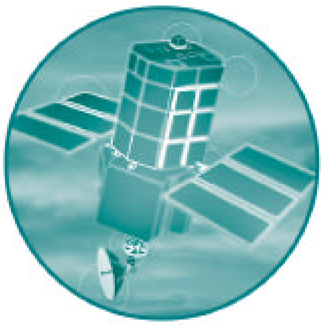
The Past, Current and Future Radiological Impact of the Sellafield Marine Discharges on the People Living in the Coastal Communities Surrounding the Irish Sea



Research and Development

Technical Report
P290

SNIFFER

ENVIRONMENT AGENCY

The Past, Current and Future Radiological Impact of the Sellafield Marine Discharges on the People Living in the Coastal Communities Surrounding the Irish Sea

R&D Technical Report P290

J A Goshawk and S Clarke

Research Contractor:
Westlakes Scientific Consulting

Publishing Organisation:
Environment Agency
Rio House
Waterside Drive
Aztec West
Almondsbury
Bristol
BS32 4UD

Tel: 01454 624400 Fax: 01454 624409

ISBN 1 85705 188 2

Dissemination Status
Internal: Released to Regions
External: Released to the Public Domain

Statement of Use
This report presents an assessment of past, current and future radiological impact of the Sellafield marine discharges on people living in the coastal communities surrounding the Irish Sea. This information will assist the Environment Agency in its regulation of the Sellafield nuclear site.

Keywords
Radiological impact, marine discharges, critical groups, dose exposures, Sellafield, Irish Sea

Research Contractor
This document was produced under R&D Project P3-050 by:

Westlakes Scientific Consulting Ltd
The Princess Royal Building
Westlakes Science and Technology Park
Moor Row
Cumbria CA24 3LN
Tel: 01946 514000 Fax: 01946 514040

Environment Agency's Project Manager
The Environment Agency's Project Manager for the R&D Project P3-050 was:
Matthew Emptage – North West Region

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page left blank intentionally.

EXECUTIVE SUMMARY

The Environment Agency authorises the disposal of radioactive wastes from the Sellafield site through authorisations granted under the Radioactive Substances Act, 1993. The authorised liquid and aerial discharges mainly result from the reprocessing of spent nuclear fuel, the processing of backlog reprocessing waste and the Calder Hall nuclear power station. The impact of these discharges is routinely monitored and is the subject of on-going review. The liquid discharges are made to the Irish Sea via a submerged sea pipeline approximately 2 km offshore of the Sellafield site.

The work described within this report was commissioned by the Environment Agencies (comprising the Environment Agency of England and Wales, the Scottish Environment Protection Agency, and the Northern Ireland Environment and Heritage Service), as part of the on-going review of the impact of Sellafield discharges. The study used computer modelling to re-assess the radiological impact of past, current and future liquid discharges from Sellafield on the coastal communities surrounding the Irish Sea. The last comprehensive assessment using computer modelling was conducted in 1994 (Barr and Howorth, 1994). A suite of computer models has been used to simulate the transport of Sellafield liquid discharges through the environment and to calculate the resulting past, current and future radiation dose to specified population groups (coastal communities) around the Irish Sea. The period of time considered is from 1950 (the start of Sellafield operations) to 2050.

Best estimates of Sellafield past discharges (1950-1998) have been used as input data for the model. In a few cases where complete discharge records do not exist, radionuclide discharges have been taken to be equal to the value for the first year they were reported. Ingrowth of daughter radionuclides after discharge (e.g. ^{241}Am from ^{241}Pu) has been accounted for. Four future discharge scenarios have been considered, in order to predict the impact of future discharges:

- **Scenario One:** Constant discharge, equal to the discharge levels in 1998, until the year 2050
- **Scenario Two:** An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050
- **Scenario Three:** Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050
- **Scenario Four:** Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).

The computer model simulated the transport of discharges within the water column, the uptake of radionuclides by sediment (using standard partitioning coefficients) and foodstuffs (using standard concentration factors) and the return of radionuclides to land via sea-spray. This allowed the radionuclide activity concentrations in environmental materials and foodstuffs to be calculated. These concentrations, combined with the latest available habit data and consumption rates (collated from published information), have been used to calculate the resulting radiation doses to members of the specified coastal communities. Doses have been calculated for critical groups of the coastal communities populations (i.e. those who receive the highest doses as a result of their

diets and/or habits) and also for typical members of the population of the coastal communities (people who have average seafood consumption and spend an average time on beaches).
Doses have been estimated for the coastal communities of West Cumbria, Morecambe Bay, Southwest Scotland, Northern Ireland, Whitehaven harbour, the Ribble Estuary, the Isle of Man and Wales.

Past and current doses, predicted by this study, are generally consistent with those estimated using data from routine environmental monitoring programmes. There are exceptions. For example, critical group doses for the Ribble Estuary and Morecambe Bay are underestimated by this study when compared to estimates made from monitoring data and habits surveys. This reflects the very complex hydrodynamics of estuarine and bay environments, and possibly the transport of radionuclides during low frequency, but important, storm events, which the environmental models used are not able to fully replicate.

Generally, past current and future radiation doses have been assessed as being highest at locations close to Sellafield, diminishing with distance from the site. For example, the West Cumbrian high-rate seafood consumers were found to receive the highest doses; the more remote coastal communities (e.g. Northern Ireland & North Wales) receive doses which are approximately one-tenth of theses values. A notable exception is the Welsh critical group in the period up to 1975. This group had high consumption rates of the seaweed *porphyra*, which was collected from the West Cumbrian coast and consequently the doses received by this group were similar to the high rate seafood consumers of West Cumbria. In 1976 this practice ceased and the Welsh critical group became the high seafoods consumers of the North Wales coast. This resulted in a step reduction in dose.

Assessed doses to coastal communities at all locations show a gradual increase from the start of Sellafield operations (1950) to the peak of discharges in the mid 1970s. From the mid 1970s onwards, doses have been in decline at all locations and are now approximately one-twentieth of their peak level. Doses have not declined as rapidly as discharges and this is because doses increasingly arise from past discharges, already in the environment, rather than from current discharges. This is demonstrated by the future discharge Scenario Four (which considers what would happen if discharges ceased at the end of 1998); The doses in this case decline gradually over the years to 2050.

The highest dose predicted by the study (2.3mSv a^{-1}) occurred in 1975, for members of the critical group for West Cumbria. This may be compared to the public dose limit, at the time, of 5mSv a^{-1}. Following the 1990 recommendation of the ICRP (ICRP, 1991) and the subsequent guidance of the NRPB (NRPB, 1993), 1mSv a^{-1} became the accepted dose limit. This limit may be compared to the study's highest predicted dose of 0.31mSv a^{-1} for the period 1990-2050. It can therefore be concluded that all past and current doses are less than the relevant dose limits. In addition, all future doses are predicted to be less than the current dose limit for all the future discharge scenarios considered.

1. INTRODUCTION

A radiological assessment of the impact of Sellafield marine discharges on coastal communities of the Irish Sea was published in 1994 (Barr and Howorth, 1994). The UK Environment Agencies* considered that there was a need to repeat the assessment in order to provide up-to-date estimates of radiation doses to selected population groups within the coastal communities of the Irish Sea.

In this report, details of the most recent assessment of the impact of radioactive discharges from the British Nuclear Fuels plc (BNFL) reprocessing plant at Sellafield, on coastal communities of the Irish Sea, are presented. The assessment takes into account:

- The influence of radionuclides included in the 1994 assessment together with the effect of some radionuclides not included in the 1994 assessment.
- All significant pathways of exposure to the members of the population groups considered.
- Changes in dose models introduced by the International Commission on Radiological Protection (ICRP).
- Up-to-date information on the habits of the population groups.
- Up-to-date information on past, current and likely future marine discharges from Sellafield.
- Improvements in the modelling of environmental transfer processes.

The transport of the radioactivity in the Irish Sea has been modelled for past discharges and for four future discharge scenarios. The resulting activity concentration distributions in the seawater have been used to predict the annual doses to the critical group, or a typical group, of the population at specified locations on the coast of the Irish Sea. For the purposes of this study the critical group at a given location is defined to consist of those members of the population that are high-rate seafood consumers and are high occupancy beach users. A typical group consists of members of the population with an average seafood consumption rate and an average beach occupancy rate. The annual doses predicted for the population groups considered have been compared against the predicted doses from other assessments, dose estimates obtained via measurements and habit surveys, and appropriate ICRP dose limits.

1.1 Locations at Which Critical and Typical Groups Have Been Defined

The locations on the coast of the Irish Sea at which a critical group has been considered are West Cumbria, Morecambe Bay, Southwest Scotland, Northern Ireland, Whitehaven Harbour, the Ribble Estuary, the Isle of Man and Wales. In the case of the Isle of Man the critical group of the adult and the infant populations has been considered. This is because the habit data indicate that the consumption pathways will dominate the annual dose received by the critical group of adults while the sediment pathways will dominate the dose to the critical group of infants.

---

*Consisting of the Environment Agency, the Scottish Environment Protection Agency and the Northern Ireland Environment and Heritage Service.

Three typical groups have been identified for the Irish Sea coastal communities in Northwest England, Wales, Southwest Scotland and Northern Ireland. The three groups at each location relate to the typical members of the adult, child and infant populations.

1.2 The Discharge Scenarios

The radionuclides included in this dose assessment are ^{3}H, ^{14}C, ^{60}Co, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{99}Tc, ^{106}Ru, ^{125}Sb, ^{129}I, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{237}Np, Pu(α)*, ^{241}Pu and ^{241}Am. In addition the impact of the ^{241}Am daughter of ^{241}Pu and the ^{95}Nb daughter of ^{95}Zr are included in the assessment to take account of ingrowth of these radionuclides within the environmental media. Four different discharge scenarios of the listed radionuclides have been considered. Between the years 1950 and 1998 the four scenarios are identical with discharges set equal to historical discharges (Gray et al. (1995), NRPB (1995), Gray (1997), BNFL(1973–1997) and Hadwin (1997)). From 1999 onwards the following has been assumed:

- **Scenario One:** Constant discharge, equal to the discharge levels in 1998, until the year 2050.
- **Scenario Two:** An increase in discharges, with discharges equal to the current authorised limits from the year 2000 until the year 2050.
- **Scenario Three:** Linearly decreasing discharges from 1998 levels to zero in the year 2020 and then zero until 2050.
- **Scenario Four:** Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999 until 2050).
-

1.3 The Structure of this Report

To simulate the dispersion of radionuclides in the Irish Sea and predict the annual doses received by the population groups identified at the specified locations detailed in Section 1.1, a suite of computer codes, developed at Westlakes Scientific Consulting (WSC), has been used. The main components of the suite of programs are described in Section 2 of this report. To ensure the predictions of the activity concentrations in the Irish Sea are meaningful, the dispersion model has been calibrated against existing measured data and this procedure is described in Section 3. To calculate the annual dose received by members of the population groups considered, seafood consumption data and habit data are required. These data are presented in Section 4 with the calculated annual doses given in Section 5. The work is summarised and discussed in Section 6 with suggestions for future work given in Section 7. The references and a glossary of terms are provided in Sections 8 and 9 respectively.

*In this study Pu(α) is assumed to be the sum of ^{238}Pu, ^{239}Pu and ^{240}Pu.

2. FUNCTIONALITY OF MARISA v1.1

The MARine Integrated Software Application, MARISA, is a suite of five programs that enables the simulation of the transport of pollutants in marine environments. If the pollutant whose behaviour is to be simulated is radioactive then the radiation dose to specified population groups resulting from exposure to the radioactivity through various pathways can be predicted using MARISA.

One of the five modules incorporated in MARISA is a graphical user interface, the remaining four are:

- MEAD – a long-term Marine Environment Annual Dispersion model that simulates the transport of marine-based pollutants in shelf sea environments by representing the influence of physical and chemical processes over tens of years.
- SEDMOD – an annual SEDiment transport MODel that calculates the suspended sediment distribution for the relevant shelf sea region, in this case the Irish Sea. The resulting annual average suspended sediment concentration field is required as input to MEAD.
- ADEPT – an Annual DosE Post-processing Tool that transforms MEAD results into biota flesh activity concentrations and annual dose estimates (Committed Effective Dose (CED) and external dose) for radioactive contaminants.
- PLOT – a PLOTting tool for both MEAD and ADEPT.

The functionality of each of these modules is described in this section. Additionally, the determination of the flow field and suspended sediment field, which are required as input data for MEAD, is also detailed.

2.1 Description of MEAD

MEAD (Marine Environment Annual Dispersion) version 1.1 is an annually averaged marine dispersion model that has been developed beyond the CUMBRIA model. The CUMBRIA model was originally written by AEA Technology at Harwell (Howorth and Kirby, 1988). The models simulate the long-term transport of pollutants using a residual flow field. The CUMBRIA model is restricted to modelling the transport in the Irish Sea whereas MEAD is generic and can be set up to simulate the transport of marine pollutants in any shelf sea area.

In the MEAD model, pollutants are assumed to be present in the marine environment in three phases: dissolved in the seawater, attached to suspended sediment particles or attached to fine-grained sediment that has been deposited on the seabed. The concentration field in each phase is assumed to be a function of time and is calculated in two distinct stages. In Stage one a specified quantity of a pollutant is introduced in the first year of the simulation and the subsequent transport is calculated for a period of 100 years. Mechanisms that enable the pollutant to be transferred between the three phases are also included in these calculations. For the purposes of the present investigation, the pollutant is radioactive and the quantity introduced in the first year is 1 TBq of activity. In Stage two of MEAD, the concentration field in the three phases resulting from a given discharge scenario is calculated by appropriately scaling the results generated from the single release scenario simulated in Stage one.

The transport equations solved in Stage one of MEAD are

$$\frac{\partial hC_1}{\partial t} = -\frac{\partial (hUC_1)}{\partial x} - \frac{\partial (hVC_1)}{\partial y} + \frac{\partial}{\partial x}\left(hK_x \frac{\partial C_1}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_y \frac{\partial C_1}{\partial y}\right)$$
$$+ h\alpha C_2 + h\alpha C_3 - h\left(K_D\left(\alpha \frac{P}{\rho} + \alpha \frac{l_s \rho_s \phi}{h\rho}\right) + \delta\right)C_1, \tag{1a}$$

$$\frac{\partial hC_2}{\partial t} = -\frac{\partial (hUC_2)}{\partial x} - \frac{\partial (hVC_2)}{\partial y} + \frac{\partial}{\partial x}\left(hK_x \frac{\partial C_2}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_y \frac{\partial C_2}{\partial y}\right)$$
$$+ h\alpha K_D \frac{P}{\rho} C_1 + h\frac{w_s P}{L\phi \rho_s} C_3 + h\sigma - h\left(\alpha + \frac{w_s}{h} + \delta\right)C_2 \tag{1b}$$

and

$$\frac{\partial hC_3}{\partial t} = h\alpha K_D \frac{l_s \rho_s \phi}{h\rho} C_1 + h\frac{w_s}{h} C_2 - h\left(\alpha + \frac{w_s P}{L\phi \rho_s} + \delta\right)C_3, \tag{1c}$$

where

x	is the west-east spatial measurement (m)
y	is the south-north spatial measurement (m)
t	is time (s)
$C_1(x,y,t)$	is the depth and annually averaged dissolved phase radionuclide concentration (Bq m^{-3})
$C_2(x,y,t)$	is the depth and annually averaged suspended phase radionuclide concentration (Bq m^{-3})
$C_3(x,y,t)$	is the depth and annually averaged deposited phase radionuclide concentration (Bq m^{-3})
$P(x,y)$	is the depth and annually averaged suspended sediment concentration (kg m^{-3})
$h(x,y)$	is the mean water depth (m)
$U(x,y)$	is the west-east component of the residual velocity field (m s^{-1})
$V(x,y)$	is the south-north component of the residual velocity field (m s^{-1})
$K_x(x,y)$	is the west-east component of the diffusion coefficient (m^2 s^{-1})
$K_y(x,y)$	is the south-north component of the diffusion coefficient (m^2 s^{-1})
$\phi(x,y)$	is the fraction of mud on the seabed (dimensionless)
α	is the desorption rate (s^{-1})
K_D	is the partition coefficient (dimensionless)
L	is the bed mixing length (m)
l_s	is the bed desorption depth (m)
w_s	is the mean settling velocity of the suspended sediment (m s^{-1})
ρ	is the water density (kg m^{-3})
ρ_s	is the deposited sediment density (kg m^{-3})
δ	is the radionuclide decay constant (s^{-1})
σ	is a source term (Bq m^{-3} s^{-1})

The activity transfer between the suspended and dissolved phases is governed by the desorption rate. The rate at which activity is transferred from the dissolved phase to the suspended phase is given by $\alpha K_D P/\rho$ in eqs. (1). This expression was derived by Howorth and Kirby (1988) who assumed that activity transfer between the dissolved and suspended phases is in equilibrium.

An important parameter in the definition of the rate of adsorption from the dissolved to suspended phases is the partition coefficient, K_D, which provides an equilibrium measure of the affinity a radionuclide has for sediment. A formal definition of the partition coefficient is

$$K_D = \frac{\text{radionuclide activity per unit weight of dry sediment (Bq kg}^{-1}\text{)}}{\text{radionuclide activity per unit weight of seawater (Bq kg}^{-1}\text{)}}. \tag{2}$$

Ionic exchange between the dissolved and deposited phases has recently been recognised as an important physical process in the dispersion of radioactivity in marine environments (Hunt and Kershaw, 1990). This phase transfer, in which activity is adsorbed onto or desorbed from the bed sediment, was not accounted for in CUMBRIA but is in MEAD. The transfer of radionuclides between the deposited and dissolved phases is governed by the desorption rate. The rate at which radionuclides are transferred from the dissolved phase to the deposited phase is given by $\alpha K_D l_s \rho_s \phi/(h\rho)$ in eqs. (1). This expression was derived by Goshawk (1998b) using arguments similar to those of Howorth and Kirby (1988) to model the ionic exchange between the suspended and dissolved phases.

Transfer between the suspended and deposited phases occurs through sediment deposition and this is calculated using the mean settling velocity. Resuspension of the bed sediment accounts for transfer between the deposited and suspended phases and is governed by the resuspension rate, which is given by $w_s P/L\phi\rho_s$ in eqs. (1). Since MEAD deals with long-term simulations, it is assumed that only the mud in the bed sediments contributes to the net resuspension (since sand and larger particles are eroded and deposited over relatively short periods). The resuspension rate is thus defined to be related to the spatially varying percentage of mud on the sea bed, the suspended sediment concentration field, the density of the deposited sediment and the mixing depth of the bed.

MEAD can also simulate radionuclide parent-daughter chains. This is achieved by solving eqs. (1) for the dispersion of both parent and daughter radionuclides. An additional term representing the growth of daughter from parent, δC_{pi}, is included in each of the equations solved to simulate the transport of the daughter radionuclide. In this case δ denotes the decay constant of the daughter radionuclide while C_{pi} denotes the concentration of the parent radionuclide in phase i where $i = 1$ to 3 as in eqs. (1). To determine the radionuclide transport in the Irish Sea, discrete representations of eqs. (1) are solved over the grid shown in Figure 1 using a finite-difference method.

In Stage two of MEAD the activity concentrations produced by Stage one are multiplied by a discharge data set. The discharge data set can contain either values representing a certain discharge scenario (i.e. historical/expected future discharge values) or constant values. The resulting concentration field is given by

$$CC_i = \sum_{t'=1}^{T} C_i(x, y, T+1-t')D(t'), \tag{3}$$

where

CC_i is the cumulative concentration in phase i (Bq m^{-3})
T is the total number of years for which Stage 2 is to be run
$C_i(x,y,\tau)$ is the normalised radionuclide concentration in phase i after τ years (as calculated in Stage 1)
$D(t')$ is the activity of a given radionuclide discharged in year t'
and $i = 1$ to 3.

2.2 Description of SEDMOD

The long-term sediment transport model SEDMOD is used to determine the annual mean suspended particulate material (SPM) concentration in the specified model area. SEDMOD simulates the sediment transport over a 100-year period in order to achieve an equilibrium SPM concentration field. The SPM concentration field resulting from the SEDMOD simulation is used as input data for MEAD and is denoted as P in eqs. (1).

The annually averaged sediment transport equation solved in SEDMOD is

$$\frac{\partial hP}{\partial t} + \frac{\partial(hUP)}{\partial x} + \frac{\partial(hVP)}{\partial y} = \frac{\partial}{\partial x}\left(hK_x \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_y \frac{\partial P}{\partial y}\right) + E_r + D_p \tag{4}$$

where
$E_r(x,y)$ is the annually averaged erosion rate (kg m^{-2} a^{-1})
$D_p(x,y)$ is the annually averaged deposition rate (kg m^{-2} a^{-1})
and all other quantities are as previously described. The annual erosion and deposition rates are determined by integrating the instantaneous erosion and deposition rates over 705.75 tidal cycles (the number of tidal cycles in a year) (Clarke, 1998). The instantaneous erosion and deposition rates are defined as

$$E_I = \frac{M}{u_e^2}\left(u^2 - u_e^2\right) \tag{5}$$

and

$$D_I = \frac{w_s P}{u_d^2}\left(u^2 - u_d^2\right) \tag{6}$$

respectively (Dyer, 1986). In eqs. (5) and (6) u is the magnitude of the velocity, u_e and u_d are the thresholds on the magnitude of the velocity at which erosion and deposition occurs, M is an erosion rate with units of kg m^{-2} s^{-1} and all other quantities are as previously defined.

To determine the SPM concentration field in the Irish Sea, a discrete form of eq. (4) is solved over the grid shown in Figure 1 using a finite-difference method.

2.3 The Suspended Sediment Field

SEDMOD provides a spatially varying, annually averaged SPM concentration field that is used as one of the inputs to MEAD. MEAD requires the SPM concentrations to calculate the activity transferred between the suspended phase and the dissolved and deposited phases through adsorption/desorption and sedimentation/erosion respectively.

In the CUMBRIA model the annually averaged SPM concentration was given a constant value of 4 mg l^{-1} everywhere in the Irish Sea. This was considered to be unrealistic given the tendency for higher concentrations of suspended sediment to be found in shallower waters and, conversely, lower concentrations to be found in deeper water (Bowers *et al.*, 1998). SEDMOD therefore provides a more realistic, spatially varying SPM concentration field for MEAD with the concentration varying between 2 and 12 mg l^{-1}, based on field validation.

2.4 The Flow Field

The underlying grid used by MEAD v1.1 (see Figure 1) has a 2 km resolution and is orientated north-south. The flow field was generated in house at WSC using the commercially available tidally resolving hydrodynamic model MIKE21, developed by the Danish Hydraulics Institute. MIKE21 was used to simulate hydrodynamic conditions in the Irish Sea over one year using monthly mean wind speeds and directions obtained from the Met Office. The results of the model run were analysed to obtain the residual flow field. The residual flow field was resolved into east-west and north-south components and these are used as the driving force in MEAD. The model grid used in MIKE21 for the generation of the flow field was identical to that used in MEAD v1.1.

2.5 Description of ADEPT

ADEPT is a tool that is used to convert the activity concentration fields produced by MEAD into activity concentrations in the flesh of biota and the annual dose to individuals via various exposure pathways. The pathways include ingestion of marine biota (such as fish and shellfish), external exposure resulting from time spent over contaminated sediments and internal irradiation from the ingestion and inhalation of sediment. The Committed Effective Dose (CED) is the internal dose from an intake that will accrue over the period to the age of 70 which, in this assessment, is an intake over a year. The dose to an individual from one year's discharge is therefore defined to be the sum of the CED and the dose from external exposure corresponding to the year's discharge.

To determine activity concentrations in the flesh of a particular species of biota, specific cells are selected from the underlying grid used in MEAD. These cells correspond to the locations where the specified species is harvested. An average dissolved phase activity concentration, C, is then calculated over the selected cells. The flesh activity concentration, FLC, is then given by

$$FLC = \frac{C}{\rho} CF, \qquad (7)$$

where CF is a non-dimensional concentration factor, which is species and radionuclide dependent. Dividing the average dissolved phase activity concentration by the water density converts the units of FLC to Bq kg^{-1}.

The contribution to the CED (μSv a^{-1}) due to a single biota pathway is given by

$$D_j = FLC \times R \times DF \times 10^6, \tag{8}$$

where R is the consumption rate (kg a^{-1}) of the biota species, DF is the dose coefficient (Sv Bq^{-1}) and D_j is the dose from the j^{th} pathway. The factor of 10^6 is used to convert Sv to μSv. The CED due to biota is therefore given by

$$\text{CED}_{\text{BIOTA}} = \sum_{j=1}^{N} D_j, \tag{9}$$

where N is the number of biota ingestion pathways contributing to $\text{CED}_{\text{BIOTA}}$.

For the ingestion or inhalation of contaminated sediment, the contribution to the CED is calculated from the appropriate mean dissolved concentration and a site-specific partition coefficient, K_d. The appropriate expression to calculate the contribution is

$$\text{CED}_{\text{SEDIMENT}} = \frac{C}{\rho} K_d (R_{\text{IG}} DF_{\text{IG}} + R_{\text{IH}} DF_{\text{IH}}) \times 10^6, \tag{10}$$

where R_{IG} and R_{IH} refer to the annual consumption by ingestion and inhalation respectively and DF_{IG} and DF_{IH} refer to the dose coefficients for ingestion and inhalation respectively. The total CED is given by

$$\text{CED} = \text{CED}_{\text{BIOTA}} + \text{CED}_{\text{SEDIMENT}}. \tag{11}$$

The dose due to external exposure is determined using the semi-infinite source model which was proposed by Hunt (1984) and can be written

$$\text{DOSE} = OC \frac{C}{\rho} K_d K_1 K_2 M, \tag{12}$$

(cf. eq. (1) in Hunt (1984)) where the occupancy duration, OC, is measured in hours per year and M is the photon energy per decay of the radionuclide of interest measured in MeV. K_1 is a constant with the value of 0.87, used to convert Grays to Sieverts. The constant K_2 is a model parameter with units of μGy kg h^{-1} Bq^{-1} MeV^{-1} given the value of 2.88×10^{-4} by Hunt (1984) and C, ρ and K_d are as previously defined.

The prediction of the dose to an individual, resulting from a single radionuclide, is obtained by summing the contributions to the dose from eqs. (11) and (12). The total dose is then obtained by summing over all relevant radionuclides.

It should be noted that the dose received via sea-to-land transfer is not dealt with explicitly by ADEPT and the calculation of this dose has been performed specifically for the current project. A description of this calculation is given in Section 4.

2.6 Description of PLOT

PLOT is used to display the results obtained using MEAD and ADEPT. When MEAD results are to be plotted, a digitised coastline is overlaid on a shaded contour plot of the contents of a specified MEAD results file. The ten contour levels used to plot the model results are calculated from the maximum and minimum values in each phase of the MEAD results file. ADEPT results are plotted against time on Cartesian axes and measured biota/sediment concentrations and doses may also be supplied and plotted on the same graph as the predicted values.

Page left blank intentionally.

3. THE CALIBRATION OF MEAD

To execute MEAD, values are required for a number of the parameters in eqs (1). For some of the parameters unique values can be obtained from relevant publications, for others an applicable range is quoted. To calibrate MEAD, appropriate values are assigned to the relevant parameters and the predicted seawater activity concentrations are compared with a set of measured values. The goodness of fit between the predicted and measured activity concentrations is determined, by eye, by an experienced marine modeller. When the parameter values considered to yield the best fit between the predicted and measured activity concentrations have been obtained they are used for all subsequent simulations. The method of fitting the data by eye is used in preference to a formal statistically based method such as "least squares". This is because the "automatic" fit achieved using a statistical method does not allow the knowledge of the strengths and weaknesses of the modelling process which the experienced modeller has to be applied to the calibartion. The application of such knowledge is important to ensure optimal performance of the model.

3.1 Parameters

The parameters within MEAD for which values are required fall into one of the following categories:

- Physical parameters
- Sedimentological parameters
- Ionic exchange parameters

3.1.1 Physical parameters

The transport of radionuclides is simulated in MEAD by solving a time-integrated version of the advection-diffusion equations. The solution provides an approximation of the long-term distribution of radionuclides resulting from residual advection (calculated using a residual velocity flow field) and dispersion (which, in MEAD, is a combination of the effects of tidal stirring and higher order diffusion). The dispersion terms contain coefficients which are defined as

$$K_x = a_1 u_0 \sqrt{\left(u_0^2 + v_0^2\right)} + \frac{h^3 \sqrt{\left(U^2 + V^2\right)}}{a_2 K_z} \left(|U| + \frac{|V|}{a_3} \right) \tag{13}$$

and

$$K_y = a_1 v_0 \sqrt{\left(u_0^2 + v_0^2\right)} + \frac{h^3 \sqrt{\left(U^2 + V^2\right)}}{a_2 K_z} \left(\frac{|U|}{a_3} + |V| \right), \tag{14}$$

where

K_z is the vertical diffusion coefficient,

u_0 is the west-east tidal amplitude,

v_0 is the south-north tidal amplitude,

a_1, a_2 and a_3 are constants to be determined during the calibration and all other quantities are as previously defined. The depth-averaged value of the vertical diffusion coefficient for the Irish Sea is taken to be 3×10^{-3} m^2 s^{-1} (Clarke, 1995).

The other physical parameters are defined on the open boundaries of the MEAD grid and are the ratios of the concentrations across each boundary. The open boundaries in the MEAD grid of the Irish Sea are positioned in the North Channel and St. Georges Channel. They are a substantial distance from the activity source used in this calibration which is the BNFL nuclear fuel reprocessing plant at Sellafield, Cumbria. Therefore, it is reasonable to assume that the concentration of activity either side of each boundary will be similar, i.e. the concentration gradient across each boundary is close to zero. Hence, it has been assumed that the ratios of the activity concentrations across the boundaries lie between 0.9 and 1 for the purposes of this calibration.

3.1.2 Sedimentological parameters

There are two sedimentological parameters for which values are required to calibrate MEAD; the mixing length of the bed (L) and the mean settling velocity of the fine grained suspended sediment (w_s).

The mixing length of the bed of the Irish Sea has been estimated to be between 0.1 and 0.4 m (Howorth and Kirby, 1988) and a constant value within this range is selected for the whole of the Irish Sea in the calibration MEAD. The mean settling velocity of the fine-grained suspended sediment is calculated using

$$w_s = \frac{gD^2}{18\mu}(\rho_p - \rho), \tag{15}$$

(Dyer, 1986) where

g	is acceleration due to gravity (9.81 m s^{-1})
D	is the particle diameter (m)
μ	is the molecular viscosity (kg m^{-1})
ρ_p	is the particle density (kg m^{-3})
ρ	is the water density (kg m^{-3})

It is assumed that the size of the settling particles ranges from 5 to 60 microns, the molecular viscosity is 1.03×10^{-3} kg m^{-1} and the particle and water densities are 1770 and 1000 kg m^{-3} respectively. This yields a range for mean settling velocity that can be used in MEAD of 1.0186×10^{-5} to 1.4667×10^{-3} m s^{-1}.

3.1.3 Ionic exchange parameters

The ionic exchange parameters for which values are required to calibrate MEAD are the desorption rate, α, the partition coefficient, K_D, and the bed desorption depth, l_s. Howorth and Kirby (1988) suggest a range of 1.0×10^{-7} to 7.7×10^{-4} s^{-1} for the desorption rate and the value used in MEAD is determined during the calibration procedure and is assumed to be the same for all radionuclides. The ranges of values for partition coefficients are taken from IAEA 247 (IAEA, 1985). The bed desorption depth is the seabed depth down to which radioactivity can effectively desorb from sediment. This parameter is limited by the value of the mixing length of the bed and is therefore considered to be within the range 0 to L m.

3.2 Calibration Results

The measured ^{137}Cs seawater activity concentration values reported by MAFF for 1974 (MAFF, 1976) were chosen as the calibration data set. This was considered to be the best available data relating to radionuclide concentrations in the Irish Sea at the time of the calibration procedure. The parameters within MEAD were varied within their specified ranges until the best fit between measured and predicted seawater activity concentrations was judged (by eye) to have been achieved. The results are shown in Figure 2 with the calibrated parameter values presented in Table 1.

3.3 Validation

Measured ^{137}Cs seawater activity concentrations corresponding to the years 1978, 1982 and 1985 (MAFF 1980, 1984 and 1986, respectively) were selected to validate the MEAD calibration. The MAFF measurements and MEAD predictions are compared in Figures 3 to 5. The figures show that the agreement between the measurements and the predictions is within an order of magnitude, and generally better than this, which was considered to be acceptable for contour data.

A single year of measured seawater activity concentrations for $^{239,240}Pu$ is available for 1973 (Hetherington, 1976). These data were also used to validate the results of MEAD in which a K_D equal to 10^5 was used for $^{239,240}Pu$. The predicted and measured results are shown in Figure 6 and once again agreement is to within an order of magnitude.

Due to the format of the calibration data, a more rigorous measurement of the 'goodness-of-fit' of the MEAD results than 'by eye' is not possible. However, the validation results indicated that MEAD predicts the long-term transport of radioactivity in the Irish Sea with reasonable accuracy*.

3.4 Comparison With Other Models and Measurements

To assess the accuracy of MEAD, the predictions of ^{137}Cs in seawater at St. Bees were compared to measured values from the BNFL database of environmental measurements (EPG, 1993) and to the predictions from two other models that simulate the transport of radionuclides in marine environments. The models with which MEAD was compared were CUMBRIA77, the model on which MEAD was originally based, and PC-CREAM, an assessment package developed by the NRPB (NRPB, 1997, Simmonds *et al.*, 1995). The comparison between the measured values and MEAD, CUMBRIA77 and PC-CREAM is shown in Figure 7. It is clear that MEAD provides the closest fit to the data of the three models for the activity concentrations in seawater at St. Bees.

Results from MEAD have also been compared with other data sets from the environmental measurement database (EPG, 1993). Figures 8 and 9 show the comparison between MEAD predictions and measurements from the database for ^{137}Cs and ^{90}Sr activity in seawater, respectively, in the vicinity of Sellafield. Figures 10 and 11 show similar comparisons for ^{137}Cs and ^{90}Sr activity in seawater, respectively, at

*The annual dose estimates as calculated by ADEPT were found to underestimate measured values within Morecambe Bay and the Ribble Estuary (see Section 5.2.1). It is possible that the choice of calibration parameters contribute to the low estimates, however, no low predictions of dissolved phase activity concentrations could be identified from the contour data used for the calibration/validation procedure. At the time of calibration/validation the contour data was identified as the best available data.

Seascale. The figures show good agreement between predictions and measurements from the early 1970s until the mid-1980s. Although the agreement appears as good beyond 1985 MEAD does, in fact, under-predict the measured values, the under-prediction being masked to some degree by the scale used. The probable explanation for the under-predictions beyond 1985 is that MEAD does not capture fully the ionic exchange process between the activity dissolved in the seawater and the activity attached to sediments on the seabed and further work is required in this area.

4. PARAMETER VALUES SPECIFIC TO THE PRESENT STUDY

To provide the assessment of the radiological impacts of Sellafield discharges on Irish Sea coastal communities, the following parameters are required to execute MEAD and ADEPT.

- Radiological parameters: The study is to be performed for 17 radionuclides and the parameters required for each are
  - decay constant
  - mean photon energy
  - discharge history
  - partition coefficient for the radionuclide in the Irish Sea
  - partition coefficients for the radionuclide at the locations at which the critical or typical group is defined
  - concentration factors for each species of biota
- Consumption and habit data: These are required for members of the critical or typical group defined at each location of interest.
- Grid locations: These correspond to those regions from which fish and seafood are harvested and those areas occupied by members of the critical or typical group defined at each location specified.

4.1 Radionuclide Parameters

The radionuclides discharged into the Irish Sea by the British Nuclear Fuels plant at Sellafield, considered relevant for this study by virtue of potential impact due to discharge rate or dosimetry are: ^{3}H, ^{14}C, ^{60}Co, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{99}Tc, ^{106}Ru, ^{125}Sb, ^{129}I, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{237}Np, Pu(α), ^{241}Pu and ^{241}Am.

The radioactive decay process is accounted for in the underlying equations of MEAD (see eqs. (1)), and therefore a characteristic decay constant is required for each radionuclide. The decay constants for the radionuclides listed in above are given in Table 2.

To enable ADEPT to calculate the external dose resulting from the discharged radionuclides via eq. (12), a mean measure of the photon energies associated with each of the radionuclides is required. The mean photon energy of disintegration for each radionuclide of interest, as given by MAFF (MAFF, 1997), is also presented in Table 2.

4.2 Discharge Data

The source of the majority of anthropogenic radioactivity in the Irish Sea is the British Nuclear Fuels plc. (BNFL) reprocessing plant at Sellafield. In order for a simulation of the transport of radionuclides in the Irish Sea to be performed MEAD requires, as input, time-series of the historical marine discharge from Sellafield. The pipeline discharges from Sellafield over the years 1950–1998 are given in Table 3. Complete records do not exist for all of the radionuclides of interest and for years in which data are not available the discharge has been set equal to that in the year for which a value was first given. The ingrowth of ^{95}Nb and ^{241}Am from ^{95}Zr and ^{241}Pu, respectively, is calculated automatically by MEAD (as explained in Section 2).

4.3 Partition Coefficients Used in MEAD

For a given radionuclide the partition coefficient K_D will vary as a function of the sediment particle size since, for a given mass of sediment, smaller particles provide a large surface area onto which the radionuclide can be adsorbed. In MEAD, it is assumed that radionuclides only interact with fine grain sediment, such that a single K_D can be used for each radionuclide over the complete domain of the model. The K_D values used in MEAD are given in Table 2 and were obtained from the International Atomic Energy Agency Technical Document No. 247 (IAEA 247) (IAEA, 1985). They correspond to the mean values quoted in IAEA 247, which relate to coastal sediments containing a fine grain fraction of 20%.

4.4 Consumption and Habit Data Used in ADEPT

4.4.1 Critical groups

The communities most exposed to radioactivity discharged into the Irish Sea inhabit the coastal regions of the Irish Sea. Within these communities there will be certain critical groups of the population who receive higher doses as a result of their diets and/or habits. Presented in Table 4 are the consumption and habit data for the critical group of the population within nine communities located on the coast of the Irish Sea. The data relating to the critical group at some of the locations have been separated into three time periods to reflect changes in the consumption and habit data. Additionally, the parameter values used for the years later than 1997 have been assumed to correspond to the values quoted for 1997. It is possible that the consumption and habit data may change in future years. Such changes will introduce uncertainties in the future annual doses predicted in this study.

The data for West Cumbrian seafood consumers were obtained from MAFF Aquatic Environment Monitoring reports (MAFF, 1986–1995), MAFF RIFE reports (MAFF, 1996–1998), BNFL annual reports (BNFL, 1973–1997) and a paper by Hunt (1997). The data for Morecambe Bay and Southwest Scotland were obtained from the MAFF reports alone.

The consumption of fish and shellfish by members of the critical group in West Cumbria has changed over the three periods of interest and the changes are reflected in Table 4. The consumption data for the critical group in Morecambe Bay show very little variation from year to year. Higher values are reported by MAFF for 1985 and 1986 but these appear to have been derived using a different criterion. With this in mind the figures for the period 1981–1997 are taken to be the mean values over the years 1987–1996. In the absence of data for earlier years the same mean values are used for the earlier periods.

Consumption data for the critical group in Southwest Scotland are available in MAFF reports published over the years 1993 to 1997. Once again there is little variation in the values over this period. Hence the figures for the period 1981–1997 are taken to be the mean values over the years 1992 to 1996. In the absence of data for earlier years the same mean values are used for the earlier periods.

Consumption and habit data for the critical group in Northern Ireland were obtained from the Radiological Protection Institute of Ireland report on artificial radioactivity in Carlingford Lough (Mitchell *et al.*, 1992).

The key members of the population contributing to the critical group in the Whitehaven area have changed over the period of interest. From 1951 to 1980 the critical group consisted of fishermen at the Salmon Garth in the Ravenglass estuary. From 1981 to 1990 this changed to boat dwellers in Whitehaven harbour and their occupancy time reduced from 1050 hr a^{-1} to 650 hr a^{-1} in 1986. Therefore, an average occupancy time of 850 hr a^{-1} has been assumed for the period 1981–1990. From 1991 to the present, local bait diggers form the principal component of the critical group. The consumption of fish and *Nephrops* has remained almost constant over the complete time period and this is reflected by the values presented for Whitehaven Harbour in Table 4. The consumption of fish has ranged from 40–52 kg a^{-1} (MAFF 1986–1997) and for the purposes of this study an average value of 44 kg a^{-1} has been used.

Houseboat dwellers comprise the critical group in the Ribble Estuary and the occupancy rate in Table 4 originates from the MAFF habits survey for 1996 (MAFF 1997). It has been assumed that the actual amount of time houseboat dwellers spend over sediment changes little from year to year. The best estimates of shielding factors used to calculate the effective occupancy time and/or estimates of the external dose were taken from Simmonds *et al.* (1995).

