Quantitative Uncertainty Analysis of Superfund Residential Risk Pathway Models for Soil and Groundwater: White Paper

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Quantitative Uncertainty Analysis of Superfund Residential Risk Pathway Models for Soil and Groundwater: White Paper

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1. INTRODUCTION

The quantitative assessment of uncertainties in the exposure parameters for the individual exposure pathways provides considerable information about the variability and sensitivity of the calculated results. These results are important because point estimates of these parameters are used to determine the extent of remediation necessary through the Superfund process. The point estimates that are provided as guidance by the U.S. Environmental Protection Agency (EPA) are often conservative and can result in an overestimate of the potential risk. The scope of this work is to perform an uncertainty analysis on the standard Superfund residential scenario risk equations using available statistical information for the uncertain exposure parameters. The results are used to quantify the degree to which the standard default values overestimate the predicted percentiles of exposure (90–95th) that they are intended to estimate and to determine which parameters are responsible for the majority of the variation.

Residential exposure pathways associated with contaminated soil and groundwater are evaluated in this report and include the ingestion, inhalation, and dermal contact pathways. The external exposure pathway from exposure to soil contaminated with radionuclides is also evaluated. Exposure calculations are performed using models present in the EPA's *Risk Assessment Guidance for Superfund*. In this document, these models are not used to calculate actual risk values. Instead, the exposure parameters generally held to be constant for all sites are used to evaluate the variability in the predictions of the individual models. Uncertainties in the risk estimates that result from site- or contaminant-specific variability are not assessed for this effort. For the exposure parameters, a sensitivity analysis is performed to determine the most sensitive parameters in each model.

The outcome of this work can be used to focus the attention of the risk assessor on the expected variability, range of variation, and therefore the reliability of the point estimates that are used, and on the parameters that caused the variation. In addition, a relative ratio between the point estimates (PE) as set forth in EPA guidance and the predicted percentile risk results is presented for each pathway analyzed. The predicted percentiles of the exposure parameters are referred to as multiplicative exposure factors (MEF). These PE/MEF ratios are used to quantify the degree of conservatism present in the default exposure parameters that are recommended by the EPA for Superfund sites for each residential pathway analyzed. This general method of determining a multiplicative exposure factor that is constant for all sites can be used to derive values for the exposure term that are more representative of the EPA's stated risk management goal of protecting 90 to 95% of the potentially exposed population for a given land use scenario. Alternatively, these ratios can be used as part of the uncertainty assessment in a baseline risk assessment to estimate the degree of conservatism present in the exposure parameters of each pathway.

The probabilistic distributions of the uncertain exposure parameters used in these models are collected from the most recent sources in the literature. The parameters for which distributions are assigned include exposure frequency, exposure duration, body weight, surface area to body weight, ingestion rates for water and soil, inhalation rate, exposure fraction, adherence of soil-to-skin factor, and the gamma shielding factor. Professional judgment is used to supplement the data and provide a distribution for the few parameters for which no consensus distribution is available.

2. RESIDENTIAL LAND USE RISK EQUATIONS

This section provides the equations and recommended point estimates provided in various EPA sources for the residential pathway. Under residential land use, residents are expected to be in frequent, repeated contact with contaminated media. For carcinogens, the exposure assumptions account for daily exposure over long term and generally result in high potential exposures and risk. For noncarcinogens, the exposure assumptions do not account for accumulations over the life time of the exposed receptor. Risk from groundwater contaminants is assumed to be primarily from direct ingestion, inhalation of volatiles from household water use, and dermal contact while showering. Risk from soil is assumed to be from direct ingestion, inhalation of dust and particulates, dermal exposure from chemicals, and external exposure from radionuclides.

2.1 GROUNDWATER EQUATIONS

2.1.1 Nonradionuclide Contaminant

For carcinogens, the exposure assumptions are considered in the long term; therefore, the uncertainty of the exposure duration will impact the model predictions. For noncarcinogens, the exposure assumption of a one time dose will nullify the effect of variation in the exposure duration. Mathematically, this is done by introducing the exposure duration as a factor of the averaging time in the denominator of the ingestion model.

1.Ingestion

$$Ingestion\ risk = C \times \left[\frac{IR_w \times EF \times ED}{BW \times AT}\right] \times TV_o \qquad (1)$$

2. Inhalation of vapor-phase chemicals

$$Inhalation\ risk = C \times K \times \left[\frac{IR_a \times EF \times ED}{BW \times AT}\right] \times TV_i \qquad (2)$$

3. Dermal contact

$$Dermal\ contact\ risk = C \times K_p \times CF_1 \times \left[\frac{SA \times ET \times EF \times ED}{BW \times AT}\right] \times TV_d \qquad (3)$$

where

Parameters	Definition (units)	Default Value
AT	averaging time (yr × day/yr)	70 × 365 (carcinogen) (EPA 1991a) ED × 365 (noncar.) (EPA 1991a)
BW	adult body weight (kg)	70 (EPA 1991a)
C	chemical PRG in water (mg/L)	)
CF_1	units conversion factor (L-m)/(cm-m^3)	10
ED	exposure duration (yr)	30 (EPA 1991a)

EF	exposure frequency (day/yr)	350 (EPA 1991a)
ET	exposure time (hr/day)	0.25 (EPA 1992)
IR_a	inhalation rate (m^3/day)	20 (EPA 1995)
IR_w	water ingestion rate (L/day)	2 (EPA 1991a)
K	volatilization factor of Andelman (1990) (L/m^3)	0.0005×10^3 (Andelman 1990)
K_p	permeability constant (cm/hr)	chemical-specific
SA	adult total body surface area (m^2)	1.94 (EPA 1992)
TV_{ad}	absorbed toxicity value	SF_{ad} (carcinogen) $1/RfD_{ad}$ (noncarcinogen)
TV_i	inhalation toxicity value	SF_i (carcinogen) $1/RfD_i$ (noncarcinogen)
TV_o	oral toxicity value	SF_o (carcinogen) $1/RfD_o$ (noncarcinogen)

