RAS 14150

Applying Multimedia Modeling to Karst Systems: Comparing MEPAS, MMSOILS, and RESRAD

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ABSTRACT ●

The use of multimedia models has become a popular tool to estimate exposures and assess risks. Computer-based multimedia models compute environmental transport of contaminants in air, surface water, groundwater, and soil and bioaccumulation in plants and animals across varying timeframes. This study examines the applicability of three state-of-the-art multimedia models (MEPAS, RESRAD, and MMSOILS) to karst topography using actual site data obtained from a remedial investigation conducted at Oak Ridge National Laboratory in Tennessee in 1995 and default parameters suggested by the individual model developers.

Key Words: groundwater, karst, multimedia models, risk assessment.

INTRODUCTION ●

Multimedia models estimate relationships between contaminant release rates, pollutant transport, intermedia fluxes, and subsequent exposure to assess risks (Brenner, 1995; Cheng et al., 1995; Moskowitz et al., 1996; Laniak et al, 1997; Mills et al, 1997). The multimedia approach involves tracking contaminants from sources through multiple environmental media (e.g., air, soil, groundwater, and food) to points of human and ecological exposure. Because karst and highly fractured groundwater systems are effective in transporting pollutants due to their permeability, multiple flow directions, and rapid flow-through times (Dreybrodt, 1988; Ford and Williams, 1989), such aquifers can rapidly distribute contaminants over large areas and/or at great distances with little or no change in pollutant composition. This raises the following question: Does the use of multimedia models in karst or highly fractured terrain produce realistic estimates of risk? This article, one of a series that describes the results of a multimedia model comparison study sponsored by the U.S. Department of Energy (DOE), examines the applicability of multimedia models to karst or highly fractured topography using actual site data obtained from a remedial investigation conducted at Oak Ridge National Laboratory in Tennessee (ORNL) in 1995 and default parameters suggested by the individual model developers.

Multimedia Model and Case Study Selection

The sponsoring agency, DOE, requested that MEPAS, RESRAD, and MMSOILS be reviewed, given the DOE's technical and policymaking interest in these three models. MEPAS (Multimedia Environment Pollutant Assessment System), developed by Pacific Northwest National Laboratory, MMSOILS, developed by the U.S. Environmental Protection Agency (EPA), and RESRAD (Residual Radiation), developed by Argonne National Laboratory, are multimedia environmental transport models that consider transport of contaminants in air, surface water, and groundwater and bioaccumulation in plants and animals.

Briefly, MEPAS is a highly automated multimedia model that has been applied to a wide range of potential environmental problems associated with DOE sites across the country. MEPAS was used in the Hanford Remedial Action Draft Environmental Impact Statement (EIS), the Waste Isolation Pilot Plant Supplemental EIS, the Hanford Tank Waste EIS, and the Yucca Mountain EIS. In addition, MEPAS has been used by the state of Washington to develop cleanup standards. MEPAS has an extensive database of environmental and exposure parameters necessary for model calculations.

MMSOILS was developed specifically to address risks at Resource Conservation and Recovery Act waste sites. MMSOILS was not designed to considered the transport of radionuclides, but it is possible to do so by considering radionuclides as inorganic contaminants with a first order decay. Such an approach does not allow for radioactive daughter ingrowth and thus can significantly underestimate exposures.

RESRAD is a member of a family of specialized multimedia risk models in various stages of development that include RESRAD-Chem, RESRAD Baseline, RESRAD Probabilistic, and RESRAD Recycle. RESRAD was developed primarily to assess decommission of radioactively contaminated sites and because of this, points of groundwater exposure are limited to the facility boundary. This limits

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versatility in assessing multiple future exposure scenarios found in most risk assessments.

Readers interested in the technical formulations and detailed assumptions of each model are referred to the manuals for MEPAS (Buck et al., 1995), MMSOILS (U.S. Environmental Protection Agency, 1996), and RESRAD (Yu et al., 1993). MEPAS version 3.1, MMSOILS version 4.0, RESRAD version 5.61, and RESRAD-Chem (Beta version) were used for this study. Early drafts of the full report on which this article is based were provided to the developers (Argonne, Pacific Northwest National Laboratory (PNNL), and EPA) of the three models selected for review (Regens et al., 1998).

