ASSESSING EXPOSURES AND RISKS IN HETEROGENEOUSLY CONTAMINATED AREAS: A SIMULATION APPROACH

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ABSTRACT

The U.S. Department of Energy (DOE) is responsible for cleanup activities at a number of facilities under its Environmental Restoration and Waste Management Program. The major goals of this program are to eliminate potential hazards to human health and the environment that are associated with contamination of these sites and, to the extent possible, make surplus real property available for other uses. The assessment of potential baseline health risks and ecological impacts associated with a contaminated site is an important component of the remedial investigation/feasibility study (RI/FS) process required at all Superfund sites. The purpose of this paper is to describe one phase of the baseline assessment, i.e., the characterization of human health risks associated with exposure to chemical contaminants in air and on interior building surfaces at a contaminated site. The model combines data on human activity patterns in a particular microenvironment within a building with contaminant concentrations in that microenvironment to calculate personal exposure profiles and risks within the building. The results of the building assessment are presented as probability distribution functions and cumulative distribution functions, which show the variability and uncertainty in the risk estimates.

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INTRODUCTION

A hazardous waste site can pose threats to human health via transport of on-site contaminants through environmental media to human receptors. The U.S. Environmental Protection Agency (EPA) has developed a framework for assessing these potential threats in order to support cleanup decisions on the basis of risk at Superfund sites. This frame-work consists of a baseline risk assessment, which is prepared to:

- Estimate risks that could occur either now or in the future if no cleanup action were taken at the site;

- Help focus the need for cleanup by highlighting the environmental media and locations that are associated with unacceptably high risk estimates, as well as those that are not;

- Provide a basis for determining residual levels of chemicals that can remain on-site without adversely impacting human health;

- Permit risk-based comparisons between various alternatives considered for site cleanup (by identifying incremental protectiveness relative to the baseline case); and

- Provide relative consistency with the evaluation of human health threats associated with other hazardous waste sites.

In preparing the baseline risk assessment for a site, the relationship between the sources of a pollutant and the potential receptors are developed through an exposure assessment process. Quantifying human exposures to contaminants in the environment requires information on (a) contaminant sources and strengths, (b) fate and transport of these substances from the source to the human receptor(s), and (c) receptor activity patterns. When assessing exposures associated with Superfund sites, the first two factors may be well characterized because of the extensive sampling that is often conducted as part of the Superfund decision-making process. Receptor activity patterns, however, are usually less well defined. Only a few exposure scenarios are typically considered in a baseline risk assessment. These scenarios often use set values for parameters such as the frequency and duration of exposure for each receptor. Furthermore, few sites are uniformly contaminated, and they may include large areas that are free of contamination. Hence, it is possible that an individual traversing a site might come in contact with areas that would contribute little to his or her total exposure and risk. Research indicates that, in fact, receptor dynamics and microenvironment concentrations can be important to the appropriate characterization of human exposures (1-5).

The results of an exposure assessment are combined with toxicity information to provide an estimate of the health risks (carcinogenic effects) and health hazards (noncarcinogenic effects) for a site. This impact characterization forms the basis for recommending cleanup criteria and focuses the selection of remedial action alternatives.

Thus, the uncertainty associated with exposure estimates at Superfund sites can directly affect the ultimate disposition of the site and potential cleanup costs.

Cleanup activities are currently being conducted by the U.S. Department of Energy (DOE) at the Weldon Spring site near St. Louis, Missouri. This site consists of a chemical plant area that has been inactive for more than 20 years and a noncontiguous quarry that was used for waste disposal. The Army produced nitroaromatic explosives at the 217-acre chemical plant area during the 1940s, and radioactive materials of the uranium and thorium series were processed there by DOE's predecessor during the 1950s and 1960s. The site is chemically and radioactively contaminated as a result of the past processing and disposal activities. In 1989, the EPA included the chemical plant area in its National Priorities List. Hence, site cleanup is being conducted in accordance with EPA's Superfund process under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended. Site activities are also being conducted in compliance with the National Environmental Policy Act (NEPA).