2.1.2 Radionuclide contaminants

Since most radionuclides are not volatile, the inhalation pathway is not usually considered for exposure through groundwater. The special case radionuclides (e.g., tritium and radon) are not discussed in this document. Therefore, the only pathway that will be evaluated for groundwater in this study is the ingestion pathway:

$$Ingestion\ risk = C \times [\ IR_w \times EF \times ED\ ] \times SF_o \qquad (4)$$

where

Parameters	Definition (units)	Default Value
C	radionuclide PRG in water (pCi/L)	)
ED	exposure duration (yr)	30 (EPA 1991a)
EF	exposure frequency (day/yr)	350 (EPA 1991a)
IR_w	water ingestion rate (L/day)	2 (EPA 1991a)
SF_o	oral slope factor (risk/pCi)	rad-specific (ORNL 1994)

2.2 SOIL EQUATIONS

Under residential land use, risk of contamination from soil is caused by direct ingestion, inhalation of dust and particulates, dermal exposure to chemicals, and external exposure to radionuclides. Because the soil ingestion rate is different for children and adults, the carcinogenic risk due to direct ingestion of soil is calculated using an age-adjusted ingestion factor. This takes into account the differences in daily soil ingestion rates, body weights, exposure fraction, and exposure durations for the two exposure groups. Exposure frequency is assumed to be the same for the two groups. Calculated in this manner, the factor leads to a more protective risk-based concentration compared to an adult-only assumption. Due to differences in averaging times for carcinogens and noncarcinogens, the noncarcinogenic hazard is calculated separately for adults and children. This procedure will give a more protective concentration than the adult-only assumption.

2.2.1 Nonradionuclide contaminant

1. Ingestion

a. Carcinogen

$$Ingestion\ risk = C \times CF \times \left| EF \times \left(\frac{IR_c \times ED_c}{BW_c} + \frac{IR_a \times ED_a}{BW_a} \right) \times FI \right| \times \frac{TV_o}{AT} \quad (5)$$

b. Noncarcinogenic (adult and child calculated separately)

$$Ingestion\ risk = C \times CF \times \left[\frac{EF \times ED_n \times IR_n \times FI}{BW_n \times AT_n} \right] \times TV_o \quad (6)$$

2. Inhalation only

$$Inhalation\ risk = C \times \left[\frac{EF \times ED \times IR_{air}}{BW \times AT} \right] \times \left(\frac{1}{VF} + \frac{1}{PEF} \right) \times TV_i \quad (7)$$

3. Dermal contact only

$$Dermal\ contact\ risk = C \times CF_d \times ABS \times \left[\frac{SA \times AF \times EF \times ED}{BW \times AT} \right] \times TV_{ad} \quad (8)$$

where

Parameters	Definition (units)	Default Value
ABS	absorption factor (unitless)	0.01 (organic) (EPA 1995) 0.001 (inorganic) (EPA 1995)
AF	adherence factor (mg/cm^2)	1 [11]
AT	averaging time (yr × day/yr)	70 × 365 (carcinogen) (EPA 1991a) ED × 365 (noncarc.) (EPA 1991a)
AT_n	averaging time - noncarcinogenic ingestion only (yr × day/yr)	ED_n × 365 (EPA 1991a)
BW	adult body weight (kg)	70 (EPA 1991a)
BW_n	body weight - noncarcinogenic ingestion only (kg)	70 (adult) (EPA 1991a) 15 (child) (EPA 1991a)
C	chemical PRG in soil (mg/kg)	)
CF	units conversion factor (kg/mg)	10^{-6}
CF_d	units conversion factor - dermal (kg-cm^2)/(mg-m^2)	0.01
ED	exposure duration (yr)	30 (EPA 1991a)
ED_n	exposure duration - noncarcinogenic ingestion only (yr)	24 (adult) (EPA 1991a) 6 (child) (EPA 1991a)
EF	exposure frequency (day/yr)	350 (EPA 1991a)
FI	fraction ingested (unitless)	1 [12]

IR_a	soil ingestion rate for adult (mg/day)	100 (EPA 1991a)
IR_{air}	total inhalation rate (m^3/day)	20 (EPA 1991b)
IR_n	soil ingestion rate - noncarcinogenic (mg/day)	100 (adult) (EPA 1991a) 200 (child) (EPA 1991a)
PEF	particulate emission factor (m^3/kg)	4.28×10^9 (see Eq. 40) (EPA 1991c)
RfD_{ad}	absorbed chronic reference dose (mg/kg-day)	chemical-specific (ORNL 1994)
RfD_i	inhalation chronic reference dose (mg/kg-day)	chemical-specific (ORNL 1994)
RfD_o	oral chronic reference dose (mg/kg-day)	chemical-specific (ORNL 1994)
SA	adult surface area (head, hands, forearms, lower legs) (m^2/day)	0.53 (EPA 1992)
SF_{ad}	absorbed dose slope factor ((mg/kg-day)$^{-1}$)	chemical-specific (ORNL 1994)
SF_i	inhalation slope factor ((mg/kg-day)$^{-1}$)	chemical-specific (ORNL 1994)
SF_o	oral slope factor ((mg/kg-day)$^{-1}$)	chemical-specific (ORNL 1994)
TV_{ad}	absorbed toxicity value	SF_{ad} (carcinogen) $1/RfD_{ad}$ (noncarcinogen)
TV_i	inhalation toxicity value	SF_i (carcinogen) $1/RfD_i$ (noncarcinogen)
TV_o	oral toxicity value	SF_o (carcinogen) $1/RfD_o$ (noncarcinogen)
VF	volatilization factor (volatile organics only) (m^3/kg)	chemical-specific (see Eqs. 34-39) (EPA 1991c)
W_c	average body weight from ages 1-6 (kg)	15 (EPA 1991a)
BW_a	average body weight from ages 7-31 (kg)	70 (EPA 1991a)
ED_c	exposure duration during ages 1-6 (yr)	6 (EPA 1991a)
ED_a	exposure duration during ages 7-31 (yr)	24 (EPA 1991a)
IR_c	ingestion rate of soil ages 1 to 6 (mg/day)	200 (EPA 1991a)
IR_a	ingestion rate of soil ages 7 to 31 (mg/day)	100 (EPA 1991a)

