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7.0 Watershed Module

7.1 Purpose and Scope

The Watershed Module estimates contaminant concentrations in soil resulting from aerial deposition of contaminants throughout the area of interest (AOI) around each modeled site and the resulting contaminant loadings to surface waterbodies from runoff and erosion. It also estimates some hydrological inputs for the Surface Water Module (flows, eroded soil loads) and the Vadose Zone and Aquifer Modules (infiltration rates). Figure 7-1 shows the relationship and information flow between the Watershed Module and the 3MRA modeling system .

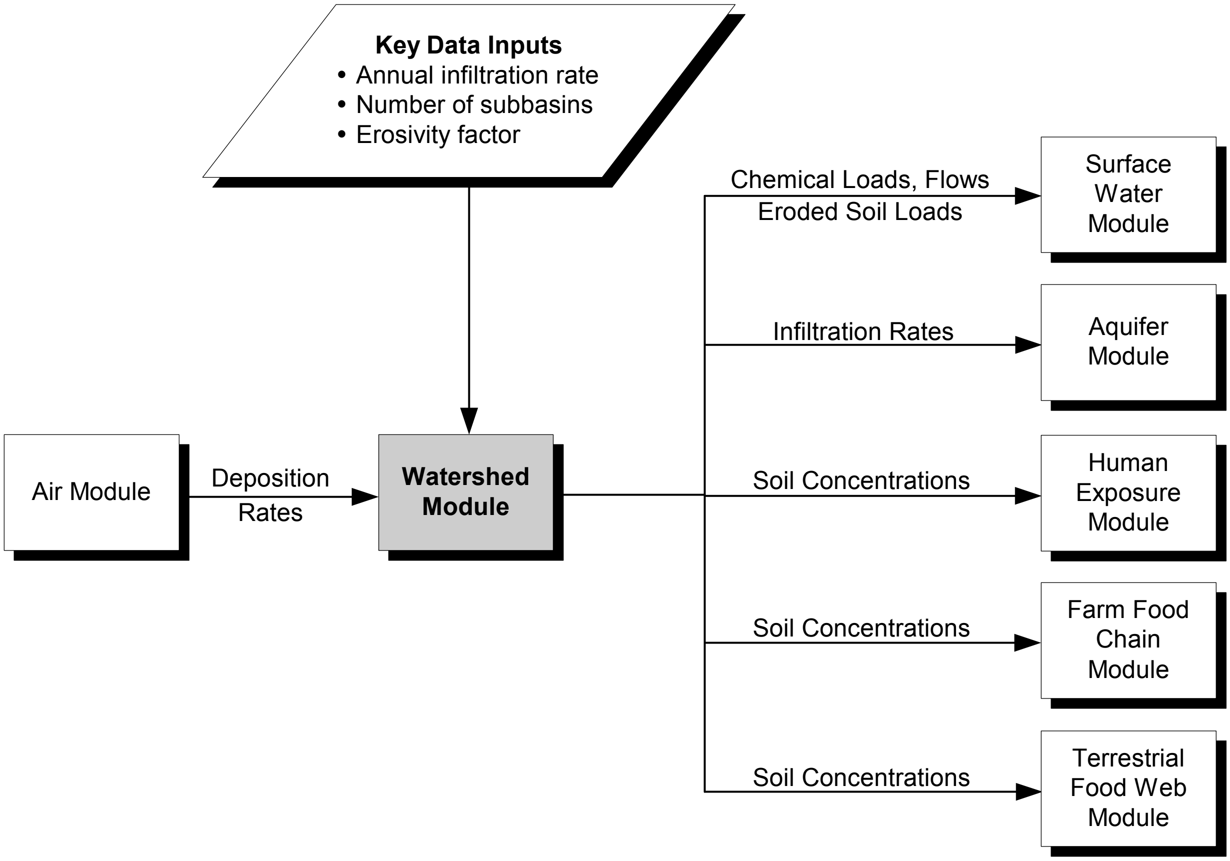

Figure 7-1. Information flow for the Watershed Module in the 3MRA modeling system.

The Watershed Module has two major functions:

1. **Calculates soil contaminant concentrations and surface water loadings.** The Watershed Module predicts the fate and transport of contaminants in the watershed subbasins to estimate soil concentration in the regional watershed and contaminant loadings to surface water from runoff and erosion.

2. **Calculates hydrological inputs.** The Watershed Module calculates several hydrological inputs for the Surface Water Module and the Aquifer Module.

7.2 Conceptual Approach

The AOI around a site consists of a set of contiguous watershed subbasins. Excluding surface waterbody areas, all land surfaces within the AOI fall within one of the watershed subbasins. Depending on the watershed delineation criteria, the number of watershed subbasins constituting an AOI varies; the typical range is 6 to 25 for the current site-based data set. Figure 7-2 shows a sample AOI that consists of all or part of 12 watersheds.