No published consumption or occupancy data exist for the Isle of Man, therefore to obtain the values in Table 4 it is assumed that coastal communities on the Isle of Man have similar consumption and habits to coastal communities in West Cumbria. Beach occupancy values for adult residents of West Cumbria have been found to be range from 12–300 hr a^{-1}, and the upper value of 300 hr a^{-1} is used for the critical group. A lower value of 30 hr a^{-1} is considered more appropriate for infants (Robinson, 1996). Inadvertent ingestion of sand occurs at a rate of 44000 mg a^{-1} for infants and 8300 mg a^{-1} for adults (Robinson, 1996). To determine the consumption of sand through inadvertent inhalation, the inhalation rates of 0.828 m^3 h^{-1} and 0.216 m^3 h^{-1} for adults and infants respectively (Robinson, 1996) have been multiplied a dust loading value of 0.1 mg m^{-3}. The value of 0.1 mg m^{-3} was recommended by the NRPB as an appropriate value for the dust loading above sandy beaches (NRPB, 1995). The results were multiplied by the beach occupancy values to yield the values given in Table 4.

The key members of the critical group for Wales have changed over the period of interest. From 1950 to 1975 *Porphyra* from the Cumbrian coast was used in South Wales to make laverbread. The percentage of the total intake of *Porphyra* from Cumbria varied, which accounts for the range given over these years in Table 4. The upper value of 9.3 kg a^{-1} is used in the calculations. Increasing rail freight costs over 1971 to 1975 led to a reduction in the amount of *Porphyra* taken from Cumbria and the practice ceased altogether in 1976. From 1976 onwards the critical group in Wales has consisted of fish and shellfish consumers, and beach users on the coast of North Wales. The consumption and habit data for the critical group in North Wales were obtained from the latest Wylfa survey (Conney Pers. Comm., 1998).

4.4.2 Typical groups

Whereas the critical group at a given location consists of individuals with the highest rate of seafood consumption or beach occupancy, a typical group contains members of the population with average seafood consumption and beach occupancy rates. Of interest to the present study is the dose incurred by typical adult, child and infant populations residing in Northwest England, North Wales, Southwest Scotland or Northern Ireland. Site-specific data do not exist for the individual locations therefore the national average is applied to all locations for the complete period from 1951 to 1997 (from Byrom *et al.* (1995) and Robinson (1996)). The parameter values used for the years after 1997 have been assumed to correspond to the values given for 1997. The consumption and habit data for typical adults, children and infants are presented in Table 5 while the coastal locations they are assumed to occupy are shown in Figure 20.

4.5 Grid Locations Relevant to the Critical/Typical Group at Each Location

MEAD produces spatially varying estimates of the annual mean activity concentrations in seawater for a given radionuclide. The variations occur from cell to cell of the underlying grid over which the model equations are solved. Seafood and fish are harvested from specific areas of the Irish Sea by members of the critical or typical group at each location. These harvesting regions can be represented by specifically chosen cells from the model grid. The regions used for the critical and/or typical group(s) at each location are presented in Figures 12–20. The seafood harvesting locations for each critical group have been inferred from habit surveys performed by MAFF (MAFF, 1990–1995). For each typical group it has been assumed that the fish are caught from areas of the Irish Sea off the coast of each typical group location and shellfish are harvested from the coast of each location, as shown in Figs. 12–20. An additional assumption applied to the typical groups is that 10% of the seafood consumed is harvested from the Irish Sea.

4.6 Sea-to-land Transfer

The dose received via the sea-to-land transfer of radioactivity through sea spray has been added to those population groups for which an external exposure pathway is likely. The sea-to-land transfer is not accounted for automatically in ADEPT and has been assessed specifically for this study.

The two contributions to the annual dose received from sea-to-land transfer are the gamma dose received through inhalation and the external dose to the skin through gamma and beta irradiation. The empirical relationships used to derive these two contributions to the annual doses are

$$\mathrm{CED_{STL}} = C_{\mathrm{A}} R_{\mathrm{B}} DF_{\mathrm{IH}} OC \times 10^{6} \qquad (16)$$

and

$$\mathrm{DOSE_{STL}} = C_{\mathrm{A}} DCF \times OC \times 3600 \times 10^{6}. \qquad (17)$$

In eqs. (16) and (17) the following quantities are introduced for the first time:

$\mathrm{CED_{STL}}$ annual Committed Effective Dose due to intakes from sea-to-land transfer in a single year (μSv a^{-1}).

$DOSE_{STL}$	annual external dose to the skin through gamma and beta irradiation (μSv a^{-1}).
C_A	activity concentration in the air (Bq m^{-3}).
R_B	breathing rate (m^3 h^{-1}).
DCF	Effective dose coefficients for air immersion which includes the effective skin dose (Sv Bq^{-1} s^{-1} m^3)

The factor of 10^6 is used to convert Sv into μSv and the factor of 3600 is used to convert hours to seconds. The effective dose coefficients for air submersion are given in Table 6 and were obtained from the Environmental Protection Agency Federal Guidance Report No. 12 (Eckerman and Ryman, 1993). The breathing rates required for eq. (16) depend on the age of the population group being considered. The values used in this study for adults, children and infants are 0.828 m^3 h^{-1}, 0.648 m^3 h^{-1} and 0.216 m^3 h^{-1} respectively (Robinson, 1996).

The air activity concentration is determined using

$$C_{\mathrm{A}} = \frac{C_{\mathrm{DEP}}}{\mathrm{s_y} v}, \tag{18}$$

in which C_{DEP} is the annual deposition on land (Bq m^{-2} a^{-1}), v is the deposition velocity (m s^{-1}) and $\mathrm{s_y}$ is the number of seconds in a year. The deposition velocity depends on the radionuclide and the distance from the mean of the high and low water marks measured in kilometres, d. For actinides v is given by

$$v = 0.327 \times 10^{-0.158d}, \tag{19}$$

while for other radionuclide it is given by

$$v = 0.0825 \times 10^{-0.155d} \tag{20}$$

(Jones Pers. Comm., 1998).

The annual deposition is defined as

$$C_{\mathrm{DEP}} = A \times 10^{-ad}(1 + B \times 10^{-bd})C, \tag{21}$$

(Howorth and Eggleton, 1988) in which A, a and b are model parameters with units of m a^{-1}, km^{-1} and km^{-1} respectively, and B is a non-dimensional parameter that is set to zero if $d > 2$. The quantity C, is the average dissolved phase activity concentration which is calculated over those cells in the underlying grid of MEAD deemed to contribute to the external exposure and is equal to that used in eq. (12) for each population group. The parameters A, a, B and b differ between radionuclides and the values used in this study are given in Table 7 (Howorth and Eggleton, 1988). For the purpose of this study d has been set equal to 1 km.

4.7 Concentration Factors and Site-specific Partition Coefficients Used in ADEPT

Concentration factors, CF, are required to calculate the flesh activity concentrations in biota from activity concentrations in seawater (see eq. (7)). They are radionuclide dependent, defined by

$$CF = \frac{\text{radionuclide activity per unit weight of biota (Bq/kg)}}{\text{radionuclide activity per unit weight of seawater (Bq/kg)}} \tag{22}$$

and assumed to be an equilibrium measure of the ratio of activity in the species of biota and the seawater. The values used in ADEPT are presented in Table 8. In the absence of location-specific information, values used are taken from IAEA 247 (IAEA 1985). Irish Sea specific values have been measured for some radionuclides and species and where possible these concentration factors have been used. Additionally, concentration factors have been obtained for crabs and lobsters sampled from the Irish Sea in the vicinity of West Cumbria for ^{99}Tc (Lyons, 1996a). These values have been used in the calculations of the dose to the critical group in West Cumbria. To ensure that the dose received from crustacea is conservative it has been assumed that 50% of the crustacea consumed are crabs and 50% are lobsters.

To calculate the external dose to the critical or typical group at each location, a site-specific K_d value is required (see eq. (12)). These differ from the K_D values used in MEAD because they are not assumed to correspond to a scenario in which 20% of the sediment is fine grained. Sediment samples have been taken from some of the locations at which a critical group has been defined and the following fine-grain fractions have been determined: Whitehaven Harbour, 32% (Lyons, 1996b), Ribble Estuary, 28% (Lambers, 1995) beaches, less that 1% (Lyons, 1996b)[1].

To derive the site-specific K_d values, a linear relationship has been assumed between the mean values, corresponding to a fine-grain fraction of 20%, and the maximum values, corresponding to a fine-grain fraction of 100%, given for coastal sediments in IAEA 247 (IAEA, 1985). The K_d values used for the beaches of the Isle of Man, Northern Ireland and Wales, which have been assumed to contain a fine-grain fraction of less than 1%, have been taken to be equal to the minimum values given for coastal sediments in IAEA 247 (IAEA, 1985). The site-specific K_d values are given in Table 9 and their derivation is given in depth in a review article by Goshawk (1998).

The site-specific K_d values for locations at which typical groups have been defined are assumed to correspond to those given for beaches in Table 9. This is because a typical beach dweller will occupy a sandy beach in preference to a muddy one.

4.8 Dose Coefficients for Ingestion and Inhalation Used in ADEPT

To convert the radionuclide activity concentrations, taken up via ingestion and inhalation, into doses, ADEPT uses the most up-to-date estimates of dose coefficients (ICRP, 1996). The values used for ingestion and inhalation are given in Table 10.

[1] The fine-grain fraction on the beaches of the Isle of Man, Northern Ireland and Wales has been assumed to correspond to that measured at a beach in Seascale and found to be less than 1%.

5. THE DOSE PREDICTIONS

The predicted annual doses are the sum of the committed effective dose and the external exposure dose, both of which include the contribution from sea-to-land transfer. The annual doses determined in the study are presented in three subsections.

In Section 5.1 the discharges assumed for those years for which discharge data are unavailable is discussed. A complete history of the marine discharges from Sellafield is not available for four of the radionuclides of interest, namely ^{60}Co, ^{125}Sb, ^{237}Np and ^{241}Am. In previous assessments it has been common practice to set the discharges for those years for which no data are available to zero (*e.g.* Gray *et al.*, 1995). However, for this project it was felt that this might lead to underestimates in the predicted activity concentrations in later years. Therefore the discharges for those years for which no data are available were set equal to that in the year for which a value was first given.

To check the effect of assuming a non-zero discharge value instead of a zero value two simulations were performed for the four radionuclides for which the complete discharge history is not available. In the first, zero discharge for the years for which data are unavailable is assumed, while in the second the discharge in those years is set equal to that in the first year for which data are available. The results from these simulations are shown in Figures 21 to 24 and discussed in Section 5.1.

In Section 5.2 the predictions of the total dose to the critical or typical group at each location, for each discharge scenario are discussed. The doses are plotted in Figures 25 to 45 as time series. The 21 figures each contain two graphs, the first of which depicts the complete time series while the second shows the series from 1990 onwards giving a more detailed view of the results from the different discharge scenarios.

In Section 5.3 the possible sources of uncertainty are discussed and it is argued that the concentration factors are by far the most sensitive parameters in the calculation of the dose.

5.1 The Assumed Discharges for Unavailable Data

A complete discharge history is not available for four of the radionuclides used in this study, namely ^{60}Co, ^{125}Sb, ^{237}Np and ^{241}Am. Discharge data are available for the first three radionuclides from 1978 onwards and for ^{241}Am from 1964 onwards (Gray *et al.*, 1995). It has been usual practice to assume that the discharges are zero for the years for which data are unavailable. However, for the present study it was felt that this assumption might be too optimistic and lead to the future dose predictions being underestimated. Therefore, for this assessment, the unknown discharge values were set equal to the discharge in 1978 for ^{60}Co, ^{125}Sb, and ^{237}Np and the discharge in 1964 for ^{241}Am.

To determine whether future dose predictions are underestimated by assuming that the unknown discharges are equal to zero, the annual doses due to the four radionuclides were calculated for the West Cumbrian critical group, using discharge Scenario Four for two different cases:

Case one: Unknown discharge values set to zero

Case two: Unknown discharge values set equal to the discharge in 1978 for ^{60}Co, ^{125}Sb, and ^{237}Np and the discharge in 1964 for ^{241}Am.

Discharge Scenario Four was chosen for the comparison since under this scenario discharges cease in 1998 whereas the other scenarios have discharges post-1998. Therefore, if there is a difference it will be more distinct for discharge Scenario Four. The dose results are presented in Figures 21 to 24 and show clearly the difference between the two cases over the years 1950 to 1978 (1964) for ^{60}Co, ^{125}Sb, and ^{237}Np (^{241}Am). The dose predictions for 1990 onwards are almost unaffected by the earlier discharge assumption. Indeed the predicted doses for ^{125}Sb, and ^{237}Np are identical from 1980 and 1987 onwards respectively. Those for ^{60}Co and ^{241}Am are within 1% and 3% respectively by 1997. Note that the step changes in Figures 21 to 24 reflect changes in the underlying habit data.

5.2 Predicted Doses

The results obtained for the total dose for the critical or typical group at each location are detailed in Figures 25 to 45. The dose to the critical group at each location is also tabulated in Tables 11 to 14. In each of the figures, the curves are superimposed until 1998 at which point they diverge as a result of the different discharge scenarios. Following 1998 the four curves appear in the same order in each figure. This is to be expected since a given discharge scenario will have the same qualitative effect on the predicted annual dose, regardless of the underlying consumption and habit data. The order the curves appear in is also expected since Scenario Two has higher discharges than Scenario One which, in turn, has higher discharges than Scenario Three which has higher discharges again than Scenario Four. In general, the curves corresponding to Scenarios One and Two tend to constant non-zero values, since the discharges remain constant from the year 2000 onwards. On the other hand the curves corresponding to Scenarios Three and Four tend to zero, reflecting the fact that discharges for these cases are zero beyond the year 2020. Although these observations say nothing about the accuracy of the predicted doses to the critical or typical group at each location, they do give confidence that the trends of the predictions are correct when related to the discharge.

5.2.1 Critical groups

The West Cumbrian (Figure 25), Whitehaven Harbour (Figure 29) and Welsh (Figure 33) critical groups have annual dose estimates that are almost an order of magnitude higher than the estimates for the other critical groups during the period from 1970 to 1980. The fact that the estimates for the West Cumbrian and Whitehaven Harbour critical groups are relatively high is not surprising since they are in the vicinity of the discharge location. The reason the estimates for the Welsh critical group are relatively high until 1975 is that, until 1975, the members of the critical group were *Porphyra* consumers and the concentration factors for *Porphyra* are generally higher than those for fish and shellfish (see Section 4 and Table 8). This is borne out by the fact that when the members of the critical group for Wales changed to fish/seafood consumers and beach users on the coast of North Wales in 1976 the dose fell sharply.

The estimates of the annual dose for the critical groups at each of Southwest Scotland (Figure 27) and Northern Ireland (Figure 28) and the critical group of adults on the Isle of Man (Figure 31) are of similar magnitude. The similarity of the dose predictions for the critical group from Southwest Scotland and the adult critical group from the Isle of Man is largely a reflection of the similar consumption levels of seafood. In addition, the similarity in the dose predictions suggests that the activity flesh concentrations in the seafood harvested from these regions are roughly similar. The fish consumption rates of the members of the critical group in Northern Ireland are higher than those by members of the critical group in Southwest Scotland and the critical group of adults on the Isle of Man. This accounts for the similarity of the predicted annual dose despite the lower activity flesh concentrations found in biota at this distance from Sellafield.

Initial predictions of the dose to members of the critical group at Morecambe Bay and the critical group associated with the Ribble Estuary were found to be lower than estimates provided by MAFF through measurements and habit surveys. On examining the MEAD residual flow field in the vicinity of Morecambe Bay in detail it was noted that the expected flow into and through the Bay was not replicated. This blocking of the flow acted to inhibit the transport of radioactivity into Morecambe Bay. The poor replication of the flow was found to be the result of insufficient resolution of the highly complex bathymetry of the inner Bay. In order to enhance the accuracy of MEAD, improvements to the detail of the residual flow field were made on the basis of an in depth study of Morecambe Bay carried out by Aldridge (1997). These improvements led to a 100% increase in the predictions of the annual dose to members of the critical group at Morecambe Bay.

Predictions of dose to these locations still, however, appear to be somewhat less than those reported by MAFF. There are a number of possible reasons for this:

It is possible that MEAD underestimates the long-term southward radionuclide transport along the coast. This is a problem that has been noted for other residual hydrodynamic models of the Eastern Irish Sea (Aldridge Pers. Comm., CEFAS, 1998). The reason that models tend to underestimate the coastal transport is not entirely clear. A predominant south-flowing residual is not apparent in simulations of coastal flow generated by high resolution, tidally resolving models under typical tidal and wind conditions. It is thought that the principal mechanism for transport of water and associated radionuclides to the south may be related to northerly winds associated with winter storm events. Such events are capable of generating significant fluxes of water and sediment in relatively short bursts. It is not possible to include the transport resulting from such events in a model such as MEAD, which simulates the transport resulting from the annually averaged residual flow pattern. Instead, the wind events must be modelled explicitly, to obtain an insight into their transport capabilities, and there is scope for further work in this area.

Additionally it should be noted that, due to the grid resolution, the Ribble estuary is not specifically replicated within the MEAD model. Dose values are calculated for the Ribble using concentrations selected from grid locations as close to the estuary mouth as is possible, however such concentrations will be representative of coastal rather than estuarine conditions. The model does not take into account the complexity of estuarine dynamics and predicted concentrations are therefore unlikely to accurately reflect the radionuclide activity concentrations measured within the Ribble itself.

Finally, the activity in the Ribble Estuary includes contributions resulting from discharges from the BNFL site at Springfields. This is an additional source of activity to that modelled in MEAD.

The annual dose estimates for the critical group consisting of infants on the Isle of Man (Figure 32) are lower than those for the critical group at the other locations (apart from the Ribble Estuary for reasons explained above). This is once again a reflection of the habit data for infants on the Isle of Man.

5.2.2 Typical groups

The dose estimates for the typical groups are shown in Figures 34 to 45. For each location the annual dose estimates are higher for adults than those for children which in turn are higher than those for infants. This is consistent with the consumption and habit data that were provided for the three different age groups.

The typical groups may be ranked in order of decreasing dose estimates. The ordering of the locations of the typical groups is thus Northwest England, Southwest Scotland, Northern Ireland and Wales. This ordering is consistent throughout the three age groups and reflects the transport of activity to the different typical group locations.

5.3 Sources of Uncertainty

An uncertainty analysis of the performance of the dispersion model on which MEAD was based has been performed (Romanowicz, 1998). It was found that the most sensitive parameters in the model are the desorption-rate and the sediment settling velocity. The same study revealed that the concentration factors that are used in ADEPT for the calculation of the activity in biota are far more sensitive than the parameters used in MEAD. Therefore a percentage change in a concentration factor will affect the final dose estimate to a greater degree than the same percentage change in the desorption-rate or the sediment settling velocity, see Figure 46 (Romanowicz, 1998).

The fact that the dose calculations are most sensitive to concentration factors is important, because there is significant uncertainty attached to the values available for the concentration factors. Where possible, Irish Sea-specific concentration factors have been used, but for the majority of the radionuclides it has been necessary to apply generic values taken from IAEA 247 (IAEA, 1985). (Comparison of the biota flesh radionuclide concentrations with measured values often show discrepancies, which are most likely due to the fact that generic concentration factors have been used. The same discrepancies are not typically observed when Irish Sea specific concentration factors are used.)

The discrepancies that result from using generic concentration factors could be reduced by calibrating ADEPT against measured biota activity concentrations. In essence, this would involve fitting the ADEPT results to measured data, and deriving a calibration factor by which the concentration factor is multiplied to yield a concentration factor equivalent. Examples of the calibration procedure are given in the Further Development section (Section 7).

6. DISCUSSION

The predicted doses may be compared with recommended ICRP dose limits, to determine whether the limits have been exceeded in the past or will be exceeded in the future. The radiation dose limit to a member of the general public from controlled operations is currently 1 mSv a^{-1}. This limit became accepted following the 1990 recommendation of the ICRP (ICRP, 1991) and the subsequent guidance of the NRPB (NRPB, 1993) but has applied as a subsidiary limit through a number of interpretations since the 1980s. Prior to the 1980s the dose limit was derived in a number of ways, however, when considered as a Committed Effective Dose, a level of 5 mSv a^{-1} is broadly applicable as far back as 1950.

The highest dose predicted in this study was approximately 2.3 mSv, received by members of the critical group in West Cumbria in 1975. All of the predicted doses to identified population groups at all of the specified locations are less than half of the pre-1980s limit of 5 mSv a^{-1}. Additionally, all of the predicted doses to population groups at all of the specified locations are less than 1 mSv a^{-1} from 1990 until 2050. The predicted doses to the critical group at West Cumbria are between 1 and 5 mSv a^{-1} for some of the years in the early 1980s. Doses of this magnitude were deemed to be acceptable during the time period in question.

It should be noted that this study only relates to marine discharges from Sellafield and that there may be contributions to the annual dose from other sources. These sources include atmospheric discharges from Sellafield, discharges from the Albright and Wilson plant at Whitehaven, Heysham and Springfields, weapons fallout and accidental releases (Chernobyl in 1986 and the Windscale fire in 1957, for example).

6.1 Comparison With Other Studies

An assessment of the radiation dose received by the Cumbrian coastal population was carried out by the National Radiological Protection Board with the results being published in 1994 (NRPB, 1994). A comparison was made between the dose predictions from the current study and the results from the NRPB study. It should be noted at the outset that there are inherent problems associated with making quantitative comparisons between different studies. This is due to the fact that the population groups, exposure pathways, habit data and future discharge scenarios may differ between the studies.

In the NRPB study, the Cumbrian coastal region was divided into six regions and exposure pathways due to atmospheric contamination, radioactivity in the seashore (marine) and radioactivity in the terrestrial environment are considered. The marine exposure pathway in the NRPB study is internal irradiation due to the ingestion of seawater. Internal irradiation due to the consumption of fish and seafood is not considered in the NRPB study.

The underlying differences between the two studies preclude a quantitative comparison. It is possible though to extract the trends of the annual doses predicted by the two studies by normalising the doses for a given year. To provide a qualitative comparison:

- The normalised dose estimates for the region containing Whitehaven Harbour (Region B) in the NRPB report are compared to the normalised dose estimates for the critical group at Whitehaven Harbour in this study.
- The average of the normalised dose estimates over the six NRPB regions are compared to the normalised dose predictions for the West Cumbrian critical group.

The actual and normalised doses resulting from liquid discharges predicted by both studies are shown Table 15. Although a quantitative comparison is not applicable it may be noted that the annual doses in the present study are larger than those quoted in the NRPB study. This could be attributed to a number of factors but the most likely reason for the order of magnitude difference is the consumption of seafood. If this is the case it highlights the importance of this exposure pathway. The lower half of Table 15 shows the predicted doses relative to values predicted for 1989 in each case. The normalised dose predictions averaged over the six NRPB regions compare well with the normalised dose predictions for the critical group in West Cumbria. In the worst case the NRPB normalised doses are 25% greater than the normalised doses from this study. The normalised doses for Region B compare well with those for the critical group at Whitehaven Harbour for all years considered except 2050 where the latter is eight times the former. These results show that the doses from the two studies decline with time in a similar manner.

A study on behalf of the Department of Environment considered the impact of Sellafield marine discharges on coastal regions through seafood, beach, intertidal and sea-spray transfer pathways (Barr and Howorth, 1994). The radionuclides considered in the assessment were ^{137}Cs, ^{238}Pu, $^{239,240}Pu$, ^{241}Pu and ^{241}Am and their impact on a critical group of the population at a number of locations including Sellafield, Authencairn, Prestatyn and Ards. The maximum calculated annual dose was 2.13 mSv to members of the critical group at Sellafield in 1974. The maximum predicted annual dose from the current study is 2.28 mSv to members of the critical group in West Cumbria in 1975. Barr and Howorth predicted the annual dose to the critical group at Sellafield to fall to 0.14 mSv by the year 2000. Beyond 1993 Barr and Howorth assumed that the discharges from Sellafield were equal to those in 1993. The present study predicts an annual dose of 0.095 mSv in the year 2000 for discharge Scenario One in which discharges beyond 1998 are assumed to be equal to those in 1998.

According to the Barr and Howorth predictions, members of the critical group in each of Southwest Scotland, Wales and Northern Ireland received maximum annual doses of 0.63 mSv, 0.41 mSv and 0.18 mSv respectively. The maximum annual dose to the critical group in each of these locations as predicted by the current study is 0.23 mSv, 2 mSv and 0.21 mSv.

The similarity of the predicted doses between the Barr and Howorth predictions and the present study is due to the similar methodology used in the two studies, something that was lacking in the comparison with the NRPB study. It should be noted that the maximum annual dose to the critical group in Wales in the current study, is larger than that predicted by Barr and Howorth due to the inclusion of *Porphyra* consumption. The comparison with the Barr and Howorth study also shows that even though the underlying habit data may have changed there has not been a great influence on results near the source of the radioactivity.

6.2 Comparison With Dose Estimates From MAFF

A comparison between the doses estimated using MARISA (i.e. MEAD and ADEPT), and those determined by MAFF from measurements and habit surveys (MAFF, 1979–1995), is made in Table 16. From 1990 onwards the comparison is made using MAFF values determined using the ICRP 60 methodology (ICRP, 1991). Prior to 1990 the MAFF values were determined using the ICRP 26 (ICRP, 1977) methodology.

The location of the population groups used differ between the two studies, but for comparison purposes the following assumptions have been made:

- The MAFF dose values corresponding to consumers in the local fishing community have been compared to the dose estimates made for the critical group in West Cumbria. For this comparison the only pathway considered in both studies is the ingestion of seafood.
- The MAFF doses for consumers associated with commercial fisheries at Whitehaven and Morecambe Bay have been compared to the dose estimates made for the critical group at Whitehaven Harbour and the critical group at Morecambe Bay respectively. For the comparison of the dose to the population groups at Whitehaven Harbour, the present study includes the dose received via external exposure in addition to the ingestion of seafood pathway, while the MAFF studies omit the external exposure pathway. The fact that like is not being compared to like should be borne in mind. For the comparison of the dose to the population groups at Morecambe Bay, it is only the dose received via ingestion of seafood that is considered in both the present study and the MAFF studies.
- Prior to 1987 the MAFF doses from the local fisheries at Whitehaven, Morecambe Bay and Fleetwood were grouped together. Since the high rate consumers were members of more than one of the sub-groups, the overall critical group was defined by summing the exposure due to the component consumption rates (MAFF, 1987). Therefore, for comparative purposes the estimated doses to the critical group at Whitehaven Harbour and the critical group at Morecambe Bay have been summed. Once again it should be noted that in the present study there is a contribution to the dose from external exposure.
- The MAFF dose values for Houseboat Dwellers in the River Ribble have been compared to the dose estimates made for the critical group in the Ribble Estuary. In both cases the pathway considered is external irradiation.

The comparison of the doses estimated using MARISA and those from the MAFF studies is shown in Table 16. The doses to the population groups in West Cumbria, Whitehaven Harbour and Morecambe Bay are of the same order of magnitude in both studies. In the worst case the predicted dose in this study differs by a factor of five from that quoted by MAFF. The dose to the critical group at West Cumbria in 1986 is five times higher in the present study while the dose to the critical group at Whitehaven Harbour in 1996 is one-fifth of that in the present study. In general though, the two sets of data agree to within a factor of two.

Comparison of the doses to the population groups around the Ribble Estuary shows that the doses predicted in the present study are about one-fortieth of those estimated by MAFF. Possible causes of the low estimates of the annual dose to the critical group at the Ribble Estuary by MARISA have already been alluded to (see Section 5.2.1) and include:

- the fact that MARISA does not model estuarine dynamics, in particular the transport of activity attached to silt deposits in the Ribble estuary,
- The fact that MARISA does not include contributions to the dose from activity discharged from the BNFL plant at Springfields.

6.3 Summary

The annual doses to the critical or typical group of the population from specified locations have been predicted for four discharge scenarios using the software application MARISA. The effect of assuming zero discharge for the years for which no discharge data are available has also been considered. Results have been compared with those from a scenario in which the discharge was considered to be constant and equal to the discharge in the first year for which data was available. In the worst case it was shown that the annual dose for 1998 onwards is 3% lower for the zero discharge case than for the constant discharge case.

The predicted annual doses to the critical and typical group at each location for the four discharge scenarios have been presented in Figures 25–45. The annual doses to the critical group at each location have also been tabulated in Tables 11–14. Stacked bar charts shown in Figures 47–50 provide an insight into the contribution to the annual dose from the individual exposure pathways and the individual radionuclides.

Figure 47 shows the annual doses to members of the critical group in West Cumbria, resulting from discharge Scenario Three, split into the contributions due to each exposure pathway. It is apparent that prior to 1971 and after 1980, the principal component of the dose is due to the consumption of molluscs. Between 1971 and 1980 (inclusive) the contribution to the annual dose due to the consumption of fish increases as a percentage of the total dose. This is a direct reflection of the change in the habit data of the members of the critical group in West Cumbria. Prior to 1971 the ratio of the amount of fish consumed to the amount of molluscs consumed was approximately 18:1. In 1971 the ratio increased to about 34:1 while in 1980 the ratio reduced to approximately 4:1.

Another reason why the proportion of the dose due to the consumption of molluscs is high relative to that due to the consumption of fish prior to 1971, is that a large amount of ^{106}Ru was discharged in this period relative to the total amount of radioactivity discharged. The concentration factor used for the uptake of activity by molluscs from ^{106}Ru is 1000 times greater than that used for fish and 200 times greater than that used for crustacea. Figure 48 shows the annual doses to members of the critical group in West Cumbria, resulting from discharge Scenario Three, split into the contributions due to each radionuclide. It is clear from Figure 48, that prior to 1971, the annual dose resulting from ^{106}Ru forms the greatest proportion of the total annual dose of any radionuclide.

In the 1970s the amount of ^{137}Cs discharged increased as a proportion of the total discharges. This is another contributory factor to the increase in the proportion of the dose received from the consumption of fish. The concentration factor used for the uptake of ^{137}Cs activity by fish is twice that used for molluscs and three times greater than that used for crustacea. Figure 48 shows that over the 1970s, the annual dose due to ^{137}Cs increases as a proportion of total dose.

The ratio of the amount of crustacea consumed to the amount of molluscs consumed almost doubles in 1971. This accounts for the increase in the dose from crustacea in proportion to the annual dose from shellfish in total seen in Figure 47. In 1980 the ratio of the amount of crustacea consumed to the amount of molluscs consumed falls to about 1:1 and the contribution to the annual dose from the consumption of crustacea also declines.

Figure 49 shows the annual doses to members of the typical group in Northwest England, resulting from discharge Scenario Three, split into the contributions due to each exposure pathway. A notable feature of Figure 49 is that the dose received via the sea-to-land transfer of activity is very small when compared to the total annual dose (i.e. sea-to-land transfer is not apparent in Figure 49). This is true of the dose received from sea-to-land transfer in general with the contribution to the total dose being at least five orders of magnitude lower than consumption pathways. Figure 49 shows similar trends to Figure 47 in that the majority of the annual dose prior to 1970 and after 1982 is received through the consumption of shellfish. In the intervening period the proportion of the annual dose due to the consumption of fish increases significantly. For the typical group in Northwest England however, this change in the relative contributions to the annual dose from fish and shell fish cannot be due to the habit data which is constant for the whole period covered by the study. Therefore, the change must result from the increased discharges of ^{137}Cs, relative to the total discharge, over the 1970s and early 1980s. The effect of the increased discharges of ^{137}Cs is mirrored in Figure 50 which shows the annual doses to members of the typical group in Northwest England, resulting from discharge Scenario Three, split into the contributions due to each radionuclide.

The annual doses predicted in this study have been shown to have similar trends to other studies that have examined the affect of Sellafield discharges on the coastal communities of the Irish Sea. Additionally, it has been demonstrated that the predicted annual doses to the critical or typical group at each specified location are lower than the applicable dose limits.

Page left blank intentionally.

7. FURTHER DEVELOPMENTS

The annual doses predicted in this study have been shown to be comparable to other studies and estimates by MAFF, for most of the population groups considered. There have, however, been some discrepancies between annual dose predictions to the population groups at Morecambe Bay and the Ribble Estuary due to the reasons outlined in Section 5.2.1. Additionally, an uncertainty analysis revealed that the most sensitive parameter in the calculation of the annual dose is the concentration factor. Moreover, of all the parameters used to determine the annual doses, the concentration factor would appear to have the greatest degree of uncertainty attached to it. In this section, further developments are suggested to address these issues.

7.1 Improvements to the Residual Flow Field

The initial low predictions of the annual dose to the critical group at Morecambe Bay were attributed to problems with the residual flow field used in MEAD. The accuracy of the dose predictions was improved by modifying the flow field, utilising data from an in-depth study of the residual flow field in Morecambe Bay (Aldridge, 1997). It is possible that low predictions of the annual dose to the critical group at the Ribble Estuary may also be partly due to inaccuracies in the residual flow field. However, an in-depth study of the residual flow field in the vicinity of the Ribble Estuary is not currently available: this aspect merits investigation. It is plausible that the intricacies of the flow field in the vicinity of other bays and estuaries included in the domain of MEAD are not captured accurately by the current residual flow field. Therefore improvements to the model could be made by an in-depth study of the flow field in the vicinity of each bay and estuary in the area covered by MEAD.

7.2 Modelling Low Frequency Events

Another possible contributory reason for the low annual dose predictions for the critical group at the Ribble Estuary is that MEAD does not model low frequency events that can lead to the transport of relatively large amounts of sediment southwards. As stated in Section 5.2.1, the principal mechanism for transport to the south are northerly winds associated with winter storm events. During such events, large fluxes of water and sediment are generated in relatively short bursts. In order to model the transport resulting from such events, the wind events would have to be modelled explicitly. This would lead to an insight into their transport capabilities, and hence there is scope for further work in this area.

7.3 The Use of Calibration Factors

The results from the uncertainty analysis, presented in Section 5.3, revealed that the most sensitive parameters applied in MARISA are the concentration factors used to convert seawater activity concentrations into activity concentrations in the flesh of biota. Where possible, Irish Sea specific concentration factors were used in the study, but for the majority of the radionuclides it was necessary to apply generic values taken from IAEA 247 (IAEA, 1985). In many cases the use of generic concentration factors leads to discrepancies between predictions of biota flesh activity concentrations and measured values. The same discrepancies are not typically observed when concentration factors specific to the Irish Sea are used (Lyons 1996a).

The discrepancies that result from using generic concentration factors can be reduced by calibrating ADEPT against measured biota activity concentrations. As an exploratory exercise, a comparison between modelled and measured data has been performed for six of the radionuclides used in this study. Data used in the comparison have been taken primarily from published annual reports from BNFL (BNFL, 1977–1995) and MAFF (MAFF, 1969–1995). Other publications that have been used are Wix *et. al* (1960), Wix *et. al* (1965), Pentreath and Lovett (1976), Smith *et. al* (1980), Hamilton and Clifton (1980), Pentreath and Harvey (1981) McDonald *et. al* (1991), Begg *et. al* (1992) and McDonald *et. al* (1993). In addition, internally published BNFL data for 1969–1979 were used (BNFL Pers. Comm.).

Under circumstances in which the predicted and measured activity concentrations in the flesh of biota do not agree, the predicted values are multiplied by a calibration factor to obtain a better fit of the predicted results to the measured data. In effect, this generates an updated measure of the concentration factor denoted here as a "concentration factor equivalent". The calibration factors and concentration factor equivalents obtained from the comparison between predicted and measured activity concentrations in the flesh of biota are presented for ^{137}Cs, ^{99}Tc, Pu(α), ^{106}Ru, ^{60}Co and ^{14}C in Tables 17 to 22, respectively.

The comparison exercise carried out for the six radionuclides suggests that to obtain an optimal prediction of the CED due to the consumption of biota, and hence the overall annual dose, requires the application of either locally derived concentration factors, or radionuclide and species-specific calibration factors, for all radionuclides of interest. Future progress in this area could be made through a full calibration of ADEPT for all radionuclides of interest.

8. REFERENCES

Aldridge, J.N. (1997) Hydrodynamic Model Predictions of Tidal Asymmetry and Observed Sediment Transport Paths in Morecambe Bay. Estuarine, Coastal and Self Science **44** 39–56

Aldridge, J.N. (1998) Personal communication, CEFAS Lowestoft.

Barr, H.M. and Howorth, J.M. (1994) The radiological impact of Sellafield on coastal communities around the Irish Sea.DOE/RW/94.005.

Begg, F.H., Cook, G.T., Baxter, M.S., Scott, E.M. and McCartney, M. (1992) Anthropogenic radiocarbon in the Eastern Irish Sea and Scottish coastal waters. Radiocarbon **34** (3) 707–716.

BNFL (1973–1997) Annual report on discharge and monitoring of the environment 1971–1996. British Nuclear Fuels plc, Risley.

Bowers, D.G., Boudjelas, S. and Harker, G.E.L. (1998) The distribution of fine suspended sediments in the surface waters of the Irish Sea and its relationship to tidal stirring. Int. J. Remote Sensing **19** (14) 2789-2805

Byrom, J., Robinson, C., Simmonds, J.R., Walters, B. and Taylor, R.R. (1995) Food consumption rates for use in generalised radiological dose assessments. J. Radiol. Prot. **15** (4) 335–341.

Conney, S.W. (1998) Personal communication, CEFAS Lowestoft.

Clarke, S. (1995) Advective/diffusive processes in the Firth of Forth. PhD Thesis, University of Wales.

Clarke, S. (1998) Programmer's Guide for MARISA v1.1. Westlakes Scientific Consulting report ED0610/09.

Dyer, K.R. (1986) Coastal and estuarine sediment dynamics. A Wiley-Interscience Publication.

Eckerman, K.F. and Ryman, J.C. (1993) External exposure to radionuclides in air, water and soil. Federal Guidance report No. 12, EPA 402-R-93-081.

EPG (1993) Environmental Protection Group Environmental Survey Instructions – Computer System Parts 1 & 2. BNFL EPG 70.

Goshawk, J.A. (1998a) A review of the partition coefficient values used in CUMBRIA 77 and DOSE 77. Westlakes Scientific Consulting report ED0610/03.

Goshawk, J.A. (1998b) Report on the improvement of CUMBRIA77: Ionic exchange with the seabed. Westlakes Scientific Consulting report ED0610/11.

Gray, J., Jones, S.R. and Smith, A.D. (1995) Discharges to the environment from the Sellafield site, 1951–1992. J. Radiol. Prot. **15** 99–131.

Gray, J. (1997) Personal communication.

Hadwin, M. (1997) Personal communication.

Hamilton, E.I. and Clifton, R.J. (1980) Concentration and distribution of the transuranium radionuclides PU-239+240, Pu-238 and Am-241 in Mytilus edulis, Fucus vesiculosus and surface sediment of Esk Estuary, Marine Ecology-Progress Series **3**.

Hetherington, J.A. (1976) The behaviour of plutonium nuclides in the Irish Sea. In: Environmental Toxicity of Aquatic Radionuclides. Models and Mechanisms Rochester Int. Conf. On Env. Toxicity. Ann Arbor Sci. Pub. 81-106.

Howorth, J.M. and Eggleton, A.E.J. (1988) Studies of environmental radioactivity in Cumbria Part 12: Modelling of the sea-to-land transfer of radionuclides and an assessment of the radiological consequencies. AERE R-11733. UKAEA Harwell.

Howorth, J.M. and Kirby, C.R. (1988) Studies of environmental radioactivity in Cumbria Part 11: Modelling the dispersion of radionuclides in the Irish Sea. AERE-R 11734. UKAEA Harwell.

Hunt, G.J. (1984) Simple models for prediction of external radiation exposure from aquatic pathways. Rad. Prot. Dosim. **8** (4) 215–224.

Hunt, G.J. (1997) Radiation doses to critical groups since the early 1950's due to discharges of liquid radioactive waste from Sellafield. Health Phys. **72** 558–567.

Hunt, G.J. and Kershaw, P.J. (1990) Remobilization of artificial radionuclides from sediment of the Irish Sea. J. Radiol. Prot., **10**. Pp 147–151.

IAEA (1985) Sediment K_ds and concentration factors for radionuclides in the marine environment. IAEA Technical Report 247. International Atomic Energy Agency, Vienna.

ICRP (1977) Recommendations of the International Commission on Radiation Protection. ICRP publication 26, Pergammon Press.

ICRP (1991) 1990 Recommendations of the International Commission on Radiation Protection. ICRP publication 60, Pergammon Press.

ICRP (1996) Age dependant doses to members of the public from intake of radionuclides: Part 5 compilation of ingestion and inhalation dose coefficients. ICRP publication 72, Pergammon Press.

Jones, S.R. (1998) Personal communication.