2.2.2 Radionuclide contaminant

1. Ingestion

$$Ingestion\ risk = C \times CF \times [\ EF \times (IR_c \times ED_c + IR_a \times ED_a) \times FI\ ] \times SF_o \quad (9)$$

2. External radiation only

$$External\ risk = C \times T_e \times [\ ED \times EF_x \times (1 - S_e)\ ] \times SF_x \quad (10)$$

where

Parameters	Definition (units)	Default Value
C	radionuclide PRG in soil (pCi/g)	)
CF	units conversion factor (g/mg)	10^{-3}
ED	exposure duration (yr)	30 (EPA 1991a)
EF	exposure frequency (day/yr)	350 (EPA 1991a)
EF_x	exposure frequency - external (day/day)	350/365 (EPA 1991a)
FI	fraction ingested (unitless)	1 [12]
IR_a	soil ingestion rate for adult (mg/day)	100 (EPA 1991a)
S_e	gamma shielding factor (unitless)	0.2 9(EPA 1991a)
SF_o	oral slope factor (risk/pCi)	radionuclide-specific (ORNL 1994)
SF_x	external exposure slope factor ((risk-g)/(pCi-yr))	radionuclide-specific (ORNL 1994)
T_e	gamma exposure time factor (hr/hr)	24/24 (EPA 1991a)

3. UNCERTAIN PARAMETERS

For the groundwater equations (i.e., Eqs. 1 through 4), the assessed parameters are the ingestion rate, inhalation rate, exposure frequency, exposure duration, averaging time, body weight, surface area, and exposure time. For the soil equations (i.e., Eqs. 5 through 10), the assessed parameters are the ingestion rate, inhalation rate, exposure frequency, exposure duration, averaging time, body weight, surface area, adherence of soil-on-skin factor, and fraction ingested. Specific uncertain parameters were collected for two age groups (children and adults).

Table 1 summarizes the varying parameters used in the groundwater and soil exposure pathway equations. Their statistical distribution, descriptive statistics, and source of information is also presented.

Table 1. Uncertain parameters and corresponding statistical distributions used in the groundwater and soil models

Parameter	PE	Distribution	Mean	S.D.	Min.	Max.	Likeliest	Reference
EF(days/year)	350	Triangular			180	365	345	Smith 1994
ED_{adult} (year)	30	Lognormal	11.36	13.72				Israeli 1992
ED_{child} (year)	6	Lognormal	11.36 truncate at 6	13.72				Israeli 1992
BW_{adult}	70	Lognormal	77.1	13.5				Smith 1994
SABW(m^2/kg)	0.027	Normal	0.025	0.003				Finley 1994b
IR_{water}(L/day)	2	Lognormal	1.26	0.66				Smith 1994
IR_{air}(m^3/day)	20	Uniform			5.05	17.76		Finley 1994a
ET(h/day)	.25	Triangular			0.13	0.33	0.20	Smith 1994
IR_{child}(mg/day)	200	Triangular			5	500	100	Finley 1994b
IR_{adult}(mg/day)	100	Triangular			0.1	50	25	Lagoy 1987
FI_{child}	1	Uniform			0.1	1		Finley 1994a
FI_{adult}	1	Uniform			0.1	0.5		Finley 1994a

Table 1. (continued)

Parameter	PE	Distribution	Mean	S.D.	Min.	Max.	Likeliest	Reference
AF(mg/cm^3)	1	Lognormal	0.52	0.9				Finley 1994c
Se	0.2	Triangular			0.0	1.0	0.2	Judgement

The following subsection elaborates on these data and compares the ranges of variation of these parameters with the point estimates recommended by EPA guidance.

3.1 INGESTION RATE OF GROUNDWATER

EPA's recommended value for an adult's ingestion rate of water is 2 L/day. A lognormal distribution with a geometric mean and a geometric standard deviation of 0.11 and 0.49 (i.e., arithmetic values of 1.26 and 0.66 L/day), respectively, was used by Smith (1994) and is reproduced for this study.

3.2 INGESTION RATE OF SOIL

The ingestion rates of soil recommended by EPA are 100 and 200 mg/d for adults and children, respectively. Lagoy (1987) suggested an average ingestion rate of 25 mg/d for adults. Other studies indicate that a 50 mg/day is likely to be an overestimate. Therefore, soil ingestion was assigned a value of 25 mg/day as the most likely value in a triangular distribution with minimum and maximum values of 0.1 and 50 mg/d, respectively. Finley et al (1994b) suggested a uniform distribution between 5 and 50 mg/day for children. Based on several studies, Lagoy (1987) suggested 100 mg/day as the soil ingestion rate for an average child and a value of 500 mg/day for a maximally exposed child. For this study, these values were selected as the most likely and the maximum values in a triangular distribution with a minimum value of 5 mg/d.

3.3 INHALATION RATE

Finley et al. (1994b) used a uniform distribution with minimum and maximum values of 5.04 and 17.76 m^3/day, respectively, for the inhalation rates for adults. These values were reported by EPA (1989) and are reproduced in this document.

