the computational time step used to determine contaminant concentrations in runoff water. In the LAU/WP source modules, contaminant concentrations in runoff water and in the surface soil column layer are determined daily, even though the computational time step in the subsurface soil column layers (calculated for any given year primarily as a function of the annual average effective convection velocity of the contaminant in soil and the soil column layer thickness) is typically much larger than one day. It was determined that the daily time step was necessary in the LAU/WP source module's implementation of the watershed/soil column algorithm for two reasons:

It was considered impractical to simulate annual average runoff without building up that annual average from daily precipitation and runoff events. (The precipitation/runoff model is nonlinear in the independent variable. One cannot simply input average annual precipitation as the independent variable and output average annual runoff.)

- # An approximately daily time step is the fundamental temporal scale at which surface transport of chemical downslope in the local watershed is occurring. It was considered important to honor this time scale in simulating fate and transport from the sources.

For the Watershed Module, both of these considerations are still valid. However, **indirect** soil concentrations resulting from aerial deposition are likely to be significantly less than soil concentrations resulting from **direct** runoff/erosion from a source, and aerial deposition rates are known only on an average annual basis, not daily. For these reasons, it was decided that, in the Watershed Module, to minimize run time and accommodate data limitations:

- # Soil erosion and runoff models would be executed on a daily time step. Daily results would then be used to determine annual average soil erosion (CSL) and runoff volume (Q).
- # Annual average Q and CSL would be used to estimate the annual averages of the other runoff/erosion-related parameters (e.g., k_{ev}, k_{bu}, d_1, d_2, m_1), as defined in U.S. EPA (1999).
- # The computational time step used by the watershed/soil column algorithm would be the same as that calculated each year for the subsurface soil column layers; that is, based on numerical considerations, not physical. This time step does not exceed 1 year as a maximum.
- # The annual average runoff-related parameters and the annual average aerial deposition rates would be used in applying the watershed/soil column algorithm at each computational time step.

In summary, annual average soil erosion and runoff are estimated on a daily time step, while the remainder of the model (contaminant mass fate and transport simulation) is executed on a computational time step that is typically much larger than one day and can vary each year of the simulation. All outputs are ultimately reported as annual averages, regardless of their individual computational time steps.

2.0 Chemical Fate and Transport Equations

2.1 Overview

This section provides an overview of the equations that describe contaminant fate and transport in the soil column and runoff water. In the watershed module, the depth of the soil column is a user-specified input, set at a default of 5 cm in the HWIR analysis. Each soil column layer is 1 cm thick. The surficial soil column layer (top 1 cm) is linked to the runoff compartment using the “local watershed/soil column” algorithm, with the two general adaptations noted above. The chemical fate and transport equations used are described in Section 2.1.1. The equations used in the subsurface soil column layers are described in Section 2.1.2.

2.1.1 Runoff and Surficial Soil Column Layer

Similar to the presentation in Section 3.4 (U.S. EPA, 1999), the runoff water is considered as compartment 1 and the surficial soil column layer as compartment 2 of the two-compartment conceptual model for the watershed/soil column algorithm. The total (particulate plus dissolved) chemical concentration in the watershed runoff denoted as C_1, is coupled to the total concentration in the soil layer, C_2, at any time by Equation 3-46 (U.S. EPA, 1999), with the understanding that the subarea “i” index has now been dropped because each watershed is considered as a single, homogeneous area. In addition, parameters with the subarea i-1 index, indicating the up-slope subarea, are assigned a value of zero because there is no up-slope subarea.

The governing differential equation describing total chemical concentration in the surficial soil column layer in the watershed, C_2, is written here as

$$\frac{\partial C_2}{\partial t} = D_E \frac{\partial^2 C_2}{\partial z^2} - V_E \frac{\partial C_2}{\partial z} - k' C_2 + ld_{dep} \tag{2-1}$$

where ld_{dep} is the annual average wet plus dry deposition mass loading rate (g/m^3/d) and k'(1/d) is the lumped first-order decay rate — equal to the sum of the hydrolysis loss rate (k_{hy}, 1/d), the aerobic biodegradation loss rate (k_{ae}, 1/d), and k_{ev} (1/d) and k_{bu} (1/d), where these latter two rate constants incorporate the rainfall runoff and erosional processes. (C_2 is coupled with C_1 through k_{ev} and k_{bu}.)

