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Necessity of uncertainty analyses in risk assessment

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Abstract

The potential risks to human health associated with contaminant discharges from the waste area groupings (WAGs) at Oak Ridge National Laboratory (ORNL) have been estimated and ranked. Human health risks are estimated using selected exposure relationships for human receptors and local contaminant concentrations associated with individual waste sites. The ranking of the waste areas using deterministic methods yields disparate rankings because risk assessment results are very user-specific and depend on the user's selection of models, parameter values and uncertainty about important model parameters. Rankings obtained without an uncertainty analysis are unreliable because of large inconsistencies in the amount of conservatism used to quantify model parameters for specific contaminant and exposure pathways. Through the use of uncertainty analyses on the risk assessment of the waste sites, it was possible to rank the waste areas in a more reliable manner. The WAGs are ranked based on potential human health risk in the following order: (1) WAG 1; (2) WAG 2, 6, and 7, and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8. The dominant pathway contributing to human health risks is through fish ingestion, while the contaminant contributing the greatest risk over all exposure pathways considered is ^{137}Cs.

1. Introduction

In recent years, concern has increased about the potential for adverse health effects and impacts on the environment due to contaminant releases from waste sites, and numerous regulations regarding environmental contaminants have been promulgated. Contaminated areas across the country have been identified, and although remediation of all contaminated areas may be desirable, it is not practical to achieve this goal for all areas simulataneously. It has become necessary to evaluate the contaminated sites and determine which areas pose the most immediate or greatest potential threat to the environment, and some objective means of ranking the sites must be used. Potential impacts

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to human health and the environment can be evaluated through risk assessment calculations. Quantitative estimates of risk provide a means for ranking or prioritizing contaminated areas for investigation and remediation.

In the past, risk assessment calculations have generally been conducted using deterministic approaches. These approaches use constant model parameter values which are subjectively selected on a case by case basis by the risk assessor. In some cases default parameter values are used by individuals conducting risk assessment calculations and these values may not be realistic for the particular situation under consideration. It has become increasingly apparent that deterministic calculations are not appropriate in risk assessment due to the large uncertainty associated with models and their parameter values. This shortcoming of deterministic calculations has been recognized in recent years, and greater attention is being paid to evaluating and quantifying the uncertainty in parameters used in the risk assessments (i.e. [1, 2]).

We present one case study of radionuclide risk at Oak Ridge National Laboratory (ORNL) for which deterministic calculations were made and then followed by a more thorough evaluation of the site through the use of uncertainty analyses. The method discussed here involves a screening approach which uses human health risk as an end point. Human health risks are estimated using selected exposure relationships for human receptors and local contaminant concentrations associated with individual waste sites. This work demonstrates the importance of conducting uncertainty analyses to rank the important contributions to health risk and to rank the risk associated with each contaminated site. Substantial uncertainty in model parameters dictates that deterministic calculations are not reliable other than as an initial screening exercise to identify high versus low priority situations.

2. The Oak Ridge Reservation

Operations and waste disposal activities began at the Oak Ridge National Laboratory (ORNL) in the 1940s, and these activities have introduced a variety of wastes into the environment. Several Waste Area Groupings (WAGs) on the Oak Ridge Reservation (ORR) contain and release contaminants to the environment. Four radionuclides were selected for ranking of ORNL WAGs in this work because these contaminants are believed to be among the most important at all ORNL WAGs. The contaminants selected were ^{60}Co, ^{137}Cs, ^{90}Sr, and ^{3}H, and the assessment end point was the maximally exposed individual.

It is believed that the majority of contaminant discharge at ORNL is from runoff and groundwater to on-site surface waters [3–5]. Hence, measured concentrations and flow rates of on-site surface waters are used to calculate current risks associated with contaminant discharge to surface waters from each WAG. The ORNL waste sites are then ranked based on potential risk to human health. Currently, EPA Superfund Guidance [6] indicates that a reasonable estimate of the maximally exposed individual is to be targeted in risk assessment calculations. Consequently, this work focuses on the hypothetical maximally exposed individual, assuming that current fences would be removed and members of the public would be permitted access to the contaminated sites. Currently, all sites considered in this study are off-limits to the public.

3. Model parameters and formulation

It is assumed that all future human exposure to contaminants is through surface water use and contact (i.e., no water wells are assumed to be drilled). ORNL contaminant concentration and flow rate data from surface water monitoring stations are used in this procedure ([7, 8]; see Fig. 1 for locations). Potential risks associated with surface water contamination are modeled, and the following pathways are considered: vegetable, fish, beef, water, and milk consumption; inadvertent water ingestion; shoreline exposure; swimming; boating; and bathing.

