



# **A Probabilistic Modelling Suite for the Marine Environment**

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**A Probabilistic Modelling Suite for the Marine Environment**

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## Summary

Under contract SA168, the Food Standards Agency asked CEFAS to develop a probabilistic model for predicting dose distributions from radionuclides discharged to the marine environment.

CEFAS' deterministic models for dose assessments have been developed to allow the model parameter uncertainties to be propagated through the codes. A probability density function of water concentrations is output from WAT (renamed as WATP for probabilistic modelling), which is fed into ADO (ADOP) which then outputs a probability density function of doses. The new codes were implemented in a Windows PC environment, using FORTRAN 77.

Two different methods of selecting random numbers from specified distributions for use in the model were evaluated for accuracy (as the efficiency of each was similar enough to not be an issue). These were Simple Random Sampling and Latin Hypercube Sampling. The latter was deemed to be the best choice as it proved to give smoother distribution predictions for the input considered.

The uncertain parameters were identified and the uncertainty distributions (for the entire UK coast) determined by informal expert elicitation of CEFAS Scientists. These distributions were then propagated through each of the models using the technique known as Monte Carlo analysis. This results in distributions of water concentrations (WATP) and doses (ADOP), which have been plotted and analysed using Microsoft Excel.

A case study was conducted whereby the new models were applied to an assessment at Sizewell to investigate the issues that may arise in their regular usage. In this case, distributions of critical group consumption and occupancy/exposure rates have been defined according to the results of habits surveys. The outputs have been compared to those obtained with a deterministic assessment, and the uncertainty due to the habits survey has been investigated.

The main conclusions drawn are:

- The habits survey should be included in all probabilistic assessments as a distribution of values. Whether this distribution should take into account the variability of the entire habits survey group or the highest users only is the subject of further work to be considered (the former approach is taken here).
- The 95<sup>th</sup> percentile of the dose output distribution is recommended for use as an indicator of the upper bound of dose to the critical group. This value is usually always higher than that obtained using the deterministic model, but will take into account uncertainty and variability in the dose prediction.
- Future work recommended includes further validation of the probabilistic modelling suite and the development of a standard procedure for conducting assessments with WATP and ADOP.

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# 1. Introduction

Under the Radioactive Substances Act 1993, as amended by the Environment Act 1995, the Food Standards Agency (FSA) is a Statutory Consultee in applications for Authorisations for disposal of radioactive waste to the environment. As part of this responsibility FSA needs to maintain an ability to predict the possible impact of such disposals on man. Up until now, deterministic approaches to local marine pollution dispersion and dosimetric models have been regularly used to predict the impact of disposals to the marine environment.

The aim of this project is to develop a suite of models as probabilistic versions of the deterministic WAT and ADO models (Round, 1998a; Round 1998b). Those parameters in WAT and ADO that have a significant uncertainty associated with them, as identified by Brownless et al. (2001), are incorporated into the probabilistic models. Additionally, the variation of consumption and occupancy data within the critical group during habits surveys is also taken into account in a specific assessment (Section 6). The type of distribution expected for each parameter is investigated by informal expert elicitation. The new suite of codes are developed from these models so that model parameters are given by a probability distribution to represent uncertainty about the exact value, rather than a single value as in the deterministic versions. These parameter uncertainties are propagated through the new probabilistic water dispersion model (known as WATP) to give a resultant distribution of water concentrations. This distribution is in turn propagated with other uncertain parameters through a development of the ADO model (probabilistic version known as ADOP) to give a distribution of doses that reflects the uncertainty in the input parameters.

Various aspects of the model development are described and tested. These include the overall method and derivation of random numbers from given distributions using different sampling techniques (see Section 2).

A discussion of the parameters to be used in WATP and ADOP, and the reasons for doing so, is given in Section 3. The expert elicitation of the relevant parameter distributions is also included in this Section.

Section 4 focuses on the application of the defined parameter distributions to the WATP Advection-Diffusion model. The methods for determining random number generation are compared, and a decision is made as to which is the more desirable in this context. For smoothness of output results a total of 1000 values for each parameter are derived. These are used to conduct 1000 runs to obtain distributions of radionuclide concentrations in the sea for the range of values expected throughout the UK.

The resulting distribution of water concentrations is used in the ADOP model (Section 5), along with various other parameter distributions discussed in Section 3. Output distributions of possible doses for the UK are produced and discussed.

Section 6 features a deterministic assessment of the Sizewell region using WAT and ADO for 31 radionuclides and 4 pathways. This is used as a benchmark with which to compare the results of the probabilistic assessment.

Water concentrations at Sizewell are calculated using the WATP model in Section 7. Uncertainties in the calculation are considered and discussed, and the relative values of the 5<sup>th</sup> and 95<sup>th</sup> percentiles and means are compared with the results of Section 6.

The results of Section 7 are combined with the ADOP model to produce a probabilistic assessment for dose distributions at Sizewell (Section 8). Distributions of consumption and occupancy habits are discussed, and the effect of the distributions of habits rates on the uncertainty of the solution is investigated.

Overall conclusions and recommendations for future work are made in Sections 9 and 10 respectively.

*It should be noted* that this project is intended to complement the uncertainty analysis of WAT and ADO considered by Brownless et al. (2001). This report focuses on the derivation of the models and the treatment of statistical output. A more thorough physical description of each of the model parameters and their treatment by the modelling suite may be found in the aforementioned report.

## 2. The Monte Carlo Method

Monte Carlo simulations are widely used for quantitative risk assessments within computational models. The application of the method involves the statistical combination of individual parameter distributions to yield a single, overall distribution. This distribution is often interpreted as the overall variation of the predicted risk (Binkowitz and Wartenberg, 2001).

A number of steps are involved in the application of the Monte Carlo analysis, each of which will be described:

- 1) Expert elicitation of parameter distribution
- 2) Random Sampling of parameters
- 3) Modelling propagation of data
- 4) Analysis of results

### 2.1 Expert Elicitation of Parameter Distributions

Each uncertain parameter involved in the Monte Carlo analysis must be assigned a probability distribution, which is based on the possible values that it may take. In the cases of the models considered here, personal communications with experts in the field have been undertaken (Aldridge, 2001 and Kershaw, 2001). Parameters that have been shown to have no significant effect upon uncertainty within the models have been excluded from consideration, and are given a most likely value (see Brownless et al., 2001). The treatment of consumption and occupancy habits data is discussed in Section 6.

Assignment of uncertainty distributions to parameters described in the sections following refers to the WATP and ADOP models.

### 2.2 Random Sampling of Parameters

Once the distributions have been allocated, a computational sampling technique must be considered to determine random values for each parameter. A number of methods for doing this exist, but two have been chosen for comparison here. In each case a distribution of values has been chosen for the variables to be sampled. A similar approach has been followed by NRPB (1998a,b), NCRP (1996) and IAEA (1989).

- *Simple Random Sampling (SRS)*  
A random value is taken from the specified distribution for each uncertain parameter, and a single estimate of the desired endpoint is calculated. This is repeated for a specific number of iterations.
- *Latin Hypercube Sampling (LHS)*  
Assume  $n$  iterations are to be considered, with  $m$  variables  $(x_1, \dots, x_m)$ . Each variable has its distribution divided into  $n$  subintervals through its range, with equal probability of choosing each variable within the interval. An interval is chosen for variable  $x_i$  with probability  $1/n$ . A single variable is then chosen from

the interval at random. This is repeated for all the other intervals, and then for the other  $(m-1)$  variables. Overall we have  $n$  values of  $x_1$ ,  $n$  values of  $x_2$ , etc.

The LHS is a sequence:  $(x_{1j}, x_{2j}, \dots, x_{mj})$   $j = 1, 2, \dots, n$ ; where  $x_{ij}$  = value of variable  $x_i$  in sample element  $j$ .

### 2.3 Modelling Propagation of Data

In a deterministic approach parameters are given a single value and a single endpoint is reached. In the case of WAT this is the radionuclide concentration in the water. Using the output from WAT, ADO calculates and outputs dose to the critical group.

The probabilistic approach incorporates this methodology, but relies on multiple runs of the deterministic model. Each set of parameter values randomly chosen using Simple Random Sampling (SRS) or Latin Hypercube Sampling (LHS) may be used as a single deterministic model run. When multiple runs are considered, the single value outputs from each run produces a set of values. This set forms a distribution of the output data as a result of the input parameter distributions previously defined.

### 2.4 Analysis of Model Results

The output distribution of the Monte Carlo simulation is analysed in various ways. It is useful to calculate statistical measures, such as the most likely output value and the 5<sup>th</sup> and 95<sup>th</sup> percentiles (90% confidence). These enable a quick check if the range of possibilities considered will exceed any previously specified concentration or dose standard. Additionally, a *measure of the uncertainty* is included, defined as:

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

as used by NRPB (1998).

More complex graphical outputs are also desirable. In this report, these include the plotting of histograms to show probability density functions of the outputs. This allows conclusions about the outputs to be more quickly made.

### **3. Definition of Parameters and Distributions to be Considered - UK Situation**

Various hydrographic parameters must be input into the models, each of which will be considered in turn. To test the method applied in the construction of the probabilistic models, a consideration of the parameter distributions around the entire coast of the UK is undertaken.

It is important to note that the **uncertainty** and **variability** may be confused during such an analysis. In the case of some parameters, both are important. It has been decided that the error due to the combination of these quantities should be considered, as they both contribute to the overall error and output distribution obtained. For example, an uncertainty in the value of the mean depth is likely to be mixed with the variability of depth over the area being considered. In addition to this, the variation of individuals in the habits survey can outweigh the uncertainty associated with specific consumption or occupancy rates. Parameters are normally defined specifically for the region being studied, but some can have local variability within the model domain.

In this section each parameter that may be user-specified in the WAT (and WATP) and ADO (and ADOP) models is discussed. Information about a parameter is obtained from expert elicitation and in the uncertainty analysis conducted upon the deterministic models by Brownless et al. (2001). It is then possible to determine which parameters have the greatest influence on the solution. These should be applied as varying distributions in the Monte Carlo simulation, and less influential parameters may be given constant values.

The probabilistic modelling suite has been constructed to enable the user to input each parameter value as a distribution. Distributions available to be used include uniform, normal, log-normal and triangular types. Mathematical derivations of these distribution types are given by IAEA (1989). These determine the 'shape' about the mean of the values the parameter can be given. For some of the parameters considered in the 'entire UK' situation a distribution of observed values is available (e.g. depth, residual velocity). Distributions for use in the analysis have generally been fitted to the data by eye. In these cases, the upper and lower percentiles and their values, obtained from Brownless et al. (2001), have been modified to obtain the closest fit. One example of this is the use of the 1<sup>st</sup> and 99<sup>th</sup> percentiles in the case of the residual velocity, and the 5<sup>th</sup> and 95<sup>th</sup> percentiles for mean depth.

#### **3.1 WATP (Advection-Diffusion) Model Parameters**

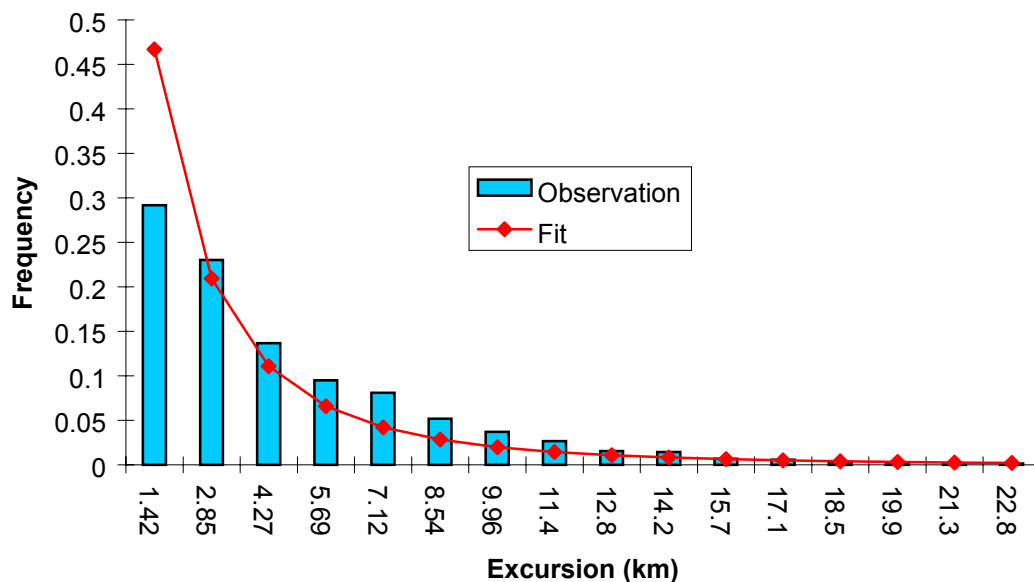
This version of the WAT model uses the advection-diffusion method to determine the concentration of radionuclides due to controlled discharges in an aquatic environment (Round, 1998a). The major underlying assumptions are that the installation discharging to the marine environment is on an open coastline, the dominant dispersion processes are longshore advection and transverse diffusion, and that

radionuclides are lost from the water column by sediment scavenging and radioactive decay. Also, it is assumed that discharges are sufficiently regular to treat the system as a steady state.

### Tidal Excursion, $a$

The tidal excursion varies considerably over short time scales through the spring-neap and other astronomical cycles, and due to meteorological conditions. These values can be averaged to give the mean tidal excursion for a region over a given time scale (a year is required in this case). For this reason the short-term variability of the tidal excursion will not be important. However, the values that can be obtained for this parameter, from hydrodynamic models or admiralty charts, do have a small uncertainty associated with them. The WAT model has been shown to be relatively insensitive to variation of this parameter, however there is an increase in the uncertainty when the critical group is deemed to be within the tidal excursion. For this reason, the tidal excursion is included in the simulations considered here.

It has been suggested by Aldridge (2000) that the distribution to be used in this case be defined from a binned histogram of values around the UK coast. The distribution shown in Figure 1 was obtained from the use of available soundings organised into boxes around the coastline. This data for the half tidal excursion has been found to approximately fit a log-normal curve, with upper (95<sup>th</sup> percentile in this case) of 11km, and lower (5<sup>th</sup> percentile) values set to 0.24km.



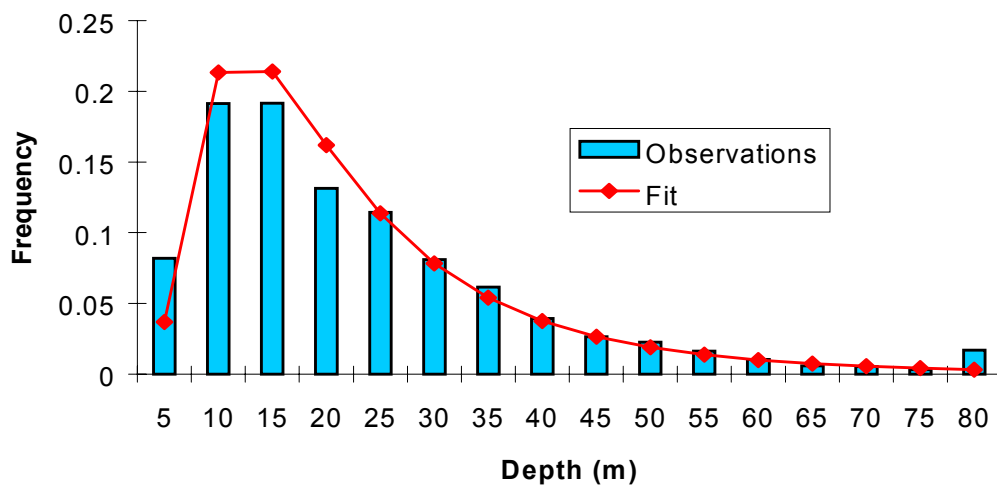
**Figure 1** The frequency plot of half tidal excursion around the UK coast (observation) plotted against the log-normal fitted distribution.

### Mean Depth, $h$

The depth over the area of interest can vary within the model domain, but the parameter of interest in this model is the mean depth, which will always take a

specific value. This parameter has been shown to have a large influence on the uncertainty of the model output, so is included in this analysis.

As in the case of tidal excursion, it has been suggested that a binned histogram of observations should be used, obtained from around the UK coast. This has been determined from model boxes nearest to the coastline. As with the tidal excursion, this has been fitted to a log-normal curve. The best fit 'by eye' was obtained with an upper value of 52m, and a lower value of 5m. The 95<sup>th</sup> and 5<sup>th</sup> percentile values were used in this case (see Figure 2).

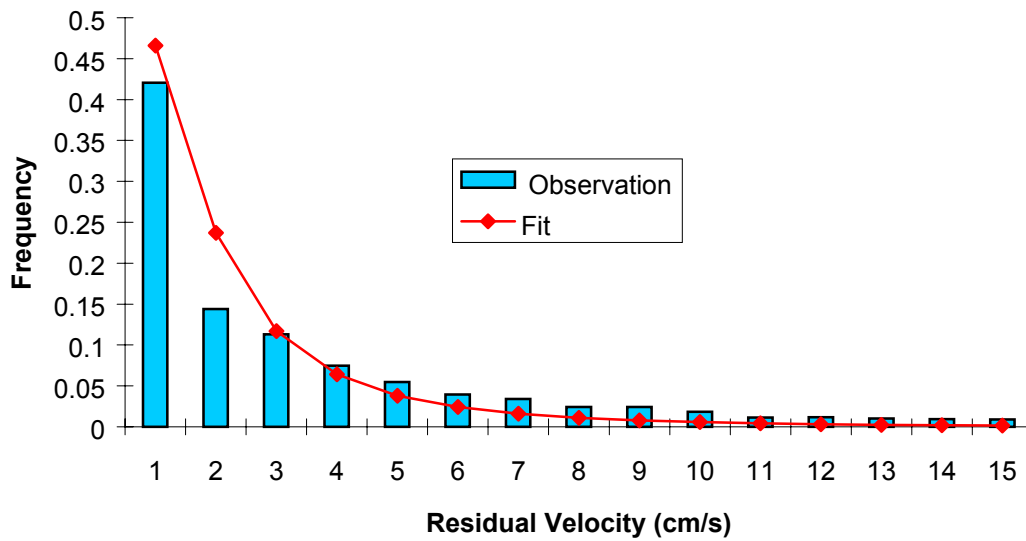


**Figure 2** The fitted log-normal curve compared with the normalised distribution of depth around the UK coast.

### Residual Velocity, $v_x$

Similar reasoning applies as for the tidal excursion. The mean annual value of the residual velocity is required as input, so the parameter does not vary within the model, but has been shown to have a large uncertainty associated with it. Because of this, a distribution of the residual velocity is included here.

As with tidal excursion and mean depth, the residual velocity distribution is determined from its frequency around the UK coast. A log-normal curve has been fitted to the data, with an upper value at 14cm s<sup>-1</sup> and a lower percentile value of 0.12cm s<sup>-1</sup>. The best fit was obtained using the 99<sup>th</sup> and 1<sup>st</sup> percentiles.

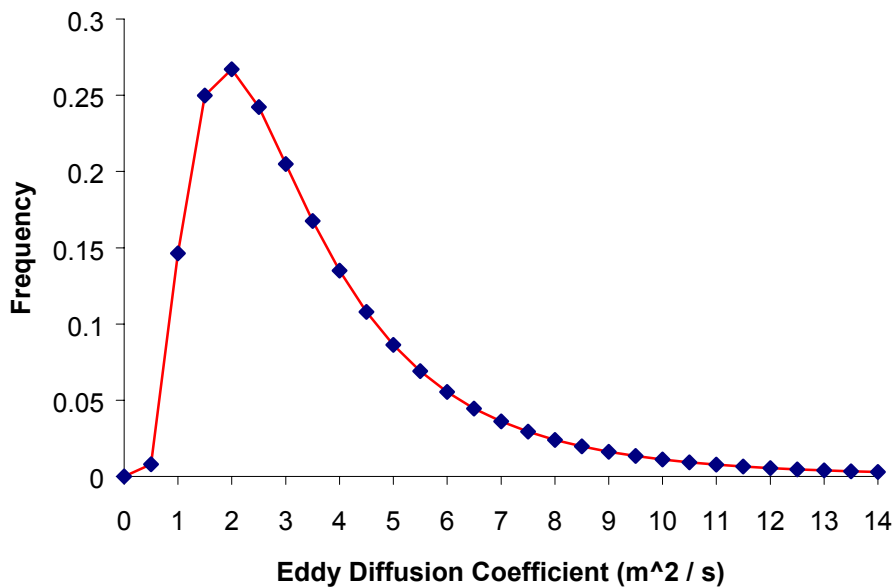


**Figure 3** The fitted log-normal curve for the frequency of residual velocity values around the UK coast.

**Eddy Diffusion Coefficient (normal to coast),  $k_y$**

The eddy diffusivity is a model parameter designed to encompass a range of physical effects that may not otherwise be simulated. As defined for this model there is no spatial variation in the model domain, but the value is uncertain, and is best found through tuning the model during validation within a physically meaningful range of diffusion. This coefficient has been found to contribute a moderate amount to the overall uncertainty, and is incorporated into this Monte Carlo analysis.

Aldridge (2000) has suggested that the optimal distribution that could be applied here would be log-normal, with a lower value of  $0.52\text{m}^2\text{s}^{-1}$ , and an upper percentile value of  $14\text{m}^2\text{s}^{-1}$ . The 1<sup>st</sup> and 99<sup>th</sup> percentiles are used in this case.



**Figure 4** The distribution of parameter values expected from the Eddy Diffusion Coefficient.

#### **Initial Spreading Radius, $r_0$**

This parameter is also designed to encompass a range of physical diffusion effects, so is best found by tuning the model. The parameter has been found to have a negligible uncertainty associated with it for values above 10m. Because it is unlikely that values below the 10m threshold would be specified, this parameter is set to take a single value of 50m.

#### **Radioactive Decay Constant, $\lambda$**

This parameter can be assumed to have no uncertainty in the context of the model, as it is given a constant value for a specific radionuclide.

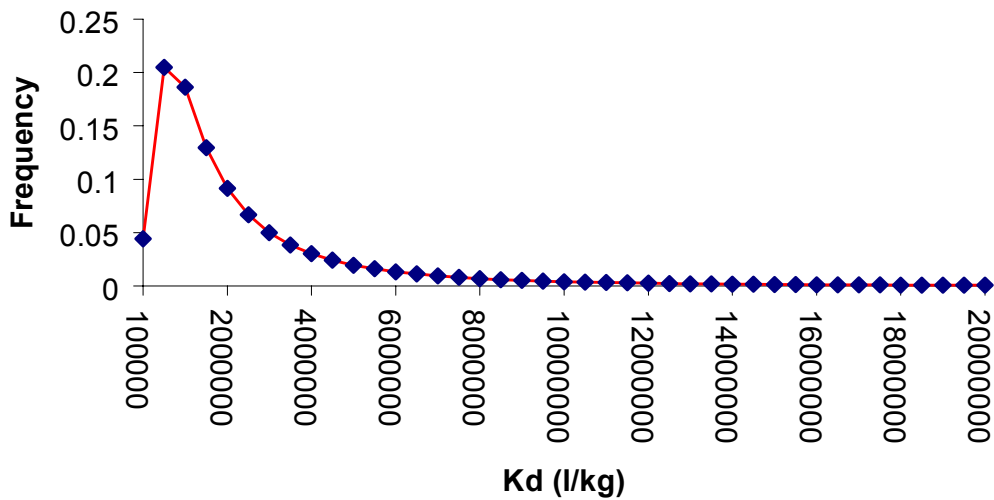
#### **Sediment Distribution Coefficient, $K_d$**

This parameter may be influenced by factors such as the salinity and pH of seawater, grain size and composition of sediment, and chemical speciation of the nuclides in the water. These will vary over the course of a year. The uncertainty in the value is large, as there is insufficient knowledge about the quantitative effects of the factors that may influence the  $K_d$  value. This has been the case in the uncertainty analysis of Brownless et al. (2001), therefore this parameter is included in the Monte Carlo analysis.

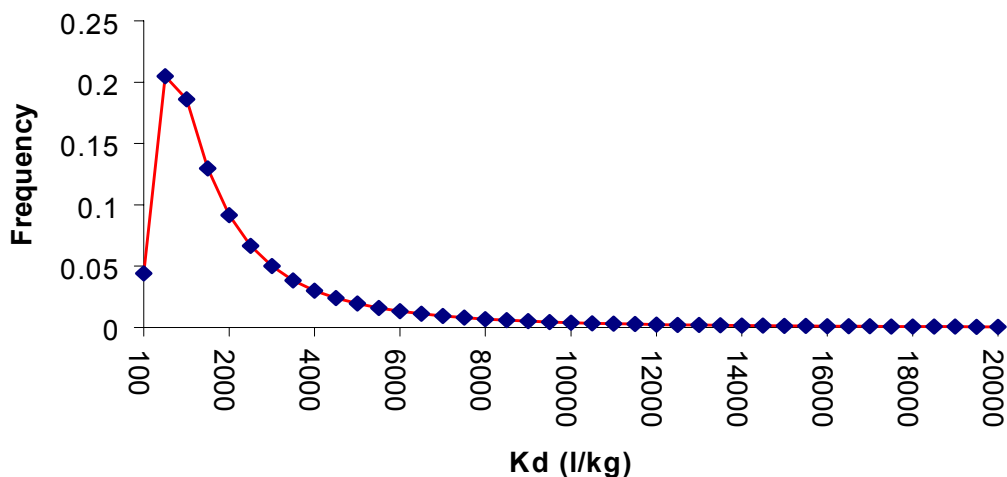
The ranges of  $K_d$  are obtained from IAEA (1985). It has been suggested (Kershaw, 2000) that a log-normal distribution would give a reasonable representation of this parameter. There are two cases to be considered, one for a conservative radionuclide (<sup>137</sup>Cs), and the other for a particle-reactive radionuclide (<sup>241</sup>Am).

The distributions for both of these have been defined using the 1<sup>st</sup> and 99<sup>th</sup> percentiles for the lower and upper percentiles, with values as follows:

- $^{137}\text{Cs}$ : lower  $10^2$ , upper  $2 \times 10^5$  ( $1 \text{ kg}^{-1}$ ).
- $^{241}\text{Am}$ : lower  $10^5$ , upper  $2 \times 10^7$  ( $1 \text{ kg}^{-1}$ ).



**Figure 5** The predicted frequency for the sediment distribution coefficient of  $^{241}\text{Am}$ .

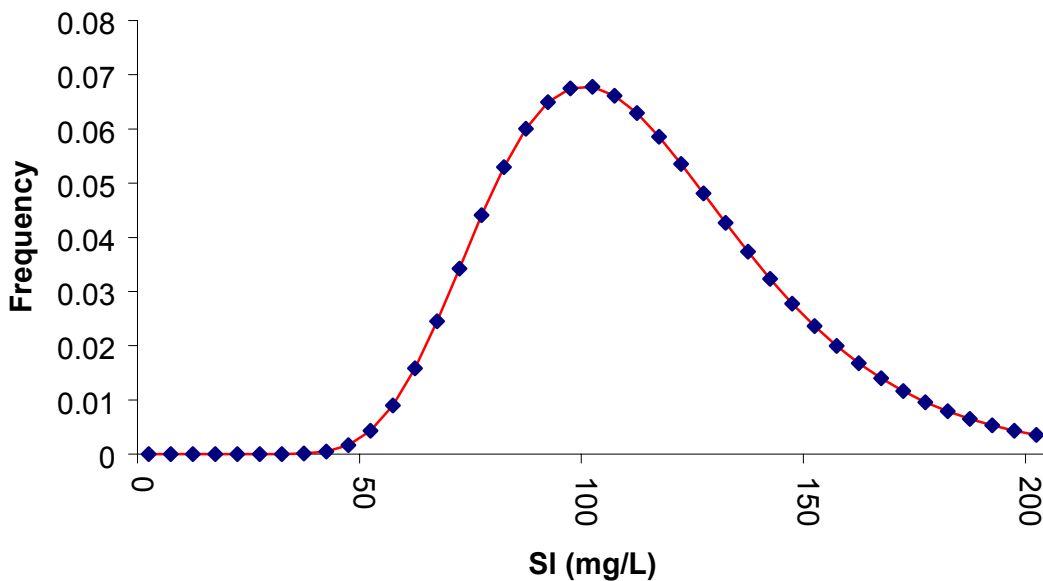


**Figure 6** The predicted frequency for the sediment distribution coefficient of  $^{137}\text{Cs}$ .

### Suspended Sediment Load, $S_f$

Large short-term variations may be expected in the sediment load, particularly through the tidal cycle and due to significant meteorological events. For the WAT models the mean yearly value is required, so these variations are on a time scale that is too short to be significant. There is a large uncertainty shown by Brownless et al. (2001) to be associated with this parameter, so it is included in the analysis.