The Consortium for Environmental Risk Evaluation model comparison effort applied the three multimedia models to case studies at two DOE sites: the Rocky Flats Environmental Technology Site in Colorado and ORNL in Tennessee. The Rocky Flats site focuses on Operable Unit 2, which contains radioactive-contaminated oils and solvents, plutoniumm-239–contaminated soils, liquid chemical waste disposal trenches, and an inactive reactive metal destruction site. The ORNL site is a solid waste storage area with trenches containing alpha-contaminated low-level waste and remote-handled transuranic wastes deposited in concrete casks and combination (wood/metal) boxes and a small number of steel drums. ORNL involves exposures primarily via the groundwater pathway and has a fractured or karst hydrogeological topography in which groundwater flow is channeled. Under these conditions, the groundwater component of multimedia models may not perform well. Because this article examines the applicability of multimedia models to karst topography, and this topography does not exist at Rocky Flats, we focus on the results from the ORNL case study in this review.

Site Description

ORNL's Solid Waste Storage Area 5 North (SWSA5N) is an ~7-hectare (70,000-m^2) site that contains buried wooden, combination (wooden/metal), and concrete containers as well as steel drums of radioactive waste disposed of from 1970–1981 (Figure 1) (Bechtel National 1995).

Topography and Drainage

White Oak Creek drains the western section, a tributary (Northern Tributary) drains the northern end, and intermittent drainage D-1 drains the eastern section of the site (Figure 1). White Oak Creek's average flow is .32 m^3/sec; intermittent drainage D-l has an average flow of ~.0031 m^3/sec and is typically dry during the summer and fall (Bechtel National, 1995). White Oak Creek and intermittent drainage D-1 meet immediately south of the site. Elevations range from ~232 m above mean sea level (AMSL) at White Oak Creek, 328 m AMSL at drainage D-1, and 241 m AMSL at the Northern Tributary to ~256 m AMSL at the highest point. Slopes of the site are wooded, whereas the flatter areas surrounding the buildings, roadways, and capped trenches are grassy (Figure 1).

Geology

The site is underlain by folded and faulted Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, and Lower and Upper Maryville Limestones of Cambrian age. Rutledge Limestone underlies most of the northern scarp

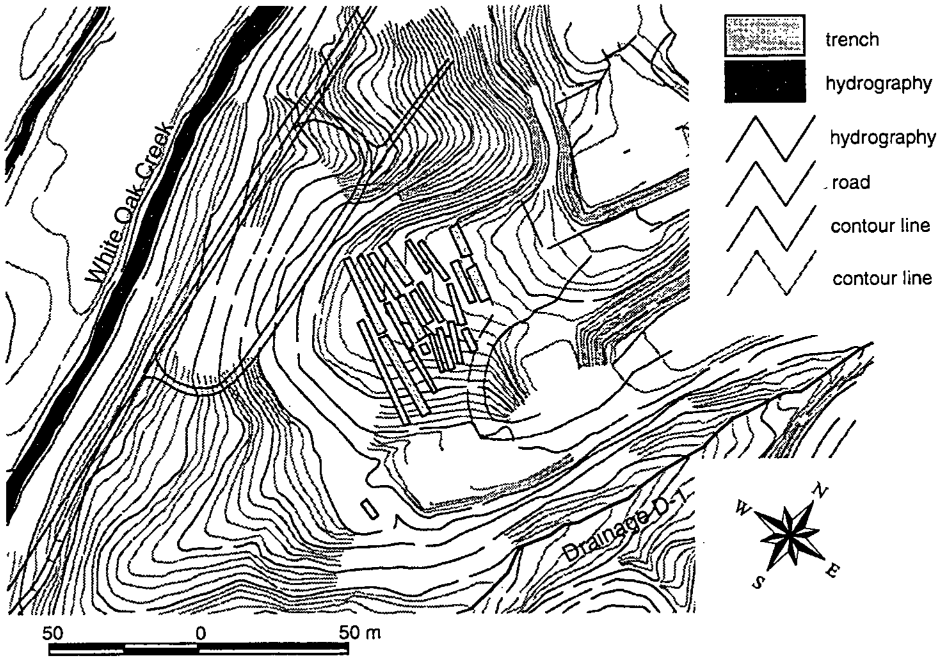

FIGURE 1: Waste Area Grouping 5, Solid Waste Storage Area 5, North.