The risk assessment model formulation and parameters used in the study are those recommended by the National Council on Radiation Protection (NCRP) for screening-level assessments [9]. Generic screening calculations are recommended when site-specific data are not available. The current screening approach, referred to as ORNL/ESD (Oak Ridge National Laboratory/Environmental Sciences Division), uses models and methods recommended by the NCRP and the International Atomic Energy Agency (IAEA; [9, 10]) which were derived by national and international committees for use in the absence of site-specific data. The recommended parameter values were evaluated for applicability to local conditions. As a result, some parameters were adjusted to more accurately reflect local conditions. This ORNL/ESD method is a screening tool used to determine which contaminants and waste sites may be potentially important and which are clearly unimportant.

The ORNL/ESD rankings are based on a 30-year exposure period for the maximally exposed individual. The 30-year value is conservative given that individuals in the population are unlikely to live in the same locality for an entire 30-year period, with most moving from a location every nine years [11]. Ultimately, the ranking scheme is based on calculated risks, and the risks over all contaminants and all exposure pathways are summed to determine the relative health risk associated with potential exposure to each WAG's contaminants. It is assumed that all of the equations used in the formulations adequately represent the conditions and variables leading to the calculated risks.

4. Deterministic risk calculations

An initial ranking of ORNL waste sites was based on the results of the Multimedia Environmental Pollutant System (MEPAS) model [12, 13]. This

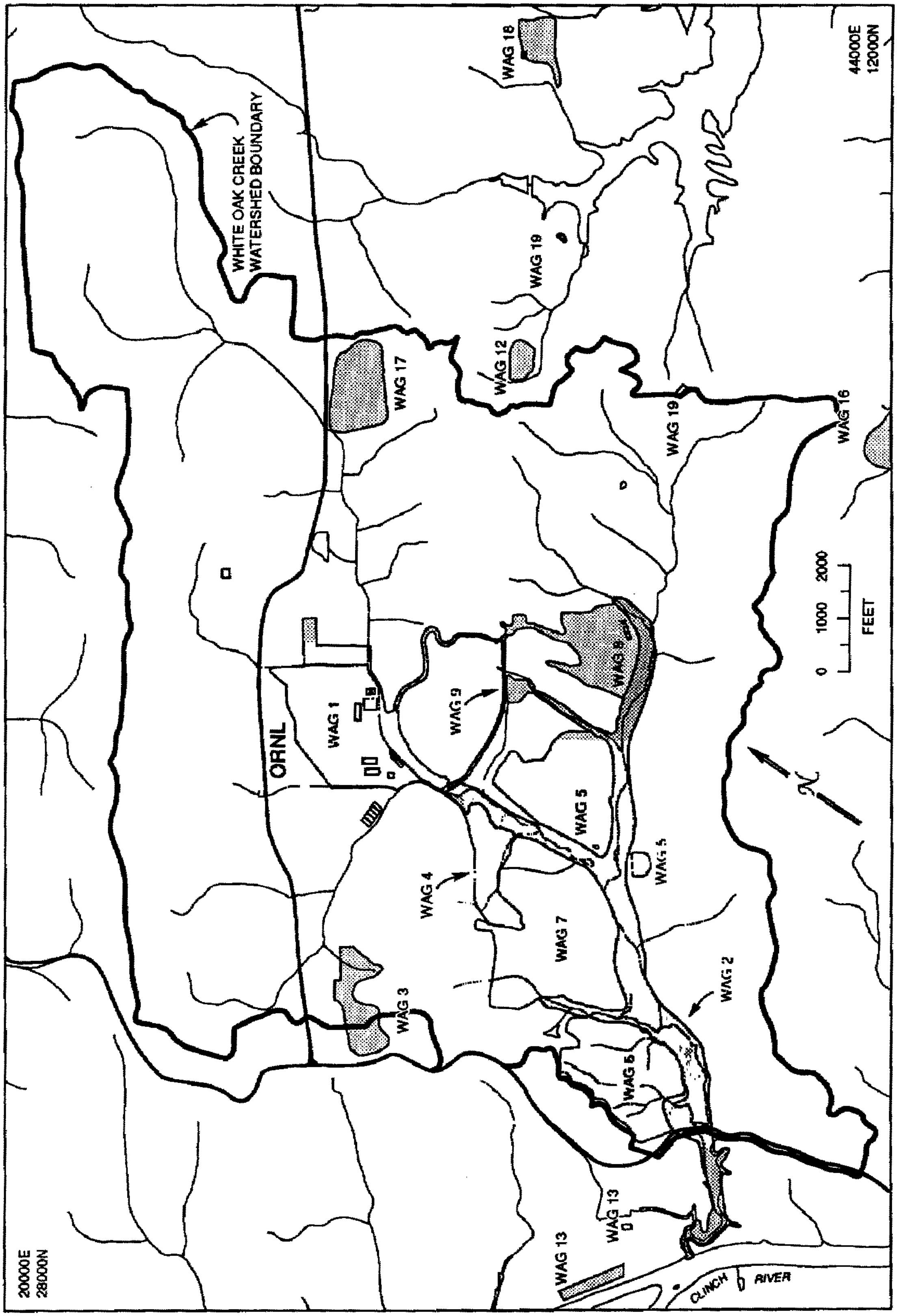

Fig. 1. Locations of the WAGs and surface water monitoring stations discussed in this report.

