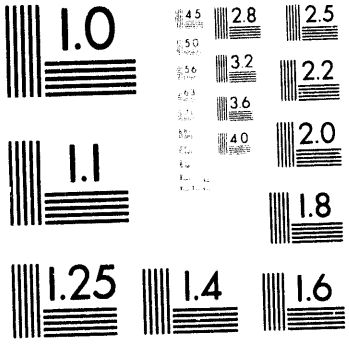
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SENSITIVITY STUDY OF SIX PUBLIC HEALTH RISK COMPUTATION CASES FROM THE U.S. DEPARTMENT OF ENERGY RISK- AND COST-ESTIMATE PROCESS PILOT STUDY

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MASTER

EXECUTIVE SUMMARY

This report contains a description of the results from the analysis of the sensitivity of estimated public health risks to changes in model parameters relating to the contaminant source releases, contaminant transports, and human exposures contaminants from six waste sites. Estimated public health risks associated with these and other sites at U.S. Department of Energy (DOE) compounds were reported in a pilot study done by the Oak Ridge National Laboratory (ORNL) for the DOE (ORNL 1992).

The objective of the sensitivity analysis was to identify the subset of model input parameters whose variations accounted for the majority of the variation in the computed public health risk values. All environmental modeling in this study and the pilot study done by ORNL (1992) was based on the Multimedia Environmental Pollutant Assessment System (Whelan et al. 1992).

The results of the sensitivity analysis for the atmospheric case indicate that the most influential variables were emission rate and, to a lesser extent, population size. For groundwater cases, there was no consistent ordering of the influential variables. Depending on the case considered, some influential variables include the following: equilibrium partition coefficient (K_d), size of population, pore water velocity, constituent inventory, contaminant flux rate from source, and thickness of saturated zone. For the overland transport case, the regression model fit was not adequate for a reliable identification of the influential variables.

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1.0 INTRODUCTION

This report describes the results from the analysis of the sensitivity of public health risks to changes in model parameters relating to the contaminant source releases, contaminant transports, and human exposures from six waste sites. Estimated public health risks associated with these and other sites at U.S. Department of Energy (DOE) compounds were reported in a pilot study done by the Oak Ridge National Laboratory (ORNL) for the DOE (ORNL 1992).

The objective of the sensitivity analysis was to identify the subset of model input parameters whose variations accounted for the majority of the variation in the computed public health risk values. All aspects of environmental modeling in this study and the pilot study done by ORNL (1992) were done using the Multimedia Environmental Pollutant Assessment System (MEPAS) (Whelan et al. 1992).

Six sites from the DOE pilot study were selected for examination. These sites (primary cases in Table 1) were chosen based on

- the requirement to select sites from the low, medium, and high-risk categories
- the objective that the modeled pathways in these sites represent the majority of the dominant environmental pathways associated with DOE sites
- the extent to which the modeled scenarios contained input parameters that were among those that were typically influential as identified in an earlier sensitivity study using the MEPAS system done in support of the DOE Environmental Survey (Doctor et al. 1990).

The last of the above considerations was used to provide a confirmation that the results of Doctor et al. (1990) apply to these sites as well as strengthen the case for a generalized interpretation of the results of that earlier study.

Within each of the six sites selected for study, the major contaminants and pathways were identified based on their contributions to the overall site population risk as calculated in the DOE pilot study. In addition to the six principal cases, three special study scenarios were analyzed. The special

TABLE 1. Receptor Constituent Pathways Sensitivity Study Cases

Study Case/Site	Pathways(s)	Independent Inputs[a]	Constituent
Primary Cases:			
1. Oak Ridge WAG6 (Waste Area Grouping)	Groundwater to Clinch River Irrigation	63	Strontium-90
2. Argonne ANL570 Holding Pond	Overland to Illinois River	49	Arsenic
3. Hanford NRDWL (Non-Radioactive Dangerous Waste)	Groundwater to Well, Richland	20	Benzene
4. Lawrence Livermore LLNL Site 300 Pit 6	Groundwater to Well, Ranger	32	Trichlorethylene
5. Fernald OU1	Groundwater to Well SW Ohio Water Company	68	Uranium-238
6. Fernald OU4	Air emissions, Inhalation	11(b)	Radon-222 with decay products
Special Study Cases:			
7. Two Constituents at Hanford NRDWL	Groundwater to Well, Richland	23	Benzene Methylene Chloride
8. SIX Constituents at Hanford NRDWL	Groundwater to Well, Richland	23	Benzene Methylene Chloride Carbon Tetrachloride Chloroform Trichloroethylene Tetrachloroethylene
9. Population-Distance at Fernald OU4	Air emissions, Inhalation	21(c)	Radon-222 with decay products

(a) Number of model parameters (inputs) considered.
(b) Nine inputs plus 2 factors for 576 wind and 160 population inputs.
(c) Nine inputs, a wind data factor, and 10 factors for 10 sets of population inputs.

cases for the Hanford Site involved considering additional significant contaminants and the special Fernald case involved further inquiry into the sensitive populations for that study. All of these cases are listed in Table 1. A complete description of each of the cases is given in ORNL (1992). Thus there was one modeling scenario for each of the six sites selected by ORNL from the DOE study; these scenarios comprised five waterborne transport cases and one airborne transport case. Among the waterborne scenarios, one involves overland flow to a river, three are based on groundwater transport to a well, and the remaining one involves groundwater transport to surface water.

As indicated, the MEPAS system was used for all environmental modeling; this modeling consisted of computing contaminant releases (where unknown),

modeling contaminant transport to the human receptor location, and computing potential human exposures to the contaminants and their corresponding carcinogenic risks to the total exposed populations. These population risks, also referred to as the number of health effects, were based on (average) chronic exposures over a 70-year lifetime. Because the MEPAS system computes future exposures up to 10,000 years (in 70-year segments) into the future, the time-discounting option was selected to downweight the population risks that occur in the distant future. The reader is referred to Whelan et al. (1989) or Whelan et al. (1992) for further information about the MEPAS system.

This report was prepared by Pacific Northwest Laboratory (PNL).[a]

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

2.0 APPROACH OF SENSITIVITY ANALYSIS

The steps involved in performing the sensitivity analysis were as follows:

- Select a statistical distribution for each input variable (model parameter) to be varied.
- Randomly generate a series of values for each input via the Latin hypercube sampling algorithm (Iman et al. 1980).
- Perform a series of complete MEPAS runs, each run being based on a single realization of the randomly generated set of model parameters. These repeated runs produced a corresponding series of model output values (time-discounted number of health effects).
- Fit a multiple linear regression response surface that relates variation in the model output (time-discounted number of health effects) to model input variations. This response surface is a surrogate for the MEPAS model; the partial regression coefficients obtained provide a quantitative measure of the output responses to changes in each of the input variables. The partial R-Square values for the coefficients are used to identify the influential model inputs (e.g., those inputs whose variations account for the majority of the model output variability).

Normal distribution was used for each of the inputs, although for some parameters this distribution was truncated from below to ensure that realizations would be non-negative. Because the objective of the sensitivity analysis is to identify the set of influential input variables, the distributions of these inputs were constructed to exhibit conservatively high, yet feasible, ranges of variability so that model output responses at all influential input values would be induced.

The independent (input) variables in this study are the user-definable MEPAS model parameters for source, transport, and exposure calculations associated with each scenario. Site conceptualization inputs in MEPAS were not considered to be stochastic (i.e., control parameters reflecting the choice of source configurations, pathways, etc., were not varied). The number of independent inputs considered for each study case is listed in Table 1. The sensitivity analysis described above was very similar in approach to that of Doctor et al. (1990).

For the atomospheric transport cases, the inputs that involved a large table of values, subsets of values within the table were varied as a block. The distance-related subgroups of the population table were jointly varied, and for the wind-dispersion table, the frequency of conditions in the significant sectors (contributing 90% of the total computed risk) were also jointly varied. Because the MEPAS model normalizes the frequencies in the wind dispersion table, this procedure resulted in a lesser change in the frequencies in the selected sectors along with a corresponding opposite change in frequencies of the remaining sectors.

The form of the regression response surface used in this study was the multiple linear model with no interaction terms. Several regression models were recursively fitted between the output (time-discounted number of health effects) and subsets of the varied inputs to determine the "best" subset of inputs to represent the output response relation. Typically, the selected subset model "explains" nearly the same amount of variation in the output as the full model does, but contains fewer parameters. This approach is consistent with the goal of this sensitivity analysis, which is the identification of the subset of environmental model inputs whose changes cause significant change in the modeling result (e.g., the number of time-discounted health effects).

Commonly available subsetting algorithms are forward selection, backward elimination, all possible regressions, and stepwise selection (Draper et al. 1981). The stepwise approach was taken in this study, having been used by Doctor et al. (1990) and recommended by Draper et al. (1981), using the Statistical Analysis System (SAS) Software.[a] The stepwise algorithm recursively adds and removes variables from a set according to their statistical significance until 1) the model improvement from adding another variable is negligible, and 2) the loss of model performance from deleting a variable is high. After the optimal set of variables was determined, we used the (sequentially) partial R-Square for the variables as the basis for doing the sensitivity ranking of the inputs. This partial R-Square is defined as the model

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(a) SAS. 1991. Statistical Analysis System Software. Cary, North Carolina.

R-Square for the variable added to subset minus the model R-Square for the variables already in subset. The partial R-Square value represents the incremental contribution to model fit from adding a given variable to the existing subset of variables. The partial R-Square for that variable will generally depend on which variables are already in the selected subset; thus we use the term "partially sequential" (which originally was used with respect to the regression sums-of-squares [Draper et al. 1981]) to characterize this measure of regression model fit.

In all scenarios, each input was generated from the normal distribution, and there were zero pairwise correlations between all inputs. In general, the inventories, initial concentrations, fluxes, distribution coefficients (K_d), and hydraulic conductivities were given +/- 50% ranges; populations ranged between +/- 10% and 40% depending on the pathway; and all other inputs ranged from +/- 10% to +/- 30% (all percentages with respect to the average [base case] value). As indicated, these ranges were made conservatively wide so that any input ranges producing local nonlinearity would be discovered.

Because the normal distribution has no finite range, upper and lower truncations were imposed at respective distances of 2 standard deviations above and below the mean. However, because the base case values of K_ds were zero for contaminants in the Oak Ridge WAG 6 and Fernald OU1 scenarios, the distributions assigned to these model parameters were normal with zero means, the lower truncations also at zero, and the upper truncations at 2 standard deviations above zero.

The ranges of the input variables should be wider in a sensitivity analysis than an uncertainty analysis. To identify all sensitivities, the output is assessed over the entire feasible space of the inputs, while an uncertainty analysis is intended to quantify the output variability in response to inputs being varied in their believed ranges.

3.0 RESULTS

This section describes the results of fitting response surface approximations to the MEPAS model for each of the cases. The results for each case are presented in a table as an ordered listing of the most influential input variables based on their relative contributions to model output along with the statistical measures of their contributions. Each case has been analyzed in detail to validate the indicated importances of the model inputs.

The results given below support the objective of identifying model-sensitive input variables, rather than determining the actual uncertainty of the output. Thus the ranges of outputs provided are for informational purposes only.

Because of the complex nature of the waterborne pathways, the inputs that are identified as influential variables are highly case specific. Doctor et al. (1990) show that the importance of parameters will vary greatly with constituent, transport, and exposure properties. It is quite possible for the output to be positively related to an input variable in one case and negatively so in another case. For example, factors such as decay or degradation of a constituent and time-discounting of effects can counter the increase in concentration that occurs with a decrease in pore-water velocity, so the results for a highly radioactive contaminant would expectedly differ in this way from a scenario with a stable or non-degrading contaminant.

The results for the six primary cases are given in Tables 2 through 4 and 7 through 9. The results for the special study cases are given in Tables 5, 6, and 10. All tables include both the sensitivity analysis results and a description of the statisticals distributions of all varied model inputs; for example, Table 2a contains the results from a sensitivity analysis of the inputs for the Oak Ridge WAG 6 results and Table 2b provides an identification and statistical description of all inputs that were varied for that case.