Lambers, B. (1995) Contribution of natural background radiation to the total gamma dose rate over sediments and salt marshes. MSc thesis, Imperial College of Science, Technology and Medicine, pp73.

Lyons, M.G. (1996a) Calibration of the CUMBRIA model for ^{99}Tc concentrations in marine organisms collected from Cumbrian coastal waters: 1996 update. Westlakes Research Institute report EA1402/01.

Lyons, M.G. (1996b) Radiological assessments of the proposed liquid discharges from BNFL Sellafield. Westlakes Research Institute report EA1406/02.

Lyons, M.G., Bradley, S.B. and Parker, T.G. (1998) Developments in the CUMBRIA model and its application to radiological assessment in the Irish Sea. Rad. Prot. Dosim., **75**, 91-97.

MAFF (1969–1995) Aquatic environment monitoring report. Radioactivity in surface and coastal waters of the British Isles. Directorate of Fisheries Research, Lowestoft.

MAFF (1996–1997) Radioactivity in food and the environment. RIFE 1–2

McDonald, P. (1995) 1995 final review of marine K_d and Concentration Factor database. Westlakes Research Institute report EA0103/01.

McDonald, P., Baxter, M.S. and Fowler, S.W. (1993) Distribution of Radionuclides in Mussels, Winkles and Prawns. Part 1. Study of Organisms, under Environmental Conditions using Conventional Radio-analytical Techniques. J. Environ. Radioactivity **3** (18) 181–202

McDonald, P., Cook, B.T. and Baxter, M.S. (1991) Investigation of natural and anthropogenic radioactivity in coastal regions of UK, *BNFL Risley (contract H5488B).*

Mitchell P.I., Vives Batlle J., Ryan T.P., McEnri C., Long S. O'Colm↔in, Cunningham J.D., Caulfield J.J., Larmour R.A. and Ledgerwood F.K. (1992) Artificial Radioactivity in Carlingford Lough. RPII, September 1992.

NRPB (1993) Occupational, Public and Medical Exposure. Documents of the NRPB **4** (2).

NRPB (1994) Assessment of the Present and Future Implications of Radioactive Contamination of the Irish Sea Coastal Region of Cumbria. NRPB-R267 (London: HMSO).

NRPB (1995) Risks of leukaemia and other cancers in Seascale from all sources of ionising radiation exposure. NRPB-R276 (London: HMSO).

NRPB (1997) PC-CREAM97 Installing and Using the PC System for Assessing the Radiological Impact of Routine Releases, NRPB-SR296 (London: HMSO).

Pentreath, J.D. and Harvey, B.R. (1981) The presence of Np-237 in the Irish Sea, Marine Ecology-Progress Series **6**.

Pentreath, R.J. and Lovett, M.B. (1976) Occurrence of plutonium and americium in plaice from the north-eastern Irish Sea, Nature **262**.

Robinson, C.A. (1996) Generalised habit data for radiological assessments. NRPB-M636. HMSO, London.

Romanowicz, R (1998) Sensitivity analysis and estimation of prediction errors of the marine dispersion CMUBRIA/DOSE model. Westlakes Scientific Consulting report EL0202/02.

Simmonds, J.R., Lawson, G.L. and Mayall, A (1995) Radiation Protection 72. Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment, Directorate-General Environment, Nuclear Safety and Civil Protection, Commission of the European Communities.

Smith, T.J., Parker, W.R., and Kirby, R. (1980) Sedimentation studies relevant to low level radioactive effluent dispersal in the Irish Sea, Part 1 Radionuclides in Marine Sediments, IOS Report No 110, NERC.

Wix, L.F.U., Fairbairn, A. and Dunster, H.J. (1960) A review of the monitoring associated with the discharge of radioactive liquid effluent to the sea at Windscale from early 1953 until the end of 1958. Harwell, AEA, AHSB(RP)R1.

Wix, L.F.U., Morley, F., Garner, R.J. and Dalton, J.C. (1965) A review of the liquid effluent discharges and marine monitoring program at Windscale Works 1959-1963. Harwell, UKAEA, AHSB(RP) R56.

9. GLOSSARY OF TERMS

ADEPT – Annual DosE Post-processing Tool
AEA – Atomic Energy Authority
BNFL – British Nuclear Fuels plc
CED – Committed Effective Dose
CEFAS – Centre for Environment Fisheries and Aquaculture Science
CUMBRIA – A model developed by the AEA at Harwell
EPG – Environmental Protection Group
FLC – Flesh activity concentration
FUNCTIONALITY – The tasks performed by a computer program.
IAEA – International Atomic Energy Agency
ICRP – International Commission on Radiological Protection
MAFF – Ministry of Agriculture Farming and Fisheries
MARISA – MARine Integrated Software Application
MEAD – Marine Environment Annual Dispersion model
MIKE21 – A model developed by the Danish Hydraulics Institute
NRPB – National Radiological Protection Board
PLOT – PLOTting tool
Pu(α) – ^{238}Pu+^{239,240}Pu
SEDMOD – SEDiment transport MODel
SPM – Suspended Particulate Material
WSC – Westlakes Scientific Consulting

Page left blank intentionally.

Table 1: Parameter values resulting from the calibration of MEAD using predicted and measured seawater activity concentrations for ^{137}Cs.

Physical Parameters	Calibrated Value
a_1	700
a_2	26
a_3	3
BC_1^*	0.95
BC_2^*	0.98
Sedimentological Parameters	
w_s	2.5×10^{-5}
L	0.4
Ionic Exchange Parameters	
α	7.7×10^{-4}
l_s	0.06
K_D (^{137}Cs)	3000

*BC_1 and BC_2 are the ratios of the seawater activity concentrations across the northern and southern open boundaries respectively.

Table 2: Partition coefficients, decay rates and mean gamma energies used in MARISA.

Nuclide	Partition Coeff. K_D	Decay rate s^{-1}	Mean γ energy MeV per disintegration
^{3}H	1×10^{0}	1.79×10^{-9}	0.00×10^{0}
^{14}C	2×10^{3}	3.83×10^{-12}	0.00×10^{0}
^{60}Co	2×10^{5}	4.17×10^{-9}	2.50×10^{0}
^{90}Sr	1×10^{3}	7.71×10^{-10}	3.16×10^{-3}
^{95}Zr	1×10^{6}	1.25×10^{-7}	1.51×10^{0}
^{95}Nb	5×10^{5}	2.29×10^{-7}	7.66×10^{-1}
^{99}Tc	1×10^{2}	1.03×10^{-13}	0.00×10^{0}
^{106}Ru	3×10^{2}	2.15×10^{-8}	2.05×10^{-1}
^{125}Sb	1×10^{3}	7.96×10^{-9}	4.31×10^{-1}
^{129}I	2×10^{1}	1.40×10^{-15}	2.46×10^{-2}
^{134}Cs	3×10^{3}	1.07×10^{-8}	1.55×10^{0}
^{137}Cs	3×10^{3}	7.32×10^{-10}	5.65×10^{-1}
^{144}Ce	2×10^{6}	2.82×10^{-8}	5.28×10^{-2}
^{237}Np	5×10^{3}	1.03×10^{-14}	2.38×10^{-1}
Pu(α)	1×10^{5}	9.15×10^{-13}	1.73×10^{-3} §
^{241}Pu	1×10^{5}	1.51×10^{-9}	2.55×10^{-6}
^{241}Am	2×10^{6}	5.08×10^{-11}	3.25×10^{-2}

§ ^{240}Pu value used (which provides a worst case scenario)

Table 3: Sellafield pipeline discharges 1950–1998 (TBq a^{-1}).

Year	^{3}H	$^{14}C^{a}$	$^{60}Co^{b}$	^{90}Sr	$^{95}Zr^{c}$	$^{95}Nb^{c}$	$^{99}Tc^{d}$	^{106}Ru	$^{125}Sb^{b}$	$^{129}I^{e}$	^{134}Cs	^{137}Cs	^{144}Ce	^{237}Np	$^{238}Pu^{f}$	$^{239,240}Pu^{f}$	$Pu(\alpha)$	^{241}Pu	^{241}Am
1950	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1951	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1952	250	0.2	1	33	68	140	8	91	29.1	0.02	1.2	46	66	0.593	0.02	0.54	0.56	2	4.5
1953	250	0.2	1	36	68	140	8	180	29.1	0.02	1.2	46	66	0.593	0.02	0.5	0.52	1	4.5
1954	250	0.2	1	19	68	140	8	270	29.1	0.02	1.2	46	66	0.593	0.02	0.6	0.62	2.3	4.5
1955	250	0.2	1	9.3	78	160	8	210	29.1	0.02	0.52	21	35	0.593	0.02	0.7	0.72	1.9	4.5
1956	250	0.2	1	71	78	160	8	1600	29.1	0.02	4.1	160	47	0.593	0.06	1.8	1.86	3.7	4.5
1957	250	0.2	1	61	88	180	8	990	29.1	0.02	3.5	138	96	0.593	0.05	1.6	1.65	3.4	4.5
1958	250	0.2	1	93	110	210	8	1600	29.1	0.02	5.7	230	220	0.593	0.06	1.9	1.96	3.9	4.5
1959	250	0.2	1	57	190	370	8	1300	29.1	0.02	2.7	73	260	0.593	0.06	2.1	2.16	4.4	4.5
1960	250	0.2	1	19	110	210	8	1500	29.1	0.02	1.4	34	33	0.593	0.08	2.7	2.78	6.2	4.5
1961	250	0.2	1	18	110	220	8	930	29.1	0.02	1.8	40	80	0.593	0.14	4.6	4.74	18	4.5
1962	250	0.2	1	38	64	130	8	850	29.1	0.02	3.9	74	89	0.593	0.20	6.6	6.8	37	4.5
1963	140	0.2	1	20	47	95	8	1200	29.1	0.02	6.1	85	52	0.593	0.25	8.1	8.35	55	4.5
1964	290	0.2	1	36	540	1100	8	910	29.1	0.02	6.1	104	120	0.593	0.22	5.5	5.72	62	4.5
1965	330	0.2	1	56	610	1200	8	750	29.1	0.02	10	110	140	0.593	0.30	6.9	7.2	81	8.1
1966	460	0.2	1	34	460	930	8	920	29.1	0.02	16	181	250	0.593	0.66	13	13.66	172	7.5
1967	590	0.2	1	52	550	1100	8	640	29.1	0.02	15	150	510	0.593	1.2	17	18.2	292	17
1968	790	0.2	1	50	800	1600	8	900	29.1	0.02	48	372	370	0.593	2.1	28	30.1	633	21
1969	870	0.2	1	110	760	1500	8	850	29.1	0.02	62	444	500	0.593	2.8	27	29.8	729	14
1970	1200	1	1	230	240	470	40	1000	29.1	0.1	220	1154	460	0.593	3.8	31	34.8	999	19
1971	1200	1	1	460	440	870	40	1400	29.1	0.1	240	1325	640	0.593	9.3	46	55.3	1783	38
1972	1200	1	1	560	610	1200	40	1100	29.1	0.1	220	1289	500	0.593	9.9	47	56.9	1902	80
1973	740	1	1	280	530	1100	40	1400	29.1	0.1	170	768	540	0.593	11	54	65	2755	109
1974	1200	1	1	390	120	240	40	1100	29.1	0.1	1000	4061	240	0.593	8.0	38	46	1708	118
1975	1400	1	1	470	110	210	40	760	29.1	0.1	1100	5231	210	0.593	8.8	35	43.8	1817	36
1976	1200	1	1	380	115	221	40	770	29.1	0.13	740	4289	150	0.593	8.8	38	46.8	1297	12
1977	910	1	1	430	92	203	40	820	29.1	0.11	600	4478	150	0.593	7.5	29	36.5	981	3.7

Year	^{3}H	^{14}C[a]	^{60}Co[b]	^{90}Sr	^{95}Zr[c]	^{95}Nb[c]	^{99}Tc[d]	^{106}Ru	^{125}Sb[b]	^{129}I[e]	^{134}Cs	^{137}Cs	^{144}Ce	^{237}Np	^{238}Pu[f]	$^{239,240}Pu$[f]	Pu(α)	^{241}Pu	^{241}Am
1978	1000	1	1	600	82	148	180	810	29.1	0.074	400	4088	100	0.593	12	46	58	1773	7.9
1979	1200	1	0.52	250	60	98	43	390	13.9	0.12	240	2562	83	0.33	12	37	49	1494	7.8
1980	1300	1	0.78	350	60	100	57	340	21.3	0.24	240	2966	37	0.67	6.9	20	26.9	728	8.2
1981	2000	1	0.74	280	130	200	5.8	530	26.1	0.19	170	2357	17	0.41	5	15	20	597	8.8
1982	1800	1	1.1	320	212	304	3.6	420	22.6	0.1	140	2000	22	0.3	4.7	16	20.7	485	6.4
1983	1800	1	1.7	204	211	385	4.4	553	17.7	0.2	89	1200	24	0.3	2.9	8.7	11.6	331	2.2
1984	1600	0.7	1.3	72	162	312	4.3	348	12.0	0.1	35	434	9	0.3	2.6	8.3	10.9	345	2.3
1985	1100	1.3	2.3	52	18	28	1.9	81	11.0	0.1	30	325	5	0.2	0.8	2.6	3.4	81	1.6
1986	2200	2.6	1.5	18	8.5	6.2	6.6	28	15.0	0.12	1.3	18	3.3	0.4	0.62	2.0	2.62	63	1.3
1987	1400	2.1	1.4	15	8.9	4.5	3.6	22	13.7	0.1	1.2	12	3.9	0.23	0.35	0.97	1.32	31.9	0.65
1988	1700	3	0.96	10	5.2	4.6	4.2	24	10.7	0.13	0.95	13	3.2	0.28	0.38	1.0	1.38	36.1	0.75
1989	2100	2	0.17	9.2	6.5	4.6	6.1	25	15.6	0.17	1.73	29	3.8	0.4	0.31	0.90	1.21	30.2	1.1
1990	1700	2	0.17	4.2	4.2	2.6	3.8	17	15.2	0.11	1.2	23	2.0	0.28	0.29	0.84	1.13	31.6	0.75
1991	1800	2.4	0.09	4.1	7.4	5	3.9	19	11.6	0.15	0.76	16	1.7	0.29	0.26	0.82	1.08	29.5	0.74
1992	1200	0.8	0.07	4.2	7.0	3.3	3.2	13	9.8	0.068	0.83	15	1.7	0.18	0.24	0.69	0.93	25.3	0.54
1993	2300	2	0.09	17	6.3	3.4	6.1	17	12.0	0.16	1.2	22	2.5	0.39	0.36	0.97	1.33	37.5	0.87
1994	1700	8.2	0.11	29	2.1	1.2	72	6.7	12.0	0.16	0.61	14	0.84	0.33	0.17	0.50	0.67	14.4	0.38
1995	2660	12.4	1.28	28	0.34	0.40	192	7.3	9.3	0.25	0.51	12	1.1	0.18	0.08	0.23	0.31	7.7	0.1
1996	3000	11	0.43	16	0.52	0.63	150	9.0	6.7	0.41	0.27	10	0.78	0.04	0.06	0.15	0.21	4.4	0.07
1997	2600	4.4	1.5	37	0.18	0.18	84	9.8	3.4	0.52	0.3	7.9	0.49	0.03	0.04	0.11	0.15	3.3	0.05
1998	2640	4.2	2.3	19	0.33	0.4	57	6.4	5.4	0.5	0.33	6.1	0.82	0.05	0.05	0.10	0.15	3.6	0.04

Sources
All data are from Gray *et al.* (1995) except:
[a]Years 1952–1983 from NRPB R276 (NRPB, 1995), years 1984–1996 from BNFL annual reports (BNFL 1985–1997)
[b]BNFL annual reports (BNFL 1973–1997)
[c]Years 1952–1975 from NRPB R276 (NRPB, 1995), years 1976–1996 from BNFL annual reports (BNFL 1977–1997)
[d]Years 1952–1977 from NRPB R276 (NRPB, 1995), years 1978–1996 from BNFL annual reports (BNFL 1979–1997)
[e]Years 1952–1976 from Gray (1997), years 1977–1996 from BNFL annual reports (BNFL 1978–1997)
[f]Years 1993–1996 from Hadwin (1997)
All 1996 and 1997 data are from the 1997 and 1998 BNFL annual reports respectively except [f] above.
All 1998 data are based on the 1998 discharges until October1998
Discharge data for earlier years are not available for all radionuclides and the discharges for those years have been assumed to be equal to the discharge in the first year for which data are available.

Table 4: Consumption and occupancy data for the critical group at each location specified.

Location	Time period	Fish (kg a^{-1})	Crustacea (kg a^{-1})	Molluscs (kg a^{-1})	*Nephrops* (kg a^{-1})	*Porphyra* (kg a^{-1})	Over sediment (hr a^{-1})	Ingestion of sand (mg a^{-1})	Inhalation of sand (mg a^{-1})
West Cumbria	1951–1970	36.5	6.0	2.0					
	1971–1980	78.7	13.1	2.3					
	1981–2050	36.1	7.7	9.4					
Morecambe Bay	1951–1970	53.2	20.4	20.6					
	1971–1980	53.2	20.4	20.6					
	1981–2050	53.2	20.4	20.6					
Southwest Scotland	1951–1970	38.4	13.4	10.7					
	1971–1980	38.4	13.4	10.7					
	1981–2050	38.4	13.4	10.7					
Northern Ireland	1951–1970	50	10	10			1000	10000	
	1971–1980	50	10	10			1000	10000	
	1981–2050	50	10	10			1000	10000	
Whitehaven Harbour	1951–1980	44			3.4		300		
	1981–1990	44			3.4		850		
	1991–2050	44			3.4		580		
Ribble Estuary	1951–2050						3000		
Isle of Man Adults	1951–2050	40#	5#	5#			300*	8300*	25
Isle of Man Infants	1951–2050	15#					30*	44000*	0.65
Wales	1951–1975					1.8–9.3			
	1976–2050	94	23	1.8			370		

Source
*from Robinson (1996)
#from Byrom *et al.* (1995)

Table 5: Consumption and occupancy data for typical members of the population in Northwest England, Wales, Southwest Scotland and Northern Ireland over the years 1951–2050.

Age group	Fish ($kg\ a^{-1}$)	Shellfish ($kg\ a^{-1}$)	Over sediment ($hr\ a^{-1}$)
Adults	$10^{\#}$	$2.5^{\#}$	30^{*}
Children	$4.75^{\#}$	$1.5^{\#}$	30^{*}
Infants	$2.5^{\#}$		30^{*}

Source
*from Robinson (1996)
#from Byrom *et al.* (1995)

Table 6: Effective dose coefficients for air submersion including the effective skin dose (Sv per Bq s m^{-3}) (i.e. The coefficients contain both gamma and beta contributions).

Nuclide	Dose Coeff.
^{3}H	3.31×10^{-19}
^{14}C	2.65×10^{-18}
^{60}Co	1.27×10^{-13}
^{90}Sr	9.95×10^{-17}
^{95}Zr	3.65×10^{-14}
^{95}Nb	3.78×10^{-14}
^{99}Tc	2.90×10^{-17}
^{106}Ru	0.00×10^{0}
^{125}Sb	2.05×10^{-14}
^{129}I	3.91×10^{-16}
^{134}Cs	7.66×10^{-14}
^{137}Cs	9.40×10^{-17}
^{144}Ce	8.82×10^{-16}
^{237}Np	1.05×10^{-15}
^{238}Pu	5.29×10^{-18}
$^{239,240}Pu$	5.14×10^{-18}§
^{241}Pu	7.37×10^{-20}
^{241}Am	8.31×10^{-16}

§ ^{240}Pu value used (which provides a worst case scenario)

Table 7: Parameter values used to calculate the air activity concentration from sea-to-land transfer (eq. (21))

	A	*a*	*B*	*b*
Plutonium	0.1030	0.025	2.95	0.616
Americium	0.0577	0.065	1.77	0.466
Others	0.0055	0.028	0.95	0.370

Table 8: Concentration factors for molluscs, fish, crustacea and *Porphyra*.

	Concentration Factors							
Nuclide	Generic Molluscs	Winkles	Mussels	Fish	Generic Crustacea	Crab	Lobster	*Porphyra*
^{3}H	1			1	1			1
^{14}C		5000[c]		3000[c]			6000[c]	10000
^{60}Co	5000			1000	5000			10000
^{90}Sr	1			2	2			5
^{95}Zr	5000			20	200			3000
^{95}Nb	1000			30	200			3000
^{99}Tc	1000	6000[b]		30	1000	140[b]	9000[b]	1000
^{106}Ru	2000			2	100			2000
^{125}Sb	200			400	400			400
^{129}I	10			10	10			1000
^{134}Cs		50[a]	20[a]	90[a]	30			50
^{137}Cs		50[a]	20[a]	90[a]	30			50
^{144}Ce	5000			50	1000			5000
^{237}Np	400			10	100			50
Pu(α)	3000[a]	2700[a]	1500[a]	0.1[a]	300[a]			2000
^{241}Pu	3000[a]	2700[a]	1500[a]	0.1[a]	300[a]			2000
^{241}Am	3000[a]			0.1[a]	500[a]			8000

Unless otherwise noted *CF* values are from IAEA 247 (IAEA 1985)
[a]Irish Sea specific values recommended by McDonald (1995)
[b]Values from Lyons (1996a) and Lyons (1998)
[c]Values calculated from environmental measurements, WSC unpublished data

Table 9: Site-specific partition coefficients.

Nuclide	Ribble Estuary	Whitehaven Harbour	Beaches
^{3}H	1.0×10^{0}	1.0×10^{0}	1.0×10^{0}
^{14}C	2.8×10^{3}	3.2×10^{3}	4.0×10^{2}
^{60}Co	2.5×10^{3}	2.5×10^{3}	2.5×10^{3}
^{90}Sr	1.4×10^{3}	1.6×10^{3}	1.0×10^{2}
^{95}Zr	1.4×10^{6}	1.6×10^{6}	2.0×10^{5}
^{95}Nb	6.5×10^{5}	7.3×10^{5}	1.0×10^{5}
^{99}Tc	1.9×10^{2}	2.4×10^{2}	1.0×10^{1}
^{106}Ru	5.7×10^{2}	7.1×10^{2}	1.0×10^{2}
^{125}Sb	1.4×10^{3}	1.6×10^{3}	2.0×10^{2}
^{129}I	2.8×10^{1}	3.2×10^{1}	5.0×10^{0}
^{134}Cs	2.3×10^{2}	2.3×10^{2}	1.0×10^{2}
^{137}Cs	2.3×10^{2}	2.3×10^{2}	1.0×10^{2}
^{144}Ce	2.8×10^{6}	3.2×10^{6}	1.0×10^{5}
^{237}Np	1.0×10^{3}	1.6×10^{3}	1.4×10^{1}
Pu(α)	1.8×10^{4}	1.8×10^{4}	1.8×10^{4}
^{241}Pu	1.8×10^{4}	1.8×10^{4}	1.8×10^{4}
^{241}Am	1.9×10^{5}	2.4×10^{5}	5.0×10^{3}

Table 10: Dose coefficients for ingestion and inhalation, to age 70 years (Sv Bq^{-1}).

	Ingestion			Inhalation		
Nuclide	Infant	Child	Adult	Infant	Child	Adult
^{3}H	4.8×10^{-11}	2.3×10^{-11}	1.8×10^{-11}	1.0×10^{-9}	3.8×10^{-10}	2.6×10^{-10}
^{14}C	1.6×10^{-9}	8.0×10^{-10}	5.8×10^{-10}	1.7×10^{-8}	7.4×10^{-9}	5.8×10^{-9}
^{60}Co	2.7×10^{-8}	1.0×10^{-8}	3.4×10^{-9}	8.6×10^{-8}	4.0×10^{-8}	3.1×10^{-8}
^{90}Sr	7.3×10^{-8}	6.0×10^{-8}	2.8×10^{-8}	1.0×10^{-7}	5.1×10^{-8}	3.6×10^{-8}
^{95}Zr	5.6×10^{-9}	1.9×10^{-9}	9.5×10^{-10}	1.6×10^{-8}	6.8×10^{-9}	4.8×10^{-9}
^{95}Nb	3.2×10^{-9}	1.0×10^{-9}	5.8×10^{-10}	5.9×10^{-9}	2.5×10^{-9}	1.8×10^{-9}
^{99}Tc	4.8×10^{-9}	1.3×10^{-9}	6.4×10^{-10}	3.7×10^{-8}	1.7×10^{-8}	1.3×10^{-8}
^{106}Ru	4.9×10^{-8}	1.5×10^{-8}	7.0×10^{-9}	2.3×10^{-7}	1.0×10^{-8}	6.6×10^{-8}
^{125}Sb	6.1×10^{-9}	2.1×10^{-9}	1.0×10^{-9}	3.8×10^{-8}	1.6×10^{-8}	1.2×10^{-8}
^{129}I	2.2×10^{-7}	1.9×10^{-7}	1.0×10^{-7}	8.6×10^{-8}	6.7×10^{-8}	3.6×10^{-8}
^{134}Cs	1.6×10^{-8}	1.4×10^{-8}	1.9×10^{-8}	6.3×10^{-8}	2.8×10^{-8}	2.0×10^{-8}
^{137}Cs	1.2×10^{-8}	1.0×10^{-8}	1.3×10^{-8}	1.0×10^{-7}	4.8×10^{-8}	3.9×10^{-8}
^{144}Ce	3.9×10^{-8}	1.0×10^{-8}	5.2×10^{-9}	1.8×10^{-7}	7.3×10^{-8}	5.3×10^{-8}
^{237}Np	2.1×10^{-7}	1.0×10^{-7}	1.0×10^{-7}	9.3×10^{-5}	5.0×10^{-5}	5.0×10^{-5}
Pu(α)	4.2×10^{-7}	2.7×10^{-7}	$^{*}2.5 \times 10^{-7}$	2.0×10^{-4}	1.2×10^{-4}	1.2×10^{-4}
^{241}Pu	5.7×10^{-9}	5.1×10^{-9}	$^{*}4.8 \times 10^{-9}$	2.9×10^{-6}	2.4×10^{-6}	2.3×10^{-6}
^{241}Am	3.7×10^{-7}	2.2×10^{-7}	$^{*}2.0 \times 10^{-7}$	1.8×10^{-4}	1.0×10^{-4}	9.6×10^{-5}

*The dose coefficients for adults that consume winkles harvested in Cumbria are 1.0×10^{-7}, 1.9×10^{-9} and 8.4×10^{-8} Sv Bq^{-1} for Pu(α), ^{241}Pu and ^{241}Am respectively.

Table 11: Dose ($\mu Sv\ a^{-1}$) to the critical groups at the specified locations resulting from discharge Scenario One.

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1951	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1952	2.127E+01	4.580E+00	4.838E+00	3.913E+00	1.201E+01	1.908E+00	5.216E+00	2.233E+00	5.919E+01
1953	3.471E+01	9.144E+00	9.287E+00	7.348E+00	1.475E+01	2.981E+00	7.624E+00	2.533E+00	1.143E+02
1954	4.782E+01	1.339E+01	1.352E+01	1.047E+01	1.692E+01	3.681E+00	9.787E+00	2.681E+00	1.695E+02
1955	3.760E+01	1.088E+01	1.100E+01	8.519E+00	1.246E+01	3.217E+00	7.310E+00	2.149E+00	1.382E+02
1956	2.447E+02	7.171E+01	7.198E+01	5.353E+01	6.135E+01	1.276E+01	4.542E+01	6.925E+00	9.389E+02
1957	1.620E+02	5.028E+01	5.054E+01	3.841E+01	4.679E+01	1.022E+01	3.280E+01	5.804E+00	5.994E+02
1958	2.570E+02	7.582E+01	7.653E+01	5.772E+01	7.265E+01	1.436E+01	5.089E+01	8.486E+00	9.533E+02
1959	2.012E+02	6.407E+01	6.419E+01	4.833E+01	4.672E+01	1.229E+01	3.739E+01	5.449E+00	7.848E+02
1960	2.244E+02	7.059E+01	7.095E+01	5.255E+01	4.466E+01	1.257E+01	3.890E+01	4.765E+00	9.014E+02
1961	1.514E+02	4.625E+01	4.717E+01	3.502E+01	3.309E+01	8.802E+00	2.662E+01	3.849E+00	5.899E+02
1962	1.507E+02	4.159E+01	4.306E+01	3.203E+01	3.641E+01	8.136E+00	2.648E+01	4.369E+00	5.621E+02
1963	2.072E+02	5.699E+01	5.876E+01	4.353E+01	4.640E+01	1.054E+01	3.552E+01	5.215E+00	7.806E+02
1964	1.724E+02	4.610E+01	4.871E+01	3.628E+01	4.351E+01	9.142E+00	3.114E+01	5.191E+00	6.239E+02
1965	1.562E+02	3.906E+01	4.252E+01	3.176E+01	4.283E+01	8.162E+00	2.874E+01	5.246E+00	5.459E+02
1966	2.023E+02	4.717E+01	5.152E+01	3.864E+01	5.809E+01	9.716E+00	3.699E+01	6.855E+00	6.843E+02
1967	1.819E+02	3.655E+01	4.162E+01	3.140E+01	5.083E+01	8.232E+00	3.079E+01	6.144E+00	5.846E+02
1968	2.854E+02	4.974E+01	5.735E+01	4.379E+01	9.523E+01	1.139E+01	5.107E+01	1.101E+01	8.512E+02
1969	3.222E+02	5.185E+01	6.196E+01	4.791E+01	1.124E+02	1.303E+01	5.883E+01	1.318E+01	9.135E+02
1970	4.817E+02	6.810E+01	8.550E+01	6.948E+01	2.421E+02	2.088E+01	1.127E+02	2.936E+01	1.124E+03
1971	9.816E+02	9.594E+01	1.168E+02	9.558E+01	2.924E+02	2.915E+01	1.410E+02	3.562E+01	1.569E+03
1972	1.007E+03	8.915E+01	1.150E+02	9.420E+01	2.883E+02	2.895E+01	1.394E+02	3.543E+01	1.593E+03
1973	1.029E+03	9.997E+01	1.302E+02	1.011E+02	2.248E+02	2.710E+01	1.231E+02	2.610E+01	2.000E+03
1974	1.981E+03	1.229E+02	1.813E+02	1.575E+02	7.936E+02	5.286E+01	3.413E+02	9.703E+01	2.012E+03
1975	2.276E+03	1.525E+02	2.175E+02	2.027E+02	9.910E+02	7.796E+01	4.265E+02	1.250E+02	1.871E+03
1976	1.973E+03	1.632E+02	2.240E+02	2.070E+02	8.193E+02	7.770E+01	3.715E+02	1.056E+02	8.407E+01
1977	1.937E+03	1.671E+02	2.325E+02	2.102E+02	8.088E+02	7.314E+01	3.722E+02	1.050E+02	8.209E+01

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1978	1.844E+03	1.697E+02	2.331E+02	2.071E+02	7.250E+02	6.727E+01	3.422E+02	9.527E+01	7.812E+01
1979	1.356E+03	1.399E+02	1.968E+02	1.703E+02	4.799E+02	4.992E+01	2.445E+02	6.345E+01	6.148E+01
1980	1.360E+03	1.336E+02	1.958E+02	1.656E+02	5.131E+02	4.380E+01	2.570E+02	6.785E+01	5.701E+01
1981	2.001E+03	1.423E+02	2.002E+02	1.658E+02	4.979E+02	4.072E+01	2.272E+02	5.663E+01	5.289E+01
1982	1.736E+03	1.359E+02	1.900E+02	1.553E+02	4.233E+02	3.480E+01	2.006E+02	4.870E+01	4.713E+01
1983	1.530E+03	1.353E+02	1.819E+02	1.444E+02	2.884E+02	2.792E+01	1.552E+02	3.312E+01	3.876E+01
1984	1.165E+03	1.167E+02	1.559E+02	1.193E+02	1.390E+02	1.729E+01	1.007E+02	1.661E+01	2.737E+01
1985	8.217E+02	9.838E+01	1.333E+02	9.974E+01	9.573E+01	1.038E+01	8.001E+01	1.228E+01	2.069E+01
1986	6.171E+02	9.111E+01	1.194E+02	8.763E+01	3.606E+01	6.558E+00	5.596E+01	5.870E+00	1.593E+01
1987	5.035E+02	8.732E+01	1.107E+02	8.063E+01	2.746E+01	4.863E+00	4.906E+01	4.685E+00	1.347E+01
1988	4.256E+02	8.515E+01	1.037E+02	7.573E+01	2.410E+01	4.572E+00	4.452E+01	4.188E+00	1.242E+01
1989	3.667E+02	8.267E+01	9.710E+01	7.130E+01	2.541E+01	4.985E+00	4.138E+01	4.246E+00	1.179E+01
1990	3.108E+02	7.896E+01	8.989E+01	6.626E+01	2.255E+01	5.197E+00	3.730E+01	3.838E+00	1.105E+01
1991	2.710E+02	7.495E+01	8.319E+01	6.136E+01	1.675E+01	5.218E+00	3.356E+01	3.332E+00	1.026E+01
1992	2.328E+02	7.021E+01	7.642E+01	5.637E+01	1.462E+01	5.219E+00	3.019E+01	2.869E+00	9.449E+00
1993	2.143E+02	6.594E+01	7.075E+01	5.218E+01	1.561E+01	5.484E+00	2.812E+01	3.004E+00	8.863E+00
1994	1.977E+02	6.151E+01	6.530E+01	4.808E+01	1.522E+01	5.530E+00	2.585E+01	3.346E+00	8.403E+00
1995	2.010E+02	5.784E+01	6.096E+01	4.472E+01	1.570E+01	5.476E+00	2.428E+01	3.716E+00	8.097E+00
1996	1.715E+02	5.335E+01	5.592E+01	4.093E+01	1.348E+01	5.396E+00	2.188E+01	3.219E+00	7.455E+00
1997	1.381E+02	4.859E+01	5.072E+01	3.700E+01	1.018E+01	5.275E+00	1.915E+01	2.312E+00	6.653E+00
1998	1.160E+02	4.418E+01	4.607E+01	3.352E+01	9.138E+00	5.285E+00	1.714E+01	2.094E+00	6.017E+00
1999	1.046E+02	4.043E+01	4.217E+01	3.058E+01	8.677E+00	5.285E+00	1.562E+01	2.000E+00	5.542E+00
2000	9.499E+01	3.698E+01	3.866E+01	2.795E+01	8.301E+00	5.270E+00	1.427E+01	1.924E+00	5.129E+00
2001	8.682E+01	3.377E+01	3.546E+01	2.555E+01	7.981E+00	5.243E+00	1.307E+01	1.856E+00	4.755E+00
2002	7.983E+01	3.081E+01	3.255E+01	2.338E+01	7.703E+00	5.207E+00	1.200E+01	1.794E+00	4.414E+00
2003	7.383E+01	2.808E+01	2.992E+01	2.141E+01	7.456E+00	5.163E+00	1.104E+01	1.737E+00	4.105E+00
2004	6.862E+01	2.560E+01	2.753E+01	1.962E+01	7.235E+00	5.110E+00	1.018E+01	1.684E+00	3.824E+00
2005	6.408E+01	2.333E+01	2.538E+01	1.801E+01	7.035E+00	5.049E+00	9.406E+00	1.637E+00	3.569E+00
2006	6.011E+01	2.126E+01	2.343E+01	1.655E+01	6.851E+00	4.981E+00	8.713E+00	1.593E+00	3.337E+00

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2007	5.663E+01	1.939E+01	2.168E+01	1.524E+01	6.684E+00	4.907E+00	8.093E+00	1.554E+00	3.127E+00
2008	5.358E+01	1.770E+01	2.009E+01	1.406E+01	6.530E+00	4.826E+00	7.534E+00	1.518E+00	2.936E+00
2009	5.087E+01	1.617E+01	1.866E+01	1.299E+01	6.388E+00	4.743E+00	7.033E+00	1.486E+00	2.762E+00
2010	4.847E+01	1.479E+01	1.737E+01	1.203E+01	6.258E+00	4.655E+00	6.583E+00	1.457E+00	2.604E+00
2011	4.634E+01	1.355E+01	1.621E+01	1.116E+01	6.138E+00	4.562E+00	6.176E+00	1.431E+00	2.460E+00
2012	4.445E+01	1.243E+01	1.516E+01	1.038E+01	6.028E+00	4.468E+00	5.811E+00	1.407E+00	2.329E+00
2013	4.275E+01	1.143E+01	1.421E+01	9.670E+00	5.927E+00	4.373E+00	5.482E+00	1.386E+00	2.210E+00
2014	4.124E+01	1.053E+01	1.336E+01	9.032E+00	5.834E+00	4.276E+00	5.185E+00	1.367E+00	2.101E+00
2015	3.988E+01	9.714E+00	1.258E+01	8.454E+00	5.748E+00	4.179E+00	4.917E+00	1.350E+00	2.001E+00
2016	3.865E+01	8.984E+00	1.188E+01	7.930E+00	5.670E+00	4.081E+00	4.674E+00	1.334E+00	1.910E+00
2017	3.755E+01	8.330E+00	1.125E+01	7.456E+00	5.597E+00	3.984E+00	4.454E+00	1.320E+00	1.826E+00
2018	3.656E+01	7.740E+00	1.067E+01	7.025E+00	5.530E+00	3.888E+00	4.255E+00	1.308E+00	1.749E+00
2019	3.567E+01	7.212E+00	1.015E+01	6.634E+00	5.468E+00	3.791E+00	4.074E+00	1.296E+00	1.678E+00
2020	3.486E+01	6.735E+00	9.675E+00	6.278E+00	5.411E+00	3.696E+00	3.909E+00	1.286E+00	1.613E+00
2021	3.413E+01	6.306E+00	9.241E+00	5.955E+00	5.358E+00	3.604E+00	3.759E+00	1.277E+00	1.552E+00
2022	3.346E+01	5.920E+00	8.847E+00	5.659E+00	5.309E+00	3.512E+00	3.623E+00	1.269E+00	1.497E+00
2023	3.286E+01	5.571E+00	8.486E+00	5.389E+00	5.264E+00	3.421E+00	3.498E+00	1.262E+00	1.445E+00
2024	3.230E+01	5.256E+00	8.157E+00	5.143E+00	5.222E+00	3.334E+00	3.384E+00	1.255E+00	1.397E+00
2025	3.180E+01	4.973E+00	7.854E+00	4.915E+00	5.183E+00	3.246E+00	3.280E+00	1.249E+00	1.352E+00
2026	3.135E+01	4.714E+00	7.578E+00	4.708E+00	5.146E+00	3.162E+00	3.184E+00	1.243E+00	1.310E+00
2027	3.093E+01	4.482E+00	7.322E+00	4.517E+00	5.113E+00	3.079E+00	3.097E+00	1.238E+00	1.271E+00
2028	3.055E+01	4.270E+00	7.085E+00	4.342E+00	5.081E+00	2.998E+00	3.016E+00	1.234E+00	1.235E+00
2029	3.020E+01	4.079E+00	6.868E+00	4.180E+00	5.052E+00	2.920E+00	2.941E+00	1.230E+00	1.201E+00
2030	2.988E+01	3.904E+00	6.666E+00	4.030E+00	5.025E+00	2.843E+00	2.873E+00	1.226E+00	1.169E+00
2031	2.958E+01	3.745E+00	6.479E+00	3.892E+00	4.999E+00	2.769E+00	2.809E+00	1.223E+00	1.139E+00
2032	2.931E+01	3.599E+00	6.304E+00	3.763E+00	4.975E+00	2.696E+00	2.750E+00	1.220E+00	1.111E+00
2033	2.906E+01	3.466E+00	6.141E+00	3.644E+00	4.953E+00	2.625E+00	2.696E+00	1.217E+00	1.084E+00
2034	2.884E+01	3.345E+00	5.989E+00	3.533E+00	4.932E+00	2.557E+00	2.645E+00	1.215E+00	1.059E+00
2035	2.862E+01	3.233E+00	5.847E+00	3.430E+00	4.912E+00	2.490E+00	2.598E+00	1.212E+00	1.036E+00

2036	2.843E+01	3.130E+00	5.714E+00	3.333E+00	4.894E+00	2.425E+00	2.554E+00	1.210E+00	1.013E+00
2037	2.825E+01	3.035E+00	5.589E+00	3.243E+00	4.876E+00	2.362E+00	2.513E+00	1.209E+00	9.917E-01
2038	2.808E+01	2.948E+00	5.469E+00	3.159E+00	4.860E+00	2.302E+00	2.475E+00	1.207E+00	9.715E-01
2039	2.793E+01	2.867E+00	5.358E+00	3.079E+00	4.845E+00	2.242E+00	2.439E+00	1.205E+00	9.523E-01
2040	2.778E+01	2.792E+00	5.252E+00	3.005E+00	4.830E+00	2.185E+00	2.406E+00	1.204E+00	9.341E-01
2041	2.765E+01	2.723E+00	5.152E+00	2.935E+00	4.817E+00	2.130E+00	2.374E+00	1.202E+00	9.167E-01
2042	2.752E+01	2.659E+00	5.056E+00	2.869E+00	4.804E+00	2.077E+00	2.344E+00	1.201E+00	9.002E-01
2043	2.741E+01	2.598E+00	4.965E+00	2.807E+00	4.792E+00	2.025E+00	2.317E+00	1.200E+00	8.843E-01
2044	2.730E+01	2.542E+00	4.879E+00	2.748E+00	4.780E+00	1.974E+00	2.290E+00	1.199E+00	8.692E-01
2045	2.720E+01	2.490E+00	4.797E+00	2.692E+00	4.769E+00	1.925E+00	2.265E+00	1.198E+00	8.549E-01
2046	2.711E+01	2.441E+00	4.717E+00	2.640E+00	4.759E+00	1.878E+00	2.242E+00	1.197E+00	8.411E-01
2047	2.702E+01	2.394E+00	4.641E+00	2.590E+00	4.749E+00	1.833E+00	2.220E+00	1.196E+00	8.279E-01
2048	2.694E+01	2.351E+00	4.569E+00	2.543E+00	4.740E+00	1.788E+00	2.199E+00	1.196E+00	8.152E-01
2049	2.686E+01	2.310E+00	4.498E+00	2.498E+00	4.731E+00	1.746E+00	2.179E+00	1.195E+00	8.031E-01
2050	2.679E+01	2.272E+00	4.432E+00	2.455E+00	4.723E+00	1.704E+00	2.160E+00	1.194E+00	7.916E-01

Table 12: Dose ($\mu Sv\ a^{-1}$) to the critical groups at the specified locations resulting from discharge Scenario Two.