A log-normal distribution has been suggested for this parameter by Kershaw (2000), and is shown in Figure 7. The upper (99<sup>th</sup> percentile) value is set at  $200 \text{ mg l}^{-1}$ , and the lower value (1<sup>st</sup> percentile) at  $0 \text{ mg l}^{-1}$ . Note that in this case the mean is set at the value  $100 \text{ mg l}^{-1}$ , as  $\ln(0)$  is undefined.



**Figure 7** The predicted distribution for the suspended sediment load ( $S$ ).

#### **Sedimentation Rate, $S_r$**

Similar comments apply as for the sediment load. The mean rate of loss of sediment to the seabed is required by the model, so short term variations are not of importance. Uncertainty in this parameter is large, however, so it is considered in the probabilistic analysis. It is taken to be proportional to the value of the suspended sediment load.

The distribution considered is identical to that for the suspended sediment load, with a factor of  $1/20$  ( $\text{kg m}^{-2} \text{yr}^{-1}$  per  $\text{mg l}^{-1}$ ) applied.

#### **Distance to Critical Group, $x_c$**

The critical group encompasses a finite number of people such that they must cover a finite area. An example of the variation in this parameter is that of a single individual, such as a mollusc collector, who collects over a finite length of the coastline, and thus a finite area. The uncertainty due to this parameter has been found to be relatively low (Brownless et al., 2001), but does increase significantly when the distance to the critical group is within the tidal excursion. For this reason the tidal excursion parameter is included in the Monte Carlo analysis, but the parameter representing the distance to the critical group will be set at the default value of 0km (i.e. at the point of maximum concentration, the discharge point). It should be further noted that the choices of the representative location from available habits data, as well as the accuracy and precision of this data, can contribute to the uncertainty of the prediction.

#### **Discharge Rate of Nuclide, $q$**

It is assumed that discharges are continuous, or at least continuous over set periods of the tidal cycle. This is often the assumption made for prospective assessments. However, in reality the variation in instantaneous discharges can be large, particularly

if discharges are infrequent. Round (1999, 2000), in an investigation of the impact of variability, concluded that it is not of importance in the context of the model usage. The uncertainty due to this parameter has been found to be insignificant (Brownless et al., 2001), and so a constant discharge rate of  $1\text{TBq yr}^{-1}$  will be assumed in this case.

### Discharge times, $t_s$ and $t_e$

Similar comments apply as for discharge rate. The model was found by Brownless et al. (2001) to be relatively insensitive to changes in these parameters. Because of this, in the UK situation simulation of a continuous discharge is assumed at all times.

### Summary

Six parameters with various distributions are therefore included in the Monte Carlo analysis. These are listed with their considered percentiles, which define log-normal distributions for each parameter (see Table 1). The default values of the remaining parameters are listed in Table 2.

**Table 1** Summary of variables to be used in the Monte Carlo analysis for the WATP advection-diffusion model, and the parameters applied to the log-normal distributions which define them. Where the lower percentile is 0, the mean value is calculated by  $(\text{max}+\text{min})/2$ , regardless of the distribution (see Appendix 1).

<i>Parameter</i>		<i>Distribution Characteristics</i>		
		<i>lower</i>	<i>upper</i>	<i>Percentiles (%)</i>
Tidal Excursion (m)		240	11000	95
Mean Depth (m)		5	52	95
Residual Velocity ( $\text{m s}^{-1}$ )		0.0012	0.14	99
Eddy Diffusion ( $\text{m}^2 \text{s}^{-1}$ )		0.52	14	99
Sediment Distribution	Cs ( $1\text{kg}^{-1}$ )	100	20000	99
	Am ( $1\text{kg}^{-1}$ )	100000	20000000	99
Suspended Sediment Load ( $\text{mg l}^{-1}$ )		0	200	99

**Table 2** The default values for parameters that are set for the Monte Carlo analysis of the WATP advection-diffusion model.

<i>Parameter</i>		<i>Value</i>
Initial Spreading Radius (m)		50.0
Distance to Critical Group (m)		0.0
Discharge Rate of Nuclide ( $\text{TBq y}^{-1}$ )		1.0
Discharge Start Time	(fraction of tide cycle)	0.0
Discharge End Time		1.0

## 3.2 ADOP Model Parameters

As with the WATP model, expert elicitation for the ADOP model was undertaken to obtain distributions of uncertain input parameters. The ADOP model is used to determine radioactivity doses to critical (or most at risk) groups of the population. This incorporates information on the habits of members of the critical group, as well as the water concentrations predicted by the WATP model. A number of sediment processes are also taken into account, as suspended and settling sediments can affect radionuclides differently.

The following parameters are input into the ADOP model, with distributions where relevant:

### **Water Concentration**

The concentration of each radionuclide in the water column is determined by the WATP model. This means that the input distribution of this parameter is given by the distribution of outputs from WATP.

### **Suspended Sediment Load**

The values of suspended sediment load are identical to those used for the WATP model, so the distribution applied previously is used.

### **Sedimentation Rate**

The values of sedimentation rate are identical to those used for the WATP model, so the distribution applied previously is used.

### **Sediment Distribution Coefficient, $K_d$**

The values of sediment distribution coefficient are identical to those used for the WATP model, so the distribution applied previously is used.

### **Dosimetric data**

ADOP uses dose coefficients from the most recent ICRP publications to assess exposures due to intakes of radionuclides. These are calculated for a standard individual, whereas in reality there will be variations in dose per unit intake of any given nuclide associated with differences in height, weight, and metabolism, for example. There will also be uncertainty from the bio-kinetic models used to derive the dose coefficients. However, it can be argued that these are both accounted for by ICRP philosophy, which allows for the uncertainty and variability in the definition of the critical group approach. In this report we have not explicitly considered these aspects.

### **Concentration factors/distribution coefficients**

ADOP calculates radionuclide concentrations in environmental materials from concentrations in water by assuming a steady state and using concentration factors for various aquatic environmental materials, such as sediment and fish. Comments made previously about the sediment distribution coefficient ( $K_d$ ) for WATP are appropriate here. For biota the categories allowed for by the IAEA data (IAEA, 1985) are generic, for example there is a single, generic 'crustaceans' category. This encompasses a range of different species of crustaceans that may each have their own specific concentration factors. Therefore, in practice, concentration factors have an implicit variability due to differences across different species, as well as intra-species differences such as size and seasonality. Such variability can be significant. There is for example, a substantial difference between the uptake of technetium-99 by crabs and lobsters. However in these situations, where generic values are questionable, site and species specific data are sought to generate a more representative value. Uncertainty in the parameter values is increased due to a lack of representative data from which the concentration factors are derived, and can be large. The subject is covered in greater detail by Swift (1999).

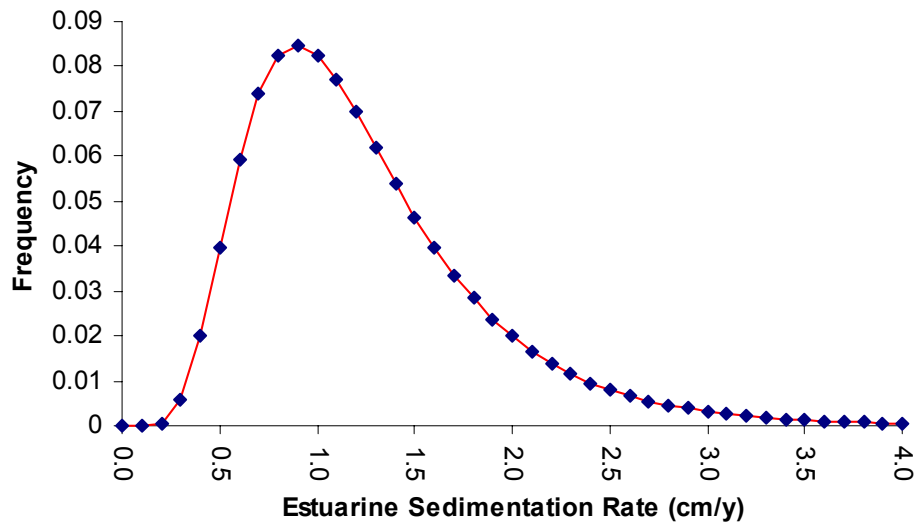
### **Consumption/occupancy rates of the critical group**

A rate of consumption ( $\text{kg y}^{-1}$  or  $\text{l y}^{-1}$ ) or occupancy ( $\text{h y}^{-1}$ ) is determined for each pathway from surveys of the habits of the critical group (see Round, 1998b, for a list of pathways). There is fundamental variability in these habits rates within a critical group. The group will be made up of a small number of individuals, all of whom, in general, will have different habits rates. Over a period of time the individuals making up the critical group will also vary. The philosophy of the ICRP is that the individuals making up the critical group should not be considered separately but as components of the whole. It is the mean dose to this critical group that is of importance, and it is the allowed variability, limited to be within a factor of three when near limiting values, that defines the critical group. However uncertainty is present due to limitations in the techniques for determining the consumption and occupancy rates of potential critical group members.

For the general situation of the UK considered here, a *unit rate* will be considered for each pathway to the critical group. For specific assessments however, the distribution obtained from the survey data is incorporated into the model to include the uncertainty in this measurement.

### **Estuarine Sedimentation Rate**

This parameter is specific to the ADOP model. It refers to the depth of sediment deposited in estuaries, and affects only those pathways involving exposure to a bed of sediment. It has been suggested by Kershaw (2000) that a log-normal distribution would adequately represent the variation in this parameter. In this case, the 1<sup>st</sup> percentile is set at  $0.0\text{m y}^{-1}$  and the 99<sup>th</sup> percentile at  $0.03\text{m y}^{-1}$  (Figure 8).



**Figure 8** The expected distribution of the estuarine sedimentation rate.

### Summary

Generally the same parameter distributions are used for the ADOP model as for WATP. The radionuclide concentrations output from the WATP model are used, as are the sediment parameters previously described. The sedimentation rate in estuaries is defined as a log-normal distribution and defined for specific use in ADOP. In the situation of the entire UK coast to be considered the habits rates have been set to unit values for 26 possible pathways (described by Round (1998b)). For more specific situations these may be specified as input distributions (see Section 8).

## 4. Application to the WAT Advection-Diffusion Model - UK Situation

To run the Monte Carlo analysis on the WAT model the parameters to be varied are input using either the Simple Random Sampling (SRS) or Latin Hypercube Sampling (LHS) methods according to the distributions defined in Section 3.1. This is repeated to give 1000 sets of parameter values, which are used in the model to obtain a distribution of outputs from 1000 runs. This was deemed to be sufficient to allow smooth output distributions to be constructed, and reasonable statistical analyses to be undertaken.

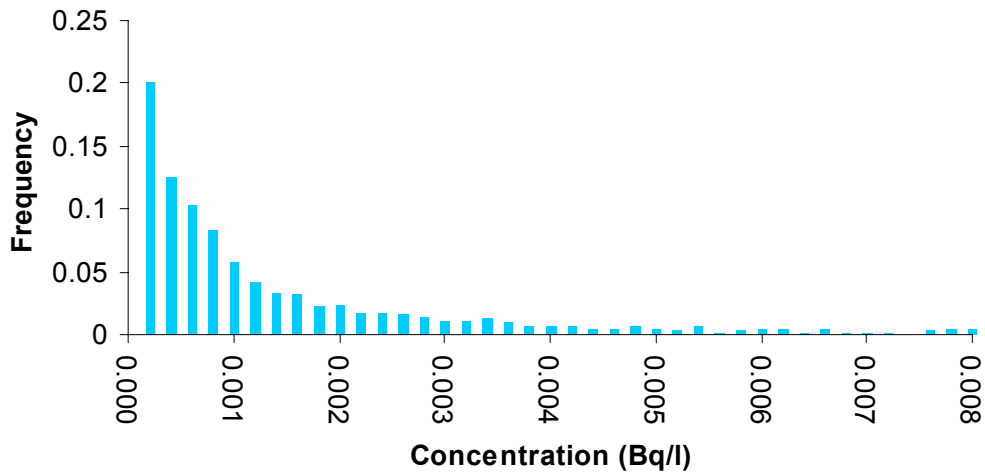
Annex A shows a comparison between SRS and LHS in this application. Overall the LHS technique is thought to give a slightly better representation of the distributions required, so this method is used exclusively for all probabilistic simulations considered.

### 4.1 Output Distributions of Monte Carlo Analysis on WAT

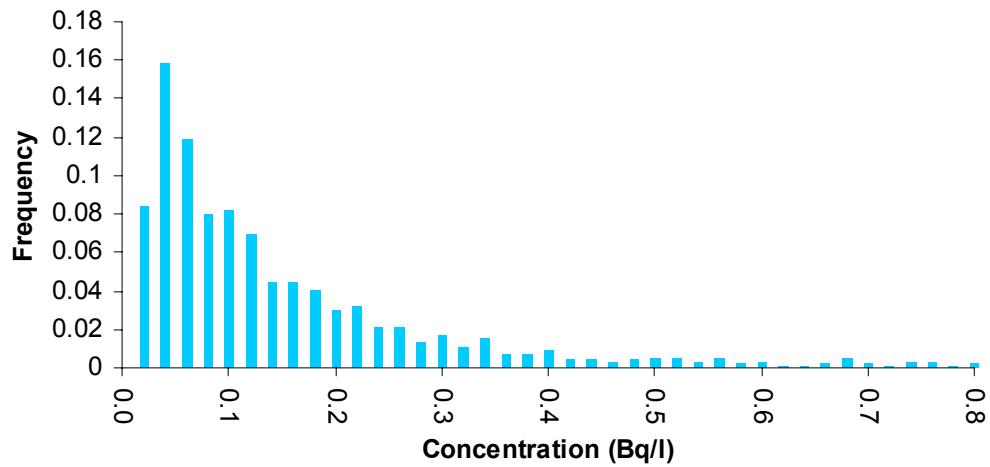
As stated above, 1000 runs of the model are used for the Monte Carlo analysis. In the case of a regular assessment, this number of runs may not be feasible (as a total time of approximately 70 hours is required for completion of WATP with the current set-up). In this case, preliminary trials may be undertaken with less runs, and the final distribution can then be obtained using more samples should time permit. Further time savings could be made by halving the number of runs to 500, as used during a study of terrestrial model uncertainty by NRPB (1998a). It should be noted that increasing the number of nuclides will raise computational time and effort. This occurs in the specific assessment considered in Sections 7 and 8.

The output distributions predicted by the WATP model are shown in Figures 9 and 10 for  $^{241}\text{Am}$  and  $^{137}\text{Cs}$  respectively. In each case, it is the concentration of radionuclide activity in water excluding activity associated with suspended particles that is presented.

It is immediately obvious that both of the distributions have fairly long 'tails', that is the maximum value of concentration is much higher than the most likely value. This can be attributed to the input distributions used. In many cases the 1<sup>st</sup> (or 5<sup>th</sup>) and 99<sup>th</sup> (or 95<sup>th</sup>) percentiles are used as the minimum and maximum values of the input distributions. It may be desirable in the real world application of this model to use the 0.1<sup>st</sup> and 99.9<sup>th</sup> percentiles, or to apply absolute maximum/minimum values. This should increase the focus of the inputs and reduce the chances of 'outliers' dominating the extremes of the solution. This was also experienced by NRPB (1998b), in an investigation of variability in critical group doses.



**Figure 9** The output distribution of water concentrations of the radionuclide  $^{241}\text{Am}$  from the WATP model (UK situation) using 1000 runs with the LHS method.



**Figure 10** The output distribution of water concentrations of the radionuclide  $^{137}\text{Cs}$  from the WATP model (UK situation) using 1000 runs with the LHS method.

## 4.2 Output Statistics

Table 3 includes a summary of the output from the Monte Carlo analysis. This shows the maximum and minimum values at 90% confidence (i.e. the 5<sup>th</sup> and 95<sup>th</sup> percentiles), but other values may be chosen if desired. The two distributions overlap, as the maximum value of <sup>241</sup>Am concentration (9.92E-2Bq l<sup>-1</sup>) is greater than the minimum of <sup>137</sup>Cs (1.96E-3Bq l<sup>-1</sup>), but the tabulated mean and median (50<sup>th</sup> percentile) values show that the concentration of <sup>137</sup>Cs in the water column is generally greater than <sup>241</sup>Am for unit discharges. This is expected, as <sup>241</sup>Am tends to bond with sediment particles (thus reducing the concentration of radionuclide in water), whereas <sup>137</sup>Cs isotopes are generally free in the water column (conservative radionuclide).

**Table 3** Summary statistics of distributions from the Monte Carlo analysis of the WATP advection-diffusion model.

	<sup>241</sup> Am	<sup>137</sup> Cs
5 <sup>th</sup> Percentile (Bq/l)	5.879E-5	0.01478
95 <sup>th</sup> Percentile (Bq/l)	0.01131	0.6527
Uncertainty (ratio)	192.3	44.16
Mean (Bq/l)	0.002770	0.1819
50 <sup>th</sup> Percentile - Median (Bq/l)	0.0007610	0.09510
Mode (μSv/y)	0.01180	0.1050

## 4.3 Uncertainty

The uncertainty associated with the prediction of the concentration of <sup>241</sup>Am is approximately 4 times larger than that associated with the prediction of <sup>137</sup>Cs. An increased uncertainty for the prediction of water concentrations of particle-reactive radionuclides was noted by Brownless et al. (2001), and it was mainly attributed to increased sensitivity of sediment parameters, such as the sediment distribution coefficient and suspended sediment load and rate.

These uncertainty ratios are quite large (192 for Am, 44 for Cs), but this is expected due to the input parameters being applied for the situation of the entire UK. A localised assessment should have a much lower value, provided an investment is made in deriving site-specific information from previously or newly determined field observations.

## 4.4 Summary

The WATP model has been successfully applied to the situation of the UK coastline. The distributions of water concentrations obtained may be used as input to the probabilistic dosimetric model (ADOP) in Section 5.

## 5. Application to the ADO Dosimetric Model - UK Situation

In this section, randomly distributed values (obtained through the use of the LHS technique or from the WATP model) are applied to the ADOP model with parameters relevant to the whole of the UK. There are a number of parameters which have an uncertainty associated with them which are incorporated in the model.

### 5.1 Output Distributions of ADO Monte Carlo Analysis

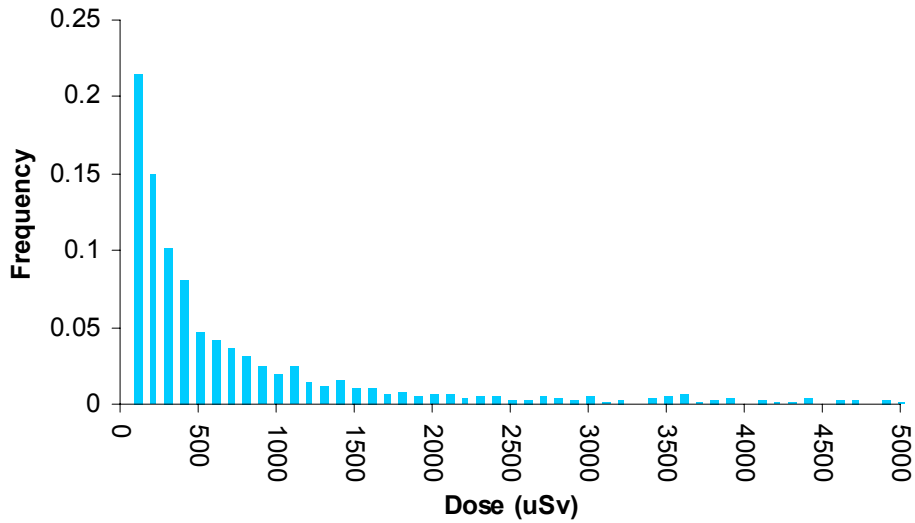
A total of 1000 runs have been conducted in the Monte Carlo analysis of the ADO model (i.e. ADOP). The following distributions have been used as input:

- Concentrations of radionuclides in the water column (output from WATP in Section 4),
- Suspended sediment load (previously defined for WATP),
- Sediment distribution coefficient (previously defined for WATP),
- Estuarine sedimentation rate (defined in Section 3.2).

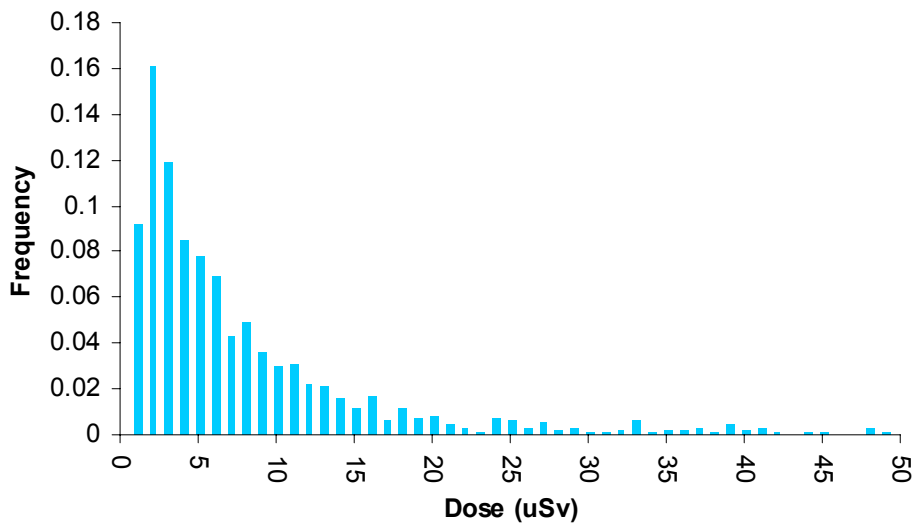
Other parameters, such as concentration factors, dosimetric data and consumption and occupancy rates, have been given constant values for this analysis, but may be given randomly distributed values in cases where these are thought to contribute to the overall solution. In this case unit values of consumption ( $\text{kg y}^{-1}$ ) and occupancy/exposure ( $\text{h y}^{-1}$ ) have been given to the 26 pathways specified by Round (1998b)

Dose rates ( $\mu\text{Sv y}^{-1}$ ) have been calculated using ADOP for exposure to  $^{241}\text{Am}$  and  $^{137}\text{Cs}$  (see Figures 11 and 12). It is quite obvious from these that the dose due to  $^{241}\text{Am}$  is of a much greater magnitude than that due to  $^{137}\text{Cs}$ . This is further emphasised by the total dose (Figure 13), which is plotted on the same scale as Figure 11. The total dose is dominated by the dose due to  $^{241}\text{Am}$ . This is mainly attributed to pathways involving sediment and sand ingestion, such as IMUD and ISND. This follows the results from Section 4, where concentrations of  $^{241}\text{Am}$  in the water column were reduced due to its bonding with sediment particles.

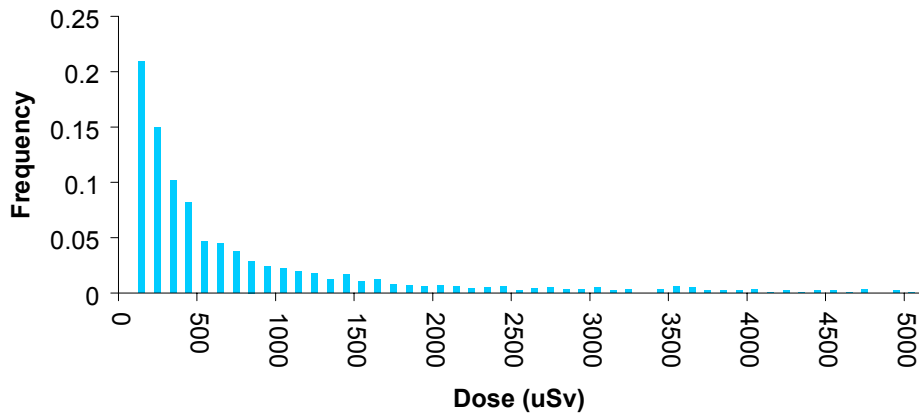
It is important to note the large range of dose values that are output, which indicates that the overall uncertainty will be quite large.



**Figure 11** The prediction by the ADOP model (UK situation) of doses to the critical group due to 1TBq y<sup>-1</sup> discharge of <sup>241</sup>Am (µSv y<sup>-1</sup>).



**Figure 12** The prediction by the ADOP model (UK situation) of doses to the critical group due to due to 1TBq y<sup>-1</sup> discharge of <sup>137</sup>Cs (µSv y<sup>-1</sup>).



**Figure 13** The prediction by the ADOP model (UK situation) of total doses to the critical group due to  $1\text{TBq y}^{-1}$  discharge of both radionuclides ( $\mu\text{Sv y}^{-1}$ ).

## 5.2 Output Statistics

A summary of the output from the ADOP model applied over the entire UK coastline is shown in Table 4. The 5<sup>th</sup> and 95<sup>th</sup> percentiles show that the distributions of doses from both radionuclides overlap. It is obvious from the mean, median and modes, however, that dose due to  $^{241}\text{Am}$  dominates that due to  $^{137}\text{Cs}$  in this case (where unit discharge and habit rates have been applied). The overall median dose is high ( $348.5\mu\text{Sv y}^{-1}$ ), but the inputs to the model are not intended to give a true indication of dose.

**Table 4** Summary statistics of distributions from the Monte Carlo analysis of the ADOP dosimetric model for unit discharges in the situation of the entire UK coast.

	$^{241}\text{Am}$	$^{137}\text{Cs}$	Total
5 <sup>th</sup> Percentile ( $\mu\text{Sv/y}$ )	26.195	0.71305	27.895
95 <sup>th</sup> Percentile ( $\mu\text{Sv/y}$ )	5042.5	31.540	5053.5
Uncertainty (ratio)	192.50	44.230	181.16
Mean ( $\mu\text{Sv/y}$ )	1236.27	8.7900	1244.9
50 <sup>th</sup> Percentile - Median ( $\mu\text{Sv/y}$ )	339.00	4.5900	348.50
Mode ( $\mu\text{Sv/y}$ )	133.00	10.100	135.00

It is interesting to note the differences in each of the statistical output values. Indeed, this is one of the issues that is raised with the large amount of information given by a distribution of doses. It is difficult to determine which number(s) should be used as the overall dose prediction. The 95<sup>th</sup> percentile gives a measure of the maximum dose that may be possibly received by an individual (excluding extreme outliers), but would usually coincide with the worst case for many of the included parameters. The mean may be a better indicator of the dose to the critical group, but any danger of an

under-prediction of dose must be investigated. The Sizewell site assessment of Sections 7-9 may give further insight into which approach should be used in future probabilistic modelling exercises.

### **5.3 Uncertainty**

The uncertainty values associated with ADOP are slightly higher than those associated with the water concentration output from WATP. Again the uncertainty associated with  $^{241}\text{Am}$  (192.5) is approximately four times higher than that of  $^{137}\text{Cs}$  (44.23). Because  $^{241}\text{Am}$  dominates the overall dose it also dominates the uncertainty calculations, the total of which exceeds two orders of magnitude in the case where the entire UK coastline is considered.