In the results tables, influential input variables (as identified in the stepwise selection procedure) are ranked in terms of their partial R-Square (largest first). The first column has MEPAS variable names and the last

column expanded descriptions with references to appropriate sections in the document of Droppo et al. (1989). The column labeled "Parameter Estimate" contains the estimated regression coefficients for the listed variables. These coefficients represent the estimated change in health effects from unit changes in inputs and thus indicate whether the relationships are positive or negative. The full model R-Square for each case is given at the bottom of the tables.

3.1 OAK RIDGE WAG 6

The Oak Ridge WAG 6 scenario involved releases of strontium-90 from the waste area grouping into groundwater, subsequent transport from groundwater into Clinch River, and use of contaminated river water for irrigation. The sensitivity analysis results for this case are given in Table 2. The initial sensitivity runs for Oak Ridge WAG 6 had lower total model R-Square values (being about 0.44). Additional test runs showed that the nonlinearity of the influence of the subsurface K_d (WASUBKD) for near-zero values results in a low model R-Square for relatively small ranges of this input variable.

Experimentally it was determined that for K_d a standard deviation of 0.05 in a normal distribution with a mean of 0.0 truncated on the left resulted in an acceptable full model R-Square value. This range for the variable K_d also resulted in it having an importance on the same order as other input variables. Table 2 contains the results for the Oak Ridge WAG 6 case using the limited range of values for the subsurface K_d. The analysis has a full model R-Square of 0.80 and identifies seven input variables having a partial R-Square greater than 0.01.

The subsurface K_d for strontium-90 has a base case value of zero. In terms of the transport of this particular constituent to off-site receptors, a zero K_d is the most conservative value of K_d, indicating that there is no adsorption of the contaminant onto the porous medium and, therefore, all of the contaminant is in solute form and available for transport. Furthermore, for a fixed level of pore water velocity, a zero value for K_d results in the greatest contaminant velocity and thus the earliest exposure at the receptor;

TABLE 2a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Oak Ridge WAG 6 Groundwater to Surface Water Case

Name	Partial R-Square	Parameter Estimate	Description
WZPVELOC	0.268		2.5j Pore-Water Velocity (SZ), lyr #1
WASUBKD	0.144	-3.37E-01	2.7a Subsurface adsorption coefficients, lyr #1, STRONTIUM-90
WASURFKD	0.117	-2.80E-03	2.7b Surface adsorption coefficients, STRONTIUM-90
WWDISCHG	0.112	-6.90E-06	2.6e Average annual discharge at each receptor location, rcptr #1
WSCONC	0.0855		2.1k Contaminant concentration, STRONTIUM-90
WZDIST	0.0203	-9.36E-05	2.5m Travel distance in saturated zone to receptors, lyr #1, rcptr #1
EWIRRATE	0.0130		4.2i Irrigation rate, rcptr #1
WZLDISP	0.00660		2.5n Longitudinal dispersivity, lyr #1, rcptr #1
WCRAIN	0.00590		2.8g Mean monthly precipitation
WZTOTPOR	0.00380		2.5h Total porosity of SZ, lyr #1
WCRAIN	0.00340		2.8g Mean monthly precipitation
WCTEMP	0.00310	-1.71E-04	2.8f Mean monthly temperature
WWDEPTH	0.00310	-3.22E-04	2.6b River depth
WCRAIN	0.00250		2.8g Mean monthly precipitation
WCRAIN	0.00280		2.8g Mean monthly precipitation
WCRAIN	0.00250		2.8g Mean monthly precipitation
WCTEMP	0.00240		2.8f Mean monthly temperature
WZPERPOR	0.00200		2.5z Percent of total porosity substituted for effective porosity, lyr #1

TABLE 2a. (contd)

Name	Partial R-Square	Parameter Estimate	Description
WZBULKD	0.00200	-7.13E-03	
WCRAIN	0.00160		2.8g Mean monthly precipitation
WCTEMP	0.00140		2.8f Mean monthly temperature
EWPRODOV	0.00120		4.2f Other vegetable production, rcptr #1
WCPRENUM	0.00110	-1.26E-03	2.8j Mean number days where precipitation >0.01

Model R-Square: 0.805

TABLE 2b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Oak Ridge WAG 6 Groundwater to Surface Water Case

Name	Dist. Type	Range +/- 2*SD	Mean	SD	Description
WSINVENT	Normal	50.0	1.55E+04		2.1j Constituent inventories, STRONTIUM-90
EWPRODLV	Normal	20.0	1.40E+04		4.2e Leafy vegetable production, rcptr #1
EWPRODOV	Normal	19.9	4.03E+04		4.2f Other vegetable production, rcptr #1
EWPRODMT	Normal	20.2	3.41E+03		4.2g Meat production, rcptr #1
EWPRODMK	Normal	19.9	5.18E+04		4.2h Milk production, rcptr #1
EWIRRATE	Normal	20.0	1.00E+01		4.2i Irrigation rate, rcptr #1
WSMOISTC	Normal	14.9	2.80E+00		2.1g Moisture content associated with ranking unit
WSBULKD	Normal	14.7	1.45E-01		2.1h Bulk density of top soil at ranking unit
WSCONC	Normal	49.8	2.85E+04		2.1k Contaminant concentration, STRONTIUM-90
WTVEGCOV	Normal	6.29	5.00E+00		2.2h % vegetative cover
WTAVAILW	Normal	10.2	4.90E-01		2.2i Top soil water capacity
WZTOTPOR	Normal	15.1	3.68E+00		2.5h Total porosity of SZ, lyr #1
WZPERPOR	Normal	14.9	2.75E+00		2.5z Percent of total porosity substituted for effective porosity, lyr #1
WZPVELOC	Normal	49.9	5.75E-03		2.5j Pore-Water Velocity (SZ), lyr #1
WZTHICK	Normal	30.1	3.00E+00		2.5k Thickness of SZ, lyr #1
WZBULKD	Normal	15.0	1.47E-01		2.5l Bulk density of SZ, lyr #1
WZDIST	Normal	10.0	3.75E+01		2.5m Travel distance in saturated zone to receptors, lyr #1, rcptr #1
WZLDISP	Normal	50.3	1.89E+01		2.5n Longitudinal dispersivity, lyr #1, rcptr #1
WZTDISP	Normal	49.9	3.75E+00		2.5o Transverse dispersivity, lyr #1, rcptr #1

TABLE 2b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	SD	Description
WZVDISP	Normal	49.9	2.18E-02		2.5p Vertical dispersivity, lyr #1, rcptr #1
WWVELOC	Normal	29.9	1.20E-01		2.6a River flow velocity
WWDEPTH	Normal	49.8	4.00E+00		2.6b River depth
WWWIDTH	Normal	29.9	5.70E+01		2.6c River width
WWDIST	Normal	9.98	4.00E+02		2.6d Distance to closest receptor
WWDISCHG	Normal	49.9	1.20E+03		2.6e Average annual discharge at each receptor location, rcptr #1
WASUBKD	Normal	(a)	5.00E-02		2.7a Subsurface adsorption coefficients, lyr #1, STRONTIUM-90
WASURFKD	Normal	50.1	3.10E+00		2.7b Surface adsorption coefficients, STRONTIUM-90
WCTEMP	Normal	20.0	3.70E+00		2.8f Mean monthly temperature for Jan
WCRAIN	Normal	20.0	5.00E-01		2.8g Mean monthly precipitation for Jan
WCPRENUM	Normal	9.99	6.30E-01		2.8j Mean number days where precipitation >0.01 for Jan
WCTEMP	Normal	20.0	4.00E+00		2.8f Mean monthly temperature for Feb
WCRAIN	Normal	19.9	5.00E-01		2.8g Mean monthly precipitation for Feb
WCPRENUM	Normal	9.97	5.70E-01		2.8j Mean number days where precipitation >0.01 for Feb
WCTEMP	Normal	20.2	4.80E+00		2.8f Mean monthly temperature for Mar
WCRAIN	Normal	20.0	6.00E-01		2.8g Mean monthly precipitation for Mar
WCPRENUM	Normal	10.0	6.40E-01		2.8j Mean number days where precipitation >0.01 for Mar
WCTEMP	Normal	20.3	5.80E+00		2.8f Mean monthly temperature for Apr
WCRAIN	Normal	19.9	4.00E-01		2.8g Mean monthly precipitation for Apr

TABLE 2b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	SD	Description
WCPRENUM	Normal	9.97	5.45E-01		2.8j Mean number days where precipitation >0.01 for Apr
WCTEMP	Normal	20.1	6.60E+00		2.8f Mean monthly temperature for May
WCRAIN	Normal	20.0	4.00E-01		2.8g Mean monthly precipitation for May
WCPRENUM	Normal	9.97	5.40E-01		2.8j Mean number days where precipitation >0.01 for May
WCTEMP	Normal	20.0	7.30E+00		2.8f Mean monthly temperature for Jun
WCRAIN	Normal	19.9	4.00E-01		2.8g Mean monthly precipitation for Jun
WCPRENUM	Normal	9.99	5.20E-01		2.8j Mean number days where precipitation >0.01 for Jun
WCTEMP	Normal	20.0	7.70E+00		2.8f Mean monthly temperature for Jul
WCRAIN	Normal	20.0	5.00E-01		2.8g Mean monthly precipitation for Jul
WCPRENUM	Normal	10.0	6.00E-01		2.8j Mean number days where precipitation >0.01 for Jul
WCTEMP	Normal	20.0	7.60E+00		2.8f Mean monthly temperature for Aug
WCRAIN	Normal	20.0	4.00E-01		2.8g Mean monthly precipitation for Aug
WCPRENUM	Normal	10.0	5.15E-01		2.8j Mean number days where precipitation >0.01 for Aug
WCTEMP	Normal	20.0	7.00E+00		2.8f Mean monthly temperature for Sep
WCRAIN	Normal	20.0	4.00E-01		2.8g Mean monthly precipitation for Sep
WCPRENUM	Normal	9.99	4.10E-01		2.8j Mean number days where precipitation >0.01 for Sep
WCTEMP	Normal	20.0	5.80E+00		2.8f Mean monthly temperature for Oct
WCRAIN	Normal	20.0	3.00E-01		2.8g Mean monthly precipitation for Oct

TABLE 2b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	SD	Description
WCPRENUM	Normal	9.98	3.95E-01		2.8j Mean number days where precipitation >0.01 for Oct
WCTEMP	Normal	19.9	4.70E+00		2.8f Mean monthly temperature for Nov
WCRAIN	Normal	20.0	5.00E-01		2.8g Mean monthly precipitation for Nov
WCPRENUM	Normal	10.0	5.00E-01		2.8j Mean number days where precipitation >0.01 for Nov
WCTEMP	Normal	20.0	4.00E+00		2.8f Mean monthly temperature for Dec
WCRAIN	Normal	20.1	6.00E-01		2.8g Mean monthly precipitation for Dec
WCPRENUM	Normal	9.97	1.09E+01	5.45E-01	2.8j Mean number days where precipitation >0.01 for Dec

(a) Since distribution is either truncated and/or not symmetric +/- interpretation may not apply.

contaminant velocity in groundwater is $v/(1+\rho K_d/n)$, where v, ρ, and n, respectively, are pore water velocity, bulk density, and effective porosity in the saturated zone.

The most important variable for Oak Ridge WAG 6 is WZPVELOC (pore water velocity in the saturated zone) having a partial R-Square of 0.27. The second most influential variable was WASUBKD (the K_d in the saturated zone), with a partial R-Square of 0.14. Next, WASURFKD (K_d in the unsaturated zone) and WWDISCHG (annual discharge of the river [volumetric flux] at the receptor location), having respective R-Square values of 0.12 and 0.11. Note that the regression coefficient for WZPVELOC was positive. With other factors held constant, one would expect that decreasing WZPVELOC would result in an increase in health effects (because of decreased dilution attending a decrease in pore water velocity). However, it has been verified that the positive coefficient that was obtained reflects the dominance of the impact of both the radioactive decay and the time discounting of health effects (due to a later arrival of the contaminant at the receptor when pore water velocity is reduced) over the impact of this reduction in dilution. For the results shown in Table 2, the range of computed health effects varied from 5.5E-4 to 1.8E-1.