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1951	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1952	2.127E+01	4.580E+00	4.838E+00	3.913E+00	1.201E+01	1.908E+00	5.216E+00	2.233E+00	5.919E+01
1953	3.471E+01	9.144E+00	9.287E+00	7.348E+00	1.475E+01	2.981E+00	7.624E+00	2.533E+00	1.143E+02
1954	4.782E+01	1.339E+01	1.352E+01	1.047E+01	1.692E+01	3.681E+00	9.787E+00	2.681E+00	1.695E+02
1955	3.760E+01	1.088E+01	1.100E+01	8.519E+00	1.246E+01	3.217E+00	7.310E+00	2.149E+00	1.382E+02
1956	2.447E+02	7.171E+01	7.198E+01	5.353E+01	6.135E+01	1.276E+01	4.542E+01	6.925E+00	9.389E+02
1957	1.620E+02	5.028E+01	5.054E+01	3.841E+01	4.679E+01	1.022E+01	3.280E+01	5.804E+00	5.994E+02
1958	2.570E+02	7.582E+01	7.653E+01	5.772E+01	7.265E+01	1.436E+01	5.089E+01	8.486E+00	9.533E+02
1959	2.012E+02	6.407E+01	6.419E+01	4.833E+01	4.672E+01	1.229E+01	3.739E+01	5.449E+00	7.848E+02
1960	2.244E+02	7.059E+01	7.095E+01	5.255E+01	4.466E+01	1.257E+01	3.890E+01	4.765E+00	9.014E+02
1961	1.514E+02	4.625E+01	4.717E+01	3.502E+01	3.309E+01	8.802E+00	2.662E+01	3.849E+00	5.899E+02
1962	1.507E+02	4.159E+01	4.306E+01	3.203E+01	3.641E+01	8.136E+00	2.648E+01	4.369E+00	5.621E+02
1963	2.072E+02	5.699E+01	5.876E+01	4.353E+01	4.640E+01	1.054E+01	3.552E+01	5.215E+00	7.806E+02
1964	1.724E+02	4.610E+01	4.871E+01	3.628E+01	4.351E+01	9.142E+00	3.114E+01	5.191E+00	6.239E+02
1965	1.562E+02	3.906E+01	4.252E+01	3.176E+01	4.283E+01	8.162E+00	2.874E+01	5.246E+00	5.459E+02
1966	2.023E+02	4.717E+01	5.152E+01	3.864E+01	5.809E+01	9.716E+00	3.699E+01	6.855E+00	6.843E+02
1967	1.819E+02	3.655E+01	4.162E+01	3.140E+01	5.083E+01	8.232E+00	3.079E+01	6.144E+00	5.846E+02
1968	2.854E+02	4.974E+01	5.735E+01	4.379E+01	9.523E+01	1.139E+01	5.107E+01	1.101E+01	8.512E+02
1969	3.222E+02	5.185E+01	6.196E+01	4.791E+01	1.124E+02	1.303E+01	5.883E+01	1.318E+01	9.135E+02
1970	4.817E+02	6.810E+01	8.550E+01	6.948E+01	2.421E+02	2.088E+01	1.127E+02	2.936E+01	1.124E+03
1971	9.816E+02	9.594E+01	1.168E+02	9.558E+01	2.924E+02	2.915E+01	1.410E+02	3.562E+01	1.569E+03
1972	1.007E+03	8.915E+01	1.150E+02	9.420E+01	2.883E+02	2.895E+01	1.394E+02	3.543E+01	1.593E+03
1973	1.029E+03	9.997E+01	1.302E+02	1.011E+02	2.248E+02	2.710E+01	1.231E+02	2.610E+01	2.000E+03
1974	1.981E+03	1.229E+02	1.813E+02	1.575E+02	7.936E+02	5.286E+01	3.413E+02	9.703E+01	2.012E+03

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1975	2.276E+03	1.525E+02	2.175E+02	2.027E+02	9.910E+02	7.796E+01	4.265E+02	1.250E+02	1.871E+03
1976	1.973E+03	1.632E+02	2.240E+02	2.070E+02	8.193E+02	7.770E+01	3.715E+02	1.056E+02	8.407E+01
1977	1.937E+03	1.671E+02	2.325E+02	2.102E+02	8.088E+02	7.314E+01	3.722E+02	1.050E+02	8.209E+01
1978	1.844E+03	1.697E+02	2.331E+02	2.071E+02	7.250E+02	6.727E+01	3.422E+02	9.527E+01	7.812E+01
1979	1.356E+03	1.399E+02	1.968E+02	1.703E+02	4.799E+02	4.992E+01	2.445E+02	6.345E+01	6.148E+01
1980	1.360E+03	1.336E+02	1.958E+02	1.656E+02	5.131E+02	4.380E+01	2.570E+02	6.785E+01	5.701E+01
1981	2.001E+03	1.423E+02	2.002E+02	1.658E+02	4.979E+02	4.072E+01	2.272E+02	5.663E+01	5.289E+01
1982	1.736E+03	1.359E+02	1.900E+02	1.553E+02	4.233E+02	3.480E+01	2.006E+02	4.870E+01	4.713E+01
1983	1.530E+03	1.353E+02	1.819E+02	1.444E+02	2.884E+02	2.792E+01	1.552E+02	3.312E+01	3.876E+01
1984	1.165E+03	1.167E+02	1.559E+02	1.193E+02	1.390E+02	1.729E+01	1.007E+02	1.661E+01	2.737E+01
1985	8.217E+02	9.838E+01	1.333E+02	9.974E+01	9.573E+01	1.038E+01	8.001E+01	1.228E+01	2.069E+01
1986	6.171E+02	9.111E+01	1.194E+02	8.763E+01	3.606E+01	6.560E+00	5.596E+01	5.870E+00	1.593E+01
1987	5.035E+02	8.732E+01	1.107E+02	8.063E+01	2.746E+01	4.861E+00	4.906E+01	4.685E+00	1.347E+01
1988	4.257E+02	8.515E+01	1.037E+02	7.573E+01	2.410E+01	4.573E+00	4.452E+01	4.188E+00	1.242E+01
1989	3.667E+02	8.267E+01	9.710E+01	7.130E+01	2.541E+01	4.988E+00	4.138E+01	4.246E+00	1.179E+01
1990	3.108E+02	7.896E+01	8.989E+01	6.626E+01	2.255E+01	5.202E+00	3.731E+01	3.838E+00	1.105E+01
1991	2.710E+02	7.495E+01	8.319E+01	6.136E+01	1.675E+01	5.215E+00	3.356E+01	3.332E+00	1.026E+01
1992	2.328E+02	7.021E+01	7.642E+01	5.637E+01	1.462E+01	5.220E+00	3.019E+01	2.869E+00	9.449E+00
1993	2.143E+02	6.594E+01	7.075E+01	5.218E+01	1.561E+01	5.480E+00	2.812E+01	3.004E+00	8.863E+00
1994	1.977E+02	6.151E+01	6.529E+01	4.809E+01	1.522E+01	5.531E+00	2.585E+01	3.346E+00	8.403E+00
1995	2.010E+02	5.784E+01	6.096E+01	4.472E+01	1.570E+01	5.473E+00	2.428E+01	3.716E+00	8.097E+00
1996	1.715E+02	5.335E+01	5.592E+01	4.093E+01	1.348E+01	5.398E+00	2.188E+01	3.219E+00	7.455E+00
1997	1.381E+02	4.859E+01	5.072E+01	3.700E+01	1.018E+01	5.271E+00	1.915E+01	2.312E+00	6.653E+00
1998	1.160E+02	4.418E+01	4.607E+01	3.352E+01	9.138E+00	5.284E+00	1.714E+01	2.094E+00	6.017E+00
1999	1.316E+02	4.357E+01	4.431E+01	3.235E+01	1.731E+01	5.708E+00	1.903E+01	3.529E+00	6.123E+00
2000	1.521E+02	4.226E+01	4.337E+01	3.194E+01	2.620E+01	6.309E+00	2.145E+01	5.184E+00	6.538E+00
2001	1.485E+02	3.948E+01	4.073E+01	3.011E+01	2.674E+01	6.501E+00	2.073E+01	5.421E+00	6.465E+00
2002	1.446E+02	3.655E+01	3.804E+01	2.813E+01	2.690E+01	6.527E+00	1.989E+01	5.531E+00	6.202E+00

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2003	1.409E+02	3.385E+01	3.557E+01	2.629E+01	2.701E+01	6.512E+00	1.910E+01	5.601E+00	5.925E+00
2004	1.373E+02	3.141E+01	3.334E+01	2.464E+01	2.711E+01	6.490E+00	1.840E+01	5.647E+00	5.670E+00
2005	1.341E+02	2.924E+01	3.136E+01	2.318E+01	2.720E+01	6.486E+00	1.776E+01	5.679E+00	5.443E+00
2006	1.311E+02	2.730E+01	2.957E+01	2.187E+01	2.728E+01	6.465E+00	1.719E+01	5.697E+00	5.239E+00
2007	1.285E+02	2.556E+01	2.797E+01	2.070E+01	2.732E+01	6.453E+00	1.667E+01	5.707E+00	5.056E+00
2008	1.260E+02	2.402E+01	2.652E+01	1.965E+01	2.735E+01	6.436E+00	1.620E+01	5.710E+00	4.891E+00
2009	1.239E+02	2.263E+01	2.522E+01	1.871E+01	2.735E+01	6.401E+00	1.578E+01	5.708E+00	4.743E+00
2010	1.219E+02	2.139E+01	2.405E+01	1.787E+01	2.733E+01	6.369E+00	1.540E+01	5.704E+00	4.607E+00
2011	1.201E+02	2.028E+01	2.300E+01	1.710E+01	2.730E+01	6.319E+00	1.505E+01	5.698E+00	4.484E+00
2012	1.185E+02	1.928E+01	2.206E+01	1.642E+01	2.726E+01	6.272E+00	1.474E+01	5.691E+00	4.372E+00
2013	1.171E+02	1.838E+01	2.120E+01	1.579E+01	2.721E+01	6.208E+00	1.445E+01	5.682E+00	4.269E+00
2014	1.158E+02	1.757E+01	2.042E+01	1.523E+01	2.716E+01	6.139E+00	1.419E+01	5.674E+00	4.175E+00
2015	1.146E+02	1.684E+01	1.973E+01	1.472E+01	2.711E+01	6.075E+00	1.395E+01	5.665E+00	4.088E+00
2016	1.135E+02	1.619E+01	1.910E+01	1.426E+01	2.706E+01	5.996E+00	1.374E+01	5.656E+00	4.009E+00
2017	1.125E+02	1.560E+01	1.853E+01	1.384E+01	2.701E+01	5.915E+00	1.355E+01	5.647E+00	3.935E+00
2018	1.117E+02	1.506E+01	1.801E+01	1.346E+01	2.696E+01	5.841E+00	1.337E+01	5.640E+00	3.867E+00
2019	1.109E+02	1.457E+01	1.753E+01	1.311E+01	2.692E+01	5.755E+00	1.321E+01	5.632E+00	3.805E+00
2020	1.101E+02	1.414E+01	1.710E+01	1.279E+01	2.687E+01	5.677E+00	1.306E+01	5.626E+00	3.746E+00
2021	1.095E+02	1.374E+01	1.671E+01	1.250E+01	2.683E+01	5.599E+00	1.293E+01	5.619E+00	3.692E+00
2022	1.089E+02	1.337E+01	1.635E+01	1.224E+01	2.679E+01	5.510E+00	1.280E+01	5.613E+00	3.642E+00
2023	1.083E+02	1.304E+01	1.602E+01	1.200E+01	2.675E+01	5.431E+00	1.269E+01	5.607E+00	3.596E+00
2024	1.078E+02	1.274E+01	1.572E+01	1.177E+01	2.671E+01	5.352E+00	1.259E+01	5.602E+00	3.552E+00
2025	1.074E+02	1.247E+01	1.545E+01	1.157E+01	2.668E+01	5.273E+00	1.250E+01	5.598E+00	3.512E+00
2026	1.070E+02	1.222E+01	1.520E+01	1.138E+01	2.665E+01	5.194E+00	1.241E+01	5.594E+00	3.474E+00
2027	1.066E+02	1.199E+01	1.496E+01	1.121E+01	2.662E+01	5.118E+00	1.233E+01	5.589E+00	3.438E+00
2028	1.062E+02	1.178E+01	1.474E+01	1.105E+01	2.659E+01	5.042E+00	1.225E+01	5.586E+00	3.405E+00
2029	1.059E+02	1.158E+01	1.454E+01	1.090E+01	2.656E+01	4.969E+00	1.219E+01	5.582E+00	3.373E+00
2030	1.056E+02	1.141E+01	1.437E+01	1.076E+01	2.654E+01	4.896E+00	1.212E+01	5.579E+00	3.344E+00

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2031	1.053E+02	1.124E+01	1.419E+01	1.063E+01	2.652E+01	4.826E+00	1.206E+01	5.576E+00	3.316E+00
2032	1.051E+02	1.109E+01	1.403E+01	1.052E+01	2.649E+01	4.757E+00	1.201E+01	5.574E+00	3.290E+00
2033	1.049E+02	1.095E+01	1.388E+01	1.041E+01	2.647E+01	4.691E+00	1.196E+01	5.572E+00	3.265E+00
2034	1.046E+02	1.082E+01	1.374E+01	1.030E+01	2.645E+01	4.627E+00	1.191E+01	5.569E+00	3.242E+00
2035	1.044E+02	1.070E+01	1.361E+01	1.021E+01	2.644E+01	4.563E+00	1.187E+01	5.567E+00	3.220E+00
2036	1.043E+02	1.059E+01	1.348E+01	1.012E+01	2.642E+01	4.502E+00	1.183E+01	5.565E+00	3.198E+00
2037	1.041E+02	1.048E+01	1.337E+01	1.003E+01	2.640E+01	4.442E+00	1.179E+01	5.563E+00	3.178E+00
2038	1.039E+02	1.038E+01	1.326E+01	9.955E+00	2.639E+01	4.384E+00	1.175E+01	5.562E+00	3.160E+00
2039	1.038E+02	1.030E+01	1.316E+01	9.882E+00	2.637E+01	4.328E+00	1.172E+01	5.560E+00	3.142E+00
2040	1.037E+02	1.021E+01	1.305E+01	9.813E+00	2.636E+01	4.274E+00	1.169E+01	5.559E+00	3.124E+00
2041	1.035E+02	1.013E+01	1.296E+01	9.748E+00	2.635E+01	4.221E+00	1.166E+01	5.558E+00	3.108E+00
2042	1.034E+02	1.005E+01	1.288E+01	9.685E+00	2.633E+01	4.170E+00	1.163E+01	5.557E+00	3.092E+00
2043	1.033E+02	9.984E+00	1.279E+01	9.628E+00	2.632E+01	4.120E+00	1.161E+01	5.556E+00	3.078E+00
2044	1.032E+02	9.918E+00	1.271E+01	9.573E+00	2.631E+01	4.072E+00	1.158E+01	5.555E+00	3.063E+00
2045	1.031E+02	9.858E+00	1.263E+01	9.520E+00	2.630E+01	4.026E+00	1.156E+01	5.554E+00	3.050E+00
2046	1.030E+02	9.797E+00	1.255E+01	9.471E+00	2.629E+01	3.981E+00	1.154E+01	5.553E+00	3.037E+00
2047	1.029E+02	9.744E+00	1.248E+01	9.423E+00	2.628E+01	3.937E+00	1.152E+01	5.552E+00	3.024E+00
2048	1.029E+02	9.688E+00	1.242E+01	9.379E+00	2.627E+01	3.895E+00	1.150E+01	5.552E+00	3.012E+00
2049	1.028E+02	9.639E+00	1.235E+01	9.337E+00	2.627E+01	3.854E+00	1.148E+01	5.551E+00	3.001E+00
2050	1.027E+02	9.592E+00	1.230E+01	9.297E+00	2.626E+01	3.815E+00	1.146E+01	5.550E+00	2.990E+00

Table 13: Dose ($\mu Sv\ a^{-1}$) to the critical groups at the specified locations resulting from discharge Scenario Three.

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1951	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1952	2.127E+01	4.580E+00	4.838E+00	3.913E+00	1.201E+01	1.908E+00	5.216E+00	2.233E+00	5.919E+01
1953	3.471E+01	9.144E+00	9.287E+00	7.348E+00	1.475E+01	2.981E+00	7.624E+00	2.533E+00	1.143E+02
1954	4.782E+01	1.339E+01	1.352E+01	1.047E+01	1.692E+01	3.681E+00	9.787E+00	2.681E+00	1.695E+02
1955	3.760E+01	1.088E+01	1.100E+01	8.519E+00	1.246E+01	3.217E+00	7.310E+00	2.149E+00	1.382E+02
1956	2.447E+02	7.171E+01	7.198E+01	5.353E+01	6.135E+01	1.276E+01	4.542E+01	6.925E+00	9.389E+02
1957	1.620E+02	5.028E+01	5.054E+01	3.841E+01	4.679E+01	1.022E+01	3.280E+01	5.804E+00	5.994E+02
1958	2.570E+02	7.582E+01	7.653E+01	5.772E+01	7.265E+01	1.436E+01	5.089E+01	8.486E+00	9.533E+02
1959	2.012E+02	6.407E+01	6.419E+01	4.833E+01	4.672E+01	1.229E+01	3.739E+01	5.449E+00	7.848E+02
1960	2.244E+02	7.059E+01	7.095E+01	5.255E+01	4.466E+01	1.257E+01	3.890E+01	4.765E+00	9.014E+02
1961	1.514E+02	4.625E+01	4.717E+01	3.502E+01	3.309E+01	8.802E+00	2.662E+01	3.849E+00	5.899E+02
1962	1.507E+02	4.159E+01	4.306E+01	3.203E+01	3.641E+01	8.136E+00	2.648E+01	4.369E+00	5.621E+02
1963	2.072E+02	5.699E+01	5.876E+01	4.353E+01	4.640E+01	1.054E+01	3.552E+01	5.215E+00	7.806E+02
1964	1.724E+02	4.610E+01	4.871E+01	3.628E+01	4.351E+01	9.142E+00	3.114E+01	5.191E+00	6.239E+02
1965	1.562E+02	3.906E+01	4.252E+01	3.176E+01	4.283E+01	8.162E+00	2.874E+01	5.246E+00	5.459E+02
1966	2.023E+02	4.717E+01	5.152E+01	3.864E+01	5.809E+01	9.716E+00	3.699E+01	6.855E+00	6.843E+02
1967	1.819E+02	3.655E+01	4.162E+01	3.140E+01	5.083E+01	8.232E+00	3.079E+01	6.144E+00	5.846E+02
1968	2.854E+02	4.974E+01	5.735E+01	4.379E+01	9.523E+01	1.139E+01	5.107E+01	1.101E+01	8.512E+02
1969	3.222E+02	5.185E+01	6.196E+01	4.791E+01	1.124E+02	1.303E+01	5.883E+01	1.318E+01	9.135E+02
1970	4.817E+02	6.810E+01	8.550E+01	6.948E+01	2.421E+02	2.088E+01	1.127E+02	2.936E+01	1.124E+03
1971	9.816E+02	9.594E+01	1.168E+02	9.558E+01	2.924E+02	2.915E+01	1.410E+02	3.562E+01	1.569E+03
1972	1.007E+03	8.915E+01	1.150E+02	9.420E+01	2.883E+02	2.895E+01	1.394E+02	3.543E+01	1.593E+03
1973	1.029E+03	9.997E+01	1.302E+02	1.011E+02	2.248E+02	2.710E+01	1.231E+02	2.610E+01	2.000E+03
1974	1.981E+03	1.229E+02	1.813E+02	1.575E+02	7.936E+02	5.286E+01	3.413E+02	9.703E+01	2.012E+03

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1975	2.276E+03	1.525E+02	2.175E+02	2.027E+02	9.910E+02	7.796E+01	4.265E+02	1.250E+02	1.871E+03
1976	1.973E+03	1.632E+02	2.240E+02	2.070E+02	8.193E+02	7.770E+01	3.715E+02	1.056E+02	8.407E+01
1977	1.937E+03	1.671E+02	2.325E+02	2.102E+02	8.088E+02	7.314E+01	3.722E+02	1.050E+02	8.209E+01
1978	1.844E+03	1.697E+02	2.331E+02	2.071E+02	7.250E+02	6.727E+01	3.422E+02	9.527E+01	7.812E+01
1979	1.356E+03	1.399E+02	1.968E+02	1.703E+02	4.799E+02	4.992E+01	2.445E+02	6.345E+01	6.148E+01
1980	1.360E+03	1.336E+02	1.958E+02	1.656E+02	5.131E+02	4.380E+01	2.570E+02	6.785E+01	5.701E+01
1981	2.001E+03	1.423E+02	2.002E+02	1.658E+02	4.979E+02	4.072E+01	2.272E+02	5.663E+01	5.289E+01
1982	1.736E+03	1.359E+02	1.900E+02	1.553E+02	4.233E+02	3.480E+01	2.006E+02	4.870E+01	4.713E+01
1983	1.530E+03	1.353E+02	1.819E+02	1.444E+02	2.884E+02	2.792E+01	1.552E+02	3.312E+01	3.876E+01
1984	1.165E+03	1.167E+02	1.559E+02	1.193E+02	1.390E+02	1.729E+01	1.007E+02	1.661E+01	2.737E+01
1985	8.217E+02	9.838E+01	1.333E+02	9.974E+01	9.573E+01	1.038E+01	8.001E+01	1.228E+01	2.069E+01
1986	6.171E+02	9.111E+01	1.194E+02	8.763E+01	3.606E+01	6.558E+00	5.596E+01	5.870E+00	1.593E+01
1987	5.035E+02	8.732E+01	1.107E+02	8.063E+01	2.746E+01	4.863E+00	4.906E+01	4.685E+00	1.347E+01
1988	4.256E+02	8.515E+01	1.037E+02	7.573E+01	2.410E+01	4.572E+00	4.452E+01	4.188E+00	1.242E+01
1989	3.667E+02	8.267E+01	9.710E+01	7.130E+01	2.541E+01	4.985E+00	4.138E+01	4.246E+00	1.179E+01
1990	3.108E+02	7.896E+01	8.989E+01	6.626E+01	2.255E+01	5.197E+00	3.730E+01	3.838E+00	1.105E+01
1991	2.710E+02	7.495E+01	8.319E+01	6.136E+01	1.675E+01	5.218E+00	3.356E+01	3.332E+00	1.026E+01
1992	2.328E+02	7.021E+01	7.642E+01	5.637E+01	1.462E+01	5.219E+00	3.019E+01	2.869E+00	9.449E+00
1993	2.143E+02	6.594E+01	7.075E+01	5.218E+01	1.561E+01	5.484E+00	2.812E+01	3.004E+00	8.863E+00
1994	1.977E+02	6.151E+01	6.530E+01	4.808E+01	1.522E+01	5.530E+00	2.585E+01	3.346E+00	8.403E+00
1995	2.010E+02	5.784E+01	6.096E+01	4.472E+01	1.570E+01	5.476E+00	2.428E+01	3.716E+00	8.097E+00
1996	1.715E+02	5.335E+01	5.592E+01	4.093E+01	1.348E+01	5.396E+00	2.188E+01	3.219E+00	7.455E+00
1997	1.381E+02	4.859E+01	5.072E+01	3.700E+01	1.018E+01	5.275E+00	1.915E+01	2.312E+00	6.653E+00
1998	1.160E+02	4.418E+01	4.607E+01	3.352E+01	9.138E+00	5.285E+00	1.714E+01	2.094E+00	6.017E+00
1999	1.037E+02	4.165E+01	4.213E+01	3.055E+01	8.509E+00	5.272E+00	1.556E+01	1.959E+00	5.529E+00
2000	9.305E+01	3.794E+01	3.857E+01	2.788E+01	7.955E+00	5.241E+00	1.416E+01	1.838E+00	5.099E+00
2001	8.386E+01	3.455E+01	3.532E+01	2.544E+01	7.453E+00	5.197E+00	1.290E+01	1.723E+00	4.707E+00
2002	7.583E+01	3.145E+01	3.236E+01	2.321E+01	6.989E+00	5.145E+00	1.176E+01	1.612E+00	4.348E+00

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2003	6.874E+01	2.863E+01	2.967E+01	2.120E+01	6.554E+00	5.083E+00	1.073E+01	1.506E+00	4.021E+00
2004	6.244E+01	2.606E+01	2.723E+01	1.937E+01	6.140E+00	5.013E+00	9.802E+00	1.403E+00	3.722E+00
2005	5.680E+01	2.373E+01	2.501E+01	1.771E+01	5.745E+00	4.934E+00	8.960E+00	1.304E+00	3.447E+00
2006	5.174E+01	2.163E+01	2.301E+01	1.621E+01	5.365E+00	4.848E+00	8.198E+00	1.209E+00	3.196E+00
2007	4.715E+01	1.972E+01	2.119E+01	1.485E+01	4.999E+00	4.754E+00	7.505E+00	1.118E+00	2.966E+00
2008	4.296E+01	1.800E+01	1.954E+01	1.361E+01	4.644E+00	4.654E+00	6.875E+00	1.030E+00	2.756E+00
2009	3.913E+01	1.643E+01	1.805E+01	1.249E+01	4.302E+00	4.550E+00	6.302E+00	9.454E-01	2.562E+00
2010	3.560E+01	1.502E+01	1.670E+01	1.148E+01	3.969E+00	4.441E+00	5.777E+00	8.636E-01	2.384E+00
2011	3.232E+01	1.374E+01	1.547E+01	1.055E+01	3.645E+00	4.327E+00	5.297E+00	7.845E-01	2.220E+00
2012	2.930E+01	1.259E+01	1.435E+01	9.714E+00	3.332E+00	4.212E+00	4.859E+00	7.079E-01	2.068E+00
2013	2.648E+01	1.154E+01	1.333E+01	8.951E+00	3.028E+00	4.096E+00	4.455E+00	6.339E-01	1.928E+00
2014	2.382E+01	1.058E+01	1.241E+01	8.253E+00	2.730E+00	3.976E+00	4.083E+00	5.613E-01	1.798E+00
2015	2.131E+01	9.721E+00	1.157E+01	7.617E+00	2.439E+00	3.857E+00	3.739E+00	4.906E-01	1.678E+00
2016	1.895E+01	8.931E+00	1.079E+01	7.034E+00	2.155E+00	3.736E+00	3.420E+00	4.218E-01	1.565E+00
2017	1.671E+01	8.216E+00	1.009E+01	6.501E+00	1.877E+00	3.617E+00	3.124E+00	3.545E-01	1.460E+00
2018	1.458E+01	7.560E+00	9.441E+00	6.011E+00	1.605E+00	3.496E+00	2.849E+00	2.885E-01	1.362E+00
2019	1.253E+01	6.961E+00	8.846E+00	5.559E+00	1.337E+00	3.378E+00	2.592E+00	2.237E-01	1.270E+00
2020	1.058E+01	6.410E+00	8.298E+00	5.142E+00	1.074E+00	3.260E+00	2.350E+00	1.600E-01	1.183E+00
2021	9.627E+00	5.944E+00	7.835E+00	4.791E+00	9.841E-01	3.156E+00	2.179E+00	1.385E-01	1.114E+00
2022	8.806E+00	5.524E+00	7.417E+00	4.475E+00	9.074E-01	3.057E+00	2.027E+00	1.218E-01	1.054E+00
2023	8.081E+00	5.141E+00	7.033E+00	4.185E+00	8.382E-01	2.960E+00	1.888E+00	1.077E-01	9.986E-01
2024	7.434E+00	4.791E+00	6.683E+00	3.920E+00	7.757E-01	2.866E+00	1.762E+00	9.575E-02	9.470E-01
2025	6.857E+00	4.472E+00	6.361E+00	3.676E+00	7.195E-01	2.773E+00	1.647E+00	8.550E-02	8.989E-01
2026	6.337E+00	4.178E+00	6.065E+00	3.451E+00	6.690E-01	2.682E+00	1.541E+00	7.667E-02	8.543E-01
2027	5.869E+00	3.910E+00	5.792E+00	3.245E+00	6.237E-01	2.594E+00	1.445E+00	6.904E-02	8.126E-01
2028	5.443E+00	3.664E+00	5.542E+00	3.057E+00	5.830E-01	2.508E+00	1.357E+00	6.239E-02	7.737E-01
2029	5.058E+00	3.437E+00	5.309E+00	2.882E+00	5.461E-01	2.425E+00	1.276E+00	5.659E-02	7.373E-01
2030	4.708E+00	3.229E+00	5.096E+00	2.721E+00	5.129E-01	2.345E+00	1.202E+00	5.150E-02	7.032E-01

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2031	4.387E+00	3.039E+00	4.895E+00	2.572E+00	4.826E-01	2.267E+00	1.133E+00	4.702E-02	6.714E-01
2032	4.096E+00	2.863E+00	4.712E+00	2.434E+00	4.549E-01	2.191E+00	1.070E+00	4.305E-02	6.414E-01
2033	3.827E+00	2.700E+00	4.539E+00	2.308E+00	4.294E-01	2.118E+00	1.012E+00	3.953E-02	6.133E-01
2034	3.582E+00	2.550E+00	4.378E+00	2.190E+00	4.061E-01	2.047E+00	9.582E-01	3.639E-02	5.869E-01
2035	3.357E+00	2.411E+00	4.229E+00	2.080E+00	3.844E-01	1.978E+00	9.080E-01	3.358E-02	5.619E-01
2036	3.149E+00	2.282E+00	4.088E+00	1.977E+00	3.644E-01	1.912E+00	8.616E-01	3.106E-02	5.384E-01
2037	2.957E+00	2.162E+00	3.957E+00	1.882E+00	3.457E-01	1.848E+00	8.183E-01	2.880E-02	5.162E-01
2038	2.782E+00	2.052E+00	3.833E+00	1.793E+00	3.284E-01	1.786E+00	7.781E-01	2.676E-02	4.951E-01
2039	2.619E+00	1.948E+00	3.715E+00	1.709E+00	3.120E-01	1.726E+00	7.402E-01	2.492E-02	4.752E-01
2040	2.467E+00	1.852E+00	3.605E+00	1.631E+00	2.968E-01	1.668E+00	7.051E-01	2.324E-02	4.563E-01
2041	2.328E+00	1.762E+00	3.499E+00	1.558E+00	2.825E-01	1.611E+00	6.722E-01	2.172E-02	4.382E-01
2042	2.197E+00	1.678E+00	3.402E+00	1.489E+00	2.690E-01	1.556E+00	6.413E-01	2.034E-02	4.212E-01
2043	2.077E+00	1.599E+00	3.306E+00	1.424E+00	2.565E-01	1.504E+00	6.122E-01	1.907E-02	4.049E-01
2044	1.964E+00	1.525E+00	3.216E+00	1.363E+00	2.445E-01	1.452E+00	5.848E-01	1.792E-02	3.893E-01
2045	1.859E+00	1.455E+00	3.132E+00	1.305E+00	2.333E-01	1.403E+00	5.591E-01	1.686E-02	3.745E-01
2046	1.762E+00	1.390E+00	3.050E+00	1.251E+00	2.228E-01	1.355E+00	5.348E-01	1.588E-02	3.604E-01
2047	1.670E+00	1.328E+00	2.970E+00	1.199E+00	2.127E-01	1.309E+00	5.119E-01	1.498E-02	3.469E-01
2048	1.585E+00	1.270E+00	2.896E+00	1.150E+00	2.033E-01	1.264E+00	4.902E-01	1.416E-02	3.339E-01
2049	1.505E+00	1.215E+00	2.823E+00	1.104E+00	1.944E-01	1.221E+00	4.698E-01	1.339E-02	3.215E-01
2050	1.431E+00	1.163E+00	2.755E+00	1.060E+00	1.859E-01	1.179E+00	4.503E-01	1.268E-02	3.096E-01

Table 14: Dose (μSv a^{-1}) to the critical groups at the specified locations resulting from discharge Scenario Four.

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1951	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1952	2.127E+01	4.580E+00	4.838E+00	3.913E+00	1.201E+01	1.908E+00	5.216E+00	2.233E+00	5.919E+01
1953	3.471E+01	9.144E+00	9.287E+00	7.348E+00	1.475E+01	2.981E+00	7.624E+00	2.533E+00	1.143E+02
1954	4.782E+01	1.339E+01	1.352E+01	1.047E+01	1.692E+01	3.681E+00	9.787E+00	2.681E+00	1.695E+02
1955	3.760E+01	1.088E+01	1.100E+01	8.519E+00	1.246E+01	3.217E+00	7.310E+00	2.149E+00	1.382E+02
1956	2.447E+02	7.171E+01	7.198E+01	5.353E+01	6.135E+01	1.276E+01	4.542E+01	6.925E+00	9.389E+02
1957	1.620E+02	5.028E+01	5.054E+01	3.841E+01	4.679E+01	1.022E+01	3.280E+01	5.804E+00	5.994E+02
1958	2.570E+02	7.582E+01	7.653E+01	5.772E+01	7.265E+01	1.436E+01	5.089E+01	8.486E+00	9.533E+02
1959	2.012E+02	6.407E+01	6.419E+01	4.833E+01	4.672E+01	1.229E+01	3.739E+01	5.449E+00	7.848E+02
1960	2.244E+02	7.059E+01	7.095E+01	5.255E+01	4.466E+01	1.257E+01	3.890E+01	4.765E+00	9.014E+02
1961	1.514E+02	4.625E+01	4.717E+01	3.502E+01	3.309E+01	8.802E+00	2.662E+01	3.849E+00	5.899E+02
1962	1.507E+02	4.159E+01	4.306E+01	3.203E+01	3.641E+01	8.136E+00	2.648E+01	4.369E+00	5.621E+02
1963	2.072E+02	5.699E+01	5.876E+01	4.353E+01	4.640E+01	1.054E+01	3.552E+01	5.215E+00	7.806E+02
1964	1.724E+02	4.610E+01	4.871E+01	3.628E+01	4.351E+01	9.142E+00	3.114E+01	5.191E+00	6.239E+02
1965	1.562E+02	3.906E+01	4.252E+01	3.176E+01	4.283E+01	8.162E+00	2.874E+01	5.246E+00	5.459E+02
1966	2.023E+02	4.717E+01	5.152E+01	3.864E+01	5.809E+01	9.716E+00	3.699E+01	6.855E+00	6.843E+02
1967	1.819E+02	3.655E+01	4.162E+01	3.140E+01	5.083E+01	8.232E+00	3.079E+01	6.144E+00	5.846E+02
1968	2.854E+02	4.974E+01	5.735E+01	4.379E+01	9.523E+01	1.139E+01	5.107E+01	1.101E+01	8.512E+02
1969	3.222E+02	5.185E+01	6.196E+01	4.791E+01	1.124E+02	1.303E+01	5.883E+01	1.318E+01	9.135E+02
1970	4.817E+02	6.810E+01	8.550E+01	6.948E+01	2.421E+02	2.088E+01	1.127E+02	2.936E+01	1.124E+03
1971	9.816E+02	9.594E+01	1.168E+02	9.558E+01	2.924E+02	2.915E+01	1.410E+02	3.562E+01	1.569E+03
1972	1.007E+03	8.915E+01	1.150E+02	9.420E+01	2.883E+02	2.895E+01	1.394E+02	3.543E+01	1.593E+03
1973	1.029E+03	9.997E+01	1.302E+02	1.011E+02	2.248E+02	2.710E+01	1.231E+02	2.610E+01	2.000E+03
1974	1.981E+03	1.229E+02	1.813E+02	1.575E+02	7.936E+02	5.286E+01	3.413E+02	9.703E+01	2.012E+03
1975	2.276E+03	1.525E+02	2.175E+02	2.027E+02	9.910E+02	7.796E+01	4.265E+02	1.250E+02	1.871E+03
1976	1.973E+03	1.632E+02	2.240E+02	2.070E+02	8.193E+02	7.770E+01	3.715E+02	1.056E+02	8.407E+01

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
1977	1.937E+03	1.671E+02	2.325E+02	2.102E+02	8.088E+02	7.314E+01	3.722E+02	1.050E+02	8.209E+01
1978	1.844E+03	1.697E+02	2.331E+02	2.071E+02	7.250E+02	6.727E+01	3.422E+02	9.527E+01	7.812E+01
1979	1.356E+03	1.399E+02	1.968E+02	1.703E+02	4.799E+02	4.992E+01	2.445E+02	6.345E+01	6.148E+01
1980	1.360E+03	1.336E+02	1.958E+02	1.656E+02	5.131E+02	4.380E+01	2.570E+02	6.785E+01	5.701E+01
1981	2.001E+03	1.423E+02	2.002E+02	1.658E+02	4.979E+02	4.072E+01	2.272E+02	5.663E+01	5.289E+01
1982	1.736E+03	1.359E+02	1.900E+02	1.553E+02	4.233E+02	3.480E+01	2.006E+02	4.870E+01	4.713E+01
1983	1.530E+03	1.353E+02	1.819E+02	1.444E+02	2.884E+02	2.792E+01	1.552E+02	3.312E+01	3.876E+01
1984	1.165E+03	1.167E+02	1.559E+02	1.193E+02	1.390E+02	1.729E+01	1.007E+02	1.661E+01	2.737E+01
1985	8.217E+02	9.838E+01	1.333E+02	9.974E+01	9.573E+01	1.038E+01	8.001E+01	1.228E+01	2.069E+01
1986	6.171E+02	9.111E+01	1.194E+02	8.763E+01	3.606E+01	6.558E+00	5.596E+01	5.870E+00	1.593E+01
1987	5.035E+02	8.732E+01	1.107E+02	8.063E+01	2.746E+01	4.863E+00	4.906E+01	4.685E+00	1.347E+01
1988	4.256E+02	8.515E+01	1.037E+02	7.573E+01	2.410E+01	4.572E+00	4.452E+01	4.188E+00	1.242E+01
1989	3.667E+02	8.267E+01	9.710E+01	7.130E+01	2.541E+01	4.985E+00	4.138E+01	4.246E+00	1.179E+01
1990	3.108E+02	7.896E+01	8.989E+01	6.626E+01	2.255E+01	5.197E+00	3.730E+01	3.838E+00	1.105E+01
1991	2.710E+02	7.495E+01	8.319E+01	6.136E+01	1.675E+01	5.218E+00	3.356E+01	3.332E+00	1.026E+01
1992	2.328E+02	7.021E+01	7.642E+01	5.637E+01	1.462E+01	5.219E+00	3.019E+01	2.869E+00	9.449E+00
1993	2.143E+02	6.594E+01	7.075E+01	5.218E+01	1.561E+01	5.484E+00	2.812E+01	3.004E+00	8.863E+00
1994	1.977E+02	6.151E+01	6.530E+01	4.808E+01	1.522E+01	5.530E+00	2.585E+01	3.346E+00	8.403E+00
1995	2.010E+02	5.784E+01	6.096E+01	4.472E+01	1.570E+01	5.476E+00	2.428E+01	3.716E+00	8.097E+00
1996	1.715E+02	5.335E+01	5.592E+01	4.093E+01	1.348E+01	5.396E+00	2.188E+01	3.219E+00	7.455E+00
1997	1.381E+02	4.859E+01	5.072E+01	3.700E+01	1.018E+01	5.275E+00	1.915E+01	2.312E+00	6.653E+00
1998	1.160E+02	4.418E+01	4.607E+01	3.352E+01	9.138E+00	5.285E+00	1.714E+01	2.094E+00	6.017E+00
1999	8.405E+01	4.089E+01	4.125E+01	2.986E+01	4.970E+00	5.008E+00	1.440E+01	1.094E+00	5.251E+00
2000	7.314E+01	3.705E+01	3.757E+01	2.706E+01	4.387E+00	4.915E+00	1.294E+01	9.323E-01	4.755E+00
2001	6.419E+01	3.367E+01	3.432E+01	2.463E+01	3.975E+00	4.876E+00	1.169E+01	8.224E-01	4.363E+00
2002	5.665E+01	3.061E+01	3.138E+01	2.242E+01	3.621E+00	4.837E+00	1.058E+01	7.300E-01	4.017E+00
2003	5.021E+01	2.781E+01	2.872E+01	2.043E+01	3.303E+00	4.786E+00	9.583E+00	6.492E-01	3.703E+00
2004	4.468E+01	2.528E+01	2.630E+01	1.861E+01	3.014E+00	4.725E+00	8.690E+00	5.781E-01	3.416E+00

