방사선 방어학회지
제15권 제2호 1990

■ 論 文 ■

Uncertainty and Sensitivity Analysis on A Biosphere Model

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ABSTRACT

For the performance assessment of the radioactive waste disposal system (repository), a biosphere model is suggested. This biosphere model is intended to calculate the annual doses to man caused by the contaminated river water for eight pathways and four radionuclides. This model can also be applied to assess the radiological effects of contaminated well water.

To account for the uncertainties on the model parameter values, parameter distributions are assigned to these model parameters. Then, Monte Carlo simulation method with Latin Hypercube sampling technique is used. Also, sensitivity analysis is performed by using the Spearman rank correlation coefficients. It is found that these methods are a very useful tool to treat uncertainties and sensitivities on the model parameter values and to analyze the biosphere model.

A conversion factor is proposed to calculate the annual dose rate to humans arising from a unit radionuclide concentration in river water. This conversion factor allows for the substitution of the biosphere model in a probabilistic performance assessment computer code by one single variable.

1. INTRODUCTION

The main objectives of this paper are development of a simplified biosphere model and the probabilistic safety assessment for the disposal of high level radioactive wastes in deep geological formations. In order to achieve these objectives, various researches are in progress.

The repository system consists of the repository with its engineered barriers, the geosphere and biosphere [1,2]. After the sealing of the repository its various components will eventually be contacted by the interstitial water in clay. This interstitial water will act as a medium which faciltates interactions among the different repository components including adjacent host rock[3−5].

Natural degradation of the repository will thus result in corrosion of canisters and glass blocks followed by release of radionuclides, These conditions form the source term for migration of the radionuclides through the clay formation.

For the normal evolution scenario, the only way for radionuclides to reach the adjacent aquifers is by migration through the clay formation. Once reached to the aquifers, the radionuclides will be conveyed by the ground water system as illustrated in Fig. 1.

Considerable uncertainties arise when the behavior of the complex repository system is predicted over long time periods. A probabilistic approach has been introduced to account for the uncertainties. This is done by using Monte Carlo simulatiom of the repository system's bevavior where parameter values are sampled from approp-

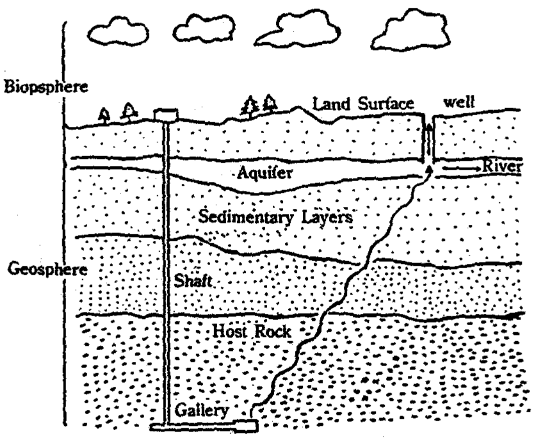

Fig. 1. Schematic diagram of repository.

riate distribution functions. Then, sensitivity analysis is performed to identify important parameters using Spearman rank correlation coefficients.

An integrated probabilistic performance assessment for the high-level radioactive repository system will be presented by combining repository failure model, geosphere model, and this biosphere model at the next issue of this journal.

2. BIOSPHERE MODEL

In the case of the normal evolution scenario for a repository in a clay layer, the release of radionuclides last for several hundred thousands of years. The variations of the amount of radionuclides entering the biosphere are relatively small during time periods considered in the biosphere model. Therefore, equilibrium state can be assumed in the biosphere.

The interface between the far field(aquifer) and biosphere consists of wells and rivers. Since the biosphere model in this paper is aimed to assess the radiological effects of contaminated river, the pathways from river to man are considered. River is primary source of drinking water for the population and the cattle and also source of irrigation water. Also, fishes uptake the radionuclides in the river water. Then the population are exposed by consuming the contaminated meat, crops, and fishes. The soil contaminated by irrigation water causes air contamination and direct irradiation to man [6-9].