TABLE 1

Ranking of ORNL WAGs[a]

Rank No.	Original MEPAS (WAG No.)	MEPAS with time weighting (WAG No.)	MEPAS without time weighting (WAG No.)	ORNL/ESD (WAG No.)
I	5	4	1	1
II	7	1	4	4
III	4	9	5	5
IV	6	3	9	2[b]
V	1	6	3	6[b]
VI	2	5	2[b]	7[b]
VII	9	2	6[b]	9
VIII	3	7	7[b]	8
IX	–	8	8	3

[a] Rankings are receptor independent. Future tank releases were not considered in the original MEPAS formulation, nor in the ORNL/ESD formulation, for WAGs 1 and 5. Hence, future risks associated with WAGs 1 and 5 may be higher than those calculated in this work.
[b] WAGs 2, 6, and 7 have the same calculated health risks associated with them.

model includes transport pathway and exposure pathway modeling and is used to rank potential risks to human health. The rankings are based on a risk related number identified as the Hazard Potential Index (HPI). The ranking effort was directed by DOE's Office of Environmental Audit and technical support was provided by NUS Corporation, Washington, DC [14].

MEPAS calculations assume a 70-year lifetime exposure to contaminants. Both the MEPAS and ORNL/ESD methods utilize similar equations for exposure, and all calculations were made on a spreadsheet [15]. The WAGs have been reranked based on these calculations and are compared with the original MEPAS rankings in Table 1. The second column of Table 1 shows the ranking of the sites using the HPI and time weighting of the results (time weighting is a subjective estimate of the expected time over which the waste area will contribute contaminants to the environment). The third and fourth columns show the rankings when the MEPAS equations were used with more site-specific parameter values, both with and without time weighting, while the last column shows the results of the ORNL/ESD method. Table 1 dramatically illustrates that a variety of results can be obtained when deterministic calculations are made because the choice of risk assessment parameters and models is highly subjective. Clearly one waste area cannot be considered a greater risk to human health than another when a deterministic calculation is made and no indication is given about the uncertainty associated with the calculation.

The importance of exposure pathways also varies when different methods and parameter values are used. Table 2 lists the order of importance of each pathway in determining health risks. Both versions of the MEPAS formulation,

TABLE 2

Listing of pathways in order of importance in estimating health risks

Rank	ORNL/ESD	MEPAS	
		time weighting	no time weighting
1	Shoreline	Vegetable consumption	Vegetable consumption
2	Fish consumption	Fish consumption	Fish consumption
3	Beef consumption	Drinking water	Drinking water
4	Milk consumption	Beef consumption	Beef consumption
5	Drinking water	Milk consumption	Milk consumption
6	Vegetable consumption	Shoreline exposure	Shoreline exposure
7	Soil irrigation[a]	Water ingestion[b]	Water ingestion[b]
8	Water ingestion[b]	Swimming	Swimming
9	Swimming	Boating	Boating
10	Boating	Bathing	Bathing
11	Bathing		

[a] Soil irrigation refers to the health risk associated with workers in fields irrigated with contaminated water. This pathway is not considered in MEPAS.

[b] Inadvertent water ingestion during bathing.

with and without time weighting, indicate the same order of importance, with vegetable consumption being the dominant pathway. The higher risk associated with vegetable consumption may result from a larger irrigation flux used by MEPAS ($1200\,\mathrm{L\,m^{-2}\,year^{-1}}$ compared with a more site-specific, yet conservatively estimated value of $240\,\mathrm{L\,m^{-2}\,year^{-1}}$ employed in the ORNL/ESD formulation [15, 16]). Likewise, a higher contaminant accumulation rate in sediments causes the shoreline exposure pathway to be dominant in ORNL/ESD calculations.

5. Risk using uncertainty analysis

The variability in calculated health risks depends in large part on the model parameter values selected; hence, an analysis was conducted to determine the uncertainty associated with these calculated risks based on uncertainty in model parameters. Large uncertainties are associated with many model parameters, such as transfer factors, dose conversion factors, consumption rates, exposure durations, etc. Any rankings obtained without an uncertainty analysis are unreliable because of large inconsistencies in the amount of conservatism used to quantify model parameters for specific contaminant and exposure pathways. In this work, the uncertainty about the model parameters is propagated through the risk assessment calculations to determine if the risks associated with the particular waste areas can be distinguished (i.e., if they differ significantly).