### **5.4 Summary**

The Monte Carlo analysis method has been successfully conducted in a test case of dose assessments using the situation of the entire coast of the UK. This has resulted in output dose distributions and various statistics derived from these. Specific probabilistic site assessments are required to further develop this method. The optimal way of presenting this information to the public is investigated further in an assessment of Sizewell in Sections 7-9.

## 6. A Deterministic Site Assessment

### 6.1 Sizewell

Sizewell A is a nuclear power station situated in Suffolk, on the eastern coast of England. Liquid wastes are discharged from a pipe to the southern part of the North Sea. This is an open coastline situation, so the Advection-Diffusion version of the WAT model can be applied with confidence.

### 6.2 Radionuclide Concentrations Using WAT

The assessment that is considered here is similar to that considered for the Magnox Authorisation, Jan 1998 (Hunt et al. 1998), but incorporates a more recent habits survey of the surrounding region (Tipple and Joyce, 2002). The most recent versions of WAT and ADO (Round 1998a,b) are used to calculate the 'best estimate' (or 'deterministic') assessment, which may be used as a benchmark for comparison of the probabilistic assessment to follow.

Input parameters are shown in Table 5. Each of these has been obtained from both the expert elicitation process (Chapter 7), and the tested and calibrated Hunt et al. (1998) assessment. It should be noted that the discharge start and end times (0.54 and 0.92) imply that discharges begin (approximately) 30 minutes after high water and end one hour before low water.

**Table 5** Input parameters used for the Sizewell site in the Magnox assessment (Hunt et al., 1998).

<i>Parameter</i>	<i>Units</i>	<i>Value</i>
Residual Velocity	$\text{m s}^{-1}$	0.03
Diffusion Coefficient	$\text{m}^2\text{s}^{-1}$	1.5
Tidal Excursion	m	7100
Initial Spreading Radius	m	50
Start & end times	$t_s, t_e$	0.54, 0.92
Distance to critical group	m	0*
Suspended sediment load	$\text{mg l}^{-1}$	80
Sedimentation rate	$\text{kg m}^{-2}\text{y}^{-1}$	1
Mean depth	m	8
Estuarine sedimentation rate	$\text{m y}^{-1}$	0.02

\* - This value is used for both consumption and occupancy in this case

This assessment simulates the discharge of 31 radionuclides, the rates (in  $\text{TBq y}^{-1}$ ) of which are shown in Table 6. It should be noted that to reduce the number of model runs, the example considered here used a hypothetical situation where it was assumed that both consumption and occupancy critical group locations are adjacent to the discharge pipe. This differs from the Magnox Authorisation case where occupancy (or exposure) pathways are 12000m from the pipe.

When these parameter values were applied in the WAT model, predictions of the radionuclide concentrations in the water column (shown in Table 6) were obtained.

**Table 6** Discharge rates (TBq/yr) applied, and radionuclide concentrations predicted ( $\text{Bq l}^{-1}$ ) for radionuclides used in the best estimate Magnox assessment at Sizewell (Hunt et al., 1998).

<i>Radionuclide</i>	<i>Discharge Rate</i>	<i>Predicted Conc</i>
H-3	1.10E+01	1.23004
C-14	1.98E-04	1.91E-05
S-35	2.85E-01	3.16E-02
Ca-45	1.18E-02	1.26E-03
Mn-54	9.88E-05	6.46E-07
Fe-55	2.58E-03	5.75E-05
Co-58	2.05E-04	1.33E-06
Fe-59	5.32E-04	1.17E-05
Co-60	1.02E-03	6.68E-06
Zn-65	4.56E-04	1.95E-05
Sr-90	1.43E-01	1.48E-02
Y-90	1.43E-01	1.56E-05
Zr-95	4.18E-04	5.68E-07
Nb-95	1.03E-03	2.74E-06
Ru-106 +	2.47E-03	2.69E-04
Ag-110M+	2.66E-04	2.75E-05
Sb-124	5.24E-03	5.36E-04
Sb-125	1.63E-03	1.69E-04
Te-125M	4.10E-04	4.19E-05
Cs-134	8.93E-02	8.04E-03
Cs-137 +	1.00E+00	9.01E-02
Ce-144 +	3.15E-03	2.17E-06
Pm-147	2.43E-05	1.68E-08
Eu-154	9.88E-05	2.68E-07
Eu-155	3.42E-04	9.28E-07
Pu-238	2.44E-05	3.02E-07
Pu-240	6.54E-05	8.09E-07
Pu-241	2.47E-03	3.06E-05
Am-241	8.05E-05	5.57E-08
Cm-242	1.01E-04	6.95E-08
Cm-243	4.14E-06	2.86E-09

+ - Indicates decay of daughters taken into account

### 6.3 Dose Assessments Using ADO

The dose assessments were calculated using the ADO model. Four critical group pathways have been included from the 2001 survey of Sizewell critical group habits (Tipple and Joyce, 2002) for use in this assessment. The pathways considered are:

- FISH ( $\text{kg y}^{-1}$ )- Generic fish consumption;
- CRUS ( $\text{kg y}^{-1}$ )- Generic crustacean consumption;
- MOLL ( $\text{kg y}^{-1}$ )- Generic mollusc consumption;
- BTMD ( $\text{h y}^{-1}$ ) - External exposure to baitdiggers over mud.

For simplicity, the dose due to each of these has been calculated at a distance of 0m from the discharge pipe. The consumption/exposure rates used are shown in Table 7.

**Table 7** Adult consumption (FISH, CRUS, MOLL) and exposure (BTMD) pathways and rates ( $\text{kg y}^{-1}$ ,  $\text{h y}^{-1}$ ) obtained from habits surveys and used for the Sizewell site in the Magnox assessment (Hunt et al., 1998). Critical groups have been assumed to be at the same location for all pathways.

<i>Pathway</i>	<i>Consumption/Occupancy Rate</i>
FISH	$40\text{kg y}^{-1}$
CRUS	$8.4\text{kg y}^{-1}$
MOLL	$6.4\text{kg y}^{-1}$
BTMD	$1000\text{h y}^{-1}$

Doses attributed to each radionuclide and pathway were calculated using the ADO program. These are shown in Table 8. In the probabilistic modelling of this region (to follow), emphasis is placed on specific results obtained using  $^3\text{H}$  (tritium),  $^{137}\text{Cs}$  and  $^{241}\text{Am}$ . The total doses obtained for these were  $0.00283$ ,  $27.2$  and  $0.00198\mu\text{Sv y}^{-1}$  respectively. The overall results of this deterministic assessment may be used as a benchmark for comparison with the probabilistic model.

**Table 8** Critical doses ( $\mu\text{Sv y}^{-1}$ ) obtained for each radionuclide and pathway calculated using the ADO model.

<i>Radio-Nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	2.07E-03	4.34E-04	3.31E-04	0.00E+00	2.83E-03
C-14	8.85E-03	1.86E-03	1.42E-03	1.21E-07	1.21E-02
S-35	1.95E-03	2.04E-04	6.23E-04	4.68E-08	2.77E-03
Ca-45	7.17E-05	3.77E-05	5.74E-06	1.29E-05	1.28E-04
Mn-54	7.34E-06	1.93E-06	1.47E-05	4.36E-03	4.38E-03
Fe-55	2.28E-03	7.96E-04	3.64E-03	3.62E-04	7.07E-03
Co-58	3.93E-05	4.13E-05	3.15E-05	3.72E-03	3.83E-03
Fe-59	2.52E-03	8.82E-04	4.03E-03	4.11E-03	1.15E-02
Co-60	9.08E-04	9.54E-04	7.27E-04	3.29E-01	3.31E-01
Zn-65	3.04E-03	3.19E-02	1.46E-02	7.81E-03	5.74E-02
Sr-90	3.32E-02	6.96E-03	2.65E-03	2.68E-03	4.55E-02
Y-90	3.38E-05	3.55E-04	2.70E-04	5.21E-01	5.22E-01
Zr-95	4.32E-07	9.07E-07	1.73E-05	5.48E-03	5.50E-03
Nb-95	1.91E-06	2.67E-06	1.02E-05	8.51E-03	8.53E-03
Ru-106 +	1.51E-04	1.58E-03	2.41E-02	1.45E-03	2.73E-02
Ag-110M+	1.54E-03	3.23E-03	4.92E-03	2.62E-03	1.23E-02
Sb-124	2.14E-02	4.50E-03	1.71E-03	1.24E-02	4.00E-02
Sb-125	2.97E-03	6.23E-04	2.37E-04	5.48E-03	9.31E-03
Te-125M	1.46E-03	3.06E-04	2.33E-04	2.01E-05	2.02E-03
Cs-134	6.11E-01	3.85E-02	2.93E-02	2.49E+00	3.16E+00
Cs-137 +	4.69E+00	2.95E-01	2.25E-01	2.20E+01	2.72E+01
Ce-144 +	2.26E-05	9.49E-05	3.62E-04	3.88E-02	3.93E-02
Pm-147	8.73E-08	3.67E-08	1.40E-07	3.26E-07	5.90E-07
Eu-154	6.44E-06	4.51E-06	2.40E-05	2.02E-02	2.03E-02
Eu-155	3.57E-06	2.50E-06	1.33E-05	2.70E-03	2.72E-03
Pu-238	1.11E-04	1.75E-04	1.33E-03	7.34E-06	1.63E-03
Pu-240	3.24E-04	5.10E-04	3.89E-03	1.88E-05	4.74E-03
Pu-241	2.35E-04	3.70E-04	2.82E-03	1.10E-06	3.42E-03
Am-241	2.23E-05	4.68E-05	1.43E-03	4.86E-04	1.98E-03
Cm-242	1.67E-06	3.50E-06	1.60E-04	6.61E-06	1.72E-04
Cm-243	8.59E-07	1.80E-06	8.25E-05	1.13E-04	1.98E-04
TOTAL	5.38E+00	3.90E-01	3.24E-01	2.54E+01	3.15E+01

\*BTMD - Bait digging over mud

## 7. A Probabilistic Site Assessment - WATP

The first part of the probabilistic assessment for Sizewell was conducted using 500 runs of the WATP model. This has been reduced from the 1000 runs used in Sections 4 and 5 due to the increased computational expense of running the program with 31 radionuclides.

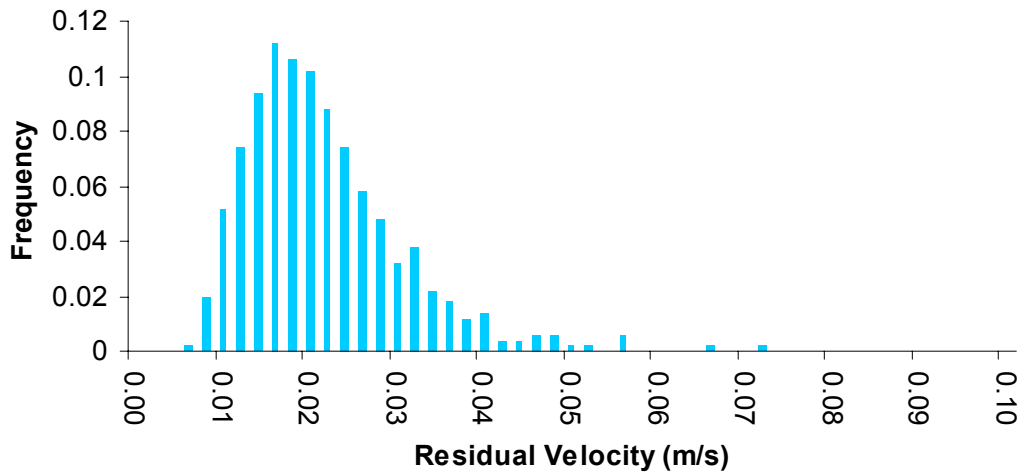
Elicitation of experts in relevant fields was used to determine distributions for the input parameters in the region of the Sizewell nuclear facility. Each of these is described in detail in the sections that follow.

### 7.1 WATP Parameter distributions

The parameter distributions of hydrodynamic and sediment processes have been obtained and presented for the Sizewell case in the same way as those for the UK situation, shown in Section 3 and Annex A. Part of the process involves the use of personal experience and field measurements to determine the relevant localised distributions.

#### **Residual Velocity**

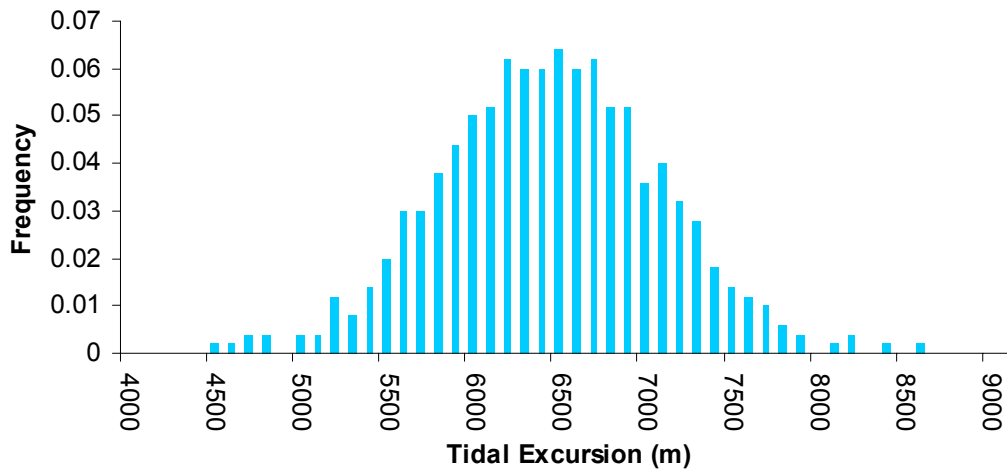
This parameter distribution was determined by Aldridge (2001). It can be a difficult distribution to obtain as there are a number of sources of information that may differ. Local information may be obtained from current meter or drifter studies, or numerical model results. These have various uncertainties associated with them. Specific meteorological conditions may influence observations. Current meters have the additional problem that only a single point value is provided, whilst considerable variation is possible with bathymetry changes. Predictions of residual currents from numerical models, particularly in the near shore region, can be subject to errors due to the coastline estimation and lack of resolution near the coast. Current meters deployed by CEFAS near Sizewell suggest offshore (10-15km from coast) residual flows to the north of approximately 2-3cm s<sup>-1</sup>. Numerical model results from the region suggest a similar range of values. Because of this, Aldridge (2001) suggests that a log-normal distribution with mean 2.0cm s<sup>-1</sup> and standard deviation given by:  $\log_e(\text{s.d.}) = 1.0$ . For input into the model, this has been narrowed slightly and represented as a log-normal distribution with 1<sup>st</sup> and 99<sup>th</sup> percentiles set to 0.007 and 0.05m s<sup>-1</sup> respectively, and the resulting LHS calculation input to the WATP model is shown in Figure 14.



**Figure 14** The LHS distribution of input values for residual velocity ( $\text{m s}^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell.

### Tidal Excursion

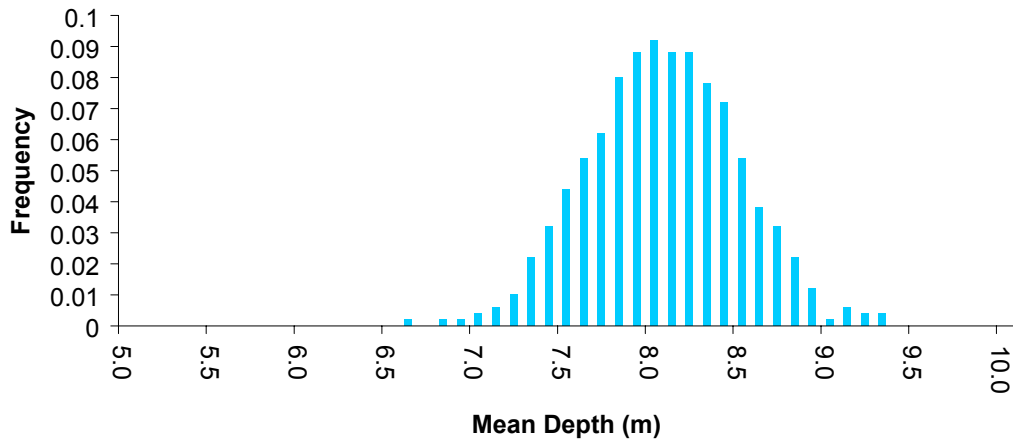
The half-tidal excursion distribution, obtained from Aldridge (2001), is shown in Figure 15. Information was taken from a combination of tidal diamond information (Admiralty charts) and hydrodynamic modelling predictions. The difference between the two introduced an uncertainty, as did extrapolating offshore measurements to the inshore region, where frictional effects are more important. Overall the tidal velocity distribution was normal with mean  $0.9$  and standard deviation  $0.1 \text{ m s}^{-1}$ . The full tidal excursion was suggested to be a normal distribution with mean  $12.8 \text{ km}$  and standard deviation  $1.5 \text{ km}$ . The half-tidal excursion (shown) has 1<sup>st</sup> and 99<sup>th</sup> percentiles as  $4930$  and  $7870 \text{ m}$  respectively.



**Figure 15** The LHS distribution of input values for the half tidal excursion (m) obtained from the expert elicitation process in the vicinity of Sizewell.

### Mean Depth

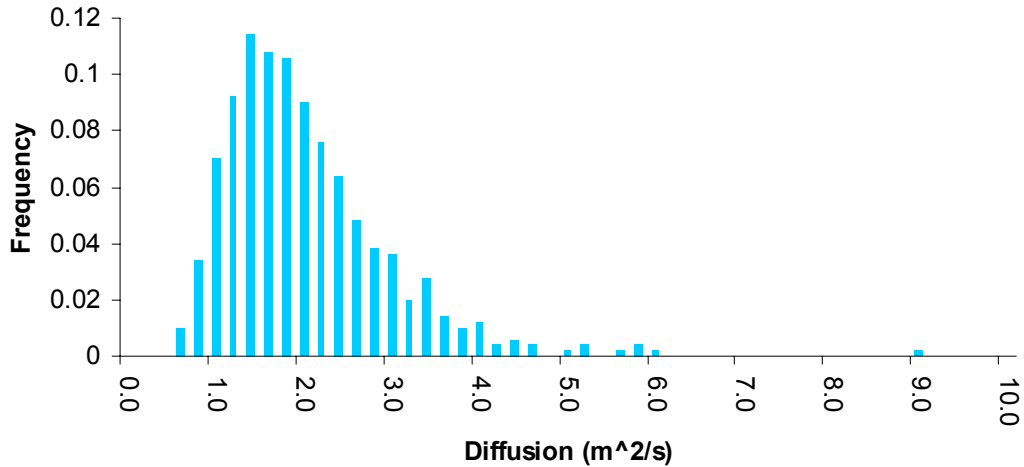
This was estimated (Aldridge, 2001) from Admiralty charts, where uncertainty is introduced due to the (well known) bias towards shallow depths of these charts. Further uncertainty occurs from the conversion of a range of depths into a single mean value over several tidal excursion lengths along shore and up to some distance offshore. This assumed offshore extent of the discharge plume was estimated at 4km, and an estimate of 8m was made for the mean depth value. The uncertainty is represented by "a normal distribution with mean 8m and standard deviation 0.5m", and is input into the model (equivalently) with 95<sup>th</sup> and 5<sup>th</sup> percentiles set to 9m and 7m respectively (see Figure 16).



**Figure 16** The LHS distribution of input values for mean depth (m) obtained from the expert elicitation process in the vicinity of Sizewell.

### **Eddy Diffusion Coefficient**

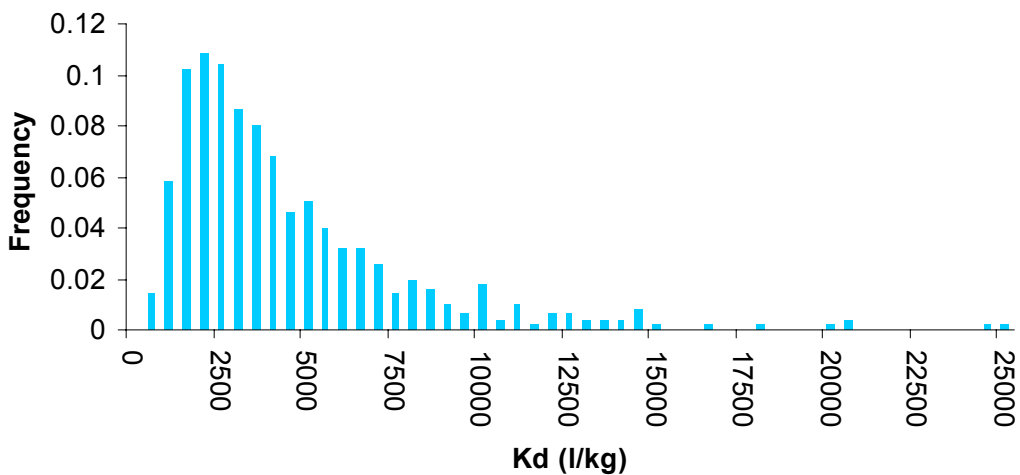
Aldridge (2001) admits that accurate estimates of this quantity can be difficult to obtain. Additionally, the uncertainty is compounded by the imprecise definition of this parameter. A number of net transport factors are often involved in the use of the diffusion coefficient. These may include small-scale turbulence, vertical and horizontal shear dispersion, transient wind and density effects, and topographic effects. Values used in models have been known to vary over several orders of magnitude ( $0.1$  to  $1000\text{m}^2\text{s}^{-1}$ ), and can often depend on temporal and spatial scales. For relatively local predictions near a discharge point, Aldridge (2001) suggests values at the lower end of the range are more appropriate. Dye experiments conducted by Talbot (1976) suggest cross-shore dispersion coefficients in the range  $0.1$  to  $1.0\text{m}^2\text{s}^{-1}$ , usually for timescales of less than a day. For the models considered here, it was suggested that a log normal distribution with mean  $1.0\text{m}^2\text{s}^{-1}$  and standard deviation given by:  $\log_e(\text{s.d.}) = 1.0$ . The LHS calculation of this parameter is shown in Figure 17, with the log normal distribution narrowed slightly to be input with 1<sup>st</sup> percentile set to  $0.6\text{m}^2\text{s}^{-1}$  and 99<sup>th</sup> percentile at  $5.0\text{m}^2\text{s}^{-1}$ .



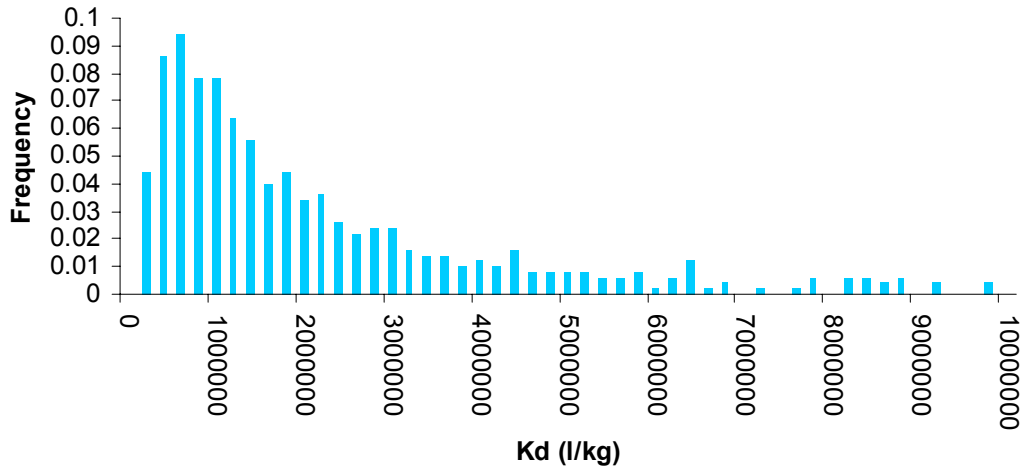
**Figure 17** The LHS distribution of input values for eddy diffusion ( $\text{m}^2\text{s}^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell.

#### Sediment Distribution Coefficient

The values for  $K_d$  were taken from IAEA Technical Report 247 (1985), as recommended by Kershaw (2001). Maximum, minimum and most likely values are given for various radionuclides under different coastal conditions. In each case, a log-normal distribution has been applied, with the quoted maximum and minimum values set as the 1<sup>st</sup> and 99<sup>th</sup> percentiles. Because of the large number of plots required here, only those for Cs-137 (1<sup>st</sup> and 99<sup>th</sup> percentiles 500 and 20000  $\text{l kg}^{-1}$ ) and Am-241 (1<sup>st</sup> and 99<sup>th</sup> percentiles  $10^5$  and  $2 \times 10^7$ ) are shown in Figures 18 and 19.



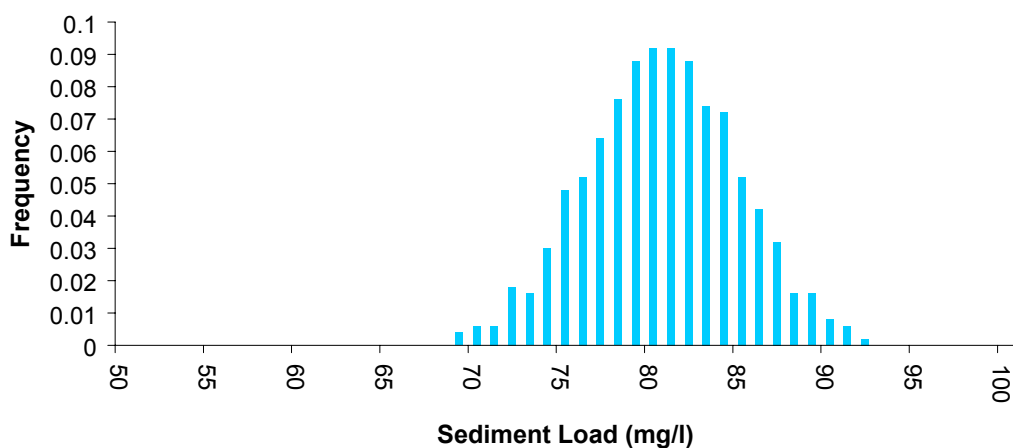
**Figure 18** The LHS distribution of input values for sediment distribution ( $\text{l kg}^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell. This refers to the radionuclide  $^{137}\text{Cs}$ .



**Figure 19** The LHS distribution of input values for sediment distribution ( $l\ kg^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell. This refers to the radionuclide  $^{241}Am$ .

### Suspended Sediment Load

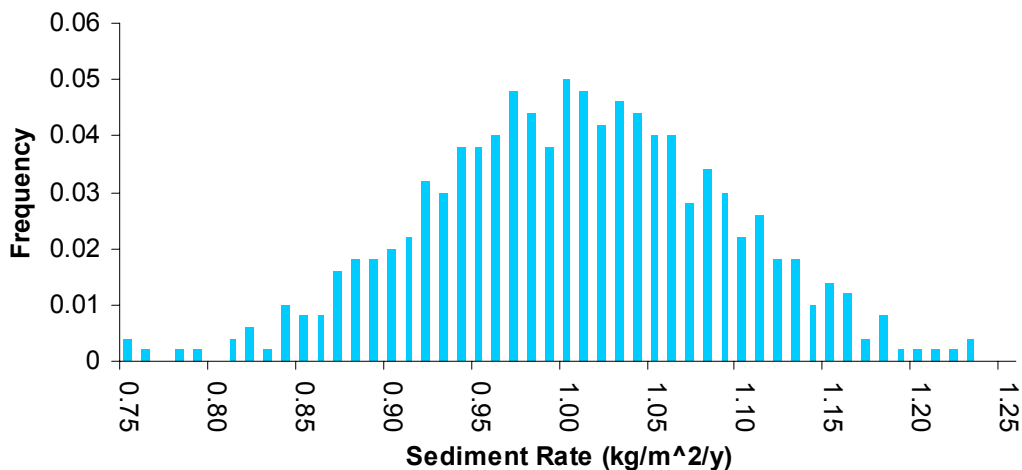
The suspended sediment load is a parameter that incorporates a number of processes. Because of this, the uncertainty caused by this parameter is difficult to quantify exactly. Experience in the use of this parameter during deterministic modelling of the Sizewell region has shown a value of  $80\ mg\ l^{-1}$  to be sufficient. To incorporate the uncertainty in this value, it was assumed to be the mean of a normal distribution with the 1<sup>st</sup> and 99<sup>th</sup> percentiles set to 70 and  $90\ mg\ l^{-1}$  respectively (see Figure 20).