An integral part of the CERCLA/NEPA process is the preparation of a comprehensive baseline assessment of human health and environmental impacts to support decision making for site cleanup. This paper focuses on one component of the baseline assessment prepared for the site in order to highlight the potential impact on exposure estimates that result from varying the exposure assumptions. This component is the characterization of human health risks associated with polychlorinated biphenyl (PCB) exposures in one of the contaminated buildings. Because of the heterogeneous nature of the PCB contamination, a nonstandard approach was used to account for variability in possible exposures. This paper describes the mathematical model that was used to quantify the human exposures and health risks associated with ingestion, inhalation, and dermal absorption of PCB's in air, dust, and spills on floors and benches in the building. This model explicitly accounts for contaminant heterogeneity and simulates the movement of a person through several microenvironments within the building. By this approach, data on human activity patterns relative to the time spent in a particular microenvironment can be combined with contaminant concentrations therein to calculate personal exposure profiles and potential risks.

METHODOLOGY

The Weldon Spring site is located in a rural area surrounded by federal and state land, including wildlife areas that total almost 7,000 ha. The site is fenced, and access by the general public is restricted. Nevertheless, potential exposures of the general public are evaluated by assuming that a hypothetical adolescent trespasser enters the building and is exposed either while walking or playing. The potential routes of exposure are inhalation of airborne particulates, incidental ingestion of residues and dust, and dermal contact with residues and dust.

Exposure Point Concentrations

The contaminated building is a 60-m by 110-m, one-story cinderblock structure that is divided in two by a wall that extends from north to south. The west half of the building is subdivided into small work bays and offices; the east half contains a main storage area and several smaller rooms that formerly housed an automotive repair shop, rest rooms, decontamination areas, and a shipping dock. Sampling for PCBs was conducted using two methods: (1) swipe sampling of floor and bench surfaces and (2) bulk sampling of spill residues and dusts. The biased sampling strategy focused on areas where PCBs were expected to be found. Concentrations in 22 surface swipe samples ranged from about 2 to > 29,000 µg/100 cm^2; however, almost 40% of the samples were below the analytical detection limit (DL) of 1 µg/100 cm^2. Concentrations in 11 bulk samples ranged from about 40 to 13,000 ppm, with 15% below the DL of 2 to 5 ppm. About 85% of the building was considered to be uncontaminated with PCBs.

Exposure point concentrations were estimated from these data by developing a strategy to address the non-detects (NDs), i.e., samples for which PCB concentrations were below the DL. Several statistical methods have recently been recommended for substituting values for the NDs (6-8), and these methods have been evaluated for application to soil data from the site by Özkaynak et al. (9). From this evaluation, it was determined that the maximum likelihood estimator method was suitable for most data sets for which the NDs ranged from a few percent to 50%. However, in this case, we found that replacing the NDs for the building PCB data with one-half the DL was adequate and did not introduce much bias in estimating the exposure point concentrations. This was largely due to the highly skewed distribution of PCB concentrations in the building samples. Because the PCB contamination is limited to several discrete areas within the building, the measured value at each of these areas was used as a location-specific exposure point concentration.

No air samples were taken for PCBs; thus, a dust resuspension model (10) was used to estimate PCB concentrations in air that could result from the resuspension of contaminated residue and dust during human activity in the building. Airborne concentrations of PCBs were estimated for each contaminated area as follows:

$$C_{air} = \frac{C_{sur} \, \Omega \, A}{V \, a} \qquad \text{(Eq. 1)}$$

where C_{air} is the PCB concentration in air (mg/m^3); C_{sur} is the surface contamination level (mg/m^2); Ω is the fraction of dust resuspended per hour (h^{-1}); A is the area of contamination within a room (m^2); V is the volume of the room (m^3); and "a" is the number of air exchanges per hour (h^{-1}).