Based on data collected and studies conducted on the Oak Ridge Reservation (i.e. [3–5, 17–19]), long-term (30 year) contaminant releases from the WAGs are expected to lie within the range of the current, measured mean value for each contaminant in surface water, ±30%. Hence, it is believed that the true, yet unknown, values of concentration will lie within the specified range of uncertainty for a period of ≈30 years [16].

Uncertainty in the parameters used to estimate potential exposure and risk are based on professional judgement and previously published uncertainty analyses [20]. The uncertainty in model parameters associated with aquatic and terrestrial food chain transport models were investigated [20]. Because ^{60}Co produced substantially lower health risks than either ^{137}Cs or ^{90}Sr in the initial deterministic screening calculations, ^{60}Co is not considered in the uncertainty analysis portion of this work.

In this analysis, the uncertainty associated with a model parameter is represented as a probability distribution. Each distribution represents subjective degrees of belief that a true, but as yet unknown, value will not be exceeded by any given value in the distribution. Table 3 lists distributions used in the uncertainty analyses for each parameter associated with the risk assessment modeling. Note that parameters associated with swimming and boating are not included in the table. These pathways are neglected in the uncertainty analysis because they were found to provide an insignificant contribution to the overall risk (see Table 2).

In the uncertainty analysis, risk assessment parameters were allowed to vary according to the distributions described in Table 3. Each distribution was specified in a spreadsheet program (Crystal Ball; [21]), and the Latin-Hypercube method was used to vary parameter values throughout their distributions over 100 iterations. The purpose of conducting the uncertainty analyses was to determine if conclusive rankings of the waste sites could be made, and if so, to determine the rankings of the WAGs.

In Table 3, the exposure duration is assumed constant. In a preliminary uncertainty analysis, the exposure duration was assumed to have a logtriangular distribution with a minimum of 5 years, a maximum of 70 years, and a mean of 9 years [20]. When the exposure duration was allowed to vary in this manner, it accounted for the majority of the uncertainty in calculated risks and uncertainty in ranking of the WAGs.

Results of the present uncertainty analyses assuming an exposure duration of 30 years, were used to investigate the correlation between the calculated health risks, contaminants and potential pathways of human exposure. The uncertainty analysis indicates that the dominant contaminant contributing to potential health risks over all pathways is ^{137}Cs, with the greatest ^{137}Cs contribution to risk acquired through fish ingestion. The two pathways contributing most to ^{90}Sr attributable risks are the fish and water ingestion pathways.

A large portion of the uncertainty of calculated risk at any given WAG can be attributed to variables in the drinking water pathway and uncertainty in the

TABLE 3

Distribution about risk assessment parameters assumed for uncertainty analysis

Human usage	Distribution type	Geometric std. dev.	Min	Mean	Max	Ref.
Exposure duration, y	C			30		a
Exposure						
Shoreline, h y^{-1}	LTR		25	100	2000	a
Ground from irrigation, h y^{-1}	LTR		100	1000[c]	8000	a
Human consumption						
Drinking water, L y^{-1}	TR		91.2	438[c]	730	a
Fish, kg y^{-1}	LTR		4	11	30	d
Beef, kg y^{-1}	LN	1.65		94		d
Milk, L y^{-1}	LN	2.23		95		d
Leafy vegetable, kg y^{-1}	TLN	1.62	0	18	55	d
Nonleafy vegetable, kg y^{-1}	TLN	2.16	0	45	540	d
Vegetation						
Irrigation flux, mm d^{-1}	LN	1.6		0.67		a
Veg. weathering constant, d^{-1}						a
Leafy	LN	1.68	8.7×10^{-3}	5.7×10^{-2}	3.5×10^{-1}	d
Nonleafy	LN	1.77		3.4×10^{-2}		d
Pasture	TLN	1.54	8.7×10^{-3}	5.7×10^{-2}	3.5×10^{-1}	d
Soil leaching constant, d^{-1}						
^{90}Sr	TLN	7.4	1.1×10^{-7}	6.7×10^{-5}	1.2×10^{-2}	d
^{137}Cs	TLN	6.7	4×10^{-7}	1.7×10^{-6}	8×10^{-4}	d
^{137}Cs flux to sediments, l $m^{-2}d^{-1}$	LTR		10	100	400	a
Build-up time in sediments, d	U		1.1×10^{3}	6.05×10^{3}	1.1×10^{4}	a
Growing period, d						
Leafy	TR		20	75	120	d
Nonleafy	TR		60	100	180	d
Pasture	TR		15	30	200	d