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2005	3.990E+01	2.297E+01	2.410E+01	1.697E+01	2.755E+00	4.652E+00	7.890E+00	5.155E-01	3.154E+00
2006	3.574E+01	2.089E+01	2.212E+01	1.548E+01	2.521E+00	4.571E+00	7.173E+00	4.603E-01	2.916E+00
2007	3.210E+01	1.900E+01	2.033E+01	1.414E+01	2.312E+00	4.485E+00	6.530E+00	4.116E-01	2.699E+00
2008	2.891E+01	1.730E+01	1.871E+01	1.292E+01	2.125E+00	4.392E+00	5.954E+00	3.685E-01	2.503E+00
2009	2.610E+01	1.577E+01	1.726E+01	1.183E+01	1.956E+00	4.297E+00	5.436E+00	3.305E-01	2.324E+00
2010	2.361E+01	1.439E+01	1.594E+01	1.084E+01	1.805E+00	4.198E+00	4.971E+00	2.967E-01	2.161E+00
2011	2.141E+01	1.314E+01	1.475E+01	9.951E+00	1.669E+00	4.097E+00	4.553E+00	2.667E-01	2.013E+00
2012	1.946E+01	1.202E+01	1.368E+01	9.147E+00	1.546E+00	3.996E+00	4.178E+00	2.400E-01	1.878E+00
2013	1.771E+01	1.100E+01	1.271E+01	8.421E+00	1.434E+00	3.892E+00	3.839E+00	2.162E-01	1.755E+00
2014	1.615E+01	1.009E+01	1.184E+01	7.765E+00	1.333E+00	3.790E+00	3.534E+00	1.951E-01	1.643E+00
2015	1.476E+01	9.271E+00	1.105E+01	7.172E+00	1.241E+00	3.688E+00	3.258E+00	1.763E-01	1.540E+00
2016	1.350E+01	8.528E+00	1.033E+01	6.636E+00	1.157E+00	3.586E+00	3.010E+00	1.594E-01	1.446E+00
2017	1.238E+01	7.858E+00	9.683E+00	6.149E+00	1.080E+00	3.485E+00	2.784E+00	1.444E-01	1.360E+00
2018	1.136E+01	7.251E+00	9.096E+00	5.708E+00	1.009E+00	3.385E+00	2.580E+00	1.310E-01	1.281E+00
2019	1.045E+01	6.705E+00	8.563E+00	5.308E+00	9.450E-01	3.286E+00	2.394E+00	1.189E-01	1.209E+00
2020	9.621E+00	6.206E+00	8.077E+00	4.944E+00	8.856E-01	3.190E+00	2.226E+00	1.081E-01	1.142E+00
2021	8.872E+00	5.757E+00	7.637E+00	4.613E+00	8.308E-01	3.094E+00	2.073E+00	9.849E-02	1.080E+00
2022	8.194E+00	5.349E+00	7.233E+00	4.311E+00	7.805E-01	3.000E+00	1.934E+00	8.980E-02	1.023E+00
2023	7.576E+00	4.977E+00	6.864E+00	4.035E+00	7.337E-01	2.909E+00	1.806E+00	8.201E-02	9.704E-01
2024	7.015E+00	4.638E+00	6.528E+00	3.782E+00	6.906E-01	2.819E+00	1.690E+00	7.501E-02	9.214E-01
2025	6.506E+00	4.330E+00	6.221E+00	3.552E+00	6.507E-01	2.730E+00	1.584E+00	6.870E-02	8.759E-01
2026	6.042E+00	4.048E+00	5.938E+00	3.340E+00	6.136E-01	2.645E+00	1.486E+00	6.302E-02	8.335E-01
2027	5.617E+00	3.791E+00	5.676E+00	3.146E+00	5.792E-01	2.561E+00	1.397E+00	5.790E-02	7.939E-01
2028	5.228E+00	3.555E+00	5.436E+00	2.966E+00	5.470E-01	2.480E+00	1.314E+00	5.327E-02	7.570E-01
2029	4.872E+00	3.339E+00	5.214E+00	2.801E+00	5.173E-01	2.400E+00	1.239E+00	4.908E-02	7.224E-01
2030	4.546E+00	3.141E+00	5.009E+00	2.649E+00	4.894E-01	2.323E+00	1.169E+00	4.530E-02	6.900E-01
2031	4.248E+00	2.958E+00	4.819E+00	2.507E+00	4.635E-01	2.248E+00	1.104E+00	4.188E-02	6.596E-01
2032	3.973E+00	2.790E+00	4.641E+00	2.378E+00	4.392E-01	2.175E+00	1.044E+00	3.877E-02	6.309E-01

Year	West Cumbria	Morecambe Bay	Southwest Scotland	Northern Ireland	Whitehaven Harbour	Ribble Estuary	Isle of Man Adults	Isle of Man Infants	Wales
2033	3.721E+00	2.634E+00	4.475E+00	2.256E+00	4.165E-01	2.103E+00	9.889E-01	3.595E-02	6.039E-01
2034	3.488E+00	2.491E+00	4.321E+00	2.143E+00	3.952E-01	2.033E+00	9.375E-01	3.338E-02	5.785E-01
2035	3.274E+00	2.358E+00	4.177E+00	2.038E+00	3.754E-01	1.967E+00	8.897E-01	3.105E-02	5.545E-01
2036	3.076E+00	2.234E+00	4.040E+00	1.940E+00	3.567E-01	1.901E+00	8.452E-01	2.894E-02	5.316E-01
2037	2.893E+00	2.119E+00	3.914E+00	1.849E+00	3.393E-01	1.838E+00	8.036E-01	2.699E-02	5.101E-01
2038	2.724E+00	2.013E+00	3.793E+00	1.763E+00	3.227E-01	1.776E+00	7.648E-01	2.522E-02	4.896E-01
2039	2.567E+00	1.913E+00	3.680E+00	1.683E+00	3.072E-01	1.718E+00	7.286E-01	2.360E-02	4.703E-01
2040	2.421E+00	1.820E+00	3.572E+00	1.607E+00	2.925E-01	1.660E+00	6.945E-01	2.212E-02	4.518E-01
2041	2.286E+00	1.733E+00	3.471E+00	1.537E+00	2.788E-01	1.604E+00	6.626E-01	2.075E-02	4.342E-01
2042	2.160E+00	1.652E+00	3.374E+00	1.470E+00	2.659E-01	1.550E+00	6.326E-01	1.950E-02	4.175E-01
2043	2.043E+00	1.575E+00	3.282E+00	1.407E+00	2.536E-01	1.498E+00	6.045E-01	1.835E-02	4.015E-01
2044	1.933E+00	1.503E+00	3.194E+00	1.347E+00	2.421E-01	1.447E+00	5.777E-01	1.729E-02	3.863E-01
2045	1.832E+00	1.436E+00	3.111E+00	1.291E+00	2.311E-01	1.398E+00	5.527E-01	1.631E-02	3.717E-01
2046	1.737E+00	1.372E+00	3.030E+00	1.238E+00	2.207E-01	1.350E+00	5.290E-01	1.541E-02	3.579E-01
2047	1.648E+00	1.312E+00	2.953E+00	1.187E+00	2.109E-01	1.304E+00	5.066E-01	1.457E-02	3.445E-01
2048	1.565E+00	1.255E+00	2.880E+00	1.140E+00	2.017E-01	1.260E+00	4.854E-01	1.379E-02	3.317E-01
2049	1.487E+00	1.201E+00	2.809E+00	1.094E+00	1.928E-01	1.217E+00	4.653E-01	1.307E-02	3.195E-01
2050	1.414E+00	1.150E+00	2.741E+00	1.051E+00	1.844E-01	1.175E+00	4.462E-01	1.240E-02	3.079E-01

Table 15: Comparison of the annual dose predictions from an NRPB study and the present study ($\mu Sv\ a^{-1}$).

Predicted doses		1989	1993	1996	2006	2050
NRPB study (NRPB, 1994)	*Region B*	*2.3*	*1.6*	*1.3*	*0.58*	*0.04*
	Average	6.3	4.6	3.4	1.2	0.4
Present study	*Whitehaven Harbour*	*25*	*16*	*13*	*7*	*4*
	West Cumbria	366	214	172	60	26
Normalised doses		**1989**	**1993**	**1996**	**2006**	**2050**
NRPB study (NRPB, 1994)	*Region B*	*1.00*	*0.70*	*0.57*	*0.25*	*0.02*
	Average	1.00	0.73	0.54	0.19	0.06
Present study	*Whitehaven Harbour*	*1.00*	*0.64*	*0.52*	*0.28*	*0.16*
	West Cumbria	1.00	0.58	0.47	0.16	0.07

Doses normalised relative to the doses in 1989

Table 16: Comparison between doses predicted by MARISA (i.e. this study) and doses as determined by MAFF (mSv).

		1978	1979	1980	1981	1982	1983	1984	1985	1986
West Cumbria	MAFF	1.15	1.05	1.20	2.03	1.70	1.45	0.54	0.49	0.12
	MARISA	1.84	1.36	1.36	2.00	1.74	1.53	1.17	0.82	0.62
Local Fisheries	MAFF	0.95	0.75	0.75	0.80	0.60	0.45	0.41	0.26	0.10
Whitehaven Harbour	MARISA	0.73	0.48	0.51	0.50	0.42	0.29	0.14	0.10	0.04
Morecambe Bay	MARISA	0.17	0.14	0.13	0.14	0.14	0.14	0.12	0.10	0.09
Ribble Estuary	MAFF	0.10	0.05	0.05	0.35	0.35	0.30	0.20	0.30	0.34
	MARISA	0.07	0.05	0.04	0.04	0.03	0.03	0.02	0.01	0.007

		1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
West Cumbria	MAFF	0.10	0.15	0.19	0.11	0.11	0.12	0.10	0.08	0.12	0.14	0.10
	MARISA	0.50	0.43	0.37	0.31	0.27	0.23	0.21	0.20	0.20	0.17	0.14
Whitehaven Harbour	MAFF	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.04	0.05	0.04
	MARISA	0.03	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01
Morecambe Bay	MAFF	0.06	0.07	0.09	0.10	0.08	0.09	0.09	0.08	0.07	0.08	0.07
	MARISA	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.05
Ribble Estuary	MAFF	0.24	0.27	0.17	0.18	0.15	0.15	0.26	0.14	0.09	0.14	0.13
	MARISA	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.005	0.005

MAFF doses are based on measurements and habit surveys. From 1990 onwards the doses are determined using the ICRP 60 (ICRP, 1991) methodology, those prior to 1990 were determined using the ICRP 26 (ICRP, 1977) methodology.

Table 17: Concentration factors, calibration factors and concentration factor equivalents used to fit the ^{137}Cs predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	30	50	1	50
	Cumbria	Mussels	30	20	1	20
	Solway	Winkles	30	50	1	50
Fish	Cumbria (SOA)	Fish (cod & plaice)	100	90	1	90
	Cumbria (SCA)	Fish (cod & plaice)	100	90	2	180
	Solway	Flounder	100	90	3	270
	N Ireland	Fish	100	90	2	180
Crustacea	Cumbria	Crab	30	30	1	30
	Cumbria	Lobster	30	30	2	60
	N Ireland	*Nephrops*	30	30	1	30

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Table 18: Concentration factors, calibration factors and concentration factor equivalents used to fit the ^{99}Tc predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	1000	6000	0.75	4500
	Cumbria	Mussels	1000	6000	0.5	3000
	Cumbria	Cockles	1000	1000	0.3	300
	Solway	Cockles	1000	1000	1	1000
	Solway	Winkles	1000	6000	2	12000
Fish	Cumbria	Cod	30	30	1	30
	Cumbria	Plaice	30	30	1.5	45
	Solway	Flounder	30	30	2	60
Crustacea	Cumbria	Crab	1000	140	1.5	210
	Cumbria	Lobster	1000	9000	1	9000
	N Ireland	*Nephrops*	1000	1000	1	1000

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Table 19: Concentration factors, calibration factors and concentration factor equivalents used to fit the Pu(α) predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	3000	2700	0.35	900
	Cumbria	Mussels	3000	1500	0.6	900
	Solway	Winkles	3000	2700	0.25	700
	N. Ireland	Winkles	3000	2700	0.02	60
Fish	Cumbria	Cod	40	0.1	15	1.5
	Cumbria	Plaice	40	0.1	30	3
	N. Ireland	Cod	40	0.1	1	0.1
Crustacea	Cumbria	Crab	300	300	0.3	90
	Cumbria	Lobster	300	300	0.1	30
	N Ireland	*Nephrops*	300	300	0.02	6
Sediment	Whitehaven Harbour	-	100000	18000	3	54000

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Table 20: Concentration factors, calibration factors and concentration factor equivalents used to fit the ^{106}Ru predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	2000	2000	0.75	1500
	Cumbria	Mussels	2000	2000	0.75	1500
	Solway	Winkles	2000	2000	1	2000
	N. Ireland	Winkles	2000	2000	1	2000
Fish	Cumbria	Cod	2	2	50	100
	Cumbria	Plaice	2	2	50	100
Crustacea	Cumbria	Crab	100	100	2	200
	Cumbria	Lobster	100	100	2	200
	Morecambe Bay	Shrimp	100	100	1.5	150
Sediment	Whitehaven Harbour	-	300	710	25	17750

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Table 21: Concentration factors, calibration factors and concentration factor equivalents used to fit the ^{60}Co predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	5000	5000	2	10000
	Cumbria	Mussels	5000	5000	1.5	7500
	Solway	Winkles	5000	5000	5	25000
	Solway	Cockles	5000	5000	4	20000
Fish	Cumbria	Cod	1000	1000	1	1000
	Cumbria	Plaice	1000	1000	1	1000
Crustacea	Cumbria	Crab	5000	5000	0.75	3750
	Cumbria	Lobster	5000	5000	0.5	2500
	Morecambe Bay	Shrimp	5000	5000	2.5	12500
Sediment	Whitehaven Harbour	-	200000	2500	75	187500

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Table 22: Concentration factors, calibration factors and concentration factor equivalents used to fit the ^{14}C predictions to observed values.

	Location	Species	IAEA 247 CF	CF used	Calibration factor	CF equivalent
Molluscs	Cumbria	Winkles	20000	5000	1	5000
	Cumbria	Mussels	20000	5000	1	5000
	Cumbria	Cockles	20000	5000	1	5000
	Solway	Cockles	20000	5000	1	5000
Fish	Cumbria	Cod	20000	3000	3	9000
	Cumbria	Plaice	20000	3000	3	9000
	N. Ireland	Cod	20000	3000	1	3000
Crustacea	Cumbria	Crab	20000	6000	1	6000
	Cumbria	Lobster	20000	6000	1	6000

The concentration factor equivalent is equal to the concentration factor multiplied by the calibration factor.

Page left blank intentionally.

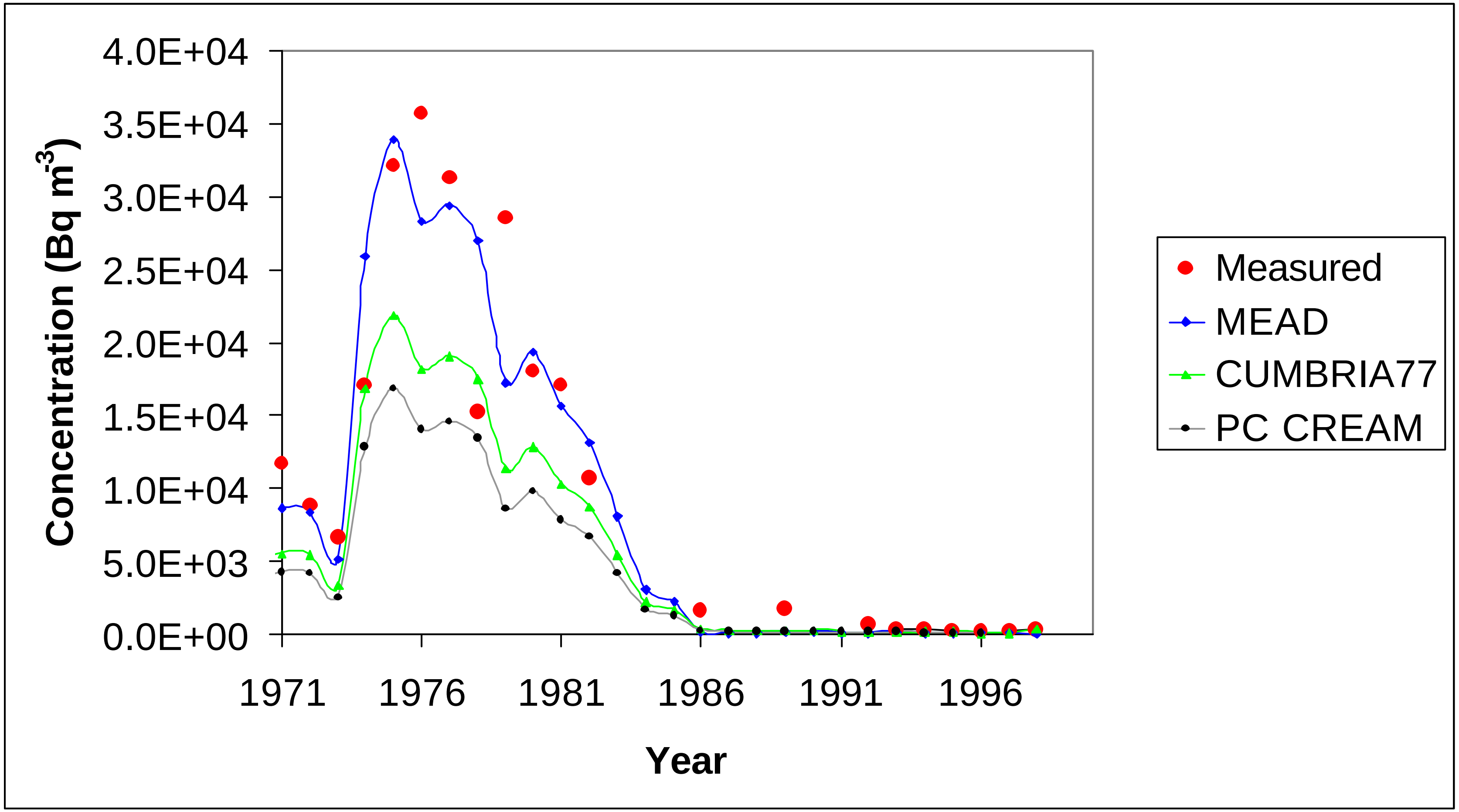


Figure 7: Comparison between seawater concentrations measured results and the MEAD, CUMBRIA77 and PC CREAM models.

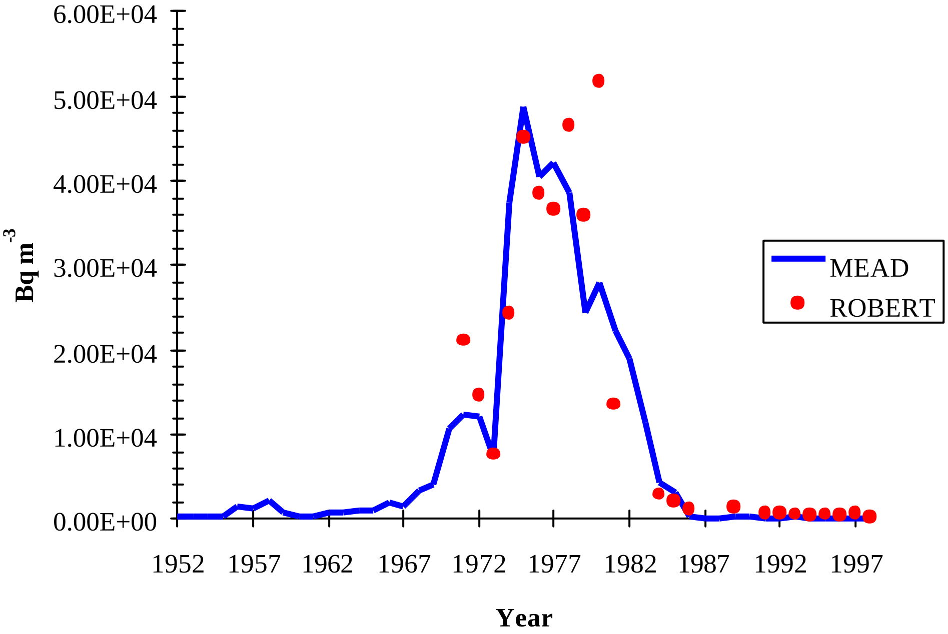


Figure 8: ^{137}**Cs activity concentrations in the seawater at Sellafield.**

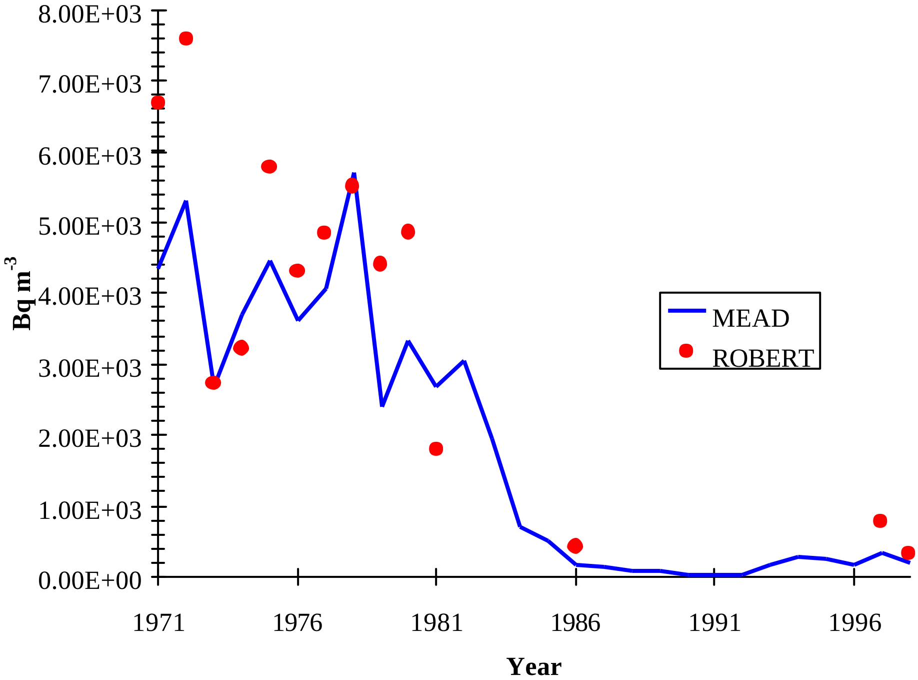


Figure 9: ^{90}**Sr activity concentrations in the seawater at Sellafield.**

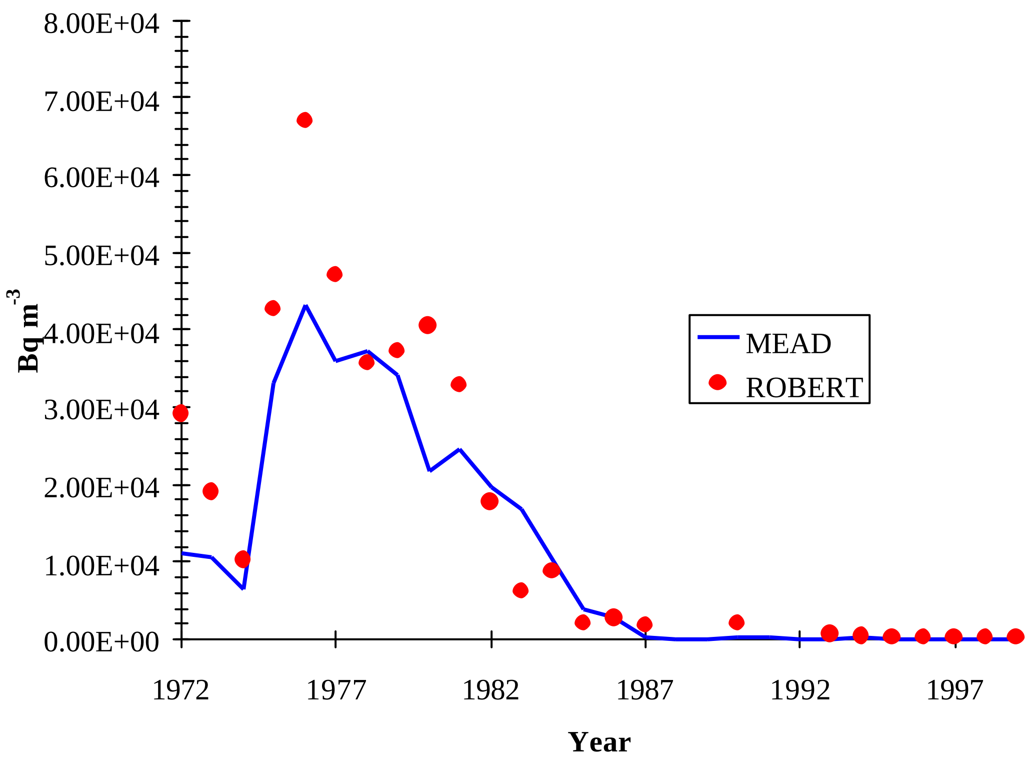


Figure 10: ^{137}**Cs activity concentrations in the seawater at Seascale.**

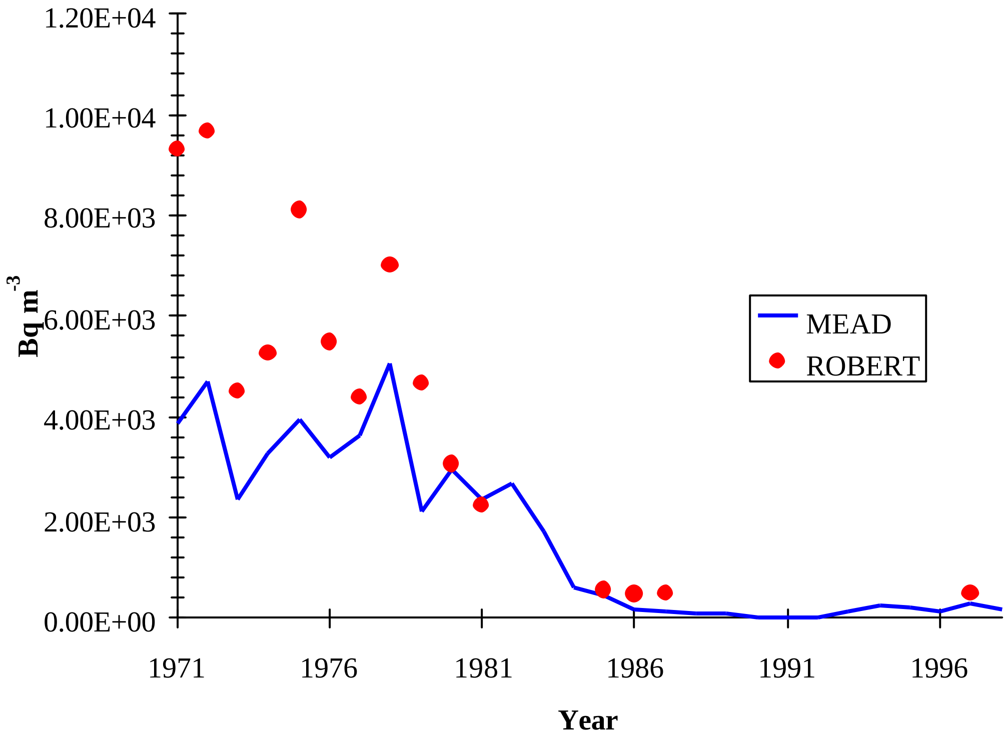


Figure 11: ^{90}**Sr activity concentrations in the seawater at Seascale.**

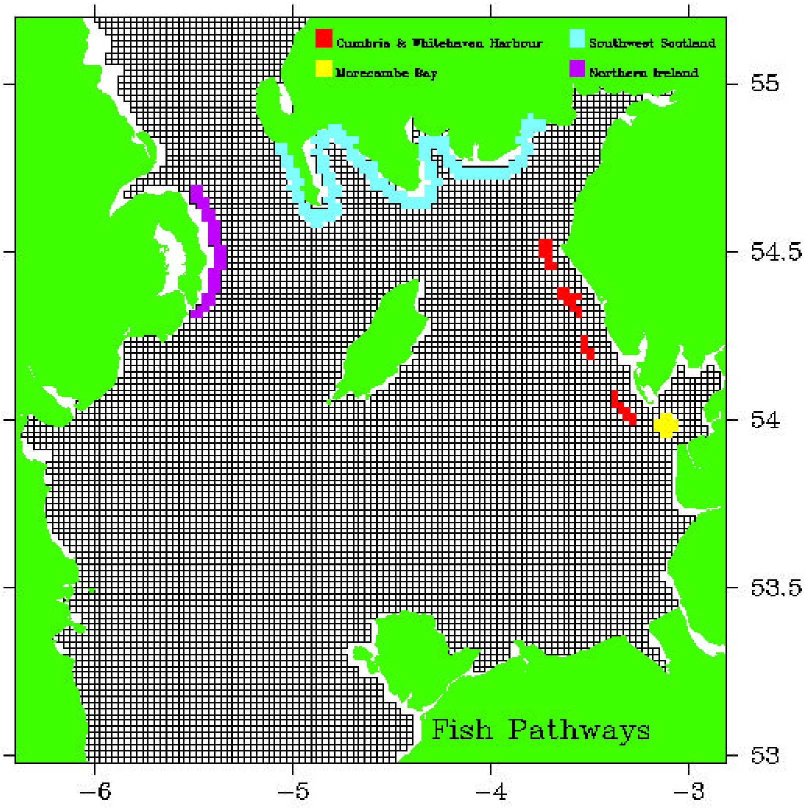


Figure 12: **Fishing locations for the Cumbria and Whitehaven Harbour, Southwest Scotland, Morecambe Bay and Northern Ireland critical groups.**

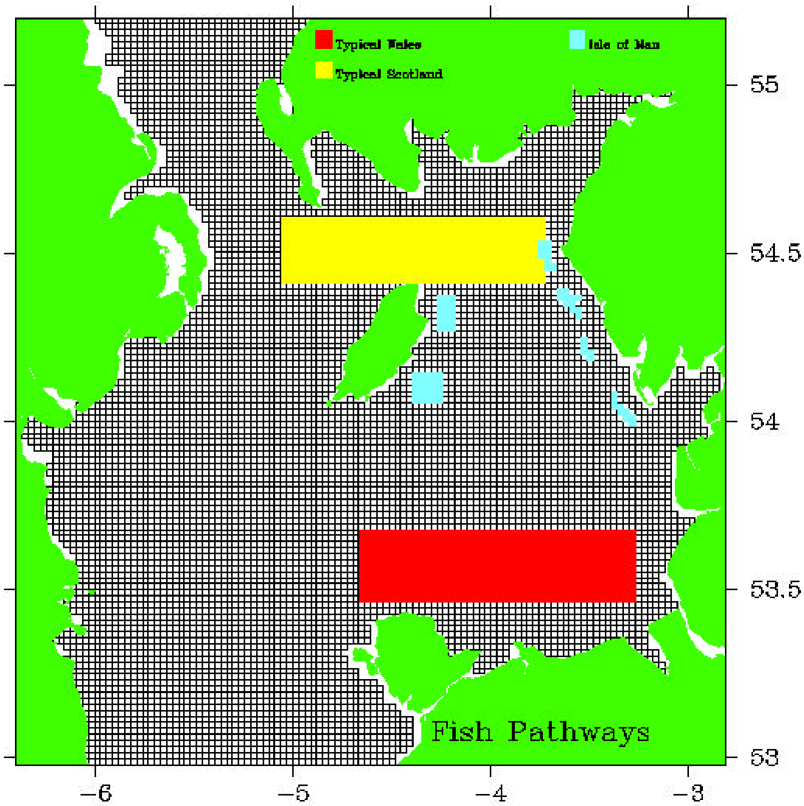


Figure 13: **Fishing locations for the Isle of Man critical group and the typical groups from Wales and Southwest Scotland.**

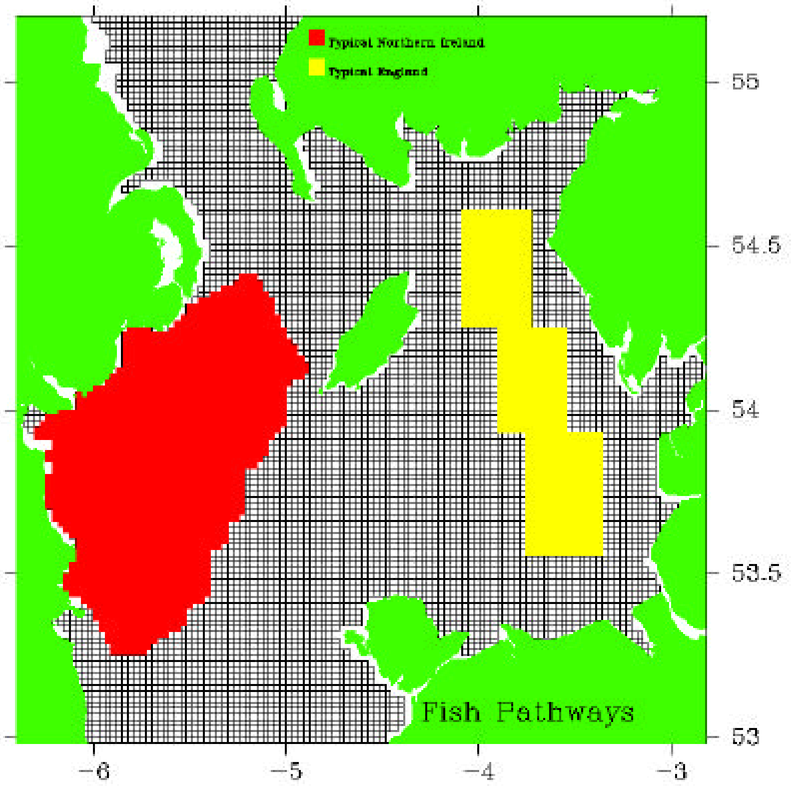


Figure 14: **Fishing locations for the typical groups from Northern Ireland and Northwest England.**

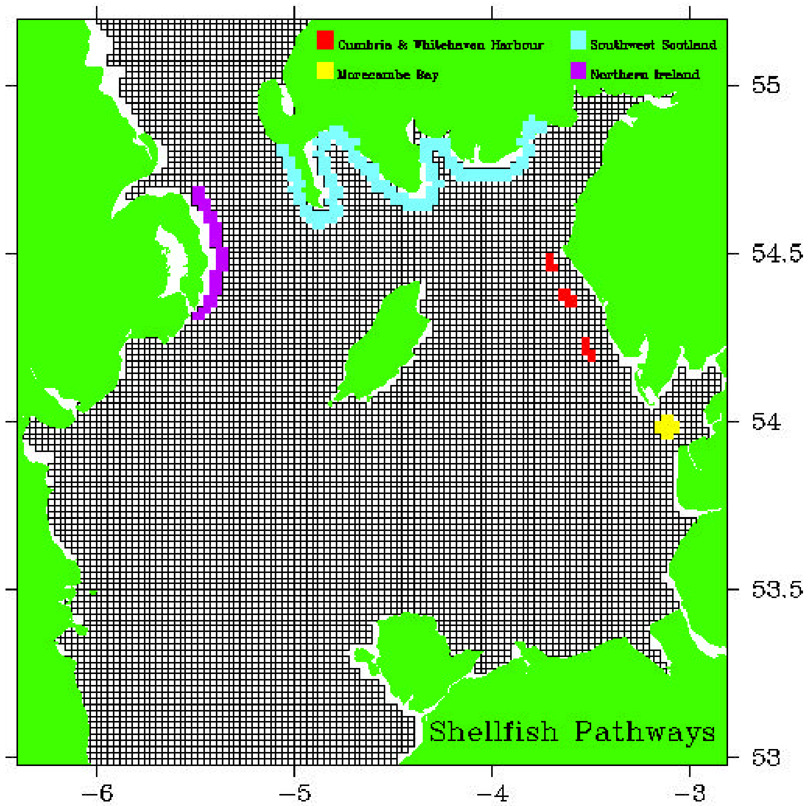


Figure 15: **Shellfish harvesting locations for the Cumbria and Whitehaven Harbour, Southwest Scotland, Morecambe Bay and Northern Ireland critical groups.**

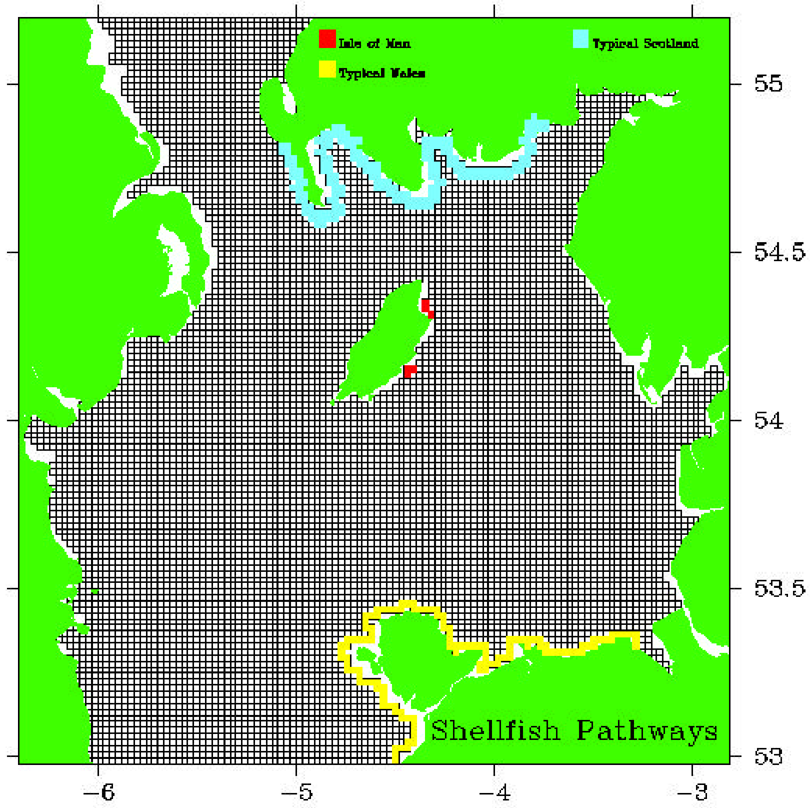


Figure 16: **Shellfish harvesting locations for the Isle of Man critical group and the typical groups from Wales and Southwest Scotland.**

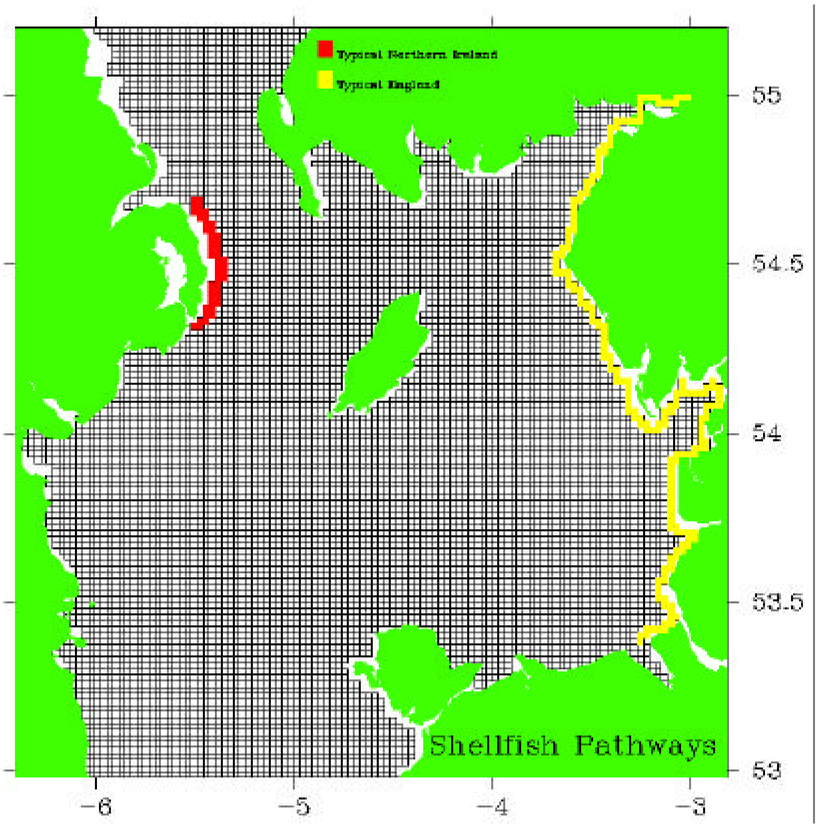


Figure 17: **Shellfish harvesting locations for the typical groups from Northern Ireland and Northwest England.**