**Figure 20** The LHS distribution of input values for suspended sediment load ( $mg\ l^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell.

### Sedimentation Rate

Like the sediment load, the uncertainty associated with this parameter is difficult to quantify. Experience with deterministic modelling in this region has suggested a value of the sediment rate of approximately  $1 \text{ kg m}^{-2} \text{ y}^{-1}$  (as shown previously). The uncertainty surrounding this mean value has been taken into account through the use of a normal distribution with 1<sup>st</sup> and 99<sup>th</sup> percentiles set to 0.8 and  $1.2 \text{ kg m}^{-2} \text{ y}^{-1}$  respectively (as shown in Figure 21).



**Figure 21** The LHS distribution of input values for sediment rate ( $\text{kg m}^{-2} \text{ y}^{-1}$ ) obtained from the expert elicitation process in the vicinity of Sizewell.

### Summary

The distribution types defined using the Latin Hypercube Sampling routine for use in the WATP model are shown in Table 9. Table 10 shows the maximum, minimum and most likely values for the  $K_d$  parameter. Each of these distributions is intended to take into account the variability and uncertainty that is inherent in the determination of each of these parameter values in the Sizewell region.

**Table 9** Values input into the Latin Hypercube Sampling routine for the probabilistic running of the WATP model at the Sizewell site.

<i>Parameter</i>	<i>Units</i>	<i>Dist<sup>n</sup></i>	<i>1<sup>st</sup> percentile</i>	<i>99<sup>th</sup> percentile</i>
Residual Velocity	$\text{m s}^{-1}$	log-normal	0.007	0.05
Diffusion Coefficient	$\text{m}^2 \text{ s}^{-1}$	log-normal	0.6	5.0
Tidal Excursion	m	normal	4930	7870
Initial Spreading Radius	m	constant	50	-
Start & end times	$t_s, t_e$	constant	0.54, 0.92	-
Distance to critical group	m	constant	0*	-
Suspended sediment load	$\text{mg l}^{-1}$	normal	70	90
Sedimentation rate	$\text{kg m}^{-2} \text{ y}^{-1}$	normal	0.8	1.2
Mean depth	m	normal	7	9

\* - This value is used for both consumption and occupancy in this case

**Table 10** The values for the sediment distribution coefficient ( $K_d$ ), as given by IAEA (1985) and applied to the LHS routine as a log-normal distribution. The 'Most Likely' values were used in the deterministic model described previously.

<i>Radionuclide</i>	<i>Most Likely</i>	<i>1<sup>st</sup> Percentile</i>	<i>99<sup>th</sup> Percentile</i>
H-3	1.0E+00	1.0E+00	1.0E+00
C-14	2.0E+03	5.0E+02	1.0E+04
S-35	1.0E+00	1.0E+00	1.0E+01
Ca-45	1.0E+02	1.0E+01	1.0E+03
Mn-54	2.0E+08	3.0E+04	5.0E+08
Fe-55	5.0E+07	3.0E+04	3.0E+08
Co-58	1.0E+07	5.0E+04	2.0E+07
Fe-59	5.0E+07	3.0E+04	3.0E+08
Co-60	1.0E+07	5.0E+04	2.0E+07
Zn-65	1.0E+05	1.0E+04	1.0E+06
Sr-90	2.0E+02	2.0E+00	5.0E+02
Y-90	2.0E+06	2.0E+05	3.0E+07
Zr-95	5.0E+05	1.0E+04	5.0E+06
Nb-95	2.0E+05	2.0E+04	2.0E+06
Ru-106 +	1.0E+03	1.0E+02	1.0E+04
Ag-110M+	1.0E+04	3.0E+03	5.0E+04
Sb-124	5.0E+02	1.0E+02	5.0E+03
Sb-125	5.0E+02	1.0E+02	5.0E+03
Te-125M	1.0E+03	1.0E+02	1.0E+04
Cs-134	2.0E+03	5.0E+02	2.0E+04
Cs-137 +	2.0E+03	5.0E+02	2.0E+04
Ce-144 +	1.0E+08	1.0E+06	2.0E+08
Pm-147	1.0E+06	5.0E+04	1.0E+07
Eu-154	4.0E+06	1.0E+05	1.0E+07
Eu-155	4.0E+06	1.0E+05	1.0E+07
Pu-238	1.0E+05	1.0E+04	1.0E+06
Pu-240	1.0E+05	1.0E+04	1.0E+06
Pu-241	1.0E+05	1.0E+04	1.0E+06
Am-241	2.0E+06	1.0E+05	2.0E+07
Cm-242	2.0E+06	2.0E+05	2.0E+07
Cm-243	2.0E+06	2.0E+05	2.0E+07

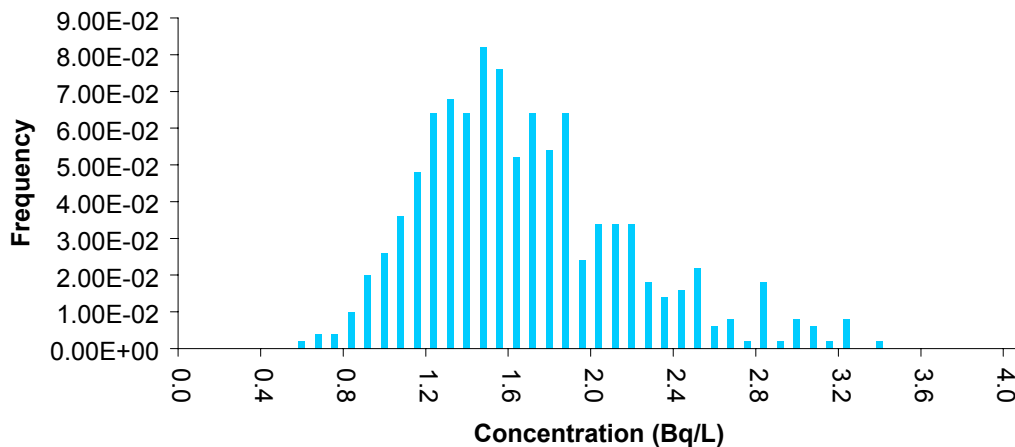
+ - Indicates decay of daughters taken into account

## 7.2 Water concentration output distributions

When the WATP model is run using the parameter values of Section 7.1 a water concentration is obtained for each of the 31 radionuclides used. Only three of these will be considered here in graphical form, namely:

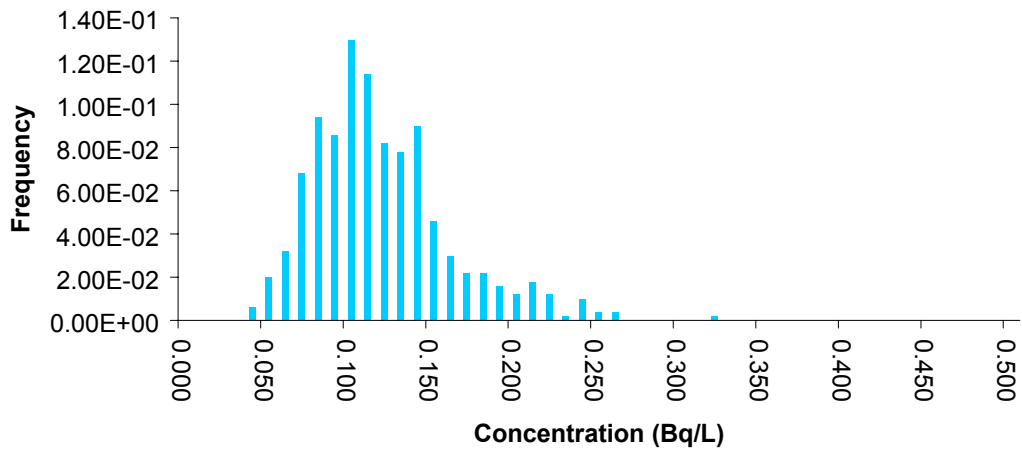
- $^3\text{H}$ , or tritium - This radionuclide has the largest discharge rate, so it will be shown in detail here.
- $^{127}\text{Cs}$  - As in the UK situation, this is representative of a conservative radionuclide.
- $^{241}\text{Am}$  - Representative of a particle-reactive radionuclide.

The output distributions of water concentration ( $\text{Bq l}^{-1}$ ) are shown in Figures 22, 23 and 24 for each of the three respective radionuclides.

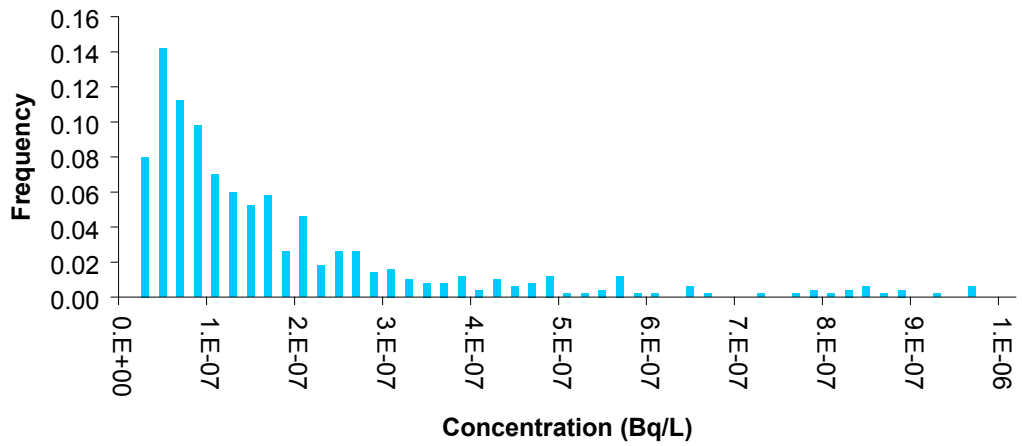


**Figure 22** The WATP distribution of predicted concentration of tritium ( $^3\text{H}$ ) at the discharge pipe. The 5<sup>th</sup> percentile is  $0.9119\text{Bq l}^{-1}$  and the 95<sup>th</sup> percentile is  $2.683\text{Bq l}^{-1}$ .

It appears that individual radionuclides will perform in different ways in probabilistic assessments. In the three cases considered here the distribution shapes differ significantly. Tritium and  $^{137}\text{Cs}$  have much higher concentrations than  $^{241}\text{Am}$ , and appear to have more compact distributions. In fact,  $^3\text{H}$  and  $^{137}\text{Cs}$  display a 'normal' shape to their output distributions, particularly compared to  $^{241}\text{Am}$  which seems distinctly log-normal in appearance.



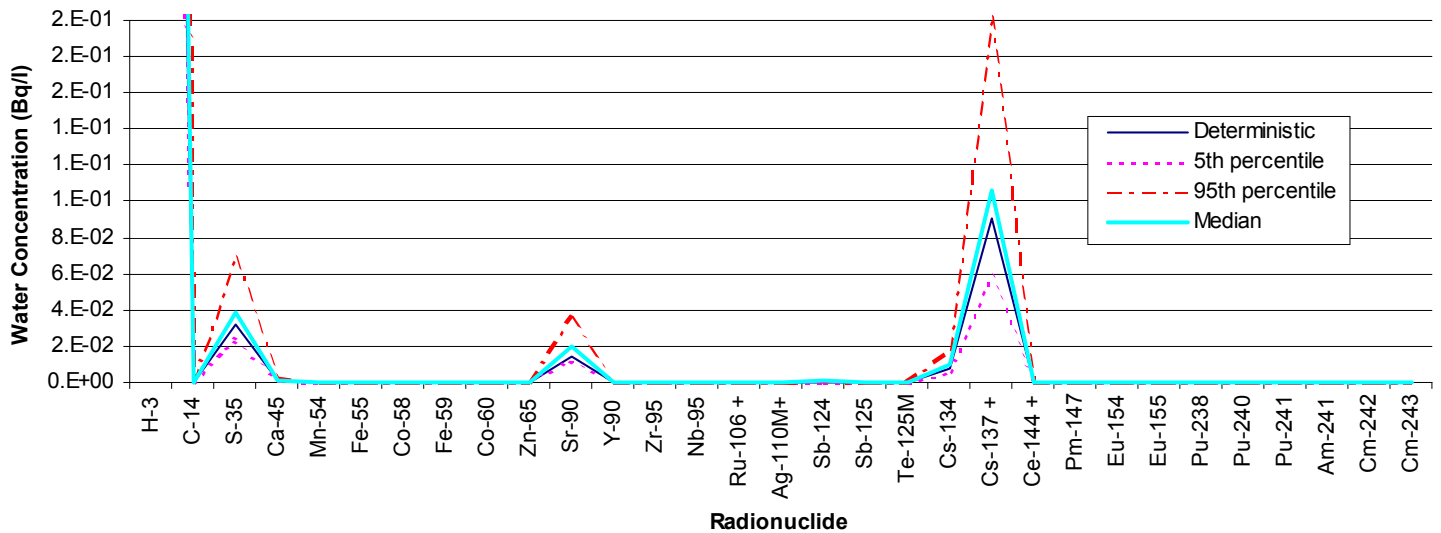
**Figure 23** The WATP distribution of predicted concentration of <sup>137</sup>Cs at the discharge pipe. The 5<sup>th</sup> percentile is 0.059Bq l<sup>-1</sup> and the 95<sup>th</sup> percentile is 0.201Bq l<sup>-1</sup>.



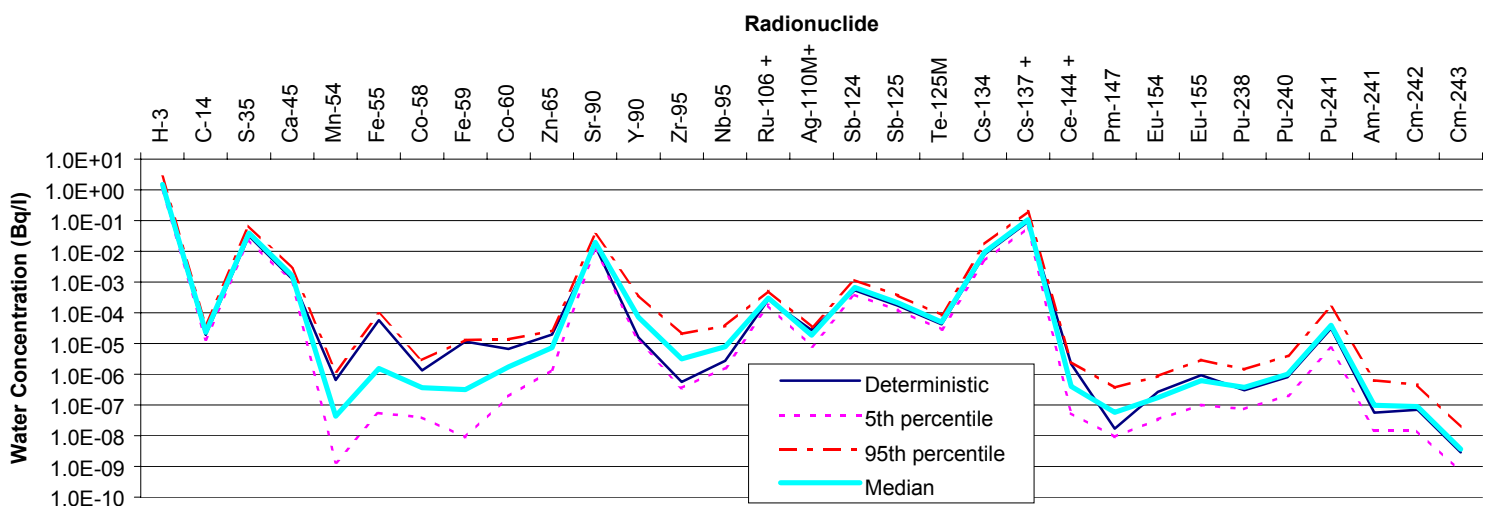
**Figure 24** The WATP distribution of predicted concentration of <sup>241</sup>Am at the discharge pipe. The 5<sup>th</sup> percentile is  $1.468 \times 10^{-8} \text{Bq l}^{-1}$  and the 95<sup>th</sup> percentile is  $6.381 \times 10^{-7} \text{Bq l}^{-1}$ .

### 7.3 Comparison of WAT and WATP Output

A comparison of the deterministic and probabilistic prediction of the water concentrations is shown in Figure 25 on a standard scale, and Figure 26 on a logarithmic scale. For each radionuclide, this shows the output of the deterministic model and various outputs of the probabilistic model. These include the 5<sup>th</sup> and 95<sup>th</sup> percentiles and mean values.



**Figure 25** A comparison between the output from the WAT (deterministic) and WATP (5<sup>th</sup> and 95<sup>th</sup> percentiles, mean) models for predicting water concentration.



**Figure 26** A logarithmic plot of the comparison between the output from the WAT (deterministic/best estimate) and WATP (5<sup>th</sup> and 95<sup>th</sup> percentiles, mean) models for predicting water concentration.

**Table 11** Radionuclide concentrations as calculated by the WAT (deterministic) and WATP (5<sup>th</sup> and 95<sup>th</sup> percentiles, mean) models. The uncertainty value is calculated using the ratio of 95<sup>th</sup> to 5<sup>th</sup> percentiles. In the 7<sup>th</sup> column each estimate is arranged into ascending order in abbreviated form, e.g. 5<sup>th</sup> percentile = 5, etc.

<i>Radio-nuclide</i>	<i>WAT Model</i>	<i>5<sup>th</sup> Percentile</i>	<i>50<sup>th</sup> Percentile</i>	<i>95<sup>th</sup> Percentile</i>	<i>Uncert. (95/5 %)</i>	<i>Ascending Order</i>
H-3	1.23004	9.12E-01	1.52E+00	2.68E+00	2.94E+00	5 W 50 95
C-14	1.91E-05	1.33E-05	2.30E-05	4.02E-05	3.02E+00	5 W 50 95
S-35	3.16E-02	2.35E-02	3.90E-02	6.82E-02	2.90E+00	5 W 50 95
Ca-45	1.26E-03	9.63E-04	1.61E-03	2.79E-03	2.90E+00	5 W 50 95
Mn-54	6.46E-07	1.37E-09	4.36E-08	1.24E-06	9.07E+02	5 50 W 95
Fe-55	5.75E-05	5.46E-08	1.55E-06	9.19E-05	1.68E+03	5 50 W 95
Co-58	1.33E-06	3.90E-08	3.62E-07	2.88E-06	7.39E+01	5 50 W 95
Fe-59	1.17E-05	8.96E-09	3.20E-07	1.30E-05	1.45E+03	5 50 W 95
Co-60	6.68E-06	1.90E-07	1.75E-06	1.36E-05	7.14E+01	5 50 W 95
Zn-65	1.95E-05	1.39E-06	7.33E-06	2.59E-05	1.86E+01	5 W 50 95
Sr-90	1.48E-02	1.18E-02	1.97E-02	3.48E-02	2.95E+00	5 W 50 95
Y-90	1.56E-05	1.16E-05	7.21E-05	3.87E-04	3.33E+01	5 W 50 95
Zr-95	5.68E-07	3.53E-07	3.17E-06	2.06E-05	5.84E+01	5 W 50 95
Nb-95	2.74E-06	1.63E-06	7.93E-06	3.74E-05	2.30E+01	5 W 50 95
Ru-106 +	2.69E-04	1.73E-04	3.05E-04	5.28E-04	3.06E+00	5 W 50 95
Ag-110M+	2.75E-05	8.16E-06	1.85E-05	3.51E-05	4.30E+00	5 50 W 95
Sb-124	5.36E-04	3.87E-04	6.66E-04	1.15E-03	2.97E+00	5 W 50 95
Sb-125	1.69E-04	1.21E-04	2.11E-04	3.66E-04	3.02E+00	5 W 50 95
Te-125M	4.19E-05	2.90E-05	5.02E-05	8.51E-05	2.94E+00	5 W 50 95
Cs-134	8.04E-03	5.03E-03	9.60E-03	1.72E-02	3.42E+00	5 W 50 95
Cs-137 +	9.01E-02	5.91E-02	1.07E-01	2.01E-01	3.40E+00	5 W 50 95
Ce-144 +	2.17E-06	5.31E-08	3.98E-07	2.54E-06	4.78E+01	5 50 W 95
Pm-147	1.68E-08	9.17E-09	5.77E-08	3.68E-07	4.01E+01	5 W 50 95
Eu-154	2.68E-07	3.38E-08	1.74E-07	8.60E-07	2.55E+01	5 50 W 95
Eu-155	9.28E-07	9.98E-08	6.15E-07	2.92E-06	2.93E+01	5 50 W 95
Pu-238	3.02E-07	7.29E-08	3.73E-07	1.45E-06	1.98E+01	5 W 50 95
Pu-240	8.09E-07	1.99E-07	9.96E-07	3.99E-06	2.01E+01	5 W 50 95
Pu-241	3.06E-05	6.93E-06	3.88E-05	1.51E-04	2.18E+01	5 W 50 95
Am-241	5.57E-08	1.47E-08	9.80E-08	6.38E-07	4.35E+01	5 W 50 95
Cm-242	6.95E-08	1.42E-08	8.86E-08	4.55E-07	3.21E+01	5 W 50 95
Cm-243	2.86E-09	6.69E-10	3.64E-09	1.90E-08	2.84E+01	5 W 50 95

The radionuclides of highest concentration can be easily seen in Figure 25 as <sup>3</sup>H, <sup>35</sup>S, <sup>90</sup>Sr and <sup>137</sup>Cs. These correspond to some of the largest discharges from the pipeline (apart from <sup>90</sup>Y). Unfortunately, the relative strengths of each prediction cannot be determined, which is why the logarithmic scale (Figure 26) is introduced. It seems that in most cases the deterministic and the median predictions are relatively close to each other. In many cases the ascending order of the water concentration values is 5<sup>th</sup>

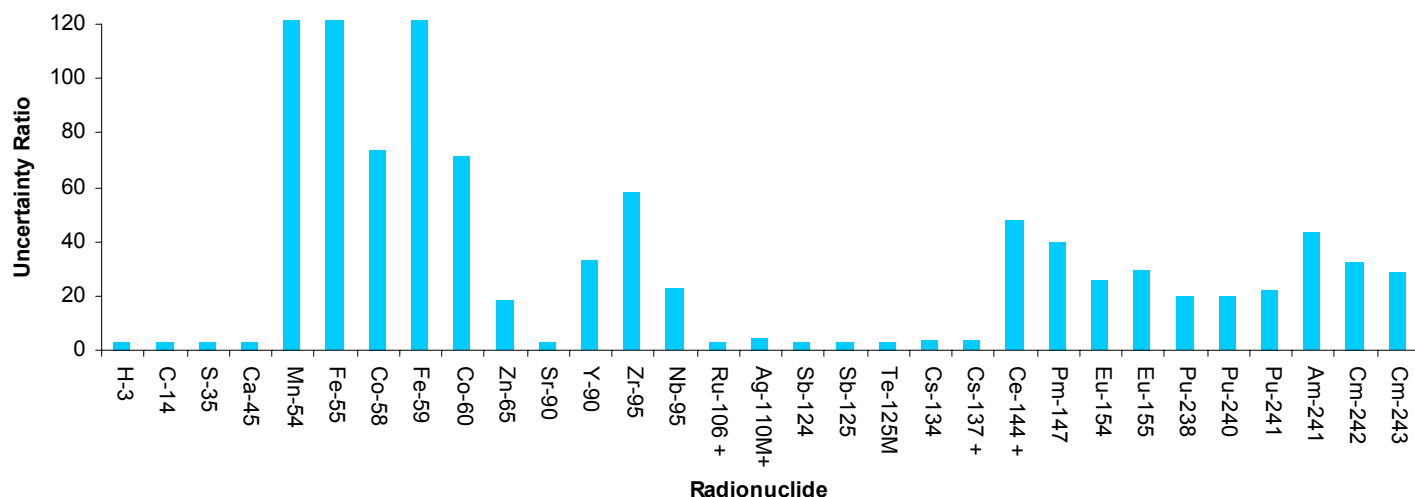
percentile (WATP), deterministic (WAT), median (WATP) and 95<sup>th</sup> percentile (WATP). This is not always the case however, as can be seen in the detail of Table 11. The right-most column shows the ascending order of the predictions for each radionuclide, with the deterministic WAT prediction (W) highlighted in bold type. This shows that 22 of the 31 radionuclides have the WAT prediction between the 5<sup>th</sup> percentile and median (50<sup>th</sup> percentile) value of the WATP probabilistic model. The remaining 9 radionuclides had the best estimate between the 50<sup>th</sup> and 95<sup>th</sup> percentiles.

## 7.4 WATP Uncertainties

The distribution of output concentrations from the WATP model has been used to determine the uncertainties associated with the prediction of the water concentrations. These are defined in Section 2.4 as:

$$\text{Uncertainty} = (95^{\text{th}} \text{ percentile}) / (5^{\text{th}} \text{ percentile}).$$

The uncertainty ratios are shown graphically in Figure 27.



**Figure 27** The uncertainties (ratio of 95<sup>th</sup> and 5<sup>th</sup> percentiles) calculated for each radionuclide in the running of the WATP model. Uncertainties beyond the scale of the chart are <sup>54</sup>Mn (907), <sup>55</sup>Fe (1680) and <sup>59</sup>Fe (1450).

The uncertainty values of <sup>54</sup>Mn, <sup>55</sup>Fe and <sup>59</sup>Fe are the highest, approximately 3 orders of magnitude. 12 (of 31) radionuclides have uncertainty values below 5, with the remainder above 15. The high magnitude of some of these uncertainty ratios can be attributed to the broadness of the input distributions, particularly that due to the sediment distribution factor ( $K_d$ ). In fact, the radionuclides with the highest variation in  $K_d$  also have the largest overall uncertainties, which indicates the importance of this parameter in the overall prediction, supporting Brownless et al. (2001).

When compared to the uncertainties of the UK situation, the uncertainties due to <sup>137</sup>Cs (UK 44.16, Sizewell 3.4) and <sup>241</sup>Am (UK 192.3, Sizewell 43.5) are significantly reduced. The reduction is approximately an order of magnitude, which can obviously

be attributed to the narrowing of the input distributions for the specific site assessment.

It should be noted that the uncertainty in prediction calculated here refers to the calculation of a 'deterministic' water concentration. Because the output from a probabilistic assessment is a distribution that takes into account uncertainties/variabilities in parameter inputs, the actual uncertainty associated with the WATP model is extremely small. The calculated uncertainties refer to those associated with parameter determination in the WAT model. Only the uncertainties associated with the model assumptions, formulation and computation are not taken into account in the distribution of output from the WATP model.

## **7.5 Summary**

Use of the probabilistic water concentration model (WATP) at Sizewell for 31 radionuclides has determined that uncertainty ratios range from 3 to 1680, or up to approximately 3 orders of magnitude. This depends on the radionuclide being studied, and refers to the associated uncertainty in the prediction of a single deterministic value (as in the WAT model). Note that this also refers to the combined uncertainty and variability of all input variables for the model. Higher uncertainties have been found to be associated with particle-reactive radionuclides, as in the uncertainty analysis of Brownless et al. (2001).

## 8. A Probabilistic Site Assessment - ADOP

Following from the use of the WATP model (Section 7), 500 runs of the ADOP model have been considered in the specific assessment of doses near Sizewell. The radionuclide water concentrations that were output from the WATP model were used as input to ADOP.

