Environment Report RL 07/05

Parameter Sensitivities for Radionuclide Concentration Prediction in PRAME

The Centre for Environment, Fisheries and Aquaculture Science
Lowestoft Laboratory
Pakefield Road
Lowestoft
Suffolk
NR33 0HT

M.P. Grzechnik

March 2005

The work in this report was completed under contract to
the Food Standards Agency.
FSA Service Level Agreement
CEFAS Contract RB102

Table of Contents

1. Introduction

The PRAME model (Probabilistic Radiological Assessments for the Marine Environment) has been developed as a tool for assessing the environmental impact of licensed site discharges to coastlines and estuaries. Its basis is the WATP/ADOP models of Grzechnik et al. (2002), which were in turn based upon the deterministic WAT/ADO suite of models (Round, 1998a,b). The development of the PRAME suite of models has been commissioned under the Food Standards Agency's Service Level Agreement for Radiological Assessments with the Centre for Environment, Fisheries and Aquaculture Science.

The aim of this report is to determine which parameters associated with liquid discharge assessments dominate uncertainty in United Kingdom waters. In this way the model's sensitivity to changes in various parameters can be investigated, as well as the shape of specific output distributions. This enables resources to be focussed on improving the knowledge of parameters to which the model is particularly sensitive.

Parameters identified as being potentially uncertain in previous studies (Brownless et al., 2001) have been considered in this investigation. It is intended that a definitive classification of primary and secondary parameter values can be summarised here to improve the efficiency of probabilistic radiological assessments in the marine environment.

2. Previous Studies

The development of the PRAME model has undergone a number of iterations. The framework of this probabilistic modelling suite is based upon underlying deterministic models known as WAT (water concentration calculation) and ADO (dose calculation). In this report, the sensitivities of parameter changes relevant to the WAT model's two modules (Round, 1998a and Hunt, 1982) have been investigated. The parameter sensitivities of the ADO model for predicting dose is not within the scope of the current project.

The two modes (or modules) of the WAT model for the calculation of radionuclide concentration in the water column are:

- Advection-Diffusion – This uses an advection-diffusion model to calculate steady-state concentrations of radionuclides in seawater. The situation simulated here is that of an open coastline with tidal flows. To simplify the calculations, it is assumed that the dominant flow effects are parallel and perpendicular to the coast for advection and diffusion respectively.
- Single Compartment – This is an estuarine box model, where the body of water is partially enclosed and therefore not fully exposed to the open ocean. The size of the three-dimensional compartment (or 'box') is based on the tidal excursion, depth and offshore extent. Volume exchange into and out of the box is calculated based on oceanographic data.

For both modes, losses of radioactivity due to sedimentation and sediment scavenging are also taken into account. Routine discharges are modelled over the duration of a year. Further details of assumptions, equations and calculations applied are given by Round (1998a) and Hunt (1982) for the advection-diffusion and single compartment modes respectively.

The uncertainties associated with the WAT model have been investigated in a study by Brownless et al. (2001). It was found that the dominant uncertainties were associated with sedimentary parameters in both modules of the model. Specifically;

- Sediment distribution coefficient (K_D)
- Suspended sediment load in cases of low loading, particularly when moving from particle reactive to conservative mode of behaviour.

It should be noted that the ranges for K_D values used in the Brownless report were taken from IAEA (1985). In many cases these ranges were significantly greater than the updated K_D ranges used in the current study (IAEA, 2004). The major limitation of the study of uncertainties for the WAT model was that uncertainties were based on upper and lower bounds for the parameters. An additional perspective of uncertainty and sensitivity can be obtained through the inclusion of distribution profiles, as included in this probabilistic modelling study.

The initial version of the probabilistic model based on WAT was known as WATP (Grzechnik et al., 2002). Latin Hypercube Sampling was used to randomly sample input parameter distributions for use in 500 variations (or iterations) of WAT deterministic model runs (also known as a Monte Carlo analysis – 500 iterations are also applied in this study). This model was developed for both advection-diffusion and single compartment modes, however only the advection-diffusion mode was tested for parameterisations corresponding to separate UK and Sizewell scenarios. Sensitivity of specific parameters was not investigated, however uncertainty ratios were calculated for model runs using the following definition;

$$\text{Uncertainty} = (95^{th}\text{ Percentile}) / (5^{th}\text{ Percentile}),$$

as used by NRPB (1998a,b). This convention will be followed in this report. Grzechnik (2002) further describes the use of the probabilistic model and input formats of parameter distributions.

Investigation of parameter correlations led to further refinements of the probabilistic modelling suite by Grzechnik (2003). The WATP and ADOP models were tested for parameter dependencies, and it was determined that sediment interactions involve a proportionality that must be taken into account – the parameters involved were suspended sediment load and sedimentation rate. This parameter correlation was incorporated into the model by including the ratio of sedimentation rate to sediment load as an input parameter. This can either be a constant value (to ensure proportionality) or a normal distribution (to incorporate uncertainty). Testing of the correlated model was included in the report.

Other probabilistic modelling studies for dose assessment that use a similar Monte-Carlo approach have been undertaken by IAEA (1989), NRPB (1998a,b) and NCRP (1996).

3. Parameter Inputs

The aim of this study is to determine the sensitivity of both modes (advection-diffusion and single compartment) of the water concentration prediction model to each individual parameter. To achieve this, separate runs (made up of 500 iterations) are conducted with a single parameter varied whilst all others remain constant. Variations have been determined from possible ranges of values in the UK, as used by Brownless et al. (2001) and Grzechnik et al. (2002); provided by Aldridge (2000) and Kershaw (2000). Comparisons can also be made with an initial deterministic model run with constant values for all parameters – these are referred to as the 'default' parameter values. Sediment parameter values are considered separately (Section 3.3) as they are applied identically in both modes.

3.1 Advection-Diffusion Model

The advection-diffusion model simulates radionuclide dispersal on an open coastline. Because of this, oceanographic parameters of importance include tidal excursion and residual velocity parallel to the shoreline, and diffusion perpendicular to the coast. A complete description of these parameters and their physical meaning can be found in Round (1998a), Grzechnik et al. (2002) and Grzechnik (2002).

3.1.1 Default parameter values & deterministic output

A deterministic run of the WAT model in advection-diffusion mode has been undertaken using the parameters shown in Table 1. The relative importance of each parameter in the context of this study has also been included. Parameters deemed to be of 'Low' importance in previous studies have been excluded from the sensitivity analysis of the current study.

Table 1. The default parameter values used for advection-diffusion runs and their relative importance according to Brownless et al. (2001) and Grzechnik et al. (2002).

Parameter	*Default Value*	*Relative Importance*
Mean depth	10 m	Medium
Residual velocity	0.01 m s^{-1}	High
Diffusion coefficient	2.5 m^2 s^{-1}	Medium
Tidal excursion (pipe)	1500 m	Medium
Tidal excursion (critical group)	1500 m	Medium
Discharge start time	0.0	Low
Discharge end time	1.0	Low
Initial spreading radius	50 m	Low
Distance to critical group	0 m	Low

It should be noted that the output can be sensitive to large changes in the 'distance to critical group' parameter, however this value is accurately known (via habits surveys) and thus can be considered to be of low importance in this study. It is also assumed that the tidal excursion at the critical group is the same as that at the discharge pipe.

Output default water concentrations for each of the 12 included radionuclides are shown in Table 2. These can be compared to output distributions obtained using the probabilistic version of the advection-diffusion model.

Table 2. Advection-Diffusion deterministic model outputs using 'default' parameter values.

Radionuclide	*Predicted Concentration ($Bq\ l^{-1}$)*
Am241	1.15E-03
Co60	7.45E-03
Cs137+	1.66E-01
H3	2.33E-01
Po210	1.15E-04
Pu239	2.10E-02
Pu240	2.10E-02
Ru106+	4.62E-02
Sb125	1.94E-01
Sr90	2.33E-01
Tc99	2.31E-01
U238+	2.21E-01

3.1.2 Advection-diffusion parameter distributions

Input parameters for the probabilistic version of the advection-diffusion model are shown as histograms in Figure 1. For each distribution shown, 500 iterations of the PRAME model have been performed with other parameters taking (constant) default values. The format of the distributions used for each parameter value is shown in Table 3. When applied to a log-normal distribution with the Latin Hypercube Sampling routine described by Grzechnik et al. (2002), the histogram distributions shown in Figure 1 were derived.

Table 3. Distributions for advection-diffusion model sensitivity analysis across the UK, provided by Aldridge (2000). All parameters are applied to a log-normal distribution.

Parameter	*Lower*	*Upper*	*Percentile (%)*
Mean depth (m)	5.0	52.0	95
Residual velocity ($m\ s^{-1}$)	0.0012	0.14	99
Diffusion coefficient ($m^2\ s^{-1}$)	0.52	14.0	99
Half tidal excursion (m)	240.0	11000.0	95

Sediment parameters are also incorporated into the advection-diffusion model. These are shown in Section 3.3.

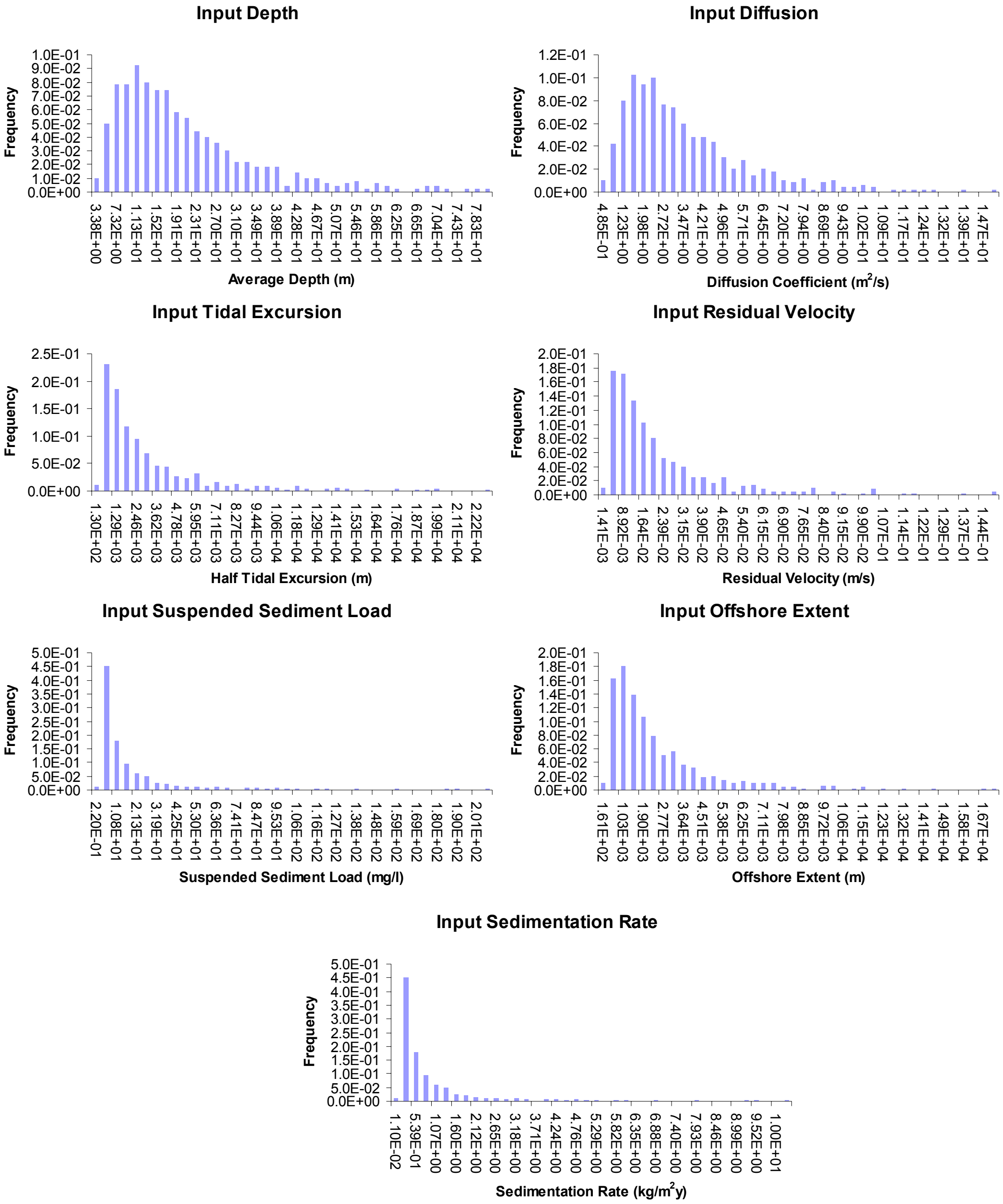


Figure 1. The input distributions for use in advection-diffusion and single compartment models. Distributions shown include; Average Depth, Diffusion (adv-diff mode only), Half Tidal Excursion, Residual Velocity, Suspended Sediment Load, Offshore Extent (single comp model only) and Sedimentation Rate (from ratio), as produced by the Latin Hypercube Sampling Routine.

Distributions are individually scaled according to 1st and 99th percentiles for minimum and maximum plotted values respectively. Frequencies (y-axis) refer to the relative likelihood that an individual iteration will take the water concentration value indicated on the x-axis.

3.2 Single Compartment Model

The single compartment model is applied to estuarine environments. It is also used in regions where the advection-diffusion model is not deemed appropriate (i.e. where there is not a relatively straight coastline, such as in the case of a headland). The important parameters in the single compartment model are:

- Exchange Volume (V_{ex}) – the volume of the body of water being considered,
- Dispersion Factor (D_f) – the fraction of the exchange volume that is 'replaced' each day.

These parameters can be simply derived from more easily obtained oceanic values using the following expressions:

$$V_{ex} = d.t_{ex}.O_{ext}\,,$$
$$D_f = \frac{v_{res}.d.S_{day}.O_{ext}}{V_{ex}}\,,$$

where: d is the depth,
t_{ex} the tidal excursion (m),
O_{ext} the assumed offshore extent of the compartment (m),
v_{res} the residual velocity (m s^{-1}),
S_{day} the number of seconds in a day (86400s).

The offshore extent describes the distance offshore that effluent is able to disperse. This is normally apparent when surveying maps of the region of interest.

3.2.1 Default parameter values & deterministic outputs

A deterministic run of the WAT model in single compartment mode has been undertaken using the parameters shown in Table 4. The relative importance of each parameter in the context of this study has also been included. As in Section 3.1.1 for the advection-diffusion model, parameters deemed to be of 'Low' importance in previous studies have been excluded from the sensitivity analysis described in this report.

Table 4. The default parameter values used for single compartment runs and their relative importance according to Brownless et al. (2001) and Grzechnik et al. (2002).

Parameter	*Default Value*	*Relative Importance*
Mean depth	10 m	Medium
Residual velocity	0.01 m s^{-1}	High
Half Tidal excursion	1500 m	Medium
Initial spreading radius	50 m	Low
Offshore extent	1500 m	Medium

Output default water concentrations for each of the 12 included radionuclides are shown in Table 5. These can be compared to output distributions obtained using the probabilistic version of the single compartment model.

Table 5. Single compartment deterministic model outputs using 'default' parameter values.

Radionuclide	*Predicted Concentration ($Bq\ l^{-1}$)*
Am241	1.00E-03
Co60	6.51E-03
Cs137+	1.49E-01
H3	2.11E-01
Po210	9.91E-05
Pu239	1.84E-02
Pu240	1.84E-02
Ru106+	4.04E-02
Sb125	1.74E-01
Sr90	2.11E-01
Tc99	2.09E-01
U238+	1.91E-01

3.2.2 Single compartment parameter distributions

Input parameters for the probabilistic version of the single compartment model are shown as histograms in Figure 1. For each distribution shown, 500 iterations of the PRAME model have been performed, with other parameters taking default (constant) values. The format of the distributions used for each parameter value is shown in Table 6. When applied to a log-normal distribution with the Latin Hypercube Sampling routine described by Grzechnik et al. (2002), the histogram distributions shown in Figure 1 were derived.

Table 6. Distributions for single compartment model sensitivity analysis across the UK, provided by Aldridge (2000). All parameters are applied to a log-normal distribution.

Parameter	*Lower*	*Upper*	*Percentile (%)*
Mean depth (m)	5.0	52.0	95
Residual velocity ($m\ s^{-1}$)	0.0012	0.14	99
Offshore extent (m)	150.0	15000.0	99
Half tidal excursion (m)	240.0	11000.0	95

Sediment parameters are also incorporated into the single compartment model. These are shown in Section 3.3.

3.3 Sediment Parameters

Sediment parameter values are common to both advection-diffusion and single compartment modes. Suspended sediment load and sedimentation rates have been sourced from Kershaw (2000), and sediment distribution coefficients (K_D) have been obtained from the recommended coastal sediment values of IAEA (2004).

3.3.1 Default sediment parameter values

Default sediment values and relative importance are shown in Table 7. It should be noted that the relative importance of sediment K_Ds for all 12 radionuclides (as recommended by Hunt, 2004) has been investigated and assumed to be of 'high' importance, even though this may not prove to be the case after a sensitivity analysis. This is because previous studies have only investigated the radionuclides Cs-137 and Am-241.