r/Y, $m^2 kg^{-1}$						
Leafy	LN	1.82		0.1		a
Nonleafy	LN	2.15		6.02×10^{-2}		a
Pasture	TLN	1.55	3.01×10^{-1}	1.8	9.97	a
Soil density, $kg m^{-2}$	LN	1.12		213		d
Soil–plant transfer factor						
Leafy						
^{90}Sr	TLN	3.3	7×10^{-3}	0.33	2.4	d
^{137}Cs	TLN	4.5	1×10^{-4}	5.5×10^{-3}	8×10^{-2}	d
Nonleafy						
^{90}Sr	TLN	4.5	8×10^{-4}	8.5×10^{-2}	3.4	d
^{137}Cs	TLN	4.5	1×10^{-5}	5.3×10^{-3}	1×10^{-1}	d
Pasture						
^{90}Sr	TLN	3.42	6×10^{-2}	1.4	46	d
^{137}Cs	LN	3.82		4.4×10^{-2}		d
Dairy/beef						
Fraction of feed contaminated	C			1^b		a
Fraction water contaminated	C			1^b		a
Dairy cows						
Feed consumption rate, $kg d^{-1}$	TN	2.6	4.0	11.0	25.0	d
Water consumption rate, $L d^{-1}$	LN	1.6		60^b		a
Veg-milk factor, $d L^{-1}$						
^{90}Sr	TLN	1.62	2×10^{-4}	1.2×10^{-3}	8×10^{-2}	d
^{137}Cs	LN	1.79		6.7×10^{-3}		d
Beef cows						
Feed consumption rate, $kg d^{-1}$	TN	2.0	1.6	8.3	18.0	d
Water consumption rate, $L d^{-1}$	LN	1.6		50^b		a
Veg-meat factor, $d kg^{-1}$						
^{90}Sr	TLN	3.3	4×10^{-5}	5.8×10^{-4}	4×10^{-3}	d
^{137}Cs	TLN	2.0	3×10^{-3}	2.1×10^{-2}	2×10^{-1}	d
Other						
Shoreline width factor	U		5×10^{-2}	1.75×10^{-1}	3.0×10^{-1}	a
Fraction of body water made of ^3H contaminated water	LU		0.02		0.33	a

(continued)

TABLE 3. Continued

Human usage	Distribution type	Geometric std. dev.	Min	Mean	Max	Ref.
Internal dose conversion factor ($Sv\ Bq^{-1}$)						
^{90}Sr	LN	1.32		1.38×10^{-8}		d
^{137}Cs	LN	1.32		1.38×10^{-8}		d
^{3}H dose rate factor, $Sv\ y^{-1}$ per $Bq\ L^{-1}$	LN	1.29		2.5×10^{-8}		a
External dose conversion factor ($Sv\ d^{-1}\ Bq^{-1}\ m^{2}$)						
Soil contact ^{137}Cs	LN	1.2		4.61×10^{-11}[b]		a
Soil contact ^{90}Sr	LN		1.2	4.2×10^{-13}[b]		a
Risk factor, Sv^{-1}	LN		2.0	7.2×10^{-2}		a
Fish BAF						
^{90}Sr	LN		6.0	11		d
^{137}Cs	LN		2.36	400		d

[a] Professional judgement of the authors.

[b] Mean value assumed equal to value selected in ORNL/ESD formulation.

[c] Mode.

[d] Ref. [20].

assumed value of the risk factor (factor used to convert a 30 year accumulated radiological effective dose equivalent into a quantitative estimate of excess cancer incidence over a human lifetime). A lesser amount of the calculated total WAG risk is associated with the hypothetical milk consumption pathway and shoreline exposure pathway. The importance of each parameter in the drinking water pathway was investigated to evaluate pathway sensitivity to parameter uncertainty. The analysis indicates that the risk associated with drinking contaminated water is best correlated with the risk factor compared with risk associated with other model parameters.

Other pathways were also investigated, including milk consumption, shoreline exposure, and fish consumption. The risk factor is important in determining the overall risk associated with the shoreline exposure and fish consumption pathways but is less important in the milk consumption pathway, which is a function of a greater number of parameters than are the shoreline and fish consumption pathways. Uncertainty in contaminant concentration in general produces little uncertainty in risks calculated for any pathway, yet the magnitude of concentration associated with each WAG tends to dictate the ultimate rankings (i.e., a WAG with a higher contaminant concentration generally ranks above a WAG associated with lower contaminant concentrations).

To rank each WAG for its contribution to total risk, the total health risk attributed to each WAG was calculated for the 5th, mean, and 95th percentile. The overlap between the 5th and 95th percentiles of a WAG was assessed to distinguish between the overall ranking of the WAGs. Based on the comparisons from Fig. 2, two distinct groups can be identified, and one group, consisting of WAGs 1 through 7 and 9, can be confidently ranked above WAG 8. There is no overlap in the confidence intervals between the two groups, suggesting that the two groups can be confidently distinguished. Figure 3 presents an alternative graphical approach which can be used to determine if the error bounds on the individual WAG risks overlap, and the figure clearly illustrates large overlaps in calculated risks between waste areas. This figure also illustrates that WAG 1 contributes the majority of the overall risk associated with the 9 WAGs considered. Because WAG 8 has a substantially lower risk associated with it, WAG 8 results are not included on the plot.