3.2 ANL 570 HOLDING POND

The Argonne ANL 570 scenario involved release of arsenic from a holding pond with subsequent overland transport of that contaminant to the Illinois River, inducing water recreational exposures and exposure from ingestion of contaminated fish. Table 3 contains the results of the sensitivity analysis for this case. The analysis identified 10 variables as influential; however, the full model R-Square was only 0.2483. The low model R-Square indicates that much of the variability is "unexplained" by the analysis. Changing the major variables causes a "switching" (on-off) of overland transport, thereby producing a non-continuous response in the health effects and a consequently low R-Square. Because the model R-Square was low, the results for this scenario are not useful for intrepreting model sensitivities.

The influential variables identified such as a temperature on a freezing transition month and the SCS curve number are consistent with the overland

TABLE 3a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - ANL 570 Holding Pond Overland Flow Case

Name	Partial R-Square	Parameter Estimate	Description
WCTEMP	0.0805	8.20E-06	2.8f Mean monthly temperature for Mar
WTSCSCN	0.0691	7.10E-06	2.2j SCS curve number
WSCONC	0.0258	3.77E+01	2.1k Contaminant concentration, ARSENIC
WCRAIN	0.0179	9.37E-04	2.8g Mean monthly precipitation for Jan
WCTEMP	0.0147	-3.47E-05	2.8f Mean monthly temperature for Nov
WCTEMP	0.0105	2.21E-05	2.8f Mean monthly temperature for May
WCPRENUM	0.0090	-1.73E-04	2.8j Mean number days where precipitation >0.01 for Apr
WSINVENT	0.0087	2.46E-06	2.1j Constituent inventories, ARSENIC
WWDISCHG	0.0064	-3.00E-09	2.6e Average annual discharge at each receptor location, rcptr #1
WOPRECIP	0.0056	1.65E-04	2.3b Precipitation frequency distribution

Model R-Square = 0.2483

TABLE 3b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - ANL 570 Holding Pond Overland Flow Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WSINVENT	Normal	50.1	4.19E+01	2.1j Constituent inventories, ARSENIC
EWPOPREC	Normal	40.1	1.11E+05	4.2o Population involved in recreational type, rcptr #1
WSMOISTC	Normal	14.9	1.55E+00	2.1g Moisture content associated with ranking unit
WSBULKD	Normal	15.0	1.00E-01	2.1h Bulk density of top soil at ranking unit
WSCONC	Normal	49.9	5.00E-06	2.1k Contaminant concentration, ARSENIC
WTVEGCOV	Normal	9.98	4.00E+00	2.2h % vegetative cover
WTAVAILW	Normal	9.96	1.00E-02	2.2i Top soil water capacity
WOSTORMI	Normal	49.8	5.00E-01	2.3a Index for storm type
WOPRECIP	Normal	49.8	5.50E-01	2.3b Precipitation frequency distribution
WOKFACTR	Normal	50.0	9.25E-02	2.3d Soil-erodibility factor
WOCFACTR	Normal	49.8	3.50E-02	2.3e Vegetative-cover factor
WOPFACTR	Normal	50.1	2.50E-01	2.3f Land management practice factor
WORIVLEN	Normal	14.9	3.75E-01	2.3j Length of river adjacent to ranking unit
WWVELOC	Normal	30.0	2.25E-01	2.6a River flow velocity
WWDEPTH	Normal	50.1	7.50E-01	2.6b River depth
WWWIDTH	Normal	30.0	3.00E+01	2.6c River width
WWDIST	Normal	10.1	2.65E+02	2.6d Distance to closest receptor
WWDISCHG	Normal	49.7	2.66E+03	2.6e Average annual discharge at each receptor location, rcptr #1
WASURFKD	Normal	49.9	4.85E+00	2.7b Surface adsorption coefficients, ARSENIC
WCTEMP	Normal	19.9	2.10E+00	2.8f Mean monthly temperature for Jan

TABLE 3b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WCRAIN	Normal	20.0	1.60E-01	2.8g Mean monthly precipitation for Jan
WCPRENUM	Normal	9.97	5.50E-01	2.8j Mean number days where precipitation >0.01 for Jan
WCTEMP	Normal	20.0	2.60E+00	2.8f Mean monthly temperature for Feb
WCRAIN	Normal	19.7	1.30E-01	2.8g Mean monthly precipitation for Feb
WCPRENUM	Normal	9.97	5.00E-01	2.8j Mean number days where precipitation >0.01 for Feb
WCTEMP	Normal	20.0	3.60E+00	2.8f Mean monthly temperature for Mar
WCRAIN	Normal	20.1	2.60E-01	2.8g Mean monthly precipitation for Mar
WCPRENUM	Normal	9.98	6.50E-01	2.8j Mean number days where precipitation >0.01 for Mar
WCTEMP	Normal	20.0	4.90E+00	2.8f Mean monthly temperature for Apr
WCRAIN	Normal	19.9	3.65E-01	2.8g Mean monthly precipitation for Apr
WCPRENUM	Normal	10.0	6.50E-01	2.8j Mean number days where precipitation >0.01 for Apr
WCTEMP	Normal	19.9	5.90E+00	2.8f Mean monthly temperature for May
WCRAIN	Normal	19.9	3.15E-01	2.8g Mean monthly precipitation for May
WCPRENUM	Normal	10.1	5.50E-01	2.8j Mean number days where precipitation >0.01 for May
WCPRENUM	Normal	9.98	5.00E-01	2.8j Mean number days where precipitation >0.01 for Jun
WCPRENUM	Normal	10.0	5.00E-01	2.8j Mean number days where precipitation >0.01 for Jul
WCPRENUM	Normal	10.1	4.50E-01	2.8j Mean number days where precipitation >0.01 for Aug
WCTEMP	Normal	19.9	6.50E+00	2.8f Mean monthly temperature for Sep
WCRAIN	Normal	19.9	3.35E-01	2.8g Mean monthly precipitation for Sep
WCPRENUM	Normal	10.0	5.00E-01	2.8j Mean number days where precipitation >0.01 for Sep
WCTEMP	Normal	20.0	5.40E+00	2.8f Mean monthly temperature for Oct
WCRAIN	Normal	20.1	2.30E-01	2.8g Mean monthly precipitation for Oct
WCPRENUM	Normal	9.98	4.50E-01	2.8j Mean number days where precipitation >0.01 for Oct

TABLE 3b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WCTEMP	Normal	19.9	4.00E+00	2.8f Mean monthly temperature for Nov
WCRAIN	Normal	19.9	2.05E-01	2.8g Mean monthly precipitation for Nov
WCTEMP	Normal	20.0	2.80E+00	2.8f Mean monthly temperature for Dec
WCRAIN	Normal	20.0	2.10E-01	2.8g Mean monthly precipitation for Dec
WCPRENUM	Normal	10.0	6.00E-01	2.8j Mean number days where precipitation >0.01 for Dec
WTSCSCN	Discrete	12.2	0.00E+00	2.2j SCS curve number

flow model formulation. This switching behavior was also noted with similar results by Doctor et al. (1990). The number of health effects varied discontinuously from 5.6E-12 to 1.0E-8.

3.3 HANFORD NRDWL SITE CASES

The Hanford NRDWL case and special study cases involve release (of one or more of the constituents identified in Table 1) from a landfill into the unsaturated zone, subsequent leaching into groundwater, and groundwater transport to a residential receptor well. Table 4 contains the sensitivity analysis results for the Hanford NRDWL Site primary case, wherein only benzene was considered. The analysis identified 17 influential variables with a full model R-Square of 0.81. The most influential variables were WSFLUXSTR (contaminant flux rate), WSLEACHV (waste liquid infiltration rate), and EGPOPDRW (size of population drinking contaminated water at the receptor well), having respective partial R-Squares of 0.21, 0.16, and 0.13. Because the lower limits on the distributions of the k_d parameters (WASUBKD) for both the unsaturated and saturated zones were small (about 0.05 ml/g), the impacts of varying them were not significant.

The health effects from benzene varied from 1.8E-4 to 1.9E-2. This interval includes the base case value of 4.4E-3 health effects. In the base case run, the total health effects from all constituents was 8.3E-3 with virtually all of the additional population risk coming from methylene chloride, carbon tetrachloride, chloroform, trichloroethylene, and tetrachloroethylene, which contribute 2.9E-3, 4.5E-4, 2.5E-4, 2.4E-4, and 8.9E-5, respectively.

The special study analysis for the combined effects of benzene and methylene chloride (Table 5) showed that including methylene chloride reduced the relative importance of the benzene flux rate considerably. Otherwise, the general order of importance of inputs was not changed. An additional analysis including four additional contaminants (carbon tetrachloride, chloroform, trichloroethylene, and tetrachloroethylene) resulted in roughly the same ordering of influential variables (Table 6). The relative influence of the thickness of the unsaturated zone (WP-THICK) increased when all of the six major contaminants were considered because this parameter is common to the transport of

TABLE 4a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects for Hanford NRDWL Groundwater Transport Case

Name	Partial R-Square	Parameter Estimate	Description
WSFLUXSTR	0.211		2.1o Contaminant flux rate, flux #1, BENZENE
WSLEACHV	0.155		2.1f Waste Liquid Infiltration Rate
EGPOPDRW	0.129		4.1a Population drinking contaminated groundwater, rcptr #1
WZTHICK	0.0951	-2.12E-05	2.5k Thickness of SZ, lyr #2
WZTDISP	0.0865	-1.83E-06	2.5o Transverse dispersivity, lyr #2, rcptr #1
WZDIST	0.0259	-1.13E-07	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WZTOTPOR	0.0201	-1.14E-04	2.5h Total porosity of SZ, lyr #2
WPTHICK	0.0181	-7.24E-06	2.4h Thickness of PSZ, lyr #1
WASUBKD	0.0188	-2.27E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WZPERPOR	0.0170	-3.68E-05	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WASUBKD	0.0141	-1.66E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE
WZLDISP	0.00870		2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WPBULKD	0.00300	-9.44E-04	2.4i Bulk density of PSZ, lyr #1
WZPVELOC	0.00270	-2.10E-04	2.5j Pore-Water Velocity (SZ), lyr #2
WZBULKD	0.00250	-7.66E-04	2.5l Bulk density of SZ, lyr #2
WPCONDUC	0.00200	-2.50E-07	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WPLDISP	0.00150	-1.12E-04	2.4l Longitudinal dispersivity of PSZ, lyr #1
Model R-Square:			

TABLE 4b. Summary of Input Variables for Snesitivity Analysis of Population Health Effects for Hanford NRDWL Groundwater Transport Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
EGPOPDRW	Normal	39.9	1.70E+03	4.1a Population drinking contaminated groundwater, rcptr #1
WSLEACHV	Normal	50.0	5.00E-03	2.1f Waste Liquid Infiltration Rate
WSFLUXSTR		49.9	8.68E+05	2.1o Contaminant flux rate, flux #1, BENZENE
WPTHICK	Normal	30.3	4.20E+01	2.4h Thickness of PSZ, lyr #1
WPBULKD	Normal	15.2	1.25E-01	2.4i Bulk density of PSZ, lyr #1
WPTOTPOR	Normal	15.0	2.85E+00	2.4j Total porosity of PSZ, lyr #1
WPFIELDC	Normal	15.2	6.88E-01	2.4k Field capacity of PSZ, lyr #1
WPLDISP	Normal	49.8	7.00E-01	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPCONDUC	Normal	49.8	3.50E+02	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WZTOTPOR	Normal	15.0	1.95E+00	2.5h Total porosity of SZ, lyr #2
WZPERPOR	Normal	15.1	7.30E+00	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WZPVELOC	Normal	50.1	5.00E-01	2.5j Pore-Water Velocity (SZ), lyr #2
WZTHICK	Normal	29.9	3.00E+01	2.5k Thickness of SZ, lyr #2
WZBULKD	Normal	15.2	1.25E-01	2.5l Bulk density of SZ, lyr #2
WZDIST	Normal	9.97	3.15E+03	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WZLDISP	Normal	50.3	1.59E+03	2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WZTDISP	Normal	50.1	3.20E+02	2.5o Transverse dispersivity, lyr #2, rcptr #1

TABLE 4b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WZVDISP	Normal	49.8	1.83E+00	2.5p Vertical dispersivity, lyr #2, rcptr #1
WASUBKD	Normal	49.5	1.25E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WASUBKD	Normal	49.4	1.25E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE

TABLE 5a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Hanford NRDWL Groundwater Transport Case - Special Study (2 Constituents)

Name	Partial R-Square	Parameter Estimate	Description
EGPOPDRW	0.184		4.1a Population drinking contaminated groundwater, rcptr #1
WSLEACHV	0.127		2.1f Waste Liquid Infiltration Rate
WZTHICK	0.115	-3.33E-05	2.5k Thickness of SZ, lyr #2
WZTDISP	0.113	-3.09E-06	2.5o Transverse dispersivity, lyr #2, rcptr #1
WSFLUXSTR	0.112		2.1o Contaminant flux rate, flux #1, BENZENE
WSFLUXSTR	0.0611		2.1o Contaminant flux rate, flux #1, METHYLENE CHLORIDE
WZDIST	0.0280	-1.55E-07	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WPTHICK	0.0244	-1.10E-05	2.4h Thickness of PSZ, lyr #1
WZTOTPOR	0.0162	-1.99E-04	2.5h Total porosity of SZ, lyr #2
WZPERPOR	0.0143	-6.94E-05	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WASUBKD	0.00940	-2.30E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WASUBKD	0.00730	-2.01E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE
WZLDISP	0.00500		2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WZPVELOC	0.00440	-3.93E-04	2.5j Pore-Water Velocity (SZ), lyr #2
WPLDISP	0.00390	-2.65E-04	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPTOTPOR	0.00250		2.4j Total porosity of PSZ, lyr #1
WPBULKD	0.00120	-8.16E-04	2.4i Bulk density of PSZ, lyr #1

Model R-Square:

TABLE 5b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Hanford NRDWL Groundwater Transport Case - Special Study (2 Constituents)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
EGPOPDRW	Normal	39.9	1.70E+03	4.1a Population drinking contaminated groundwater, rcptr #1
WSLEACHV	Normal	50.0	5.00E-03	2.1f Waste Liquid Infiltration Rate
WSFLUXSTR		49.9	8.67E+05	2.1o Contaminant flux rate, flux #1, BENZENE
WSFLUXSTR		50.6	1.21E+06	2.1o Contaminant flux rate, flux #1, METHYLENE CHLORIDE
WPTHICK	Normal	29.9	4.20E+01	2.4h Thickness of PSZ, lyr #1
WPBULKD	Normal	15.2	1.25E-01	2.4i Bulk density of PSZ, lyr #1
WPTOTPOR	Normal	14.9	2.85E+00	2.4j Total porosity of PSZ, lyr #1
WPFIELDC	Normal	15.2	6.88E-01	2.4k Field capacity of PSZ, lyr #1
WPLDISP	Normal	49.8	7.00E-01	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPCONDUC	Normal	50.0	3.50E+02	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WZTOTPOR	Normal	15.0	1.95E+00	2.5h Total porosity of SZ, lyr #2
WZPERPOR	Normal	10.9	7.30E+00	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WZPVELOC	Normal	49.8	5.00E-01	2.5j Pore-Water Velocity (SZ), lyr #2
WZTHICK	Normal	30.0	3.00E+01	2.5k Thickness of SZ, lyr #2
WZBULKD	Normal	15.3	1.25E-01	2.5l Bulk density of SZ, lyr #2
WZDIST	Normal	9.96	3.15E+03	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WZLDISP	Normal	50.2	1.59E+03	2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WZTDISP	Normal	49.9	3.20E+02	2.5o Transverse dispersivity, lyr #2, rcptr #1
WZVDISP	Normal	49.8	1.83E+00	2.5p Vertical dispersivity, lyr #2 rcptr #1

TABLE 5b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WASUBKD	Normal	49.4	1.25E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WASUBKD	Normal	49.9	1.34E-03	2.7a Subsurface adsorption coefficients, lyr #1, METHYLENE CHLORIDE
WASUBKD	Normal	49.4	1.25E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE
WASUBKD	Normal	49.9	1.34E-03	2.7a Subsurface adsorption coefficients, lyr #2, METHYLENE CHLORIDE

TABLE 6a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Hanford NRDWL Groundwater Transport Case - Special Study (6 Constituents)

Name	Partial R-Square	Parameter Estimate	Description
EGPOPDRW	0.199		4.1a Population drinking contaminated groundwater, rcptr #1
WZTHICK	0.149	-4.04E-05	2.5k Thickness of SZ, lyr #2
WSLEACHV	0.142		2.1f Waste Liquid Infiltration Rate
WZTDISP	0.0953	-2.77E-06	2.5o Transverse dispersivity, lyr #2, rcptr #1
WSFLUXSTR	0.0803		2.1o Contaminant flux rate, flux #1, BENZENE
WPTHICK	0.0437	-1.41E-05	2.4h Thickness of PSZ, lyr #1
WSFLUXSTR	0.0380		2.1o Contaminant flux rate, flux #1, METHYLENE CHLORIDE
WZDIST	0.0307	-1.85E-07	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WZTOTPOR	0.0203	-2.52E-04	2.5h Total porosity of SZ, lyr #2
WZLDISP	0.0186		2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WZPERPOR	0.0140	-7.65E-05	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WASUBKD	0.00690	-1.70E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WPLDISP	0.00660	-3.25E-04	2.4l Longitudinal dispersivity of PSZ, lyr #1
WASUBKD	0.00450	-1.39E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE
WPCONDUC	0.00410	-5.45E-07	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WSFLUXSTR	0.00220		2.1o Contaminant flux rate, flux #1, CARBON TETRACHLORIDE
WPBULKD	0.00130	-1.04E-03	2.4i Bulk density of PSZ, lyr #1
WASUBKD	0.00130	-6.97E-03	2.7a Subsurface adsorption coefficients, lyr #2, CARBON TETRACHLORIDE
WASUBKD	0.00110		2.7a Subsurface adsorption coefficients, lyr #2, CHLOROFORM

TABLE 6a. (contd)

Name	Partial R-Square	Parameter Estimate	Description
WASUBKD	0.000700	-1.49E-03	2.7a Subsurface adsorption coefficients, lyr #1, TETRACHLOROETHYLENE
WASUBKD	0.000600	-4.96E-03	2.7a Subsurface adsorption coefficients, lyr #1, CARBON TETRACHLORIDE
WPTOTPOR	0.000700		2.4j Total porosity of PSZ, lyr #1
Model R-Square	0.862		

TABLE 6b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Hanford NRDWL Groundwater Transport Case - Special Study (6 Constituents)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
EGPOPDRW	Normal	39.9	1.72E+03	4.1a Population drinking contaminated groundwater, rcptr #1
WSLEACHV	Normal	50.0	5.00E-03	2.1f Waste Liquid Infiltration Rate
WSFLUXSTR		49.9	8.67E+05	2.1o Contaminant flux rate, flux #1, BENZENE
WSFLUXSTR		50.6	1.21E+06	2.1o Contaminant flux rate, flux #1, METHYLENE CHLORIDE
WSFLUXSTR		49.9	2.35E+04	2.1o Contaminant flux rate, flux #1, CARBON TETRACHLORIDE
WSFLUXSTR		49.9	1.22E+04	2.1o Contaminant flux rate, flux #1, CHLOROFORM
WSFLUXSTR		49.8	5.12E+04	2.1o Contaminant flux rate, flux #1, TETRACHLOROETHYLENE
WSFLUXSTR		49.8	1.58E+05	2.1o Contaminant flux rate, flux #1, TRICHLOROETHYLENE
WPTHICK	Normal	29.9	4.20E+01	2.4h Thickness of PSZ, lyr #1
WPBULKD	Normal	15.0	1.23E-01	2.4i Bulk density of PSZ, lyr #1
WPTOTPOR	Normal	15.0	2.85E+00	2.4j Total porosity of PSZ, lyr #1
WPFIELDC	Normal	15.0	6.75E-01	2.4k Field capacity of PSZ, lyr #1
WPLDISP	Normal	49.8	7.00E-01	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPCONDUC	Normal	49.9	3.50E+02	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WZTOTPOR	Normal	15.0	1.95E+00	2.5h Total porosity of SZ, lyr #2
WZPERPOR	Normal	10.0	4.81E+00	2.5z Percent of total porosity substituted for effective porosity, lyr #2
WZPVELOC	Normal	50.1	5.00E-01	2.5j Pore-Water Velocity (SZ), lyr #2
WZTHICK	Normal	30.0	3.00E+01	2.5k Thickness of SZ, lyr #2
WZBULKD	Normal	15.0	1.23E-01	2.5l Bulk density of SZ, lyr #2

TABLE 6b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WZDIST	Normal	9.97	3.17E+03	2.5m Travel distance in saturated zone to receptors, lyr #2, rcptr #1
WZLDISP	Normal	49.9	1.58E+03	2.5n Longitudinal dispersivity, lyr #2, rcptr #1
WZTDISP	Normal	49.8	3.17E+02	2.5o Transverse dispersivity, lyr #2, rcptr #1
WZVDISP	Normal	49.9	1.84E+00	2.5p Vertical dispersivity, lyr #2, rcptr #1
WASUBKD	Normal	49.9	1.26E-02	2.7a Subsurface adsorption coefficients, lyr #1, BENZENE
WASUBKD	Normal	49.9	1.34E-03	2.7a Subsurface adsorption coefficients, lyr #1, METHYLENE CHLORIDE
WASUBKD	Normal	49.9	1.67E-02	2.7a Subsurface adsorption coefficients, lyr #1, CARBON TETRACHLORIDE
WASUBKD	Normal	50.1	4.71E-03	2.7a Subsurface adsorption coefficients, lyr #1, CHLOROFORM
WASUBKD	Normal	49.9	5.52E-02	2.7a Subsurface adsorption coefficients, lyr #1, TETRACHLOROETHYLENE
WASUBKD	Normal	50.0	1.91E-02	2.7a Subsurface adsorption coefficients, lyr #1, TRICHLOROETHYLENE
WASUBKD	Normal	49.9	1.26E-02	2.7a Subsurface adsorption coefficients, lyr #2, BENZENE
WASUBKD	Normal	50.0	1.34E-03	2.7a Subsurface adsorption coefficients, lyr #2, METHYLENE CHLORIDE
WASUBKD	Normal	49.9	1.67E-02	2.7a Subsurface adsorption coefficients, lyr #2, CARBON TETRACHLORIDE
WASUBKD	Normal	49.9	4.71E-03	2.7a Subsurface adsorption coefficients, lyr #2, CHLOROFORM
WASUBKD	Normal	50.4	5.52E-02	2.7a Subsurface adsorption coefficients, lyr #2, TETRACHLOROETHYLENE
WASUBKD	Normal	49.9	1.91E-02	2.7a Subsurface adsorption coefficients, lyr #2, TRICHLOROETHYLENE

all of these contaminants. The ranges of health effects of the two-contaminant and six-contaminant special study cases were 4.4E-4 to 2.9E-2 and 1.8E-3 to 7.4E-2, respectively.

3.4 LLNL SITE 300 PIT 6

The Lawrence Livermore LLNL Site 300 Pit 6 case involved release of trichloroethylene from waste Pit 6 into the unsaturated zone, with subsequent percolation in groundwater, and transport to the Ranger well. Table 7 contains the sensitivity analysis results for this case. The analysis resulted identified 17 influential variables with a full model R-Square of 0.75. The waste liquid infiltration rate (WSLEACH) has by far the most influential variable, having a partial R-Square of 0.37. Nine additional variables have R-Square values greater than 0.01. The range of health effects is 2.9E-7 to 2.8E-4, which covers the base case of 2.3E-5.

3.5 FERNALD OU-1

The Fernald OU-1 case involves release of uranium-238 from several waste pits in the operating unit OU-1 into the unsaturated zone, with subsequent leaching into groundwater, and transport to a residential use receptor well operated by the Southwest Ohio Water Company. Table 8 contains the sensitivity analysis results for this case. The analysis identified 26 influential variables with a full model R-Square of 0.65. The largest partial R-Square values were those corresponding to the uranium-238 K_d parameters for both unsaturated layers (WASUBKD) with partial R-Square values of 0.29 and 0.12. The next largest partial R-Square was for the constituent inventory (WSINVENT). Eight additional variables have R-Square values greater than 0.01. The range of health effects was 2.7E-10 to 4.7. The upper end of this range is influenced by the lower limit on K_d being the base case value of 0.0. The range is skewed downward from the base case value of 1.62. health effects.