face, Rogersville Shale underlies the high areas and the majority of the site, and Lower Maryville Limestone underlies most of the southern scarp face. The Maryville Limestone is typically a variable sequence of thinly interbedded shales, siltstones, and limestones, with the Upper Maryville generally containing greater proportion of shale and is likely to have greater numbers of fractures and hydrologically active zones than does the Lower Maryville. Residual soils produced by the weathering of the shale and limestone units are present above bedrock and vary in thickness between a few meters near the surface water bodies to ~4.6 m near the disposal trenches.

Hydrogeology

One portion of groundwater flows toward White Oak Creek, a portion flows toward intermittent drainage D-1, and a very small remaining portion flows toward the Northern Tributary. The depth to the water table generally coincides with the depth to weathered bedrock, although actual depth varies between locations depending on topography, degree and depth of weathering, and structure, in particular fracture abundance, orientation, and interconnectedness (Bechtel National, 1995). Minimal seasonal variation has been observed in the horizontal hydraulic gradient in the saturated zone (0.065 ft/ft dry season; 0.067 ft/ft wet season) (Bechtel National, 1995). The vertical gradient is consistent with infiltration and recharge near the top of the hill and discharge of groundwater (diffuse and through seeps) near White Oak Creek, the Northern Tributary, and intermittent drainage D-1. The field portion of the remedial investigation conducted in the spring 1993 included sampling and analysis of groundwater, soil, stream sediment, surface water, seep water, and surface radiation measurements. The remedial investigation results indicate americium and curium in groundwater, the Northern Tributary, White Oak Creek, intermittent drainage D-1, and the seeps (Bechtel National, 1995).

Conceptual Site Model

The conceptual site model developed for the southern most trenches of SWSA5N defines the exposure scenarios to be analyzed using the multimedia models (Table 1). Although the site and media are not homogeneous in terms of physical and chemical properties, it is necessary to make a series of general assumptions to apply multimedia models to actual site data. The source term is composed of curium-244, plutonium-239, uranium-233, americium-241, californium-252, neptunium-237, and plutonium-238. Groundwater is the transport pathway of concern and flow is bidirectional; however, because the multimedia models concerned in this study only allow for one direction of groundwater flow, the major direction of flow was selected.

The waste site is located on a hill, includes 22 trenches, and has an approximate trapezoidal geometry. The area of the waste site is 1078 m^2, including inter-trench space. The thickness of the waste layer was assumed to be 2.3 m based on the maximum height of containers that may have been stacked in some of the 3.1-m-deep trenches (exact configuration of containers is unknown). All trenches were backfilled with 0.8 m of uncontaminated soil.

In this model, contaminants move downward through the waste layer and through a 0.3-m unsaturated layer into the saturated layer. Contaminants are then transported to hypothetical on-site residents who use contaminated groundwater for irrigation, watering livestock, and general household uses. Hypothetical off-site residents would use water from seeps and creeks for the same purposes. The White Oak Creek was selected as a potential exposure location because shallow groundwater that passes through the waste layer ultimately drains into the creek. EPA exposure guidelines are applied to one hypothetical individual at each receptor location to estimate risks. Figure 2 is a schematic of the plan view and transport and exposure pathways for the conceptual site model. Transport with and without a concrete barrier was considered. No-barrier and barrier applications are used to simulate differentials in cask degradation. The no-barrier application tests the model's capabilities in an unconstrained manner, whereas the barrier application was constrained to approximate the ORNL risk assessment, conducted as part of the remedial investigation in 1995.

TABLE 1. General assumptions for the SWASA5N conceptual site model.