As described in U.S. EPA (1999), Equation 2-1 is disaggregated into three component equations — diffusion, convection, and first-order losses, each solved individually on the soil column's numerical grid. For the Watershed Module application, while the first two component equations remain the same as in the Generic Soil Column Model (GSCM), the third is revised to Equation 3-45 (U.S. EPA, 1999) with watershed parameter ld_{dep} replacing the local watershed subarea run-on load, ld_{i-1}. The solution to Equation 3-45 is the same as that described for the LAU or WP application, with the same substitutions noted above.

After C_2 in the surface layer of the soil column is determined at the end of a given time step, $\bar{C}_1$, the contaminant concentration in the runoff water averaged over the time step, is determined using Equation 3-51 (U.S. EPA, 1999) where all the parameters are annual averages determined from annual average Q and CSL. The time-step-averaged contaminant concentration in the soil compartment, $\bar{C}_2$ in Equation 3-51, is calculated using the following equation derived using Equation 3.4.2-9 (U.S. EPA, 1999) for C_2:

$$\bar{C}_2 = \frac{1}{T}\int_0^T C_2 \, dt = \begin{cases} \dfrac{C_2^0}{k'T}(1 - \exp(-k'T) + \dfrac{ld_{dep}}{k'^2 T}(k'T - 1 + \exp(-k'T)) & k' > 0 \\ C_2^0 + \dfrac{ld_{dep}T}{2} & k' = 0 \end{cases} \tag{2-2}$$

where T is the averaging time period, which is the same as the computational time step here and C_2^0 is the contaminant concentration in the soil compartment at the start of the averaging period (same as at the end of the previous time step).

At the end of each year's simulation, annual average C_1 (g/m^3) is determined and multiplied by the annual average runoff rate (m^3/d) to determine the annual average contaminant mass load to the waterbody in grams/day due to runoff and erosion.

2.1.2 Subsurface Soil Column Layers

In the subsurface layers of the soil column, the contaminant mass fate and transport governing equation is given by Equation 2-1 (U.S. EPA, 1999) with the total first-order loss rate (k) equal to the sum of the input first-order loss rates due to hydrolysis (k_{hy}) and anaerobic biodegradation (k_{an}). The solution technique used is the same as that described in Section 2 of U.S. EPA (1999).

2.2 Implementation Algorithm

2.2.1 Overview

The overall methodology for implementing the Watershed Module is illustrated in Figure 2-1. Note that C_2 is used as the symbol for the contaminant concentration in surface and subsurface soil column layers.