3.4 EXPOSURE FREQUENCY

This parameter estimates the number of days per year that an individual may be exposed to a contaminated source. For the residential scenario, EPA generally recommends an exposure frequency of 350 days/year. Smith (1994) suggested a triangular distribution with minimum, maximum, and most likely values of 180, 365, and 345, respectively.

3.5 EXPOSURE DURATION

For the residential scenario, EPA recommends a point estimate of 30 years. Based on housing surveys, statistical analysis, and modeling of the moving process, Israeli et al. (1992) found that the

average total residence time (i.e., exposure duration) varies between different housing categories (Table 2).

Table 2. Values, standard errors and standard deviations of the average total residence time for each housing category, Israeli et al. (1992)

Housing category	Average residence time (years)	Standard deviation (years)
All households	4.55 ± 0.60	8.68
Renters	2.35 ± 0.14	4.02
Owners	11.36 ± 3.87	13.72
Farms	17.31 ± 13.81	18.69
Urban	4.19 ± 0.53	8.17
Rural	7.80 ± 1.17	11.28
Northeast region	7.37 ± 0.88	11.48
Midwest region	5.11 ± 0.68	9.37
South	3.96 ± 0.47	8.03
West	3.49 ± 0.57	6.84

For this study, a lognormal distribution of the residence time of owners values are selected to represent the statistical distribution of the exposure duration of a potential adult resident. The same distribution truncated at 6 years is used to represent children.

3.6 BODY WEIGHT

EPA's body weight recommended values are 70 and 15 kg for adults and children, respectively. For adults, a lognormal distribution with a geometric mean and a geometric standard deviation of 4.34 and 0.17 (i.e., arithmetic values of 77.1 and 13.5 Kg), respectively, were used by Smith (1994). For children, the same reference suggested a triangular distribution with 6.5, 26.1, and 15 as the minimum, maximum, and most likely values. These values are used in this study.

3.7 SURFACE AREA

EPA's recommended value for an average surface area of a male adult body is 1.94 m^2. Since surface area is a function of the body weight, Finley et al. (1994b) developed a relationship between skin surface area, body weight, and age based on lognormally distributed factors. These factors are presented in Table 3.

Table 3. Distribution factors for total skin surface area/body weight ratio by age

Age	Arithmetic mean (cm^2/kg)	Standard deviation (cm^2/kg)
0-2	641	114
2-18	423	76
>18	248	28

For the dermal contact pathway, the distribution factors of this ratio are used to account for the resultant variation of the surface area and the body weight for both children and adults.

3.8 EXPOSURE TIME

EPA's recommended value for average exposure time in the shower is a value of 12 min/day. Smith (1994) suggested a triangular with minimum, maximum, and most likely values of 8, 20, and 12, respectively.

3.9 AVERAGING TIME

For carcinogens, the averaging time is constant with a value of 70 years; for noncarcinogens, the averaging time is a function of the exposure duration. Therefore, variation in the numerator (exposure duration) will be nullified by the equivalent variation in the denominator (averaging time).This is expected because exposure in this case is not an aggregate exposure over the life time of the exposed individual.

3.10 FRACTION INGESTED

EPA's recommended value for the fraction ingested for both children and adults is 1. Finley (1994a) suggested a uniform distribution with a range of 0.1 and 1 for children and 0.1 and 0.5 for adults. These values were used for this study.

3.11 ADHERENCE OF SOIL-ON-SKIN FACTOR

EPA's rough estimates for average and upper-bound soil adherence factors are 0.2 and 1.0 mg/cm^2, respectively. Finley (1994c) developed a standard soil-on-skin adherence probability density function using Monte Carlo analysis based on all data collected for all age groups. The distribution is lognormal with an arithmetic mean of 0.52 mg/cm^2 and a standard deviation of 0.9 mg/cm^2.

3.12 SHIELDING FACTOR

EPA's recommended value for the shielding factor is 0.2. Based on professional judgment, a triangular distribution was assigned for this parameter with minimum, maximum, and most likely values of 0, 0.2, and 1, respectively. The minimum and maximum values represent the physically possible range for the parameter.

4. UNCERTAINTY AND SENSITIVITY RESULTS

Uncertainties in the predictions of risk based on Eqs. 1–10 are evaluated by assessing the variability of the results associated with the uncertainties in the corresponding input parameters. Those parameters are square bracketed in Eqs. 1–10. Note that parameters outside the square brackets are either constants or treated as constants. Additionally, standard values were selected for chemical-specific parameters to pursue the calculations. Therefore, the risk estimates are not necessarily meaningful other than for the evaluation of the variability in the predictions of the individual models due to variations in the uncertain parameters. Further, the different predicted percentiles of the risk estimates were compared to the point estimate of each model to develop a relative risk ratio which can be used as tool to quantify the credibility and the conservatism of the point estimates.

Statistical analyses of the model predictions are presented in terms of the coefficient of variability (COV) and therefore the range of variation. The COV is the ratio of the standard deviation to the predicted mean value. Therefore, a higher COV indicates a wider range of variation in the multiplicative exposure factor. Correlations between parameters are not accounted for in this study. Inclusion of correlation would have the net effect of reducing the COV value.

The uncertainty analysis was performed using the software package Crystal Ball, Version 3.0 (Decisioneering, Inc. 1993). Crystal Ball performed Monte Carlo simulations, for the probabilistic distributions of the uncertain exposure parameters, using the Latin Hypercube Sampling technique to predict the multiplicative exposure factor distributions.

4.1 GROUNDWATER PATHWAYS

Table 4 presents a descriptive statistical analysis of the Monte Carlo simulations of the risk predictions associated with uncertainties in the input parameters for the exposure models and for the point estimates of the multiplicative exposure factors.