The watersheds are delineated so that surface runoff in one subbasin is modeled independently of surface runoff in other subbasins; therefore, the 3MRA modeling system assumes no contaminant transport occurs from one watershed subbasin to another via erosion or runoff, or via wind suspension or volatilization and subsequent deposition. Thus, the Watershed Module models each of the watershed subbasins at a site independently of the other subbasins at that site.

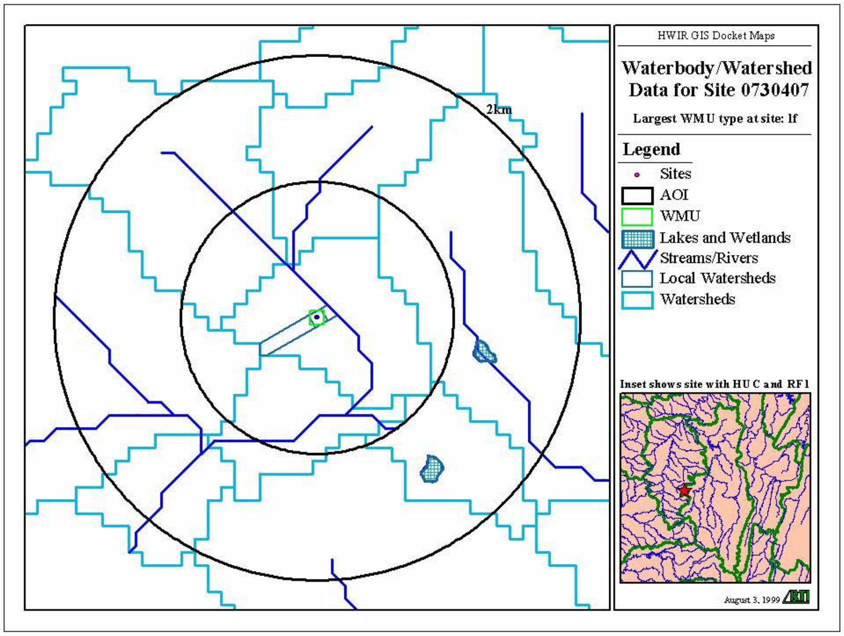

Figure 7-2. Illustration of watersheds within an AOI.

The Watershed Module simulates contaminant fate and transport related only to loads that result *indirectly* from the WMU (i.e., through the process of wind erosion or other particulate suspension or volatilization from the WMU into the atmosphere and through subsequent deposition from the atmosphere onto the surrounding regional watersheds). Contaminant loads to a waterbody resulting from *direct* runoff and erosion from a WMU are simulated by the LAU or Waste Pile Module. Watershed soil concentrations and waterbody concentrations are a function of both direct and indirect contaminant loads. Thus, if a receptor is

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located in a buffer area between a WMU and the downslope waterbody (i.e., in the WMU's local watershed), the total soil concentration to which the receptor is exposed is the aerial deposition-related concentration estimated by the Watershed Module plus the WMU runoff and erosion-related concentration estimated by the relevant source module.

There is significant overlap between the models used in the Watershed Module and those used in the Land-based Source Modules described in Section 5. This section discusses only aspects of the Watershed Module that are different from the Land-based Source Modules.

7.2.1 Calculate Soil Contaminant Concentrations and Surface Water Loadings

The Watershed Module is based on conceptual and mathematical models similar to those used in the LAU and Waste Pile Modules, such as the Generic Soil Column Model (GSCM) algorithm described in Section 5. The GSCM provides the solution to a one-dimensional (1-D), partial differential equation that describes the spatial and temporal distribution of contaminants in a porous medium subject to advective/dispersive transport and first-order losses. The governing equation is

$$\frac{\partial C_2}{\partial t} = D_E \frac{\partial^2 C_2}{\partial z^2} - V_E \frac{\partial C_2}{\partial z} - k' C_2 + ld_{dep} \qquad (7\text{-}1)$$

where

C_2 = total contaminant concentration in the soil layer (g/m^3)

D_E = vertical diffusion coefficient (m^2/d)

V_E = infiltration rate (m/d)

z = vertical distance (m)

ld_{dep} = annual average wet plus dry deposition contaminant mass loading rate (g/m^3–d)

k' = lumped first-order decay rate (d^{-1})—equal to the sum of the hydrolysis loss rate, the aerobic biodegradation loss rate, and two additional first-order rate constants that quantify the rainfall runoff and erosional loss processes.

