PROBABILISTIC CALCULATION OF AQUATIC EXPOSURE VIA SPRAY DRIFT

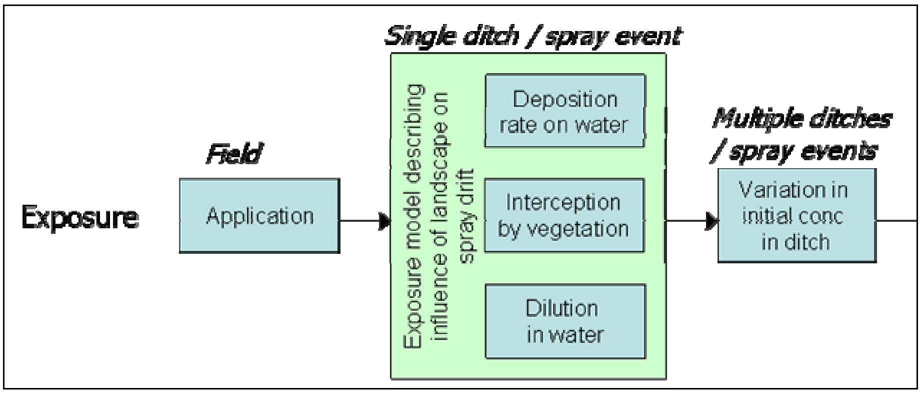
1 CONTENTS

2 INTRODUCTION

Exposure is calculated for instantaneous concentrations arising from spray drift impacting on agricultural ditches. The exposure distribution expresses the variation in concentrations of the pesticide in the water column of agricultural ditches resulting from variability in individual spray events and variability in the morphology of individual ditches. Uncertainty in the calculation is expressed using confidence intervals around the median distribution of exposure concentrations.

2.1 Conceptual model

The assessment is based on the conceptual model depicted below. Exposure of individual ditches is calculated for single spray events with a model describing the influence of landscape features.



Conversion of the conceptual model into mathematical form is described in Section 3.2. A summary of the sources of variability and uncertainty included and excluded in the assessment is given below.

Sources of variability and uncertainty in the exposure assessment, differentiating between those included and excluded in the analysis

	Considered	Not considered
Variability	Measured drift generation and deposition under reference conditions	Deviations from reference spray drift conditions (e.g. wind speed and direction, boom height, nozzle type, speed of tractor)
	Distance from edge of sprayed area to water	Variation in deposition across the water surface
	Dimensions of the water body	Volume of water in the ditch at application
Uncertainty	Sampling uncertainty in drift experiments	Measurement bias in drift experiments
	Interception of spray drift by bankside vegetation depending on type, height and density of vegetation, crop and boom height, width of vegetated strip etc.	Deviation of deposition on a surface below ground level from measured deposition at the same level as the treated area
	Errors in application rate (e.g. tank filling, machine calibration)	Interception by riparian vegetation or aquatic plants
		Reduction in initial exposure concentration due to sorption to sediment or macrophytes
		Errors in measuring ditch and bankside properties
		Bias in sampling of ditches
		Uncertainty in vertical distribution of pesticide within the water column
		Uncertainty in sprayed area relative to edge of crop
		Uncertainty in extrapolating the results to a broader landscape
		Model error for exposure model
		Uncertainties in Monte-Carlo sampling

2.2 Plan of analysis

Probabilistic risk assessment aims to show the effects of variability and uncertainty on the assessment. Variability is an inherent property of natural systems and cannot be reduced by further measurement. Uncertainty is, crudely, the sum of what we do not know; it includes, for example, sampling bias, measurement error, inadequate descriptions of processes in a model, phenomena which remain unknown and/or unquantified etc.

<u>Methods for propagating uncertainty</u>

Exposure concentrations are calculated using using a model coded in MATLAB v8. Selected sources of uncertainty and variability are accounted for in the modelling of exposure. Uncertainty and variability are separated out by 2-D Monte Carlo modelling. Second-order Monte Carlo analysis is useful in cases where it is possible to clearly classify variables as representing either variability or uncertainty. It is particularly helpful in managing parameter or model uncertainty. In first-order Monte Carlo analysis, values are repeatedly sampled from input distributions to produce an output distribution. The distributions or their parameters are estimated and hence subject to sampling error. However, in first-order Monte Carlo we assume them to be known and fixed. Second-order Monte Carlo can overcome this difficulty by explicitly considering parameter uncertainty in the outer loop of the simulation. Output distributions considering variability are then calculated for each value of the parameters in the outer loop. This results in a large number of output distributions and allows to quantify the uncertainty in the result of the 1-D Monte Carlo analysis (e.g. the probability that a particular exposure concentration will occur and the 95% confidence interval around this probability).