### 8.1 Use of the Habits Survey

In order to determine the true probabilistic dose to the group considered, the uncertainty associated with the habits survey should be incorporated. To investigate the effect that this has on the overall dose assessment, two scenarios will be considered:

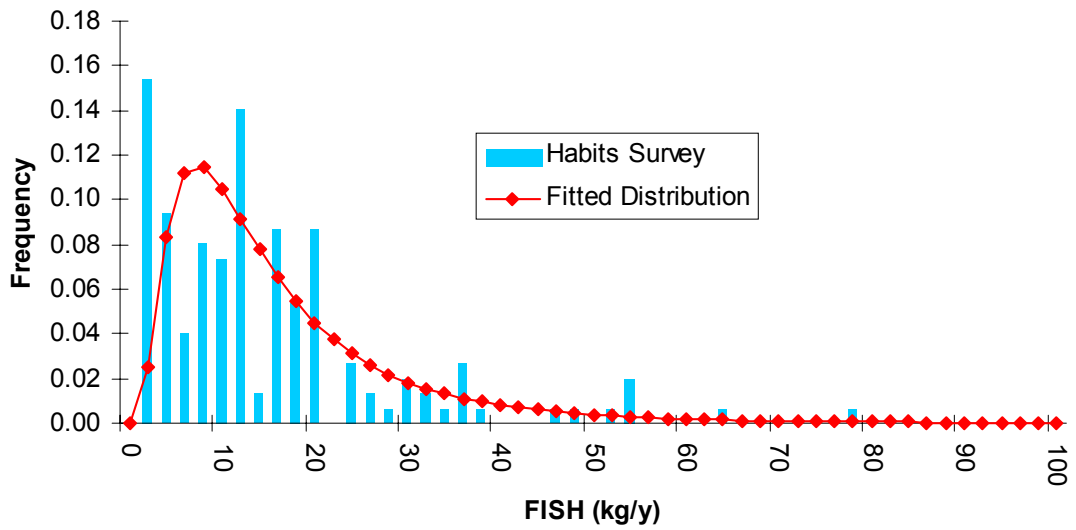
- 1) *Constant consumption and exposure*, as in the deterministic model,
- 2) *Distributions of consumption and exposure* based on the results of habit surveys of individuals that make up the critical group.

The input to the first of these is shown in Table 7, as used in the ADO model. These rates of consumption/exposure have been determined in the processing of the results of the habits survey (Tipple and Joyce, 2002).

The determination of the distributions of habits data for use in Scenario 2 is a process that is more specific to the probabilistic assessment. An attempt has been made to include the uncertainty and variability in both the survey procedure and the calculation of the final rates. Usually in the processing of the habits survey a subgroup of the individuals with the highest rate of consumption or exposure is determined (the 'critical group'). The overall consumption/exposure rate is then calculated from this subgroup. In the probabilistic treatment of the habits survey all individuals are considered, which contributes to the spread of the input data distribution. The fitting of a log-normal distribution to represent the survey results of each pathway has been undertaken. Particular emphasis has been placed upon including results of the survey which reflect higher consumption/exposure so that all uncertainties are taken into account.

#### **FISH (consumption)**

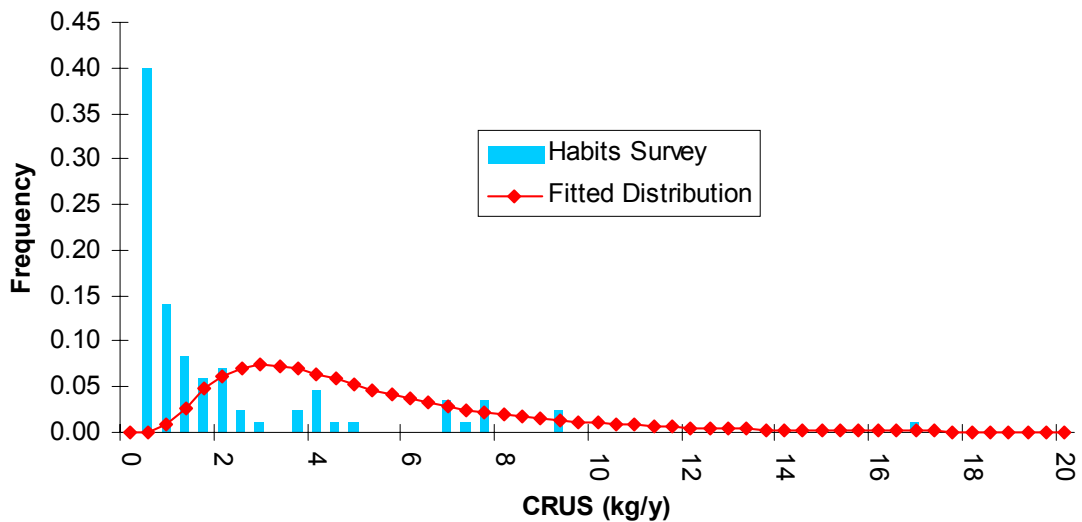
The survey of fish consumption incorporated 149 people in the Sizewell survey area. Individual consumption ranged from 0.45 to 76.27kg y<sup>-1</sup>. A histogram of the distribution of the habits survey results is shown in Figure 28. The distribution fitted by eye to the habits survey data has 5<sup>th</sup> and 95<sup>th</sup> percentiles at 1.5 and 70kg y<sup>-1</sup> respectively.



**Figure 28** The distribution of FISH (fish consumption) according to the habits survey and the distribution fitted for input into ADOP.

**CRUS (consumption)**

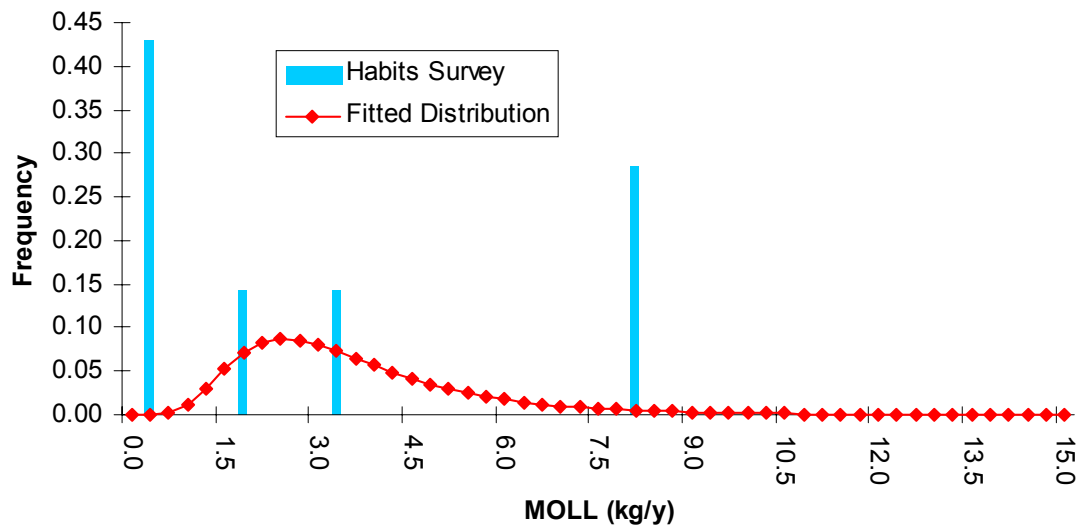
The survey of crustacean consumption included 85 individuals, with a maximum of 16.47kg y<sup>-1</sup> and a minimum of 0.05kg y<sup>-1</sup> eaten. The weighting of the resulting distribution shows that the majority of participants eat under 1kg y<sup>-1</sup>. However, to incorporate higher consumers, a log-normal distribution with 5<sup>th</sup> and 95<sup>th</sup> percentiles set to 1 and 18kg y<sup>-1</sup> was deemed appropriate (see Figure 29).



**Figure 29** The distribution of CRUS (crustacean consumption) according to the habits survey and the distribution fitted for input into ADOP.

### MOLL (consumption)

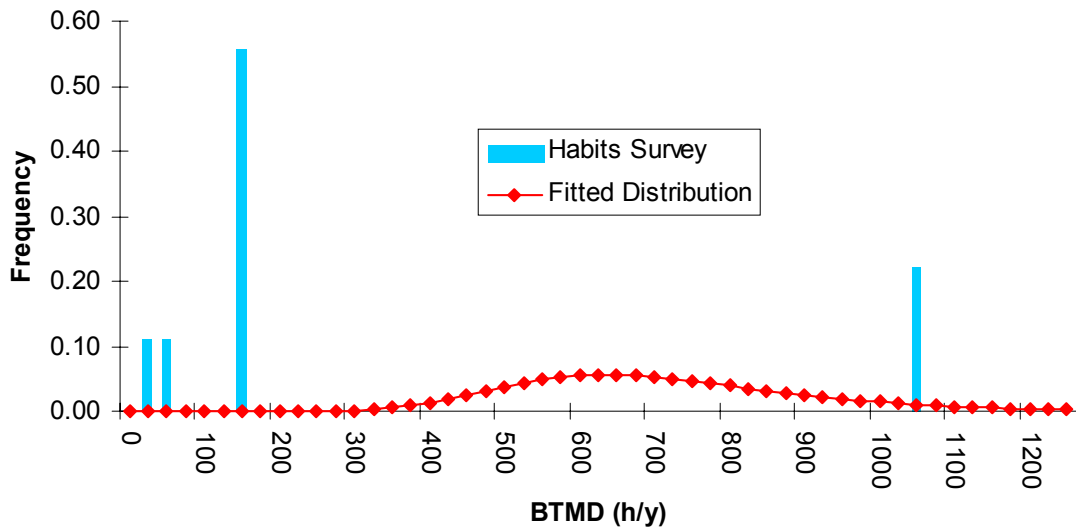
The survey of mollusc consumption included only 7 people, with maximum 8.08 and minimum 0.25kg y<sup>-1</sup>. This small amount of data means that an effective idea of the distribution cannot be obtained (see Figure 30). To incorporate this in the analysis it was decided that this pathway would be most reasonably represented by a (log-normal) curve with 5<sup>th</sup> and 95<sup>th</sup> percentiles at 1 and 10kg y<sup>-1</sup> respectively.



**Figure 30** The distribution of MOLL (mollusc consumption) according to the habits survey and the distribution fitted for input into ADOP.

### BTMD (exposure)

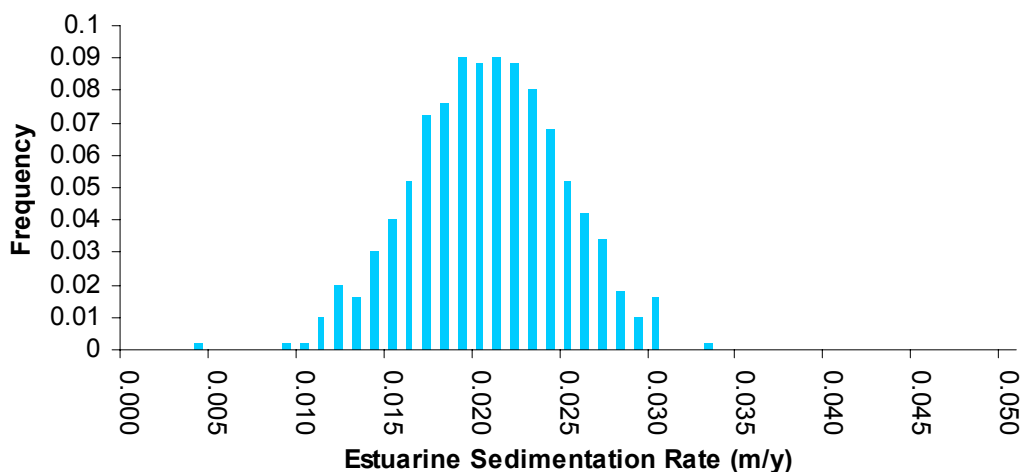
Only 9 individuals were surveyed for exposure over mud near Sizewell. Their maximum and minimum individual exposure times were 1040 and 18h y<sup>-1</sup> respectively. Because of the low number of samples, this has been a difficult distribution to accurately fit a curve to (see Figure 31). However, to take into account the range of values surveyed, a log-normal distribution with 5<sup>th</sup> and 95<sup>th</sup> percentiles set to 19 and 1300h y<sup>-1</sup> was applied.



**Figure 31** The distribution of BTMD (exposure over mud) according to the habits survey and the distribution fitted for input into ADOP.

## 8.2 Estuarine Sedimentation Rate

Apart from the habits data, there is only one input distribution to the ADOP model that was not described for use in WATP (Section 7). This is the estuarine sedimentation rate, which takes the value  $0.02\text{m y}^{-1}$  in the deterministic model. To take into account the variability and uncertainty in this parameter, a normal distribution has been applied, with 1<sup>st</sup> and 99<sup>th</sup> percentiles set to  $0.015$  and  $0.025\text{m y}^{-1}$  respectively (see Figure 32).



**Figure 32** The distribution for the estuarine sedimentation rate ( $\text{m y}^{-1}$ ), as calculated using the LHS routine and used in the ADOP model.

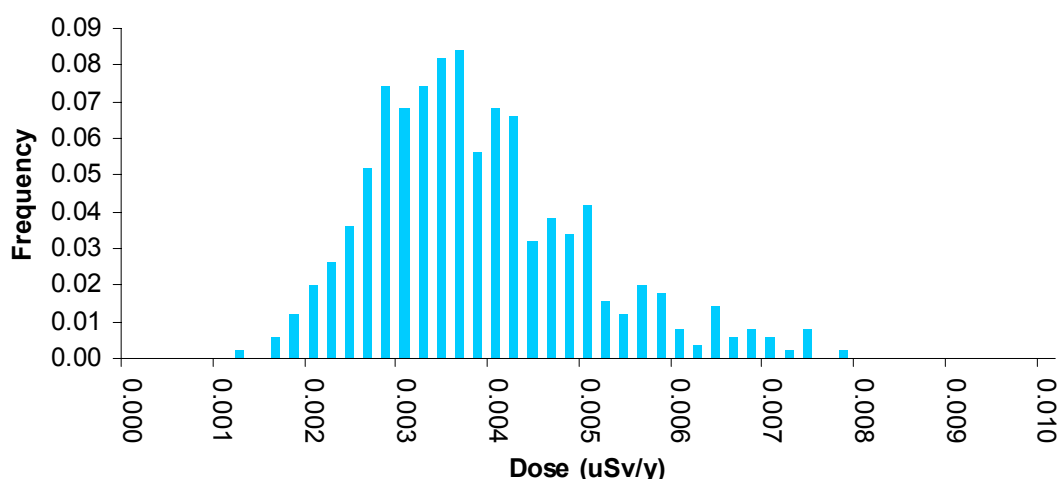
### 8.3 Calculated Dose Distributions

As discussed in Section 8.1, two calculations of doses have been considered with differing treatments of the input habits survey data. In both scenarios the same values of radionuclide concentrations in water (from WATP) have been used. The results obtained from the running of the ADOP model are shown for both scenarios in the sub-sections that follow.

#### 8.3.1 Doses using constant habits survey rates - Scenario 1

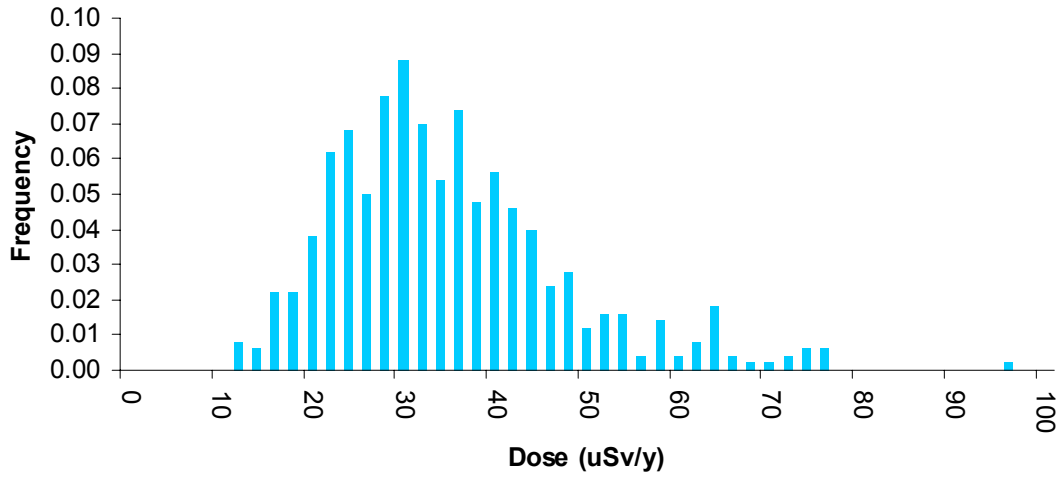
There are 4 pathways that have been included in this assessment with constant rates of occupancy/exposure, as described in Section 6.2. These have been applied in ADOP and a distribution of doses due to each radionuclide has been obtained.

Distributions of total doses for the combined pathways have been plotted for  $^3\text{H}$  (Figure 33),  $^{137}\text{Cs}$  (Figure 34) and  $^{241}\text{Am}$  (Figure 35). Additionally, dose outputs have been tabulated in Annex B for each radionuclide and pathway. Quantities such as the 5<sup>th</sup> and 95<sup>th</sup> percentiles, median values and calculated uncertainties are shown in Tables 15-18 (Annex B), but the total doses are summarised in Table 12.

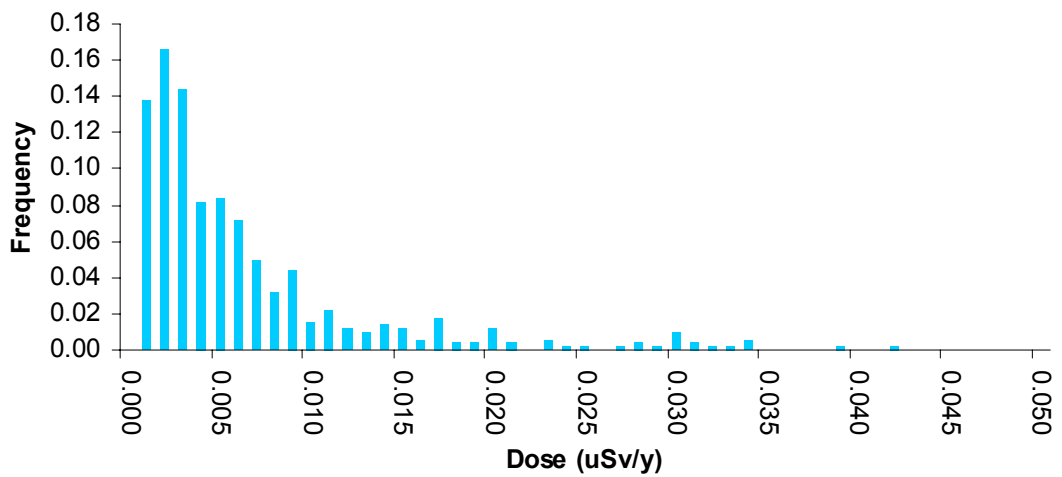


**Figure 33** The dose distribution ( $\mu\text{Sv y}^{-1}$ ) using constant habits rates predicted by the ADOP model for  $^3\text{H}$ .

For each radionuclide shown, the output distribution appears well contained, with the 'tail' not the most dominant feature. The shape of  $^{241}\text{Am}$  appears to be the format of a log-normal distribution, with the other two almost normal in their nature (as in Section 8). In this case the majority of the dose may be attributed to  $^{137}\text{Cs}$ . In fact, the dose due to  $^{137}\text{Cs}$  is the largest of all radionuclides (see Annex B), particularly for the pathway BTMD (bait digging over mud), which dominates overall dose results.



**Figure 34** The dose distribution ( $\mu\text{Sv y}^{-1}$ ) using constant habits rates predicted by the ADOP model for  $^{137}\text{Cs}$ .



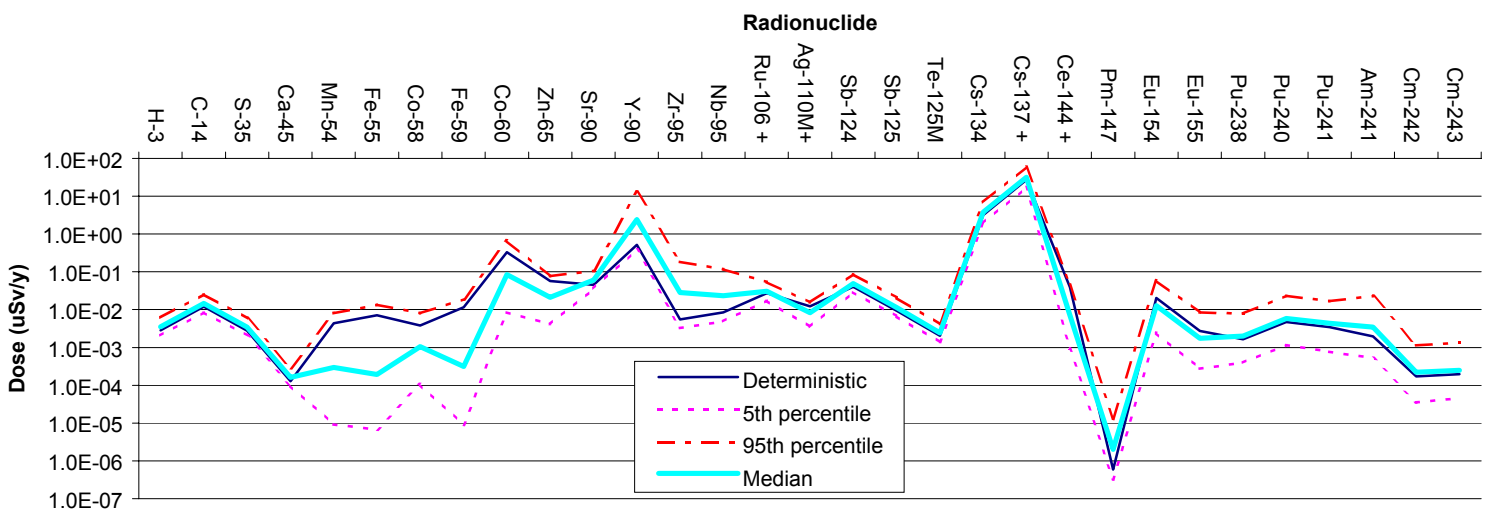
**Figure 35** The dose distribution ( $\mu\text{Sv y}^{-1}$ ) using constant habits rates predicted by the ADOP model for  $^{241}\text{Am}$ .

The dose due to  $^{241}\text{Am}$  is relatively small, which may influence the uncertainty measurement for this radionuclide. The 'tail' appears to be relatively long, and high frequencies can be attributed to the lower values than for the other radionuclides shown. This is supported by the summary data shown in Table 12.

**Table 12** Summary of doses ( $\mu\text{Sv y}^{-1}$ ) for  $^3\text{H}$ ,  $^{137}\text{Cs}$ ,  $^{241}\text{Am}$  and total dose when constant habits survey rates are used.

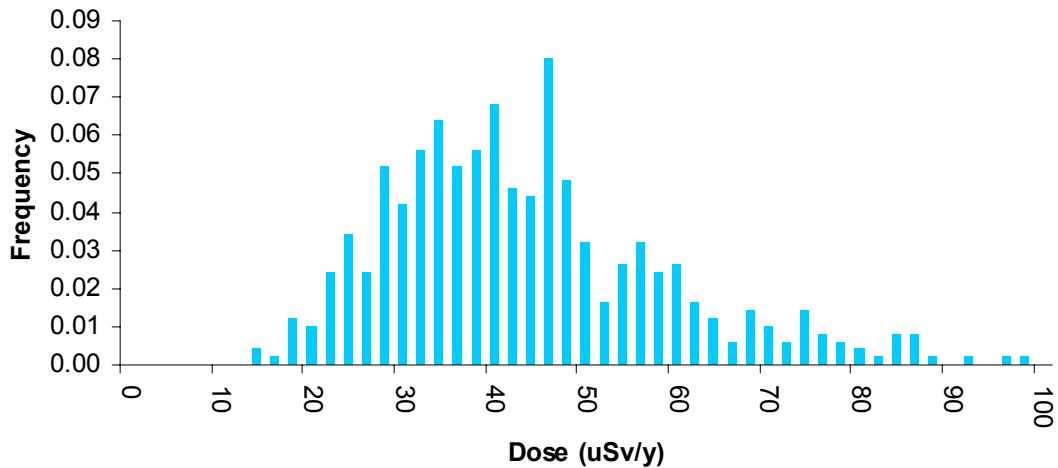
Radio-nuclide	Deterministic (ADO)	5 <sup>th</sup> Percentile	Median	95 <sup>th</sup> Percentile	Uncertainty
$^3\text{H}$	2.83E-03	2.10E-03	3.50E-03	6.18E-03	2.94
$^{137}\text{Cs}$	2.72E+01	1.74E+01	3.16E+01	6.03E+01	3.47
$^{241}\text{Am}$	1.98E-03	5.22E-04	3.49E-03	2.27E-02	43.5
Total	3.15E+01	2.20E+01	4.01E+01	7.36E+01	3.35

This table shows that in the case of Sizewell using all radionuclides the ADO deterministic estimate is between the 5<sup>th</sup> percentile and median predictions of ADOP. This is similar to what was observed with the water concentrations in Section 7. The uncertainty associated with dose due to  $^{241}\text{Am}$  is over 6 times higher than that of either  $^3\text{H}$  or  $^{137}\text{Cs}$ . An overall picture of doses due to all nuclides is shown on a logarithmic scale in Figure 36. The 5<sup>th</sup> percentile ADOP dose prediction appears to be generally lower than the deterministic (best estimate) prediction. In many cases, the ADO prediction is closest to ADOP median value, but there are a few cases of radionuclides where the deterministic value is closer to the 95<sup>th</sup> percentile.



**Figure 36** The doses predicted for each radionuclide by the ADOP model with a constant value for occupancy/consumption (logarithmic scale). Shown are the 5<sup>th</sup> and 95<sup>th</sup> percentiles and the mean value. These are compared on a logarithmic scale to the deterministic prediction by the ADO model.

The overall dose due to all nuclides and pathways with constant habits rates has the deterministic estimate ( $31.5\mu\text{Sv y}^{-1}$ ) between the 5<sup>th</sup> percentile ( $22.0\mu\text{Sv y}^{-1}$ ) and the median ( $40.1\mu\text{Sv y}^{-1}$ ). This is shown in distribution form in Figure 37. The minimum and maximum doses are  $12.4$  and  $119\mu\text{Sv y}^{-1}$  respectively.

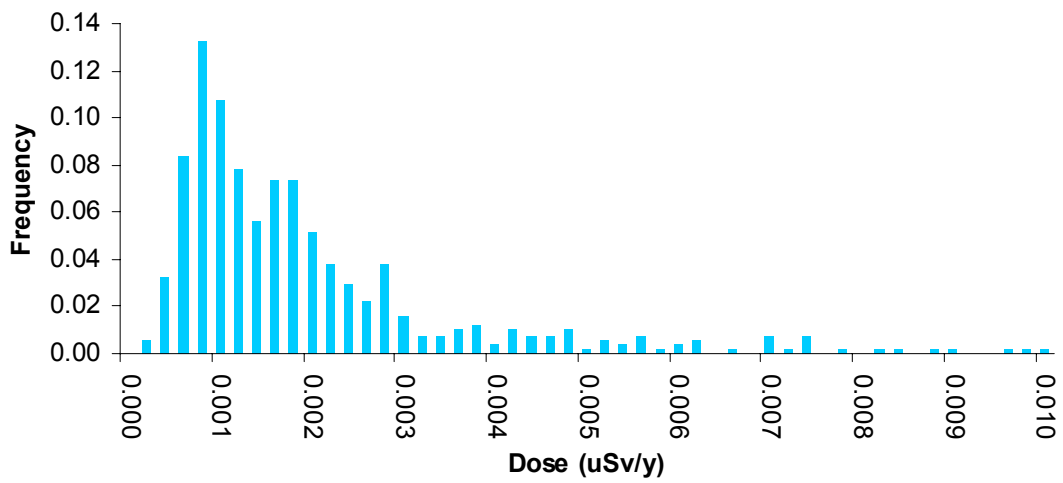


**Figure 37** The dose distribution ( $\mu\text{Sv y}^{-1}$ ) using constant habits rates predicted by the ADOP model for all 31 radionuclides.