Table 4. Results of the uncertainty analysis for the groundwater exposure pathways

	Carcinogens			Noncarcinogens			Radionuclides
Statistics	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion
COV	1.37	1.24	1.21	0.58	0.40	0.26	1.33
Minimum	4.9E-5	3.1E04	2.2E-4	1.8 E-3	1.6 E-2	1.9 E-2	8.1 E+1
50%	1.2E-3	6.0E-3	4.4E-3	1.2E-2	5.9E-2	4.4E-2	2.4E+3
95%	7.4E-3	3.3E-2	2.2E-2	2.9E-2	1.1E-1	6.6E-2	1.4E+4
97.5%	1.0E-2	4.4E-2	3.2E-2	3.4E-2	1.2E-1	7.1E-2	1.9E+4
Maximum	4.7 E-2	1.4E-1	9.9 E-2	6.6 E-2	1.7 E-1	8.8 E-2	7.3 E+4
Point Estimate (PE)	1.2E-2	5.9E-2	2.9E-2	2.7E-2	1.4E-1	6.6E-2	2.1E+4
PE/(95%)	1.6	1.8	1.3	0.9	1.3	1.0	1.5
PE/(97.5%)	1.1	1.4	0.9	0.8	1.2	0.9	1.1

This table shows that for both nonradioactive and radioactive carcinogens, the COVs are greater than 1, which implies multiple orders of magnitude of variation over the range of the model predictions. For noncarcinogens, the variability in the model predictions is much less.

The relative risk ratio (PE/MEF) is calculated to determine the location of the point estimates with respect to the uncertainty predictions of the individual models. The calculations of relative risk ratios, which is the ratio of the PE to the predicted percentiles, show that the PE lies in the last 5% predictions of the Monte Carlo simulations for all exposure pathways. The ratio varies between one and two for the different exposure pathways. For example, for the ingestion of groundwater pathway, the ratio of the PE to the 97.5% was 1.13, which means that the PE is almost equivalent to the 97.5 percentile prediction. This indicates that the EPA default parameters are reasonable approximations of the upper percentiles of the multiplicative exposure factors.

Table 5 presents the corresponding sensitivity analysis of the risk predictions associated with uncertainties in the input parameters for all groundwater exposure factors. The sensitivity results are limited to those exceeding 1% contribution.

Table 5. Results of the sensitivity analysis for the groundwater exposure pathways

	Carcinogens			Noncarcinogens			Radionuclides
Sensitivity data	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion
ED	**77%**	**84%**	**92%**	.	.	.	**79%**
IR_w	**18%**	.	.	**83%**	.	.	**18%**
BW	3%	2%	.	**10%**	**14%**	.	.
EF	2%	2%	2%	6%	**12%**	**31%**	2%
SABW	.	.	1%	.	.	**15%**	.
ET	.	**11%**	4%	.	.	**53%**	.
IR_{air}	.	.	.	.	**74%**	.	.

This table shows that for both nonradioactive and radioactive carcinogens the most important parameter of those evaluated in the risk models is the exposure duration parameter. Therefore, significant reduction in the range of variation of the exposure results can only be accomplished by reducing the COV for this variable. However, this parameter reflects the expected variability in the amount of time people live in a residence and it is not expected that this uncertainty can be reduced through the collection of additional data. For noncarcinogens, where the exposure duration plays no role in the variations of the risk predictions, the variability in the model predictions are affected by several other parameters. Contributions of sensitive parameters exceeding 10% are bolded. The following subsections elaborate on the exposure results for each pathway of the carcinogenic, noncarcinogenic, and radioactive exposure models.

4.1.1 Exposure to Nonradioactive Carcinogens in Groundwater

The COVs for ingestion, inhalation, and dermal contact pathways for groundwater are 1.37, 1.24 and 1.21, respectively. The variation in the model predictions are expected to be wide based on these COVs, and the predicted multiplicative exposure factors vary by two to three orders of magnitude from the predicted minimas.

For the ingestion pathway, sensitivity analysis shows that in addition to the exposure duration parameter (77%), the water ingestion rate parameter has an additional impact (18%) on the predicted variability. The body weight and the exposure frequency have insignificant contributions.

For the inhalation pathway, sensitivity analysis shows that the inhalation rate parameter follows the exposure duration (84%) with a very limited impact (11%) on the predicted risk. The body weight and the exposure frequency have insignificant contributions.

Sensitivity analysis for the dermal contact pathway shows that the variation in the risk prediction is 92% due to variation in the exposure duration over its distribution. Variation in the risk prediction due to variations in all other uncertain parameters is negligible.

4.1.2 Exposure to Noncarcinogens in Groundwater

The COVs for ingestion, inhalation, and dermal contact pathways for groundwater are 0.58, 0.4 and 0.26, respectively. These values are less than 1; therefore, the expected variation in the model predictions are not expected to be very wide. The predicted maximum risks vary, at most, by one order of magnitude from the predicted minimas because the impact of the most varying parameter (i.e., the exposure duration) in the carcinogenic model is screened out by an equivalent variation in the averaging time. This is the case for shorter term exposures where the impact of the averaged exposure over the life time of the receptor is not a significant factor. Therefore, models used to predict risk from exposure to noncarcinogens are not widely varying with variations of the uncertain parameters.

For the ingestion pathway, sensitivity analysis shows that the sensitivity in the risk prediction is 83% from the uncertainty in the water ingestion rate. The body weight and the exposure frequency have a limited impact (10 and 6%, respectively) on the predicted risk.

For the inhalation pathway, sensitivity analysis shows that the variation in the risk prediction is 74% from the uncertainty in the inhalation rate. The body weight and the exposure frequency have a limited impact (14 and 12%, respectively) on the predicted risk.