Some of the factors considered in the exposure model are both variable and uncertain (e.g. interception of spray drift by each type of bankside vegetation). It is, however impossible to separate uncertainty and variability due a lack of information. In this case, all variation is classified as uncertainty and considered in the outer loop.

Advantages of 2-D Monte Carlo modelling over 1-D modelling:

- The method can separate out uncertainty and variability.
- It can handle model uncertainty in a limited way.

Disadvantages:

- Simulations can take a lot of computer power to run.
- Parameterisation can be difficult.
- Results are difficult to present and explain.
- It does not take account of uncertainty about distribution shape.

Methods for representing dependencies and model uncertainty

In this study, uncertainty in the calculation is expressed using confidence intervals around the median distribution of exposure concentrations. The confidence interval(s) to be reported is a user input. The 95% confidence interval has often been used in communicating results from uncertainty analyses. However, other percentiles can be derived and reported as required.

3 PROBABILISTIC EXPOSURE CALCULATION

3.1 Introduction

Predicted environmental concentrations from spray drift are usually calculated for ditches because they have limited potential for dilution of residues and calculations are based on several worst-case assumptions. The standard exposure assessment method in Europe for a single application without any no-spray buffer restrictions assumes: (i) a treated area 1 m away from a static ditch with vertical sides in which the water column is 1 m wide and 30 cm deep; (ii) wind blowing towards the ditch and at right angles to it at a constant 2-5 m/s; (iii) 90^{th} percentile drift deposition (Rautmann et al., 2000) over the entire width of the ditch; and (iv) no vegetation in the strip between the treated crop and the edge of the water. This scenario probably represents a reasonable worst-case in that such situations may be found in agricultural landscapes. However, there are also many circumstances under which such conditions do not occur, and where exposure is much less.

The probabilistic assessment of exposure concentrations in natural agricultural landscapes is designed to account for the uncertainty and variability in ditch geometry and pesticide deposition. Uncertainty and variability in the measurement of spray drift are separated by analysing the distribution of replicate results within experiments (taken as uncertainty) and between experiments (taken as variability). Additionally, uncertainty associated with application rate (e.g. error in tank filling or in machine calibration) and interception by the bankside vegetation are characterised using available data and expert judgment.

3.2 Methodology

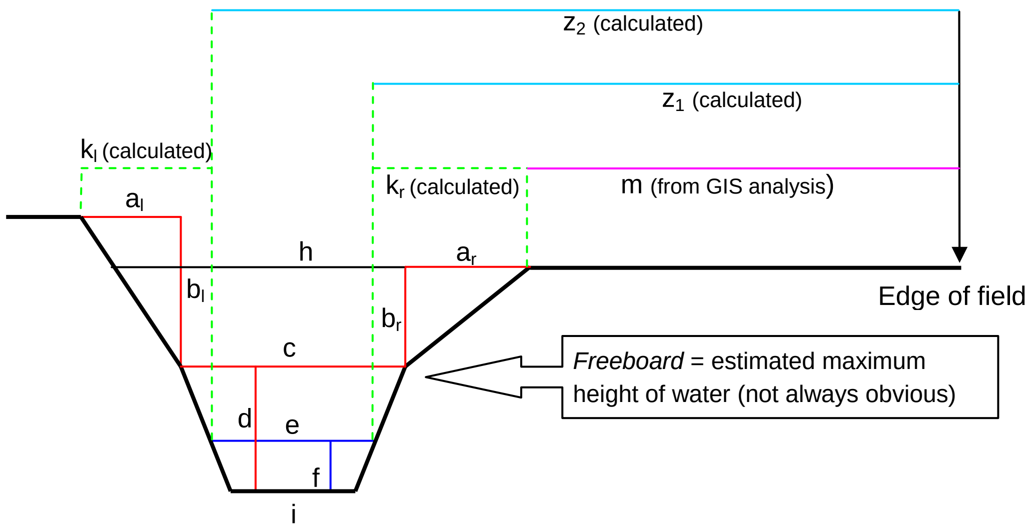
The methodology is exemplified for clay landscapes, based on data from the vicinity of Coleshill in Oxfordshire. This is one of four landscapes implemented into the WEBFRAM software. General data inputs are the same for the other three landscapes, though specific values differ and are available by viewing the relevant distribution data within the software.