As described in Section 5.0, Equation 7-1 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, while the first two component equations remain the same as in the GSCM, the third is revised to Equation 5-17 (Section 5.2.3), with watershed parameter ld_{dep} replacing the local watershed subarea run-on load, ld_{i-1}. The solution to Equation 5-17 is the same as that described for the LAU or Waste Pile Module, 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 5-15 (Section 5.2.3), where all the parameters are annual averages determined from annual average runoff flow and cumulative soil load (or mass of eroded soil). The time-step-averaged contaminant concentration in the soil compartment, $\bar{C}_2$ in Equation 5-15, is calculated using the following equation:

$$C_2 = \frac{1}{T}\int_0^T C_2 dt = \begin{cases} \dfrac{C_2^0}{k'T}\left(1 - \exp(-k'T)\right) + \dfrac{ld_{dep}}{k'^2 T}\left(k'T - 1 + \exp(-k'T)\right) & k' > 0 \\ C_2^0 + \dfrac{ld_{dep} T}{2} & k' = 0 \end{cases} \qquad (7\text{-}2)$$

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 (which is the 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 due to runoff and erosion (g/d).

In the Watershed Module, the depth of the soil column is a user-specified input, set at a default of 5 cm. Each soil column layer is 1 cm thick. The surficial soil column layer (top 1 cm) is linked to the runoff compartment during runoff events using the local watershed/soil column algorithm described in Section 5. Similar to the presentation in Section 5, the runoff water during a runoff event 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-sorbed plus dissolved) contaminant concentration in the watershed runoff is coupled to the total concentration in the soil layer.

In the subsurface layers of the soil column, the contaminant mass fate and transport governing equation is also given by Equation 7-1; however, the total first-order loss rate (k') is equal to the sum of the input first-order loss rates due to hydrolysis and anaerobic biodegradation only.

The solution technique for Equation 7-1 is identical to that used for the LAU, Waste Pile, and Landfill Modules and is described completely in Section 5. The concentration in the surface layer of the soil column is determined at the end of each time step by solving Equation 7-1; its average value over the time step is calculated by integrating over the time step. The contaminant concentration in the runoff water averaged over the time step is calculated as a function of the surface soil concentration averaged over the time step, as described in Section 5. At the end of each year's simulation, the annual average contaminant concentration in the runoff water is determined and multiplied by the annual average runoff rate to determine the annual average contaminant mass load to the waterbody due to runoff and erosion.

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7.2.2 Calculate Hydrological and Soil Erosion Inputs

Streamflow. The Watershed Module uses the identical hydrology submodel described in detail in Section 5 to estimate stormwater runoff and ground water infiltration. The hydrology submodel is applied to entire, individual watersheds where 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). 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 analyzing runoff hydrographs that include runoff as well as pre- and post-runoff flows. For the purposes of the 3MRA modeling system, within-year variability in baseflows is not estimated. Rather, a single estimate is sought that reasonably characterizes annual average baseflow conditioned on stream reach order (or tributary drainage area), year, and hydrologic region.

The single flow statistic that best represents annual average baseflow for a given region, reach order, and year is an important issue. The widely available annual average streamflow would, in general, tend to overestimate baseflow. 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 tend to underestimate baseflow. Therefore, the 30Q2 low flow, i.e., the minimum 30-day average flow occurring, on average, at least once every other year, was selected as a reasonable estimate of annual average baseflow for any given year.

The Watershed Module estimates the 30Q2 flow based on the area of the regional watershed, using a regression equation developed for each of the 18 hydrologic unit codes (HUCs) in the United States. The general equation is

$$Q = a \times WSA^{b} \tag{7-3}$$

where

Q = 30Q2 baseflow
a = HUC-specific regression parameter
WSA = watershed area
b = HUC-specific regression parameter.

Watershed Slope for Soil Erosion. The Watershed Module uses the modified Universal Soil Loss Equation (MUSLE), as described in Section 5, to predict soil erosion from entire watersheds. To do so, the slope parameter of the length-slope factor presented in Section 5 must reflect subbasin average conditions, rather than local watershed conditions as in the source modules application. Sheet-flow slope for a subbasin is not the slope of the stream network draining the watershed; rather, it is the average slope of the (essentially infinite) individual sheet-flow paths that form the land surfaces of that subbasin. As presented in Williams and Berndt

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(1977), the watershed-subbasin-average slope is estimated from the following equation, which was first proposed by Horton (1914):

$$S = \frac{Z\ (LC_{25} + LC_{50} + LC_{75})}{4A} \tag{7-4}$$

where

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

7.3 Module Discussion

7.3.1 Strengths and Advantages

The Watershed Module has two overall objectives: (1) to simulate contaminant concentrations in soils surrounding WMUs over time, and (2) to generate needed hydrological inputs and contaminant loads required by other modules. Relative to other known models that might have been candidates to satisfy these two objectives, the strengths and advantages of the Watershed Module include the following:

- **Appropriate level of spatial resolution.** Time-varying soil concentrations surrounding the WMU arise only as a result of deposition of airborne particles and vapors originating from the WMU. The threshold issue for designing the spatial resolution for the Watershed Module was, how fine did this resolution need to be, given such competing objectives such as minimizing runtime and data collection? Although it could reasonably be expected that soil concentrations resulting from atmospheric deposition are, on average, quite low, it is also possible that land areas in relative proximity to the WMU might have loadings of some concern. Therefore, the balancing act for spatial resolution was to not have so much spatial resolution as to unduly affect runtimes and data collection, but to also avoid as much as possible the "diluting-out" of contaminant hot spots in close proximity to the WMU. This balance led to the approach of assuming that each watershed subbasin being modeled has uniform spatial concentration (a "completely-mixed" approach), which tends to "dilute" hot spots, but having the ability to delineate "watershed subbasins" such that those in close proximity to the WMU are relatively small, so that hot spots are reasonably well represented, with larger (and presumably less important from a contamination standpoint) subbasins resulting at greater distances. Thus, although each watershed subbasin is modeled identically, the spatial resolution is highly flexible. Within a watershed subbasin, concentrations at any time are uniform, but they can vary among watershed subbasins. This level of spatial resolution control by the model user has proven to be very advantageous in modeling a wide variety of different sites.

- **Ability to generate needed hydrological inputs for other modules.** In addition to having the functionality to simulate different time-varying soil concentrations (and depth profiles) within each watershed subbasin (to be used for subsequent exposure calculations), the Watershed Module also generates hydrological inputs and contaminant loadings for other modules over a variety of meteorological and environmental conditions representing the continental United States. For the Surface Water Module, subbasin-specific stormwater runoff, eroded soil loads, stream baseflow (dry weather streamflow), and contaminant loadings are generated as time series outputs. Of particular note, baseflows are estimated in addition to stormwater runoff, so that the total streamflow (not just the surface runoff portion of streamflow) is available to the Surface Water Module. The baseflows were estimated by fitting 18 different regression models to USGS low-flow streamflow data, each model being specific to one of 18 Hydrologic Units (HUCs) in the conterminous United States. This ability to simulate region-specific baseflow is extremely important as a Surface Water Module input.

- **Consistency between the GSCM and hydrology algorithms used for Land-based Source Modules.** The algorithms used to estimate watershed subbasin soil concentrations over time and depth (the GSCM), as well as the hydrological algorithms (soil erosion, stormwater runoff) are identical to those used in the Land-based Source Modules. This commonality provided not only economies with respect to model development and ease-of-use, but, more importantly, it ensures that underlying assumptions are consistent across these modules.

7.3.2 Uncertainty and Limitations

The Watershed Module includes the following limitations or uncertainties:

- **GSCM limitations.** As mentioned previously, the GSCM is the computational engine for the Watershed Module. Accordingly, all uncertainties or limitations inherent to the GSCM, and described for the LAU, Waste Pile, and Landfill Modules (Section 5), also apply to the Watershed Module.

- **Spatial dilution of intra-watershed hot spots.** Because each watershed subbasin is assumed to be uniform with respect to contaminant concentrations in soil, hot spots resulting from nonuniform aerial deposition within a watershed subbasin will not be detected.

- **30Q2 equivalent to baseflow.** There is uncertainty in the baseflow estimates with regard to whether the module uses the correct low flow statistic (e.g., 30Q2), and in representing the variability in the baseflow for any given watershed. For a given watershed, the 30Q2 estimate of constant baseflow is a point estimate, generated from a regression model. Thus, the same baseflow will always be estimated for a given hydrologic region and watershed size.

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- **Sheetflow runoff assumption**. The MUSLE application to estimate eroded solids loads and associated sorbed contaminant loads in each watershed subbasin assumes that sheet-flow runoff and erosion apply across the entire area. Watersheds are delineated, in part, to support that assumption, but it is unlikely that true sheetflow runoff occurs over all portions of all watershed subbasins. To the extent that channelized flow occurs and can "short-circuit" contaminant loads directly to adjacent waterbodies without first traversing downslope land surfaces, the estimated contaminant loadings to waterbodies may be underestimated by the Watershed Module. Conversely, this assumption would tend to overestimate average soil concentrations across the watershed subbasin, leading to overestimated soil exposures.

7.4 References

Horton, R.E., 1914. Discussion of rainfall and run-off. *Transactions of the American Society of Civil Engineers*, 77:369-375. December.

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