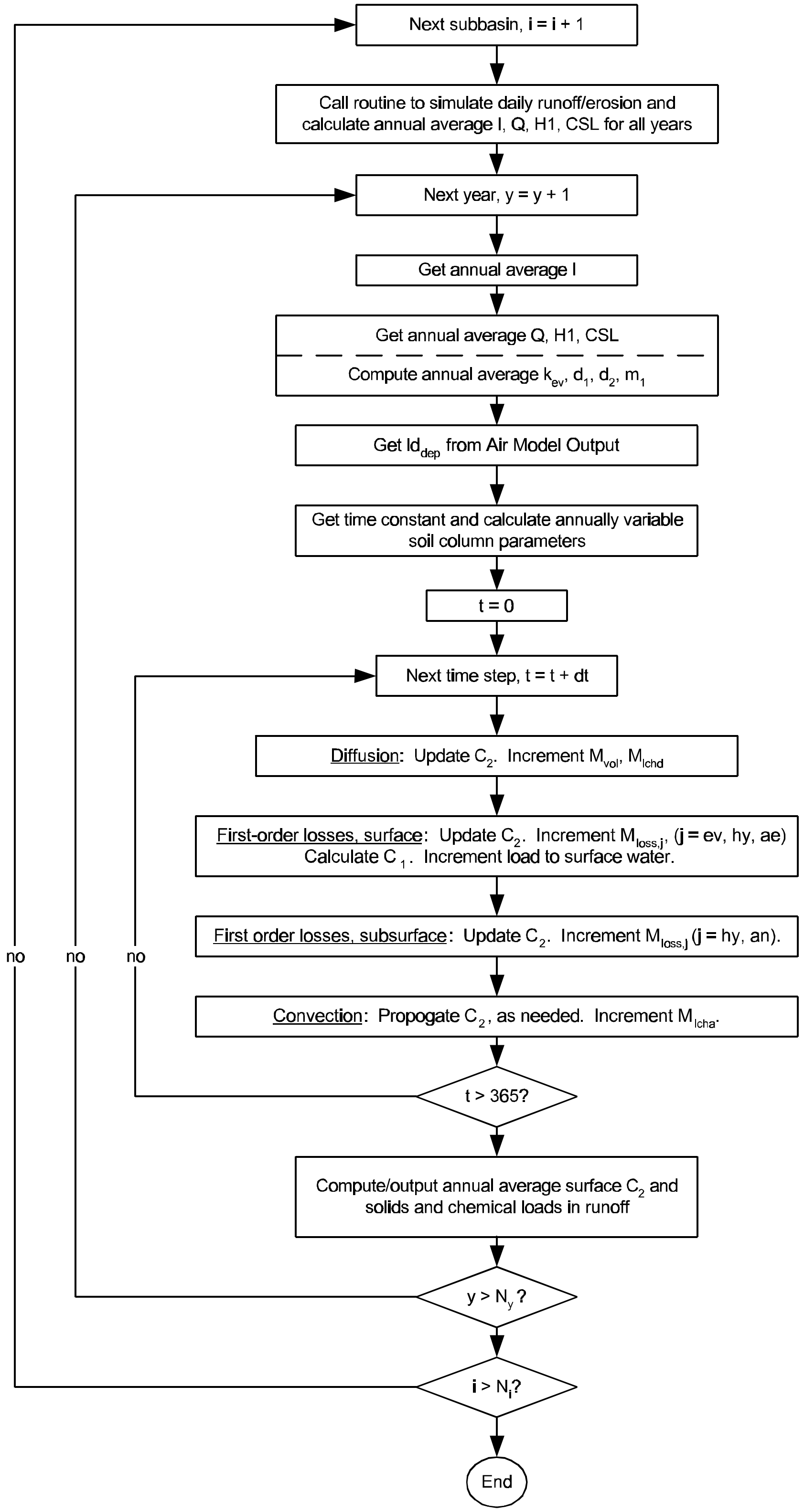

Figure 2-1. Watershed module implementation flowchart.

2.2.2 Simulation Stopping Criteria

The criteria for stopping the Watershed Module simulation are similar to those described in U.S. EPA (1999). Specifically, the simulation terminates for a watershed i when the contaminant mass in watershed i drops below the user-input parameter TermFrac fraction times the peak contaminant mass in that watershed over time, or NyrMax – the maximum possible years simulated — whichever comes first. The annual contaminant mass is monitored during the simulation to determine peak contaminant mass. (Note: As of this writing, the NyrMax computer memory constraint corresponding to 200 years, as discussed in U.S. EPA, 1999, for the source modules, also applies to the Watershed Module. Simulations will run until TermFrac is satisfied, or 200 years, whichever comes first.)

2.2.3 End of Simulation Mass Balance Check

An end-of-simulation mass balance check is performed on the Watershed Module results using a similar procedure as that described for the LAU/WP models (Section 3.5.4 in U.S. EPA, 1999). The difference is that in the Watershed Module, the system includes a collection of watersheds, each consisting of one subarea. There is no WMU. Therefore the term *fMlost* in Equation 3-54 (U.S. EPA, 1999) includes only the last five variables listed in Table 3-2 (U.S. EPA, 1999).

3.0 Streamflow

The Watershed Module uses the identical hydrology submodel described in detail in Section 3.2 (U.S. EPA, 1999) to estimate stormwater runoff and ground water infiltration. The hydrology submodel is applied to individual watersheds considered in their entirety; that is, no further spatial disaggregation occurs. Streamflows are assumed to be made up of both stormwater runoff and baseflow. Baseflow is streamflow occurring during nonrunoff periods and is derived from ground water discharge to streams or interflow (shallow infiltration flowing parallel to the ground surface). The method used for estimating annual average baseflow is described below.