Source term properties
  - Radioactive waste buried in wooden, metal, and concrete containers
  - Groundwater major pathway of concern
  - Bidirectional groundwater flow

Site geometry
  - Located on a hill top
  - Trapezoid shape
  - 1078-m^2 area
  - Waste located in 22 trenches, 3.05 m deep
  - 0.76-m clean cover, 2.29-m waste layer, 0.30-m unsaturated layer, and saturated layer

Transport properties
  - Homogenous media in all strata
  - All strata have the same chemical and physical properties
  - Groundwater begins 0.30 m below the waste layer
  - Shallow aquifer flow follows topography
  - Negligible horizontal subsurface flow in the unsaturated zone

Receptors properties
  - Future land use is residential
  - Receptors located at down-gradient edge of the site, at a seep, and at White Oak Creek
  - Exposure results from the use of groundwater

Exposure factors
  - One individual affected
  - EPA exposure guidelines applied

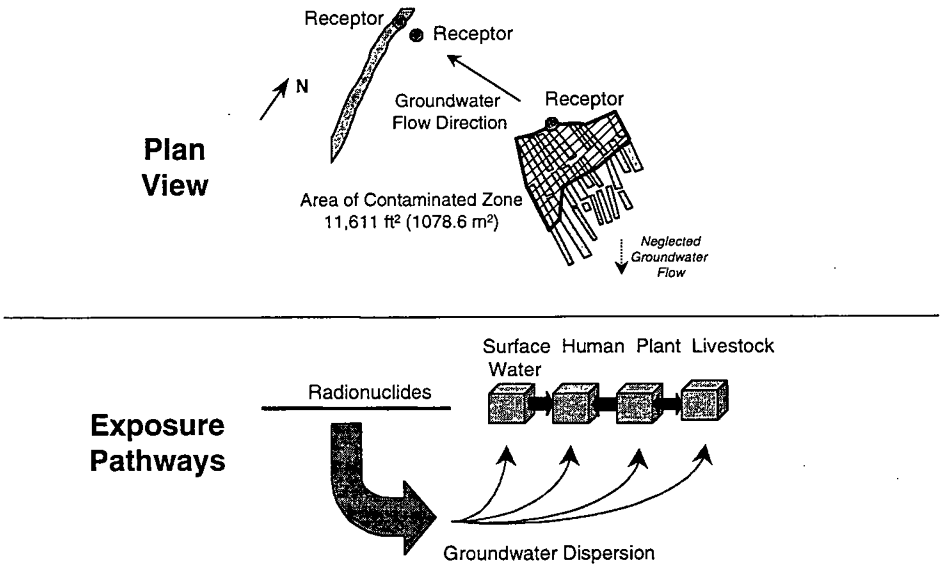

FIGURE 2: Plan view and exposure pathways for conceptual site model used in the Oak Ridge Case Study.

No-Barrier Application

The no-barrier application simulates leaching from a well-mixed waste layer that contains no barriers through an unsaturated layer and into the saturated layer to estimate potential risks (Figure 3). Table 2 summarizes the assumptions for the no-barrier application. Some source term properties were generalized to encompass the radionuclides reportedly buried in the trenches: curium-244, plutonium-239, uranium-233, americium-241, californium-252, neptunium-237, and plutonium-238. Waste containers were assumed to decompose immediately upon burial, leaving no barriers to contaminant migration with the contaminants evenly distributed within the waste layer upon burial. The total inventory of contaminants was divided into the volume of soil in the waste layer and the source term was partitioned based on surface topography to determine the fraction that flows toward White Oak Creek. Site geometry was defined using site documentation and a Geographic Information System; the area of the portion of the waste site that drains into White Oak Creek is 1078 m^2. Four strata were used with the multimedia models: 0.76-m uncontaminated cover layer, 2.29-m waste layer, 0.30-m unsaturated layer beneath the waste layer, and a saturated layer. All media were assumed to be homogenous; because of limitations of the available data, the physical and chemical characteristics are identical for all strata. Precipitation, topography, vegetative cover, and soil physical properties were used to compute infiltration. The no-barrier application estimated risk for groundwater-related exposure pathways for an individual at the three defined receptor locators.