Table 7. The default parameter values used for description of sediment processes as applied in both advection-diffusion and single compartment models.

Parameter		*Default Value*	*Relative Importance*
Suspended sediment load		100 mg l^{-1}	Very High
Sedimentation rate / Suspended sediment load		5.0E+4 l m^{-2} y^{-1}	High
Sediment distribution coefficient (K_D)	Am241	2.0E+6	High
	Co60	3.0E+5	High
	Cs137+	4.0E+3	High
	H3	1.0E+0 l kg^{-1}	High
	Po210	2.0E+7	High
	Pu239	1.0E+5	High
	Pu240	1.0E+5	High
	Ru106+	4.0E+4	High
	Sb125	2.0E+3	High
	Sr90	8.0E+0	High
	Tc99	1.0E+2	High
	U238+	1.0E+3	High

3.3.2 Sediment parameter distributions

Input sediment parameter distributions for the probabilistic version of both the single compartment and advection-diffusion models are shown as histograms in Figure 1. For each distribution shown a run of the PRAME model has been performed (for 500 iterations) with other parameters taking default values. The format of the distributions used for each parameter value is shown in Table 8. When applied to a log-normal distribution with the Latin Hypercube Sampling routine described by Grzechnik et al. (2002), the histogram distributions shown in Figure 1 were derived.

It should be noted that the initial recommended value for suspended sediment load was a log-normal distribution with minimum 0, maximum 200 mg l^{-1} and a mean of 100 mg l^{-1}. When this was applied to the Latin Hypercube Sampling routine the resultant distribution was skewed towards the upper values (mainly due to the minimum value being ln(0), which is undefined). This meant that the resolution at low sediment loadings was very poor. Because previous studies have stated that the model is more sensitive to parameter changes when loadings are low, the lower value has been replaced with 0.2 mg l^{-1}.

Table 8. Distributions for sediment parameters used in the sensitivity analysis across the UK, provided by Kershaw (2000) and IAEA (2004). All parameters are applied to a log-normal distribution, unless otherwise indicated.

Parameter		*Lower*	*Upper*	*Percentile (%)*
Suspended sediment load (mg l^{-1})		0.2	200	99
Sedimentation rate / Suspended sediment load (l m^{-2} y^{-1})*		5.0E+4	5.0E+4	100
Sediment distribution coefficient, K_D (l kg^{-1})	Am241	2.0E+5	2.0E+7	99
	Co60	3.0E+4	3.0E+6	99
	Cs137+	4.0E+2	4.0E+4	99
	H3	1.0E-1	1.0E+1	99
	Po210	2.0E+6	2.0E+8	99
	Pu239	1.0E+4	1.0E+6	99
	Pu240	1.0E+4	1.0E+6	99
	Ru106+	4.0E+3	4.0E+5	99
	Sb125	2.0E+2	2.0E+4	99
	Sr90	8.0E-1	8.0E+1	99
	Tc99	1.0E+1	1.0E+3	99
	U238+	1.0E+2	1.0E+4	99

* A constant value has been applied for the ratio between sedimentation rate and load. This is expressed as a uniform distribution with identical upper and lower values.

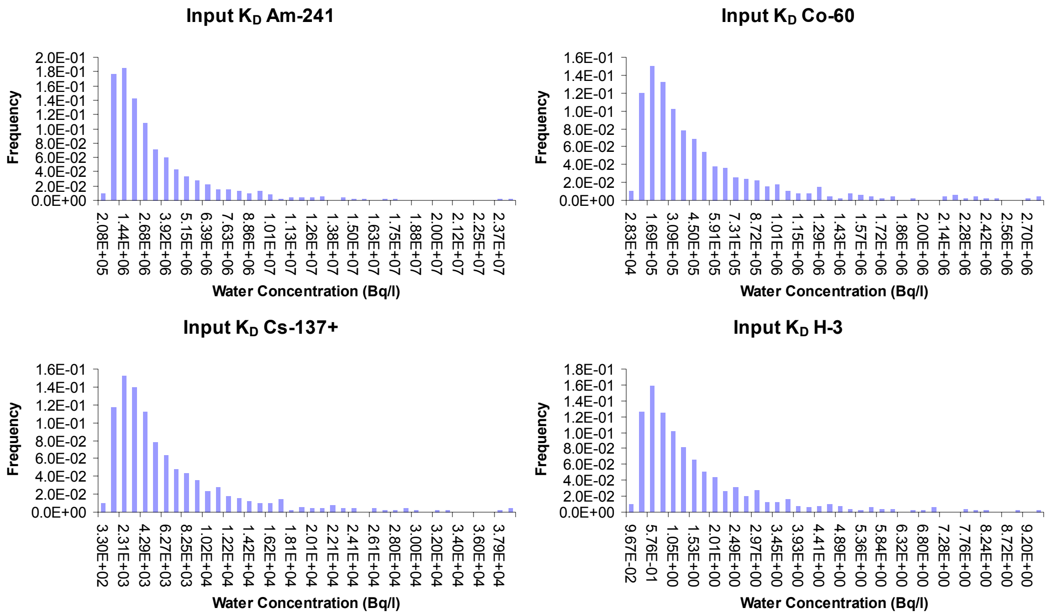


Figure 2a. The input distributions for the WATP model obtained using the Latin Hypercube Sampling routine for K_D (Sediment Distribution Coefficient) for the first four radionuclides; Am-241, Co-60, Cs-137+ & H-3

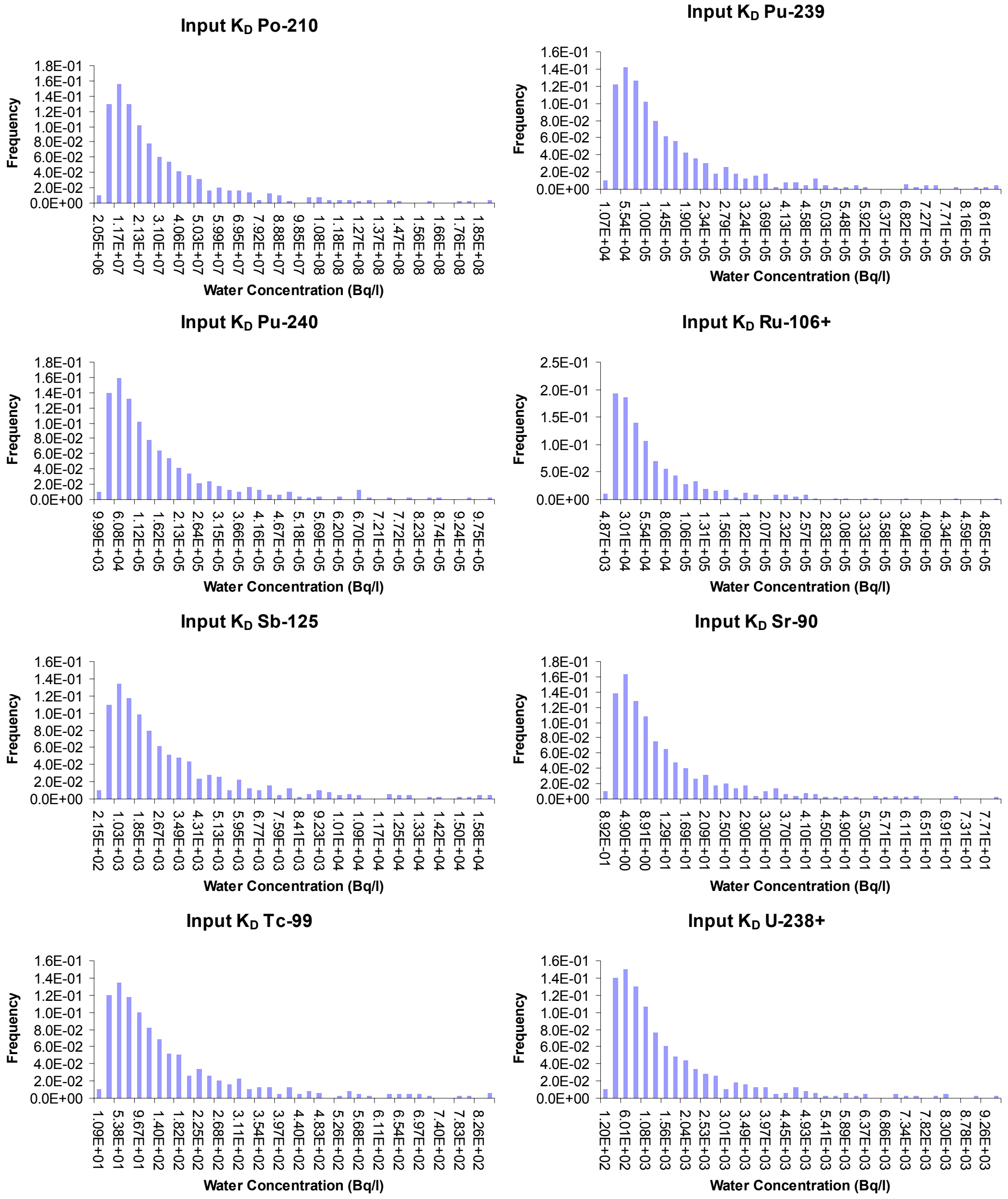


Figure 2b. The input distributions for the WATP model obtained using the Latin Hypercube Sampling routine for K_D (Sediment Distribution Coefficient) for the remaining 8 radionuclides; Po-210, Pu-239, Pu-240, Ru-106+, Sb-125, Sr-90, Tc-99 & U-238+.

Sediment Distribution coefficient (K_D) inputs are also shown for each radionuclide considered here (Table 8 and Figures 2a & 2b). These distributions have been derived according to IAEA Technical Report 422 (IAEA 2004). In this case, each K_D value has been assigned an uncertainty of an order of magnitude above and below the recommended value. These extremities have been assigned the 1st and 99th percentiles for lower and upper extremes respectively.

4. Results & Discussion

The results of model runs for the advection-diffusion and single compartment sensitivity analyses are presented in this section. Variation of each parameter is discussed in turn and water concentration outputs (Bq l^{-1}) are presented as 5^{th}, 50^{th} and 95^{th} percentile, uncertainty ratio ($95^{th}/5^{th}$ percentile) and histogram plots for each of the 12 included radionuclides.

4.1 Advection-Diffusion Model Results

The results for varying specific parameters in the advection-diffusion model are described below. Each parameter and its discussion are considered as a separate sub-section. Pointers are given to histogram plots, which reside in Appendix A.

4.1.1 Variation of average depth

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing average depth was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section A.1. In this case the outputs for all nuclides are similar in shape, generally log-normal in appearance with the higher frequencies in the lower part of the histogram (approximately 10% of the maximum plotted value).

Table 9. The 5^{th}, 50^{th} and 95^{th} percentiles of water concentration (Bq l^{-1}) and uncertainty ratio ($95^{th}/5^{th}$) obtained through the variation of the average depth parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Uncertainty*
Am241	2.27E-04	7.17E-04	2.19E-03	9.66E+00
Co60	1.47E-03	4.65E-03	1.42E-02	9.68E+00
Cs137	3.26E-02	1.04E-01	3.19E-01	9.80E+00
H3	4.57E-02	1.46E-01	4.50E-01	9.86E+00
Po210	2.27E-05	7.18E-05	2.19E-04	9.66E+00
Pu239	4.14E-03	1.32E-02	4.01E-02	9.70E+00
Pu240	4.14E-03	1.32E-02	4.01E-02	9.70E+00
Ru106	9.09E-03	2.88E-02	8.84E-02	9.72E+00
Sb125	3.80E-02	1.21E-01	3.73E-01	9.83E+00
Sr90	4.56E-02	1.45E-01	4.49E-01	9.86E+00
Tc99	4.52E-02	1.44E-01	4.45E-01	9.86E+00
U238	4.15E-02	1.32E-01	4.08E-01	9.85E+00

Table 9 presents calculations of the 5^{th}, 50^{th} and 95^{th} percentiles, as well as the uncertainty ratio ($95^{th}/5^{th}$). In each case the uncertainty factor is within 2% of the average value (9.8). The initial distribution applied for the input of depth uses 95^{th} percentile of 52m and 5^{th} percentile 5m (ratio 10.4). This indicates that the input distribution is propagated through the model without any significant amplification. In practise, because of the data available for water depth in coastal areas, the input distribution at a particular site will be far narrower than that used here as this encompasses the possibilities throughout the UK. Overall, these factors indicate a low-medium sensitivity to average depth.

4.1.2 Variation of residual velocity

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing residual velocity was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section A.2. In this case the outputs for all nuclides are similar in shape, generally log-normal in appearance with the highest frequencies approximately one quarter of the maximum plotted value (corresponding to 99th percentile).

Table 10 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the residual velocity parameter in the advection-diffusion model. In each case the uncertainty factor is within 2.5% of the average value (5.4). The initial distribution applied for the input uses 99th percentile of 0.14ms^{-1} (upper value) and 1st percentile 0.0012ms^{-1} (lower value). The ratio between upper and lower values is 117. This indicates that the uncertainty introduced by the variation of the parameter has decreased by approximately 22 times. Additionally, this parameter value may be estimated relatively easily, reducing the width of the input distribution. This indicates a low sensitivity to residual velocity.

Table 10. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the residual velocity parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	4.36E-04	1.01E-03	2.29E-03	5.25E+00
Co60	2.83E-03	6.54E-03	1.49E-02	5.27E+00
Cs137	6.27E-02	1.46E-01	3.40E-01	5.42E+00
H3	8.78E-02	2.05E-01	4.83E-01	5.50E+00
Po210	4.38E-05	1.01E-04	2.27E-04	5.18E+00
Pu239	7.97E-03	1.85E-02	4.21E-02	5.28E+00
Pu240	7.97E-03	1.85E-02	4.21E-02	5.28E+00
Ru106	1.75E-02	4.06E-02	9.24E-02	5.28E+00
Sb125	7.31E-02	1.70E-01	3.98E-01	5.45E+00
Sr90	8.77E-02	2.04E-01	4.82E-01	5.50E+00
Tc99	8.69E-02	2.03E-01	4.78E-01	5.50E+00
U238	7.98E-02	1.86E-01	4.37E-01	5.48E+00

4.1.3 Variation of diffusion coefficient

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing diffusion was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section A.3. In this case the outputs for all nuclides are similar in shape, with an appearance of a mixture between normal and log-normal plots. The highest frequencies occur in a band at approximately 40% of the plotted maximum.

Table 11 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the diffusion parameter in the advection-diffusion model. In each case the uncertainty factor is within 1% of the average value (3.1). The initial distribution applied as input uses 99th percentile of $14 m^2 s^{-1}$ (upper value) and 1st percentile $0.52 m^2 s^{-1}$ (lower value). The ratio between upper and lower values is 26.9. This indicates that the uncertainty introduced by the variation of the parameter has decreased by approximately 9 times. The diffusion coefficient input distribution can also be narrowed in a site-specific situation when compared with the deterministic model value, for example. These factors indicate that sensitivity of the model to diffusion is low.

Table 11. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the diffusion parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	6.29E-04	1.11E-03	1.97E-03	3.14E+00
Co60	4.08E-03	7.15E-03	1.27E-02	3.12E+00
Cs137	9.10E-02	1.60E-01	2.84E-01	3.12E+00
H3	1.28E-01	2.24E-01	3.99E-01	3.12E+00
Po210	6.29E-05	1.11E-04	1.97E-04	3.14E+00
Pu239	1.15E-02	2.02E-02	3.59E-02	3.12E+00
Pu240	1.15E-02	2.02E-02	3.59E-02	3.12E+00
Ru106	2.53E-02	4.43E-02	7.91E-02	3.13E+00
Sb125	1.06E-01	1.86E-01	3.32E-01	3.14E+00
Sr90	1.28E-01	2.24E-01	3.99E-01	3.12E+00
Tc99	1.27E-01	2.22E-01	3.95E-01	3.11E+00
U238	1.16E-01	2.03E-01	3.63E-01	3.13E+00

4.1.4 Variation of half tidal excursion

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing half tidal excursion was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section A.4. In this case the outputs for all nuclides are generally weighted towards the higher percentiles. The highest frequencies appear very close to the maximum plotted value.

Table 12 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the half tidal excursion parameter variation in the advection-diffusion model. In each case the uncertainty factor is within 5% of the average value (6.9). The initial distribution applied for the input uses 95th percentile of 11000m and 5th percentile 240m (ratio 45.8). This indicates that the uncertainty introduced by the variation of the parameter has decreased by approximately 6.5 times upon propagation through the model. The tidal excursion can be estimated relatively accurately at specific sites and as such it can be expected that this parameter has a relatively low sensitivity in the advection-diffusion model.