Intake Equations

Human intakes of PCBs via various pathways -- that is, PCB exposures normalized for time and body weights -- were estimated consistent with EPA guidance (11). Intakes resulting from exposures via the air pathway were estimated as follows:

$$I_{ihl} = \frac{(C_{air})\ (IR_{ihl})\ (PM_{10})\ (ET)\ (EF)\ (ED)}{(BW)\ (AT)} \tag{Eq. 2}$$

where I_{ihl} is the normalized intake for inhalation of resuspended contaminated dust (mg/kg-d); IR_{ihl} is the inhalation rate (m^3/h); PM_{10} is the fraction of resuspended dust with an aerodynamic mean diameter of less than 10 µm; ET is the exposure time (h/event); EF is the exposure frequency (events/yr); ED is the exposure duration (yr); BW is the body weight (kg); and AT is the averaging time (d).

Because the extent of PCB contamination was characterized by both bulk sampling and surface swipe methods, two algorithms were needed to estimate intakes resulting from incidental ingestion of contaminated residues. For data reported in ppm (i.e., bulk sample data), intakes were estimated following EPA guidance (11):

$$I_{ing} = \frac{(C_{rsd})\ (IR_{rsd})\ (FI_{rsd})\ (ET)\ (EF)\ (ED)\ (CF_1)}{(BW)\ (AT)} \tag{Eq. 3}$$

where I_{ing} is the intake for incidental ingestion of residue (mg/kg-d); C_{rsd} is the PCB concentration of the residue (mg/kg); IR_{rsd} is the residue ingestion rate (mg/h); FI_{rsd} is the fraction ingested from the contaminated residue; and CF_1 is a unit conversion constant $(10^{-6}$ kg/mg). However, for data reported in µg/100 cm^2 (i.e., surface swipe data), the EPA guidance needs to be modified; for this case, intakes were calculated as follows:

$$I_{ing}^* = \frac{(C_{sur})\ (SA^*)\ (FR)\ (ET)\ (EF)\ (ED)\ (CF_2)}{(BW)\ (AT)} \tag{Eq. 4}$$

where I_{ing}^* is the intake for incidental ingestion of residue (mg/kg-d); SA^* is the exposed skin surface area that could come in contact with the mouth (cm^2/h); FR is the fraction of contaminant removed during contact; and CF_2 is a unit conversion constant $(10^{-4}\ m^2/cm^2)$.

Similar to the ingestion pathway, two approaches were used to estimate intakes from skin absorption as a result of dermal contact with contaminated residue and dust. For data reported in µg/g (bulk samples), intakes were estimated following EPA guidance (11):

$$I_{der} = \frac{(C_{rsd})\ (SA)\ (AF)\ (AB)\ (EF)\ (ED)\ (CF_1)}{(BW)\ (AT)} \tag{Eq. 5}$$

where I_{der} is the intake via dermal absorption (mg/kg-d): SA is the exposed skin surface area (cm^2/event): AF is the residue-to-skin adherence factor (mg/cm^2); and AB is the absorption factor. However, for data reported in µg/100 cm^2 (surface swipes), intakes were estimated as follows:

$$I_{der}^* = \frac{(C_{sur})\ (SA)\ (FR)\ (AB)\ (EF)\ (ED)\ (CF_2)}{(BW)\ (AT)} \qquad \text{(Eq. 6)}$$

where I_{der}^* is the intake via dermal adsorption (mg/kg-d).

Consistent with EPA guidance (11), health risks are assessed by estimating the reasonable maximum exposure (RME) expected to occur at a site. The RME is estimated for individual pathways and is combined across pathways as appropriate. Scenario-specific assumptions and intake parameters used to estimate the RME are given in Table I (12-20). In general, the parameter values selected are the 90th or 95th percentile upper-bound value of the parameter cumulative distribution; however, for some parameters, the 50th percentile value is recommended (11). The input parameters given in Table I have varying degrees of uncertainty associated with them. In addition, those parameters pertaining to exposure frequency and duration are often subjective judgments that are based on area demographics. Nevertheless, the RME approach ensures that the resultant health risk estimates will be conservative.