The results of the uncertainty analysis conducted by allowing all model parameters to vary indicate that WAGs 2, 6, and 7 (combined) and WAG 4 are indistinguishable, as are WAGs 3, 5, and 9, which appear to contribute lower risks than do WAGs 2, 6, and 7 (combined) and WAG 4 (Fig. 2). WAG 1 may also be ranked slightly above WAGs 2, 6, and 7 (combined) and WAG 4.

Although there is significant overlap in the error bounds among the WAGs, it may still be possible to distinguish between them. Most parameters contributing to the uncertainty in the total risk at each WAG are common among all WAGs for the hypothetical receptor considered in this particular case study. Most notable among these parameters is the risk conversion factor for exposure to radionuclides. Holding these parameters constant to account for only the uncertainty in parameters unique to the risk assessment for a particular

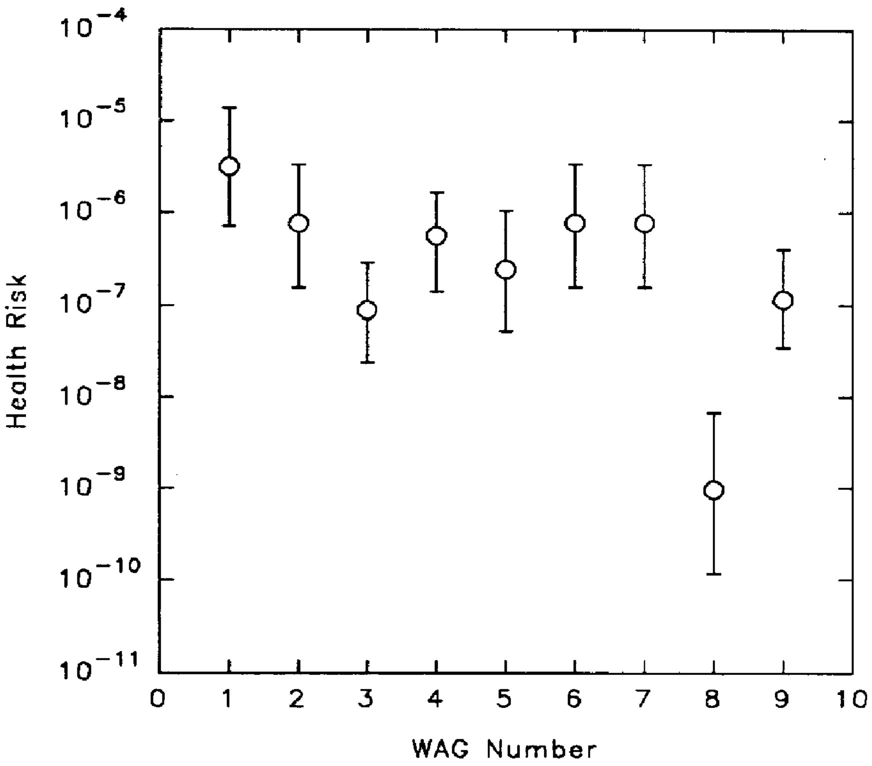

Fig. 2. Plot showing the total health risk attributable to each WAG and the associated uncertainty (error bars) about the calculated risks when all parameter values are allowed to vary. The plotted points are based on the 5th and 95th percentile values.

WAG would reduce the overall relative uncertainty for each WAG and thus decrease the extent to which the error bounds between WAGs would overlap.

The uncertainty in the rankings shown in Figs. 2 and 3 can be reduced in the current model because the same pathways and contaminants were modeled at all WAGs, and the uncertainty in calculated risks resulting from these factors should be the same among all WAGs. In the method in which the ranking was conducted, it may be reasonable to rank the WAGs based solely on the uncertainty in contaminant concentrations. Hence, additional calculations were made while holding model parameter values constant and allowing only the contaminant concentrations to vary through their distributions. The results of this new simulation are plotted in Fig. 4, where the error bars are located at the value of risk calculated for the 5th and 95th percentiles. WAG 8 is not included on this plot because it is clearly associated with a much lower risk than the other WAGs; hence, the vertical scales of Figs. 2 and 4 differ. These results suggest that the WAGs can be confidently ranked in the following order: (1) WAG 1; (2) WAGs 2, 6, and 7 (combined) and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8.