3.6 FERNALD OU-4

The Fernald OU-4 case involved computing releases of radon-222 from an effluent stack, atmospheric transport to the surrounding population, and evaluating exposures and population risk associated with outdoor inhalation of

TABLE 7a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - LLNL Site 300 Pit 6 Case

Name	Partial R-Square	Parameter Estimate	Description
WSLEACHV	0.3685	+6.12E-02	2.1f Waste Liquid Infiltration Rate
WASUBKD	0.0846	-4.02E-05	2.7a Subsurface adsorption coefficients, lyr #1, TRICHLOROETHYLENE
WSFLUXSTR	0.0661	+1.98E-06	2.1o Contaminant flux rate, flux #1, TRICHLOROETHYLENE
WASUBKD	0.0477	-3.98E-05	2.7a Subsurface adsorption coefficients, lyr #2, TRICHLOROETHYLENE
EGPOPDRW	0.0306	+4.01E-09	4.1a Population drinking contaminated groundwater, rcptr #1
WZVDISP	0.0261	-3.49E-05	2.5p Vertical dispersivity, lyr #3, rcptr #1
WPCONDUC	0.0244	+2.75E-02	2.4m Saturated hydraulic conductivity of PSZ, lyr #2
WZTDISP	0.0236	-1.64E-06	2.5o Transverse dispersivity, lyr #3, rcptr #1
WPTHICK	0.0203	-2.08E-06	2.4h Thickness of PSZ, lyr #2
WPTHICK	0.0174	-1.46E-06	2.4h Thickness of PSZ, lyr #1
WPLDISP	0.0093	-6.25E-05	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPBULKD	0.0087	-4.44E-05	2.4i Bulk density of PSZ, lyr #2
WPBULKD	0.0072	-4.64E-05	2.4i Bulk density of PSZ, lyr #1
WASUBKD	0.0039	-1.80E-05	2.7a Subsurface adsorption coefficients, lyr #3, TRICHLOROETHYLENE
WPTOTPOR	0.0030	+1.00E-06	2.4j Total porosity of PSZ, lyr #1
WZTOTPOR	0.0026	-1.17E-06	2.5h Total porosity of SZ, lyr #3
WZPERPOR	0.0022	-6.17E-07	2.5z Percent of total porosity substituted for effective porosity, ly

Model R-Square = 0.7462

TABLE 7b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - LLNL Site 300 Pit 6 Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WSINVENT	Normal	49.9	4.05E+02	2.1j Constituent inventories, TRICHLOROETHYLENE
EGPOPDRW	Normal	40.0	2.16E+03	4.1a Population drinking contaminated groundwater, rcptr #1
WSLENGTH	Normal	10.0	9.50E+00	2.1d Length of Site
WSWIDTH	Normal	10.2	9.50E+00	2.1e Width of Site
WSLEACHV	Normal	49.9	5.00E-04	2.1f Waste Liquid Infiltration Rate
WSFLUXSTR		49.9	6.75E+00	2.1o Contaminant flux rate, flux #1, TRICHLOROETHYLENE
WTVEGCOV	Normal	9.96	2.50E+00	2.2h % vegetative cover
WTAVAILW	Normal	14.9	1.43E-01	2.2i Top soil water capacity
WPTHICK	Normal	29.9	4.50E+00	2.4h Thickness of PSZ, lyr #1
WPBULKD	Normal	15.1	1.05E-01	2.4i Bulk density of PSZ, lyr #1
WPTOTPOR	Normal	14.9	2.80E+00	2.4j Total porosity of PSZ, lyr #1
WPFIELDC	Normal	14.9	1.30E+00	2.4k Field capacity of PSZ, lyr #1
WPLDISP	Normal	49.8	7.50E-02	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPCONDUC	Normal	49.9	1.00E-03	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WPTHICK	Normal	30.1	3.75E+00	2.4h Thickness of PSZ, lyr #2
WPBULKD	Normal	15.1	1.05E-01	2.4i Bulk density of PSZ, lyr #2
WPTOTPOR	Normal	15.2	3.23E+00	2.4j Total porosity of PSZ, lyr #2
WPFIELDC	Normal	15.0	2.55E+00	2.4k Field capacity of PSZ, lyr #2
WPLDISP	Normal	49.9	6.25E-02	2.4l Longitudinal dispersivity of PSZ, lyr #2
WPCONDUC	Normal	49.8	2.50E-04	2.4m Saturated hydraulic conductivity of PSZ, lyr #2

TABLE 7a. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WZTOTPOR	Normal	15.0	2.25E+00	2.5h Total porosity of SZ, lyr #3
WZPERPOR	Normal	14.9	4.13E+00	2.5z Percent of total porosity substituted for effective porosity, lyr #3
WZPVELOC	Normal	49.9	6.75E-02	2.5j Pore-Water Velocity (SZ), lyr #3
WZTHICK	Normal	29.9	7.50E+00	2.5k Thickness of SZ, lyr #3
WZBULKD	Normal	15.1	1.05E-01	2.5l Bulk density of SZ, lyr #3
WZDIST	Normal	10.2	4.88E+01	2.5m Travel distance in saturated zone to receptors, lyr #3, rcptr #1
WZLDISP	Normal	50.0	2.38E+01	2.5n Longitudinal dispersivity, lyr #3, rcptr #1
WZTDISP	Normal	49.9	4.75E+00	2.5o Transverse dispersivity, lyr #3, rcptr #1
WZVDISP	Normal	50.0	2.75E-01	2.5p Vertical dispersivity, lyr #3, rcptr #1
WASUBKD	Normal	49.9	3.47E-01	2.7a Subsurface adsorption coefficients, lyr #1, TRICHLOROETHYLENE
WASUBKD	Normal	50.0	3.47E-01	2.7a Subsurface adsorption coefficients, lyr #2, TRICHLOROETHYLENE
WASUBKD	Normal	49.8	1.97E-01	2.7a Subsurface adsorption coefficients, lyr #3, TRICHLOROETHYLENE

TABLE 8a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Fernald OU 1 Groundwater to Surface Water Case

Name	Partial R-Square	Parameter Estimate	Description
WASUBKD	0.286	-9.48E-01	2.7a Subsurface adsorption coefficients, lyr #2, URANIUM-238
WASUBKD	0.118	-5.64E-01	2.7a Subsurface adsorption coefficients, lyr #1, URANIUM-238
WSINVENT	0.0506		2.1j Constituent inventories, URANIUM-238
WZPVELOC	0.0318	-4.90E-02	2.5j Pore-Water Velocity (SZ), lyr #3
WPTHICK	0.0270	-2.59E-02	2.4h Thickness of PSZ, lyr #2
EGPOPDRW	0.0178		4.1a Population drinking contaminated groundwater, rcptr #1
WZVDISP	0.0157	-1.99E-01	2.5p Vertical dispersivity, lyr #3, rcptr #1
WPTHICK	0.0112	-6.79E-03	2.4h Thickness of PSZ, lyr #1
WZPERPOR	0.0121	-9.66E-03	2.5z Percent of total porosity substituted for effective porosity, lyr #3
WZTDISP	0.0118	-9.65E-04	2.5o Transverse dispersivity, lyr #3, rcptr #1
WCRAIN	0.0106		2.8g Mean monthly precipitation for Mar
WASUBKD	0.00940	-1.81E-01	2.7a Subsurface adsorption coefficients, lyr #3, URANIUM-238
WCTEMP	0.00540	-9.33E-03	2.8f Mean monthly temperature for Feb
WCPRENUM	0.00500		2.8j Mean number days where precipitation >0.01 for Sep
WCRAIN	0.00430		2.8g Mean monthly precipitation for Oct
WPBULKD	0.00410	-2.58E-01	2.4i Bulk density of PSZ, lyr #2
WPTOTPOR	0.00400		2.4j Total porosity of PSZ, lyr #2
WCTEMP	0.00380	-6.27E-03	2.8f Mean monthly temperature for Mar
WCRAIN	0.00360	-8.36E-02	2.8g Mean monthly precipitation for Aug
WSMOISTC	0.00240		2.1g Moisture content associated with ranking unit

TABLE 8a. (contd)

Name	Partial R-Square	Parameter Estimate	Description
WTVEGCOV	0.00240		2.2h % vegetative cover
WCTEMP	0.00250	-4.61E-03	2.8f Mean monthly temperature for Apr
WCRAIN	0.00220		2.8g Mean monthly precipitation for Apr
WCRAIN	0.00250	-6.00E-02	2.8g Mean monthly precipitation for May
WZTOTPOR	0.00200	-6.44E-03	2.5h Total porosity of SZ, lyr #3
WPFIELDC	0.00160		2.4k Field capacity of PSZ, lyr #1

Model R-Square:

TABLE 8b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Fernald OU 1 Groundwater to Surface Water Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WSINVENT	Normal	49.8	6.85E+02	2.1j Constituent inventories, URANIUM-238
EGPOPDRW	Normal	40.0	2.60E+01	4.1a Population drinking contaminated groundwater, rcptr #1
WSMOISTC	Normal	15.0	2.06E+00	2.1g Moisture content associated with ranking unit
WSBULKD	Normal	15.1	1.05E-01	2.1h Bulk density of top soil at ranking unit
WSCONC	Normal	49.9	9.68E+02	2.1k Contaminant concentration, URANIUM-238
WTVEGCOV	Normal	50.2	1.50E+01	2.2h % vegetative cover
WTAVAILW	Normal	15.0	1.50E-02	2.2i Top soil water capacity
WPTHICK	Normal	30.0	6.00E+00	2.4h Thickness of PSZ, lyr #1
WPBULKD	Normal	15.1	1.05E-01	2.4i Bulk density of PSZ, lyr #1
WPTOTPOR	Normal	15.0	3.53E+00	2.4j Total porosity of PSZ, lyr #1
WPFIELDC	Normal	14.9	2.55E+00	2.4k Field capacity of PSZ, lyr #1
WPLDISP	Normal	49.9	1.00E-01	2.4l Longitudinal dispersivity of PSZ, lyr #1
WPCONDUC	Normal	49.9	1.23E-01	2.4m Saturated hydraulic conductivity of PSZ, lyr #1
WPTHICK	Normal	30.2	3.00E+00	2.4h Thickness of PSZ, lyr #2
WPBULKD	Normal	15.2	1.25E-01	2.4i Bulk density of PSZ, lyr #2
WPTOTPOR	Normal	15.1	2.85E+00	2.4j Total porosity of PSZ, lyr #2
WPFIELDC	Normal	15.2	6.88E-01	2.4k Field capacity of PSZ, lyr #2
WPLDISP	Normal	49.8	5.00E-02	2.4l Longitudinal dispersivity of PSZ, lyr #2
WPCONDUC	Normal	49.9	8.75E+01	2.4m Saturated hydraulic conductivity of PSZ, lyr #2
WZTOTPOR	Normal	15.0	2.85E+00	2.5h Total porosity of SZ, lyr #3