Barrier Application

The barrier application simulates concrete cask degradation and leaching through the unsaturated layer into the saturated layer from the buried waste (Figure 4). Table 2 summarizes our assumptions for the barrier application. Only the three radionuclides contributing the most to risk in the ORNL risk assessment (plutonium-239, curium-244, and uranium-233) are included. The three multimedia models under consideration do not allow for the simulation of leaching through a concrete barrier. To simulate this process, the Disposal Unit Source Term (DUST) computer model results were used to determine mean contaminant flux rates into the saturated zone (Brookhaven National Laboratory, 1993). DUST output was used to represent the

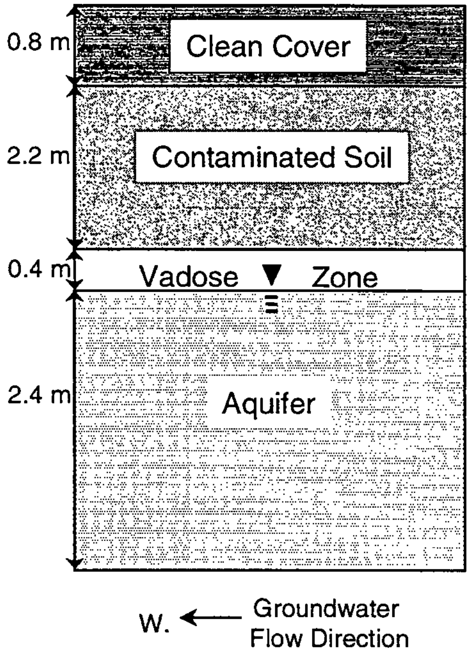

FIGURE 3: Profile view of the conceptual site model barrier application.

TABLE 2. Generalizations and assumptions unique to the no-barrier and barrier applications.

No-barrier applications
  Source term
    - Curium-244, plutonium-238/239, uranium-233, americium-241, californium-252, neptunium-237
    - Waste containers immediately decomposed
    - Contaminants well mixed within the waste layer
    - All contaminants available to immediately leach into the underlying unsaturated layer
    - Waste layer partitioned based on topography
  Site geometry
    - Four strata defined including clean cover layer, waste layer, unsaturated uncontaminated layer, and a saturated layer
  Transport properties
    - Infiltration was a function of climatic data, land cover, and surface runoff coefficient
Barrier application
  Source term
    - Plutonium-239, curium-244, uranium-233
    - Flux into groundwater began in 1971 and remained constant for 95 years
    - Flux rate derived from DUST mathematical computer model
  Site geometry
    - Two strata defined: waste layer and a saturated layer
  Transport properties
    - Infiltration rate fixed at 25.4 cm/year

time history of contaminant inputs released from the source area. Two strata are defined for the barrier application: the waste layer and the saturated layer. Based on site documentation, the infiltration rate was fixed at 25 cm/year. The multimedia models simulated transport through the saturated layer to the defined receptors.

RESULTS ●

This section summarizes the output for the two applications. The simulation period is for 1971–2066 (95 years), the risk assessment period is from 1996–2066 (70 years), and the hypothetical on-site resident exposure period is 30 years, in accordance with EPA's Risk Assessment Guidance for Superfund.

No-Barrier Application

The no-barrier application considers a uniform distribution of the radionuclide inventory in a 2.29-m unsaturated zone interval and uses site-specific climatic and soil property information to estimate the movement of the radionuclides through a "clean" 0.3-m unsaturated zone interval to the saturated zone and their subsequent potential to expose human populations. Table 3 summarizes the excess lifetime cancer risks by pathway of concern and contaminant of concern. Risk is usually expressed in quantitative probability terms such as some number of additional cancer deaths over a lifetime in a population of exposed people. For example, a risk of 1 in 10,000 is often expressed as a "10^{-4} risk," 1 in 1 million as "10^{-6} risk," and so on.