For a given stream reach, baseflow can vary seasonally, or even near continuously, as ground water levels and/or interflow varies, and can be estimated for a given time period by analysis of runoff hydrographs that include runoff as well as pre- and postrunoff flows. For HWIR purposes, however, it was considered unnecessary (and computationally impractical) to attempt to estimate within-year variability in baseflows. Rather, a single estimate was sought that would reasonably characterize annual average baseflow conditioned on stream reach order (or tributary drainage area), year, and hydrologic region.

The issue then becomes — what single flow statistic best represents annual average baseflow for a given region, reach order, and year? The widely available annual average streamflow would, in general, tend to overestimate baseflow. (Some losing streams might be exceptions.) Conversely, the common low flow statistic, 7Q10 (the minimum 7-day average flow expected to occur within a 10-year return period, i.e., at least once in 10 years), would, in general (if not always), tend to underestimate baseflow. As a compromise, it was assumed for HWIR purposes that the 30Q2 low flow, i.e., the minimum 30-day average flow occurring, on average, at least once every other year, is a reasonable estimate of annual average baseflow for any given year. This flow statistic was not widely available from U.S. Geological Survey (USGS) gaging data and therefore was developed as a part of the HWIR effort. The procedure used was the following:

1. For each of the 18 USGS Hydrologic Units (HUCs) in the conterminous United States, retrieve from EPA's STORET database the long-term historical record of daily average streamflows for each USGS gage in that region and the gage's tributary drainage area.

2. Statistically analyze each gage's daily flow record to estimate 30Q2 values by gage.

3. Fit a regression model of the form 30Q2 = aA^b (a power function) to the data for all gages in a given region, where A is the gage tributary area. (In a few of the 18 regions, a linear model, i.e., 30Q2 = a + bA, provided a slightly better fit in the sense of explaining greater overall variation [R^2]. However, the improvement in R^2 was not considered to be significantly great as to outweigh the considerable advantage of the power function model of predicting zero flow for zero tributary area, which the linear model with an intercept term does not achieve.)

Results of the baseflow analysis are presented in Table 3-1. (Note that the "a" parameter has been converted to units of meters/day in Table 3-1. Use of the a and b parameters from Table 3-1 with area in m^2 gives 30Q2 baseflows in m^3/day.)

Table 3-1. Baseflow Regression Analysis Results

HUC Region	Number of Observations (Gages)	R^2	Point Estimate of Parameter "a" (m/d)	Point Estimate of Parameter "b" (unitless)
1	395	0.93	.0128	1.16
2	912	0.78	1.09	0.920
3	1012	0.60	0.252	0.984
4	520	0.73	.00880	1.16
5	856	0.84	.00320	1.17
6	204	0.76	0.304	1.02
7	577	0.71	.0142	1.08
8	201	0.76	.00632	1.14
9	86	0.26	15.6	0.639
10	1083	0.41	3.73	0.750
11	564	0.42	0.948	0.795
12	412	0.36	1.44	0.751
13	167	0.39	584.	0.488
14	565	0.59	1.17	0.854
15	187	0.49	6.32	0.686
16	316	0.37	613.	0.522
17	1127	0.59	1.54	0.907
18	424	0.34	8.89	0.678

4.0 USLE Length-Slope Factor

The Watershed Module uses the (modified) Universal Soil Loss Equation (MUSLE), as described in U.S. EPA (1999), to predict soil erosion from watersheds considered in their entirety. To do so, the length (X) and slope (θ) parameters of the length-slope factor presented in Equation 3-19 of that documentation must now reflect watershed-average, sheet-flow conditions, rather than local watershed sheet-flow conditions as in the source modules application. It should be noted that sheet-flow length and slope for a watershed are **not** the length and slope of the **stream** network draining the watershed; rather, they are the average sheet-flow length and slope of the (essentially infinite) individual sheet-flow paths comprising the land surfaces of that watershed.