Table 12. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the half tidal excursion parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	3.94E-04	1.11E-03	2.82E-03	7.16E+00
Co60	2.56E-03	7.18E-03	1.83E-02	7.15E+00
Cs137	5.99E-02	1.61E-01	4.05E-01	6.76E+00
H3	8.58E-02	2.25E-01	5.67E-01	6.61E+00
Po210	3.85E-05	1.11E-04	2.83E-04	7.35E+00
Pu239	7.26E-03	2.03E-02	5.15E-02	7.10E+00
Pu240	7.26E-03	2.03E-02	5.15E-02	7.10E+00
Ru106	1.59E-02	4.46E-02	1.13E-01	7.11E+00
Sb125	7.03E-02	1.87E-01	4.73E-01	6.73E+00
Sr90	8.58E-02	2.25E-01	5.67E-01	6.61E+00
Tc99	8.50E-02	2.23E-01	5.62E-01	6.61E+00
U238	7.75E-02	2.05E-01	5.16E-01	6.66E+00

4.1.5 Variation of suspended sediment load and sedimentation rate

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing suspended sediment load and sedimentation rate was varied according to the log-normal distribution described in Section 3.3.2. All other parameters were given default values as listed in Tables 1 & 7.

Table 13 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the suspended sediment load parameter in the advection-diffusion model. Because the ratio between sediment load and sedimentation rate is kept constant the sedimentation rate is varied proportionally. In each case the output uncertainty factor is nuclide dependent. The initial distribution applied for the input uses 99th percentile of 200mg l^{-1} (upper value) and 1st percentile 0.2mg l^{-1} (lower value). The ratio between upper and lower values is 1000.

Table 13. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the suspended sediment load parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	1.62E-03	1.70E-02	1.08E-01	6.68E+01
Co60	1.04E-02	8.00E-02	1.99E-01	1.92E+01
Cs137	1.82E-01	2.28E-01	2.33E-01	1.28E+00
H3	2.33E-01	2.33E-01	2.33E-01	1.00E+00
Po210	1.63E-04	1.81E-03	1.85E-02	1.14E+02
Pu239	2.86E-02	1.43E-01	2.21E-01	7.74E+00
Pu240	2.86E-02	1.43E-01	2.21E-01	7.74E+00
Ru106	6.03E-02	1.86E-01	2.28E-01	3.78E+00
Sb125	2.04E-01	2.30E-01	2.33E-01	1.14E+00
Sr90	2.33E-01	2.33E-01	2.33E-01	1.00E+00
Tc99	2.32E-01	2.33E-01	2.33E-01	1.00E+00
U238	2.18E-01	2.32E-01	2.33E-01	1.07E+00

The output distributions for each radionuclide are presented as histograms in Section A.5. In this case the outputs for all nuclides differ significantly. Radionuclides can be broken up into four groups, namely;

1) Very Low sediment affinity ($K_D \equiv 10^0$). H3, Sr90. These show zero sensitivity to changes in sediment load and output the same value for each of the 500 runs.
2) Low sediment affinity ($K_D \equiv 10^3$). Cs137+, Sb125, Tc99, U238+. The plots are generally weighted towards the higher percentiles. These nuclides also show a low sensitivity to sediment load changes, with an average uncertainty ratio of 1.1.
3) Medium sediment affinity ($K_D \equiv 10^4$ to 10^5). Co60, Pu239, Pu240, Ru106+. These nuclides show an increase of uncertainty (average 9.6) and a flattening of distributions. There is a distinct movement of higher frequencies from the higher part of the distribution towards the minimum plotted value as K_D increases.
4) High sediment affinity ($K_D \equiv 10^6$ to 10^7). Am-241, Po-210. These nuclides correspond with the highest uncertainty ratios (average 90.4 – high sensitivity), with plots resembling log-normal distributions. Highest histogram frequencies are obtained at less than 10% of the plotted maximum.

The suspended sediment load and sedimentation rate are often difficult to quantify for an entire site. Because of this, input distributions can often span one or two orders of magnitude. As such, high sensitivities are expected for nuclides with high affinity for sediment (high K_D).

4.1.6 Variation of sediment distribution coefficient (K_D)

A run of 500 iterations of the advection-diffusion model was conducted whereby the parameter describing sediment distribution coefficient was varied according to the log-normal distribution described in Section 3.3.2. All other parameters were given default values as listed in Tables 1 & 7.

Table 14 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the sediment distribution coefficient variation in the advection-diffusion model. In each case the uncertainty factor is nuclide dependent. The initial distributions applied for the input are nuclide dependent (see Table 8), but use a ratio of 100 between the upper (99th) and lower (1st) percentiles.

Table 14. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the sediment distribution parameter in the advection-diffusion model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	2.31E-04	1.15E-03	5.65E-03	2.45E+01
Co60	1.48E-03	7.48E-03	3.31E-02	2.24E+01
Cs137	7.63E-02	1.66E-01	2.16E-01	2.83E+00
H3	2.33E-01	2.33E-01	2.33E-01	1.00E+00
Po210	2.34E-05	1.15E-04	5.56E-04	2.38E+01
Pu239	4.46E-03	2.11E-02	7.60E-02	1.70E+01
Pu240	4.57E-03	2.11E-02	7.77E-02	1.70E+01
Ru106	1.09E-02	4.60E-02	1.29E-01	1.18E+01
Sb125	1.16E-01	1.94E-01	2.24E-01	1.93E+00
Sr90	2.32E-01	2.33E-01	2.33E-01	1.00E+00
Tc99	2.22E-01	2.31E-01	2.33E-01	1.05E+00
U238	1.57E-01	2.12E-01	2.29E-01	1.46E+00

The output distributions for each radionuclide are presented as histograms in Section A.6. In this case the water concentration distribution output for each nuclide differs in shape. As with Section 4.1.5, the radionuclides fall into one of four categories in which the distribution shapes and uncertainty ratios when varying K_D values can be described. Note that recommended K_D values are shown below rather than the ranges that are input into the model for the sensitivity analysis.

1) Very Low sediment affinity ($K_D \equiv 10^0$). H3, Sr90. These show little to no variation with changes in sediment distribution coefficient. Uncertainty ratios of 1.0 show that these nuclides are insensitive to changes in the K_D parameter.
2) Low sediment affinity ($K_D \equiv 10^3$). Cs137+, Sb125, Tc99, U238+. The plots are generally weighted towards the higher percentiles, with highest frequencies at approximately 90% of the maximum plotted value. These nuclides also show a low sensitivity to K_D changes, with an average uncertainty ratio of 1.8.
3) Medium sediment affinity ($K_D \equiv 10^4$ to 10^5). Co60, Pu239, Pu240, Ru106+. These nuclides show an increase of uncertainty (average

17.0) and a flattening of distributions. Lower K_D values tend to be more evenly distributed.

4) High sediment affinity ($K_D \equiv 10^6$ to 10^7). Am-241, Po-210. These nuclides correspond with the highest uncertainty ratios (average 24.2), with plots resembling log-normal distributions with the highest frequency of values near 20% of the maximum plotted value.

It should be noted that the sediment distribution coefficient (K_D) is defined from IAEA (2004), and the input distributions for this parameter cannot be narrowed down for specific sites unless accurate detailed site-specific data is available. This is not often available for K_D. In general, the inputs will remain the same as the values applied in this study, meaning that the sensitivity of changes to K_D for Am-241, Po-210 and Co-60 can be considered to be high, and sensitivity of Pu239, Pu240 and Ru106+ medium to high. Other radionuclides are relatively insensitive to changes in K_D in the advection-diffusion model.

4.2 Single Compartment Model Results

The results for varying specific parameters in the single compartment model are described below. Each parameter and its discussion are considered as a separate sub-section. Pointers are given to histogram plots, which reside in Appendix B.

4.2.1 Variation of average depth

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing average depth was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.1. In this case the outputs for all nuclides are similar in shape, generally log-normal in appearance with highest frequencies at approximately 10% of the maximum plotted value.

Table 15 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th). In each case the uncertainty factor is within 5% of the average value (10.2). The initial distribution applied for the input of depth uses 95th percentile of 52m and 5th percentile 5m (ratio 10.4). This indicates that the parameter is propagated through the model with little amplification in a similar manner to the advection-diffusion model (Section 4.1.1). Thus a low-medium sensitivity can be expected.

Table 15. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the average depth parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Uncertainty*
Am241	1.98E-04	6.33E-04	1.95E-03	9.86E+00
Co60	1.28E-03	4.10E-03	1.26E-02	9.86E+00
Cs137	2.86E-02	9.28E-02	2.98E-01	1.04E+01
H3	4.02E-02	1.31E-01	4.28E-01	1.07E+01
Po210	1.96E-05	6.26E-05	1.92E-04	9.81E+00
Pu239	3.63E-03	1.16E-02	3.58E-02	9.88E+00
Pu240	3.63E-03	1.16E-02	3.58E-02	9.88E+00
Ru106	7.92E-03	2.55E-02	7.91E-02	9.99E+00
Sb125	3.34E-02	1.09E-01	3.51E-01	1.05E+01
Sr90	4.02E-02	1.31E-01	4.28E-01	1.07E+01
Tc99	3.98E-02	1.30E-01	4.24E-01	1.07E+01
U238	3.65E-02	1.19E-01	3.86E-01	1.06E+01

4.2.2 Variation of residual velocity

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing residual velocity was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.2. In this case the outputs for all nuclides are similar in shape, generally log-normal in appearance with the highest frequencies at approximately 20% of the maximum plotted value.

Table 16. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the residual velocity parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	1.47E-04	7.85E-04	3.64E-03	2.48E+01
Co60	9.53E-04	5.09E-03	2.35E-02	2.47E+01
Cs137	2.12E-02	1.16E-01	5.90E-01	2.79E+01
H3	2.98E-02	1.64E-01	8.72E-01	2.93E+01
Po210	1.48E-05	7.79E-05	3.45E-04	2.33E+01
Pu239	2.69E-03	1.44E-02	6.74E-02	2.51E+01
Pu240	2.69E-03	1.44E-02	6.74E-02	2.51E+01
Ru106	5.91E-03	3.17E-02	1.47E-01	2.49E+01
Sb125	2.48E-02	1.36E-01	6.98E-01	2.82E+01
Sr90	2.98E-02	1.64E-01	8.72E-01	2.93E+01
Tc99	2.95E-02	1.62E-01	8.64E-01	2.93E+01
U238	2.71E-02	1.48E-01	7.81E-01	2.89E+01

Table 16 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the residual velocity parameter in the single compartment model. For each nuclide the uncertainty factor is within 10% of the average value (26.7). The initial distribution applied for the input uses 99th percentile of 0.14ms^{-1} (upper value) and 1st percentile 0.0012ms^{-1} (lower value). The ratio between upper and lower values is 117. This indicates that the uncertainty introduced by the variation of the parameter has decreased by approximately 4.4 times. For site-specific application the span of the input distribution can be reduced for this parameter. However, it should be noted that the single compartment model is more sensitive to this parameter than the advection-diffusion model (Section 4.1.2). Because of this, the parameter is deemed to be of low-medium sensitivity.

4.2.3 Variation of offshore extent

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing offshore extent was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.3. In this case the outputs for all nuclides are similar in shape, generally log-normal in appearance with peak frequencies at the lower end of the distribution (approximately 10% of the maximum plotted value).

Table 17. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the offshore extent parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	2.03E-04	9.99E-04	5.08E-03	2.50E+01
Co60	1.32E-03	6.49E-03	3.29E-02	2.50E+01
Cs137	3.01E-02	1.49E-01	7.53E-01	2.50E+01
H3	4.27E-02	2.11E-01	1.07E+00	2.51E+01
Po210	2.01E-05	9.89E-05	5.02E-04	2.50E+01
Pu239	3.72E-03	1.84E-02	9.32E-02	2.51E+01
Pu240	3.72E-03	1.84E-02	9.32E-02	2.51E+01
Ru106	8.18E-03	4.04E-02	2.04E-01	2.50E+01
Sb125	3.52E-02	1.74E-01	8.82E-01	2.51E+01
Sr90	4.27E-02	2.11E-01	1.07E+00	2.51E+01
Tc99	4.23E-02	2.09E-01	1.06E+00	2.51E+01
U238	3.87E-02	1.91E-01	9.68E-01	2.50E+01

Table 17 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the offshore extent parameter in the single compartment model. In each case the uncertainty factor is within 1% of the average value (25.1). The initial distribution applied for the input uses 99th percentile of 14m^{2}s^{-1} (upper value) and 1st percentile 0.52m^{2}s^{-1} (lower value). The ratio between upper and lower values is 26.9. This indicates that the uncertainty introduced by the variation of the parameter has been propagated through the model without amplification, as with the average depth (Section 4.2.1). This is expected, as these two parameters occupy identical positions in the definition of Exchange Volume and Dispersion Factor in Section 3.2. The physical environment of the site in question usually defines the offshore extent. Because of this, uncertainty in the parameter can be decreased sufficiently to consider sensitivity to be low-medium.

4.2.4 Variation of half tidal excursion

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing half tidal excursion was varied according to the log-normal distribution described in Section 3.1.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.4. In this case the outputs for all nuclides are similar in shape, with the highest frequencies close to the maximum of the distribution.

Table 18 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the half tidal excursion parameter variation in the single compartment model. In each case the uncertainty factor is within 25% of the average value (1.2), with a maximum value of 1.46. The initial distribution applied for the input uses 95th percentile of 11000m and 5th percentile 240m (ratio 45.8). This indicates that the uncertainty introduced by the variation of the parameter has decreased to an almost insignificant level, which in turn implies a very low sensitivity.

Table 18. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the half tidal excursion parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	7.77E-04	1.00E-03	1.04E-03	1.34E+00
Co60	5.04E-03	6.48E-03	6.76E-03	1.34E+00
Cs137	1.37E-01	1.49E-01	1.51E-01	1.10E+00
H3	2.10E-01	2.11E-01	2.11E-01	1.00E+00
Po210	7.11E-05	9.87E-05	1.04E-04	1.46E+00
Pu239	1.45E-02	1.84E-02	1.91E-02	1.32E+00
Pu240	1.45E-02	1.84E-02	1.91E-02	1.32E+00
Ru106	3.17E-02	4.03E-02	4.19E-02	1.32E+00
Sb125	1.63E-01	1.74E-01	1.76E-01	1.08E+00
Sr90	2.11E-01	2.11E-01	2.11E-01	1.00E+00
Tc99	2.08E-01	2.09E-01	2.09E-01	1.00E+00
U238	1.86E-01	1.91E-01	1.92E-01	1.03E+00

4.2.5 Variation of suspended sediment load and sedimentation rate

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing suspended sediment load and sedimentation rate was varied according to the log-normal distribution described in Section 3.3.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.5. In this case the outputs for all nuclides are similar in shape, to those described in the advection-diffusion model run (see Section 4.1.5).

Table 19. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the suspended sediment load parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	1.35E-03	1.49E-02	9.91E-02	7.34E+01
Co60	8.65E-03	7.09E-02	1.80E-01	2.08E+01
Cs137	1.61E-01	2.06E-01	2.11E-01	1.31E+00
H3	2.11E-01	2.11E-01	2.11E-01	1.00E+00
Po210	1.33E-04	1.56E-03	1.69E-02	1.27E+02
Pu239	2.40E-02	1.28E-01	2.00E-01	8.34E+00
Pu240	2.40E-02	1.28E-01	2.00E-01	8.34E+00
Ru106	5.10E-02	1.66E-01	2.05E-01	4.02E+00
Sb125	1.82E-01	2.08E-01	2.11E-01	1.16E+00
Sr90	2.11E-01	2.11E-01	2.11E-01	1.00E+00
Tc99	2.10E-01	2.11E-01	2.11E-01	1.00E+00
U238	1.96E-01	2.10E-01	2.11E-01	1.08E+00

Table 19 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the variation of the suspended sediment load parameter in the single compartment model. Because the ratio between sediment load and sedimentation rate is kept constant, the sedimentation rate is also varied proportionally. In each case the output uncertainty factor is nuclide dependent. The initial distribution applied for the input uses 99th percentile of 200mg l^{-1} (upper value) and 1st percentile 0.2mg l^{-1} (lower value). The ratio between upper and lower values is 1000.

Similar behaviour to the advection-diffusion model output is seen, with the groupings of nuclides according to their K_D values apparent. The groupings and relevant uncertainty ratios are:

1) Very Low sediment affinity ($K_D \equiv 10^0$). H3, Sr90. These show zero sensitivity to changes in sediment load and output the same value for each of the 500 runs.
2) Low sediment affinity ($K_D \equiv 10^3$). Cs137+, Sb125, Tc99, U238+. These nuclides also show a low sensitivity to sediment load changes, with an average uncertainty ratio of 1.1.
3) Medium sediment affinity ($K_D \equiv 10^4$ to 10^5). Co60, Pu239, Pu240, Ru106+. These nuclides show an increase of uncertainty (average 10.4). There is an obvious increase in calculated uncertainty as K_D increases.

4) High sediment affinity ($K_D \equiv 10^6$ to 10^7). Am-241, Po-210. These nuclides correspond with the highest uncertainty ratios (average 100), corresponding to high sensitivity.

4.2.6 Variation of sediment distribution coefficient (K_D)

A run of 500 iterations of the single compartment model was conducted whereby the parameter describing sediment distribution coefficient was varied according to the log-normal distribution described in Section 3.3.2. All other parameters were given default values as listed in Tables 1 & 7.