Sensitivity analysis for the dermal contact pathway shows that variation in the risk prediction is 53% due to variations in the exposure time, 31% due variation in the exposure frequency, and 15% due to variation in the surface area to the body weight ratio.

4.1.3 Exposure to Radionuclides in Groundwater

The COVs for ingestion of contaminated groundwater is 1.33. This value reflects a variation of three orders of magnitude between the maximum and minimum predicted risk results (see Table 4). Sensitivity analysis shows that the variation in the risk prediction is 79% from the uncertainty in the exposure duration parameter, 18% from the ingestion rate of water, and a negligible contribution from the exposure frequency (2%).

4.2 SOIL PATHWAYS

Table 6 presents a descriptive statistical analysis of the Monte Carlo simulations of the risk predictions associated with the uncertainties in the input parameters for the soil exposure models. The point estimate of the risk calculations and the ratios between the point estimates and the 95th and 97.5th percentiles are given.

Table 6. Results of the uncertainty analysis for the soil exposure pathways

	Carcinogens			Noncarcinogens				Radionuclides	
Statistics	Ingestion	Inhalation	Dermal	Ingestion-ad	Ingestion-ch	Inhalation	Dermal	Ingestion	External
COV	1.01	1.24	2.95	0.65	0.88	0.44	1.65	0.84	1.24
Minimum	3.1 E-9	6.2E-7	3.5 E-10	8.2E-10	1.1E-7	3.2E-5	9.3 E-9	2.2E+0	2.3E-2
50%	1.2E-7	1.2E-5	5.5E-8	7.0E-8	2.3E-6	1.2E-4	5.1E-7	6.3E+1	3.4E+0
95%	4.7E-7	6.5E-5	6.4E-7	1.9E-7	8.3E-6	2.2E-4	3.6E-6	2.1E+2	1.8E+1
97.5%	5.8E-7	8.7E-5	1.3E-6	2.2E-7	1.0E-5	2.3E-4	5.3E-6	2.6E+2	2.5E+1
Maximum	2.0 E-6	2.7E-4	1.3 E-5	3.4E-7	2.7E-5	3.3E-4	2.4E-5	5.8E+2	7.3E+1
Point Estimate	1.6E-6	1.2E-4	1.1E-6	1.4E-6	1.3E-5	2.7E-4	2.7E-6	1.3E+3	2.3E+1
PE/(95%)	3.3	1.8	1.8	7.2	1.6	1.3	0.7	6.0	1.3
PE/(97.5%)	2.7	1.34	0.9	6.4	1.3	1.2	0.5	4.8	0.9

This table shows that for both nonradioactive and radioactive carcinogens the COVs are greater than one, which implies multiple orders of magnitude of variation over the range of the model predictions. For noncarcinogens, the variability in the model predictions was much less.

The relative risk ratio is calculated to determine the location of the point estimates with respect to the uncertainty predictions of the individual models. The calculations of relative risk ratios, the ratio of the PE to the predicted percentiles, show that the PEs lie in the last 2.5% predictions of the Monte Carlo simulations for different exposure pathways. In the following subsections, the individual pathway ratios are evaluated, and the PE/MEF ratios are assessed.

Table 7 presents the corresponding sensitivity analysis of the risk predictions associated with uncertainties in the input parameters for all soil models presented in Sect, 2. Note that sensitivity results exceeding 1% contribution only are presented in Table 7.

Table 7. Results of the sensitivity analysis for the soil exposure pathways

	Carcinogens			Noncarcinogens				Radionuclides	
Sensitivity data	Ingestion	Inhalation	Dermal	Ingestion-ad	Ingestion-ch	Inhalation	Dermal	Ingestion	External
FI_{ch}	**31%**	.	.	.	**43%**	.	.	**24%**	.
ED_{ch}	**29%**	.	.	.	.	.	.	**24%**	.
IR_{ch}	**29%**	.	.	.	**45%**	.	.	**25%**	.
BW_{ch}	6%	.	.		8%	.	.	.	.
EF	3%	2%	1%	6%	3%	**12%**	2%	5%	2%
IR_{ad}	1%	1 %	.	**47%**	.	.	.	5%	1%
ED_{ad}	1%	**84%**	**36%**	.	.	.	.	**15%**	**82%**
FI_{ad}	.	.	.	**42%.**	.	.	.	3%	.
SABW	.	.	1%	6%	.		2%	.	.

Table 7. (continued)

	Carcinogens			Noncarcinogens				Radionuclides	
Sensitivity data	Ingestion	Inhalation	Dermal	Ingestion-ad	Ingestion-ch	Inhalation	Dermal	Ingestion	External
BW	.	2%	.	.	.	**14%**	.	.	.
Se	.	.	.	.	.	.	.	.	**15%**
IR_{air}	.	**11%**	.	.	.	**74%**	.	.	.
AF	.	.	**61%**	.	.	.	**96%**	.	.

This table shows that several parameters are found to be significant for each pathway. Therefore, to reduce the range of variation in each model, and therefore to increase the confidence in the predicted risk values, the statistical information of the most sensitive parameter in the model of concern must be considered. The sensitivities exceeding 10 % contributions are bolded. The following subsections elaborate on the risk results for each pathway for the carcinogenic, noncarcinogenic, and radioactive exposure models.

4.2.1 Exposure to Nonradioactive Carcinogens in Soil

The COVs for ingestion, inhalation, and dermal contact pathways for groundwater are 1.01, 1.24 and 2.95, respectively. Since these values deviate from zero, the expected variation in the model predictions are expected to be wide. For the ingestion and inhalation pathways, the predicted maximum risks vary by two to three orders of magnitude from the predicted minimas. The dermal contact pathway range of variation is even wider (almost five orders of magnitude) and the confidence in the distributions of the most sensitive parameters in this model have to be examined in greater detail to see whether they can be more fined based on additional data.