A probabilistic assessment of concentrations of the pesticide is carried out for ditches within the Coleshill catchment in Oxfordshire, UK. This location is centred on the Brimstone Farm experimental site which is the basis for the FOCUS D2 scenario. Detailed field and GIS measurements were made within Defra project PS2304 to describe the morphology of ditches within a 10x10 km square centred on Coleshill, Oxfordshire, UK (Brown et al., 2006). Analysis of aerial photographs overlaid with remotely-sensed land use data were used to calculate the distance from ditch to nearest cropped area for 125 ditches. In addition, information was extracted on vegetation and features in the margin between ditch and field (trees, hedge, rough vegetation, track etc.). Next, the morphology of 25 ditches was measured during a site visit. Measurements were made for the ditch (height, bottom and top width, water height and width, freeboard, bank width) and for the margin between ditch and crop (width, type and height of vegetation).

The uncertainty considered in the exposure assessment for the Coleshill landscape includes (1) errors in the application rate of the pesticide, (2) uncertainty in the amount of pesticide intercepted by the bankside vegetation and (3) uncertainty in measured drift generation and deposition. The variability considered includes (1) variations between ditches in distance to treated fields, and in morphology and (2) variation in drift deposition.

3.2.1 Waterbody dimensions

Figure 1. Conceptualisation of the field surroundings and receiving ditch



a_l = left bank width to freeboard
b_l = left bank height from freeboard
c = freeboard width
e = water width
h = top width (total width from lowest bank)
k = distance from top of bank to edge of water
l and r subscripts refer to left and right bank
m = distance from edge of field to top of bank

a_r = right bank width to freeboard
b_r = right bank height from freeboard
d = freeboard height (includes water)
f = water depth
i = bottom width
l = length of water body

The conceptualisation of the water body receiving the drift input and the surrounding field is shown in Figure 1. Detailed field measurements of the geometry of water bodies in the Coleshill catchment have been made for 25 ditches for DEFRA project PS2304. These measurements included bank width and height, water width and depth, freeboard width and height, top and bottom width. The length of the water body (l) is adjusted such that the surface area at water level corresponds to 1 m^2. The remaining model input variables are calculated from:

Distance from top of bank to edge of water (k) = 0.5 (c – e) + a

Distance from edge of field to near edge of water (z1) = k + m

Distance from edge of field to far edge of water (z2) = z1 + e

Water volume = [i × f + ((e-i) × f) / 2] x l

Ditches which contained no or very small volumes of water (depth ≤ 1 cm) just after a significant rainfall event are excluded from the analysis (6 ditches). The width of the left bank of the remaining 19 ditches differed from the dimensions of the right bank. Each side is considered a separate measurement giving a total of 38 sets of data. One of the 38 ditch sides is sampled randomly in each of the model iterations (all values are given equal weight). The measured and calculated variables describing the geometry of the sampled ditch are used in the drift calculations.

Data on the distance from the edge of the field to the top of the bank of the ditch are available from a GIS analysis of aerial photographs within the Coleshill catchment. Where a field is located on both sides of the ditch, each side is considered separately. This results in a total of 156 data records. Each ditch is sampled with a frequency weighted according to its length. The distance from the field to the top of the bank for this ditch is then used in the calculations.

3.2.2 Drift deposition

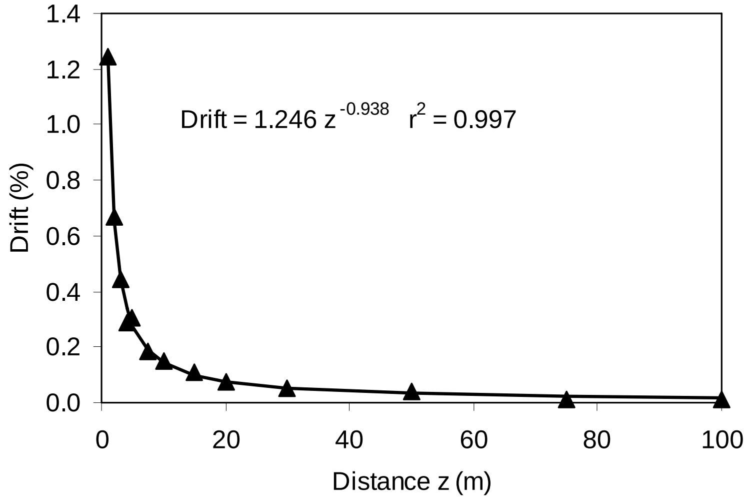
Mean (integrated) drift deposition across the width of the water body is calculated according to the algorithm presented by FOCUS (2001):