Stochastic Approach for Estimating Contaminant Intakes and Risk

The PCB contamination within the building is limited to a few discrete locations that represent only about 15% of the total building area. Because of the highly skewed distribution of exposure point concentrations in the building, a nonstandard approach was used for quantifying possible PCB exposures in addition to following the standard EPA approach. That is, risks from PCB exposures were first estimated on the basis of both the arithmetic mean of the exposure point concentration and the upper 95% confidence limit on the arithmetic mean of the exposure point concentration (UL$_{95}$), as recommended by the EPA (11, 21). The underlying assumption in this approach is that an individual will always come in contact with a contaminated area during each RME event. However, in this specific case, 85% of the building is free of contamination and, thus, a trespasser is more likely to come in contact with an uncontaminated area than a contaminated one.

For comparison, a stochastic model was developed to explicitly account for the heterogeneous nature of the PCB contamination as well as the uncertainty in defining the time spent at any specific exposure point. Equations (2) through (6) were implemented with the Monte Carlo spreadsheet program @RISK(22) to simulate the movement of a hypothetical trespasser through several microenvironments within the contaminated building. In the simulation, it was assumed that the trespasser comes in contact with a discrete area inside the building for 1 hour during each of five visits per year over a 10-year period. This interior area, i.e., the exposure point, was selected on the basis of the probability of entering a given room and the probability of coming in contact with a contaminated area within that room.

Place Table I here

Table I Input parameters for PCB exposure assessment

Variable	Parameter Description	Value	Reference
AT	Averaging time, period over which exposure is averaged	3.65×10^3 d (noncarcinogens) 2.56×10^4 d (carcinogens)	11
AB	Absorption factor[a]	0.032	12
AF	Residue to skin adherence factor	2.77 mg/cm^2	11
BW	Body weight, adolescent[b]	50 kg	13,14
ED	Exposure duration	10 yr	c
EF	Exposure frequency	5 events/yr	c
ET	Exposure time	1 h/event	c
FI_{rsd}	Fraction ingested from contaminated residue	1	c
FR	Fraction of contaminant removed during dermal contact	0.1	c
IR_{ihl}	Inhalation rate	1.2 m^3/h	15
IR_{rsd}	Residue ingestion rate[d]	10 mg/h	11
a	Number of air exchanges per hour	0.5 h^{-1}	c
Ω	Fraction of dust resuspended per hour[e]	10^{-4} h^{-1}	10
SA	Exposed skin surface area[f]	2,800 cm^2/event	13
SA*	Exposed skin surface area that could come in contact with the mouth[g]	475 cm^2/event	c
AE_{orl}	Oral absorption efficiency	0.9516	
SF_{ihl}	Inhalation slope factor	7.7 (mg/kg-d)$^{-1}$	17
SF_{orl}	Oral slope factor	7.7 (mg/kg-d)$^{-1}$	18
SF_{der}	Dermal slope factor[h]	8.7 (mg/kg-d)$^{-1}$	11
RfD_{orl}	Inhalation reference dose	8.6×10^{-7} mg/kg-d	19
RfD_{orl}	Oral reference dose	1×10^{-4} mg/kg-d	20
RfD_{der}	Dermal reference dose[h]	9×10^{-5} mg/kg-d	11

[a] Derived from data in References 16 and 17.

[b] Estimated average body weight for an adolescent over the 10-year exposure period.

[c] Authors' best professional judgment considering scenario-specific and site-specific conditions.

[d] The EPA-recommended value of 100 mg/d adjusted to account for the fact that a receptor may be present at a contaminated area for only a certain portion of the exposure period.

[e] Assumes moderate activity within the building.