For the ingestion pathway, sensitivity analysis shows that the most sensitive parameters are fraction ingested, exposure duration, and ingestion rate of a child with contributions of 31, 29, and 29 %, respectively, to the exposure model. The exposure prediction sensitivity associated with variations in the exposure parameters that pertains to the adult exposure scenario are insignificant.

For the inhalation pathway, sensitivity analysis shows that the exposure duration is the most sensitive parameter with an 84% contribution to the sensitivity of the predicted risk. Additionally, the distribution of the inhalation rate has a limited impact (11%) on the sensitivity of the predicted risk.

Sensitivity analysis for the dermal contact pathway shows that the variation in the risk prediction is 61% governed by the lognormal distribution of the adherence of soil-to-skin factor. The next important parameter is the exposure duration with a sensitivity of 36%.

The PE/MEF ratio, the ratio of the point estimate to the predicted percentiles of the multiplicative exposure factor, show that the PE for the ingestion risk is 2.7 of the 97.5% predictions of the Monte Carlo simulations. In fact, the PE lies closer to the 99% prediction for the ingestion pathway. Additionally, the point estimates for the inhalation and the dermal contact risks lie in the 2.5% predictions (i.e., 1.34, and 0.9 of the 97.5% predictions, respectively) of the Monte Carlo simulations.

4.2.2 Exposure to Noncarcinogens in Soil

The COVs for adult ingestion, child ingestion, inhalation, and dermal contact pathways for groundwater are 0.65, 0.88. 0.44, and 1.65, respectively. For the ingestion pathways, the predicted maximum risks vary by two orders of magnitude from the predicted minimas; for the inhalation pathway, the variation is by one order of magnitude; and for the dermal contact pathway, the range of variation is more than four orders of magnitude. Note that the COVs are again reduced to less than 1 because the impact of the most varying parameter (the exposure duration) is screened out by an equivalent variation in the averaging time. Therefore, models used to predict risk from exposure to noncarcinogens do not show as much variation as exposure models used to calculate carcinogenic risk estimates.

For the adult ingestion pathway, sensitivity analysis shows that the most sensitive parameters are the ingestion rate and the fraction ingested with contributions of 47 and 42%, respectively, to the risk model. For the child ingestion pathway, the sensitivity of the predicted risk to the ingestion rate and the fraction ingested is 43 and 45%, respectively. The risk prediction sensitivity associated with variations in the other exposure parameters is negligible.

For the inhalation pathway, sensitivity analysis shows that the variation in the risk prediction is 74% from the uncertainty in the water inhalation rate. Body weight and the exposure frequency have a very limited impact (14 and 12%, respectively) on the predicted risk.

Sensitivity analysis for the dermal contact pathway shows that variation in the risk prediction is mainly associated with variations in the adherence of soil-on-skin factor (96%).

The calculations of the PE/MEF ratio show that the PE for the adult ingestion risk is 6.4 of the 97.5% predictions of the Monte Carlo simulations. The PE is actually observed to be considerably outside the range of the Monte Carlo prediction (by more than four times). For the child ingestion pathway, the PE almost lies at the 97.5% prediction (relative risk ratio of 1.3). Additionally, the point estimate for the inhalation pathway lies in the last 2.5% predictions (i.e., 1.2 of the 97.5% predictions) of the Monte Carlo simulations. For the dermal pathway, the relative risk ratio 0.7 at 95% tile. Therefore, PE is expected to lie closer to the 92.5% tile of the Monte Carlo simulation.

4.2.3 Exposure to Radionuclides in Soil

The COVs for ingestion of and external exposure to contaminated soil with radionuclides are 0.84 and 1.24. This value reflects a variation of two to three orders of magnitude between the maximum and minimum predicted risk results (see Table 5).

Sensitivity analysis shows that the variation in the risk prediction from the ingestion of contaminated soil with radionuclides is attributed to variations in several exposure parameters. Equal contributions of 25% were from the ingestion rate, exposure duration, and ingested fraction that pertains to the child exposure scenario; 15% came from variations in the exposure duration of an adult.

For the external exposure pathway, the predicted risk is most sensitive to variations in the adult exposure duration (82%). The shielding factor contribution to the sensitivity of predicted risk is 15%.

The calculations of relative risk ratio show that the PE for the ingestion risk is almost 5 times the 97.5% predictions of the Monte Carlo simulations. Actually, the PE is observed to be outside the maximum range of the Monte Carlo prediction by more than two times. For the external exposure pathway, the relative risk ratio is 0.9 at the 97.5% tile.

5. RISK MANAGEMENT APPLICATION

It is widely recognized that the values used to generate point risk assessment results are conservatively biased (e.g., Burmaster and Harris 1993) and often yield an exposure estimate that is greater than the 99th percentile. Indeed, the results documented here show that point estimates can be as high as 4 times the maximum of the range of the Monte Carlo analysis for some pathways. However, the attempts at Monte Carlo analyses for sites are often confounded by site-specific and contaminant-specific factors related to estimates of the concentration term and in difficulties in estimating the dose-response relationship. Therefore, Monte Carlo analyses are not often implemented for particular sites. By segregating the uncertainties that are specific for the exposure parameters in a particular land use scenario from those that are site- and contaminant-specific, the assessor can work to reduce the uncertainties associated with the site while being able to recognize the uncertainties inherent in the exposure process.