TABLE 8b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WZPERPOR	Normal	15.0	4.95E+00	2.5z Percent of total porosity substituted for effective porosity, lyr #3
WZPVELOC	Normal	50.0	1.30E+00	2.5j Pore-Water Velocity (SZ), lyr #3
WZTHICK	Normal	30.0	2.25E+01	2.5k Thickness of SZ, lyr #3
WZBULKD	Normal	15.3	1.25E-01	2.5l Bulk density of SZ, lyr #3
WZDIST	Normal	9.99	5.25E+02	2.5m Travel distance in saturated zone to receptors, lyr #3, rcptr #1
WZLDISP	Normal	50.4	2.64E+02	2.5n Longitudinal dispersivity, lyr #3, rcptr #1
WZTDISP	Normal	50.0	5.25E+01	2.5o Transverse dispersivity, lyr #3, rcptr #1
WZVDISP	Normal	49.9	3.05E-01	2.5p Vertical dispersivity, lyr #3, rcptr #1
WASUBKD	Normal	(a)	5.00E-01	2.7a Subsurface adsorption coefficients, lyr #1, URANIUM-238
WASUBKD	Normal	(a)	5.00E-01	2.7a Subsurface adsorption coefficients, lyr #2, URANIUM-238
WASUBKD	Normal	(a)	5.00E-01	2.7a Subsurface adsorption coefficients, lyr #3, URANIUM-238
WASURFKD	Normal	(a)	5.00E-01	2.7b Surface adsorption coefficients, URANIUM-238
WCTEMP	Normal	20.0	2.70E+00	2.8f Mean monthly temperature for Jan
WCRAIN	Normal	20.0	2.60E-01	2.8g Mean monthly precipitation for Jan
WCPRENUM	Normal	10.0	6.50E-01	2.8j Mean number days where precipitation >0.01 for Jan
WCTEMP	Normal	20.1	3.00E+00	2.8f Mean monthly temperaturefor Feb
WCRAIN	Normal	20.0	2.04E-01	2.8g Mean monthly precipitation for Feb
WCPRENUM	Normal	10.0	5.40E-01	2.8j Mean number days where precipitation >0.01 for Feb
WCTEMP	Normal	19.9	4.00E+00	2.8f Mean monthly temperature for Mar
WCRAIN	Normal	20.0	3.10E-01	2.8g Mean monthly precipitation for Mar
WCPRENUM	Normal	10.0	6.50E-01	2.8j Mean number days where precipitation >0.01 for Mar

TABLE 8b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WCTEMP	Normal	20.2	5.20E+00	2.8f Mean monthly temperature for Apr
WCRAIN	Normal	20.0	3.40E-01	2.8g Mean monthly precipitation for Apr
WCPRENUM	Normal	9.99	6.40E-01	2.8j Mean number days where precipitation >0.01 for Apr
WCTEMP	Normal	19.9	6.20E+00	2.8f Mean monthly temperature for May
WCRAIN	Normal	20.0	3.70E-01	2.8g Mean monthly precipitation for May
WCPRENUM	Normal	10.0	6.05E-01	2.8j Mean number days where precipitation >0.01 for May
WCTEMP	Normal	20.0	7.10E+00	2.8f Mean monthly temperature for Jun
WCRAIN	Normal	20.0	3.80E-01	2.8g Mean monthly precipitation for Jun
WCPRENUM	Normal	10.1	5.20E-01	2.8j Mean number days where precipitation >0.01 for Jun
WCTEMP	Normal	20.0	7.50E+00	2.8f Mean monthly temperature for Jul
WCRAIN	Normal	20.0	3.40E-01	2.8g Mean monthly precipitation for Jul
WCPRENUM	Normal	9.98	5.05E-01	2.8j Mean number days where precipitation >0.01 for Jul
WCTEMP	Normal	20.0	7.30E+00	2.8f Mean monthly temperature for Aug
WCRAIN	Normal	20.1	3.10E-01	2.8g Mean monthly precipitation for Aug
WCPRENUM	Normal	10.0	4.75E-01	2.8j Mean number days where precipitation >0.01 for Aug
WCTEMP	Normal	19.9	6.60E+00	2.8f Mean monthly temperature for Sep
WCRAIN	Normal	20.0	2.40E-01	2.8g Mean monthly precipitation for Sep
WCPRENUM	Normal	9.96	4.05E-01	2.8j Mean number days where precipitation >0.01 for Sep
WCTEMP	Normal	19.9	5.50E+00	2.8f Mean monthly temperature for Oct
WCRAIN	Normal	20.0	2.00E-01	2.8g Mean monthly precipitation for Oct
WCPRENUM	Normal	9.98	4.35E-01	2.8j Mean number days where precipitation >0.01 for Oct
WCTEMP	Normal	20.0	4.20E+00	2.8f Mean monthly temperature for Nov
WCRAIN	Normal	20.0	2.60E-01	2.8g Mean monthly precipitation for Nov

TABLE 8b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
WCPRENUM	Normal	10.0	5.65E-01	2.8j Mean number days where precipitation >0.01 for Nov
WCTEMP	Normal	20.0	3.20E+00	2.8f Mean monthly temperature for Dec
WCRAIN	Normal	20.0	2.50E-01	2.8g Mean monthly precipitation for Dec
WCPRENUM	Normal	9.96	6.05E-01	2.8j Mean number days where precipitation >0.01 for Dec

(a) Since distribution is either truncated and/or not symmetric +/- interpretation may not apply.

this contaminant. Although there were other potential exposure routes in this scenario, the inhalation route was the primary contributor to the population risk. As in the DOE pilot study, radon-222 was modeled as a nondepositing gas. This assumption was also used in the earlier Environmental Survey runs for this particular case (Doctor et al. 1990).

Table 9 contains the results for the Fernald OU-4 case. The full model R-Square was 0.98. The most influential variable was emission rate (AEEMRATE). The second most important variable, EAPOPMUL, was used to adjust the population in the most populous sector of the exposure region. The variable EAJFDMUL was less influential. This variable was used as a multiplier of the most influential elements in the joint frequency table of wind data that describe local transport and dispersion climatology. The remaining variables having partial R-Square values in excess of 0.01 were anemometer height, AJANEMHT (used to describe vertical wind field), and the building height, AEHBUILD (used to define the initial dispersion for a release into a building wake). The range of computed health effects was 1.49 to 2.56 covering the base value of 2.0.

A special study case was examined to determine which population distances (in the most populated sector) were most influential. The general population in a sector is divided in terms of distance from the source release, each population category being within a distinct range of distance from the release. Whereas, for the primary OU-4 case, one multiplier was used to vary the whole population in the sector, the special study case was developed to identify the influential population categories in that sector.

To accomplish this objective, a population multiplier for each of ten different downwind distance ranges were independently varied. The results for this case are given in Table 10. The full model R-Square is slightly lower (0.97) than for the primary case wherein the entire population in the sector is varied as a block. Although the population group that is located between 10 and 20 miles from the site was the most influential, the results indicate that the risk outputs for Fernald OU4 are not as sensitive to independent changes in the individual population groups as they are to a simultaneous increase or decrease in the overall population.

TABLE 9a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Fernald OU 4 Air Emissions Case

Name	Partial R-Square	Parameter Estimate	Description
AEEMRATE	0.754	+2.09E-07	3.4g Emission rate, RADON-222+D (MOCK)
EAPOPMUL	0.138	+1.38E-02	0.0z Population Multiplier for .Pop file for distance of 0-1 miles
EAJFDMUL	0.0364	+4.42E-03	0.0z Multiplier for the Joint Frequency distribution data
AJANEMHT	0.0361	+1.41E-01	3.2b Joint frequency data anemometer height
AEHBUILD	0.0113	-4.94E-02	3.4f Structure height

Model R-Square = 0.976

TABLE 9b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Fernald OU 4 Air Emissions Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
ACMIXAM	Normal	9.98	2.50E+01	3.1a Morning mixing height
ACMIXPM	Normal	9.93	7.25E+01	3.1b Afternoon mixing height
ACNUMTS	Normal	9.97	2.15E+00	3.1f # of thunderstorms per year
ACPRENUM	Normal	10.1	6.50E+00	3.1m Number of precipitation days per year
ACRAIN	Normal	10.0	2.05E+00	3.1l Annual precipitation
AJANEMHT	Normal	9.98	3.00E-01	3.2b Joint frequency data anemometer height
AJRLEN	Normal	9.96	5.00E-01	3.2c Joint frequency data roughness length
AEHBUILD	Normal	9.94	4.60E-01	3.4f Structure height
AEEMRATE	Normal	19.9	9.53E+05	3.4g Emission rate, RADON-222+D (MOCK)
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 0-1 miles
EAJFDMUL	Normal	19.9	1.00E+01	0.0z Multiplier for the Joint Frequency distribution data

TABLE 10a. Summary of Stepwise Regression Procedure for the Sensitivity Analysis of Population Health Effects - Fernald OU 4 Special Study Case

Name	Partial R-Square	Parameter Estimate	Description
AEEMRATE	0.446	1.96E-07	3.4g Emission rate, RADON-222+D (MOCK)
EAJFDMUL	0.394	4.54E-03	0.0z Multiplier for the Joint Frequency distribution data
AJANEMHT	0.0610	1.42E-01	3.2b Joint frequency data anemometer height
AEHBUILD	0.0299	-5.55E-02	3.4f Structure height
EAPOPMUL	0.0142	3.14E-03	0.0z Population Multiplier for .Pop file for distance of 10-20 miles
EAPOPMUL	0.00990	3.02E-03	0.0z Population Multiplier for .Pop file for distance of 5-10 miles
EAPOPMUL	0.00750	2.36E-03	0.0z Population Multiplier for .Pop file for distance of 40-50 miles
AJRLEN	0.00220	-1.26E-02	3.2c Joint frequency data roughness length
EAPOPMUL	0.00130	1.05E-03	0.0z Population Multiplier for .Pop file for distance of 2-3 miles
EAPOPMUL	0.00100	1.01E-03	0.0z Population Multiplier for .Pop file for distance of 20-30 miles

Model R-Square = 0.968

TABLE 10b. Summary of Input Variables for Sensitivity Analysis of Population Health Effects - Fernald OU 4 Special Study Case

Name	Dist. Type	Range +/- 2*SD	Mean	Description
ACMIXAM	Normal	9.98	2.50E+01	3.1a Morning mixing height
ACMIXPM	Normal	9.93	7.25E+01	3.1b Afternoon mixing height
ACNUMTS	Normal	9.97	2.15E+00	3.1f # of thunderstorms per year
ACPRENUM	Normal	10.1	6.50E+00	3.1m Number of precipitation days per year
ACRAIN	Normal	10.0	2.05E+00	3.1l Annual precipitation
AJANEMHT	Normal	9.98	3.00E-01	3.2b Joint frequency data anemometer height
AJRLEN	Normal	9.96	5.00E-01	3.2c Joint frequency data roughness length
AEHBUILD	Normal	9.94	4.60E-01	3.4f Structure height
AEEMRATE	Normal	10.2	4.88E+05	3.4g Emission rate, RADON-222+D (MOCK)
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 0-1 miles
EAPOPMUL	Normal	9.97	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 1-2 miles
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 2-3 miles
EAPOPMUL	Normal	9.96	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 3-4 miles
EAPOPMUL	Normal	9.99	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 4-5 miles
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 5-10 miles
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 10-20 miles

TABLE 10b. (contd)

Name	Dist. Type	Range +/- 2*SD	Mean	Description
EAPOPMUL	Normal	10.0	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 20-30 miles
EAPOPMUL	Normal	9.99	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 30-40 miles
EAPOPMUL	Normal	9.98	5.00E+00	0.0z Population Multiplier for .Pop file for distance of 40-50 miles
EAJFDMUL	Normal	39.9	2.00E+01	0.0z Multiplier for the Joint Frequency distribution data

4.0 NONLINEARITY OF OUTPUT AND STABILITY OF RESULTS

4.1 NONLINEARITY

Because the number of health effects associated with a single population group, exposure route, contaminant, exposure location, and time period is not a linear additive function of the (varied) input parameters (see Whelan et al. 1987 for equations describing hazard potential index, contaminated media concentrations, etc.), the output "response surface" is, therefore, curvilinear. For some groundwater cases, this general curvilinear feature can be augmented by a significant nonlinearity of the (average) exposure concentration in small values of dispersivities, intermediate or small values of K_d coefficients (e.g., 0.1 and 5 L/kg), and small aquifer thicknesses (e.g., less than computed mixing depth). The output can respond almost explosively to decreases in either dispersivities or mixing depth; however, because of the monotonic nature of the nonlinearities in these input parameters, their effects on the output are accounted for (qualitatively) in the least-squares estimation of a planar surface and their effects are thus detected in the stepwise variable selection process.

The partition coefficient, K_d, only appears within the retardation factor (viz. $R_f = (n + b\ K_d)/n_e$, R_f, b, n, and n_e, respectively, retardation factor, bulk density (g/ml), total porosity, and effective porosity). Therefore, because changes in $1/R_f$ have roughly the same effect as changes in longitudinal and transverse dispersivities on the instantaneous concentration (see equations 5.31 and 5.32 of Whelan et al. 1987), only intermediate and larger K_d values would cause $1/R_f$ to decrease significantly, with increasingly large k_d values having a diminishing effect on $1/R_f$. The LLNL Site 300 case results reflect considerable sensitivity to changes in K_d parameters for trichlorethylene in both the unsaturated and saturated zones, each having a base case value of 1.39 ml/g. Similarly, for the Fernald OU 1 case, the most influential inputs were K_d parameters for uranium-238 in the unsaturated and saturated zones, each ranging from 0 to 1 ml/g.