So, in this biosphere model, eight pathways to man are considered: ingestion of drinking water, milk, meat, green and root vegetables, fish, inhalation of air containing resuspended dust, and direct irradiation from the contaminated field. These pathways are illustrated in Fig.2.

Generally, the annual dose rate can be calculated by the following equation:

$$DR = DF \times R \times C$$

where,

DR = Annual dose rate (Sv/y)

DF = Dose rate factor (Sv/Bq)

R = Consumtion rate (kg/y or m^3/y)

C = Radionuclide concentration (Bq/kg or Bq/m^3)

Here, the most important factor is the dose rate factor which is defined as the does rate per unit radionuclide taken up.

For each pathway, the annual dose to man is calculated by the following equations. The variables are defined in Table 1.

* Pathway 1: drinking water

$$DR_1 = DF_{ing} \times R_{mw} \times C_w \quad (1)$$

* Pathway 2&3: milk and meat[10, 11]

$$DR_2 = DF_{ing} \times R_{mm} \times C_m \quad (2)$$

$$DR_3 = DF_{ing} \times R_{mf} \times C_f \quad (3)$$

where, $C_m = F_m \times D_c \quad (4)$

$$C_f = F_f \times D_c \quad (5)$$

$$D_c = R_{cw} \times C_w + R_{cg} \times C_{gr} + R_{cs} \times C_s \quad (6)$$

$$C_{gr} = B_{vp} \times C_s \quad (7)$$

$$C_s = \frac{Q_{ir}}{Q_n + Q_{ir}} \left(K_d + \frac{\eta}{\rho}\right) C_w \quad (8)$$