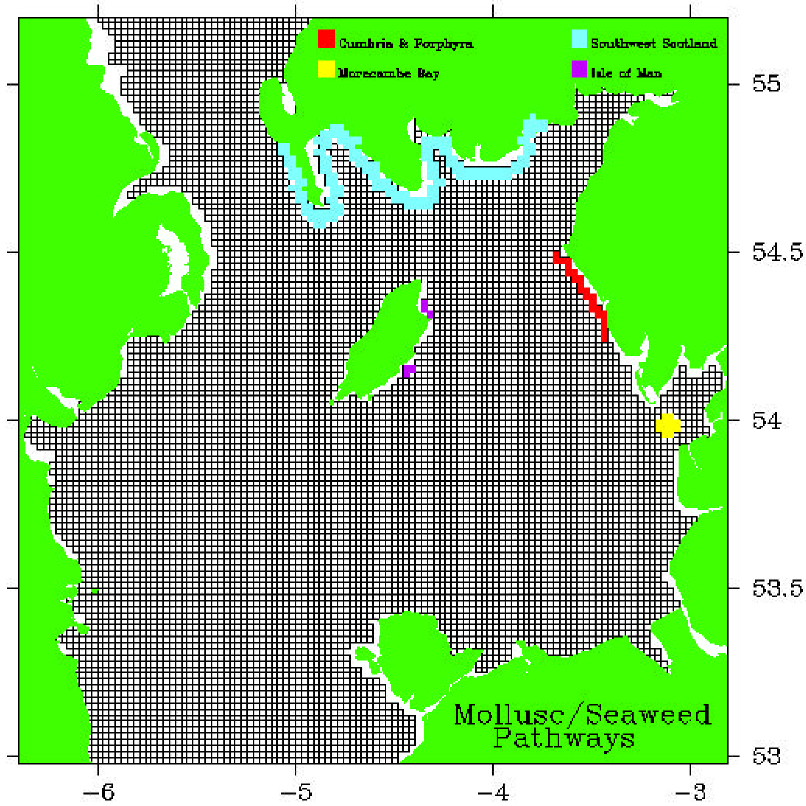


Figure 18: **Mollusc/seaweed harvesting locations for critical the groups in West Cumbria Wales, Southwest Scotland, More cambe Bay & the Isle of Man.**

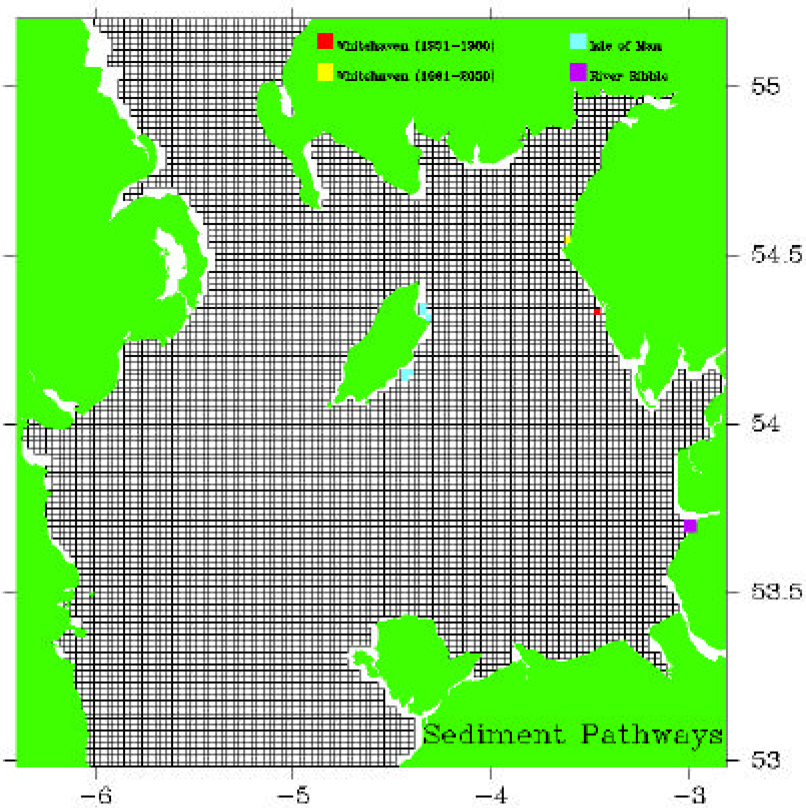


Figure 19: **Occupancy locations for the Whitehaven Harbour, Isle of Man and the Ribble Estuary critical groups.**

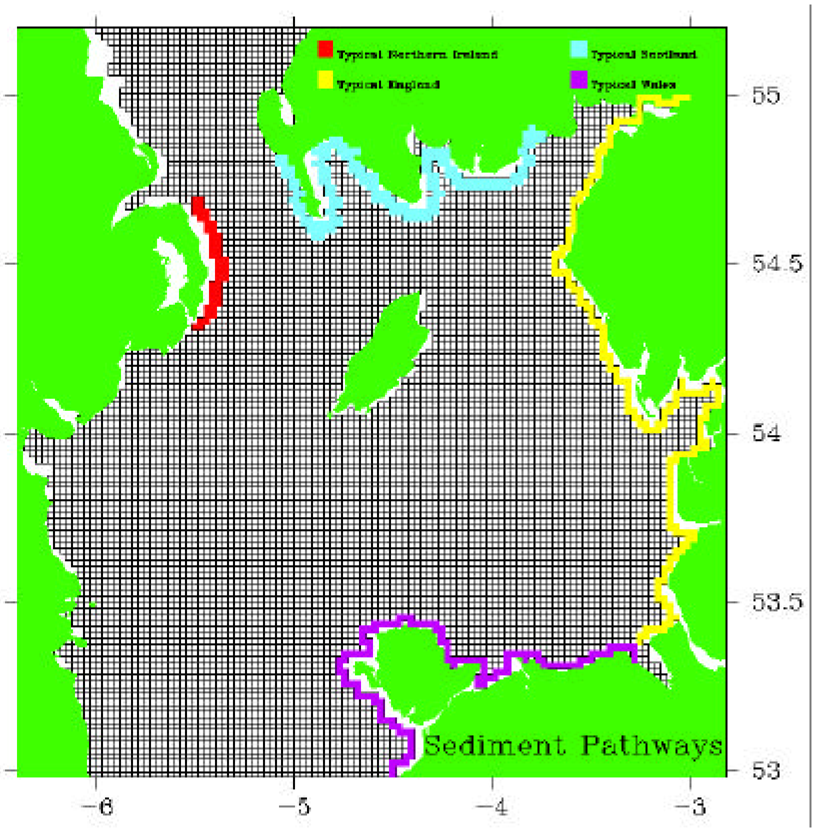


Figure 20: **Occupancy locations for the typical groups from Wales, Southwest Scotland and Northwest England and Northern Ireland.**

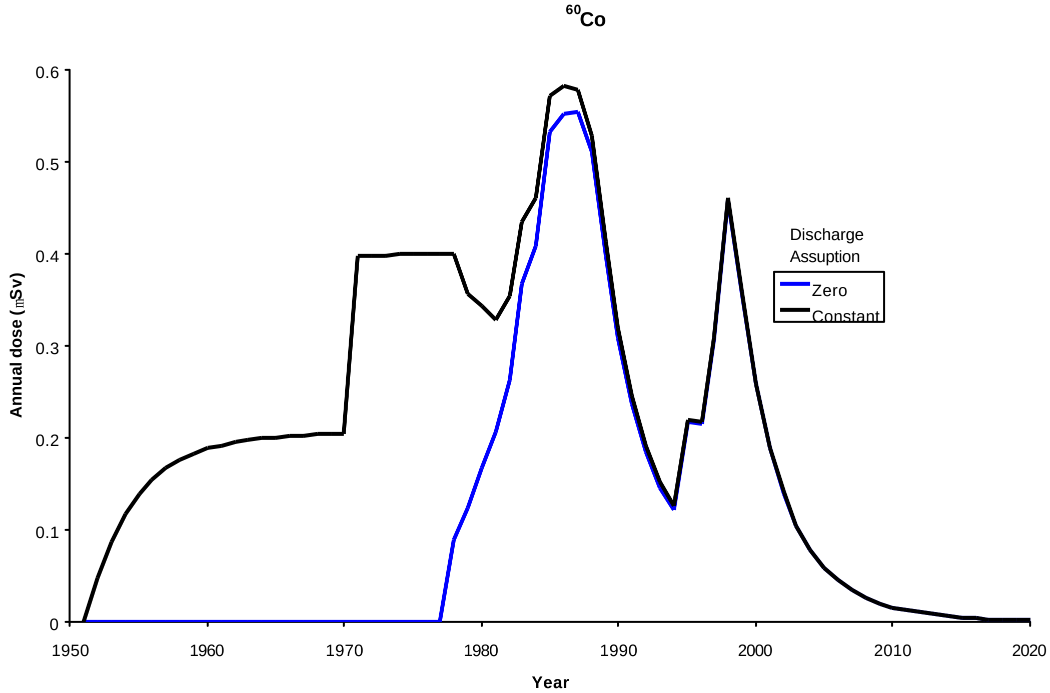


Figure 21: **The effect of assumed discharge levels, for unknown discharges of ^{60}Co, on the dose to the critical group in West Cumbria resulting from discharge Scenario Four.**

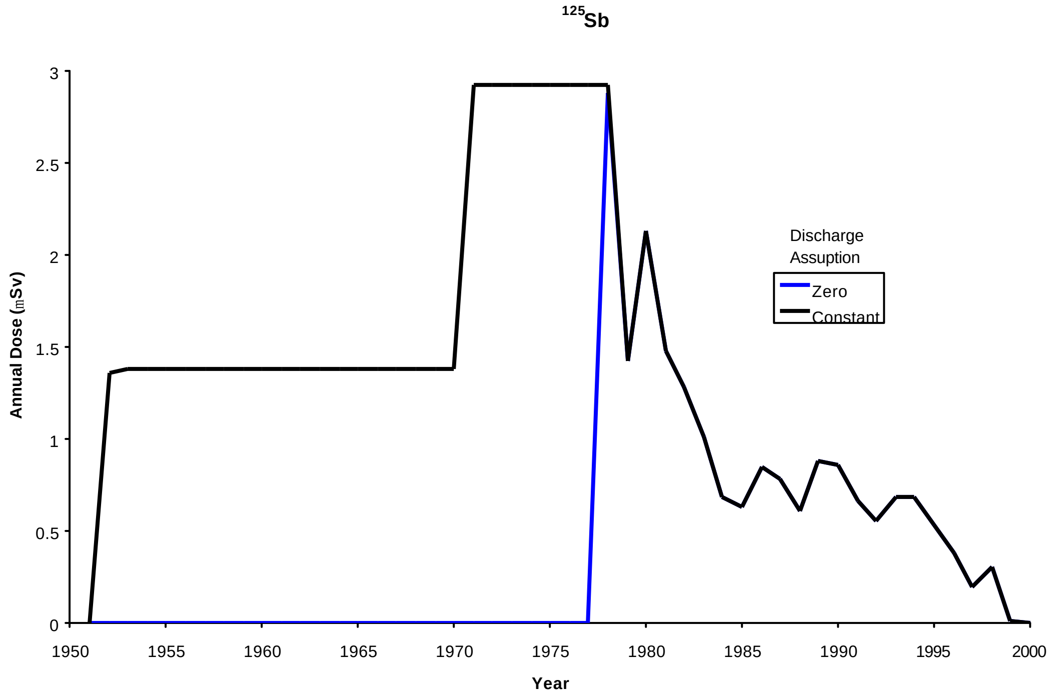


Figure 22: **The effect of assumed discharge levels, for unknown discharges of ^{125}Sb, on the dose to the critical group in West Cumbria resulting from discharge Scenario Four.**

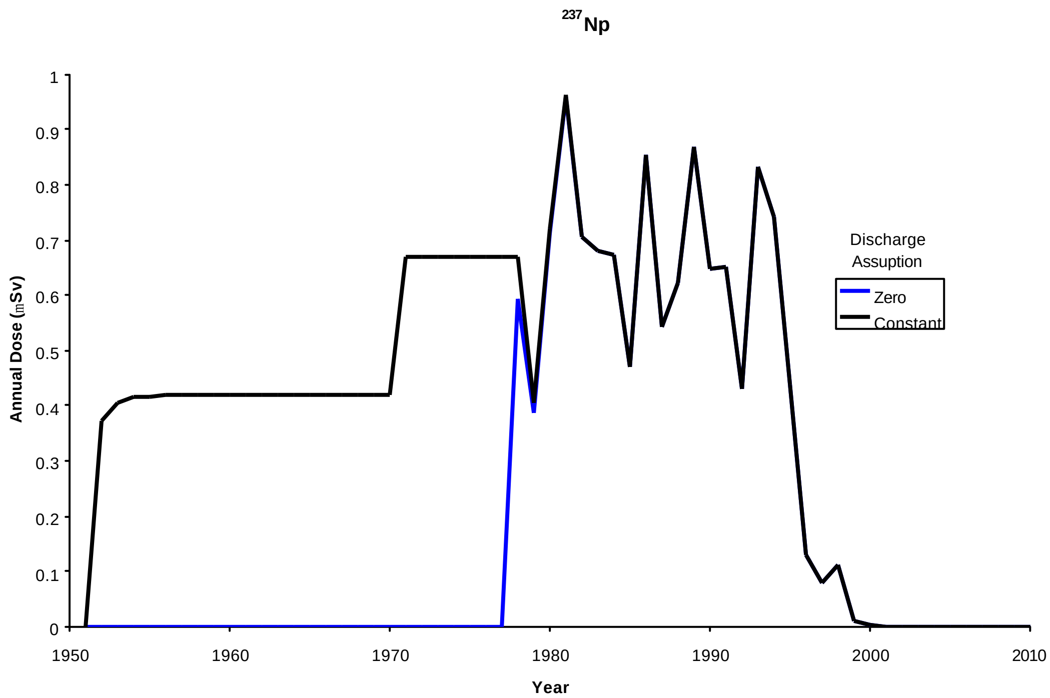


Figure 23: **The effect of assumed discharge levels, for unknown discharges of ^{237}Np, on the dose to the critical group in West Cumbria resulting from discharge Scenario Four.**

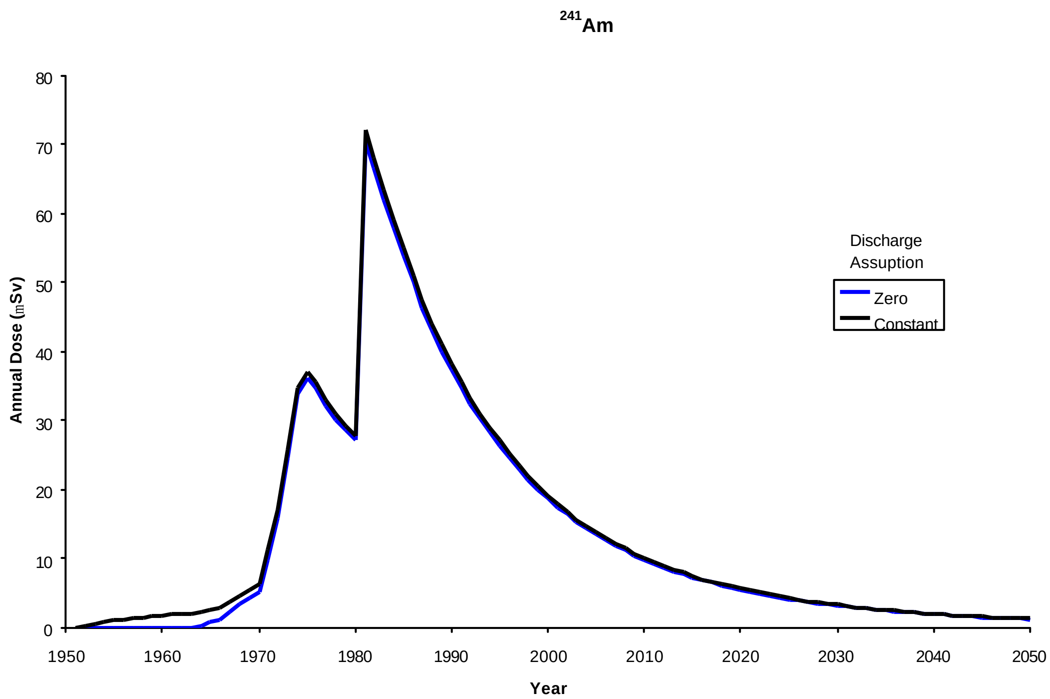
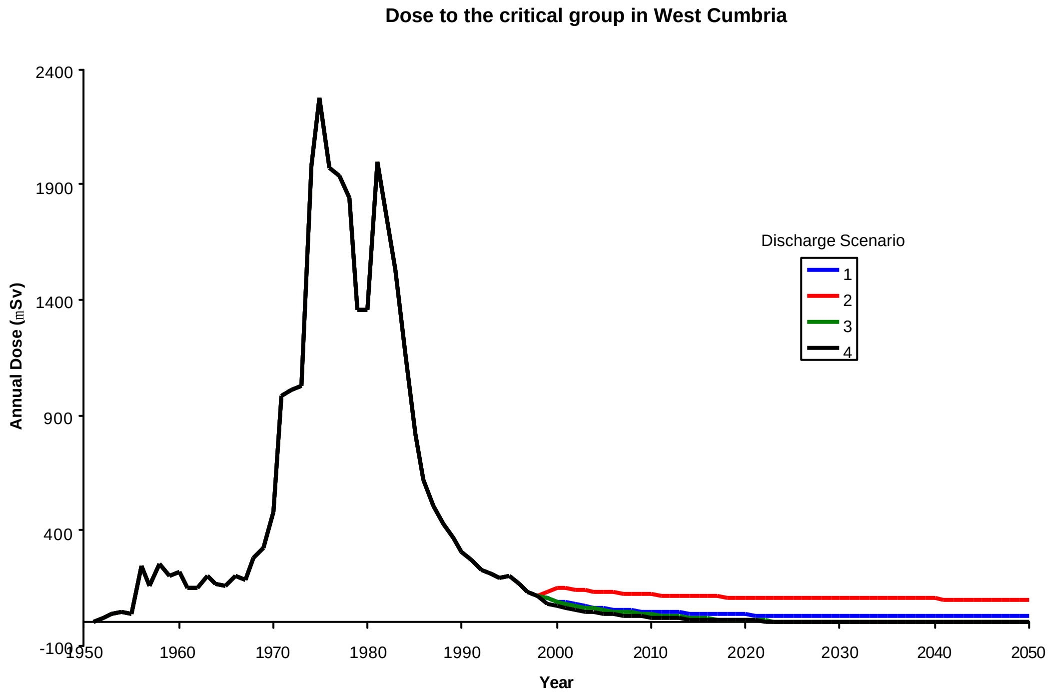


Figure 24: **The effect of assumed discharge levels, for unknown discharges of ^{241}Am, on the dose to the critical group in West Cumbria resulting from discharge Scenario Four.**



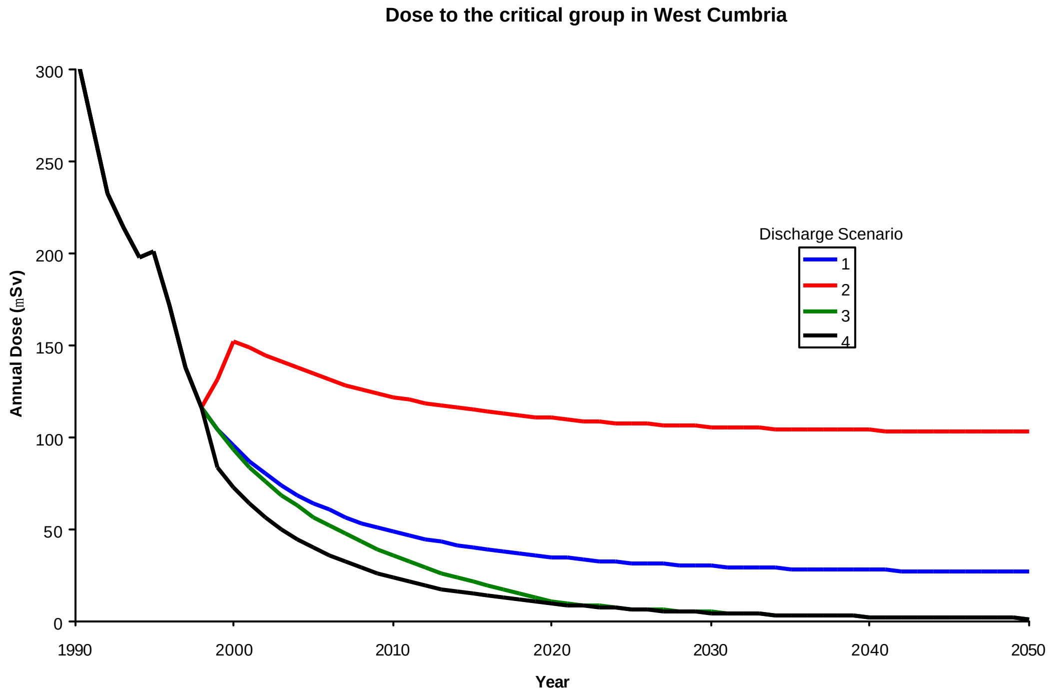


Figure 25: The dose to the critical group in West Cumbria.

<u>Scenarios:</u> One - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).

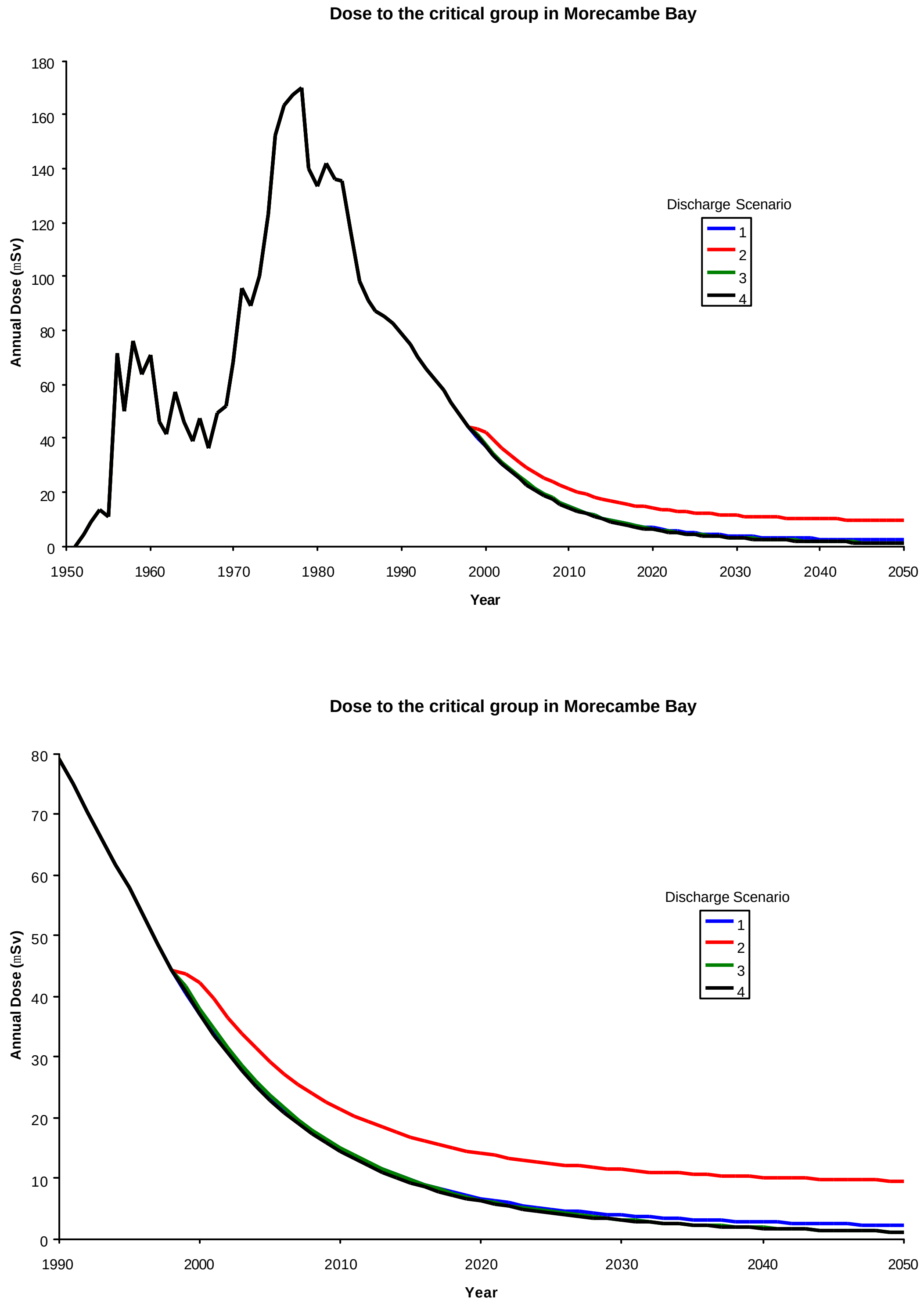
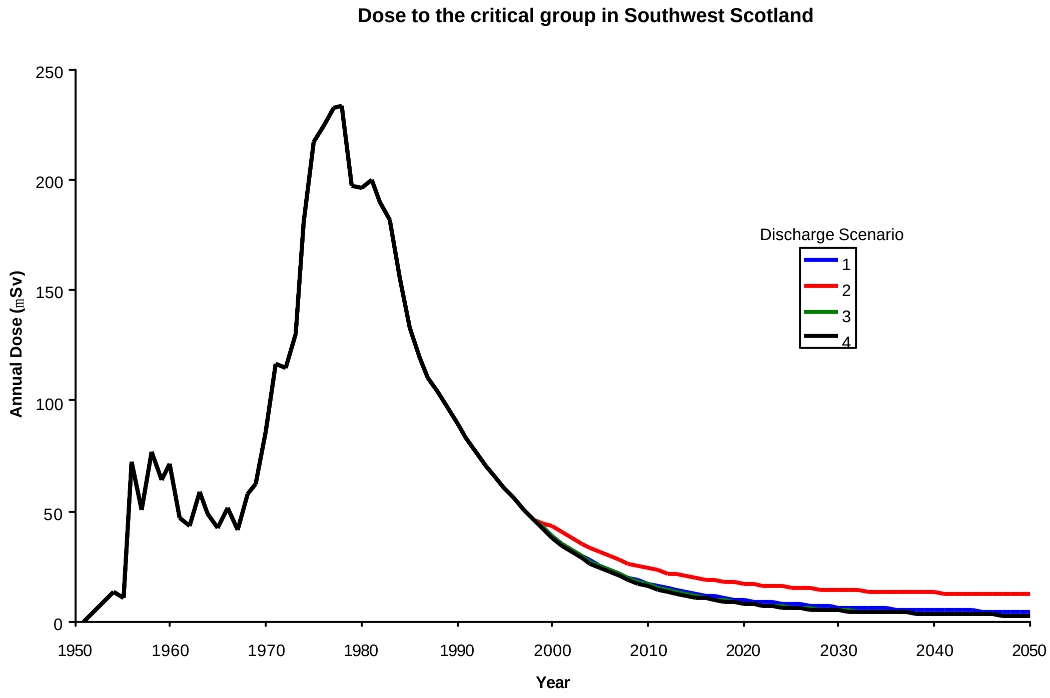


Figure 26: The dose to the critical group in Morecambe Bay.

Scenarios: **One** - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



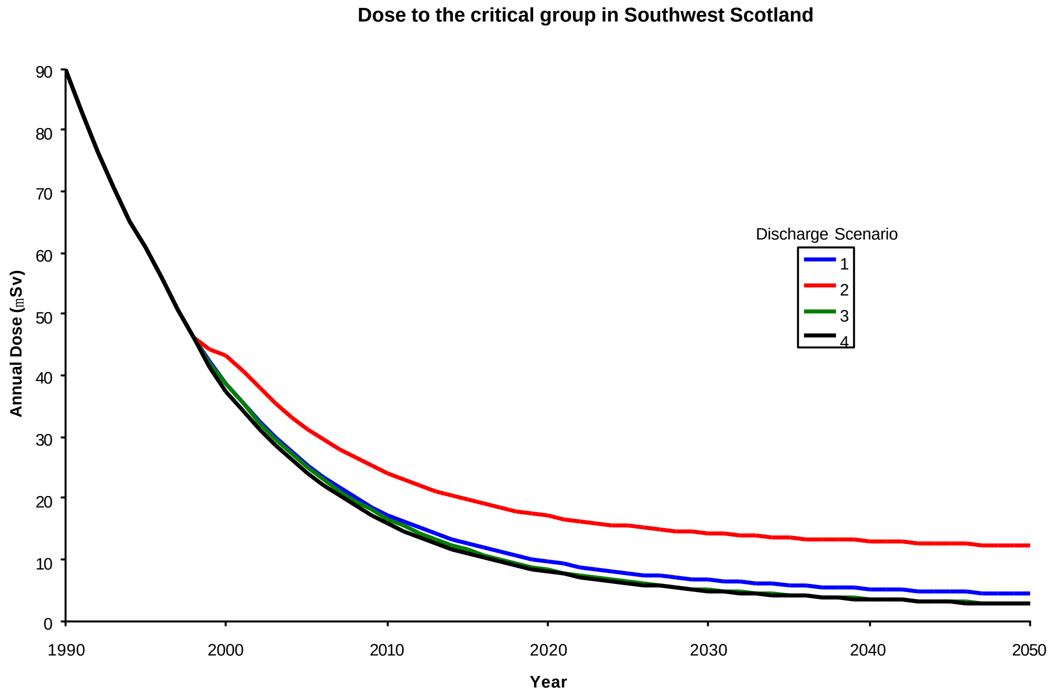
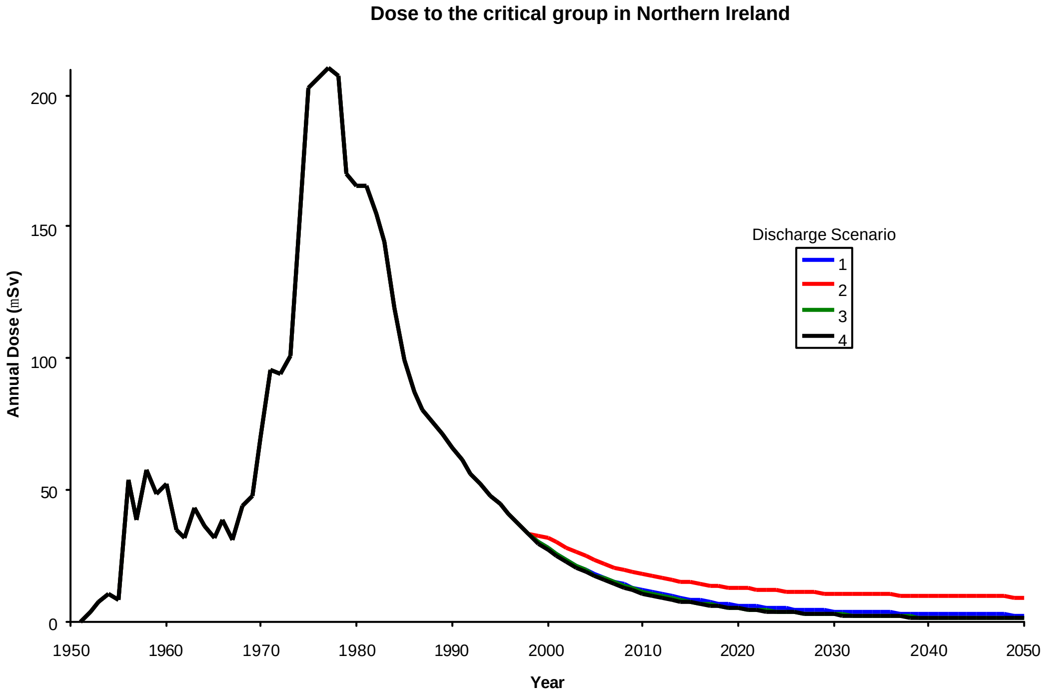


Figure 27: The dose to the critical group in Southwest Scotland.

<u>**Scenarios:**</u> **One** - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



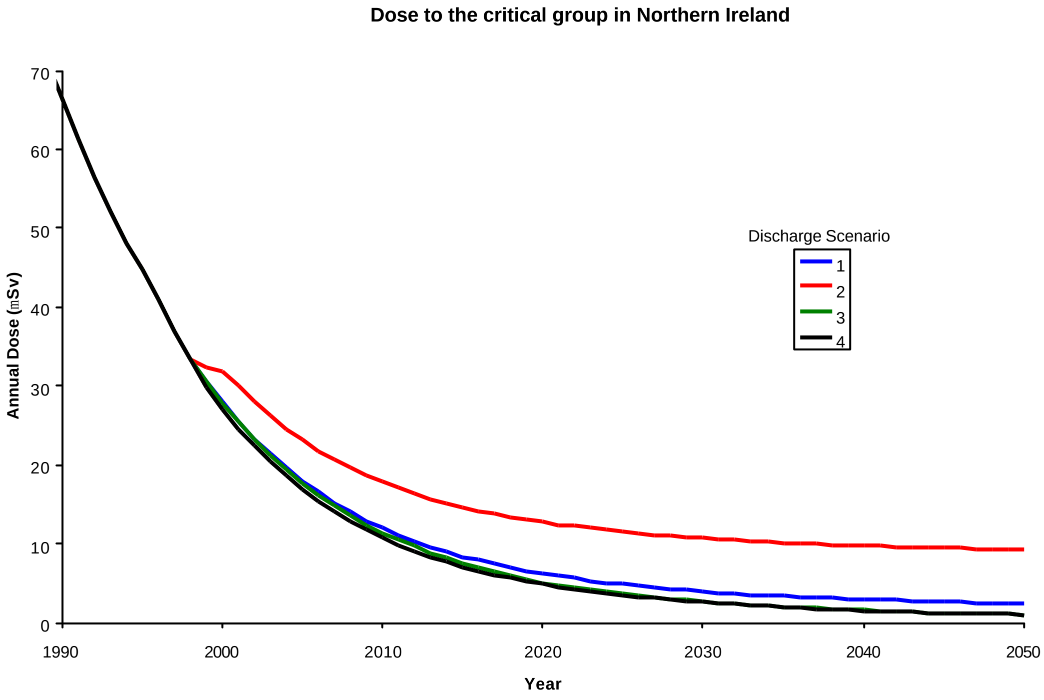
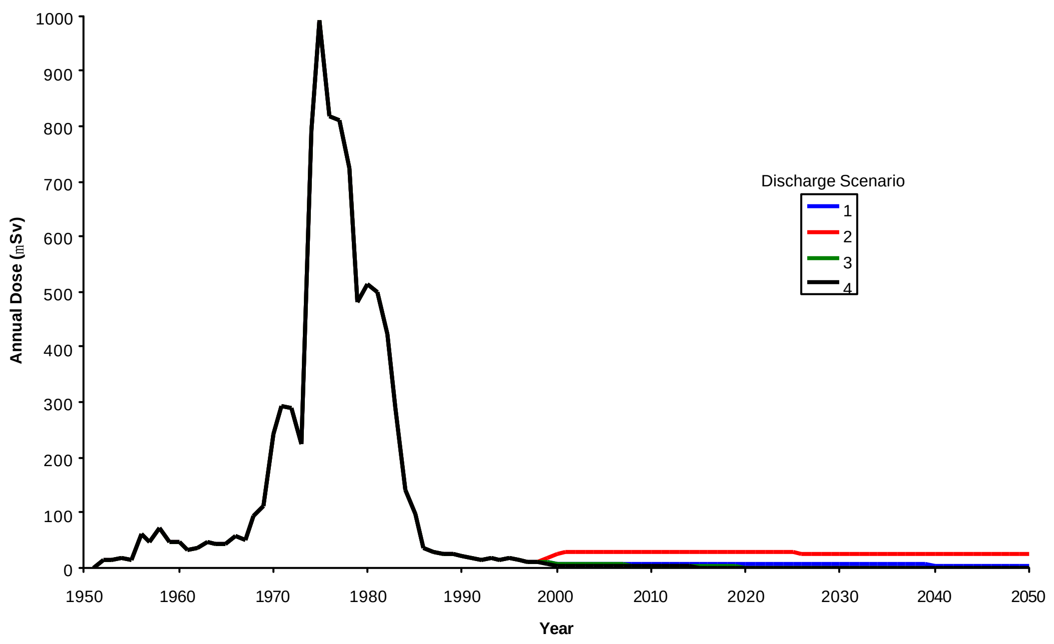


Figure 28: **The dose to the critical group in Northern Ireland.**

Scenarios: **One** - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).

Dose to the critical group at Whitehaven Harbour



Dose to the critical group at Whitehaven Harbour

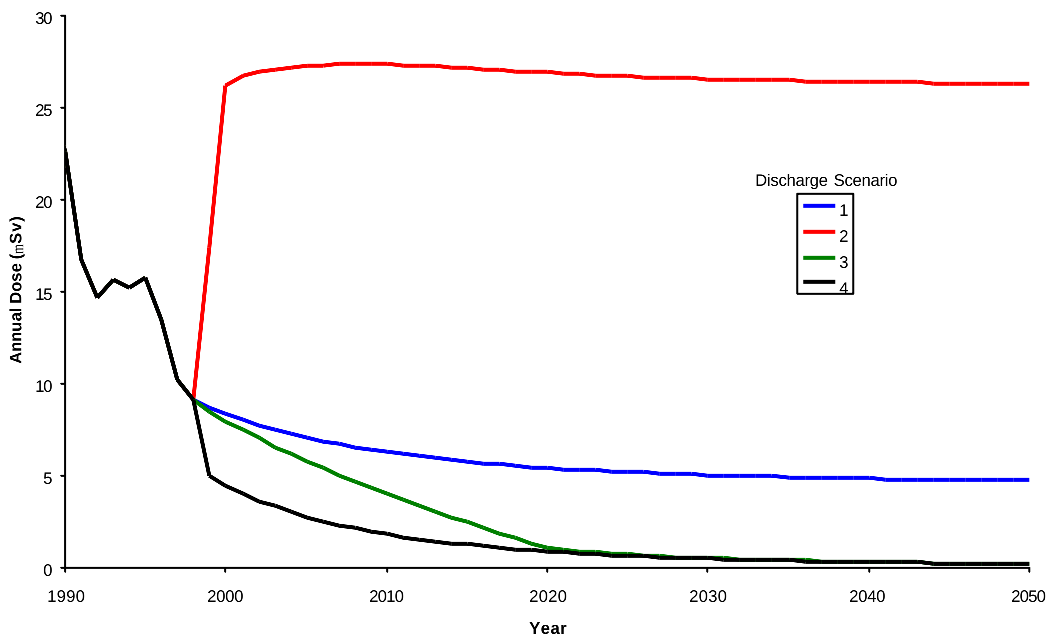
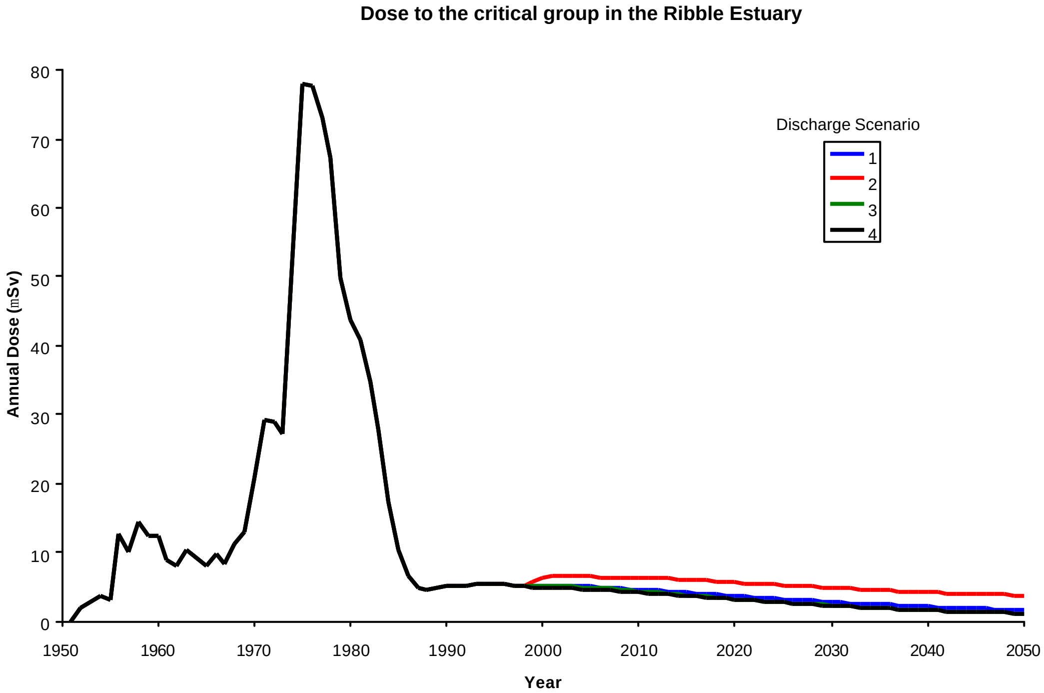


Figure 29: The dose to the critical group at Whitehaven Harbour.