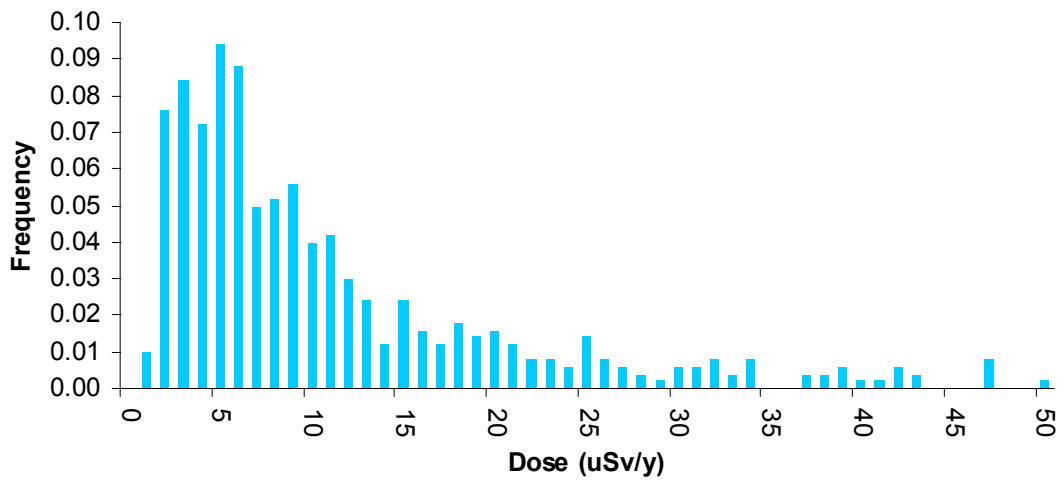
### 8.3.2 Doses using probabilistic habits survey rates - Scenario 2

The assessment of probabilistic doses at Sizewell has been conducted with the distributions of habits data described in Section 8.1. Each of these incorporates all individuals in the surveys, and represents consumption and exposure rates which are generally less than those used in the deterministic method (Section 6) and in Section 8.3.1.

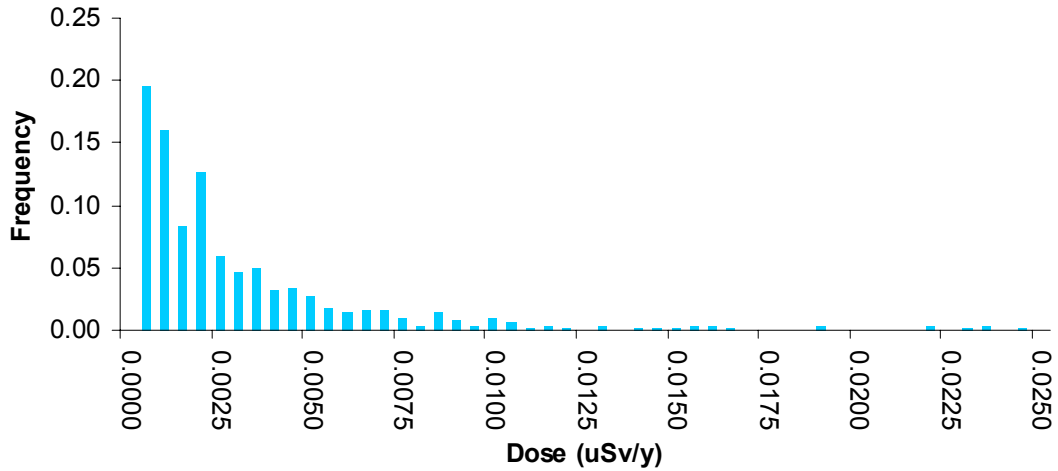
Distributions of total doses for the combined pathways have been plotted for  $^3\text{H}$  (Figure 38),  $^{137}\text{Cs}$  (Figure 39) and  $^{241}\text{Am}$  (Figure 40). The distributions have been presented on the same axes as Figures 34, 35 and 36 (respectively), for relatively easy comparison. The feature that is most obvious initially is that the doses are of a lower magnitude than those of Section 8.3.1. The 'tails' of the distributions tend to be longer and thinner, which would contribute to an increase in the uncertainty of the prediction (see Table 13). Because of the nature of the habits survey distributions, this behaviour relative to 8.3.1 is not unexpected.



**Figure 38** The total dose distribution predicted by the ADOP model for  $^3\text{H}$  with variable habits rates.



**Figure 39** The total dose distribution predicted by the ADOP model for  $^{137}\text{Cs}$  with variable habits rates.



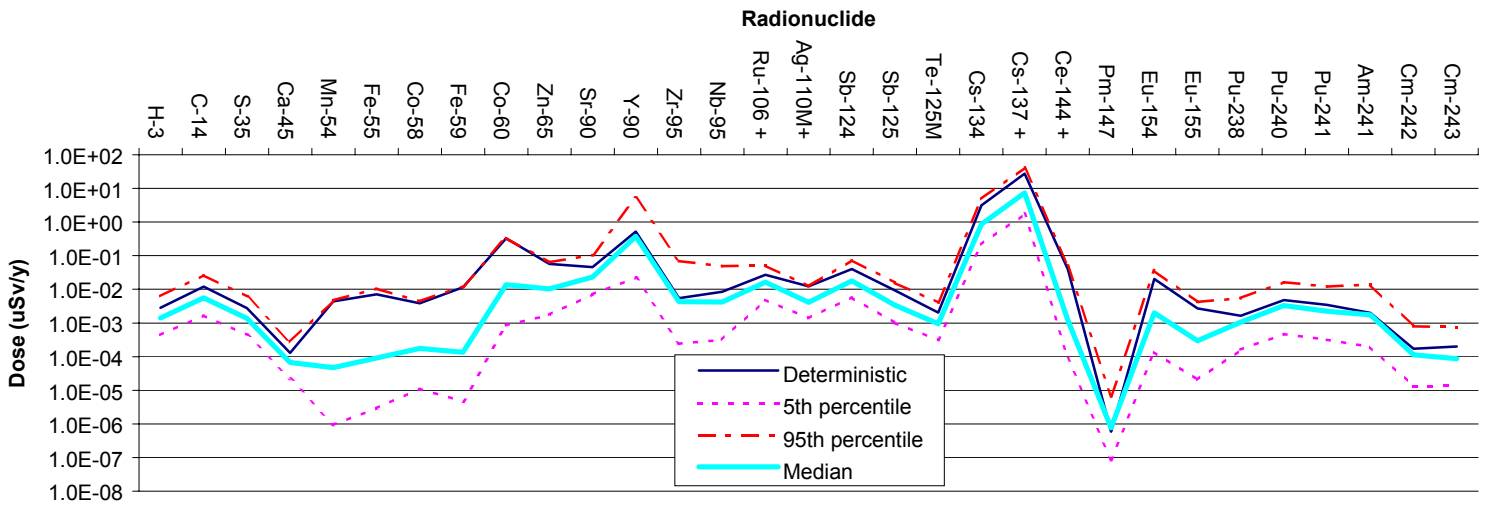
**Figure 40** The total dose distribution predicted by the ADOP model for  $^{241}\text{Am}$  with variable habits rates.

**Table 13** Summary of doses ( $\mu\text{Sv y}^{-1}$ ) for  $^3\text{H}$ ,  $^{137}\text{Cs}$ ,  $^{241}\text{Am}$  and total dose when variable habits survey rates are used.

<i>Radio-nuclide</i>	<i>Deterministic (ADO)</i>	<i>5<sup>th</sup> Percentile</i>	<i>Median</i>	<i>95<sup>th</sup> Percentile</i>	<i>Uncertainty</i>
$^3\text{H}$	2.83E-03	4.37E-04	1.41E-03	6.19E-03	14.16
$^{137}\text{Cs}$	2.72E+01	1.76E+00	7.41E+00	4.16E+01	23.69
$^{241}\text{Am}$	1.98E-03	1.94E-04	1.75E-03	1.39E-02	71.7
Total	3.15E+01	2.20E+00	9.10E+00	4.95E+01	22.55

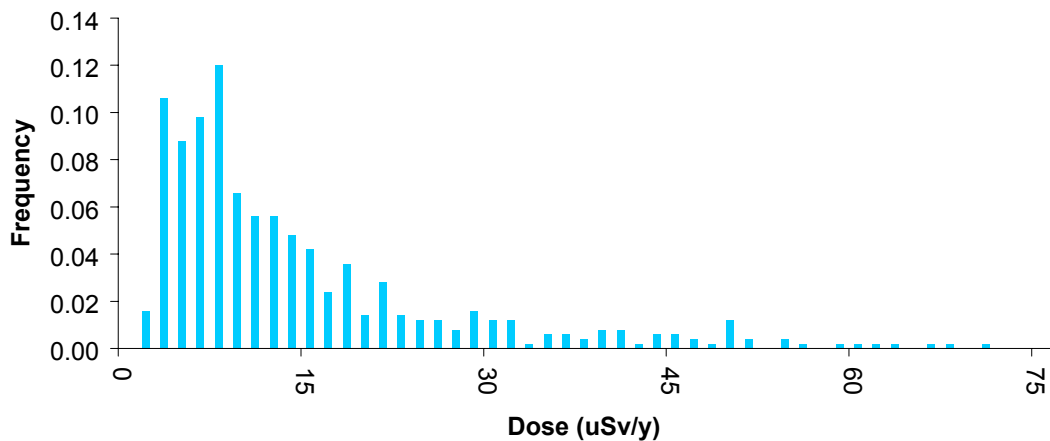
Dose outputs have been tabulated in Annex C for each radionuclide and pathway. Quantities such as the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles and calculated uncertainties are shown in Tables 19-22 and the total doses are summarised in Table 13. This table shows that in this case the ADO estimate is between the median and the 95<sup>th</sup> percentile predictions of ADOP. This is different to the behaviour of the model in Section 8.3.1, and can be attributed directly to the use of distributions for habits surveys. The uncertainties for each radionuclide are much higher than those when constant numbers are used for habits rates, the uncertainty factor calculated to be 22.55 for the overall dose.

An overall picture of dose due to each nuclide is shown in Figure 41. It is obvious that the 5<sup>th</sup> percentile ADOP dose prediction is always lower than the deterministic (best estimate) prediction. Generally the ADO prediction with variable habits survey data is close to (or between) either the ADOP 50<sup>th</sup> or 95<sup>th</sup> percentile values even though there are some variations with different radionuclides.



**Figure 41** The doses predicted for each radionuclide by the ADOP model with a constant value for occupancy/consumption. Shown are the 5<sup>th</sup> and 95<sup>th</sup> percentiles and the median value. These are compared on a logarithmic scale to the deterministic prediction by the ADO model.

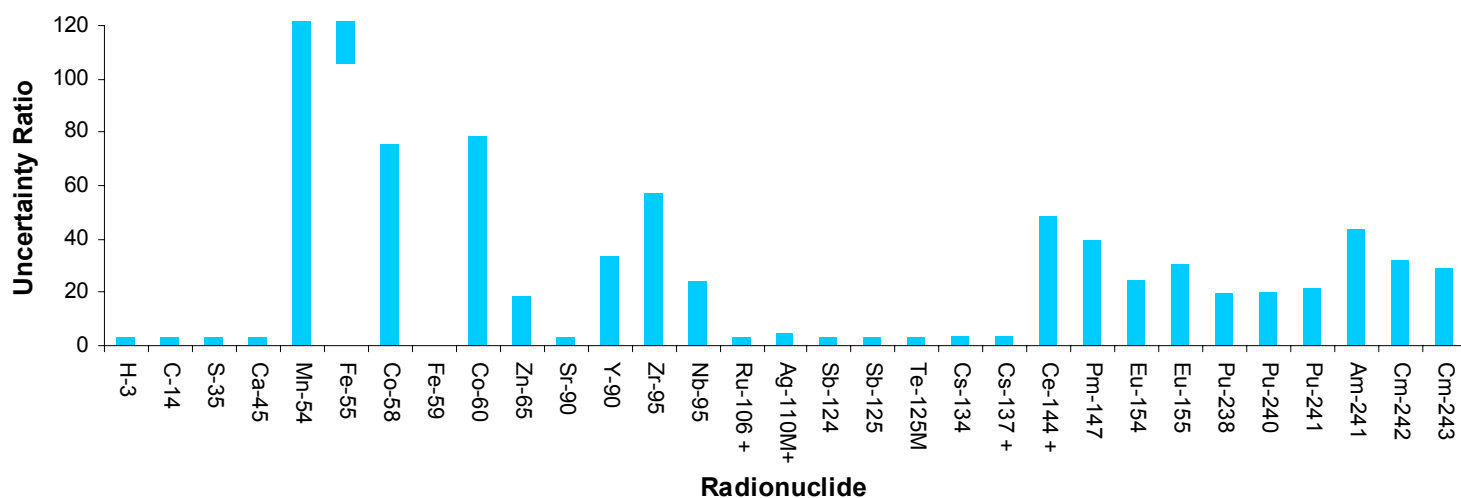
The overall dose due to all nuclides and pathways with variable habits rates has the deterministic estimate ( $31.5\mu\text{Sv y}^{-1}$ ) higher than the median ( $9.1\mu\text{Sv y}^{-1}$ ) and lower than the 95<sup>th</sup> percentile ( $49.5\mu\text{Sv y}^{-1}$ ). This is shown in distribution form in Figure 42. The minimum and maximum doses are  $0.846$  and  $190\mu\text{Sv y}^{-1}$  respectively.



**Figure 42** The total dose distribution predicted by the ADOP model for all radionuclides with variable habits rates.

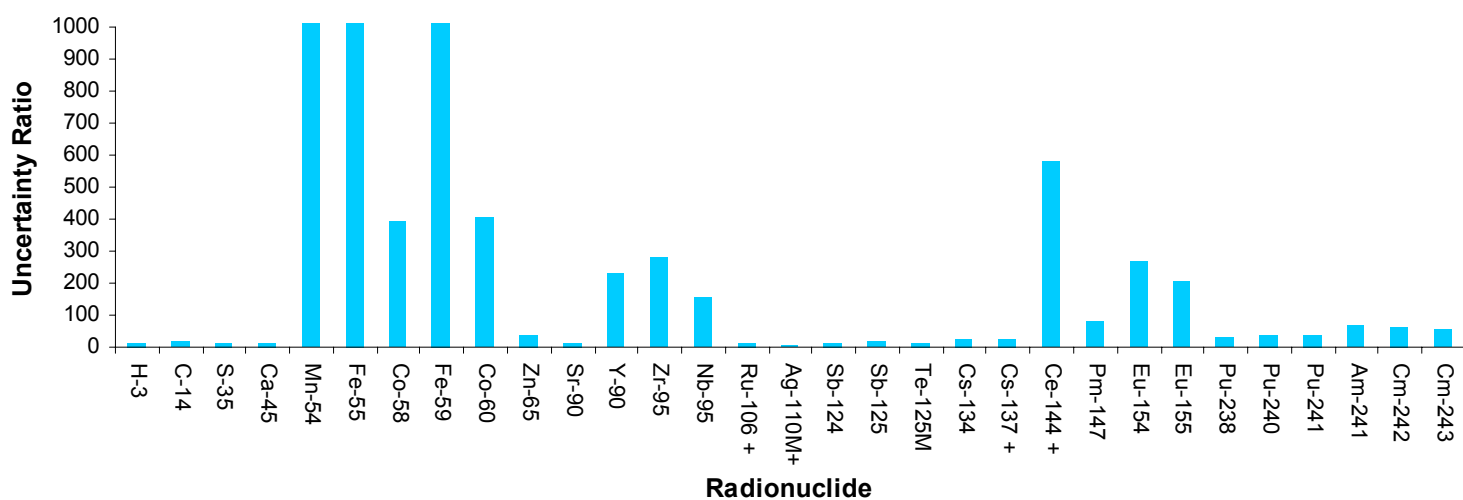
## 8.4 Uncertainties and Discussion

The uncertainty values for each radionuclide using the ADOP model with constant habits rates (Scenario 1) are shown graphically in Figure 43. These are also tabulated in Annex B, Table 18. The maximum uncertainty ratio is 2140, with the overall uncertainty ratio in dose determination calculated to be 3.35. Almost all uncertainties are less than two orders of magnitude (100), with the exception of  $^{54}\text{Mn}$  (869),  $^{55}\text{Fe}$  (2020) and  $^{59}\text{Fe}$  (2140). However, as shown in Figure 35, each of these radionuclides contribute relatively little to the overall dose, which decreases the significance of these large uncertainties.



**Figure 43** The uncertainty values for each radionuclide obtained using the ADOP model with constant consumption/occupancy. Uncertainties beyond the scale of the chart are  $^{54}\text{Mn}$  (869),  $^{55}\text{Fe}$  (2020) and  $^{59}\text{Fe}$  (2140).

The uncertainty values for each radionuclide using the ADOP model with distributions representing habits rates (Scenario 2) are shown graphically in Figure 44. These are also tabulated in Annex C, Table 22. The overall uncertainty ratio in dose determination has been calculated to be 22.55. The largest uncertainties are again from the radionuclides  $^{54}\text{Mn}$  (5040),  $^{55}\text{Fe}$  (3590) and  $^{59}\text{Fe}$  (2670), with other uncertainty values under 350. Figure 41 shows that these three radionuclides contribute relatively little to the overall dose.



**Figure 44** The uncertainty values for each radionuclide obtained using the ADOP model with variable consumption/occupancy. Uncertainties beyond the scale of the chart are <sup>54</sup>Mn (5040), <sup>55</sup>Fe (3590) and <sup>59</sup>Fe (2670).

Overall, the uncertainty ratio obtained using variable habits survey rates (22.55) is approximately 5-6 times greater than that obtained using constant values (3.35). This indicates that the treatment of the habits survey data is extremely important in determining the overall dose in the assessment. Because of its importance, the treatment of the habits survey in future assessments should be investigated more closely to ensure that each pathway is correctly simulated.

The much higher uncertainty ratio when distributions are considered for habits surveys (Scenario 2) shows the need to incorporate this feature into the probabilistic model for dose assessments (ADOP). If a true distribution of doses is required then the significance of the uncertainty and variability of the survey data should not be underestimated, and it is recommended that this is included in any future study of this nature.

In an assessment where the output dose is given as a distribution, such as that considered here for Sizewell, it can sometimes be difficult to determine which statistics are of importance. The deterministic model gives an overall 'best estimate' ( $31.5\mu\text{Sv y}^{-1}$ ), which is relatively easy for the public to understand. Various output statistics for the scenarios considered for probabilistic modelling are shown in Table 14. These include the mean, median (50<sup>th</sup> percentile) and mode (most frequent value), as well as the 5<sup>th</sup> and 95<sup>th</sup> percentiles.

**Table 14** Summary of dose statistics ( $\mu\text{Sv y}^{-1}$ ) for total dose for Scenarios 1 and 2 for habits rates. The ADO model calculates the 'best estimate' as  $31.5\mu\text{Sv y}^{-1}$ .

<i>Habits Rate</i>	<i>5<sup>th</sup> Percentile</i>	<i>95<sup>th</sup> Percentile</i>	<i>Mean</i>	<i>Median</i>	<i>Mode</i>
(1) Constant	22.0	73.6	42.8	40.1	31.4
(2) Variable	2.2	49.5	16.1	9.1	10.1

Through the experience of undertaking this assessment, it seems that the probabilistic variation of the habits surveys should be taken into account. If this is the case, it seems that the 50<sup>th</sup> and 95<sup>th</sup> percentiles would be the important values for dose assessment. However, to take into account all uncertainties the 95<sup>th</sup> percentile should be used as the "upper bound" of dose calculation. The 95<sup>th</sup> percentile is preferred to the maximum predicted dose as the latter can contain outlying solutions, which would give an artificially inflated value for the overall dose if emphasised as the most important value.

It is interesting to note that the mode calculated for Scenario 1 ( $31.4\mu\text{Sv y}^{-1}$ ) is a similar value to the deterministic dose prediction ( $31.5\mu\text{Sv y}^{-1}$ ). The input distributions of most parameters have the most likely value as the choice of input to the deterministic model. The parameters that this does not apply to at all are the habits consumption/occupancy rates. Thus, when the constant habits rates are used in a probabilistic assessment the mode (or most likely value) is likely to be similar to the deterministic model output. Because of the choice of habits distributions, the mode for Scenario 2 differs from that of Scenario 1.

In the case of the Sizewell site assessments considered here it is clear that the deterministic approach contains uncertainties and variabilities in the determination of each of the input parameters. Predictions of dose obtained using the WAT/ADO modelling suite can be considered to have uncertainty ratio values of approximately 22. It is recommended that the 95<sup>th</sup> percentile be used as a more accurate measure of the upper bound of dose calculation. However, because of assumptions made in the habits survey to ensure that the dose is not under-predicted by the deterministic model, the best estimate has been found in this assessment to be quite high in the distribution when variable habits rates are used.

## 9. Summary and Conclusions

A probabilistic modelling suite has been developed for use in the modelling of radionuclide dispersal and uptake in a marine environment due to regular discharges. This has been based upon the CEFAS WAT and ADO (Round 1998a,b) suite of programmes, and the application of the Monte-Carlo technique for propagating uncertainties. The resulting models have been re-named as WATP and ADOP for probabilistic modelling.

Distributions of the most sensitive input parameters (as determined by Brownless et al 2001) have been determined by the method of expert elicitation. These have generally been input as normal or log-normal distributions, which have been numerically sampled using the Latin Hypercube Sampling technique in preference to Simple Random Sampling. Parameter distributions have been constructed from observations and hydrodynamic model data for the entire UK coast and the specific situation of Sizewell, Suffolk.

The initial test application (1000 iterations) of the probabilistic models was undertaken using input for the UK coastline. The WATP model predicted distributions of radionuclide concentrations around the coast for unit discharges of  $^{241}\text{Am}$  and  $^{137}\text{Cs}$  ( $\text{Bq y}^{-1}$ ). Uncertainty ratios (fraction of 95<sup>th</sup> and 5<sup>th</sup> percentiles) were calculated to be 190 ( $^{241}\text{Am}$ ) and 44 ( $^{137}\text{Cs}$ ). These high values were expected due to the broad distributions used for input to the model.

Output from WATP for the UK situation was applied to ADOP (1000 iterations). A total of 26 pathways with unit consumption/occupancy rates have been used. The output distribution of doses ( $\mu\text{Sv y}^{-1}$ ) was dominated by doses due to  $^{241}\text{Am}$  and sand/mud ingestion pathways. This can be attributed to the bonding of  $^{241}\text{Am}$  to sediment particles in the water column. Overall uncertainty in the dose calculation is 180, or more than 2 orders of magnitude over the entire UK coastline. It was decided that more specific assessments were required to determine which output statistics were the most relevant for probabilistic models.

The WATP and ADOP programs were then compared to a deterministic site assessment of Sizewell (overall dose of  $31.5\mu\text{Sv y}^{-1}$ ). This was conducted with 31 radionuclides and 4 consumption/occupancy pathways. Input parameter distributions were obtained from expert elicitation and distributions of water concentrations were obtained from the running of WATP. 5<sup>th</sup> percentile, mean and 95<sup>th</sup> percentile WATP output has been compared to the deterministic WAT prediction. It was found that for most radionuclides the WAT prediction is between the 5<sup>th</sup> percentile and median value of WATP. WATP uncertainties were found to be greatest for the radionuclides with the largest  $K_d$  values (up to 3 orders of magnitude). As expected, the uncertainties of  $^{241}\text{Am}$  (43.5) and  $^{137}\text{Cs}$  (3.4) were found to be much lower than for the UK situation.

Two scenarios were considered for the ADOP model. These involve two treatments of the habits survey consumption and occupancy rates, as shown below.

- Scenario 1:** This involved the use of constant consumption and exposure rates as used in the deterministic assessment. Overall uncertainty was found to be relatively small (3.4), and the deterministic dose ( $31.5\mu\text{Sv y}^{-1}$ ) was found to be between the 5<sup>th</sup> percentile ( $22.0\mu\text{Sv y}^{-1}$ ) and median value ( $40.1\mu\text{Sv y}^{-1}$ ) ADOP predictions. Significantly, the mode was extremely close to the deterministic estimate at  $31.4\mu\text{Sv y}^{-1}$ .
- Scenario 2:** Distributions of consumption and exposure have been input to the assessment. These are based upon the results of the habits survey, and have incorporated uncertainty and variability in the critical group. Overall uncertainty was found to be higher than Scenario 1 (23), and the deterministic estimate dose ( $30.7\mu\text{Sv y}^{-1}$ ) was found to be between the median ( $9.1\mu\text{Sv y}^{-1}$ ) and 95<sup>th</sup> percentile ( $49.5\mu\text{Sv y}^{-1}$ ) ADOP predictions. The mode was  $10.1\mu\text{Sv y}^{-1}$ .

The experience of this specific assessment has led to a number of recommendations for future probabilistic assessments. It is important that the uncertainty of the critical group is incorporated, but it is not clear exactly how this should be done. In the site assessment considered here in Scenario 2 the variability of the survey group has been taken into account, but this does not follow the current methodology of assessments, where the individuals with the highest rates of exposure/occupancy are given the main focus. It may be desirable to consider the distribution associated with these higher consumers, otherwise known as the critical group. If the uncertainty distributions of habits rates were based upon these higher users rather than the entire survey group, the mode of Scenario 2 could be expected to be much closer to the deterministic model value (as seen with Scenario 1).

In order to sufficiently take into account all uncertainties and variabilities in the calculation of dose to the survey group it is recommended that a high percentile value should be used as the measure of the maximum possible dose to the group being considered, for example the 95<sup>th</sup> percentile. It may in fact be desirable to present a range of output errors, such as the 5<sup>th</sup> (minimum), 50<sup>th</sup> (likely) and 95<sup>th</sup> (maximum) percentiles. These values may indicate an increase in the maximum dose compared to the deterministic method, but they take into account the possible margin for error whilst excluding undesired outlying solutions.

## 10. Future Work

The probabilistic modelling methodology appears to have the potential to supersede the deterministic method. For this to occur further work to develop the use of the WATP and ADOP models should be considered.

From the simulations considered in this report, it is extremely important for the treatment of habits survey data to be accurately incorporated. Further studies are required to determine the differences in dose outputs when individuals with higher consumption/exposure rates are focussed upon. Of particular interest is the effect on the 95<sup>th</sup> percentile value.

Additionally, it is important that a standard methodology for probabilistic assessments is developed. This enables the comparison of each assessment on a site-by-site basis.

Further elicitation processes should be investigated for each site in the UK. This includes investigation of the uncertainty attributed to variation in dose coefficients, which was outside the scope of this study. A database of distributions for various sites would be an extremely useful addition to the probabilistic modelling suite. It is important that the process of describing parameter values for aquatic assessments conforms to that used in other areas of radiological assessment.

Finally, further validation of WATP and ADOP must be considered. This includes consideration of the single compartment model, IDLE (Hunt 1982), which has not been investigated here. It should be noted that the uncertainty due to parameter prediction has been considered here, and that uncertainties attributed to the model are assumed to be insignificant compared to these. As in the case of all relatively new mathematical models, confidence in the accuracy and reliability of the model is raised through application to real-world situations. Because of this, continual validation of modelled output using field observations is highly recommended.

## **11. Acknowledgements**

This study was undertaken on behalf of the Food Standards Agency. We are grateful to Dr Zitouni Ould-Dada (FSA) for his comments on the report.