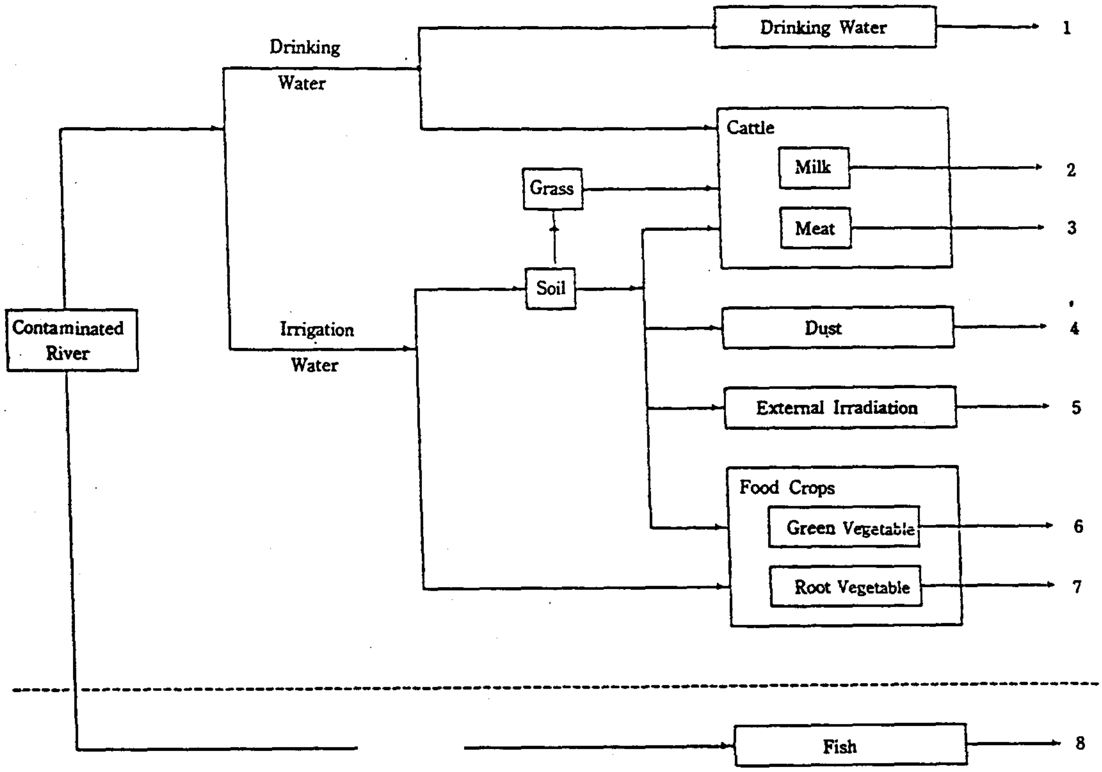

Fig. 2. Pathways considered in the biosphere model

* Pathway 4: inhalation

$$DR_4 = DF_{inh} \times R_{ma} \times D_a \times C_s \quad (9)$$

* Pathway 5: direct irradiation from soil [12−14] (uniform source distribution is assumed)

$$DR_5 = DF_{irr} \times C_s \times \rho \quad (10)$$

* Pathway 6: green vegetables[9, 15, 16] (direct deposition is considered)

$$DR_6 = DF_{ing} \times R_{mgv} \times C_{gv} \quad (11)$$

where, $C_{gv} = C_{gv1} + C_{gv2}$ (12)

$$C_{gv1} = \frac{1}{K_{21}} \left(K_{12} C_s' + Q_{irr} C_w \frac{R_v}{Y_v}\right) \quad (13)$$

$$C_{gv2} = B_{vg} \times C_s' \quad (14)$$

$$C_s' = \frac{\left[\dfrac{Q_{irr}(1-R_v)}{\rho_d}\right]}{\left[\dfrac{Q_{irr}(1-R_v)+Q_n}{(\rho K_d+\eta)d} + K_{12}\right]} C_s \quad (15)$$

* Pathway 7: root vegetables

$$DR_7 = DF_{ing} \times R_{mrv} \times C_{rv} \quad (16)$$

where, $C_{rv} = B_{rv} \times C_s$ (17)

* Pathway 8: fish

$$DR_8 = DF_{ing} \times R_{mfh} \times C_{fh} \quad (18)$$

where, $C_{fh} = F_{fh} \times C_w$ (19)

3. UNCERTAINTY AND SENSITIVITY ANALYSIS

Generally, probabilistic performance analysis

Table 1. Parameters of the biosphere model.

NOTATION	DEFINITION	UNIT	VALUE
B_{vg}	Soil-to-plant concentration factor for green vegetables	-	Table 3
B_{vp}	Soil-to-plant concentration factor for pasture	-	Table 4
B_{vr}	Soil-to-plant concentration factor for root vegetables	-	B_{vg}
C_f	Concentration in meat	Bq/kg	eq.(5)
C_{fh}	Concentration in fish	Bq/kg	eq.(19)
C_{gr}	Concentration in the pasture	Bq/kg	eq.(7)
C_{gv}	Concentration in the green vegetables	Bq/kg	eq.(12)
C_{gv1}	Concentration in the leaf of the green vegetables	Bq/kg	eq.(13)
C_{gv2}	Concentration in the root of the green vegetables	Bq/kg	eq.(14)
C_m	Concentration in milk	Bq/m^3	eq.(4)
C_{rv}	Concentration in the root vegetables	Bq/kg	eq.(17)
C_s	Concentration in the root zone of the soil	Bq/kg	eq.(8)
C'_s	Concentration in the root zone of the soil (for green vegetables)	Bq/kg	eq.(15)
C_w	Concentration in the river	Bq/m^3	1
D_a	Dust concentration in air	kg/m^3	4.DATA
D^c	Intake of radionuclide by the cattle	Bq/y	eq.(6)
DF_{ing}	Dose factor for ingestion	SvBq	Table 4
DF_{inh}	Dose factor for inhalation	SvBq	Table 4
DF_{irr}	Dose factor for direct irradiation from soil	$\frac{Sv/y}{Bq/m^3}$	Table 4
DR_1	Dose rate from drinking water pathway	Sv/y	eq.(1)
DR_2	Dose rate from milk pathway	Sv/y	eq.(2)
Dr_3	Dose rate from meat pathway	Sv/y	eq.(3)
DR_4	Dose rate from inhalation pathway	Sv/y	eq.(9)
DR_5	Dose rate from direct irradiation pathway	Sv/y	eq.(10)
DR_6	Dose rate from green vegetables pathway	Sv/y	eq.(11)
DR_7	Dose rate from root vegetables pathway	Sv/y	eq.(16)
DR_8	Dose rate from fish pathway	Sv/y	eq.(18)
F_f	Concentration factor for meat	y/kg	Table 3
F_m	Concentration factor for milk	y/m^3	Table 3
F_{fh}	Concentration factor for fish	y/kg	Table 2
K_{12}	Transfer coefficient from soil to vegetable	1/y	0.0035-0.02
K_{21}	Transfer coefficient from vegetable to soil	1/y	Table 2