The output distributions for each radionuclide are presented as histograms in Section B.6. In this case the outputs for all nuclides are similar in shape to those obtained for the advection-diffusion model (Section 4.1.6).

Table 20 presents calculations of the 5th, 50th and 95th percentiles, as well as the uncertainty ratio (95th/5th) for the sediment distribution coefficient variation in the single compartment model. In each case the uncertainty factor is nuclide dependent. The initial distributions applied for the input are nuclide dependent (see Table 8), but use a ratio of 100 between the upper (99th) and lower (1st) percentiles.

Table 20. The 5th, 50th and 95th percentiles of water concentration (Bq l^{-1}) and uncertainty ratio (95th/5th) obtained through the variation of the sediment distribution parameter in the single compartment model.

	5th %	*50th %*	*95th %*	*Ratio*
Am241	2.07E-04	1.00E-03	5.19E-03	2.51E+01
Co60	1.31E-03	6.55E-03	2.80E-02	2.14E+01
Cs137	6.62E-02	1.49E-01	1.95E-01	2.94E+00
H3	2.11E-01	2.11E-01	2.11E-01	1.00E+00
Po210	1.89E-05	9.94E-05	4.80E-04	2.54E+01
Pu239	4.17E-03	1.85E-02	7.08E-02	1.70E+01
Pu240	4.04E-03	1.84E-02	6.91E-02	1.71E+01
Ru106	9.03E-03	4.05E-02	1.13E-01	1.25E+01
Sb125	1.03E-01	1.75E-01	2.02E-01	1.96E+00
Sr90	2.10E-01	2.11E-01	2.11E-01	1.00E+00
Tc99	2.00E-01	2.09E-01	2.11E-01	1.06E+00
U238	1.40E-01	1.91E-01	2.07E-01	1.48E+00

As with Section 4.1.6, the radionuclides fall into one of four categories in which the distribution shapes and uncertainty ratios when varying K_D values can be described. Note, as in Section 4.1.6 the recommended K_D values are shown below rather than the ranges that are input into the model for the sensitivity analysis.

1) Very Low sediment affinity ($K_D \equiv 10^0$). H3, Sr90. These show little to no variation with changes in sediment distribution coefficient. Uncertainty ratios of 1.0 show that these nuclides are insensitive to changes in the K_D parameter.

2) Low sediment affinity ($K_D \equiv 10^3$). Cs137+, Sb125, Tc99, U238+. These nuclides also show a low sensitivity to K_D changes, with an average uncertainty ratio of 1.9.
3) Medium sediment affinity ($K_D \equiv 10^4$ to 10^5). Co60, Pu239, Pu240, Ru106+. These nuclides show an increase of uncertainty (average 17.0). Lower K_D values tend have lower sensitivities.
4) High sediment affinity ($K_D \equiv 10^6$ to 10^7). Am-241, Po-210. These nuclides correspond with the highest uncertainty ratios (average 25.3), and subsequently the highest sensitivities.

The uncertainty in K_D for the single compartment model is almost identical for that obtained in the advection-diffusion model. Thus, using the same argument as Section 4.1.6, the sensitivity of changes to K_D for Am-241, Po-210 and Co-60 can be considered to be high, and sensitivity of Pu239, Pu240 and Ru106+ medium to high. Other radionuclides are relatively insensitive to changes in K_D in the single compartment model.

5. Conclusions

A sensitivity analysis of six parameters has been investigated for two modes (advection-diffusion and single compartment) of the PRAME model for prediction of radionuclide concentrations from liquid discharges to the marine environment. These have been presented for 12 radionuclides covering a range of behaviours, with particular emphasis on sediment K_D.

A summary of results for the advection-diffusion and single compartment model parameters is shown in Tables 21 and 22 respectively. Sensitivities have been assigned a grading of Low, Medium or High (or combinations), depending on:

1) The extent of the reduction of the input uncertainty factor compared to the output.
2) The possibility of easily reducing the input distributions with current site-specific data.

If further significant effort is needed to accurately narrow the input distributions the sensitivity is based on the calculated output uncertainty ($95^{th}/5^{th}$ percentile). This enables one of the aims of a sensitivity analysis to be fulfilled; that is, to determine where effort should be focussed to reduce the uncertainty of predictions.

Table 21. Summary of input and average output uncertainties, possibility of site-specific reductions in uncertainty and overall sensitivity for advection-diffusion model parameters.

Parameter		*Uncertainty*		*Site-Specific Reduction?*	*Sensitivity*
		Input	*Output*		
Average Depth		10.4	9.8	Yes	Low-Med*
Residual Velocity		117	5.4	Yes	Low
Diffusion Coefficient		26.9	3.1	Yes	Low
Half Tidal Excursion		45.8	6.9	Yes	Low
SSL & SR	H3, Sr90	1000	1.0	Some, with effort	Insensitive
	Cs137+, Sb125, Tc99, U238		1.1		Very Low
	Co60, Pu239, Pu240, Ru106		9.6		Medium
	Am241, Po210		90.4		High
K_D	H3, Sr90	100	1.0	Unlikely	Insensitive
	Cs137+, Sb125, Tc99, U238		1.8		Low
	Co60, Pu239, Pu240, Ru106		17.0		Med-High
	Am241, Po210		24.2		High

Each of the parameter values and reasons for assigning particular sensitivity gradings has been discussed in detail in Section 5 and will not be repeated here. However, it should be noted that the asterisked parameter values propagate input uncertainties in a linear fashion. This means that the uncertainty introduced into the model in the input for this parameter will be propagated through the model and output with minimal reduction. Each of these parameters has been assigned a “Low-Medium” rating based on the availability of site-specific data (and thus narrowing of input distributions), but has the potential to introduce “High” uncertainty if the user inputs a UK-wide parameter as considered in this study.

Table 22. Summary of input and output uncertainties, possibility of site-specific reductions in uncertainty and overall sensitivity for single compartment model parameters.

Parameter		*Uncertainty*		*Site-Specific Reduction?*	*Sensitivity*
		Input	*Output*		
Average Depth		10.4	10.2	Yes	Low-Med*
Residual Velocity		117	26.7	Yes	Low-Med
Offshore Extent		26.9	25.1	Yes	Low-Med*
Half Tidal Excursion		45.8	1.2	Yes	Very Low
SSL & SR	H3, Sr90	1000	1.0	Some, with effort	Insensitive
	Cs137+, Sb125, Tc99, U238		1.1		Low
	Co60, Pu239, Pu240, Ru106		10.4		Medium
	Am241, Po210		100		High
K_D	H3, Sr90	100	1.0	Unlikely	Insensitive
	Cs137+, Sb125, Tc99, U238		1.9		Low
	Co60, Pu239, Pu240, Ru106		17.0		Med-High
	Am241, Po210		25.3		High

It is apparent that the major effort and resource should concentrate on the parameters deemed to be of “High” sensitivity. These are:

- Suspended Sediment Load and Sedimentation Rate,
- Sediment Distribution Coefficient (K_D).

The sensitivity of both advection-diffusion and single compartment models increases with higher K_D value, and as such radionuclides with high sediment affinity should be focussed upon.

In addition, it is important that Average Depth (both modes), Residual Velocity (single compartment) and Offshore Extent input distributions are refined as much as possible to ensure that unnecessary uncertainty is not introduced and propagated through the model.

In their respective modes and situations, these six parameters can be considered to be of *primary* importance, with the remaining parameters assigned as *secondary*. This is based upon the propagation of uncertainty through the model for prediction of filtered water concentration.

It is envisaged that this sensitivity analysis may be used as a tool to help refine the PRAME model by focussing on reduction of uncertainties in the primary parameters. Further work to be conducted on the PRAME suite of models may include;

- Assessments at specific sites using expert-derived parameter distributions,
- Investigation of sensitivity and derivation of primary and secondary parameters for the ADOP module for dose calculation,
- Further refinement of K_D and sediment loads through a monitoring programme at specific sites, where the radionuclides present are found to significantly increase uncertainty.

6. References

Aldridge, J. N. (2000). Personal Communication, CEFAS Lowestoft.

Brownless, G. P., Grzechnik, M. P., Round, G. D. and Pidcock, A. J. (2001). Uncertainties in Assessing Doses to Members of the Public due to Radioactive Discharges to the Marine Environment. Environment Report RL 12/01, CEFAS Lowestoft.

Grzechnik, M. P. (2002). User Guide for Probabilistic Radiological Assessments of the Marine Environment PC Version 1.0, Environment Report RL 9/03, CEFAS Lowestoft.

Grzechnik, M. P., Round, G. D., Brownless, G. P., Camplin, W. C. (2002). A Probabilistic Modelling Suite for the Marine Environment. Environment Report RL 3/02, CEFAS Lowestoft.

Hunt, G. J. (1982). IDLE – A computer program to estimate individual doses from liquid effluents. Sizewell enquiry series, MAFF Direct. Fish Res., Lowestoft.

IAEA (1985). Sediment Kds and concentration factors in the marine environment. Technical Report Series 247, IAEA Vienna.

IAEA (1989). Evaluating the reliability of predictions made using environmental transfer models. Safety Series 100, IAEA Vienna.

IAEA (2004). Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment. Technical Report Series 422, IAEA Vienna.

Kershaw, P. (2000). Personal Communication, CEFAS Lowestoft.

NCRP (1996). A guide for uncertainty analysis in dose and risk assessments related to environmental contamination. Commentary No. 14.

NRPB (1998a). The variability in critical group doses from routine releases of radionuclides to the environment. National Radiological Protection Board, Contract Report M952

NRPB (1998b). Uncertainties in the assessment of terrestrial foodchain doses. National Radiological Protection Board, Memorandum M922

Round, G. D. (1998a). Individual Doses from Discharges of Liquid Effluents to the Aquatic Environment: Water Concentration Model – WAT. Environmental Tech. Note RL 2/98.

Round, G. D. (1998b). Individual Doses from Discharges of Liquid Effluents to the Aquatic Environment: Dosimetric Model – ADO. Environmental Tech. Note RL 8/98.

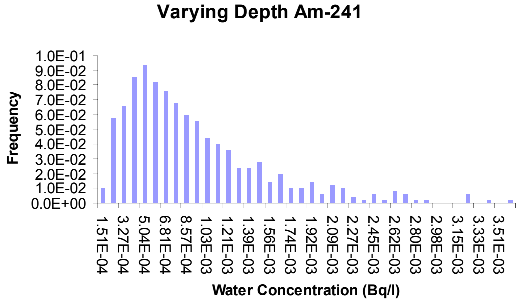
Appendix A – Output Distributions of Parameter Values from the Advection-Diffusion Model

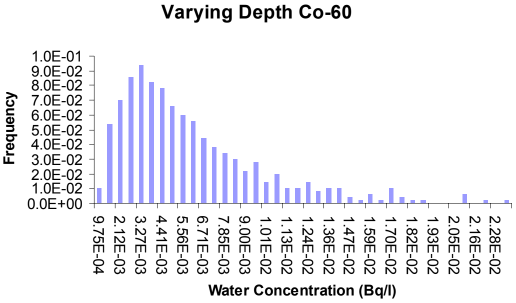
Output distributions of radionuclide concentrations in water from the advection-diffusion model are shown in the following Appendix, arranged according to the parameter that is being varied. Other parameters remain at the constant default values discussed in Section 3. The 1st and 99th percentiles of each distribution determine the minimum and maximum plotted values respectively.

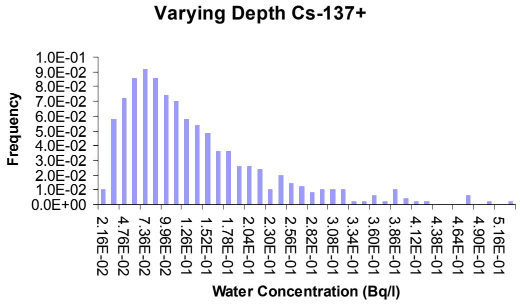
Note that sediment load and sedimentation rate are proportional due to correlations between the two (see Grzechnik 2003). Because of this, the sediment load is varied and the ratio between the two is kept constant. In this way, the sedimentation rate is varied proportionally.

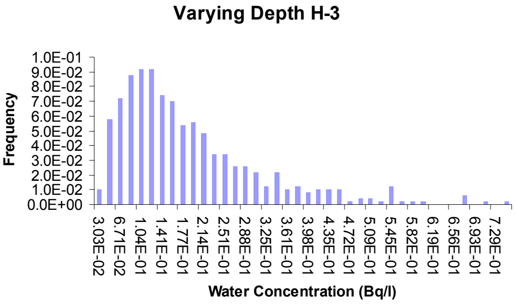
The K_D value for each radionuclide was initially varied independently in separate model runs to determine if any non-linear effects would occur. It was found that running the variation in all nuclides together gives the same distribution in the output water concentration for that nuclide as is obtained when independent runs are considered.