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# ANNEX A - Comparison of SRS and LHS

## A.1 Distributions Using Simple Random Sampling (SRS) and Latin Hypercube Sampling (LHS)

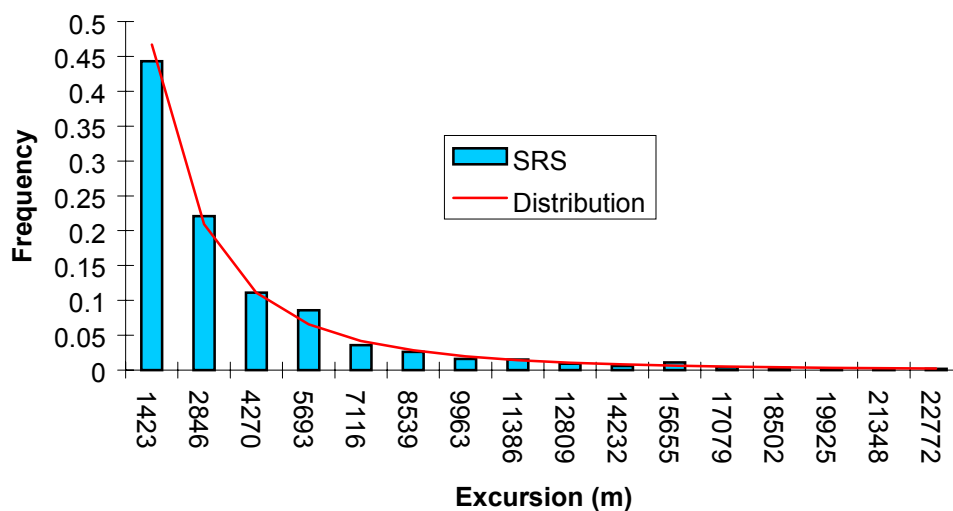
The SRS and LHS techniques (as described in Section 2.2) have been used to independently obtain 1000 random values of the following parameters:

- 1) Tidal Excursion
- 2) Mean Depth
- 3) Residual Velocity
- 4) Eddy Diffusion Coefficient
- 5) Sediment Distribution Coefficient ( $^{137}\text{Cs}$  and  $^{241}\text{Am}$ )
- 6) Suspended Sediment Load

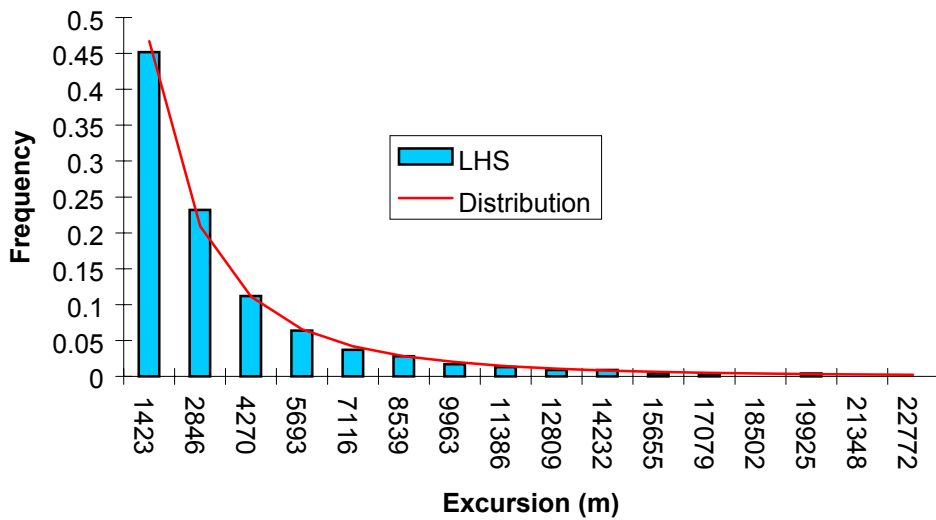
For completeness, the LHS distribution of estuarine sedimentation rate (for use in the ADOP model) is also included.

### A.1.1 Tidal Excursion

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for tidal excursion in Figures 45 and 46 respectively. The magnitude of the SRS and LHS data increases as the tidal excursion decreases, and both compare well with the input distribution (from expert elicitation). The LHS method appears to give a slightly smoother reduction in frequency as excursion increases, but the difference is marginal.



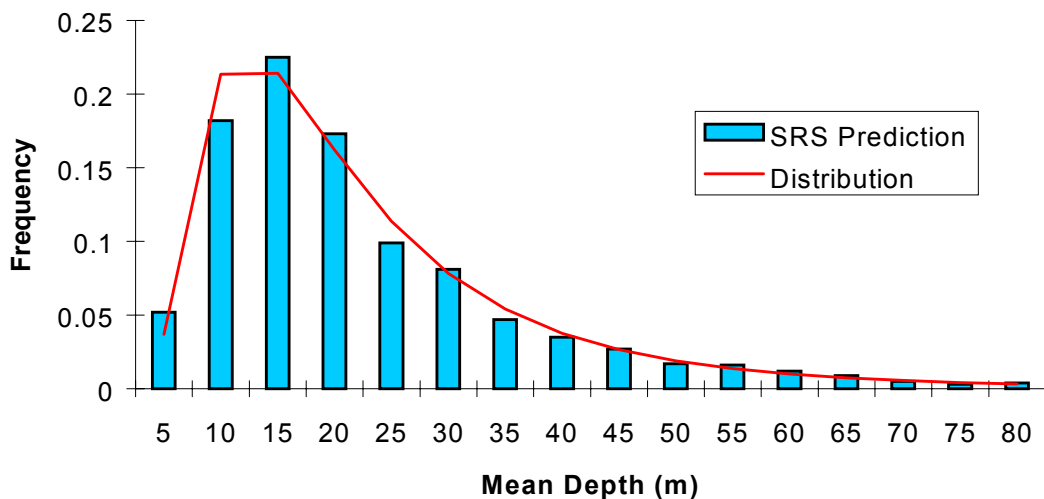
**Figure 45** The frequency distribution of the SRS predictions for tidal excursion compared to the distribution curve determined by expert elicitation.



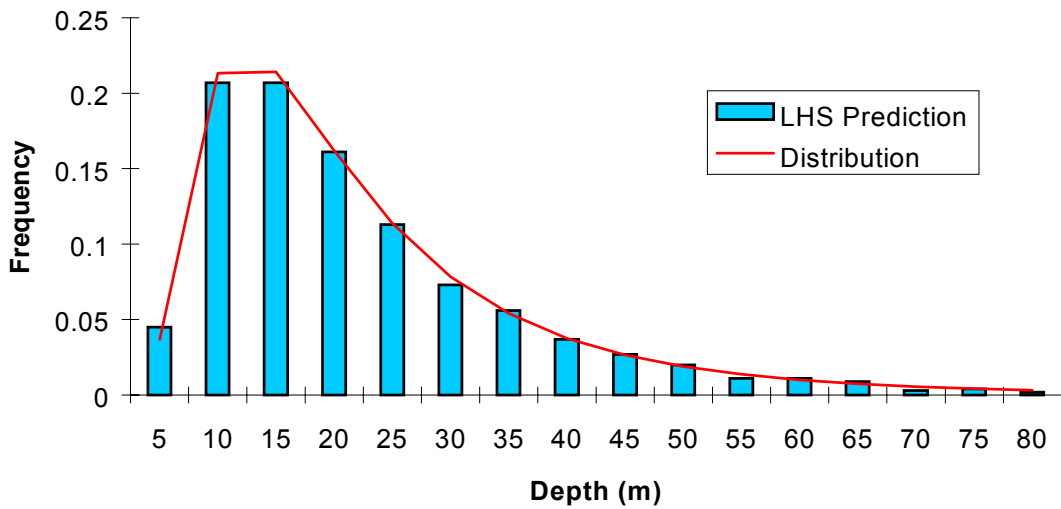
**Figure 46** The frequency distribution of the LHS predictions for tidal excursion compared to the distribution curve determined by expert elicitation.

### A.1.2 Mean Depth

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for mean depth around the UK coast in Figures 47 and 48 respectively. The peaks of the SRS and LHS data occur in a similar position to the input distribution, and both methods appear to give similar results. The SRS method has its maximum in two adjacent columns (for the intervals of depth used), but the LHS method gives a peak of a single column.



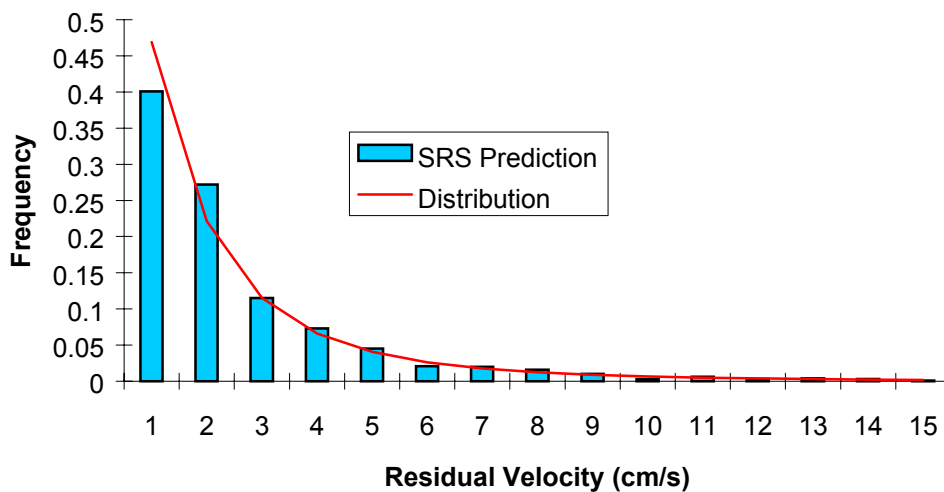
**Figure 47** The frequency distribution of the SRS predictions for mean depth compared to the distribution curve determined by expert elicitation.



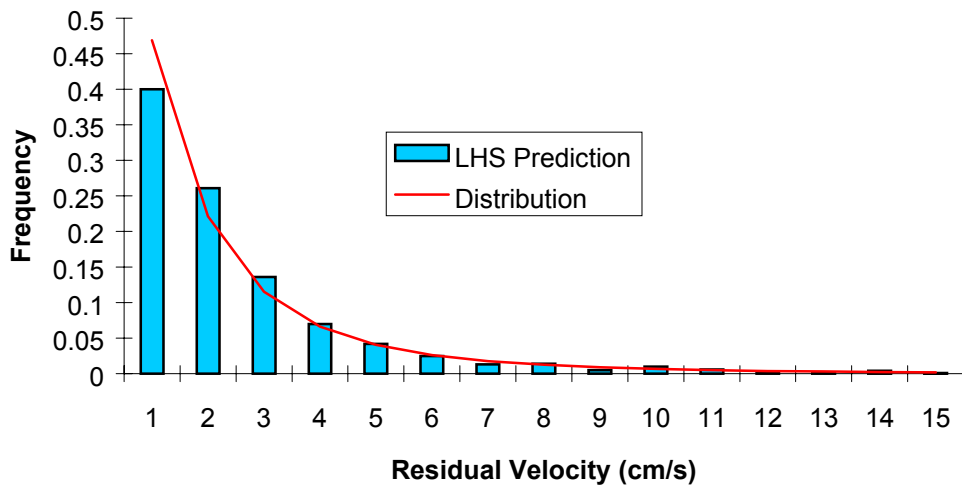
**Figure 48** The frequency distribution of the LHS predictions for mean depth compared to the distribution curve determined by expert elicitation.

### A.1.3 Residual Velocity

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for residual velocity around the UK coast in Figures 49 and 50 respectively. The elicited distribution curve is followed using both methods, and there is no significant difference between them.



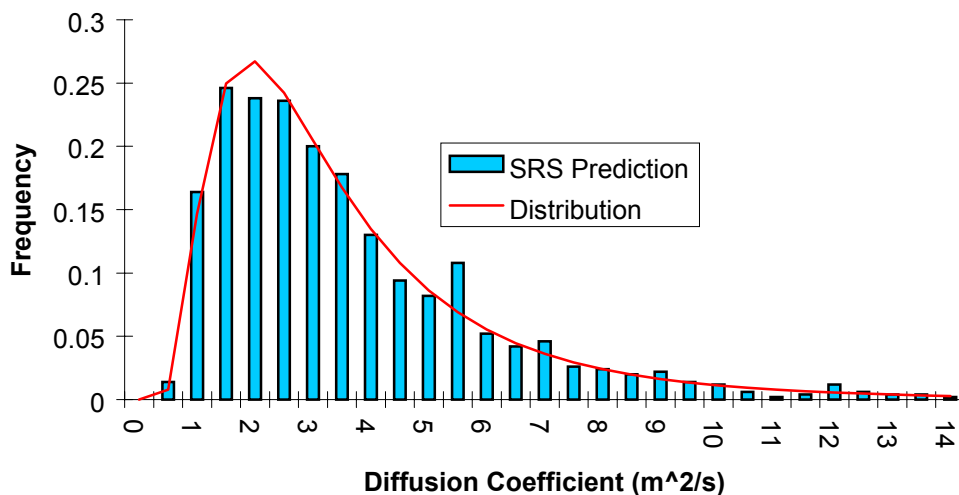
**Figure 49** The scaled frequency distribution of the SRS predictions for residual velocity compared to the distribution curve determined by expert elicitation.



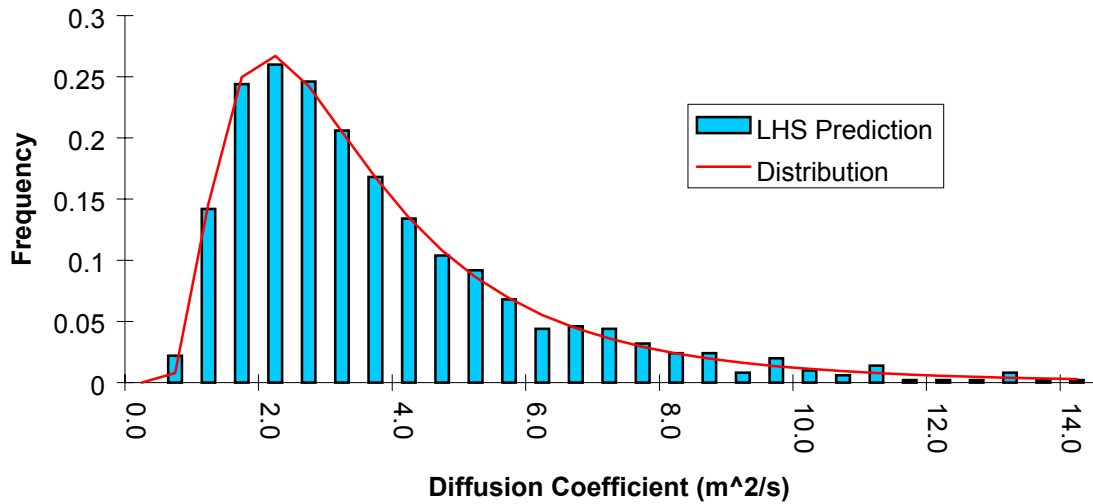
**Figure 50** The frequency distribution of the LHS predictions for residual velocity compared to the distribution curve determined by expert elicitation.

#### A.1.4 Eddy Diffusion Coefficient

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for the eddy diffusion coefficient in Figures 51 and 52 respectively. Both SRS and LHS methods appear to give similar results and both follow the elicited distribution curve well. However, the LHS method appears to give a marginally smoother representation of this curve, with increases and decreases in adjacent columns seeming to fluctuate around the elicited curve more often in the SRS case.



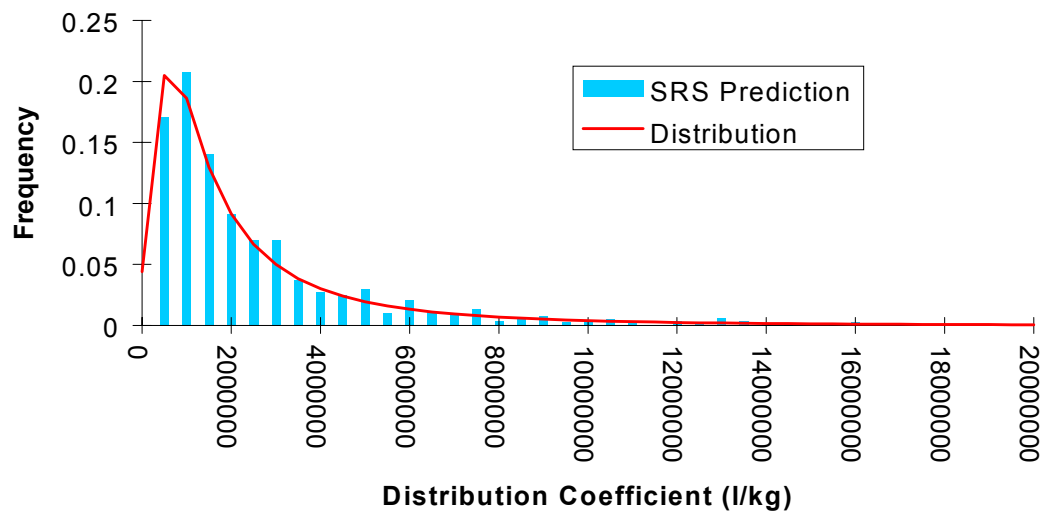
**Figure 51** The frequency distribution of the SRS predictions for the eddy diffusion coefficient compared to the distribution curve determined by expert elicitation.



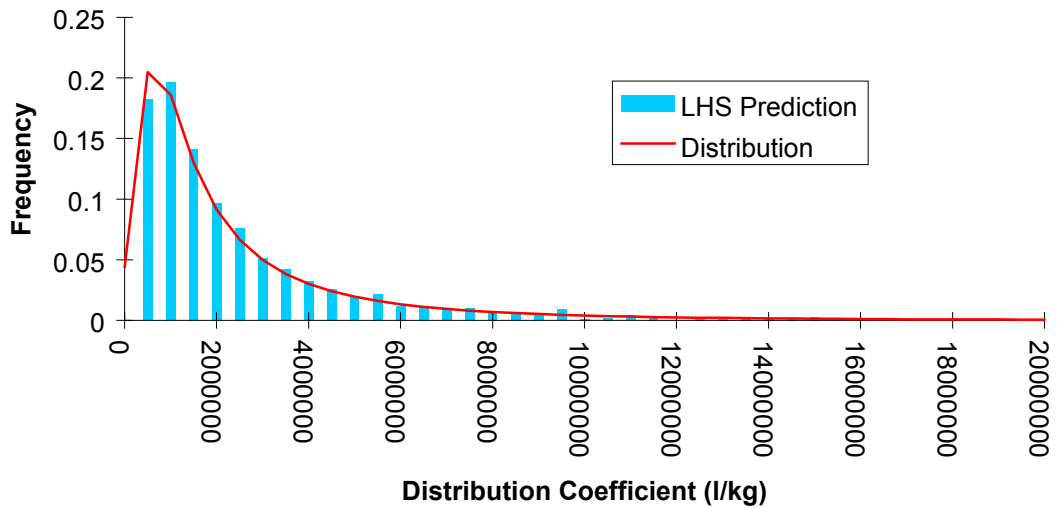
**Figure 52** The frequency distribution of the LHS predictions for the eddy diffusion coefficient compared to the distribution curve determined by expert elicitation.

#### A.1.5 Sediment Distribution Coefficient

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for the sediment distribution coefficient for  $^{241}\text{Am}$  around the UK coast in Figures 53 and 54 respectively. The peaks obtained using the SRS and LHS data occur in similar positions to the input distribution, and both methods appear to give similar results. However, the LHS method appears to give rise to a distribution that is smoother and more accurate than the SRS method.

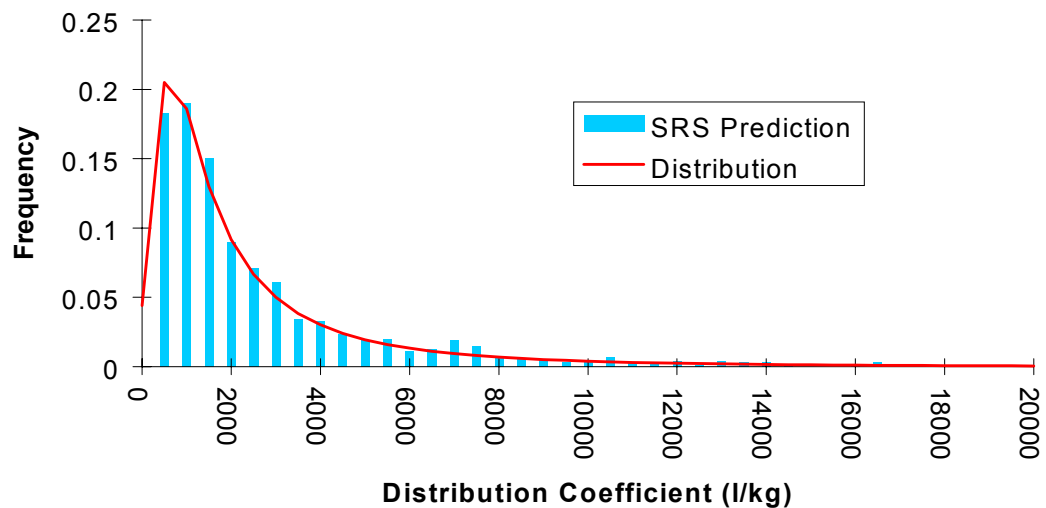


**Figure 53** The frequency distribution of the SRS predictions for the sediment distribution coefficient for  $^{241}\text{Am}$  compared to the distribution curve determined by expert elicitation.

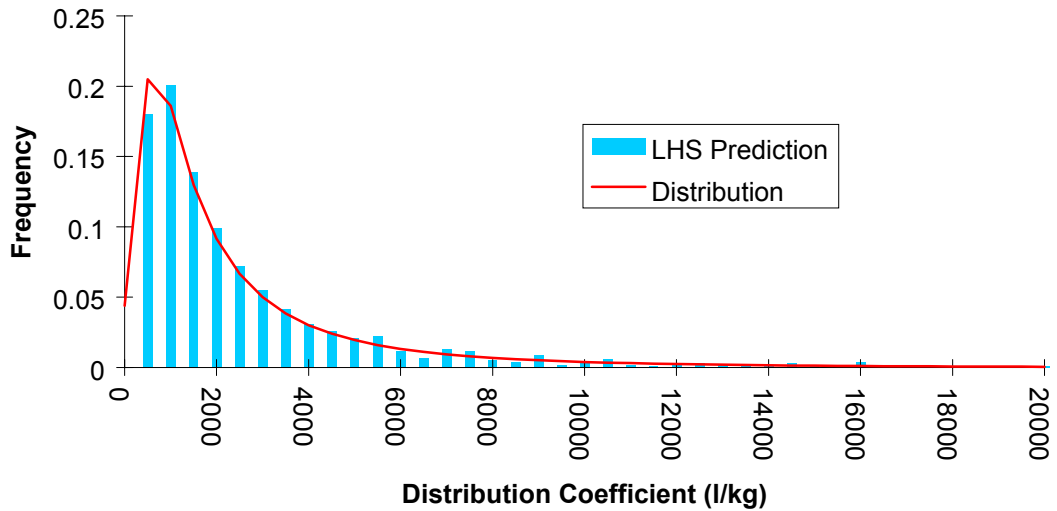


**Figure 54** The frequency distribution of the LHS predictions for the sediment distribution coefficient for  $^{241}\text{Am}$  compared to the distribution curve determined by expert elicitation.

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for the sediment distribution coefficient for  $^{137}\text{Cs}$  around the UK coast in Figures 55 and 56 respectively. As noticed for  $^{241}\text{Am}$ , the peaks obtained using the SRS and LHS data occur in similar positions to the input distribution, but the LHS method appears to give rise to a distribution that is slightly smoother and more accurate than the SRS method.



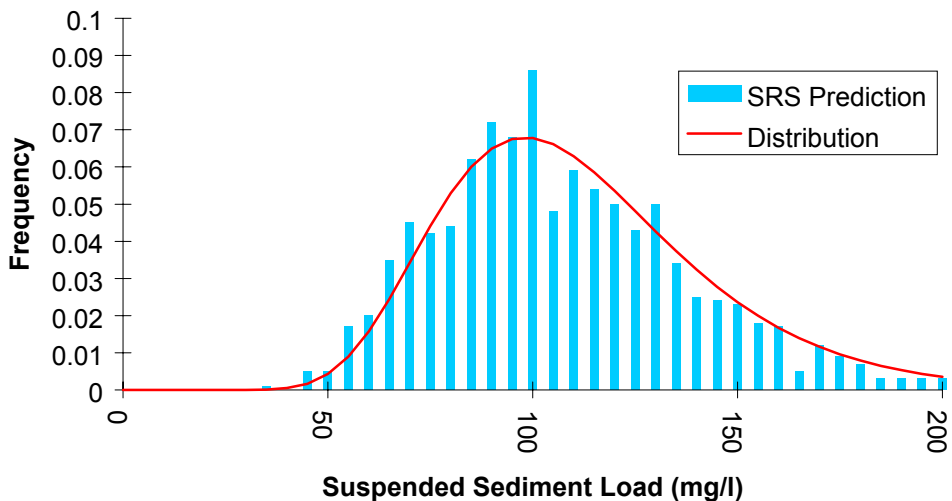
**Figure 55** The frequency distribution of the SRS predictions for the sediment distribution coefficient for  $^{137}\text{Cs}$  compared to the distribution curve determined by expert elicitation.



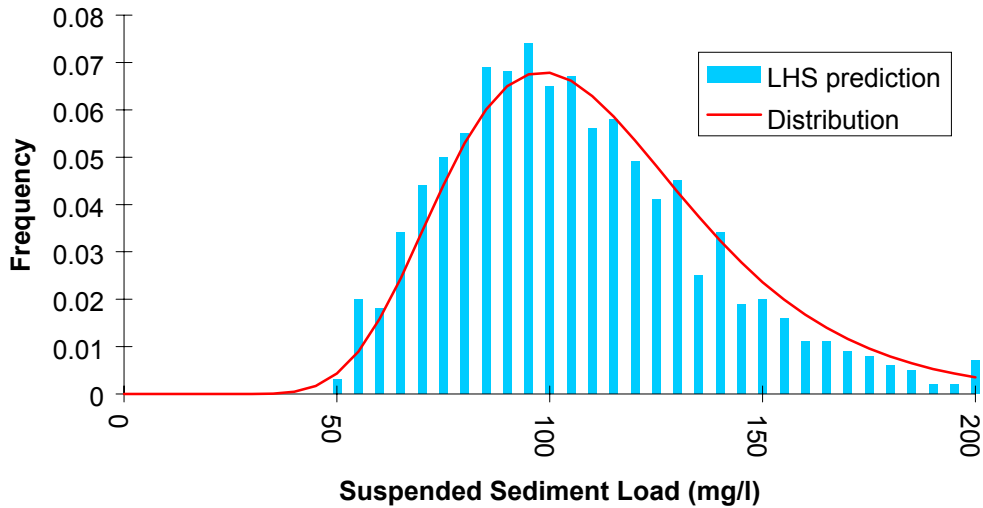
**Figure 56** The frequency distribution of the LHS predictions for the sediment distribution coefficient for  $^{137}\text{Cs}$  compared to the distribution curve determined by expert elicitation.

#### A.1.6 Suspended Sediment Load

The frequency distributions of SRS and LHS data have been plotted against the distribution obtained by expert elicitation for the suspended sediment load around the UK coast in Figures 57 and 58 respectively. The peaks obtained using the SRS and LHS data occur in similar positions to the input distribution. It seems that the SRS distribution dips significantly just before and after the peak, but the LHS method does not appear to exhibit this behaviour to the same extent. The LHS prediction appears to be smoother than that obtained using SRS.