NOTATION	DEFINITION	UNIT	VALUE
K_d	Distribution coefficient for the root zone	m^3/kg	Table 3
R_{cg}	Pasture consumption rate by cattle	kg/y	20,000
R_{cs}	Soil consumption rate by cattle (during intaking the pasture)	kg/y	180
R_{cw}	Water consumption rate by cattle	m^3/y	29
R_{ma}	Inhalation rate of man	m^3/y	7,300
R_{mf}	Meat consumption rate by man	kg/y	90
R_{mfh}	Fish consumption rate by man	kg/y	20
R_{mgv}	Green vegetables consumption rate by man	kg/y	130
R_{mrv}	Root vegetables consumption rate by man	kg/y	120
R_{mm}	Milk consumption rate by man	m^3/y	0.3
R_{mw}	Water consumption rate by man	m^3/y	0.73
R_v	Fraction of irrigation water which is directly deposited on vegetables	-	0.05-0.3
Q_{irr}	Irrigation rate	m/y	0.04-0.4
Q_n	Net precipitation rate	m/y	0.25
Y_v	Productivity of the edible portion of vegetation	kg/m^3	0.4-2.5
d	Thickness of the root zone	m	0.3
η	Void fraction in the root zone	-	0.3
ρ	Bulk density of the dry soil	kg/m^3	1,650

considers the uncertainties which arise when the behavior of the complex disposal system is predicted over long time periods. The fact that uncertainties will always remain in far future prediction is the objective ground of risk-based performance studies in waste disposal.

Uncertainties in performance assessment for radioactive waste disposal may arise from the following areas[17].

- Scenarios
- Models
- Data

Uncertainties due to scenarios may be reduced by carefully selecting and describing relevant scenarios. Uncertainties due to models may result because ;

1. some phenomena are not correctly described by the models,
2. approximations are introduced to facilitate the calculations.

Uncertainties of the first type may be evaluated by model validations and the effect of approximations and simplifications on the models should be estimated in separate sensitivity studies with respect to validated detailed models. Uncertainies resulting from those affecting the values assigned to the model parameters may be evaluated through appropriate mathematical/statistical methodologies.

In this biosphere model, normal evolution scenario is assumed and only the uncertainties arising from data are considered.

3.1. UNCERTAINTY ANALYSIS

The uncertainties of the values for the selected model parameters need to be described by histograms or by assigning to each model parameter a probability distribution function. Depending on the availability of information, the probability distribution may be approximated to one of the following functions ; normal or log-normal, uniform or log-uniform, etc.

A number of statistical methods are proposed for the uncertainty analysis[18, 19, 20]. Currently, techniques to evaluate the impact of parameter uncertainties by performing stochastic calculations using Monte Carlo simulations are widely used. For these simulations a number of vectors containing parameter values are sampled from the distribution functions. The biosphere model is run repeatedly for different input vectors. The important parameter sampling techniques used for uncertainty analysis are random sampling (Monte Carlo Method) and stratified sampling (Latin Hypercube Sampling).

Random Sampling

This technique is relatively easy to use. But it requires a large number of runs to ensure that all combinations of parameter values are considered.