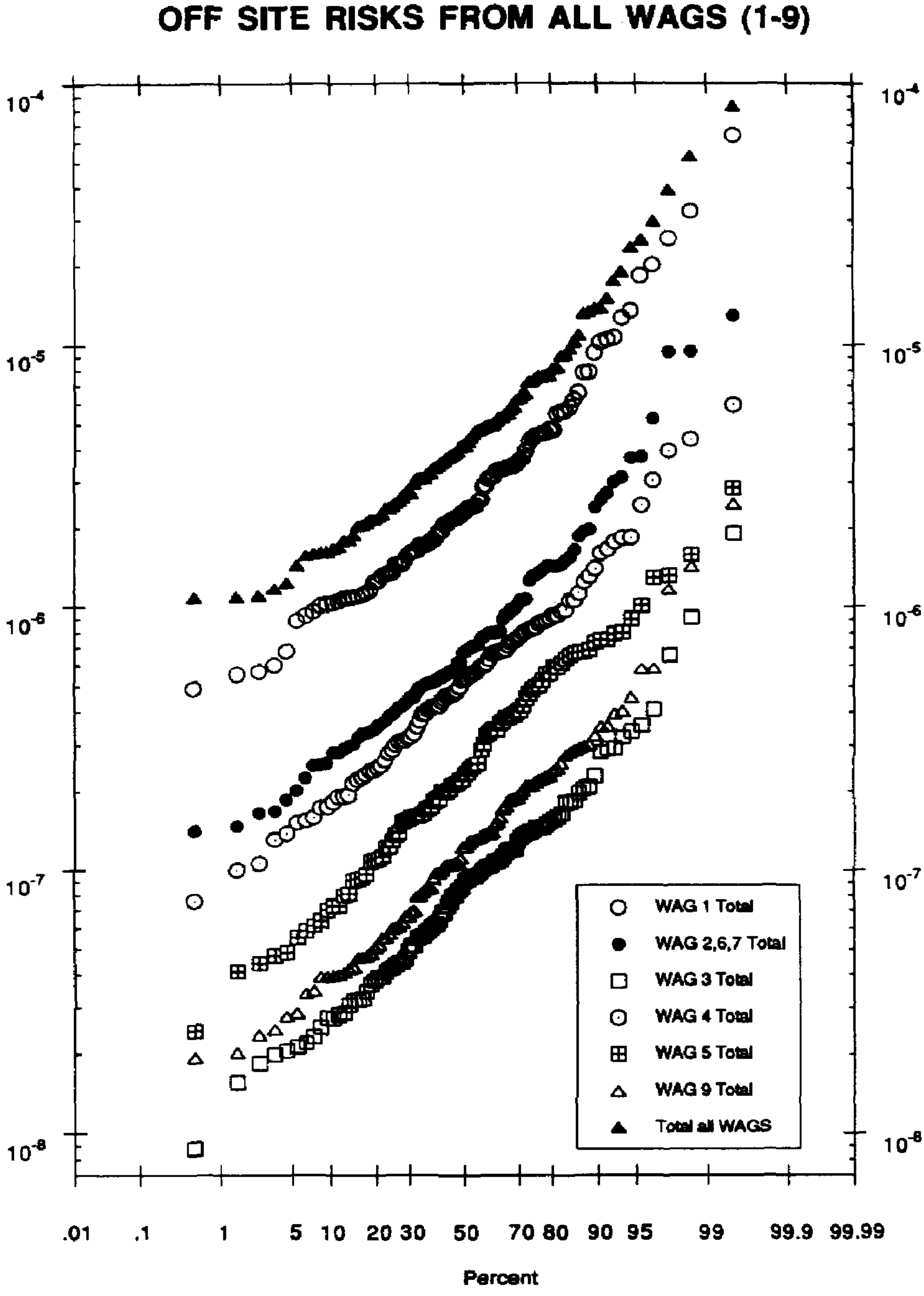

Fig. 3. Plot of individual WAG risks between the 1st and 99th percentile values.

If different contaminants were associated with each WAG, the uncertainty in parameter values would be different for the individual WAGs (i.e., uncertainty in the dose conversion factor for ^{137}Cs is different from that for PCBs). In this situation, the rankings would need to be based on the uncertainty bounds of those model parameters unique to the contaminants at each WAG