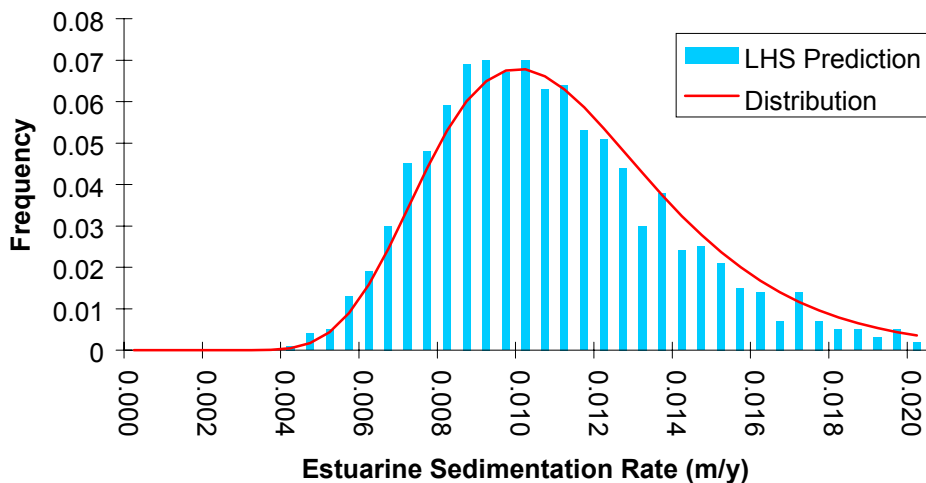
**Figure 57** The frequency distribution of the SRS predictions for the suspended sediment load compared to the distribution curve determined by expert elicitation.



**Figure 58** The frequency distribution of the LHS predictions for the suspended sediment load compared to the distribution curve determined by expert elicitation.

### A.1.7 Estuarine Sedimentation Rate

The Latin Hypercube sampling of random numbers for the input of the Estuarine Sedimentation Rate is shown in Figure 59. As with the parameters for the WATP model, the distribution appears to be well represented by this sampling technique for the 1000 parameter values derived.



**Figure 59** The LHS prediction of the distribution for estuarine sedimentation rate (cm/y) as used in the ADOP model. The curve marked 'Distribution' is the log-normal plot using the same maximum and minimum values.

## **A.2 SRS or LHS?**

The distributions produced for input to the WATP Advection-Diffusion model using LHS and SRS have shown that both methods adequately produce random numbers that match a specific distribution applied to each variable. Either of the sampling techniques may be used, but the distributions shown in Section A.1 indicate that the Latin Hypercube Sampling technique tends to give a smoother distribution. It is for this reason that the LHS method will be used in the Monte Carlo Analysis considered here. This applies for both the WATP and ADOP models and their application.

## ANNEX B - Tabular Output from ADOP with constant habits data in the Sizewell Probabilistic Assessment

**Table 15** The 5<sup>th</sup> percentile of doses for each pathway as calculated by the ADOP model with constant consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	1.53E-03	3.22E-04	2.45E-04	0.00E+00	2.10E-03
C-14	6.17E-03	1.30E-03	9.87E-04	8.46E-08	8.45E-03
S-35	1.45E-03	1.52E-04	4.63E-04	3.48E-08	2.06E-03
Ca-45	5.47E-05	2.87E-05	4.38E-06	9.82E-06	9.76E-05
Mn-54	1.56E-08	4.08E-09	3.10E-08	9.21E-06	9.25E-06
Fe-55	2.16E-06	7.57E-07	3.46E-06	3.56E-07	6.74E-06
Co-58	1.15E-06	1.21E-06	9.24E-07	1.03E-04	1.06E-04
Fe-59	1.94E-06	6.77E-07	3.10E-06	3.17E-06	8.88E-06
Co-60	2.58E-05	2.71E-05	2.07E-05	8.46E-03	8.53E-03
Zn-65	2.17E-04	2.28E-03	1.04E-03	5.32E-04	4.11E-03
Sr-90	2.64E-02	5.55E-03	2.11E-03	2.14E-03	3.62E-02
Y-90	2.51E-05	2.63E-04	2.00E-04	3.86E-01	3.87E-01
Zr-95	1.13E-06	1.59E-06	6.05E-06	4.89E-03	4.90E-03
Nb-95	2.68E-07	5.63E-07	1.07E-05	3.24E-03	3.26E-03
Ru-106 +	9.68E-05	1.02E-03	1.55E-02	9.14E-04	1.75E-02
Ag-110M+	4.57E-04	9.59E-04	1.46E-03	7.16E-04	3.53E-03
Sb-124	1.55E-02	3.25E-03	1.24E-03	8.07E-03	2.87E-02
Sb-125	2.13E-03	4.47E-04	1.70E-04	3.87E-03	6.74E-03
Te-125M	1.01E-03	2.12E-04	1.61E-04	1.27E-05	1.39E-03
Cs-134	3.82E-01	2.41E-02	1.83E-02	1.49E+00	1.95E+00
Cs-137 +	3.07E+00	1.94E-01	1.48E-01	1.39E+01	1.74E+01
Ce-144 +	5.52E-07	2.32E-06	8.84E-06	9.22E-04	9.33E-04
Pm-147	4.77E-08	2.00E-08	7.63E-08	1.79E-07	3.23E-07
Eu-154	8.11E-07	5.68E-07	3.03E-06	2.44E-03	2.44E-03
Eu-155	3.83E-07	2.68E-07	1.43E-06	2.73E-04	2.74E-04
Pu-238	2.68E-05	4.23E-05	3.22E-04	1.77E-06	3.93E-04
Pu-240	7.96E-05	1.25E-04	9.55E-04	4.62E-06	1.16E-03
Pu-241	5.87E-06	1.23E-05	3.76E-04	1.28E-04	5.22E-04
Am-241	5.32E-05	8.38E-05	6.39E-04	2.53E-07	7.76E-04
Cm-242	3.40E-07	7.15E-07	3.26E-05	1.37E-06	3.52E-05
Cm-243	2.01E-07	4.22E-07	1.93E-05	2.57E-05	4.55E-05
TOTAL	3.54E+00	2.48E-01	2.14E-01	1.80E+01	2.20E+01

\*BTMD - Bait digging over mud

**Table 16** The 95<sup>th</sup> percentile of doses for each pathway as calculated by the ADOP model with constant consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	4.51E-03	9.47E-04	7.21E-04	0.00E+00	6.18E-03
C-14	1.87E-02	3.92E-03	2.98E-03	2.56E-07	2.56E-02
S-35	4.19E-03	4.40E-04	1.34E-03	1.01E-07	5.99E-03
Ca-45	1.58E-04	8.33E-05	1.27E-05	2.84E-05	2.83E-04
Mn-54	1.41E-05	3.70E-06	2.81E-05	7.97E-03	8.03E-03
Fe-55	1.39E-03	4.87E-04	2.22E-03	2.37E-04	4.31E-03
Co-58	8.52E-05	8.95E-05	6.82E-05	7.76E-03	8.03E-03
Fe-59	1.81E-03	6.33E-04	2.89E-03	2.95E-03	8.36E-03
Co-60	1.85E-03	1.94E-03	1.48E-03	6.64E-01	6.69E-01
Zn-65	4.04E-03	4.24E-02	1.94E-02	1.09E-02	7.65E-02
Sr-90	7.81E-02	1.64E-02	6.25E-03	6.31E-03	1.07E-01
Y-90	8.35E-04	8.76E-03	6.68E-03	1.29E+01	1.29E+01
Zr-95	2.60E-05	3.64E-05	1.39E-04	1.17E-01	1.17E-01
Nb-95	1.57E-05	3.29E-05	6.26E-04	1.84E-01	1.85E-01
Ru-106 +	2.96E-04	3.10E-03	4.73E-02	2.89E-03	5.35E-02
Ag-110M+	1.97E-03	4.13E-03	6.29E-03	3.44E-03	1.56E-02
Sb-124	4.60E-02	9.66E-03	3.68E-03	2.81E-02	8.78E-02
Sb-125	6.43E-03	1.35E-03	5.15E-04	1.23E-02	2.09E-02
Te-125M	2.96E-03	6.22E-04	4.74E-04	4.35E-05	4.10E-03
Cs-134	1.31E+00	8.24E-02	6.27E-02	5.36E+00	6.86E+00
Cs-137 +	1.05E+01	6.58E-01	5.02E-01	4.82E+01	6.03E+01
Ce-144 +	2.64E-05	1.11E-04	4.23E-04	4.53E-02	4.58E-02
Pm-147	1.91E-06	8.03E-07	3.06E-06	7.13E-06	1.29E-05
Eu-154	2.06E-05	1.44E-05	7.71E-05	5.97E-02	5.98E-02
Eu-155	1.12E-05	7.85E-06	4.19E-05	8.36E-03	8.42E-03
Pu-238	5.32E-04	8.38E-04	6.38E-03	3.51E-05	7.79E-03
Pu-240	1.60E-03	2.51E-03	1.92E-02	9.27E-05	2.34E-02
Pu-241	2.55E-04	5.36E-04	1.63E-02	5.57E-03	2.27E-02
Am-241	1.16E-03	1.83E-03	1.39E-02	5.24E-06	1.69E-02
Cm-242	1.09E-05	2.29E-05	1.05E-03	4.24E-05	1.14E-03
Cm-243	5.70E-06	1.20E-05	5.47E-04	7.66E-04	1.33E-03
<b>TOTAL</b>	<b>1.18E+01</b>	<b>8.01E-01</b>	<b>6.71E-01</b>	<b>5.95E+01</b>	<b>7.36E+01</b>

\*BTMD - Bait digging over mud

**Table 17** The mean values of doses for each pathway as calculated by the ADOP model with constant consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	2.55E-03	5.36E-04	4.09E-04	0.00E+00	3.50E-03
C-14	1.07E-02	2.24E-03	1.71E-03	1.46E-07	1.46E-02
S-35	2.40E-03	2.52E-04	7.69E-04	5.77E-08	3.42E-03
Ca-45	9.14E-05	4.80E-05	7.32E-06	1.64E-05	1.63E-04
Mn-54	4.95E-07	1.30E-07	9.91E-07	2.96E-04	2.98E-04
Fe-55	6.14E-05	2.15E-05	9.82E-05	9.50E-06	1.91E-04
Co-58	1.07E-05	1.13E-05	8.57E-06	1.03E-03	1.06E-03
Fe-59	6.91E-05	2.42E-05	1.11E-04	1.12E-04	3.16E-04
Co-60	2.38E-04	2.50E-04	1.91E-04	8.32E-02	8.39E-02
Zn-65	1.14E-03	1.20E-02	5.49E-03	2.78E-03	2.13E-02
Sr-90	4.41E-02	9.27E-03	3.53E-03	3.57E-03	6.05E-02
Y-90	1.56E-04	1.64E-03	1.25E-03	2.40E+00	2.40E+00
Zr-95	5.52E-06	7.73E-06	2.95E-05	2.31E-02	2.31E-02
Nb-95	2.41E-06	5.06E-06	9.64E-05	2.82E-02	2.83E-02
Ru-106 +	1.71E-04	1.79E-03	2.73E-02	1.62E-03	3.09E-02
Ag-110M+	1.04E-03	2.17E-03	3.31E-03	1.74E-03	8.25E-03
Sb-124	2.66E-02	5.59E-03	2.13E-03	1.49E-02	4.92E-02
Sb-125	3.71E-03	7.78E-04	2.97E-04	6.64E-03	1.14E-02
Te-125M	1.75E-03	3.67E-04	2.80E-04	2.34E-05	2.42E-03
Cs-134	5.89E+00	5.43E+00	5.12E+00	5.15E+00	3.75E+00
Cs-137 +	5.54E+00	3.49E-01	2.66E-01	2.56E+01	3.16E+01
Ce-144 +	4.14E-06	1.74E-05	6.62E-05	7.00E-03	7.08E-03
Pm-147	3.00E-07	1.26E-07	4.80E-07	1.11E-06	2.02E-06
Eu-154	4.17E-06	2.92E-06	1.56E-05	1.27E-02	1.27E-02
Eu-155	2.36E-06	1.65E-06	8.82E-06	1.74E-03	1.75E-03
Pu-238	1.37E-04	2.16E-04	1.65E-03	9.05E-06	2.01E-03
Pu-240	3.99E-04	6.27E-04	4.78E-03	2.31E-05	5.83E-03
Pu-241	3.92E-05	8.23E-05	2.51E-03	8.55E-04	3.49E-03
Am-241	2.98E-04	4.70E-04	3.58E-03	1.37E-06	4.35E-03
Cm-242	2.13E-06	4.47E-06	2.04E-04	8.46E-06	2.20E-04
Cm-243	1.09E-06	2.29E-06	1.05E-04	1.40E-04	2.49E-04
<b>TOTAL</b>	<b>6.35E+00</b>	<b>4.34E-01</b>	<b>3.66E-01</b>	<b>3.28E+01</b>	<b>4.01E+01</b>

\*BTMD - Bait digging over mud

**Table 18** The uncertainty values (ratio of 95<sup>th</sup> and 5<sup>th</sup> percentile) of doses for each pathway as calculated by the ADOP model with constant consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	2.94	2.94	2.94	**Undef.	2.94
C-14	3.03	3.02	3.02	3.03	3.03
S-35	2.89	2.90	2.90	2.91	2.91
Ca-45	2.89	2.90	2.90	2.90	2.90
Mn-54	906.87	906.55	906.43	866.24	868.87
Fe-55	643.04	643.56	642.86	666.34	638.72
Co-58	74.11	73.99	73.86	75.73	76.11
Fe-59	934.98	934.08	934.13	933.20	942.20
Co-60	71.60	71.52	71.31	78.47	78.42
Zn-65	18.62	18.60	18.66	20.50	18.62
Sr-90	2.96	2.96	2.96	2.95	2.96
Y-90	33.29	33.33	33.40	33.47	33.39
Zr-95	23.01	22.90	22.98	23.97	23.94
Nb-95	58.64	58.50	58.57	56.74	56.70
Ru-106 +	3.06	3.04	3.06	3.16	3.06
Ag-110M+	4.31	4.31	4.31	4.81	4.42
Sb-124	2.97	2.97	2.97	3.48	3.06
Sb-125	3.02	3.03	3.03	3.18	3.10
Te-125M	2.93	2.94	2.95	3.43	2.95
Cs-134	3.43	3.42	3.43	3.60	3.52
Cs-137 +	3.42	3.39	3.39	3.47	3.47
Ce-144 +	47.85	47.84	47.88	49.15	49.11
Pm-147	40.04	40.14	40.17	39.83	39.84
Eu-154	25.42	25.37	25.46	24.45	24.49
Eu-155	29.26	29.30	29.30	30.64	30.74
Pu-238	19.85	19.82	19.83	19.85	19.82
Pu-240	20.13	20.11	20.14	20.08	20.20
Pu-241	43.43	43.64	43.42	43.57	43.47
Am-241	21.81	21.85	21.76	20.76	21.79
Cm-242	32.05	32.07	32.18	31.05	32.36
Cm-243	28.44	28.45	28.43	29.83	29.23
<b>TOTAL</b>	<b>3.33</b>	<b>3.23</b>	<b>3.14</b>	<b>3.31</b>	<b>3.35</b>

\*BTMD - Bait digging over mud

\*\* - Undefined values occur due to division by zero.

## ANNEX C - Tabular Output from ADOP with variable habits data in the Sizewell Probabilistic Assessment

**Table 19** The 5<sup>th</sup> percentile of doses for each pathway as calculated by the ADOP model with variable consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	9.00E-05	5.91E-05	6.13E-05	0.00E+00	4.37E-04
C-14	3.61E-04	2.40E-04	2.59E-04	2.59E-09	1.68E-03
S-35	8.47E-05	2.77E-05	1.15E-04	9.86E-10	4.40E-04
Ca-45	3.20E-06	5.28E-06	1.09E-06	2.78E-07	2.20E-05
Mn-54	3.04E-09	1.41E-09	1.24E-08	8.88E-07	9.32E-07
Fe-55	3.00E-07	3.08E-07	1.40E-06	2.75E-08	2.93E-06
Co-58	1.86E-07	3.46E-07	3.80E-07	7.64E-06	1.12E-05
Fe-59	3.86E-07	3.70E-07	1.35E-06	2.94E-07	4.57E-06
Co-60	2.78E-06	9.99E-06	8.15E-06	7.14E-04	8.46E-04
Zn-65	2.50E-05	6.76E-04	3.68E-04	2.40E-05	1.75E-03
Sr-90	1.56E-03	1.02E-03	5.33E-04	6.09E-05	7.11E-03
Y-90	2.73E-06	7.89E-05	6.76E-05	2.13E-02	2.24E-02
Zr-95	1.27E-07	4.87E-07	1.89E-06	2.90E-04	3.15E-04
Nb-95	3.01E-08	2.31E-07	4.54E-06	2.23E-04	2.45E-04
Ru-106 +	5.60E-06	2.04E-04	3.68E-03	2.87E-05	4.91E-03
Ag-110M+	3.15E-05	2.10E-04	3.88E-04	2.75E-05	1.38E-03
Sb-124	9.20E-04	6.19E-04	3.28E-04	2.61E-04	5.79E-03
Sb-125	1.29E-04	8.52E-05	4.36E-05	1.15E-04	1.01E-03
Te-125M	6.16E-05	4.02E-05	3.86E-05	3.92E-07	3.08E-04
Cs-134	2.39E-02	4.99E-03	4.38E-03	4.95E-02	2.16E-01
Cs-137 +	1.88E-01	3.75E-02	3.57E-02	4.24E-01	1.76E+00
Ce-144 +	5.71E-08	7.68E-07	4.14E-06	5.75E-05	8.88E-05
Pm-147	5.06E-09	5.09E-09	2.69E-08	9.72E-09	8.31E-08
Eu-154	7.93E-08	1.71E-07	1.06E-06	1.37E-04	1.39E-04
Eu-155	4.66E-08	9.39E-08	5.66E-07	1.61E-05	2.05E-05
Pu-238	2.79E-06	1.30E-05	1.13E-04	8.66E-08	1.61E-04
Pu-240	7.92E-06	3.03E-05	2.92E-04	2.58E-07	4.65E-04
Pu-241	6.50E-07	4.24E-06	1.48E-04	5.67E-06	1.94E-04
Am-241	6.08E-06	2.70E-05	2.19E-04	1.36E-08	3.16E-04
Cm-242	4.50E-08	1.93E-07	1.16E-05	8.45E-08	1.32E-05
Cm-243	2.28E-08	1.20E-07	6.47E-06	1.29E-06	1.35E-05
TOTAL	2.19E-01	4.70E-02	5.19E-02	5.67E-01	2.20E+00

\*BTMD - Bait digging over mud

**Table 20** The 95<sup>th</sup> percentile of doses for each pathway as calculated by the ADOP model with variable consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	4.89E-03	1.27E-03	7.00E-04	0.00E+00	6.19E-03
C-14	2.15E-02	5.03E-03	3.07E-03	2.05E-07	2.66E-02
S-35	4.55E-03	5.98E-04	1.32E-03	7.99E-08	6.09E-03
Ca-45	1.75E-04	1.12E-04	1.22E-05	2.29E-05	2.71E-04
Mn-54	5.11E-06	1.99E-06	1.65E-05	2.02E-03	2.04E-03
Fe-55	5.04E-04	3.56E-04	1.50E-03	7.37E-05	2.67E-03
Co-58	4.66E-05	5.99E-05	4.70E-05	3.11E-03	3.14E-03
Fe-59	8.11E-04	3.51E-04	1.84E-03	5.67E-04	4.11E-03
Co-60	9.82E-04	2.20E-03	1.04E-03	2.78E-01	2.87E-01
Zn-65	3.11E-03	4.85E-02	1.59E-02	4.87E-03	6.38E-02
Sr-90	8.46E-02	2.19E-02	6.06E-03	4.96E-03	1.06E-01
Y-90	5.05E-04	6.78E-03	5.01E-03	5.17E+00	5.17E+00
Zr-95	1.74E-05	2.95E-05	1.13E-04	4.87E-02	4.88E-02
Nb-95	7.77E-06	2.40E-05	4.06E-04	6.91E-02	6.93E-02
Ru-106 +	3.34E-04	4.21E-03	4.78E-02	2.27E-03	5.14E-02
Ag-110M+	2.06E-03	5.02E-03	6.23E-03	2.47E-03	1.23E-02
Sb-124	5.06E-02	1.19E-02	3.72E-03	2.17E-02	7.41E-02
Sb-125	7.33E-03	1.86E-03	5.12E-04	9.41E-03	1.58E-02
Te-125M	3.31E-03	8.15E-04	4.96E-04	3.57E-05	4.01E-03
Cs-134	1.53E+00	1.05E-01	6.20E-02	4.36E+00	4.84E+00
Cs-137 +	1.18E+01	8.17E-01	4.90E-01	3.61E+01	4.16E+01
Ce-144 +	1.71E-05	9.96E-05	2.56E-04	1.75E-02	1.78E-02
Pm-147	9.68E-07	6.37E-07	2.12E-06	2.85E-06	6.53E-06
Eu-154	1.15E-05	1.11E-05	4.44E-05	3.68E-02	3.69E-02
Eu-155	8.60E-06	7.97E-06	3.15E-05	4.15E-03	4.17E-03
Pu-238	3.71E-04	8.24E-04	4.42E-03	1.75E-05	5.45E-03
Pu-240	1.22E-03	2.14E-03	1.46E-02	4.65E-05	1.62E-02
Pu-241	1.54E-04	4.26E-04	1.10E-02	2.28E-03	1.39E-02
Am-241	8.82E-04	1.81E-03	1.04E-02	2.44E-06	1.20E-02
Cm-242	6.84E-06	1.84E-05	7.53E-04	2.00E-05	7.93E-04
Cm-243	3.28E-06	9.47E-06	4.41E-04	3.00E-04	7.44E-04
<b>TOTAL</b>	<b>1.31E+01</b>	<b>1.06E+00</b>	<b>6.58E-01</b>	<b>4.75E+01</b>	<b>4.95E+01</b>

\*BTMD - Bait digging over mud

**Table 21** The median values of doses for each pathway as calculated by the ADOP model with variable consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	6.59E-04	2.75E-04	2.04E-04	0.00E+00	1.41E-03
C-14	2.62E-03	1.11E-03	8.30E-04	2.41E-08	5.64E-03
S-35	6.13E-04	1.29E-04	3.82E-04	9.45E-09	1.39E-03
Ca-45	2.34E-05	2.47E-05	3.61E-06	2.69E-06	6.63E-05
Mn-54	1.17E-07	7.49E-08	5.33E-07	4.32E-05	4.70E-05
Fe-55	1.70E-05	1.11E-05	4.67E-05	1.41E-06	9.12E-05
Co-58	2.45E-06	5.66E-06	3.98E-06	1.55E-04	1.75E-04
Fe-59	1.82E-05	1.27E-05	5.46E-05	1.80E-05	1.35E-04
Co-60	6.26E-05	1.15E-04	9.69E-05	1.32E-02	1.38E-02
Zn-65	2.61E-04	5.67E-03	2.43E-03	4.55E-04	1.04E-02
Sr-90	1.14E-02	4.74E-03	1.76E-03	5.82E-04	2.30E-02
Y-90	3.95E-05	9.20E-04	6.26E-04	3.76E-01	3.77E-01
Zr-95	1.44E-06	4.20E-06	1.41E-05	4.15E-03	4.19E-03
Nb-95	5.67E-07	2.46E-06	4.34E-05	4.13E-03	4.27E-03
Ru-106 +	4.34E-05	9.05E-04	1.42E-02	2.69E-04	1.62E-02
Ag-110M+	2.58E-04	1.05E-03	1.61E-03	2.88E-04	4.12E-03
Sb-124	6.79E-03	2.92E-03	1.06E-03	2.58E-03	1.78E-02
Sb-125	9.48E-04	3.97E-04	1.50E-04	1.13E-03	3.38E-03
Te-125M	4.33E-04	1.87E-04	1.41E-04	3.96E-06	9.53E-04
Cs-134	1.76E-01	2.24E-02	1.72E-02	4.97E-01	8.63E-01
Cs-137 +	1.39E+00	1.71E-01	1.31E-01	4.22E+00	7.41E+00
Ce-144 +	1.05E-06	7.92E-06	3.17E-05	1.14E-03	1.22E-03
Pm-147	8.25E-08	6.45E-08	2.44E-07	1.87E-07	7.72E-07
Eu-154	9.88E-07	1.48E-06	7.88E-06	1.97E-03	1.98E-03
Eu-155	5.47E-07	7.80E-07	4.12E-06	2.85E-04	2.94E-04
Pu-238	3.39E-05	1.06E-04	8.19E-04	1.52E-06	1.07E-03
Pu-240	1.04E-04	3.17E-04	2.46E-03	3.79E-06	3.29E-03
Pu-241	1.02E-05	4.34E-05	1.39E-03	1.51E-04	1.75E-03
Am-241	7.36E-05	2.17E-04	1.78E-03	2.08E-07	2.23E-03
Cm-242	5.16E-07	2.19E-06	9.84E-05	1.25E-06	1.12E-04
Cm-243	2.64E-07	1.20E-06	4.97E-05	2.13E-05	8.67E-05
<b>TOTAL</b>	<b>1.64E+00</b>	<b>2.18E-01</b>	<b>1.81E-01</b>	<b>5.44E+00</b>	<b>9.10E+00</b>

\*BTMD - Bait digging over mud

**Table 22** The uncertainty values (ratio of 95<sup>th</sup> and 5<sup>th</sup> percentile) of doses for each pathway as calculated by the ADOP model with variable consumption and occupancy rates.

<i>Radio-nuclide</i>	<i>FISH</i>	<i>CRUS</i>	<i>MOLL</i>	<i>BTMD*</i>	<i>TOTAL</i>
H-3	54.33	21.52	11.42	**Undef.	14.16
C-14	59.54	20.98	11.86	79.05	15.84
S-35	53.73	21.58	11.50	81.06	13.83
Ca-45	54.54	21.24	11.20	82.49	12.33
Mn-54	1678.17	1411.58	1338.73	2276.24	2191.39
Fe-55	1679.39	1156.68	1072.81	2684.38	912.60
Co-58	250.56	173.30	123.60	407.15	280.49
Fe-59	2101.42	949.03	1365.32	1929.57	899.50
Co-60	353.89	219.89	127.88	389.72	339.34
Zn-65	124.33	71.79	43.28	202.41	36.49
Sr-90	54.27	21.51	11.38	81.53	14.94
Y-90	185.17	85.90	74.12	242.37	230.95
Zr-95	137.47	60.55	59.70	167.98	154.99
Nb-95	258.34	103.86	89.49	309.40	282.98
Ru-106 +	59.60	20.70	13.00	79.32	10.48
Ag-110M+	65.37	23.95	16.07	89.89	8.94
Sb-124	55.04	19.28	11.35	83.31	12.81
Sb-125	56.84	21.88	11.75	81.96	15.65
Te-125M	53.83	20.28	12.86	91.19	13.03
Cs-134	64.06	21.07	14.16	88.11	22.42
Cs-137 +	62.93	21.75	13.73	85.23	23.69
Ce-144 +	298.76	129.64	61.78	304.88	200.75
Pm-147	191.43	125.25	78.87	293.37	78.54
Eu-154	145.27	65.13	42.04	269.24	265.89
Eu-155	184.58	84.87	55.70	258.28	203.56
Pu-238	132.82	63.38	39.17	202.45	33.84
Pu-240	154.38	70.60	50.01	180.44	34.90
Pu-241	237.46	100.60	74.64	402.59	71.75
Am-241	145.08	67.14	47.52	179.74	38.02
Cm-242	151.97	95.49	65.06	236.74	60.14
Cm-243	143.87	78.88	68.12	233.39	55.17
<b>TOTAL</b>	<b>59.88</b>	<b>22.59</b>	<b>12.69</b>	<b>83.75</b>	<b>22.55</b>

\*BTMD - Bait digging over mud

\* - Undefined values occur due to division by zero.