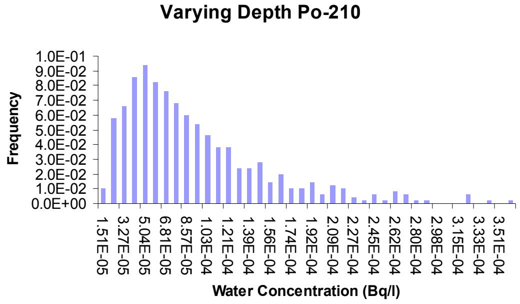
A.1 Average Depth

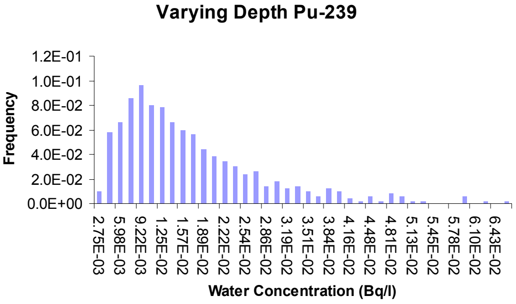

Varying Depth Am-241

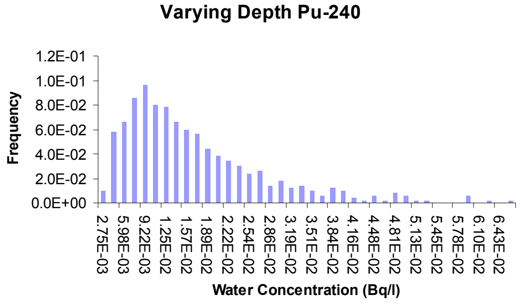

Varying Depth Co-60

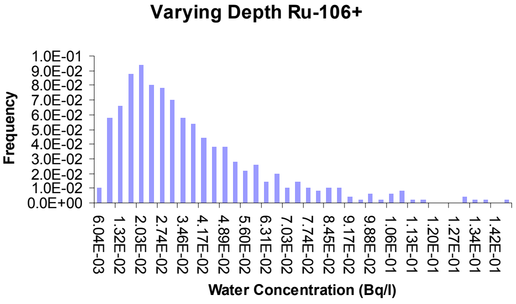

Varying Depth Cs-137+

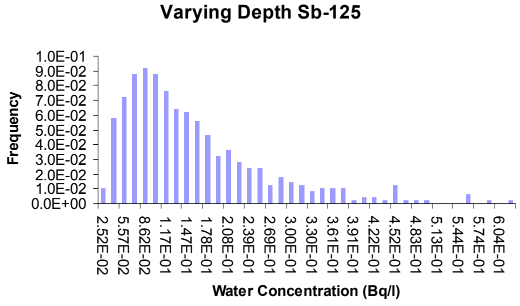

Varying Depth H-3

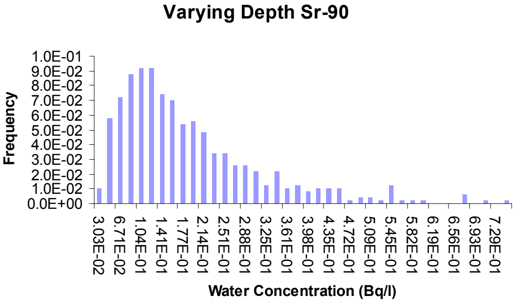

Varying Depth Po-210

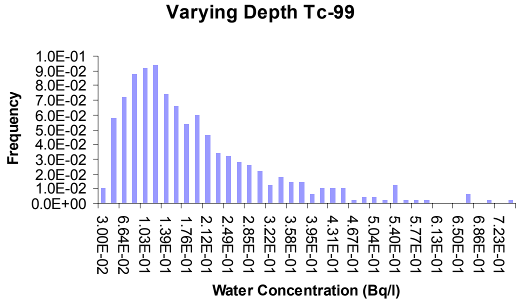

Varying Depth Pu-239

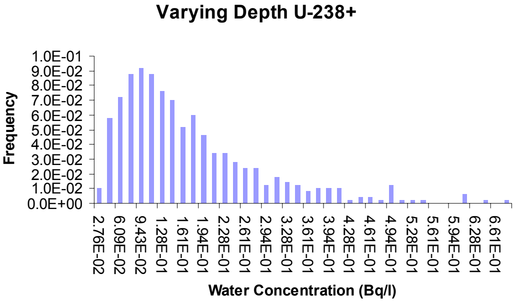

Varying Depth Pu-240


Varying Depth Ru-106+

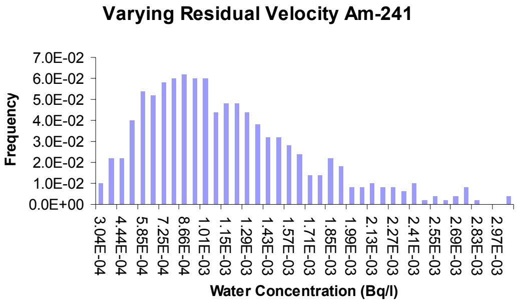

Varying Depth Sb-125

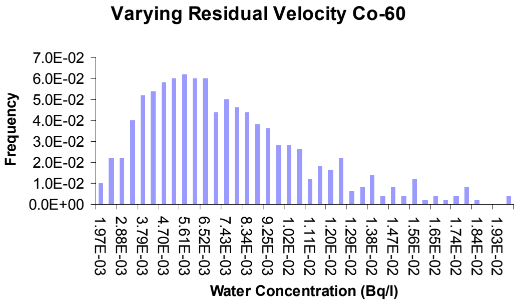

Varying Depth Sr-90

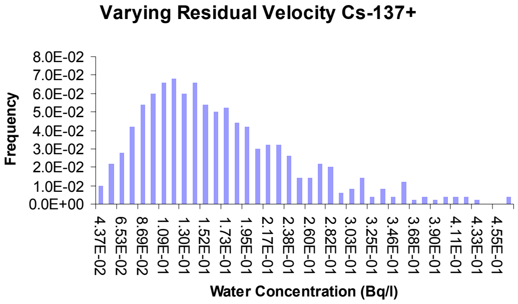

Varying Depth Tc-99

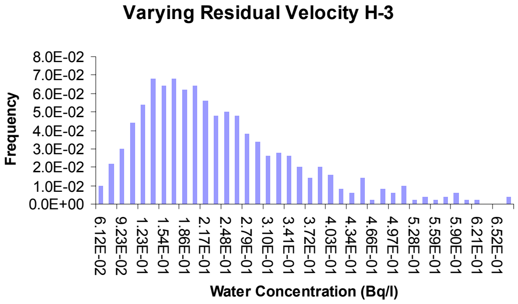

Varying Depth U-238+

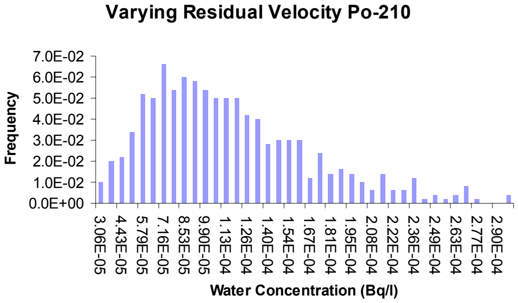
A.2 Residual Velocity

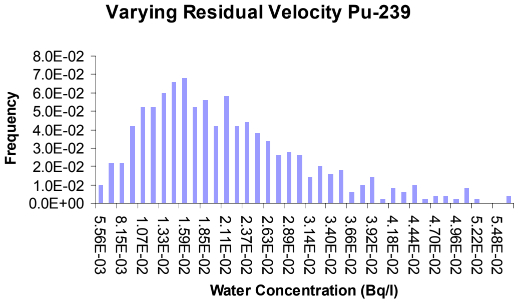


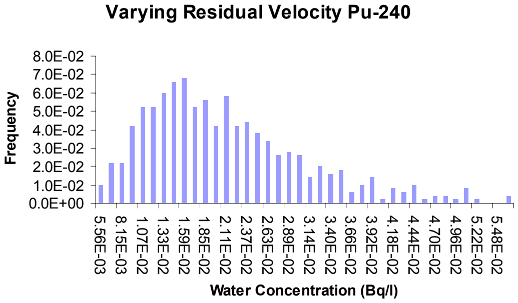


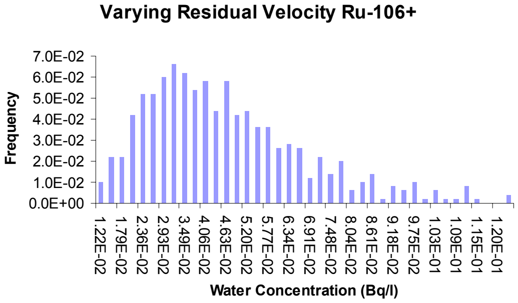


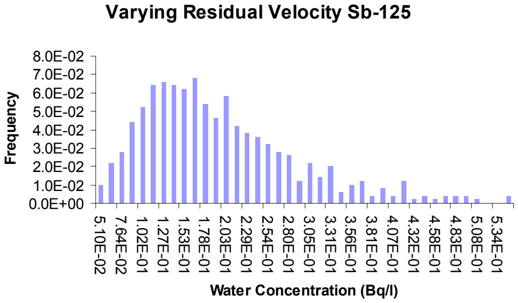


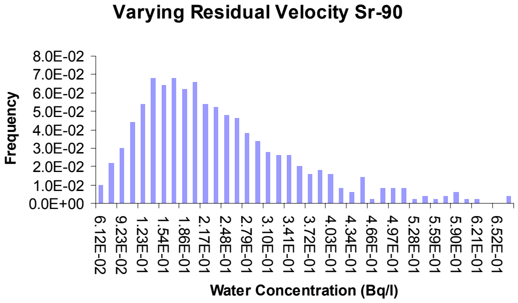


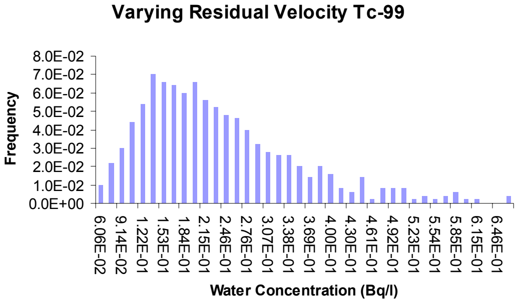


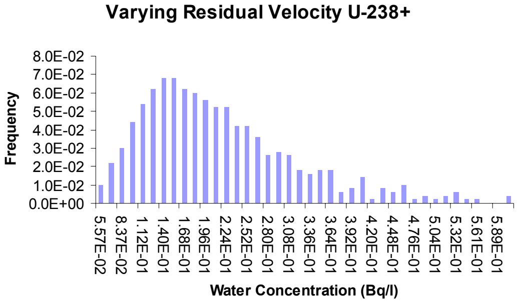




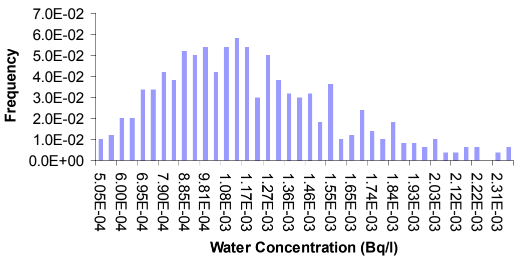


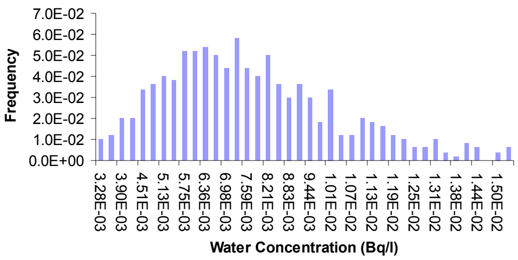


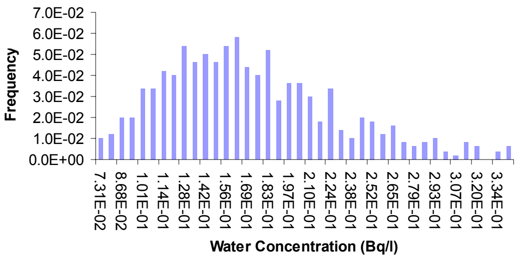


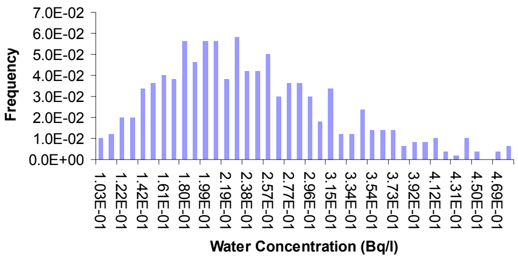


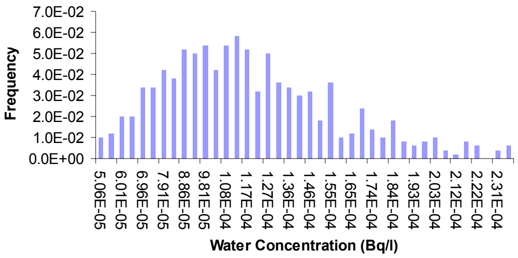
A.3 Diffusion Coefficient

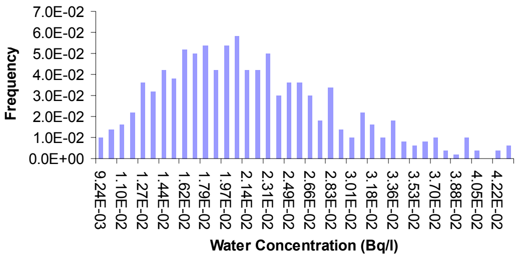

Varying Diffusion Am-241

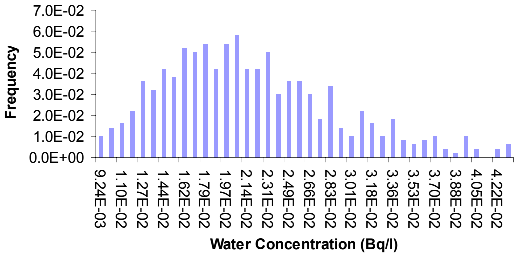

Varying Diffusion Co-60

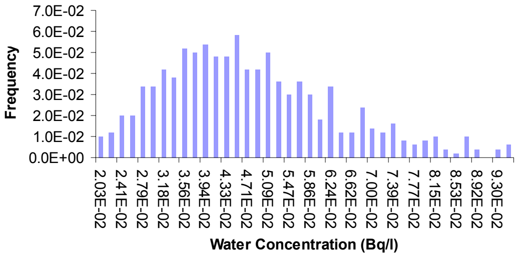

Varying Diffusion Cs-137+

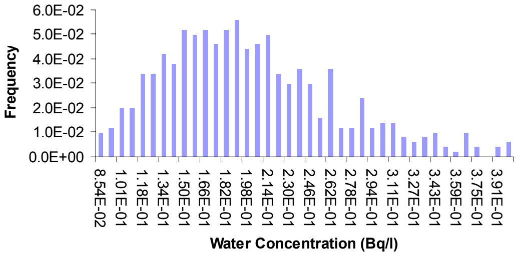

Varying Diffusion H-3

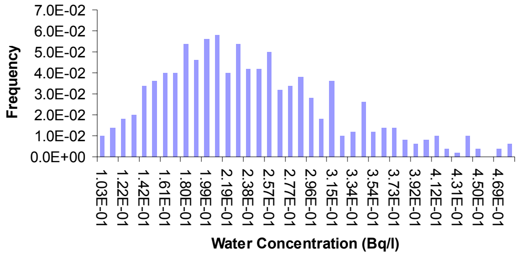

Varying Diffusion Po-210

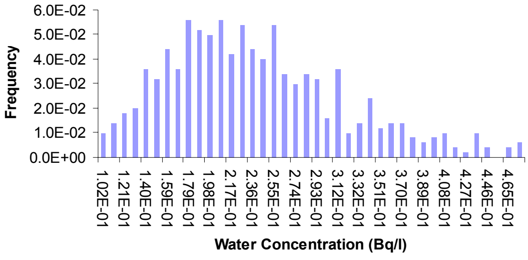

Varying Diffusion Pu-239

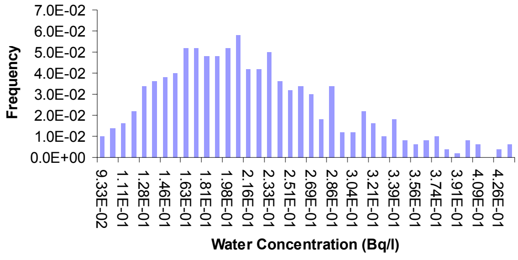

Varying Diffusion Pu-240


Varying Diffusion Ru-106+

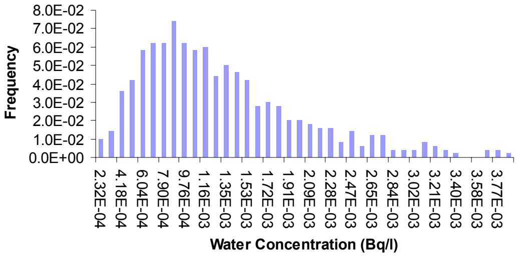

Varying Diffusion Sb-125

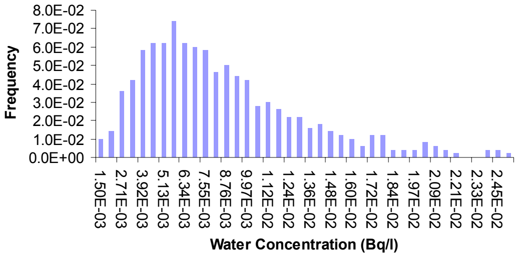

Varying Diffusion Sr-90

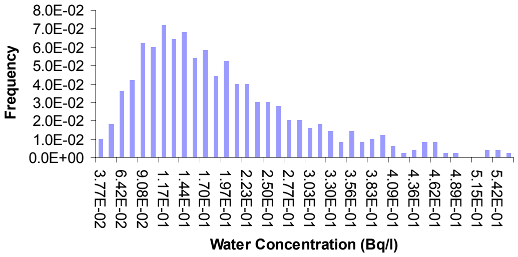

Varying Diffusion Tc-99

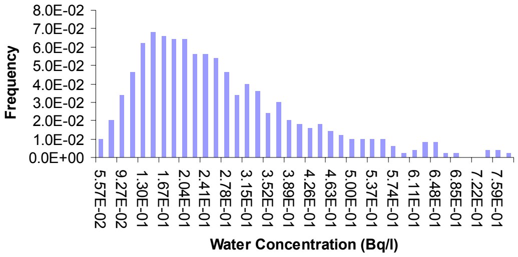

Varying Diffusion U-238+

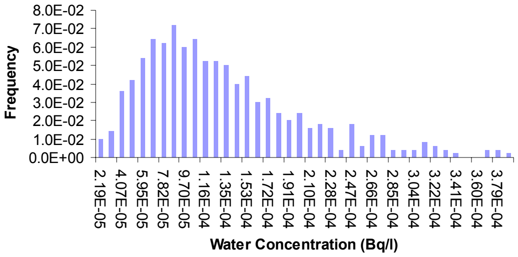
A.4 Half Tidal Excursion

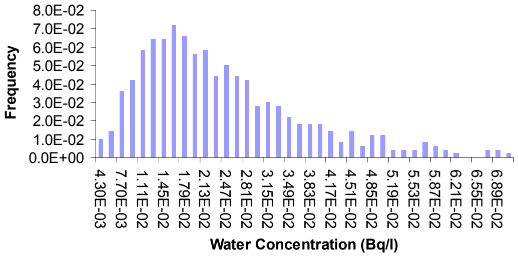

Varying Excursion Am-241

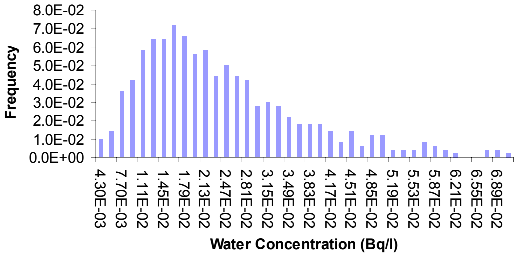

Varying Excursion Co-60

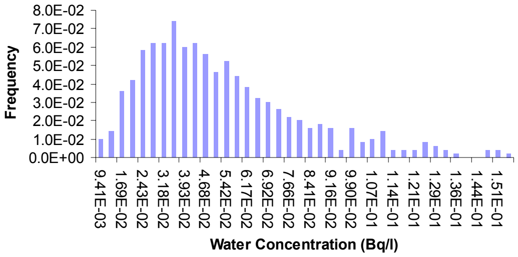

Varying Excursion Cs-137+

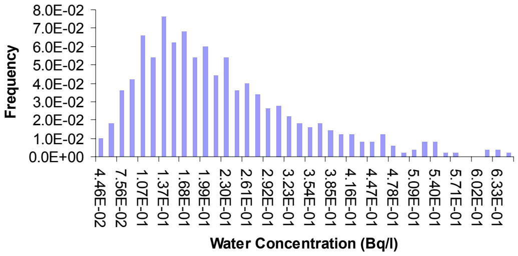

Varying Excursion H-3

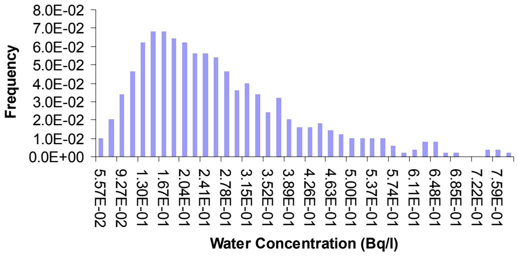

Varying Excursion Po-210

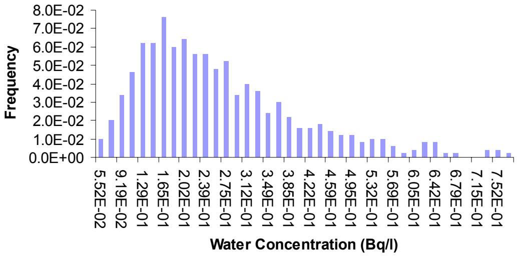

Varying Excursion Pu-239

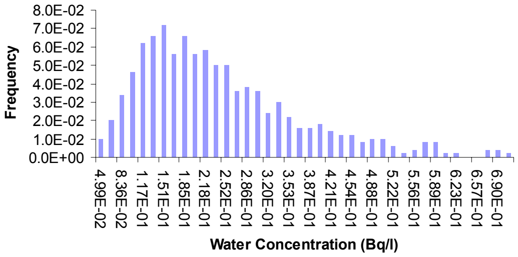

Varying Excursion Pu-240


Varying Excursion K_D Ru-106+