The above discussion relating to K_d assumes that the degradation or radioactive decay of the contaminant is negligible within any given series of two or three consecutive 70-year periods. If the rate of decay is extremely

high, as with strontium-90, then it would be expected that even a slight change in R_f would significantly impact the number of health effects, because changes in R_f induce changes in the contaminant velocity. With negligible decay rates the average concentration of a contaminant at a receptor well is only sensitive to large values of R_f. The effect of such a high decay rate is illustrated in the results of the WAG6 case; wherein, strontium-90 is the only contaminant and the base value for K_d is 3.6E-2 ml/g.

For the Hanford NRDWL cases, the foregoing and its implications for the output response can be learned by examining Figure 1, which plots the (empirical) cumulative distribution functions (CDF) for the primary and special study cases. These CDFs derived from 500 runs of each case. Because the six-constituent case considers more significant contaminants than the other special study (considering two constituents), one would expect that if the

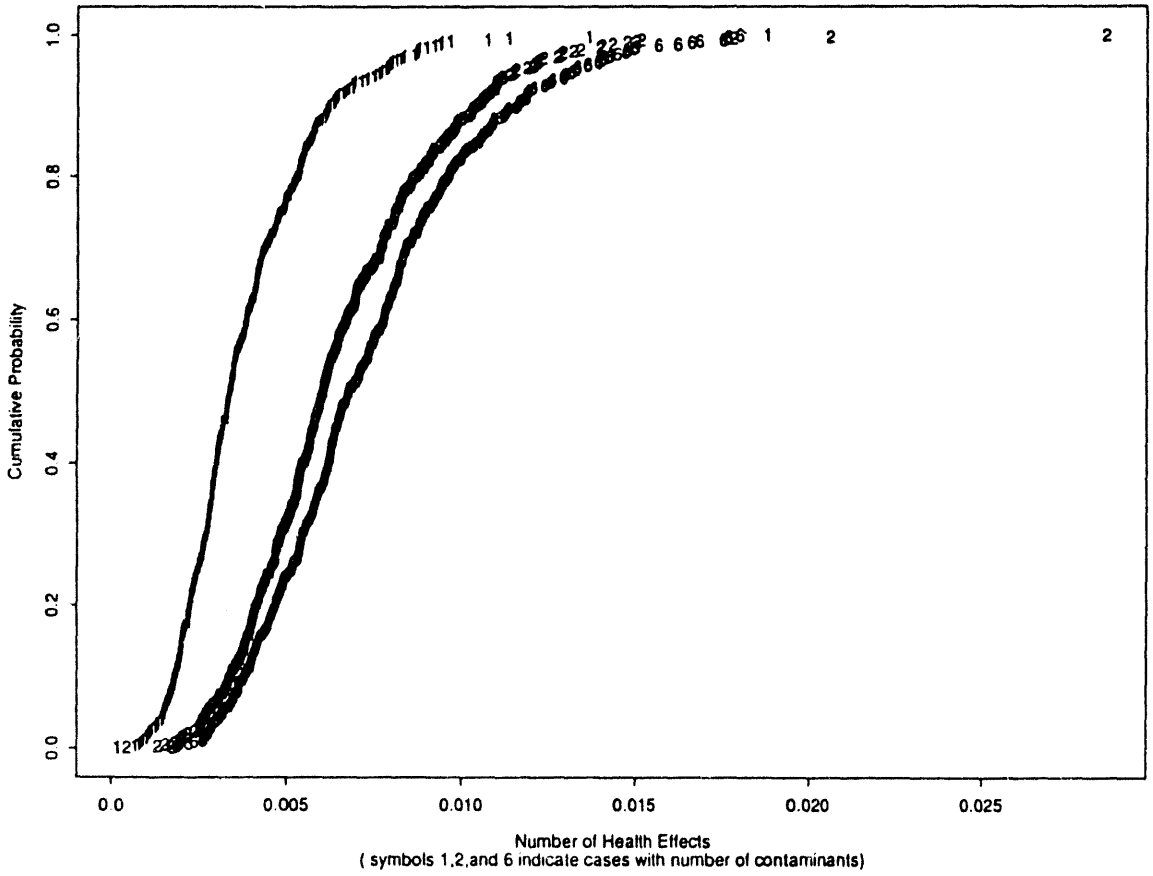

FIGURE 1. Cumulative Distribution Functions (CDF) for Hanford Cases

output was linear in the inputs, the miniumum and maximum number of health effects to be greater for the six-constituent run than the corresponding minimum and maximum output values from the two-constituent run. Accordingly, the endpoint values for the two-constituent case would be expected to exceed those of the primary NRDWL case (one constituent). Whereas, this outcome applies to the lower end of the distributions, the maximum value for the six-contaminant case was lowest (1.8E-2 health effects), being about equal to that of the primary case, and the maximum output for the two-contaminant run exceeded the other maxima by about 60% (2.7E-2 health effects). The inputs yielding the maximum for each of the cases were examined. By reducing saturated zone thickness (WZTHICK) and saturated zone transverse dispersion (WZTDISP) to the corresponding levels found in the two-constituent case, the six-constituent output increased to about 3.6E-2. Although for distributions with finite support, the minima and maxima are slower in their convergences than less extreme quantiles, it is apparent that this "jumping" of the maximum is largely attributable to the nonlinear nature of the output with respect to transverse dispersivity and depth of aquifer, which produces features characteristic of an extreme value distribution.

After consideration of all of the groundwater-related cases, it is apparent that the significance of input parameters not only depends on their base-case (e.g., mean) values, but also on the values of other input parameters for the same run. Thus a complete understanding of the degree of influence of an input parameter would be more easily obtained by considering the interaction, within the environmental model, between that input and other inputs. This interaction can be quantified by adding to the regression model additional "cross-product" terms between parameters with interactive potential (see Draper et al. 1981). Because the partial R-Square values relating to the coefficients of these interaction terms would not be expected to be as high as those for the "main effects," the results for the interaction terms should be examined carefully.

4.2 STABILITY OF REGRESSION RESULTS FOR THE HANFORD NRDWL CASE

Because for the Hanford cases there was some potential for instability of the (outlier-sensitive) least-squares regression results, ten additional

series of 500 runs were made for the six-contaminant case to assess the extent of this instability. A stepwise selection of the influential inputs was made after each series of runs, and after the completion of all the series, the sample distributions of the partial R-Squares were obtained. Using notched boxplots, these 10-sample distributions of the partial R-Squares for the significant regression coefficients are summarized in Figure 2. The interpretation of the notched boxplot is as follows: the middle horizontal line within the box is the sample median, the lower and upper horizontal lines denote the 25th and 75th percentiles, respectively, and the length of the "whisker" is the minimum of 1.5 times the length of the box or the distance between the end of the box and the lowest or highest data value. Extreme data values are identified with an asterisk. The width of the notch is an approximate 95% confidence interval on the median and a box having "ears," at the top (bottom)

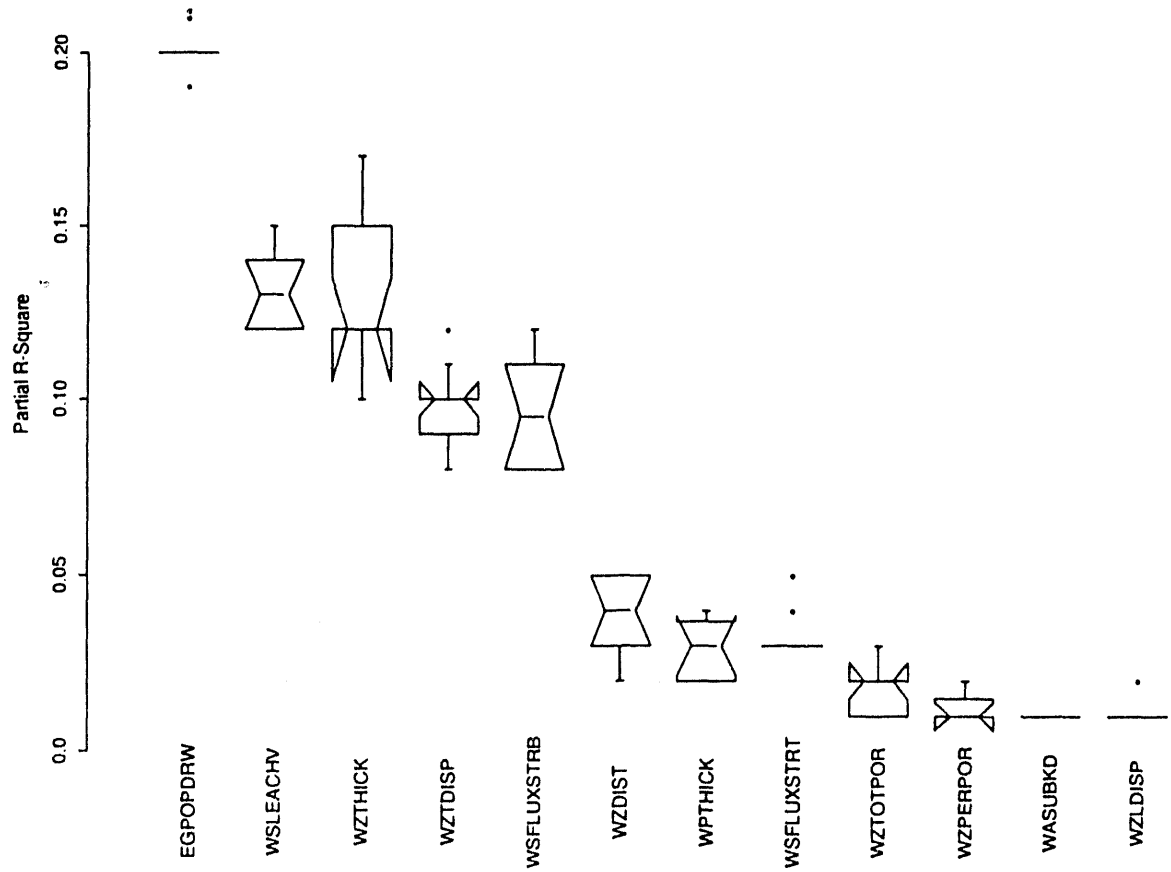

FIGURE 2. Distributions of Partial R-Squares from Regressing on 10 Independent Sites

indicates that the upper (lower) confidence limit is more distant from the median than is the 75th (25th) percentile. By doing pairwise comparisons of notchs between boxes (declaring insignificance for overlapping notches), informal tests between the medians can be made, each being approximately equivalent to tests on differences of medians, but with a higher false-reject error rate on equal medians than the rate associated with a more formal test.

Note that in all cases, the population size (EGPOPDRW) had the highest partial R-Square values, and the confidence interval for the median partial R-Square is "shrunk" to the estimated median value. This result is expected because, holding all other inputs constant, the relationship between the number of health effects and population size is linear. Often the ordering of the leach rate (WSLEACHV) and the saturated zone thickness (WZTHICK) was interchanged, as was the ordering of the benzene flux (WSFLUXSTRB) and the saturated zone transverse dispersivity (WZTDISP). Some of the remaining significant input parameters exhibited similar exchanges of ordering of R-squares. The input variables identified in Figure 2 represent the largest list of influential parameters where, for display purposes, an influential variable was one having a partial R-Square greater than 0.01. For some run results the smallest coefficients from another run were eliminated during the stepwise process.

The foregoing results for the Hanford NRDWL six-contaminant indicate that, for this case, while 1) 500 iterations are not sufficient to stabilize the exact ordering of the influential variables, 2) the majority of the influential variables can be identified, and their general ordering of importance can be characterized in 500 iterations.