[f] Time-weighted average based on estimate of skin surface area and consideration of the type of clothing that would be worn during the exposure event.

[g] Derived from data for the surface area of a hand in Reference 13.

[h] $SF_{der} = SF_{orl}/AE_{orl}$; $RfD_{der} = RfD_{orl} \times AE_{orl}$.

(Only some of the rooms in the building are contaminated with PCBs, and not all surfaces in these rooms are contaminated.) The intakes estimated for each of the 50 visits were then summed to give the total intake for the trespasser scenario. For the modeling effort, a number of 50-visit runs (each of which constituted a single iteration) were combined to form a model simulation. Because cumulative exposure was estimated over a 50-visit scenario, the assumption that the trespasser would spend the entire hour of any given visit at one location does not bias the estimate of total exposure. Conceptually, the trespasser could spend 1/50th of 1 hour at each of the 50 locations selected in any iteration of a simulation.

As previously noted, substantial uncertainty can exist for each of the intake parameters given in Table I. Clearly, the assumptions used for these parameters are based on judgment and are inherently uncertain. In addition to exposure point concentration, the total extent of exposure at an exposure point is defined by three parameters: exposure time, frequency, and duration. The values selected for the length of each visit to the building and the number of visits per year are considered to be reasonable on the basis of current land use and demographics of the surrounding area. Security at the site reduces the likelihood of more frequent entry and limits the length of time a trespasser could remain on-site. The exposure duration of 10 years is considered reasonable for adolescent trespassing behavior, and it is also consistent with the time interval projected for site cleanup (which is already under way). This paper focuses on uncertainty related to the number of contaminated areas contacted during each visit and the time spent at a specific area during the visit.

The results of the exposure assessment are combined with toxicological information to provide an estimate of incremental cancer risk and the potential for noncarcinogenic health effects. Carcinogenic risks are assessed in terms of the increased probability that an individual will develop cancer over the course of a lifetime. To estimate incremental cancer risk, the intakes calculated with Eqs. (2) through (6) are multiplied by chemical-specific slope factors. Oral and inhalation slope factors for several Group A, B1, and B2 carcinogens have been derived by EPA and represent the lifetime cancer risk per milligram of contaminant intake per kilogram body weight, assuming that the exposure occurs over a 70-year lifetime. With some qualification (depending on available toxicological data), dermal slope factors can be estimated by dividing the oral slope factor by the oral absorption efficiency (11). For Superfund sites, the EPA has identified incremental lifetime cancer risks in the range of 10^{-4} to 10^{-6} (and lower) to be "acceptably protective" (23).

The measure used to describe the potential for the occurrence of noncarcinogenic effects in an individual is not expressed in probabilistic terms. Rather, these effects are evaluated by dividing the pathway-specific intake over a specified period of time by the EPA-established reference dose (RfD) for a similar exposure period. This ratio is termed the "hazard quotient" for a contaminant. For multiple chemical exposures and/or pathways, the individual hazard quotients are summed to determine an overall "hazard index." This hazard index approach could, however, overestimate the potential for adverse health effects for compounds that affect different target organs, do not induce the same type of effect, or do not act by the same mechanism. Thus, this method is only used for screening purposes. A second-stage analysis is conducted to segregate the effect and mechanism of action so that

appropriately grouped contaminants can be considered together. Dermal RfDs can be estimated, again with qualification, by multiplying the oral RfD and the oral absorption efficiency (11). A hazard index of less than one has been identified by EPA as being "acceptably protective" for Superfund sites (11, 23). Route-specific slope factors and RfDs used in this analysis are given in Table I.

RESULTS

Results from 100 simulations of 500 iterations indicate that the incremental cancer risk estimated from the mean exposure estimate of each simulation ranged from 4×10^{-6} to 8×10^{-5}; the mean risk of the 100 simulations was 1×10^{-5}. The risk calculated from the arithmetic mean of the exposure point concentration was 1×10^{-4}, an order of magnitude higher than that determined by the stochastic approach. The 95% upper-bound value of the incremental cancer risk estimated from the cumulative distributions ranged from 2×10^{-6} to 1×10^{-4}, and the mean upper-bound value for the 100 simulations was 9×10^{-5}. The risk calculated with the UL_{95} approach was 4×10^{-4}, a factor of 4 higher than that determined by the stochastic approach.