<u>Scenarios:</u> One - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



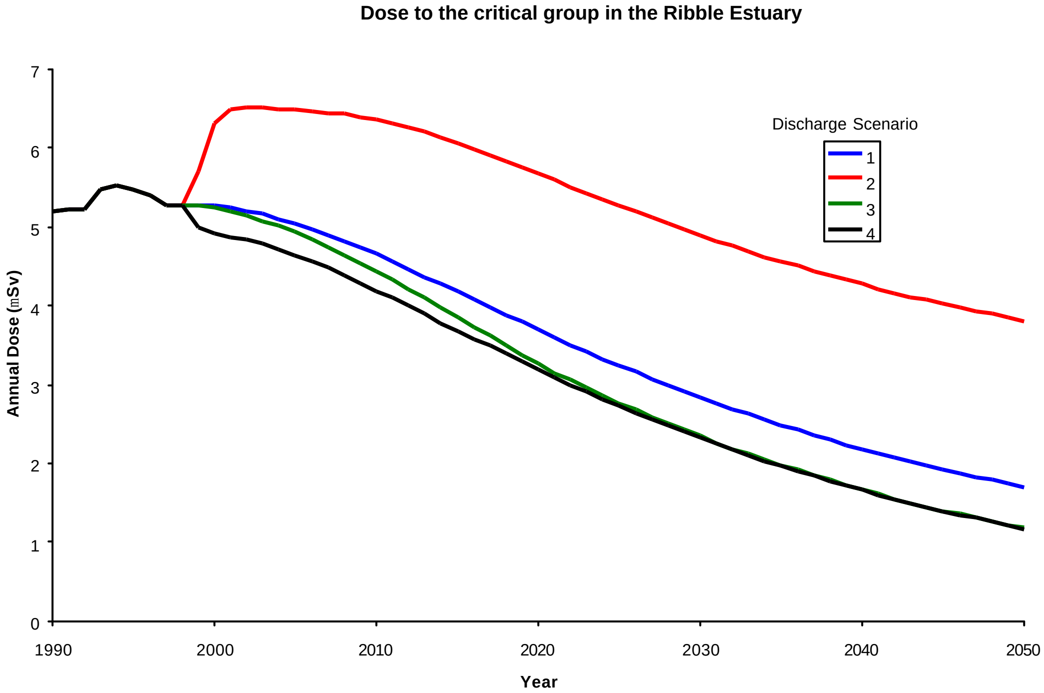
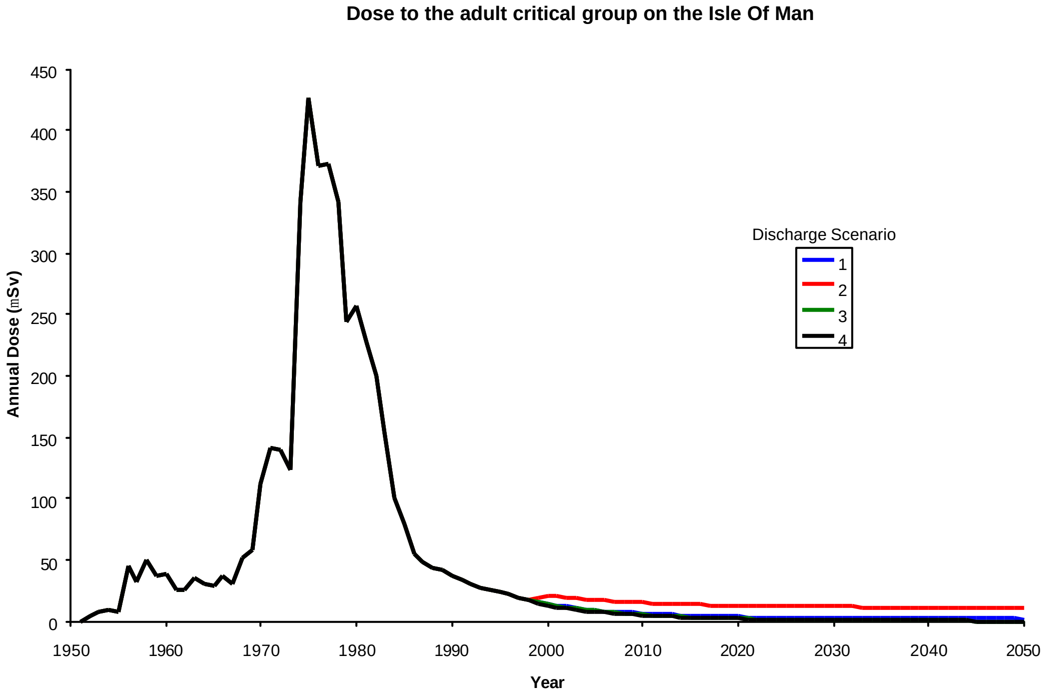


Figure 30: The dose to the critical group in the Ribble Estuary.

<u>Scenarios:</u> One - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



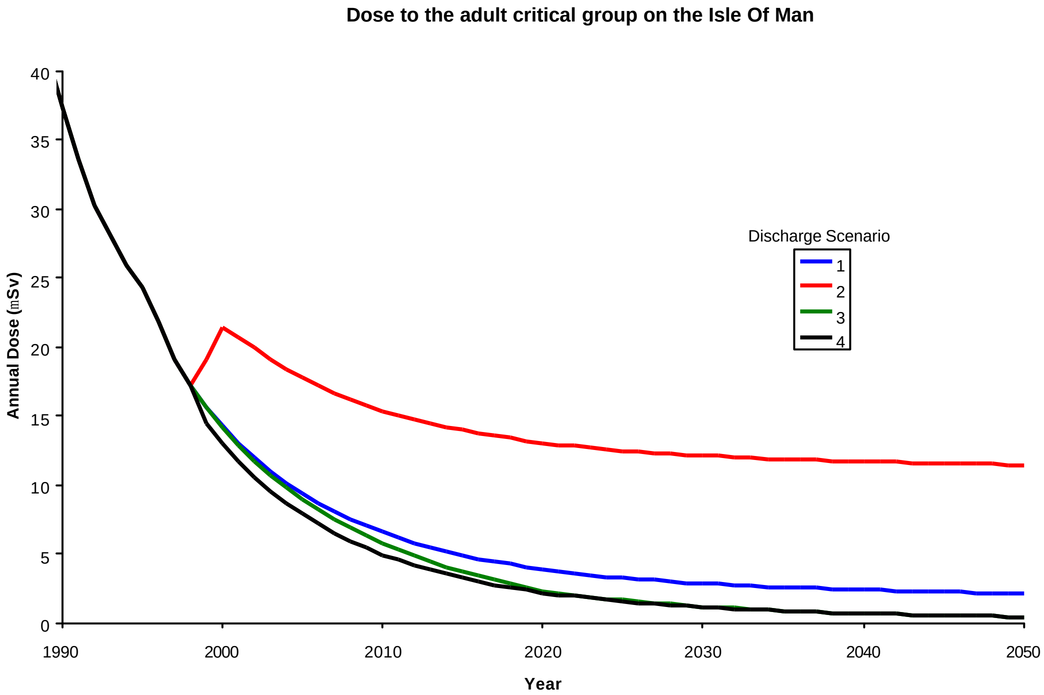
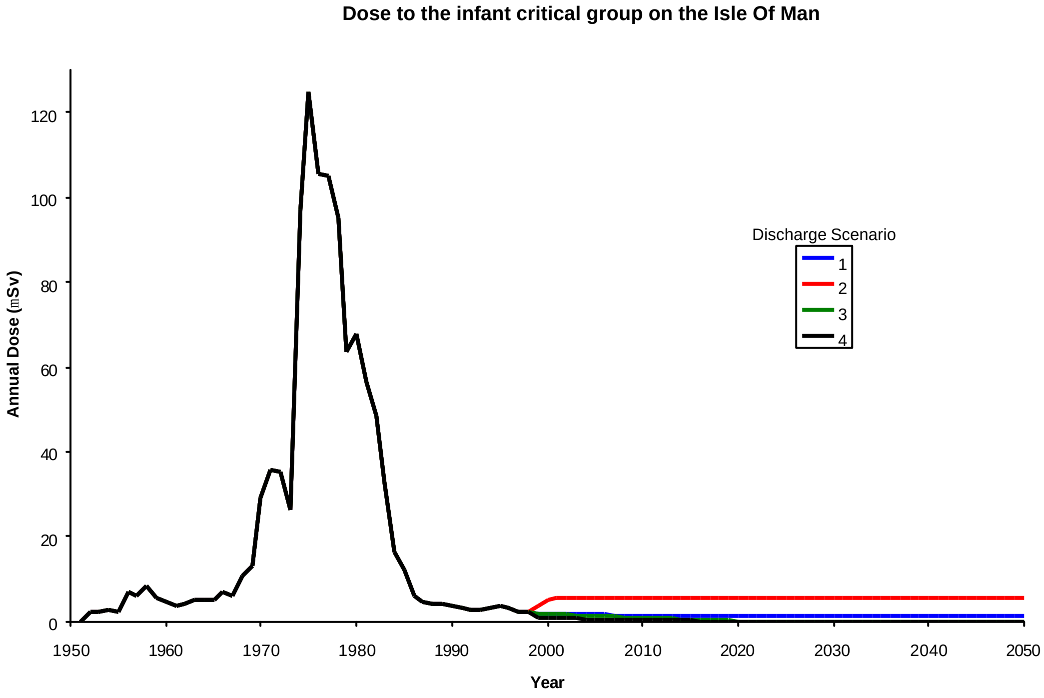


Figure 31: The dose to the adult critical group on the Isle of Man.

Scenarios: **One** - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



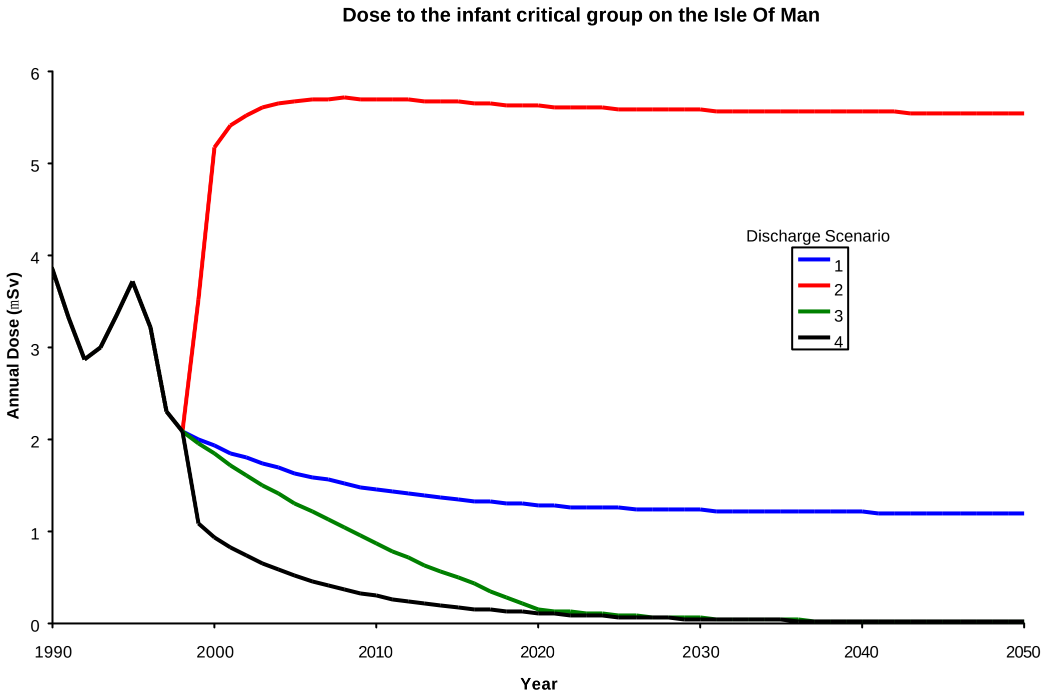
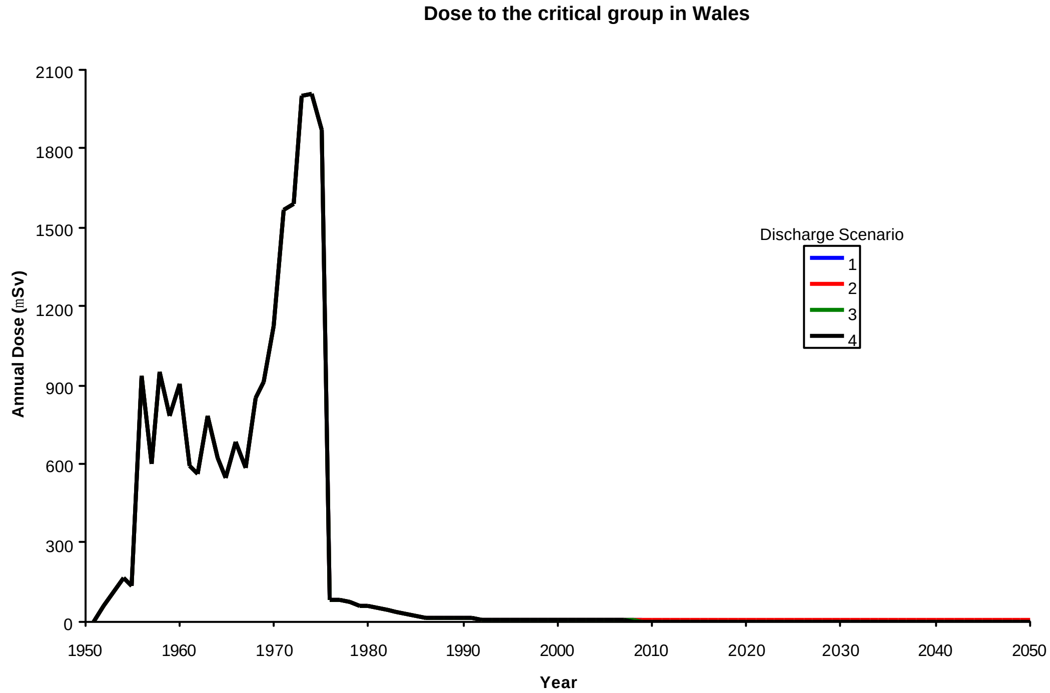


Figure 32: The dose to the infant critical group on the Isle of Man.

Scenarios: **One** - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



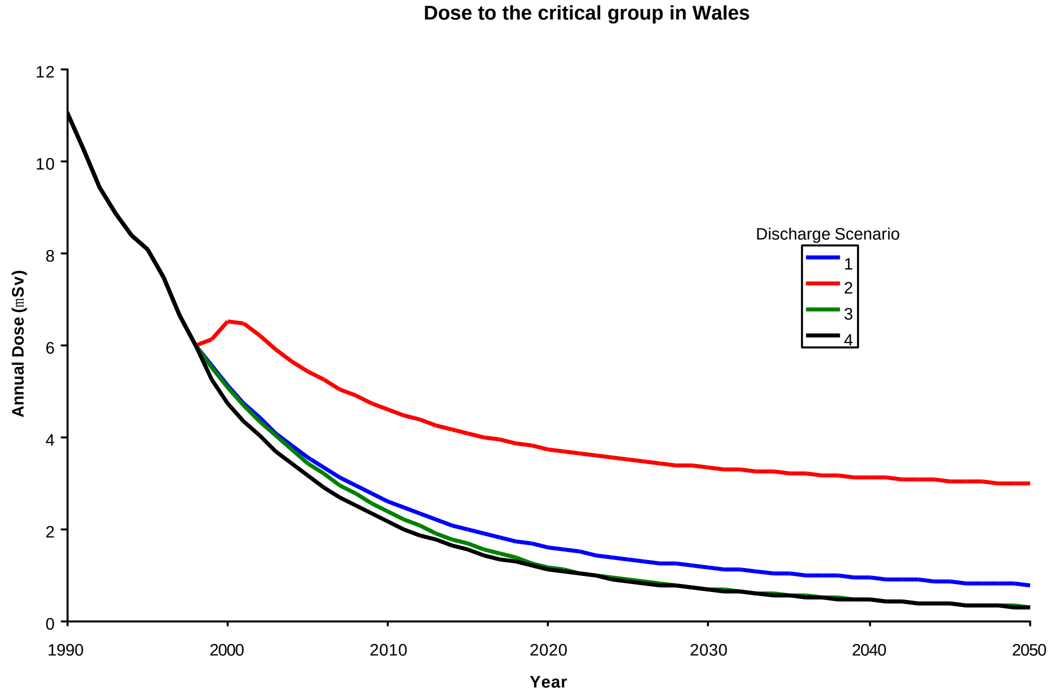
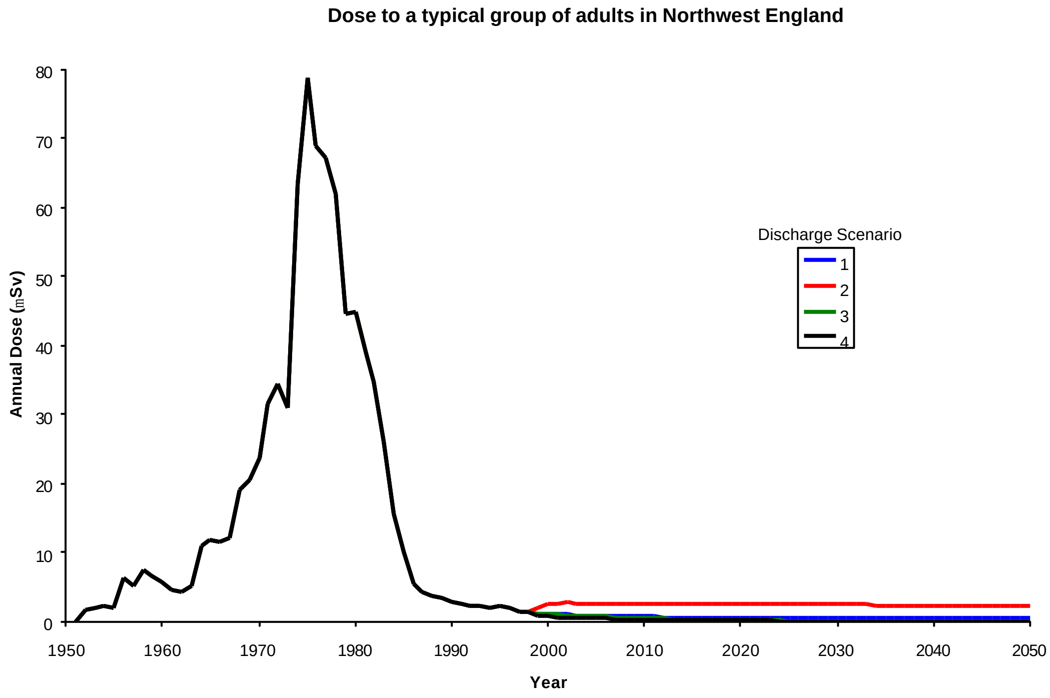


Figure 33: The dose to the critical group in Wales.

<u>Scenarios:</u> One - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



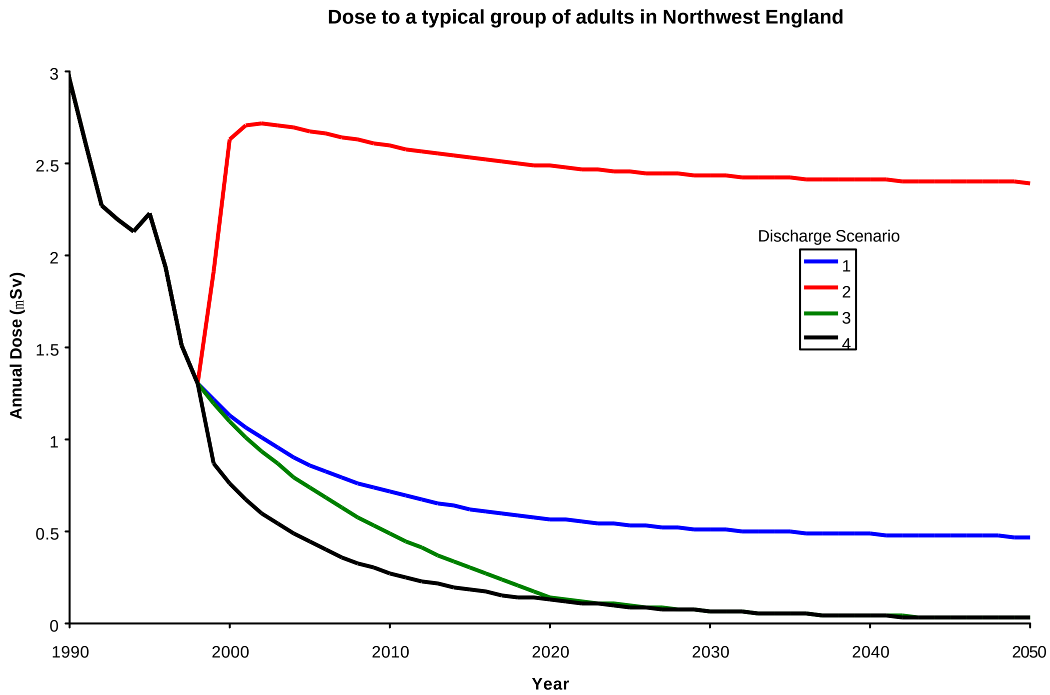
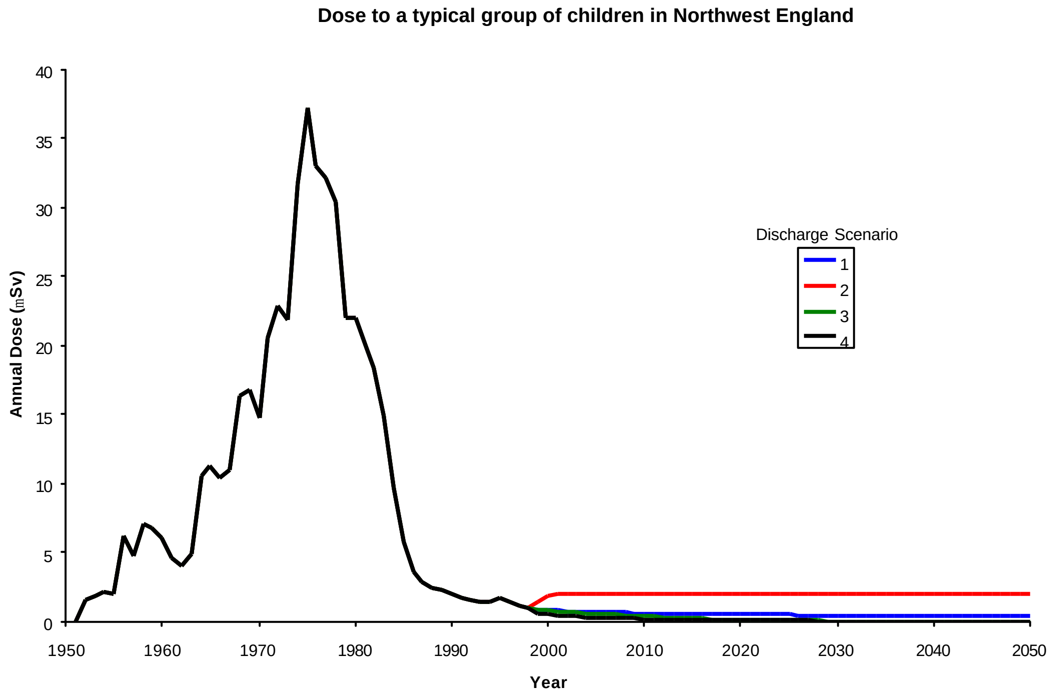


Figure 34: The dose to a typical group of adults in Northwest England.

Scenarios: One - Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



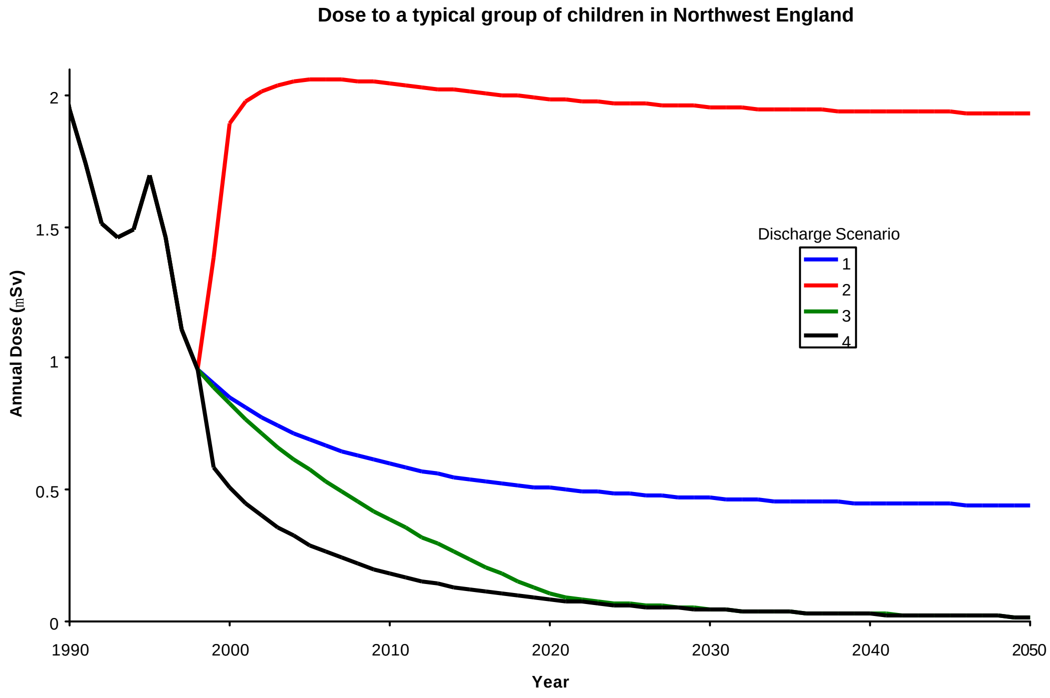
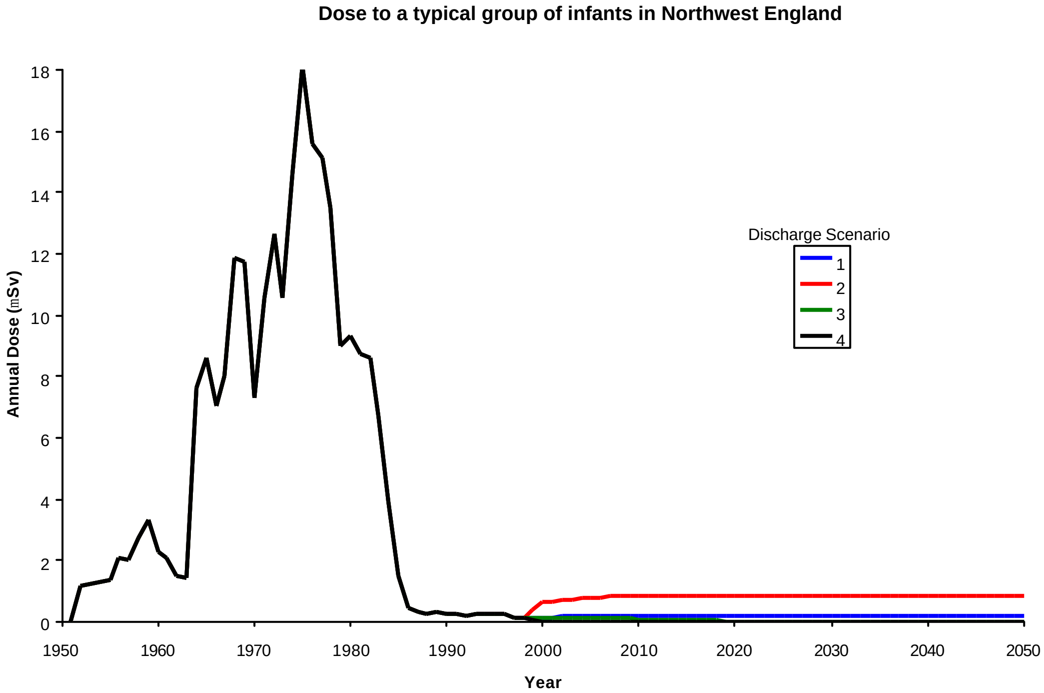


Figure 35: The dose to a typical group of children in Northwest England.

Scenarios: **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



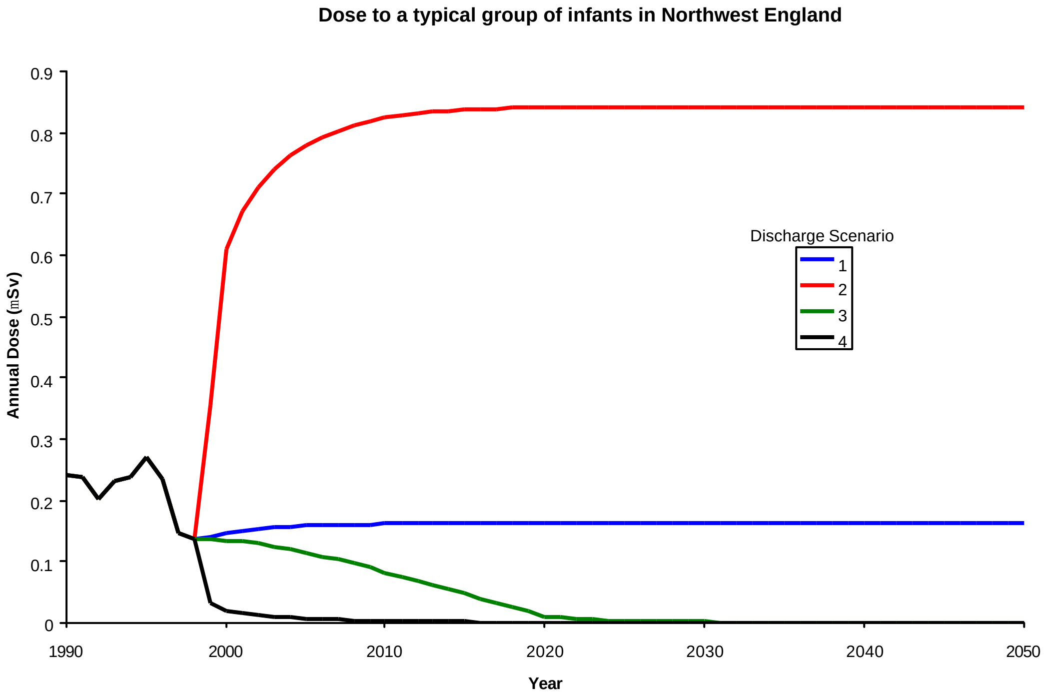
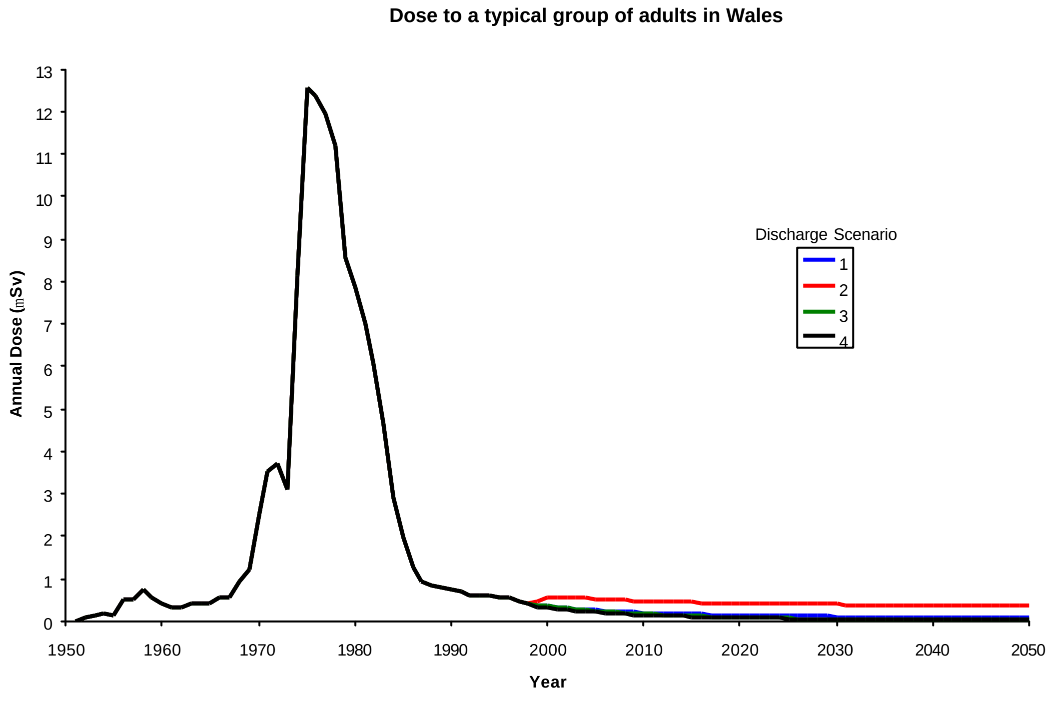


Figure 36: The dose to a typical group of infants in Northwest England.

__Scenarios:__ **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



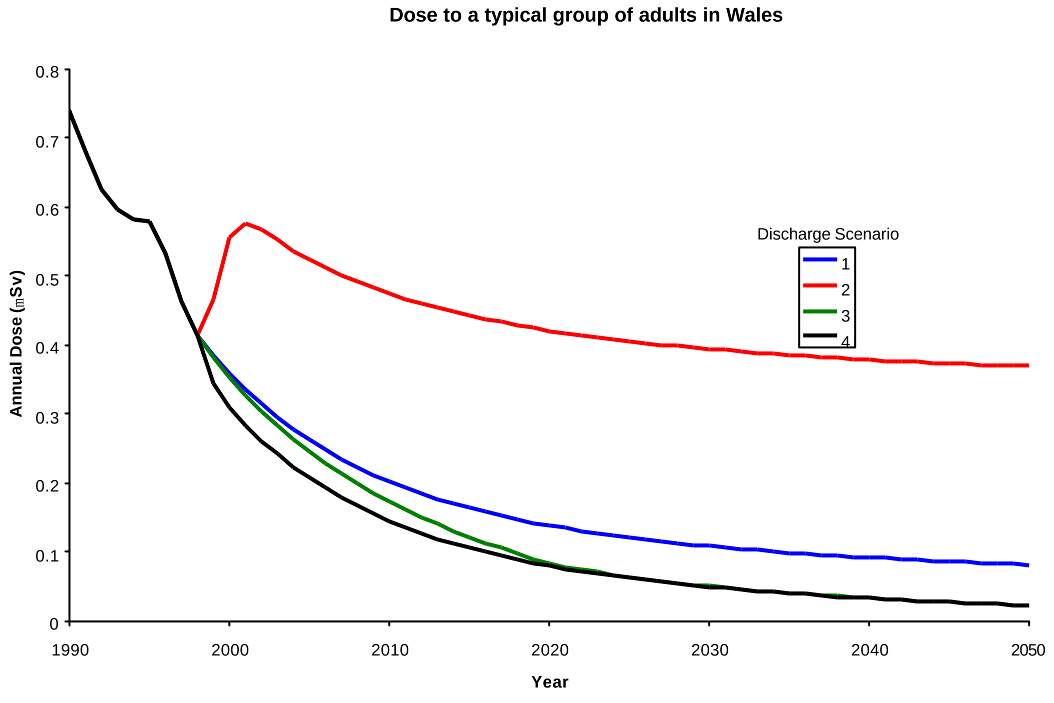
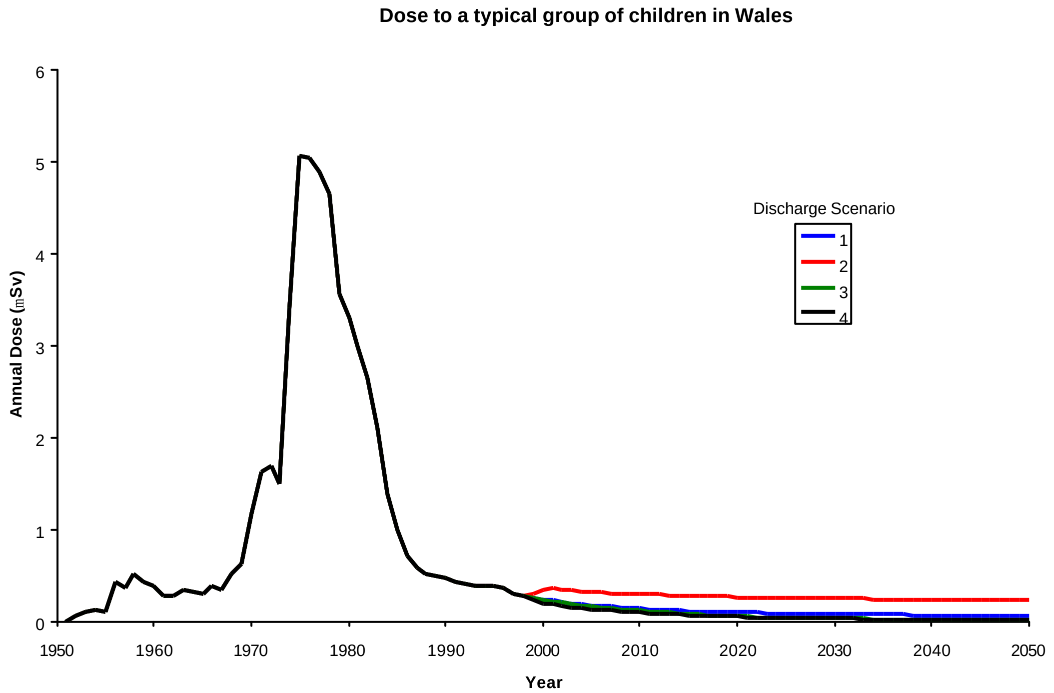


Figure 37: The dose to a typical group of adults in Wales.