The three multimedia models identified drinking water and plant ingestion as two of the three highest risk pathways for the hypothetical on-site residential receptor. MEPAS identified dermal absorption as the highest risk pathway; this is because MEPAS utilizes the dermal adsorption value for cadmium chloride as the default value for radionuclides (U.S. Environmental Protection Agency, 1992) which produces an overly conservative estimate for the radionuclides considered. Discrepancies between models in terms of radionuclides contributing most to estimated risks result primarily from differences in decay and transport mechanisms. MEPAS and RESRAD are specifically designed to simulate radionuclide transport, whereas MMSOILS, not being programmed to solve radionuclide reactions, only simulates linear radioactive decay reactions during transport. The risk estimates provided by the multimedia models generally differ on the order of two orders of magnitude for the principal pathways and radionuclides and by more than two orders of magnitude for secondary pathways and radionuclides. The probable sources of these discrepancies in magnitude will be discussed later.

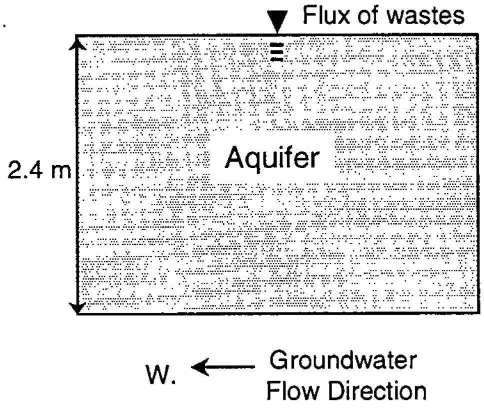

FIGURE 4: Profile view of the conceptual site model no-barrier application.

TABLE 3. Estimated risk values[a] for the barrier application.

Parameter	MEPAS	RESTRAD	MMSOILS
Exposure pathway			
Drinking water	1.6E-02	2.3E-01[b]	2.7E-01
Showering ingestion	8.2E-05	—	—
Showering dermal	1.5E-01	—	0.0E+00[c]
Leafy vegetables	1.0E-03	—	0.0E+00[c]
Other vegetables	1.1E-03	—	0.0E+00[c]
Plant total	2.1E-03	1.2E-02	0.0E+00[c]
Meat	9.1E-07	1.9E-05	1.4E-04
Milk	1.1E-05	5.1E-06	3.1E-05
Ground	—	—	—
Radon	—	1.4E-21	—
Radionuclide totals			
Plutonium-239	7.7E-02	2.3E-01	2.4E-01
Curium-244	7.0E-02	2.9E-03	1.5E-02
Uranium-233	2.1E-02	4.9E-03	6.0E-03

[a] Receptor is located at down-gradient edge of the contaminated zone on the plume centerline, and risk are maximum values calculated for individuals exposed to contaminants for 30 years between 1996–2066.

[b] Includes ingestion while showering.

[c] MMSOILS calculates nonzero values for all parameters used to compute the soil concentration of contaminants that results from irrigation. However, the reported soil concentration of contaminants from irrigation is inexplicably listed as zero, ultimately resulting in zero risk values for plant ingestion.

TABLE 4. Estimated risk values[a] for the no-barrier application.

Parameter	MEPAS	RESRAD	MMSOILS
Exposure pathway			
Drinking water	6.4E-03	1.1E-01[b]	1.6E-03
Showering ingestion	3.2E-05	—	—
Showering dermal	7.7E-02	—	0.0E+00[c]
Leafy vegetables	9.2E-04	—	5.0E-08
Other vegetables	7.2E-04	—	3.7E-06
Plant total	1.6E-03	2.1E-04	3.75E-06
Meat	4.0E-06	1.5E-06	6.5E-07
Milk	4.6E-05	2.4E-07	3.8E-07
Ground	—	1.2E-13	—
Radon	—	1.2E-11	—
Radionuclides totals			
Plutonium-239	1.1E-08	2.2E-04	3.0E-04
Curium-244	1.1E-03	6.9E-03	8.4E-06
Uranium-233	1.5E-03	3.4E-03	7.1E-05
Americium-241	6.5E-03	1.5E-01	1.2E-03
Californium-252	0.0E+00[d]	1.3E-10	8.9E-16
Neptunium-237	2.1E-06	6.6E-05	1.9E-05
Plutonium-238	5.2E-12	2.8E-07	1.8E-06

[a] Receptor is located at the down-gradient edge of the contaminated zone on the plume centerline, and risks are maximum values calculated for individuals exposed to contaminants for 30 years between 1996–2066.