4.3 STABILITY OF UPPER PERCENTILES FOR THE HANFORD NRDWL CASE

Using the output results obtained from doing the ten series of 500 runs, sampling distributions of the 90th and 95th through 100th percentiles were assessed. These distributions were obtained by repeated (100 times) random selection of a series of 500 results from the total series of 5000, and tabulating each of the above statistics. Assuming that sampling from the overall

series of 5000 is approximately equal to sampling from the underlying distribution, sampling was done with replacement for each individual result. Figure 3 illustrates the smoothed distributions of the 500-sample quantiles. Note that the variability of these quantiles increases with percentage, the maximum (100th percentile) being the most variable. The relative variabilities of these statistics (expressed in terms of 4 standard deviations divided by the sample mean) range from 0.13 for the 90th percentile to over 0.5 for the 99th and 100th percentiles.

There are methods for diagnosing the influence on least-squares regression coefficients of both extreme output and input values (Hocking et al. 1983). Although these methods were not employed in this analysis, both the considerable variability of the uppermost quantiles and the apparent nonlinear response of the output with selected changes in transverse dispersivity and aquifer thickness provide evidence that this nonlinearity is the cause of the instability of the partial R-Squares that is seen in Figure 2 for these inputs.

Based upon the above results, the conclusions for the Hanford cases are 1) the instabilities in the partial R-Square values for transverse dispersivity and aquifer thickness are attributable to the occasional nonlinear responses in the output to changes in these inputs, and 2) for a series of 500 runs, these nonlinear responses induce a considerable degree of uncertainty in the 90% and higher quantiles.

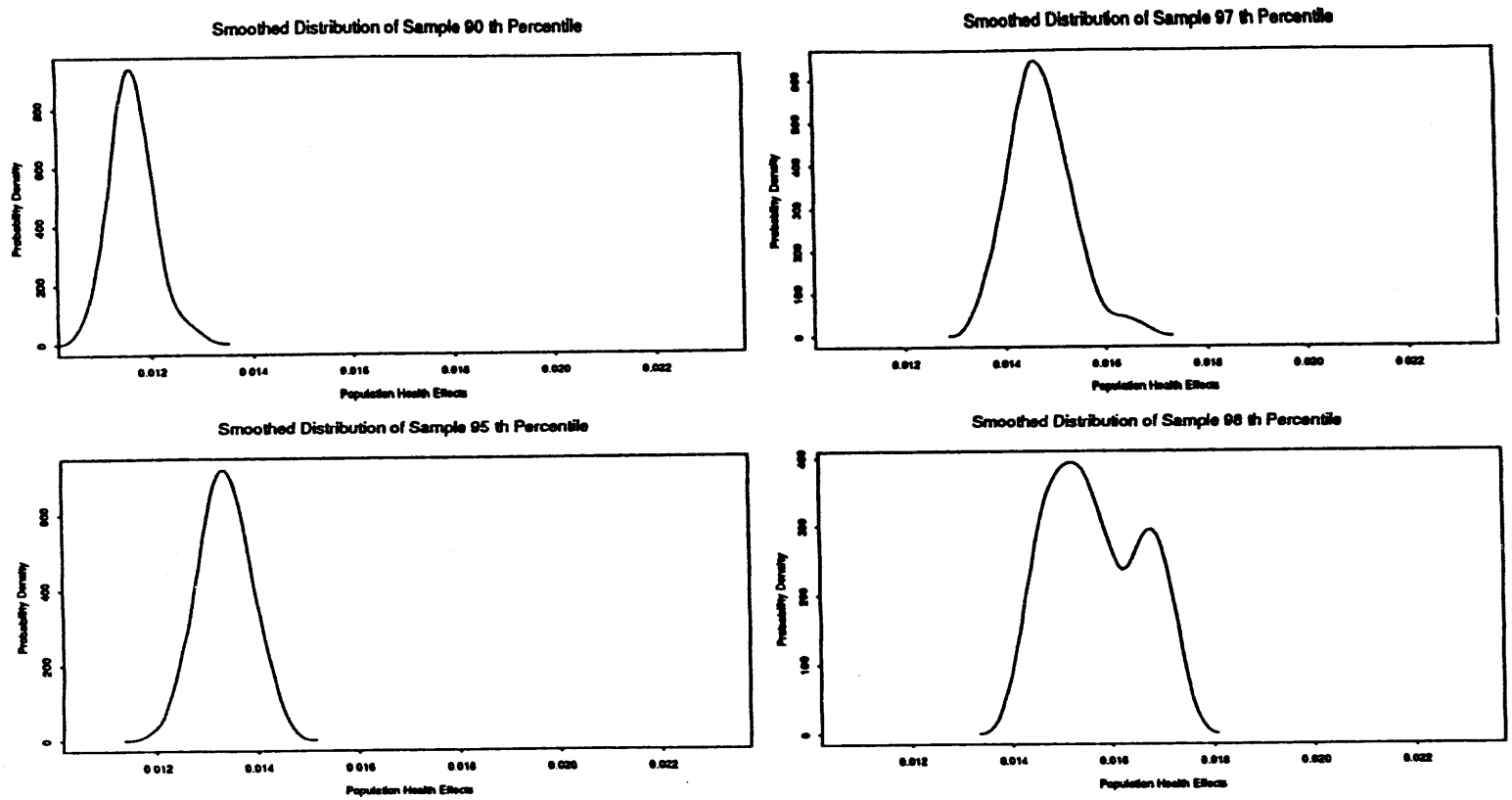

FIGURE 3. Statistical Distributions of Upper Quantiles Computed from 500 Runs

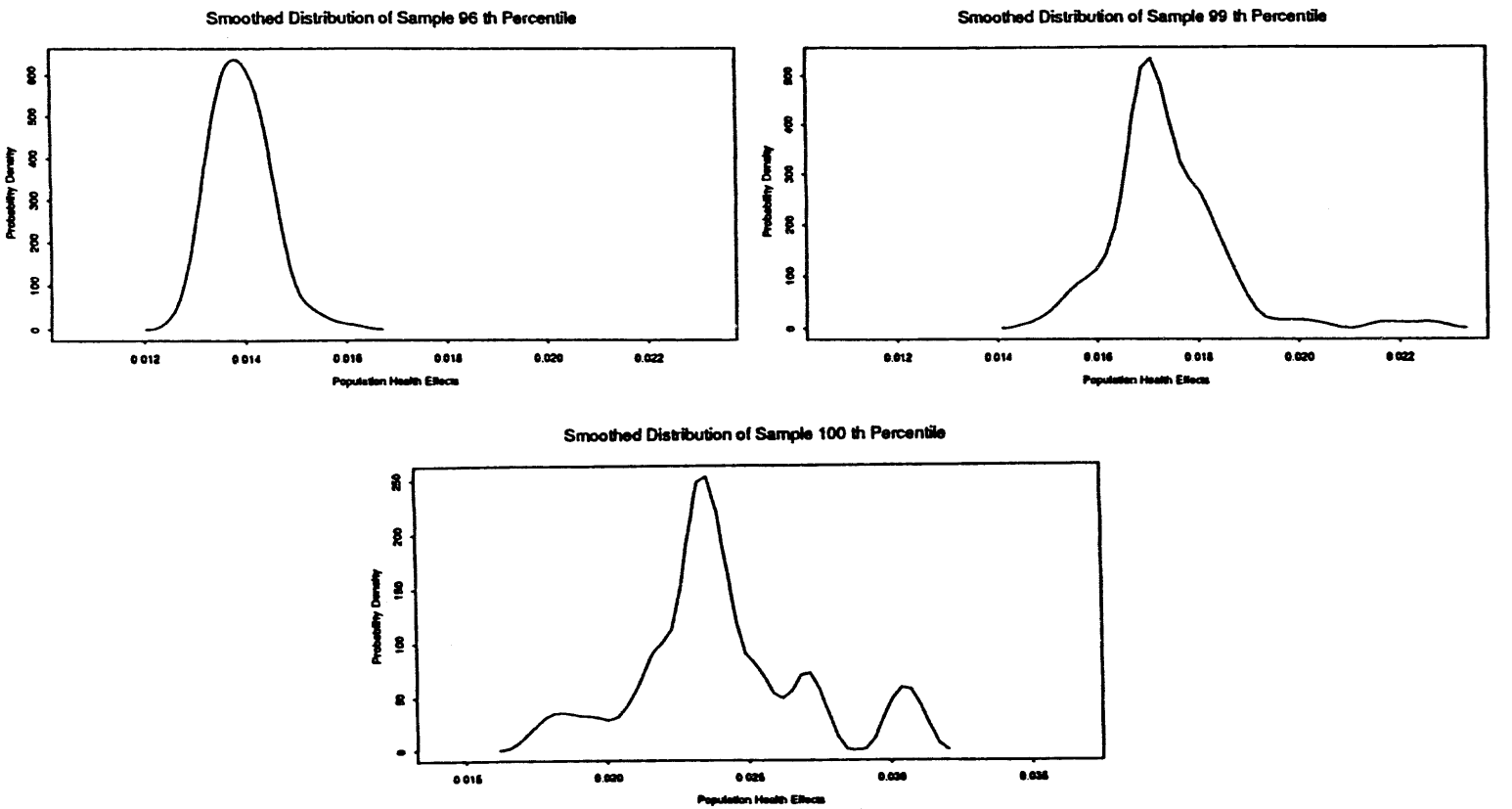

FIGURE 3. (contd)

5.0 CONCLUSIONS

In general, the results of any sensitivity analysis will be dependent on the values and ranges of the input variables and which type of model is used to fit to the output data (e.g., a curvilinear surface could have been used in lieu of a planar one). Therefore, we emphasize that the sensitivity results given above should be interpreted within the context of the input base case values ranges used and the plane regression model used for representing the output response.

Also, the assessment of sensitivity of the model is based entirely on the input values. Because model input-output linkages are actually being assessed rather than logical or physical relationships, it is possible to overstate or understate the actual (physical) sensitivity of the output to a given input. This is an artifact of the model being used.

The results depend on the relative magnitude of ranges assumed for each variable. The ranges were selected for each parameter to represent a maximum feasible range of expected variation so that the importance would reflect model sensitivity over a range representing the maximum normal resolution of that parameter. For most input parameters, the ranges used in this sensitivity study will be adequate for determining the important parameters over the range of values encountered for the sites examined.

The sensitivity of the number of health effects to various parameters is known to vary widely from situation to situation. Often this variation occurs with different magnitudes of the parameter. The results from this study represent only the important variables for the average sensitivity associated with a particular situation based on assumed ranges of variation of input values. Different parameters can become important as the situation changes (i.e., different site) or as the ranges for input values change.

Because the influence of one input is often dependent upon the values of other inputs, for models having a significantly good fit (having a full model R-Square above about 0.8), interaction terms between parameters having synergistic potential should be included in sensitivity analyses, so observed sensitivities can be verified and that their causes can be explained.

For scenarios involving overland transport, the results from both this study and from those of Doctor et al. (1990) indicate that the standard multiple linear regression model does poorly in describing the output response to changes in the inputs. This inadequacy of model fit is felt to be largely attributable to the step functional response, under a set of conditions, of health effects to changes in variables (such as average monthly temperature) above or below some threshold value. For future sensitivity studies, a consideration should be made to modify the multiple linear model to reflect such discrete changes in the output. The regression model could include indicator or "dummy" variables that change the intercept of the regression model under conditions that produce the "jumps" in the output, thus improving both the "explainability" of the model and the interpretation of the results for the remaining continuous variables.

From this and other studies, it is known that for cases involving groundwater transport, significant nonlinear changes in the number of health effects can be induced by 1) changes in K_d values near zero for highly radioactive contaminants or changes in larger K_d values for all other contaminants, and 2) changes in dispersivities and aquifer thickness. From this study, we note that in such cases, the statistical distribution of the output can be similar to an extreme-value distribution in that large values can infrequently be produced which are several standard deviations from the mean. These large values cause some instability in the ordering of importance of the sensitive variables.

For future sensitivity analysis involving overland transport, we recommend that the regression model be modified to incorporate discrete jumps in the output.

For future sensitivity analyses of groundwater cases, we recommend

- the K_d, dispersivity, and aquifer thickness parameters should be considered as possible independent variables in all cases involving groundwater transport
- interaction terms between variables with potential synergisms should be considered in the regression model to support the validation of influential variables.

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