A 90–95th percentile value of the forecast distribution can be used to determine a multiplicative exposure factor that is specific for each pathway of each land use scenario. If these values were developed for all pathways of each land use scenario, the risk assessment process itself could be greatly simplified. For example, the risk for the ingestion pathway could be expressed as the product of the exposure concentration, a dose-response relationship, and the multiplicative exposure factor rather than using all of the parameters presented in Sect. 2. This would translate to direct cost savings through easier generation of risk estimates and by reducing the amount of quality assurance that is currently necessary to ensure that the risk estimates are free of error. In addition, use of percentiles of the multiplicative exposure factors would maintain the advantages of the point estimate approach in terms of their interpretability by the general public while being more indicative of an estimate that is protective of 90–95% of the potentially exposed population. Of course, it is not necessary to employ Monte Carlo analyses to produce MEFs based on current EPA guidance. Table 5 gives values for the EPA default point estimates that can be used as MEFs. However, Table 5 also shows the extent of conservatism that is built into many of the pathways. Use of the default factors can cost significant amounts of money in essentially cleaning up to criteria that far surpass the risk management goals.

While this methodology could be applied at the vast majority of sites, it is recognized that there are sites where local exposure patterns deviate significantly from national norms. For these sites (e.g. fish consumption among Native Americans), this method would not be applicable and the distributions and resulting percentiles would have to be modified to reflect local exposure patterns. However, the vast majority of sites fall under the same general EPA guidance recommendations for exposure patterns and use of this method would result in more reliable risk estimates at less cost.

6. CONCLUSIONS

Uncertainties in the risk predictions from exposure to contaminated groundwater and soil have been evaluated for the residential scenario in this report. The variability and the sensitivity of the EPA Superfund exposure model predictions to the input parameters has been examined and documented. In addition, the confidence and conservatism of the point estimates with respect to the probabilistic estimates have been evaluated by calculating a relative risk ratio between the PE and the closest percentile prediction of the multiplicative exposure factor.

6.1 GROUNDWATER MODELS

For the ingestion, inhalation, and dermal contact exposure pathways to nonradioactive carcinogens and for the ingestion of radioactive carcinogens in groundwater the COVs tend to be greater than 1, which reflects orders of magnitude of variation between the minimum and the maximum predictions of the multiplicative exposure factor. The corresponding results of the sensitivity analysis show that the exposure duration is the most sensitive parameter and is the main cause of the wide variability of the predictions. Current studies on an acceptable distribution for the exposure distribution supports the distributions used in this study; therefore, the large standard deviations are an acceptable representation of the parameter variation and the expected variation is the model predictions are justifiable. However, point estimate to multiplicative exposure factor ratios at the 97.5% tiles for these pathways imply that the PEs are highly conservative.

For the ingestion, inhalation, and dermal contact exposure pathways to noncarcinogens in groundwater, the COVs tend to be less than 1, which reflects a smaller range of variation between the minimum and the maximum predictions of the exposure model. The corresponding results of the sensitivity analysis show that the ingestion rate and the inhalation rate are the main parameters of concern for the ingestion and inhalation pathways. The exposure time and exposure frequency are the most sensitive parameters for the dermal pathway model. The relative ratios for the point estimates and the 97.5th percentiles for these pathways imply that the EPA default point estimates are conservative and generally result in an overestimate of the actual risk.

6.2 SOIL MODELS

For the ingestion, inhalation, and dermal contact exposure pathways to nonradioactive carcinogens in soil, the COVs tend to be greater than 1, which reflects the orders of magnitude of variation between the minimum and the maximum predictions of the model. The corresponding results of the sensitivity analysis show that several parameters are contributing to this wide range of variation (refer to Table 7). The relative risk ratios lie closer to the 99% tile for the ingestion pathway and 97.5% tiles for the inhalation and dermal contact pathways. This implies that the point estimates for the exposure parameters recommended by EPA are highly conservative.

For the adult ingestion, child ingestion, and dermal contact exposure pathways for noncarcinogens in soil, the COVs reflect a wide range of variation between the minimum and the maximum predictions of the model. The smallest variation is observed in the inhalation pathway. The corresponding results of the sensitivity analysis show that the ingestion rate and the ingested fraction and the inhalation rate are the main parameters of concern for the ingestion and inhalation pathways, respectively. The adherence of soil-on-skin factor is the most sensitive parameter for the dermal contact pathway model. The relative ratio of the point estimates to the Monte Carlo percentiles for the adult ingestion pathway show that the point estimate occurs outside the wide range of predictions. This implies that the point estimates provided by EPA for this pathway are extremely conservative. The relative risk ratios at the 97.5% tiles for the child ingestion and inhalation pathways imply that the PEs are still conservative. For the dermal contact pathway the point estimate is expected to lie closer to the 92.5% tile of the Monte Carlo simulation.

For the ingestion and external exposure pathways to radioactive carcinogens in soil, the COVs reflect orders of magnitude of variation between the minimum and the maximum predictions of the model. The corresponding results of the sensitivity analysis show that several parameters are contributing to this wide range of variation (refer to Table 7). The relative risk ratio for the ingestion

pathway show that the point estimates are greater than the maximum of the predictions. The relative risk ratios lie closer to the 97.5% tile for the external exposure pathway. This again implies that the EPA point estimates are highly conservative.

An alternative to the continued use of conservative point estimates is the use of a 90–95th percentile value of the forecast distribution of the multiplicative exposure factor. These can be developed specifically for each pathway of each land use scenario. These values could greatly simplify the risk assessment process through easier generation of risk estimates and by reducing the amount of quality assurance that is currently necessary to ensure that the risk estimates are free of error. These two factors would decrease the dollar amount that a risk assessment costs to produce. Reducing the inherent conservatism in the risk estimates would also translate to reduced costs in implementing remedial action alternatives while still meeting stated risk management goals through the Superfund decision process. In addition, use of percentiles of the multiplicative exposure factors would maintain the advantages of the point estimate approach in terms of their interpretability by the general public while being more indicative of an estimate that is protective of 90–95% of the potentially exposed population.

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