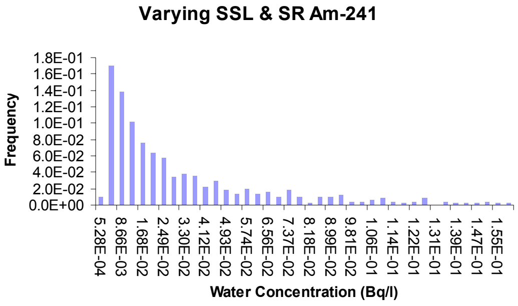

Varying Excursion Sb-125

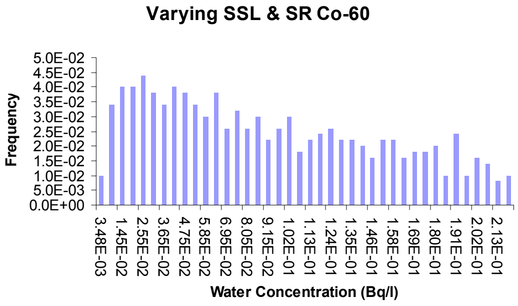

Varying Excursion Sr-90

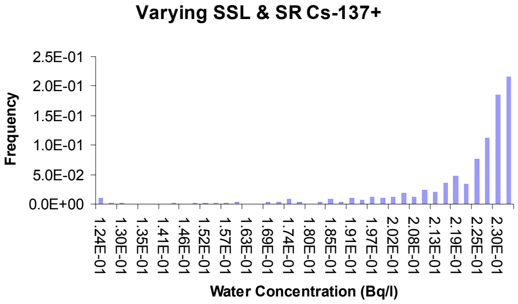

Varying Excursion Tc-99

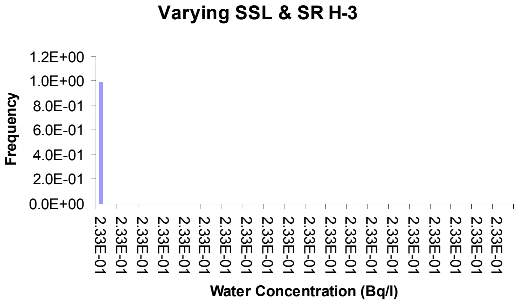

Varying Excursion U-238+

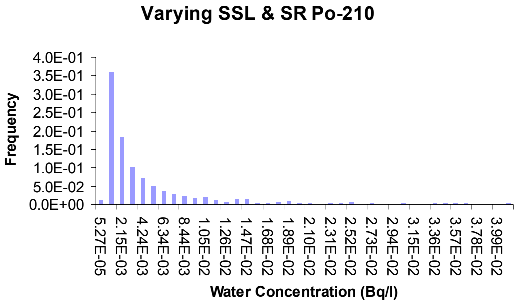
A.5 Suspended Sediment Load (SSL) & Sedimentation Rate (SR)

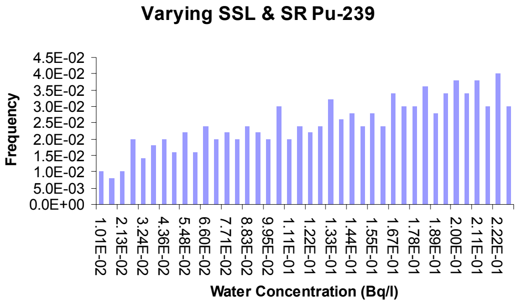


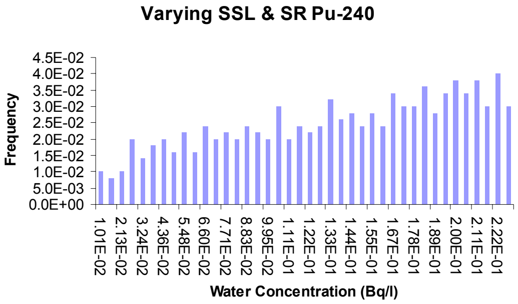


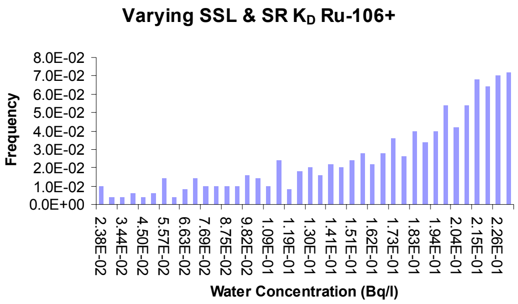


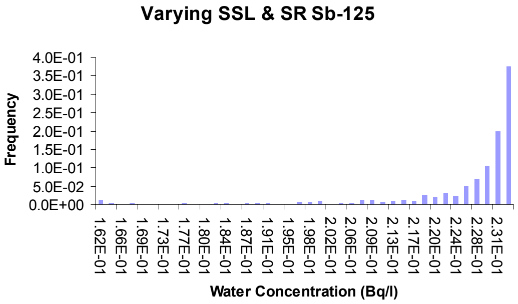


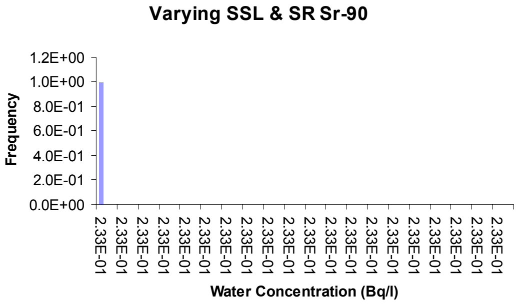


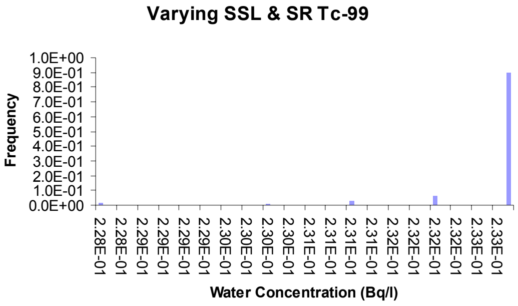


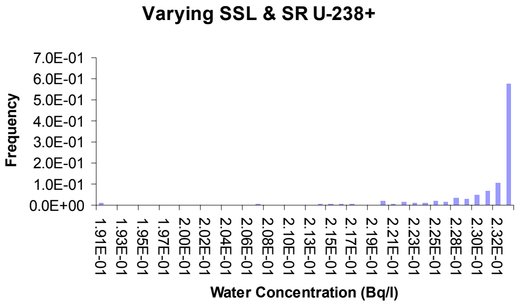




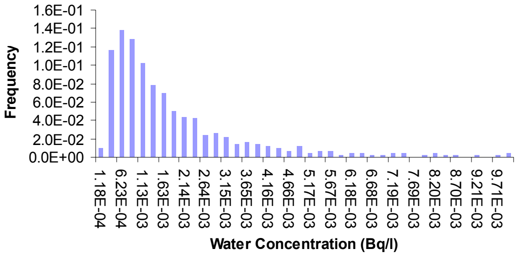


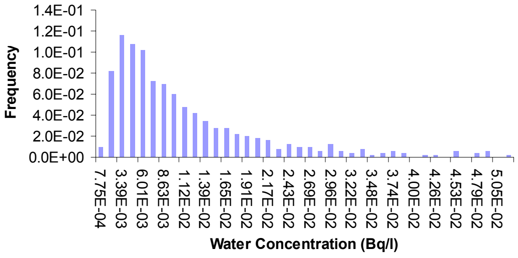


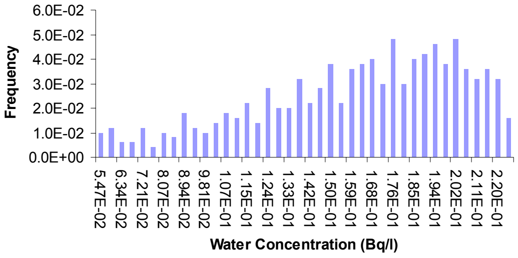


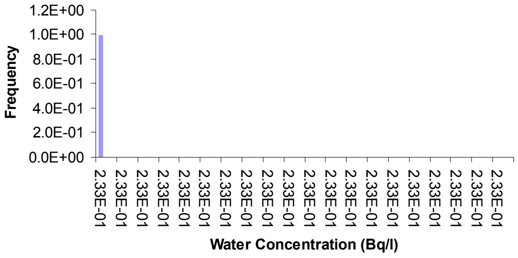


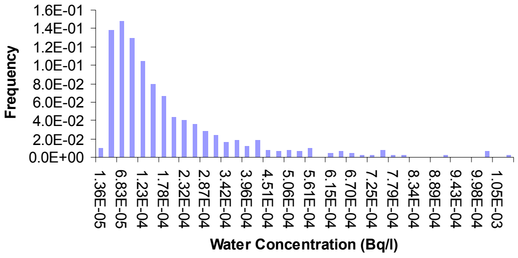
A.6 Sediment Distribution Coefficient (K_D)

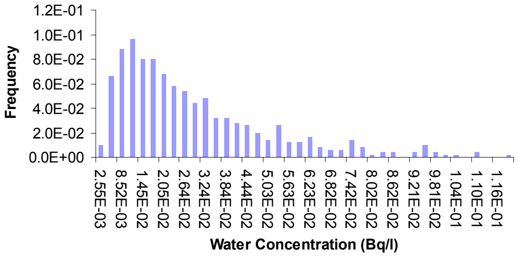

Varying K_D Am-241

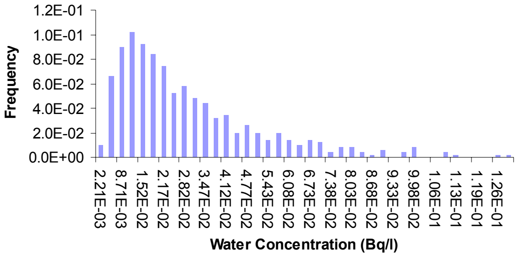

Varying K_D Co-60

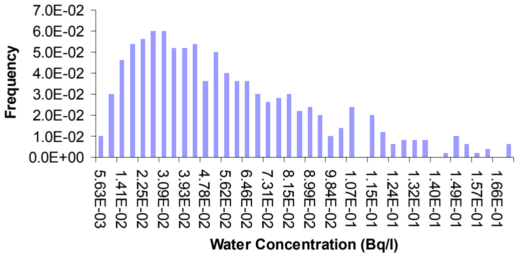

Varying K_D Cs-137+

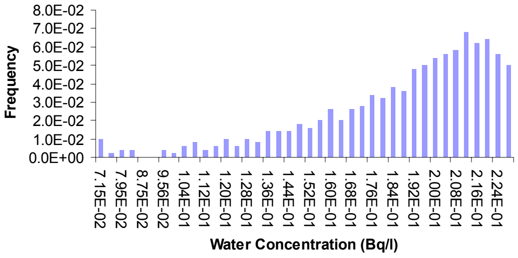

Varying K_D H-3

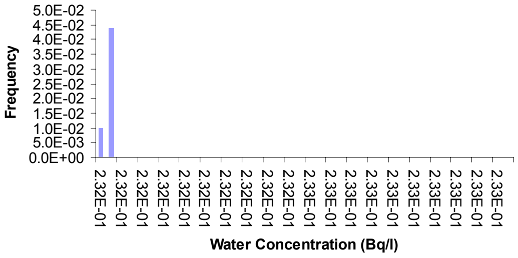

Varying K_D Po-210

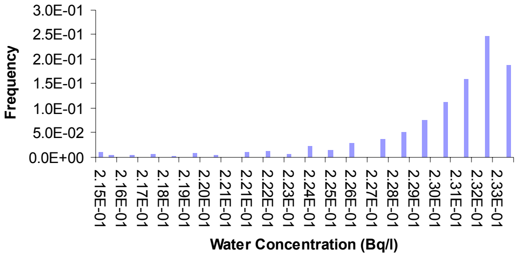

Varying K_D Pu-239

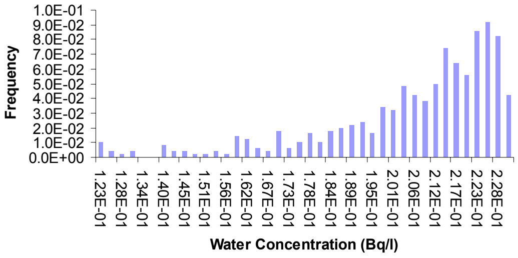

Varying K_D Pu-240


Varying K_D Ru-106+


Varying K_D Sb-125


Varying K_D Sr-90


Varying K_D Tc-99


Varying K_D U-238+

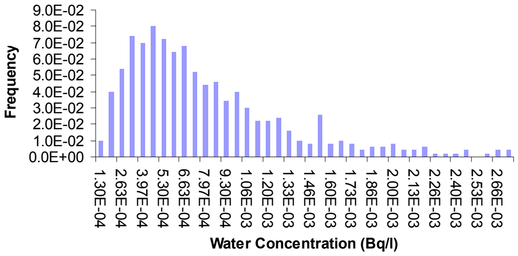
Appendix B – Output Distributions of Parameter Values from the Single Compartment Model

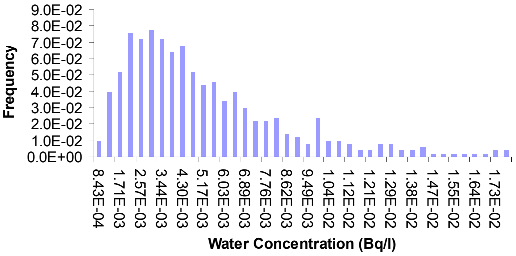
Output distributions of radionuclide concentrations in water from the single compartment model are shown in the following Appendix, arranged according to the parameter that is being varied. Other parameters remain at the constant default values discussed in Section 3. The 1st and 99th percentiles of each distribution determine the minimum and maximum plotted values respectively.

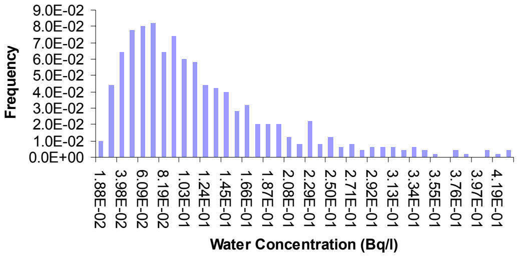
Note that sediment load and sedimentation rate are proportional due to correlations between the two (see Grzechnik 2003). Because of this, the sediment load is varied and the ratio between the two is kept constant. In this way, the sedimentation rate is varied proportionally.

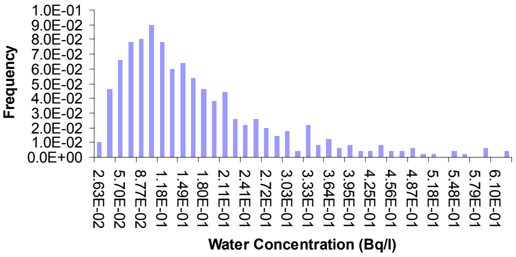
The K_D value for each radionuclide was initially varied independently in separate model runs to determine if any non-linear effects would occur. It was found that running the variation in all nuclides together gives the same distribution in the output water concentration for that nuclide as is obtained when independent runs are considered.