As presented in Williams and Berndt (1977), the watershed-average slope is estimated from the following equation, which was first proposed by Horton (1914).

$$S = \frac{Z\ (LC_{25} + LC_{50} + LC_{75})}{4A} \tag{4-1}$$

where

S = is the watershed-average slope (%)
Z = is the difference in the watershed's maximum and minimum elevations (L)
A = is the watershed total surface area (L^2)
LC_{25} = is the total length (L) of the contour line at the 25th percentile of Z
LC_{50} = is the total length (L) of the contour line at the 50th percentile of Z
LC_{75} = is the total length (L) of the contour line at the 75h percentile of Z.

When watersheds are delineated so that they are drained by stream(s) lying in the interior of the watershed, i.e., sheet-flow reaches the stream(s) from both stream banks, watershed-average sheet-flow length is estimated as (Horton, 1914)

$$X = 0.5\frac{A}{\Sigma L_{str}} \tag{4-2}$$

where

ΣL_{str} = cumulative length (L) of streams in the watershed.

Equation 4-2 is based on an approximation of the watershed as a rectangle bisected by the stream, as illustrated in Figure 4-1, and thus gives one-half of its width as the average sheet-flow distance. When watersheds are delineated so that a stream is a watershed boundary, e.g., one-half of the area in Figure 4-1, the 0.5 factor in Equation 4-2 is replaced by 1.0.

Assuming that the cumulative stream length, ΣL_{str}, has been correctly estimated, Equation 4-2 underestimates the actual sheet-flow distance because it implicitly assumes that sheet-flow is perpendicular to the stream channel, i.e., the stream channel has zero slope. In reality, the sheet-flow path will lie to some extent in the same direction as the stream gradient, because sheet-flow will be both flowing toward the stream and in the direction of the watershed slope along the stream gradient. Several adjustments to Equation 4-2 have been proposed to correct for this effect (Horton, 1945; Williams and Berndt, 1977); however, none of these proved amenable to the automated, geographical information system (GIS)-based methods used for the HWIR analysis within the time and budget available and Equation 4-2 was used as presented. (Despite the inherent bias of Equation 4-2, GIS analysis can in fact lead to **overestimates** of sheet-flow length, as discussed in U.S. EPA [1999]. Accordingly, watershed-average sheet-flow lengths estimated by Equation 4-2 are replaced by reasonable maximum values when they exceed these values, as described in U.S. EPA [1999].)

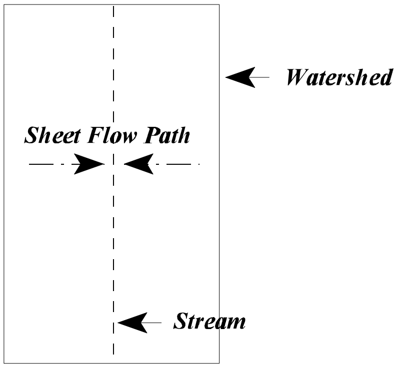

Figure 4-1. Watershed approximated as rectangle.

5.0 Output Summary

Table 5-1 summarizes the outputs of the Watershed Module.

Table 5-1. Output Summary

Output Variable	Description	Units
NyrMet	Number of years in the available meteorological record	Year
CTdaR	Depth-averaged soil concentration (from zava to zavb)	µg/g
CTdaRYR	Year associated with output	Year
CTdaRNY	Number of years in outputs	Unitless
CTssR	Surface soil concentration	µg/g
CTssRYR	Year associated with output	Year
CTssRNY	Number of years in outputs	Unitless
RunoffR	Runoff flow to waterbody	m^3/d
BFann	Long-term average baseflow to waterbody	m^3/d
AnnInfil	Annual average recharge rate	m/d
SWLoadChemR	Chemical load (resulting from deposition only) to waterbody	g/d
SWLoadChemRYR	Year associated with output	year
SWLoadChemRNY	Number of years in outputs	Unitless
SWLoadSolidR	Total suspended solids in runoff	g/d

Time series reporting is subbasin-specific; that is, all outputs for a given subbasin are reported, including zeros, up to the year that the subbasin simulation is terminated.

6.0 References

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