Stratified Sampling (LHS)

This technique is aimed at optimizing the sample selection in order to ensure that all relevant parpmeter values and their combinations are included in the calculations, even for a relatively small number of runs.

In most cases LHS has proved to be an adequate technique for uncertainty analysis [21-26]. Further, LHS can be improved with the method developed by Iman and Conover[21] for eliminating spurious correlation among the input variables. This method is based on rank correlation which is intended to induce the desired rank dependence among the input variables and has some desirable properties.

The procedure of this method is as follows.

(1) Let R be an initial sampling matrix whose columns represent independent permutations of an arbitrary set (scores) and C be a desired rank correlation matrix.

(2) Find lower triangular matrix P such that $P \cdot P' = C$.

(3) Find lower triangular matrix Q such that $Q \cdot Q' = T$, where T is sampling correlation matrix for R.

(4) Calculate $S = P \cdot Q^{-1}$

(5) Calculate new sampling matrix $R^* = R \cdot S'$ The matrix R^* has a correlation matrix exactly equal to C.

(6) Arrange the values of the variables in each column so they have the same order (rank) as the corresponding column in R^* Thus, the sample Spearman rank correlation of the input vectors will be the same as the sample Spearman rank correlation of R^*.

3.2. SENSITIVITY ANALYSIS

The main objective of the sensitivity analysis is to investigate how the output is influenced by each of the input variables. Several sensitivity analysis techniques can be used to evaluate the importance of model parameters. Since each technique considers sensitivity from a different point of view, different conclusions may be obtained[19, 20, 23-25].

In this paper, Spearman rank correlation coefficients are calculated for sensitivity analysis. Spearman rank correlation coefficients are preferred to Pearson correlation coefficients because of the non-normal distribution of the calculated dose rates. Spearman rank correlation coefficient, ρ, is defined as

$$\rho(Y, X_j) = \frac{\sum[R(X_{ij}) - \overline{R(x_j)}] \cdot \sum[R(y_i) - \overline{R(y)}]}{[\sum[R(X_{ij}) - \overline{R(x_j)}]^2 \cdot \sum[R(y_i) - \overline{R(y)}]^2]^{1/2}}$$

4. DATA

To account for the uncertainties on the irrigation rate, dust concentration, transfer factors, dose factors and concentration factors, parameter distributions are assigned to these model parameters. For each parameter, the distribution is chosen among uniform, log-uniform, normal, and log-normal distributions according to its range and characteristics.

On the other hand, fixed values are used for consumption rates for man and cattle, and soil data. For the consumption rates for man, extreme values are used.

Five parameters, common to all radionuclides, are sampled from following distribution:

—the irrigation rate Qirr is sampled from a log-uniform distribution ranging from 0.04 to 0.4 m/y,

—the dust concentration in air Da is sampled from a log-uniform distribution with parameters $\mu = -7.28$ and $\sigma = 0.22$,

—the soil-to-vegetable transfer factor K_{12}, direct deposition rate of irrigation water R_v, productivity of the edible portion of vegetation Y_v are sampled from uniform distribution(Table 1).

For each radionuclides, six parameters are sampled from uniform, log-uniform (Table 2) and log—normal distributions (Table 3). The other parameter values are given in Table 1 and Table 4.

5. CALCULATIONS

The Monte Carlo simulation method is used to perform dose rate calculations for each pathway and radionuclide. The Latin Hypercube Sampling method is used because this method yields a good estimate of the output distribution with a limited number of runs. The sensitivity analysis of each model parameter to the output dose rate is performed using the partial rank correlation coefficient. A simulation of 500 runs is performed by making use of three computer codes. The calculational flow diagram is illustrated in Fig.3. The function of each computer code is as follows:

* BIOSAMP : generate a sample matrix and parameter values according to parameter distribution,
* BIOMODL : calculate dose rate for each pathway and radionuclide according to the biosphere model,
* BIOPLOT : perform uncertainty and sensitivity analyses and plot histogram of concentration-to-dose conversion factor.