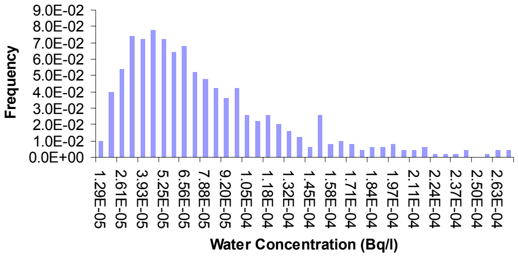
B.1 Average Depth

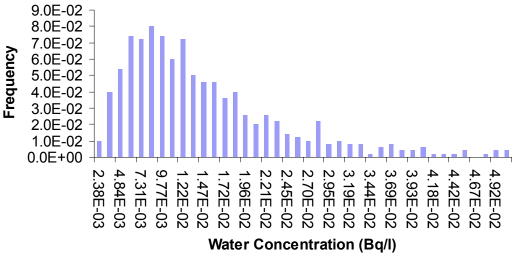

Varying Depth Am-241

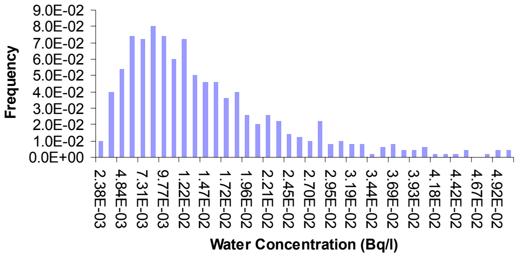

Varying Depth Co-60

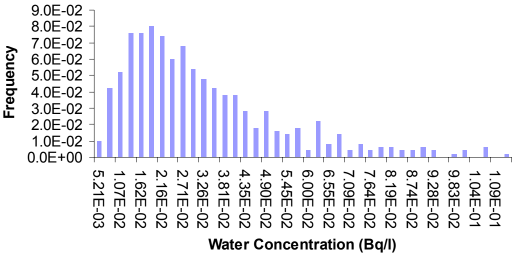

Varying Depth Cs-137+

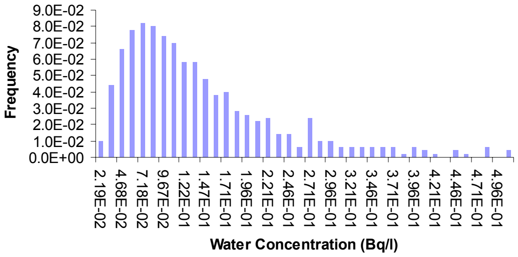

Varying Depth H-3

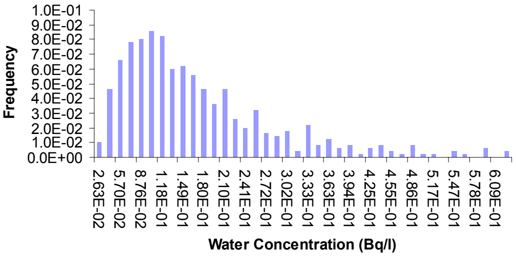

Varying Depth Po-210

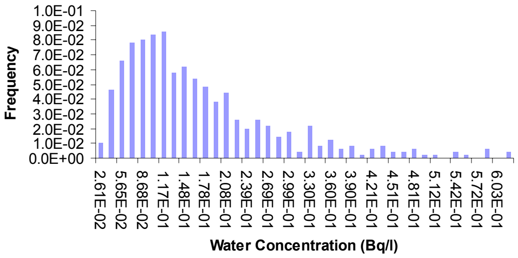

Varying Depth Pu-239

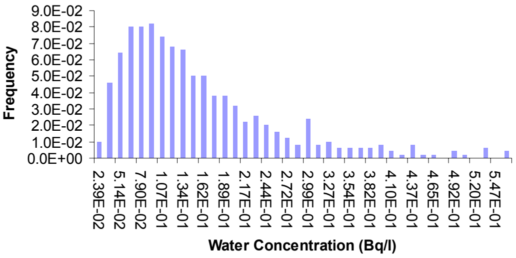

Varying Depth Pu-240


Varying Depth Ru-106+


Varying Depth Sb-125

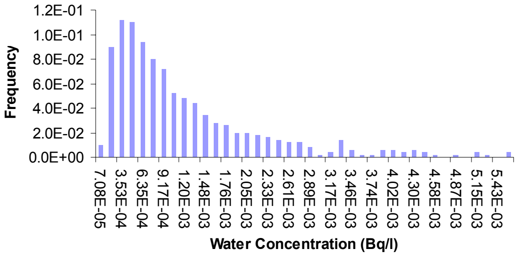

Varying Depth Sr-90


Varying Depth Tc-99

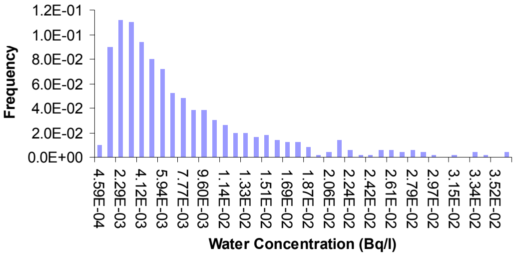

Varying Depth U-238+

B.2. Residual Velocity

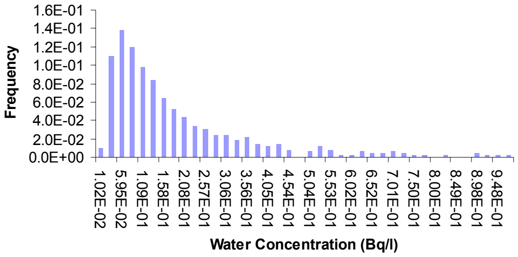
Varying Residual Velocity Am-241



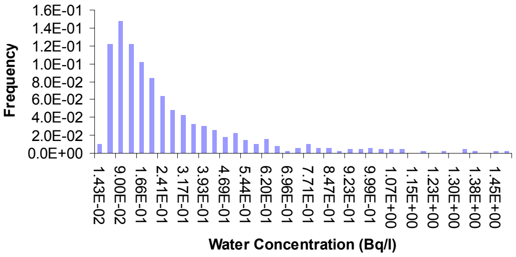
Varying Residual Velocity Co-60



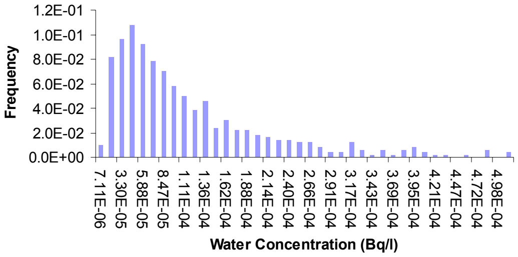
Varying Residual Velocity Cs-137+



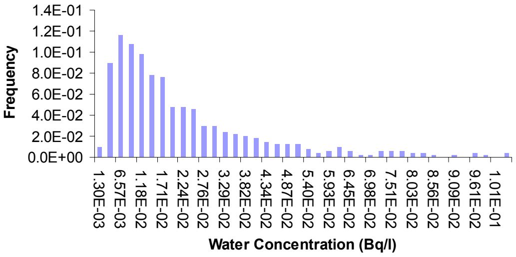
Varying Residual Velocity H-3



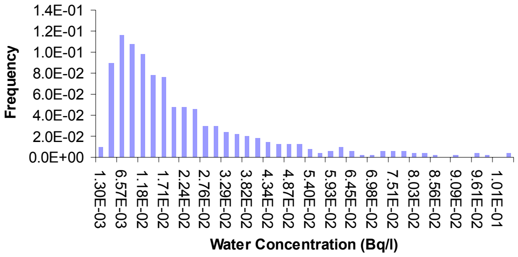
Varying Residual Velocity Po-210



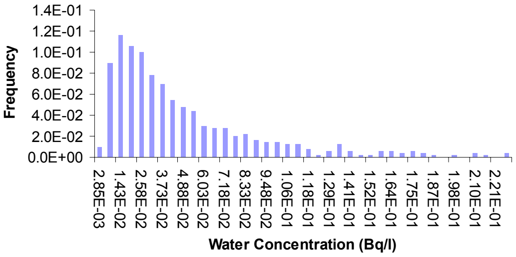
Varying Residual Velocity Pu-239



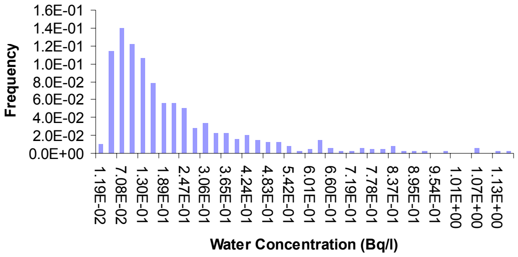
Varying Residual Velocity Pu-240



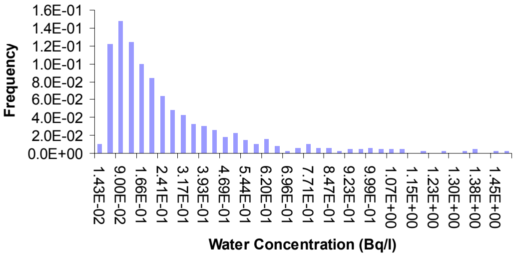
Varying Residual Velocity Ru-106+



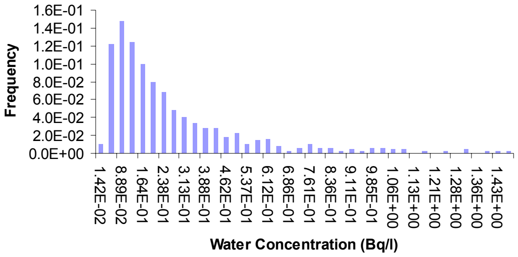
Varying Residual Velocity Sb-125



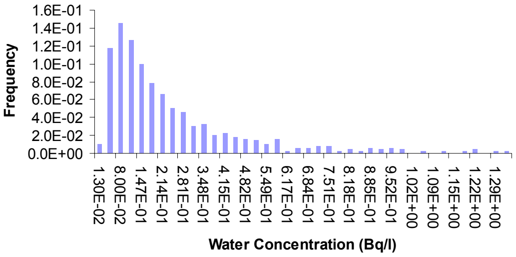
Varying Residual Velocity Sr-90



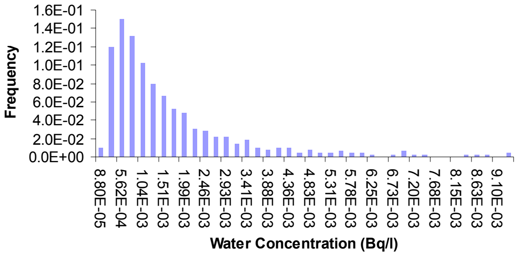
Varying Residual Velocity Tc-99

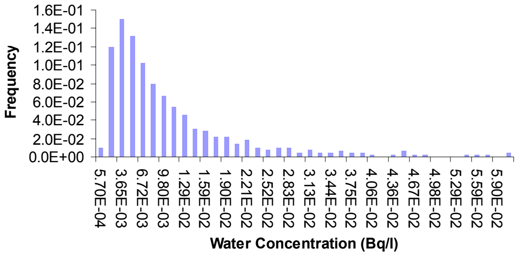


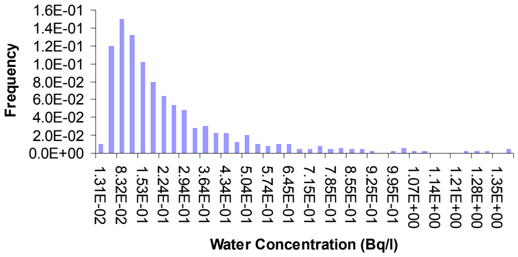
Varying Residual Velocity U-238+

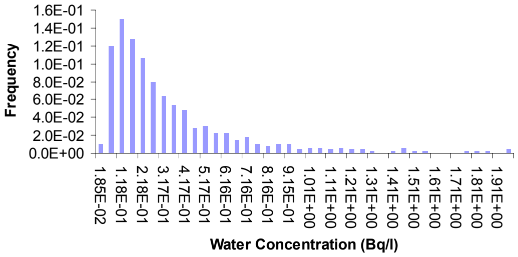


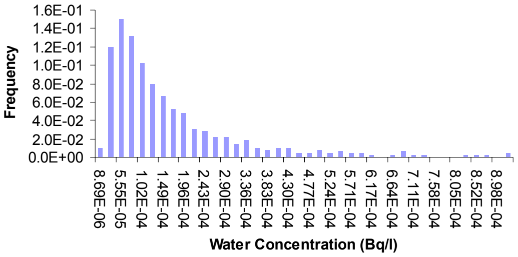
B.3 Offshore Extent

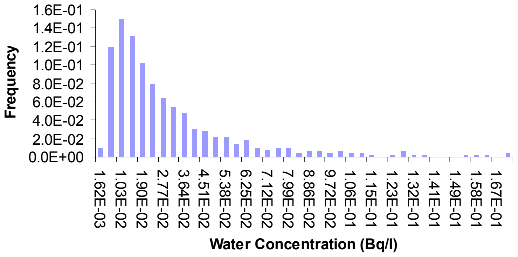

Varying Offshore Extent Am-241

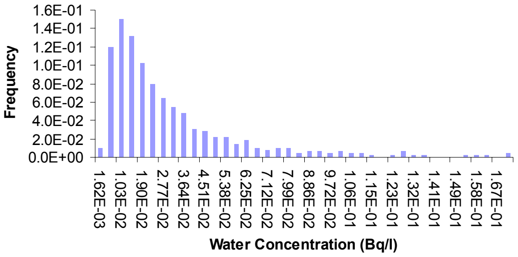

Varying Offshore Extent Co-60

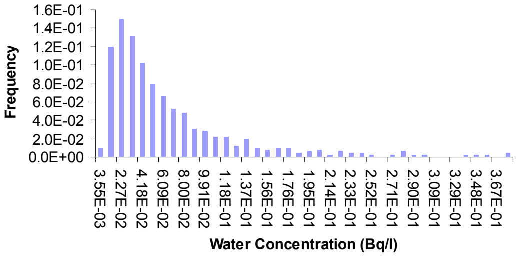

Varying Offshore Extent Cs-137+

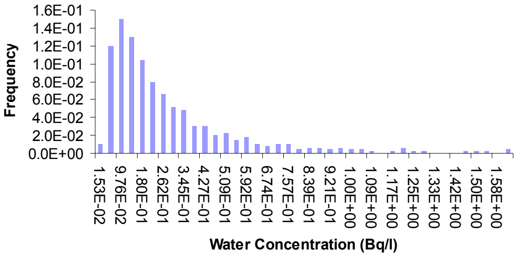

Varying Offshore Extent H-3

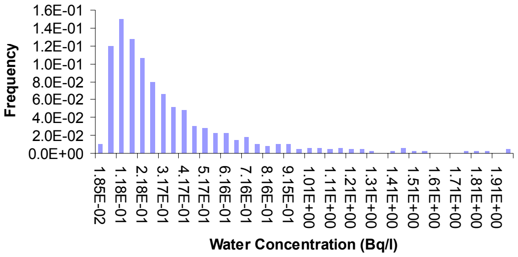

Varying Offshore Extent Po-210

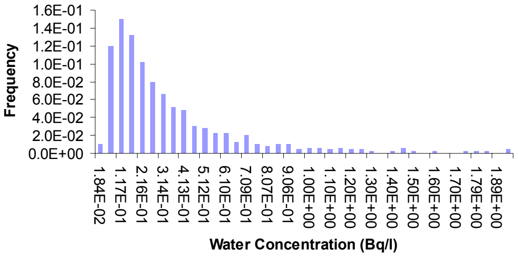

Varying Offshore Extent Pu-239

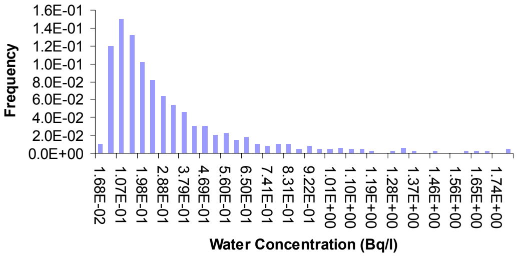

Varying Offshore Extent Pu-240


Varying Offshore Extent Ru-106+

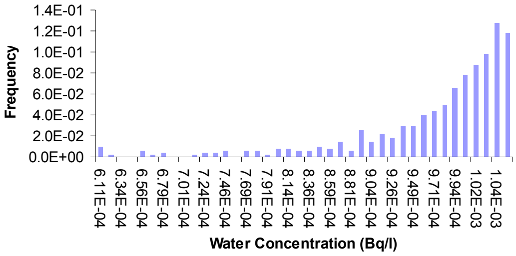

Varying Offshore Extent Sb-125

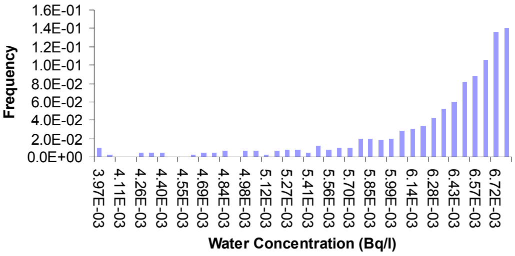