For noncarcinogenic effects, the hazard index estimated from the mean exposure estimate of each simulation ranged from 0.4 to 1; the mean hazard index of the 100 simulations was 0.7. However, the hazard index calculated from the arithmetic mean of the exposure point concentration was about 1. The 95% upper-bound value of the hazard index from the cumulative distributions ranged from about 0.2 to 10, and the mean value for the 100 simulations was about 9. The hazard index calculated using the UL_{95} was 4, which is less than half the value obtained using the average 95% upper-bound value predicted from the 100 separate simulations.

Although the values for incremental cancer risk and hazard index estimated from either the arithmetic means or the 95% upper-bound values predicted from either approach are within a factor of 10, it is obviously useful to characterize the entire distribution. Figure 1 shows a typical example of a cumulative distribution plot for the incremental cancer risk from one simulation. In this case (and in others examined), the distribution of risk is highly skewed because of contaminant heterogeneity. The risks estimated from the distribution values in the 90 to 99% range are very sensitive to the percentile selected. For the case shown in Fig. 1, the 95% upper-bound value of risk from the distribution is 1×10^{-4} whereas the 94% upper-bound value is 3×10^{-6}. That is, the estimate of risk decreased by a factor of about 30, with a 1% decrease in the cumulative percent at which the risk was evaluated. The results were similar for other simulation runs.

Results for 10 of the 100 simulation runs for estimating incremental cancer risk are presented in Fig. 2. In this example, the estimated mean values of the distributions from each simulation are relatively stable, with a coefficient of variation (CV) of about 30%. However, significant fluctuations can occur in the estimate of the 95% upper-bound value of the distribution, with the CV increasing to about 70% because of the highly skewed data set.
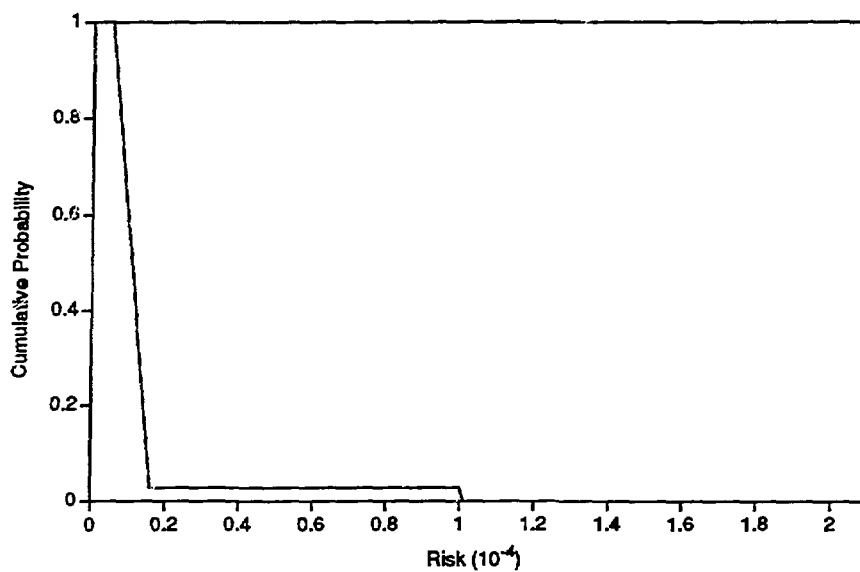
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Place Figs. 1 and 2 here