Table 2. Parameter values for uniform and log-uniform distributions.

RADIONUCLIDE	K_{21}(uniform)	F_m(log-uniform)
Pu^{239}	30 - 60	−3.0 - −1.0
Np^{237}	30 - 60	−3.0 - −1.0
Cs^{135}	8.5 - 18	−1.0 - +1.0
Tc^{99}	8.5 - 18	−2.523 - −0.523

Table 3. Parameter values for log-normal distributions.

RADIONUCLIDE	K_d		B_{vg}		F_m		F_f	
	μ	σ	μ	σ	μ	σ	μ	σ
Pu^{239}	1.000	0.67	−3.620	0.79	−7.301	0.75	−7.268	0.60
Np^{237}	−0.276	0.52	−2.194	0.61	−6.149	0.75	−6.523	0.60
Cs^{135}	−0.409	0.50	−2.051	0.59	−1.721	0.75	−4.292	0.60
Tc^{99}	−2.770	0.21	0.568	0.25	−1.398	0.75	−4.796	0.60

Table 4. Values for f and dose factors.

RADIONUCLIDE	f*	DF_{ing}	DF_{inh}	DF_{irr}
Pu^{239}	1.0	1.2×10^{-6}	1.4×10^{-4}	0
Np^{237}	1.0	1.1×10^{-6}	1.3×10^{-4}	3.06×10^{-10}
Cs^{135}	1.0	1.9×10^{-9}	1.2×10^{-9}	0
Tc^{99}	3.78	3.4×10^{-10}	2.0×10^{-9}	0

*f ; pasture to green vegetable ratio($B_{vp}=f\ B_{vg}$)

6. RESULTS

The annual doses to a man resulting from a concentration of 1 Bq/m³ in the river water are calculated for each pathway and radionuclide. Table 5 shows the minimum, maximum and mean values of the highest dose rate among eight pathways for each radionuclide. According to these values, two actinides, Pu^{239} and Np^{237} are more important radionuclides to assess the radiological effects of unit concentration in contaminated river water than Cs^{135} and Tc^{99}.

Concentration-to-dose conversion factors (Sv y^{-1}/Bqm^{-3}) for each radionuclide are illustrated in Fig.4 to 7. These histograms show the uncertainties of calculated annual doses caused by the uncertainties of the considered parameters. For Pu^{239}, Np^{237} and Tc^{99}, taking logarithm to the conversion factors will result in exponential (Pu^{239}), Np^{237}) or log-normal distribution (Tc^{99}).