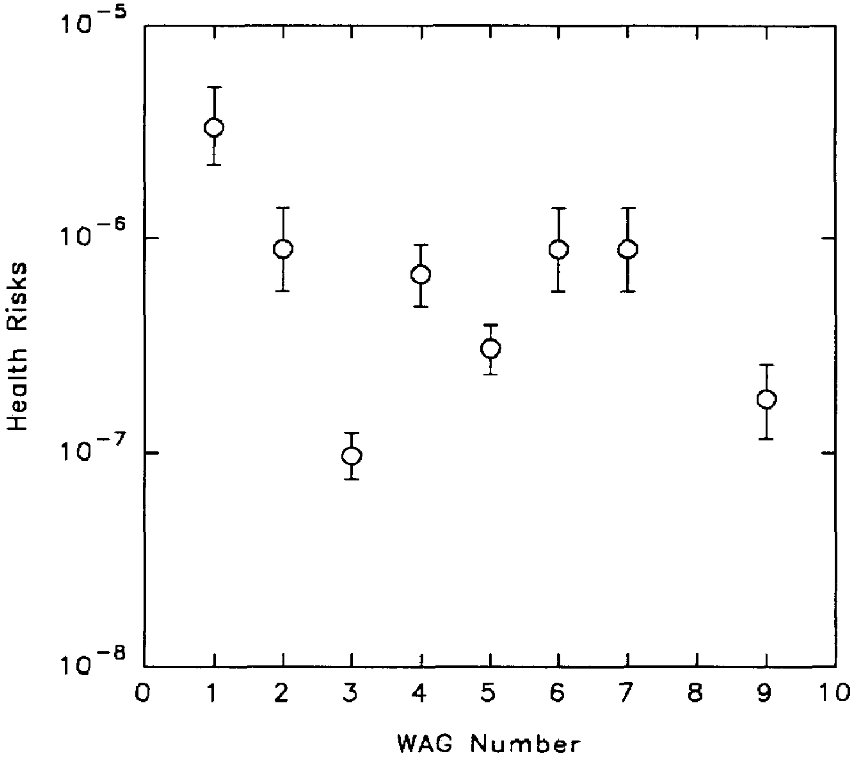

Fig. 4. Plot showing the total health risk attributable to each WAG and the associated uncertainty (error bars) about the calculated risks when only the concentration is allowed to vary. The plotted points are based on the 5th and 95th percentile values calculated in the simulation.

rather than only on the uncertainty in contaminant concentrations. Thus, rankings would be less definitive than they would if all WAGs were associated with the same contaminants and pathways.

6. Discussion and summary

The ranking of WAGs using the deterministic methods yields disparate rankings. The only agreement among the methods was found for WAGs 1 and 4, which were consistently ranked high. The differences in rankings of WAGs between the deterministic MEPAS and ORNL/ESD formulations are partly the result of different parameter values and models used and assumptions about the characteristics and locations of a hypothetically exposed individual.

A reliable ranking of the ORNL WAGs will not result from deterministic calculations that assume all parameters are constant. Both absolute and relative values of risk will depend on the models, parameters, and assumptions adopted (i.e., maximum exposure as an intruder enters a WAG when no fences are erected to surround the WAG), all of which are subjectively determined.

TABLE 4

Ranking of ORNL WAGs

Rank number	Current rankings[a] at WAGs			
	Original MEPAS (WAG No.)	MEPAS without time weighting (WAG No.)	ORNL/ESD (WAG No.)	ORNL/ESD uncert. analysis (WAG No.)
I	5	1	1	1
II	7	4	4	2, 6, 7[c,d]
III	4	5	5	4[d]
IV	6	9	2[b]	5
V	1	3	6[b]	9
VI	2	2[b]	7[b]	3
VII	9	6[b]	9	8
VIII	3	7[b]	8	
IX		8	3	

[a] Rankings are receptor independent.

[b] WAGs 2, 6, and 7 have the same calculated health risks associated with them because the same surface water concentrations are assigned to each of these WAGs.

[c] This represents the combined contribution from WAGs 2, 6, and 7.

[d] WAGs 2, 6, 7 (combined) and WAG 4 cannot be confidently distinguished.

The uncertainty analyses discussed were used to assist in the ranking of health risks attributed to individual WAGs. Table 4 lists the rankings of the WAGs for the original MEPAS formulation, the revised MEPAS formulation without time weighting, the ORNL/ESD screening model, and the risk assessment model with uncertainty analysis conducted by allowing only concentration to vary. All rankings made subsequent to the original MEPAS calculations are substantially different from the original MEPAS results.

Risk assessment results are very user-specific and depend on the user's selection of models, parameter values, and uncertainty about important parameters. Thus the same modeling results cannot be guaranteed when different individuals conduct risk assessments, even when the same, or similar, models are used. In the absence of site-specific data obtained from an appropriate experimental design, subjectivity will always be associated with selection of parameter values and their uncertainties. Because risk assessment modeling represents a highly inexact methodology, uncertainty analyses should always be conducted. Any use of deterministic approaches beyond that of a simple screening analysis cannot be considered reliable because the relative differences in uncertainty associated with specific exposure pathways and contaminants are obscured behind the deterministic estimates. This problem is particularly pronounced when model predictions rely on default values applied in the absence of site-specific data.

Diverging rankings of the ORNL WAGs using deterministic approaches were demonstrated in this work, giving the false impression that one WAG could be confidently ranked above another. Through the use of uncertainty analyses, however, it was possible to rank the ORNL WAGs in a more reliable manner. Risk assessment conducted considering uncertainty in contaminant concentrations only indicates that ORNL WAGs can be ranked in the following order: (1) WAG 1; (2) WAG 2, 6, and 7 (combined) and WAG 4; (3) WAG 5; (4) WAG 9; (5) WAG 3; and (6) WAG 8.

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