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Fig. 1. Cumulative Distribution Plot of Incremental Cancer Risk from One
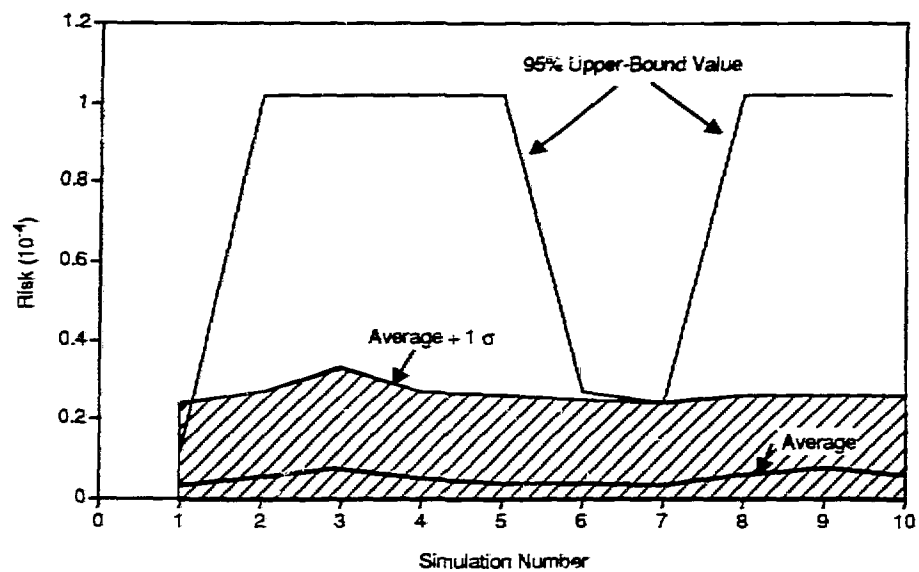500-Iteration Simulation Run

Fig. 2. Incremental Cancer Risk Predicted from Ten 500-Iteration Simulation Runs

Increasing the number of simulations from 10 to 50 or 100 can significantly reduce the CV to about 15% for the mean and about 30% for the 95% upper-bound value.

CONCLUSIONS

From this analysis, we conclude that simulation methods can be very helpful in understanding potential variability in risk estimates when dealing with stochastic processes that are complicated and involve data that are not normally distributed. This is especially true when the exposure scenarios that are being modeled involve a relatively small number of potential encounters with source(s) of contamination; in such cases, using the central limit theorem and relying on the analytical solutions may be inappropriate. Moreover, numerical solutions, like those presented here, offer the advantage of readily incorporating parameter uncertainties, varying model inputs, and explicitly characterizing the nature (stability) of the various percentiles that may be considered to predict health risks. Our analysis did not indicate a substantial difference between the 95% upper-bound value of the predicted risk distribution and the simpler, EPA-recommended approach for calculating the RME risks, which is based on the upper 95% confidence limit of the arithmetic average contaminant concentration. However, the uncertainties associated with both of these estimates were found to be quite significant.

Using the stochastic model and implementing Monte-Carlo techniques, we were able to estimate the magnitude of these prediction errors and to show that they were due primarily to the unique exposure conditions that exist inside the site buildings. We note, however, that such widely differing conditions of contamination and potential exposures are not that unusual. That is, contaminant concentrations in other media (e.g., soil) and the potential for human contact with contaminants in these media also typically require dealing with data that are widely and nonuniformly distributed. As demonstrated by the application presented in this paper, stochastic methods can be applied to predict the full distribution of health risks and associated uncertainties for receptors exposed to contaminants near a Superfund site. The methodologies presented in this paper can be used to address contaminant heterogeneity and receptor dynamics for discrete areas of contamination, as well as for an entire site. The resultant information, coupled with data from the application of a geographical information system, can provide the remedial action decision maker with a better picture of the distribution of potential risk at a site. This understanding may help to (1) prioritize site remedial actions, (2) focus cleanup activities on the locations that may present the greatest risk, and (3) lead to more efficient use of the funds available for remedial action activities.

ACKNOWLEDGMENTS

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