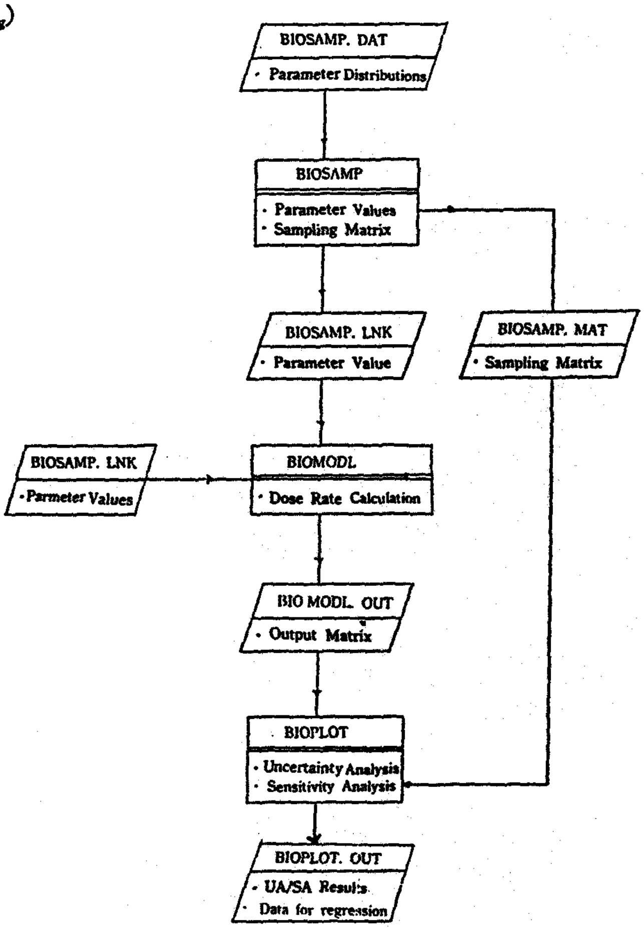

Fig. 3. Schematic diagram of computer codes.

Table 5. Calculated does rate(Sv/y)for a unit concentration in the river (Bq/m^3).

RN	MIN	MAX	MEAN	ST.DEV.	LOG.MEAN	LOG.ST.DEV.
Pu^{239}	8.76×10^{-7}	4.10×10^{-5}	1.83×10^{-6}	3.19×10^{-6}	−5.89	2.79×10^{-1}
Np^{237}	8.03×10^{-7}	2.88×10^{-5}	1.19×10^{-6}	1.57×10^{-6}	−6.00	1.91×10^{-1}
Cs^{135}	3.85×10^{-9}	7.35×10^{-7}	8.83×10^{-8}	1.04×10^{-7}	−7.36	5.55×10^{-1}
Tc^{99}.	2.48×10^{-10}	1.45×10^{-7}	3.80×10^{-9}	9.67×10^{-9}	−8.82	5.27×10^{-1}

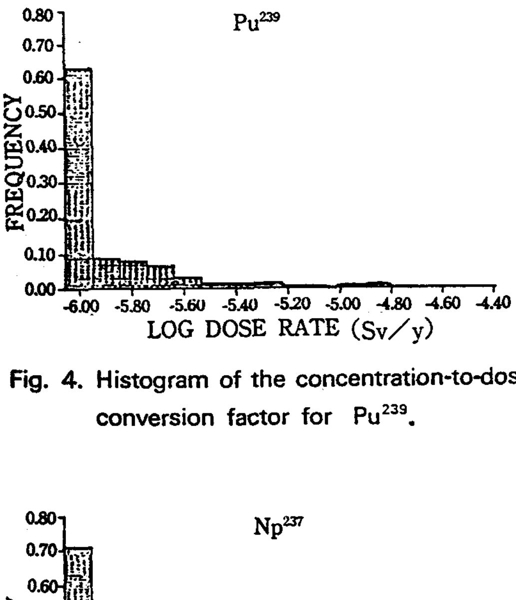

Fig. 4. Histogram of the concentration-to-dose conversion factor for Pu^{239}.

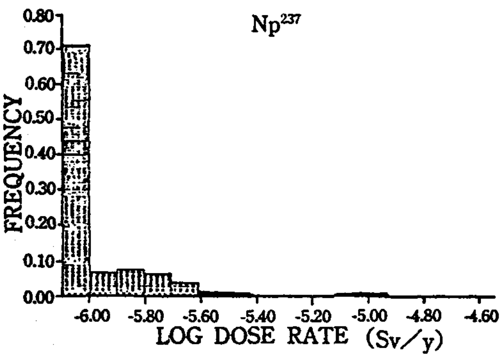

Fig. 5. Histogram of the concentration-to-dose conversion factor for Np^{237}.

For Cs^{135}, however, the distribution is similar to log-uniform distribution. The reason is that Cs^{135} has very strong correlation (0.95) with concentration factor for fish, F_{fh}, and the distribution for F_{fh} is assumed to be log-uniform distribution.

The uncertainties on the calculated annual doses are spreaded out about two or three orders of magnitude.

Relative contribution of each pathway to maximum dose rate are shown in Table 6. Drinking water (pathway 1) is the dominant pathway for Pu^{239} and Np^{237}. For Cs^{135} and Tc^{99}, the dominent contribution to dose rate is fish (pathway 8) and milk(pathway 2), respectively.