Varying Offshore Extent Sr-90

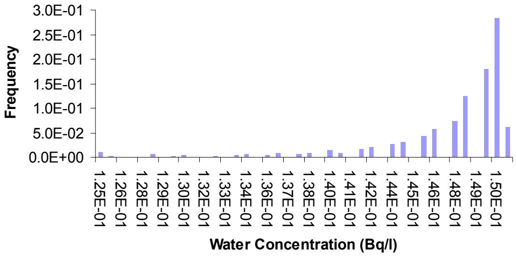

Varying Offshore Extent Tc-99

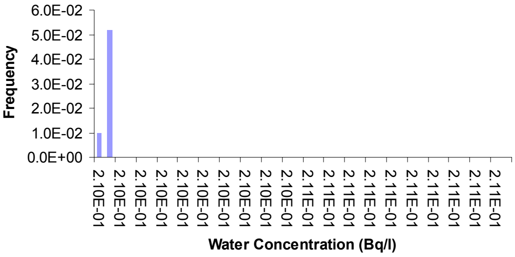

Varying Offshore Extent U-238+

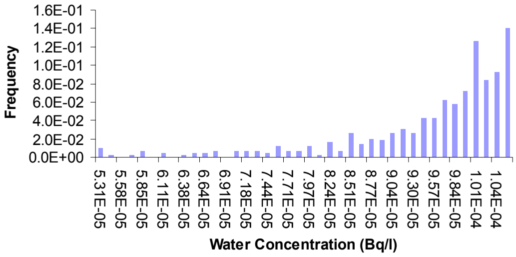
B.4 Half Tidal Excursion

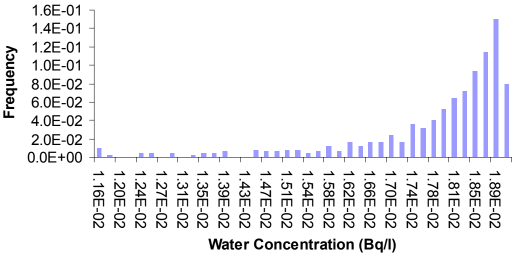

Varying Excursion Am-241

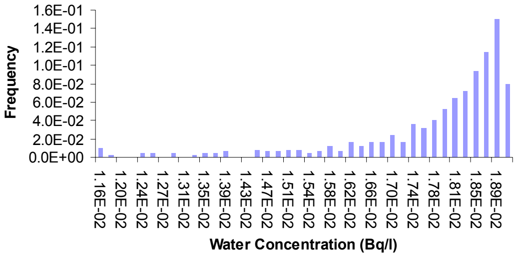

Varying Excursion Co-60

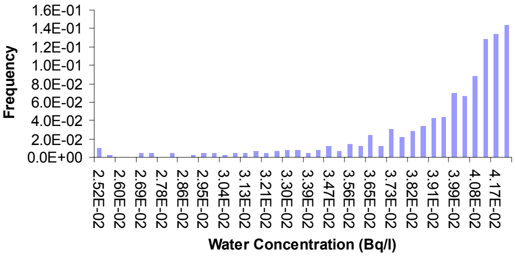

Varying Excursion Cs-137+

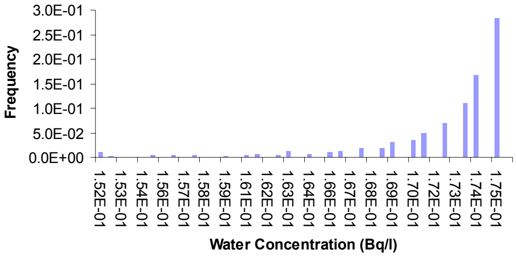

Varying Excursion H-3

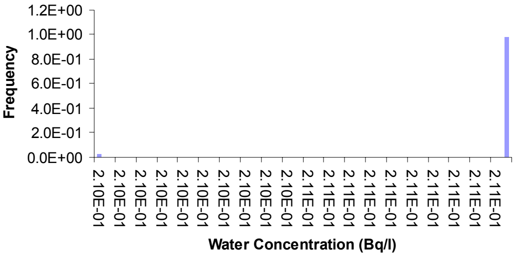

Varying Excursion Po-210

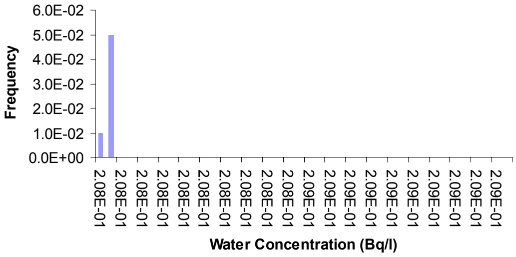

Varying Excursion Pu-239

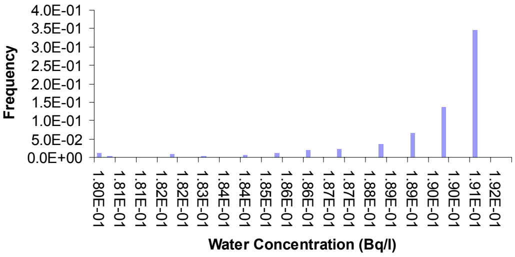

Varying Excursion Pu-240


Varying Excursion K_D Ru-106+

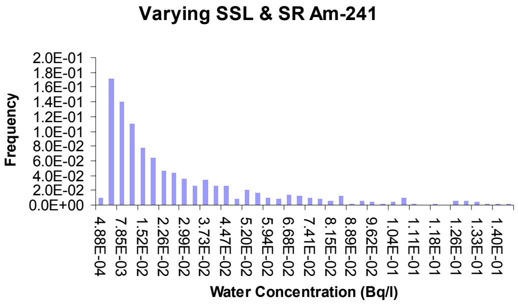

Varying Excursion Sb-125

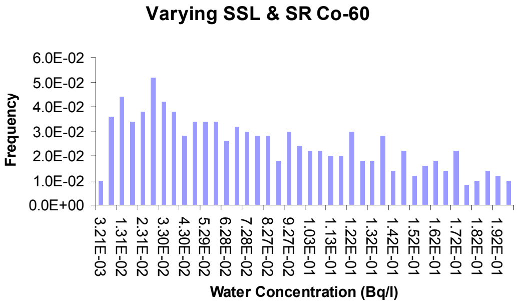

Varying Excursion Sr-90

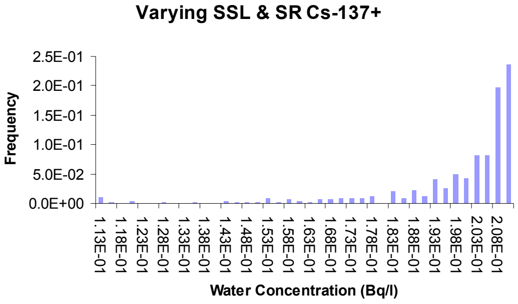

Varying Excursion Tc-99

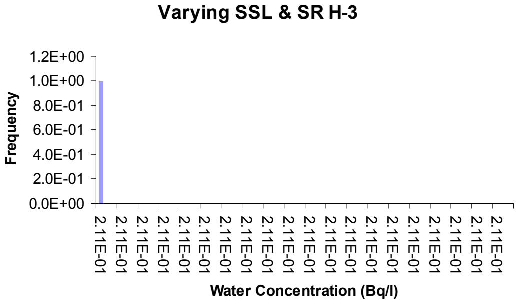

Varying Excursion U-238+

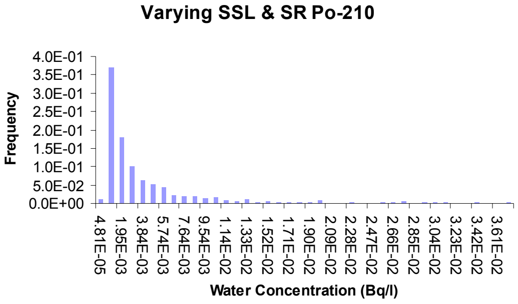
B.5 Suspended Sediment Load (SSL) & Sedimentation Rate (SR)

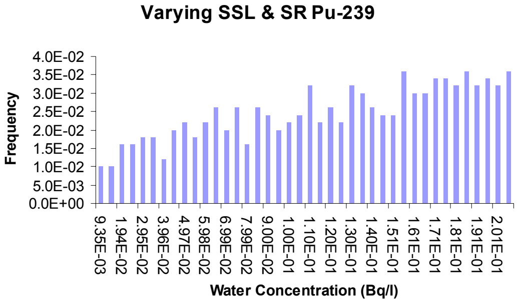

Varying SSL & SR Am-241

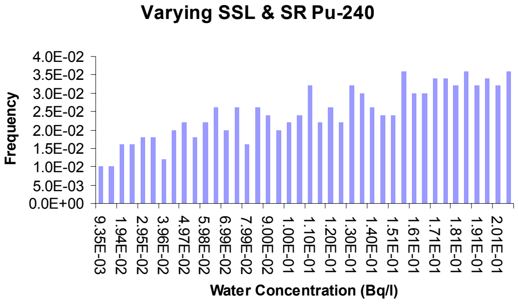

Varying SSL & SR Co-60

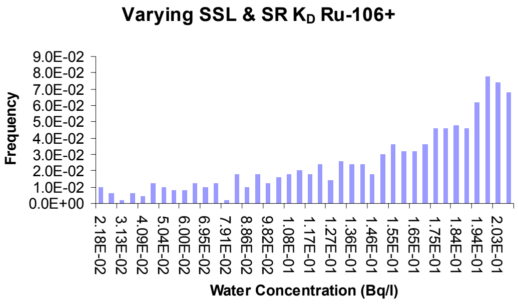

Varying SSL & SR Cs-137+

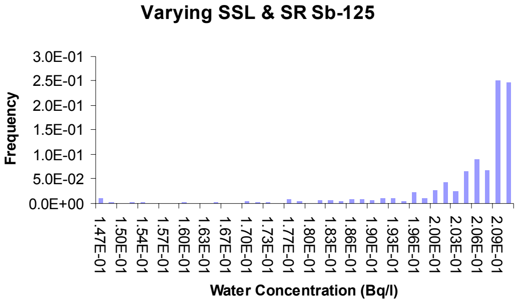

Varying SSL & SR H-3

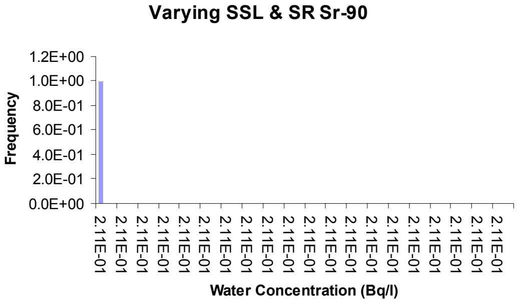

Varying SSL & SR Po-210

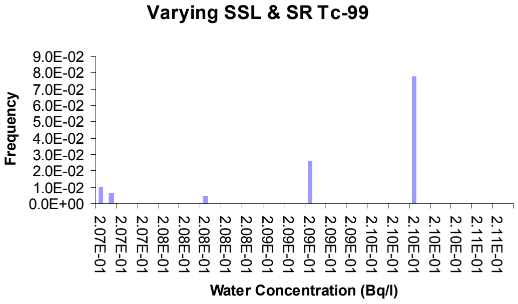

Varying SSL & SR Pu-239

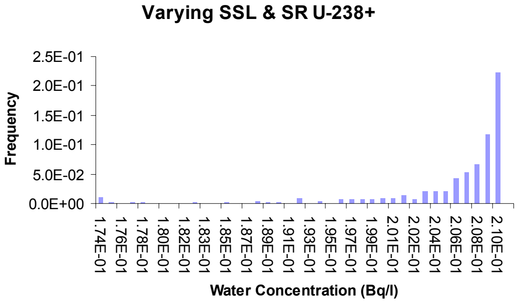

Varying SSL & SR Pu-240


Varying SSL & SR K_D Ru-106+


Varying SSL & SR Sb-125

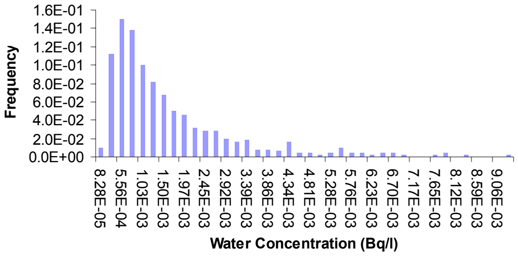

Varying SSL & SR Sr-90


Varying SSL & SR Tc-99

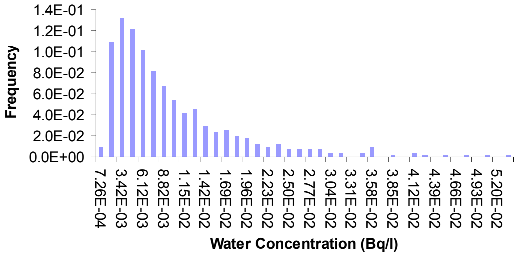

Varying SSL & SR U-238+

B.6 Sediment Distribution Coefficient (K_D)

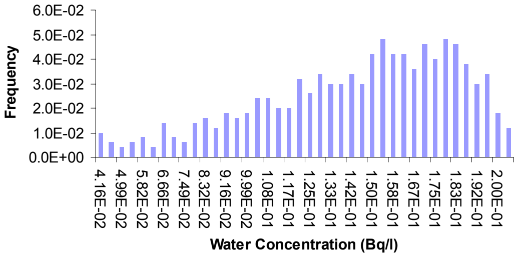
Varying K_D Am-241



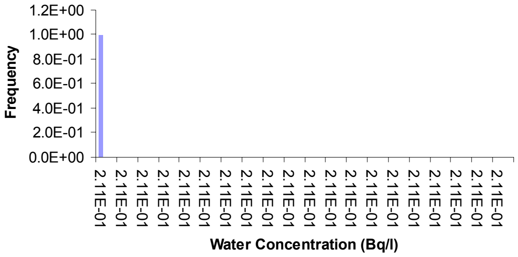
Varying K_D Co-60



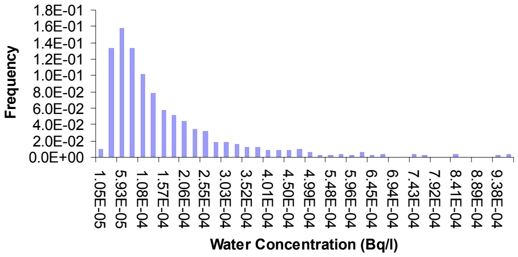
Varying K_D Cs-137+



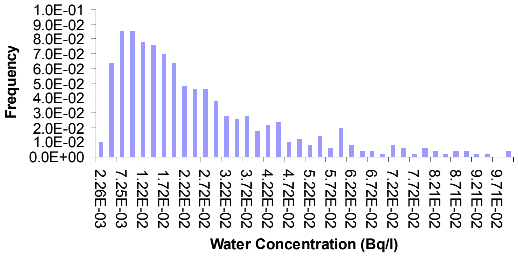
Varying K_D H-3



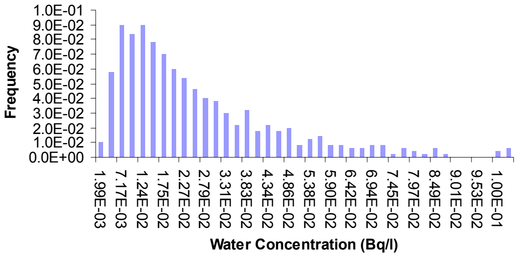
Varying K_D Po-210



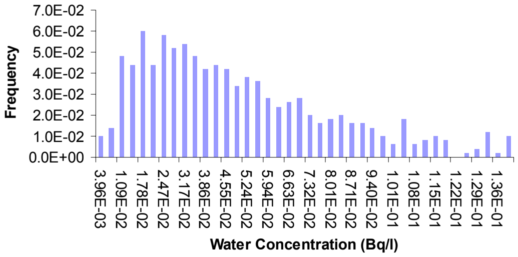
Varying K_D Pu-239



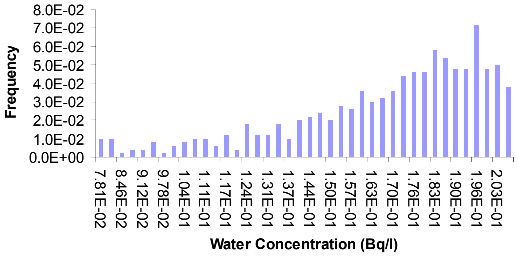
Varying K_D Pu-240



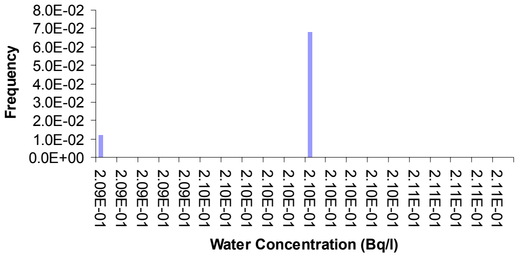
Varying K_D Ru-106+



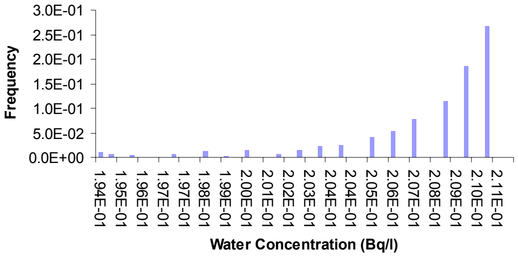
Varying K_D Sb-125



Varying K_D Sr-90



Varying K_D Tc-99



Varying K_D U-238+