$$\overline{Drift} = \frac{A}{(z2 - z1) * (B+1)} * [z2^{B+1} - z1^{B+1}]$$

where z1 and z2 are the distance from the edge of the treated field to the near and far edge of the water body, respectively, and A and B are regression constants.

The distances z1 and z2 are derived from measured data and GIS analysis as described above. The calculation of the regression constants A and B is based on measured drift data provided by Rautmann *et al.* (2001). The authors measured deposition in a number of experiments at different distances from the edge of a field cultivated with arable crops. Each experiment consisted of 5-10 replicates. A lognormal distribution is fitted to the mean values for all experiments at each individual distance. The means of these lognormal distributions are then plotted against distance. A power law function is fitted to the data (Figure 2). This results in values for A and B of 1.246 and -0.938, respectively.

Figure 2. Power law function (—) fitted to the mean values of the lognormal distributions of measured drift losses at each distance (▲)



Initial values for drift at z1 and z2

The percentage drift at the closest edge of the water D(z1) $_{initial}$ and at the far edge of the water D(z2) $_{initial}$ are calculated from the power law function.

Uncertainty in drift deposition at each distance

Drift deposition is considered to be both variable and uncertain. The difference between replicate measurements for each trial is considered to represent uncertainty (e.g. from measurement error) whereas differences between the experiments are considered to reflect variability (e.g. from differences in wind speed or in nozzle performance). A subset of data is analysed to characterise the uncertainty in the lognormal distributions fitted to the average values for each experiment at each distance (see above). Drift at 5 m distance has been measured in a total of 50 experiments. Between 5 and 10 replicate measurements were made for each trial. One of these replicates is randomly sampled from each study using the Crystal Ball software. This procedure is repeated to give 50 combinations of 50 randomly sampled values. Lognormal distributions are fitted to each of the 50 sets of data. The mean and coefficient of variation (CV) of each distribution are recorded and basic statistics calculated:

Table 1. Statistics for the means and coefficients of variation of the lognormal distributions fitted to 50 sets of 50 sampled values (1 replicate value sampled from each experiment at 5 m distance)

	Mean of lognormal distribution at 5 m distance	CV of lognormal distribution at 5 m distance
n	50	50
Min	0.2600	57.6
Max	0.3961	119.0
Average	0.3062	82.0
Stdev	0.0236	9.1
CV (%)	**7.71**	**11.1**

It is assumed that the uncertainty in the mean and the CV of the lognormal distributions at all distances is the same as at 5 m distance.

The uncertainty of the mean of the lognormal distribution at each distance is taken into account by sampling from a normal distribution in the outer loop. The standard deviation of this distribution is set to 7.71% of the mean drift loss at each distance. This resulted in a new sampled mean at each distance.

The uncertainty of the coefficient of variation of the lognormal distribution at each distance is also considered by sampling from a normal distribution in the outer loop. The mean of this distribution is set to 11.1% of the mean coefficient of variation at each distance. A new standard deviation is calculated from the sampled mean and the sampled coefficient of variation at each distance.

Individual mean values and standard deviations are sampled in each iteration of the outer loop, giving x lognormal distributions at each distance.

<u>Final values for drift at z1 and z2</u>
A value for drift loss is sampled from the updated lognormal distribution in the inner loop (a user-specified number of runs for each of the x iterations in the outer loop) to express uncertainty in the drift curve. The new drift loss at each distance is compared with the initial value. The percentage drift at distance z1 is then scaled using the ratio for the distance closest to z1.

$D(z1)\ final = D(z1)_{initial} \times [D(closest\ distance)_{final} / D(closest\ distance)_{initial}]$

Drift at z2 is scaled using the same ratio as for z1.