The rank correlation coefficients between calculated dose rate and the model parameter values (Table 7) show the important parameters for each radionuclide. For example, irrigation rate Qirr is correlated with Pu^{239}, Np^{237}, Tc^{99}. But for Cs^{135}, instead of irrigation rate, Cs^{135} has strong correlation with concentration factor for fish, F_{fh}. For dust concentration in air, D_a, it has correlation only with Pu^{239}. It is obvious that Pu^{239} is the most important radionuclide for inhalation pathway.

7. CONCLUSIONS

The proposed biosphere model is aimed to assess the radiological effects of contaminated river water. However, it can be used for analyzing the

Table 6. Relative contribution of each pathway to maximum does rate.

RN	PW1	PW2	PW3	PW4	PW5	PW6	PW7	PW8
Pu^{239}	0.786	0.000	0.016	0.331	0.000	0.081	0.277	0.387
Np^{237}	0.851	0.000	0.010	0.019	0.175	0.123	0.310	0.413
Cs^{135}	0.066	0.156	0.112	0.000	0.000	0.026	0.027	0.953
Tc^{99}	0.289	0.773	0.220	0.000	0.000	0.196	0.124	0.355

Table 7. Rank correlation coefficients between the calculated does rate and the model parameter values.

PARAM	Pu^{239}	NP^{237}	CS^{135}	TC^{99}
Q_{irr}	0.165	0.108	0.018	0.172
D_a	0.116	0.058	-0.041	0.010
K_{12}	0.077	0.101	0.033	0.033
R_v	-0.068	-0.011	0.018	-0.009
Y_v	-0.011	-0.041	0.002	-0.044
K_d	0.447	0.180	0.029	0.132
R_v	0.001	0.219	-0.006	0.062
F_m	0.135	-0.018	-0.019	0.812
F_h	0.054	0.033	0.080	0.062
K_{21}	0.065	0.003	0.015	-0.008
F_{fish}	0.415	0.509	0.951	0.169

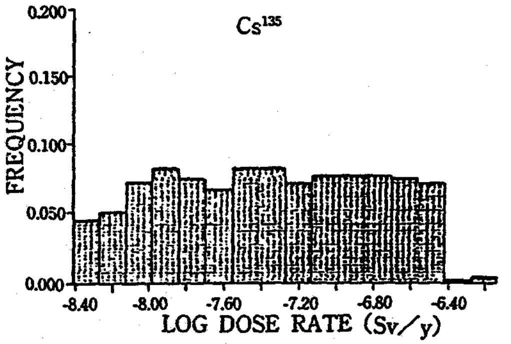

Fig. 6. Histogram of the concentration-to-dose conversion factor for Cs^{135}

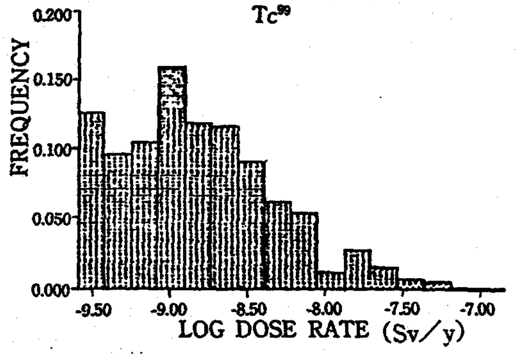

Fig. 7. Histogram of the concentration-to-dose conversion factor for Tc^{99}.

radiological effects of contaminated well water because the pathways are very similar. The Monte Carlo method with Latin Hypercube sampling technique is a very useful tool to treat uncertainties on the model parameters. With the results of uncertainty and sensitivity analyses, the effects of model parameters on each pathway can be assessed and these informations can be used to improve the biosphere model and to examine the model parameter values.

It is possible to substitute the biosphere model by concentration-to-dose conversion factor, if it is defined by suitable distribution function. This substitution will reduce the computer time needed for the execution of the computer codes and can accomodate the uncertainty analysis of model parameters to the annual doses.

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