[b] Includes ingestion while showering.

[c] MMSOILS calculates nonzero values for all parameters used to compute the soil concentration of contaminants that results from irrigation. However, the reported soil concentration of contaminants from irrigation is inexplicably listed as zero, ultimately resulting in zero risk values for plant ingestion.

[d] MEPAS generates a zero value if slope factors or other radionuclide-specific information are missing. Additional software is required to alter this information.

Barrier Application

The barrier application considers the release of given fluxes of radionuclides to the saturated zone. MEPAS and MMSOILS were capable of using contaminant fluxes as input parameters, but the fluxes needed to be transformed to equivalent soil concentrations for input to RESRAD. Table 4 summarizes the excess lifetime cancer risks by pathway of concern and contaminant of concern. RESRAD and MMSOILS identify drinking water as the highest risk pathway for the hypothetical on-site residential receptor. MEPAS identified dermal absorption as the highest risk pathway, followed by drinking water as the second highest risk pathway. The RESRAD risk estimate for plant ingestion is higher than that of either MEPAS or MMSOILS because RESRAD does not allow a cover of "clean" material over the trenches. The absence of a cover with RESRAD leads to overly conservative risk estimates for pathways that are susceptible to constituent partitioning from shallow soils. Initially, an error with the data input interface for MEPAS resulted in zero risk values for the ingestion of plants because the input interface recorded the value only for the receptor located at the seep. An undetermined error in an input file or the program code prevented MMSOILS from correctly computing the risks associated with the ingestion of plants irrigated with contaminated water. The risk estimates provided by the multimedia models generally differ by one order of magnitude for the groundwater pathway and by two orders of magnitude for the selected radionuclides. As in the case of the no-barrier application, MEPAS incorrectly identifies dermal absorption during showering as a pathway of concern due to overconservative input values for the dermal absorption fraction of radionuclides. The risk estimates differ by two or more orders of magnitude for secondary pathways. The barrier application results closely approximated the ORNL risk assessment estimates.

CONCLUSIONS ●

MEPAS, RESRAD, and MMSOILS do not consider the transport of radionuclides through a fracture system or the colloidal transport of radionuclides in groundwater. Both of these processes can lead to accelerated transport of radionuclides in the subsurface relative to the rates calculated by advective/dispersive, porous media flow models. The three models are one dimensional and can simulate only one flow direction at a time. Karst systems, however, exhibit multiple flow directions simultaneously. As a result, because of their limited transport properties, none of the three models can realistically depict the fate and transport mechanisms operating in karst systems. Therefore, although it is correct to consider the estimates provided by applying the three multimedia models to karst systems as "screening level" estimates, they are not a substitute for more comprehensive field monitoring and analysis.

The three multimedia models handled multiple pathways and contaminants, offered a consistent framework for analysis, and were easily updated to accommodate new site data. The models consistently identify groundwater, when used for drinking, showering, or irrigation, in the vicinity of the waste disposal trenches as the major pathway of concern. The multimedia model simulations and the original ORNL risk assessment estimate significant risks to potential residential receptors located at the edge of the waste management unit and indicate no significant risks for potential receptors located away from the waste disposal trenches. This result reflects the very slow calculated rate of migration of radionuclides in the subsurface. Although assessing risk from contamination of karst systems is a complex task, the results of this multimedia model comparison study demonstrate that the three multimedia models can be applied successfully to develop realistic screening level estimates of exposure and risk when used by experienced risk assessors.

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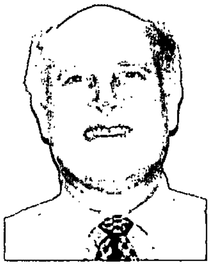

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