The parameters of the power law equation are then re-calculated from the new values for D(z1) and D(z2). Drift deposition over the total width of the water column is integrated using the updated parameters.

3.2.3 Application rate

The percentage of applied pesticide that is discharged into the ditch is multiplied by the application rate and corrected for interception by the bankside vegetation (see Section 3.2.4). The target application rate of the pesticide is a user input. The actual application rate is, however, uncertain. Possible sources of uncertainty include: errors in the concentration of active substance within the formulated herbicide product, errors in measuring the product and filling the tank, and uncertainties related to application technology (e.g. mixing in tank, pressure at nozzle, speed of the tractor, machine calibration). The rate of pesticide actually applied is assumed to be normally distributed with a mean set to the target rate . The 2.5^{th} percentile and the 97.5^{th} percentile of the distribution are assumed to correspond to the mean application rate ± 5% (e.g. for a target rate of 1500 g a.s./ha, the 2.5^{th} and 97.5^{th} percentile are 1425 and 1575 g a.s./ha, respectively).

3.2.4 Interception

Interception of spray drift by bankside vegetation is a significant process which is also very difficult to quantify. The amount intercepted depends on a large number of factors including the height of the vegetation in relation to the height of the spray boom, the type and density of the vegetation, the width of the vegetated strip and its distance from the field and from the edge of the ditch. Only limited data are available in the literature on the influence of these factors on interception. Interception within the Coleshill catchment is, thus, considered to be highly uncertain. This uncertainty is included in the outer loop of the 2-D Monte Carlo analysis.

The ditches in the Coleshill catchment have been categorised for Defra project PS2304 according to the type of features present in the zone between the field and the ditch (Table 2).

Table 2. Description of features present in the zone between the field and the ditch

Feature	Code	Description
Buffer strip	B	Bare, grassy or low scrub area: default area assumed to surround other certain features or to exist on its own
Track	T	An unsurfaced track suitable for farm vehicles: effectively a low buffer
Hedge	H	Hedge
Set-aside	S	An area at least 5 metres wide left as a strip of deliberately uncultivated land, either due to agricultural practice or due to the land being unsuitable for agriculture: low vegetation
Wooded strip	W	Shrubby or tree area: does not include widely spaced planted trees
Fence	F	A fence, probably wooden, creating a reasonably large obstruction to drift: simple wire fences not included
Bank	K	A bank where the top is significantly raised with respect to both the ditch and the field

Seven combinations of the above features have been identified as specific drift zone types for the Coleshill catchment (Table 3). Each 'type' represents a single side of the ditch. The approximate length of each ditch is estimated using GIS analysis of aerial photographs.

Table 3. Categorisation of drift zones present in the Coleshill catchment and total length of ditches in each category estimated by GIS analysis

Zone type	Feature combination	Length (m)
I	B	16739
II	BTB	1823
III	BHB	7588
IV	BHTB	1991
V	BSB	314
VI	BHSB	343
VIII	WB	2671
Io	overgrown*	462
Total		31931

* an overgrown buffer is where the ditch is not distinguishable from the surroundings on the aerial photograph due to complete cover by dense woody vegetation (e.g. bramble / sallow)

Each ditch category is sampled with a relative frequency that corresponds to the ratio of the length of ditches in that category and the total length of all ditches. Interception is then sampled from distributions assigned to each drift zone category (Table 4). The presence of hedges or wooded strips is considered to increase interception relative to grassed buffer strips on their own. Hedges are also assumed to reduce pesticide losses to a larger extent than wooded strips due to their larger density. Tracks or set-aside land with no or very short vegetation are assumed not to have any additional effect on interception.

Table 4. Distributions describing the uncertainty in interception by features present in the zone between the field and the ditch

	Category[a]	Features present[a]	Type of distribution[b]	Minimum Reduction (%)	Median / likeliest value (%)	Standard deviation	Maximum Reduction (%)
Buffer strip (on its own or in combination with a	I II V	B BT BS	Lognormal	0	30	13.1	85.00

track or set-aside land)							
Hedge (in combination with a buffer and either a track or set-aside land)	III IV VI	BH BHTB BHSB	Inverse lognormal	20	90	11.4	99.99
Buffer + Wooded strip	VIII	WB	Inverse triangular	15	70		99.99
Overgrown ditch	Io		Inverse lognormal	20	80	12.8	99.99

[a] For definition of features and categories see Tables 2 and 3

[b] A distribution is assigned to the percentage NOT intercepted and interception calculated thereafter as 100 minus sampled value

3.2.5 Concentration of the pesticide in the ditch

The amount of pesticide discharged into the water body is calculated from the percentage drift loss, the application rate and interception. The load is then divided by the volume of the water column (1 m^2 surface area) to give the concentration of the pesticide in the ditch.

3.3 Summary of assumptions and sources of uncertainty and variability

Results from the probabilistic calculation should be considered in the light of the simplifying assumptions made:

- Exposure of surface waters via spray drift is calculated for a single 100 km^2 area in the UK. The size of the study area is determined by the resource required to make detailed measurements of ditch morphology. Ditches within the study area are known to be vulnerable to pesticide contamination via spray drift because the ditches are small and thus have only limited potential for dilution of residues. However, variability across the full range of possible ditch types is not included within the analysis and the uncertainty arising from the limited study area is not factored into the assessment.
- The assessment refers to fields sown with the target crop and assumes that every field is treated at the maximum target rate and has ditches adjacent (and is therefore an over-estimate). The assessment also assumes that treated ditches are a random selection of all ditches. Ditches not adjacent to the target crop will have different exposure (other crops treated with the pesticide at different rates) or no exposure (no treated crops). Wind is blowing in one direction such that deposition of spray drift only occurs from a single side of the ditch at any one time.
- The amount of pesticide applied is assumed to be uncertain (errors in tank mixing, machine calibration etc.) and to follow a normal distribution with 95% of the values being within ± 5% of the target application rate. This range is defined using expert judgement.
- Variability and uncertainty in the calculation of exposure via spray drift are differentiated using 2-D Monte Carlo simulation. Drift generation and deposition are calculated on the basis of experiments by Rautmann et al. (2001). The authors measured deposition in a number of experiments at different distances from the edge of a field cultivated with arable crops. Each experiment consisted of 5-10 replicates. Differences between the replicates are considered to represent uncertainty due to measurement error and small-scale spatial variability in drift deposition. Differences between the experiments are considered to reflect the variability in measured drift generation and deposition under reference conditions. Uncertainty and variability are separated by analysing data for 5 m

drift distance (for details see Section 3.2.2). It is assumed that the uncertainty is the same at all distances. Differences between the variability at different distances are considered.

- The effect of deviations of drift conditions at the time of application from reference spray drift conditions (e.g. wind speed and direction, boom height, nozzle type, pressure at nozzle, speed of tractor) on relative drift losses is not factored into the assessment. However, the uncertainty in the application rate arising from these factors is considered.
- The experiments by Rautmann et al. (2001) measured drift deposition onto a flat surface at the same level as the cropped area. Deposition on a water surface that is below ground level may differ from that in the experiments. This source of uncertainty is not considered.
- The variability in the measured depth of water present in the ditch is taken into account. However, differences between water depth at the time of the field survey and the time of application are not considered.
- Interception of spray drift by bankside vegetation is highly variable and uncertain. Little information exists of the influence of vegetation type, height, density, spray boom height relative to crop height and the width of the vegetated strip on interception. In this study, interception is sampled from distributions which are defined by expert judgement (with regard to the available literature). The presence of hedges or wooded strips is considered to increase interception relative to grassed buffer strips on their own. Hedges are also assumed to reduce pesticide losses to a larger extent than wooded strips due to their greater density. Tracks or set-aside land with no or very short vegetation is assumed not to have any additional effect on interception.
- The exposure assessment considers the instantaneous concentration of pesticide in the ditch arising from drift deposition. The pesticide is assumed to be completely mixed with the entire volume of the ditch. However, the deposition of pesticide decreases with increasing distance from the treated area and is thus smaller at the far side of the ditch than at the near side. The chemical is deposited at the water surface leading to higher initial concentrations in a thin layer of water. In stagnant water bodies, the time required for a complete mixing may be relatively long and concentrations at certain points within the ditch may differ from those calculated here for considerable periods of time. Any sorption of the pesticide to sediment or macrophytes is ignored in the calculation of initial PEC values. This introduces errors into the assessment and leads to a conservative estimate of exposure concentrations.

The main sources of variability and uncertainty included and excluded in the calculation of exposure are summarised in Section 2.1.