<u>Scenarios:</u> One- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



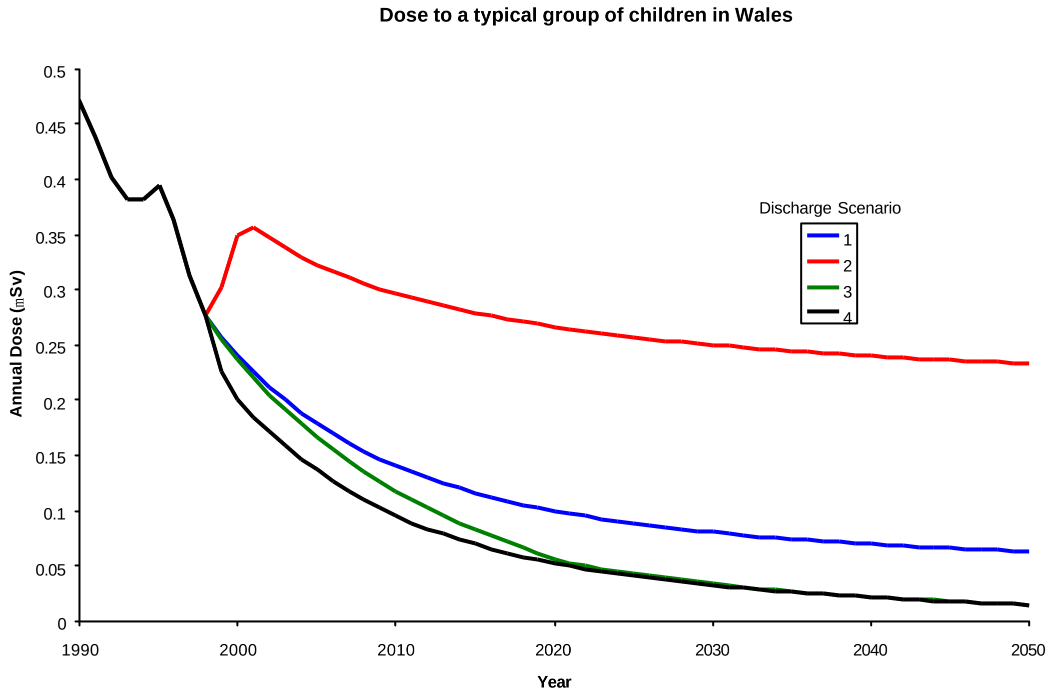
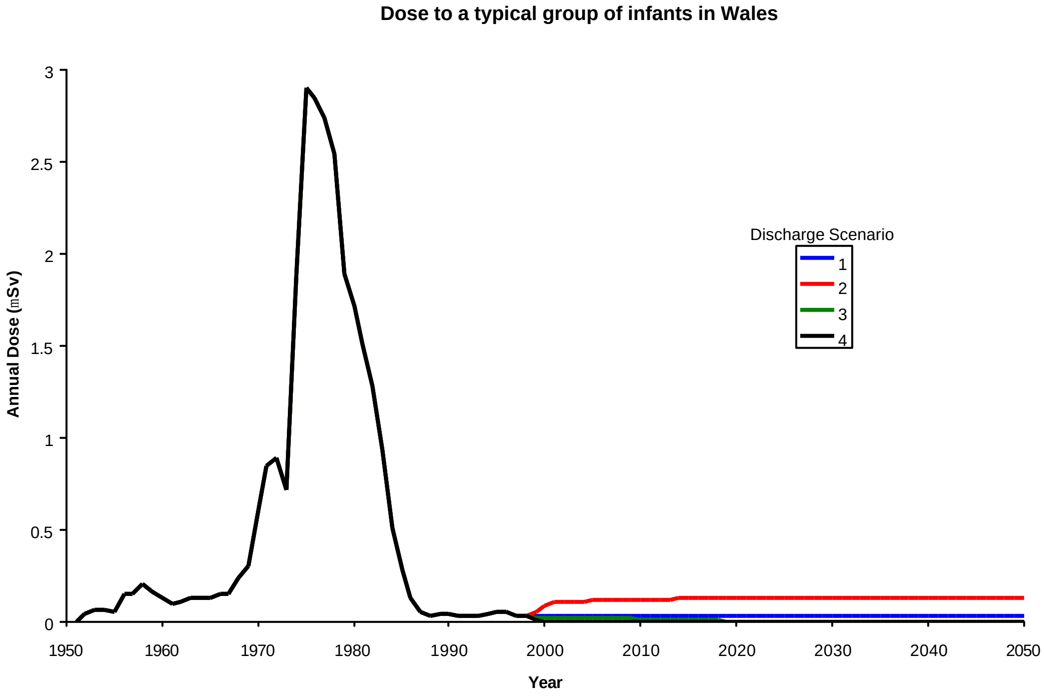


Figure 38: The dose to a typical group of children in Wales.

<u>Scenarios:</u> One- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



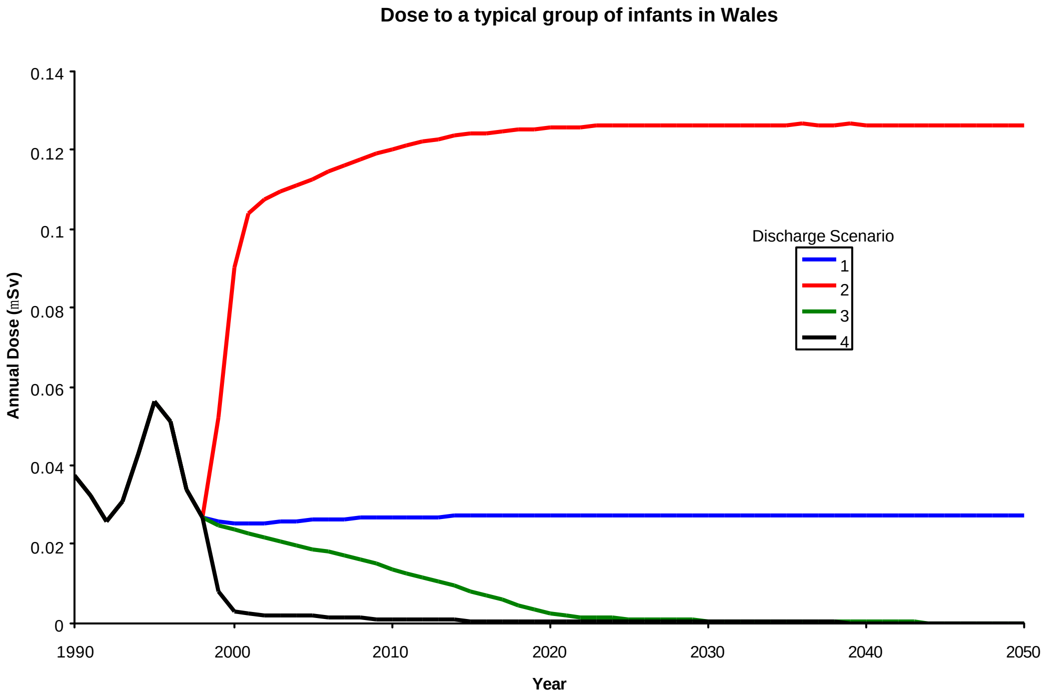
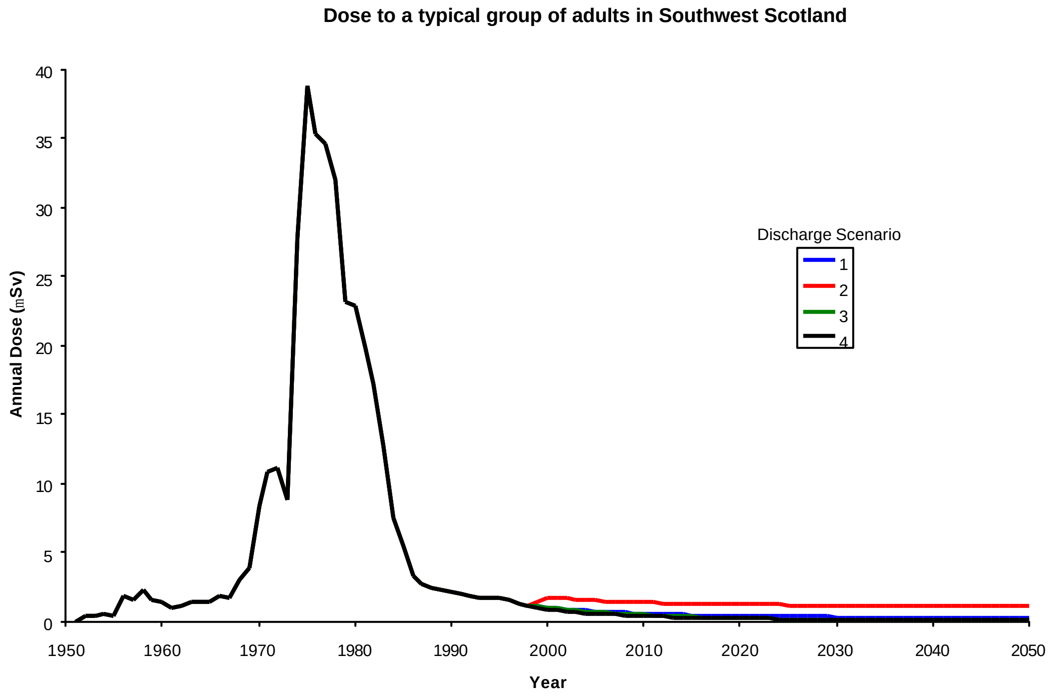


Figure 39: The dose to a typical group of infants in Wales.

Scenarios: **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



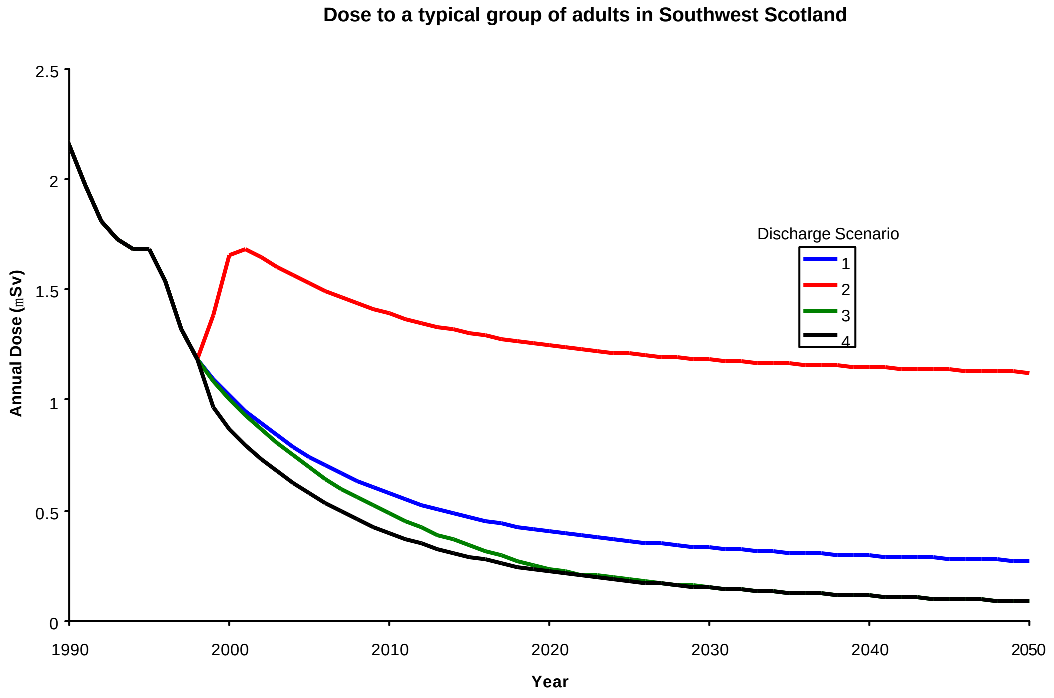
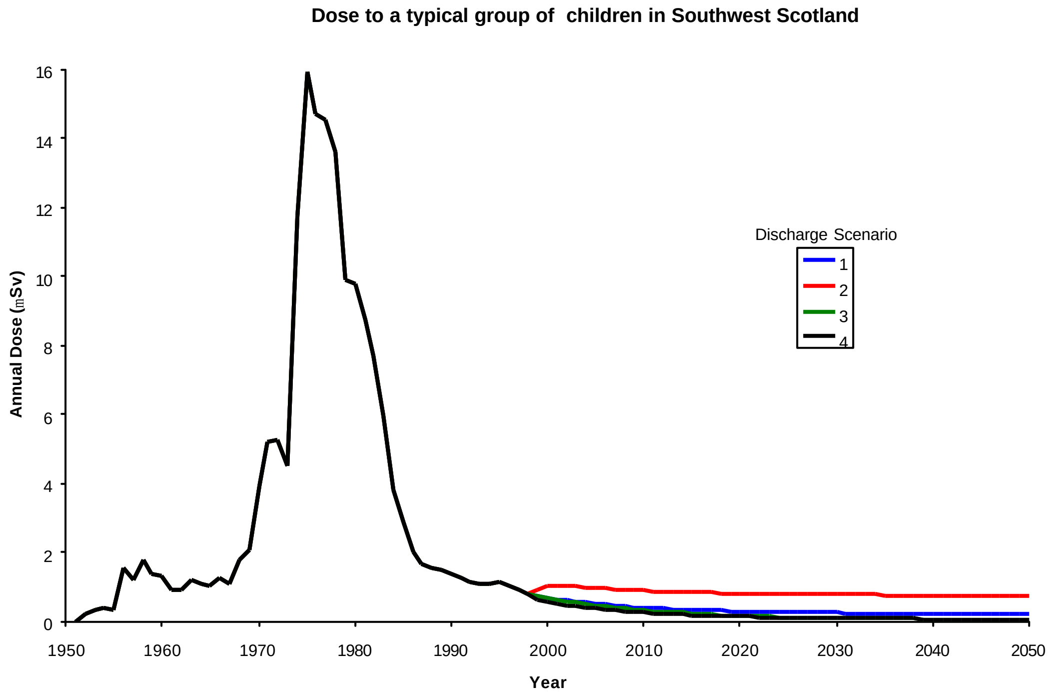


Figure 40: The dose to a typical group of adults in Southwest Scotland.

Scenarios: One- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



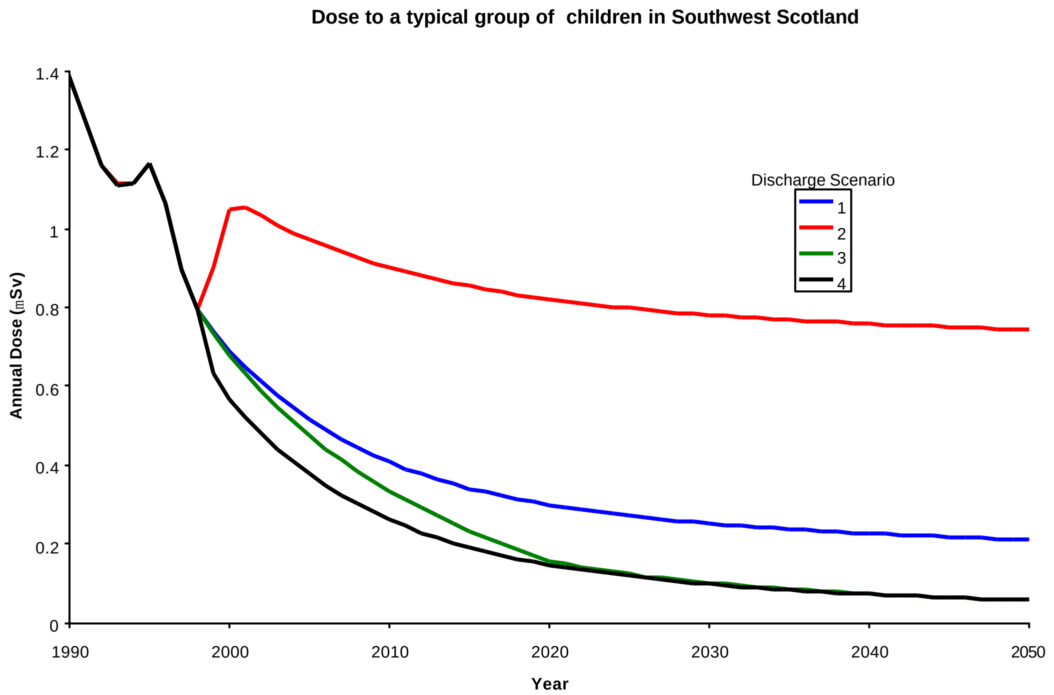
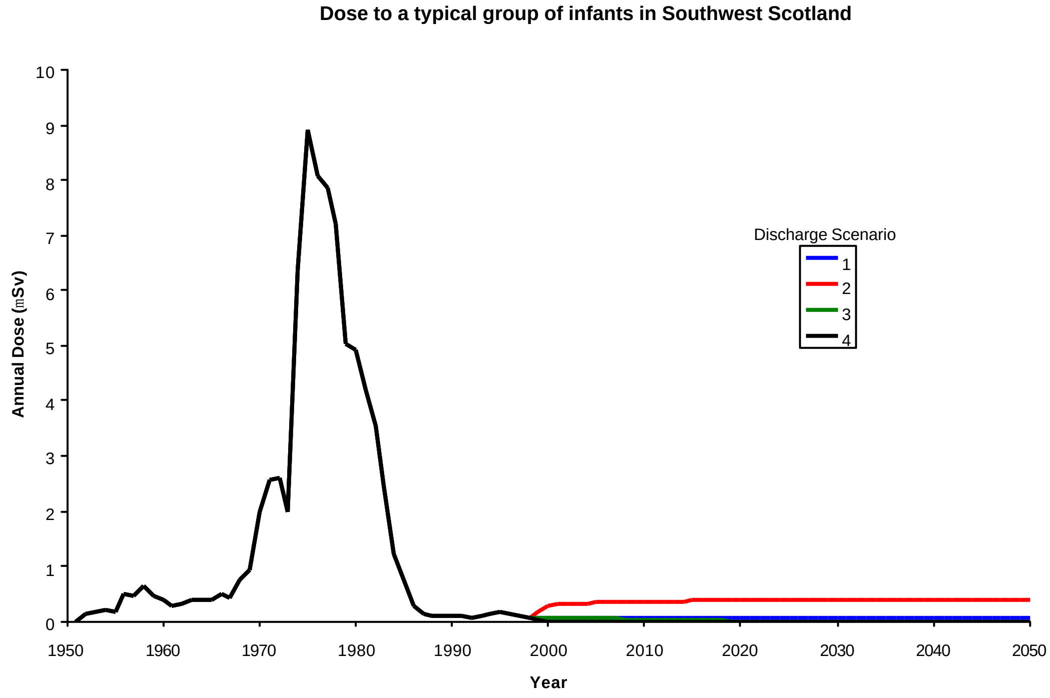


Figure 41: The dose to a typical group of children in Southwest Scotland.

Scenarios: **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



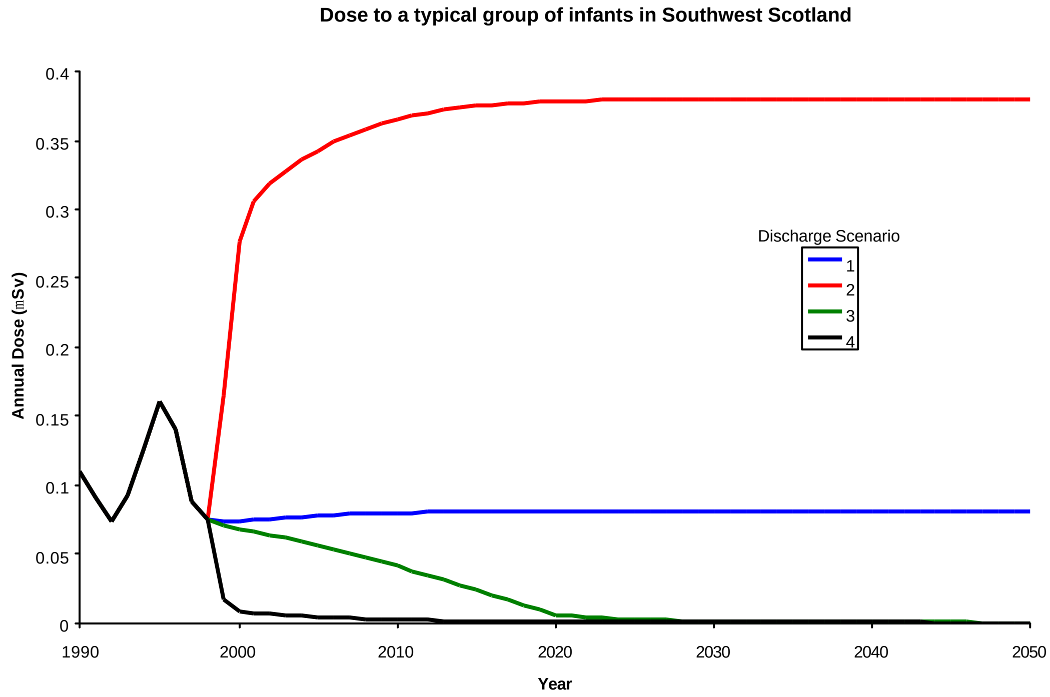
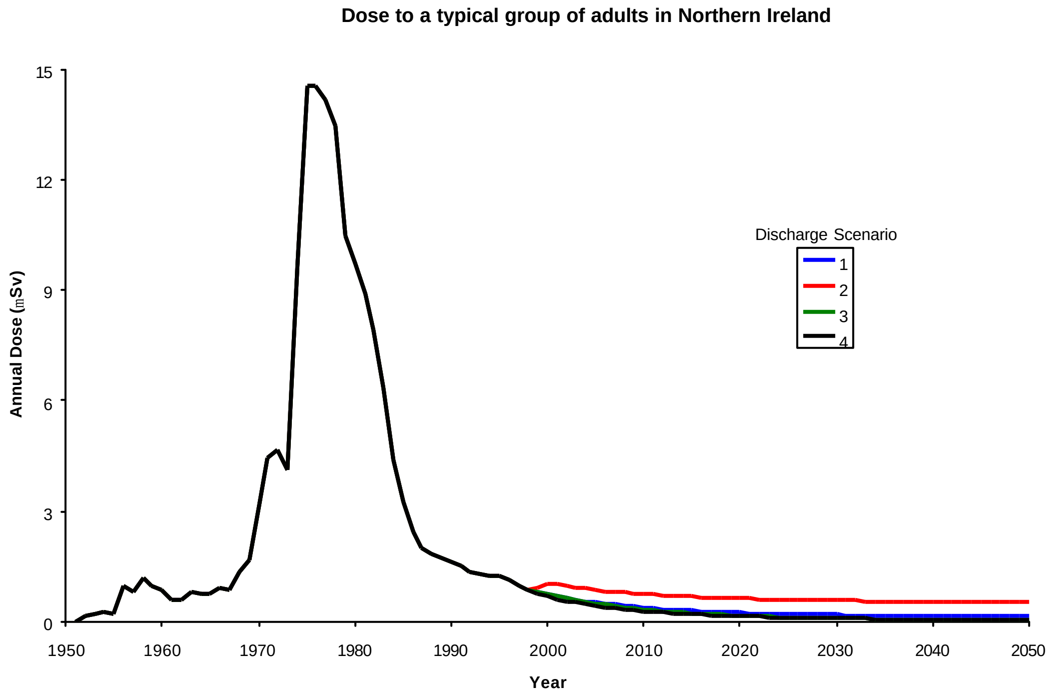


Figure 42: The dose to a typical group of infants in Southwest Scotland.

Scenarios: One- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



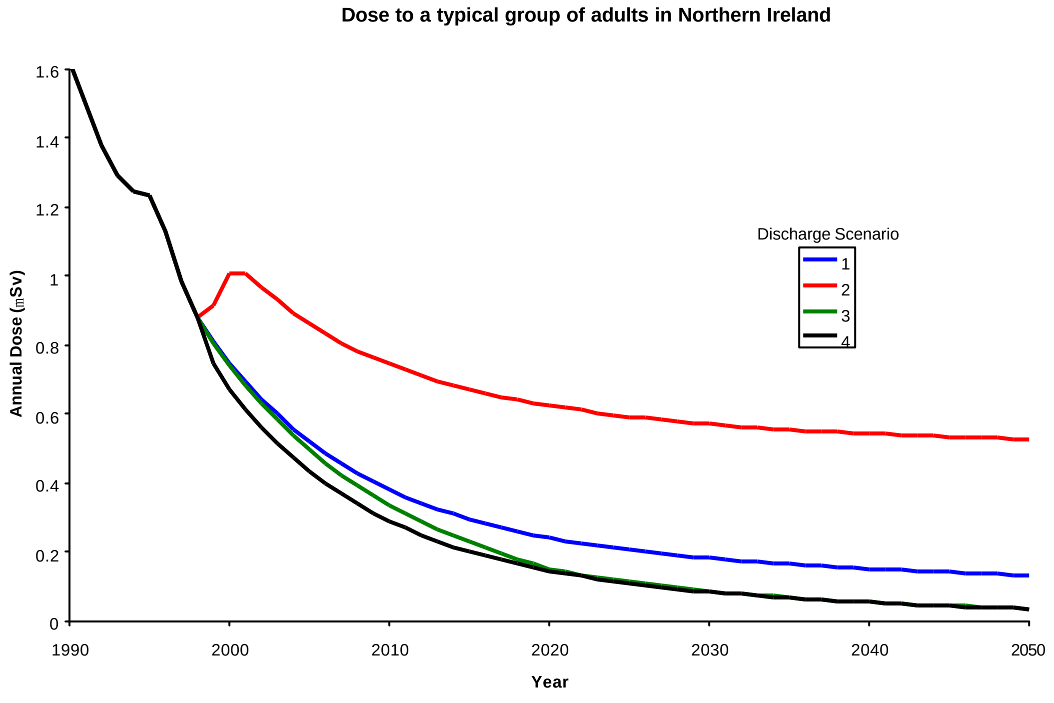
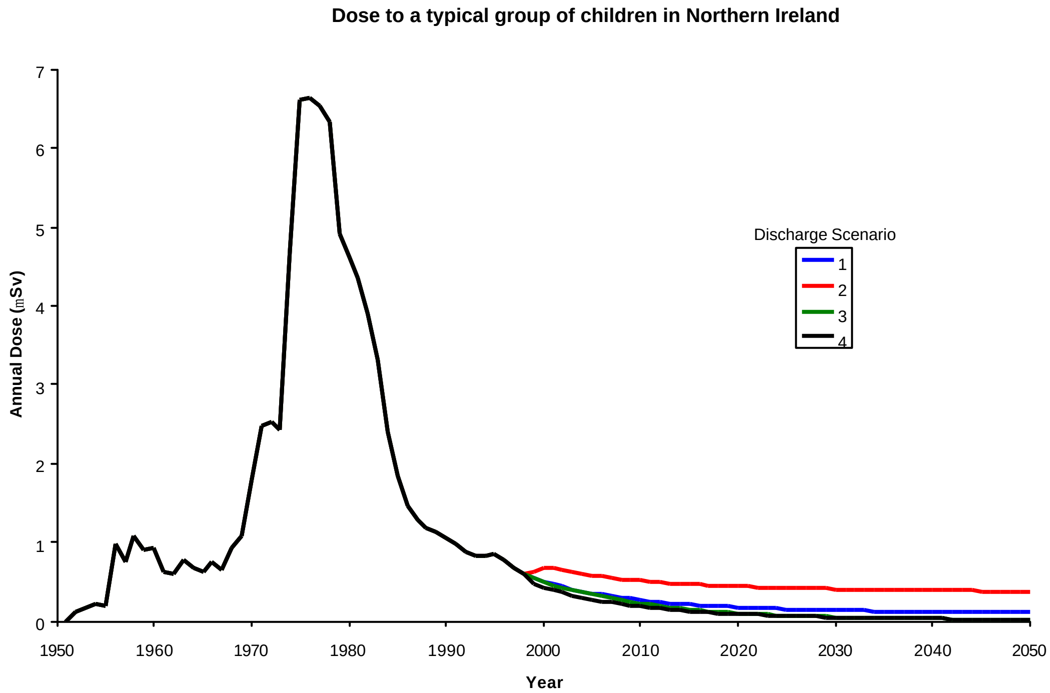


Figure 43: The dose to a typical group of adults in Northern Ireland.

<u>Scenarios:</u> One- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



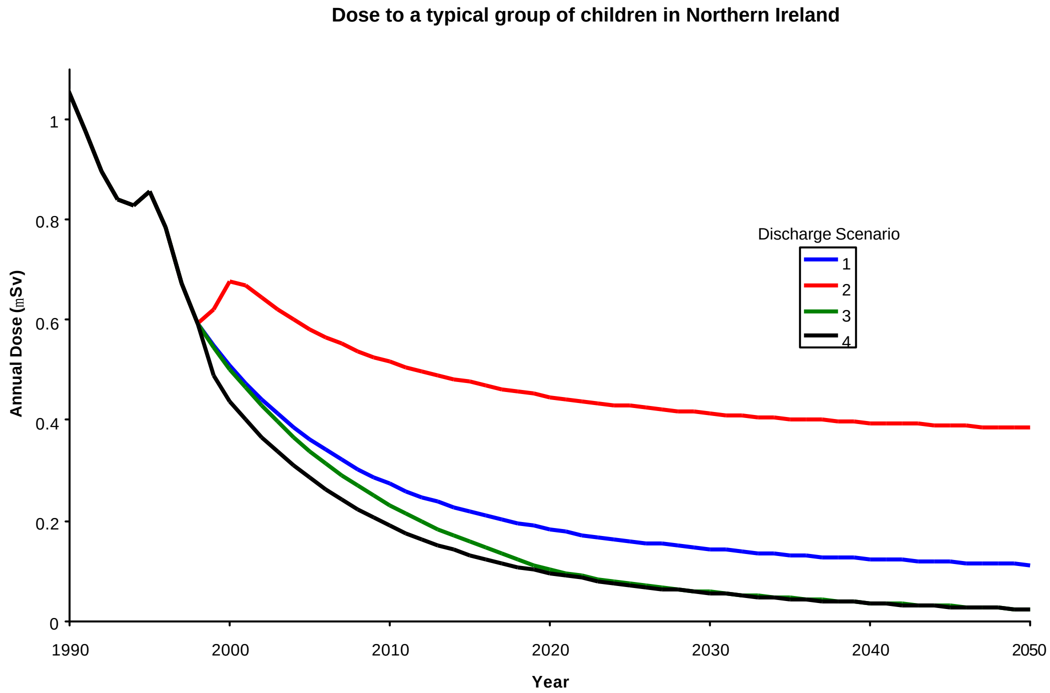
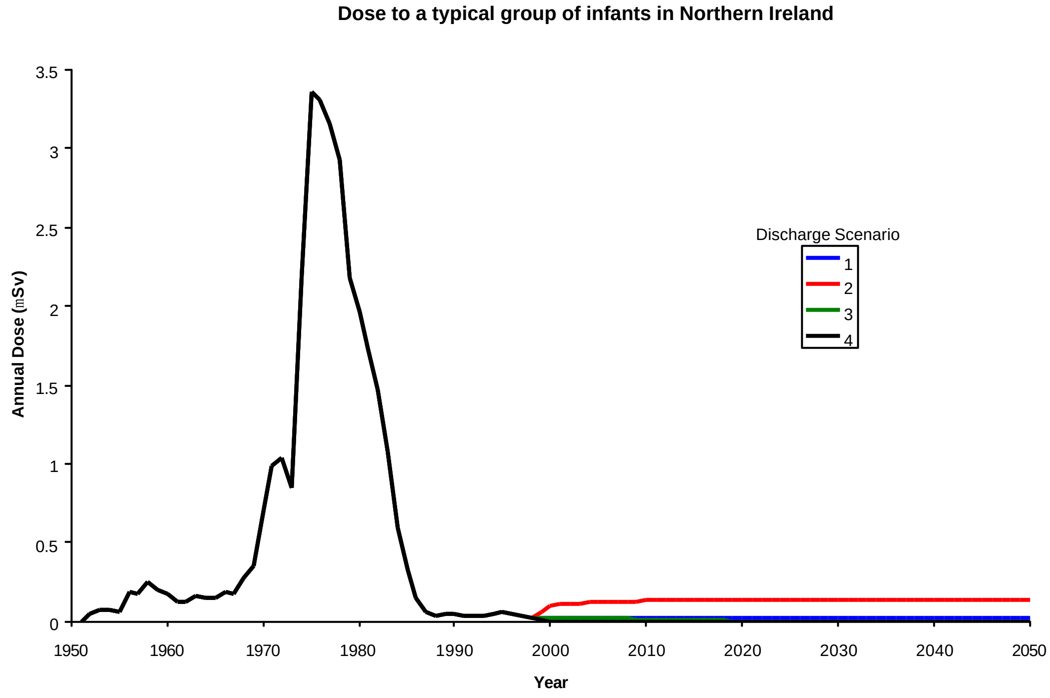


Figure 44: The dose to a typical group of children in Northern Ireland.

__Scenarios:__ **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).



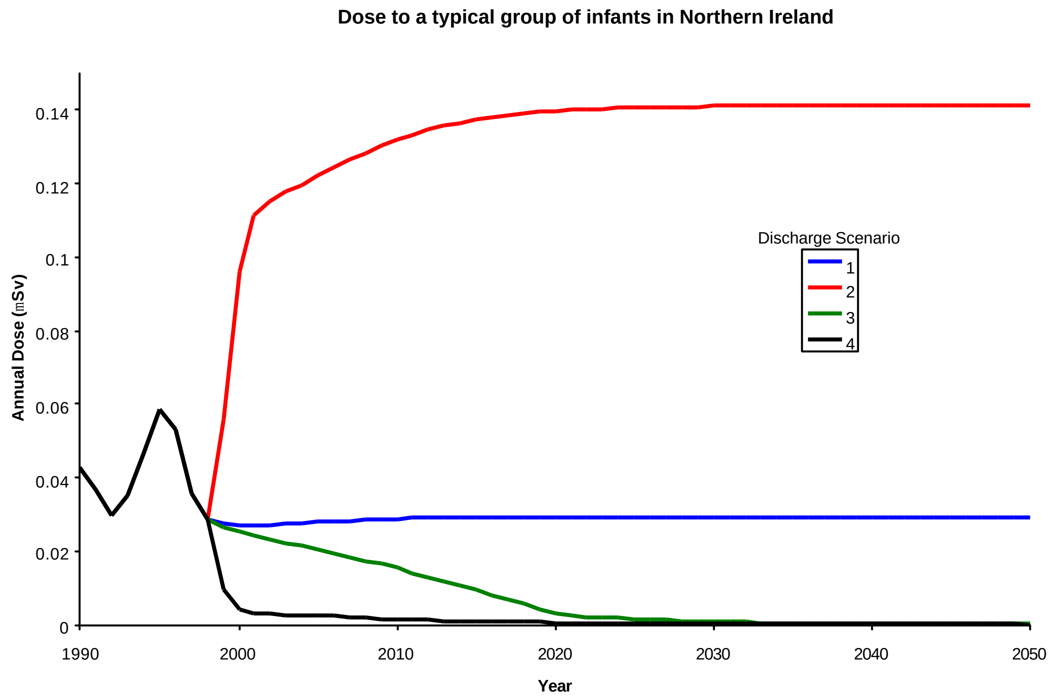


Figure 45: The dose to a typical group of infants in Northern Ireland.

__Scenarios:__ **One**- Constant discharge, equal to the discharge levels in 1998, until the year 2050; **Two** - An increase in discharges, with discharges equal to the current authorised limits, from the year 2000 until the year 2050; **Three** - Linearly decreasing discharges from 1998 levels to zero in the year 2020, and then zero discharges until 2050; **Four** - Total cessation of discharges at the end of 1998 (i.e. discharges are zero from 1999-2050).

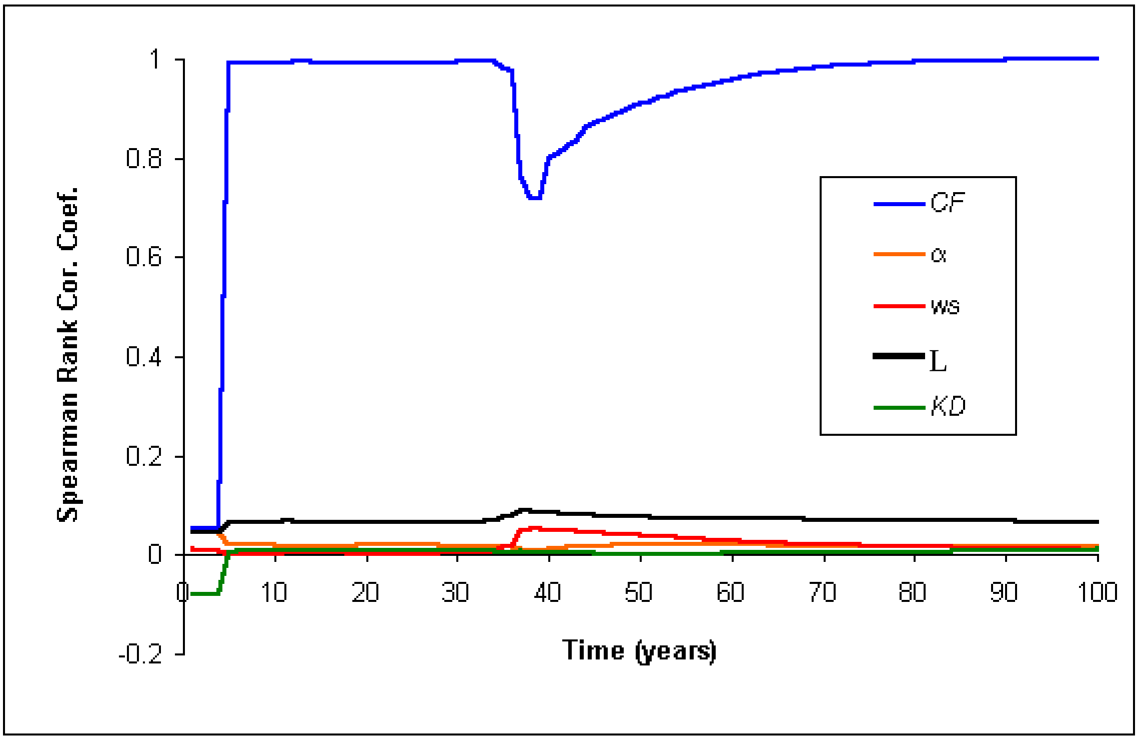


Figure 46: Comparison of the relative significance of potential error arising from variation of MARISA model parameters for ^{137}Cs concentration in fish.

The concentration factor (CF) is the most sensitive parameter with a Spearman rank correlation coefficient of between 0.8 and 1.0. Less sensitive parameters are the desorption rate (α), settling velocity (ws), bed mixing depth (L) and partition coefficient (KD).

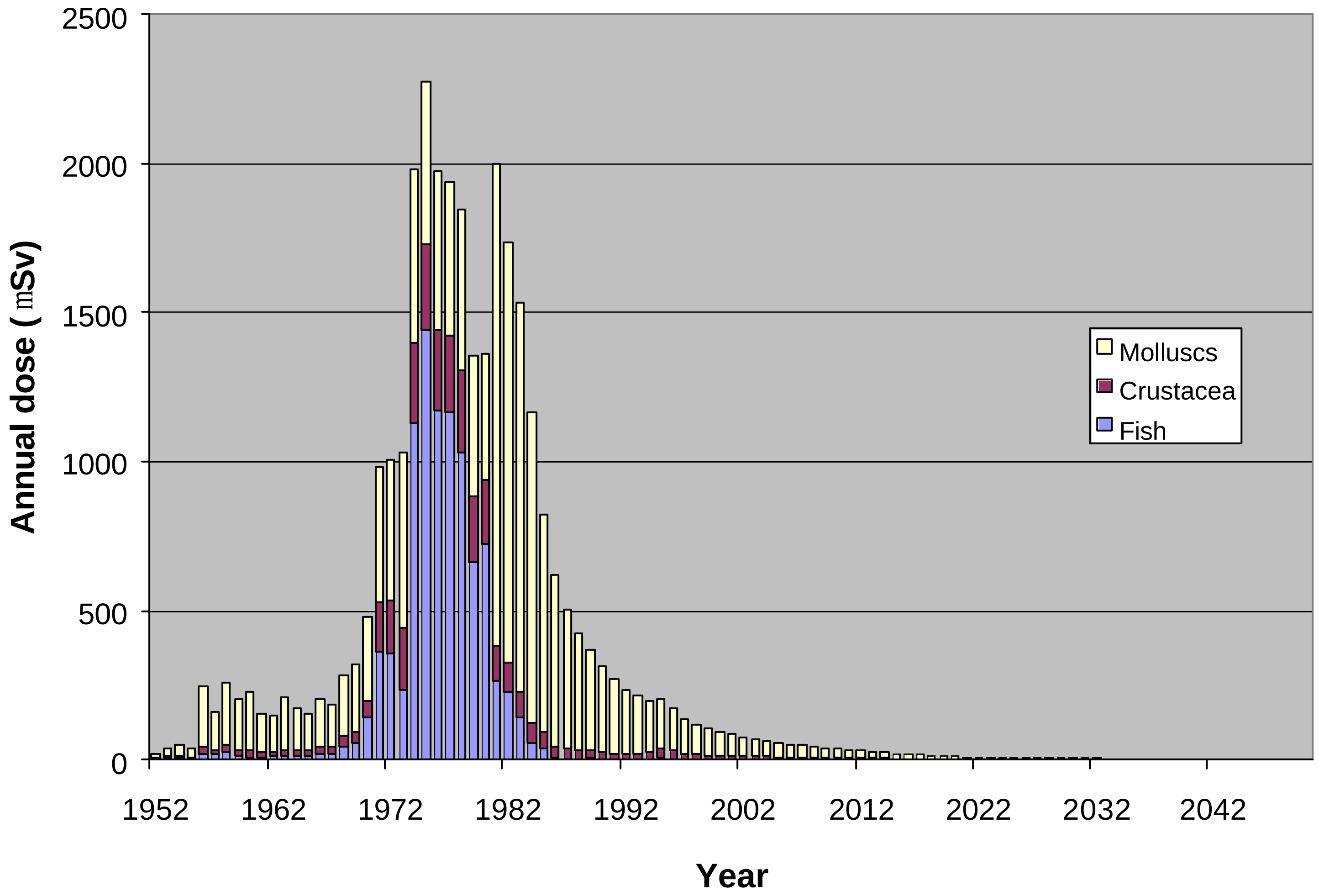


Figure 47: The annual dose to the critical group in West Cumbria broken down by exposure pathway.

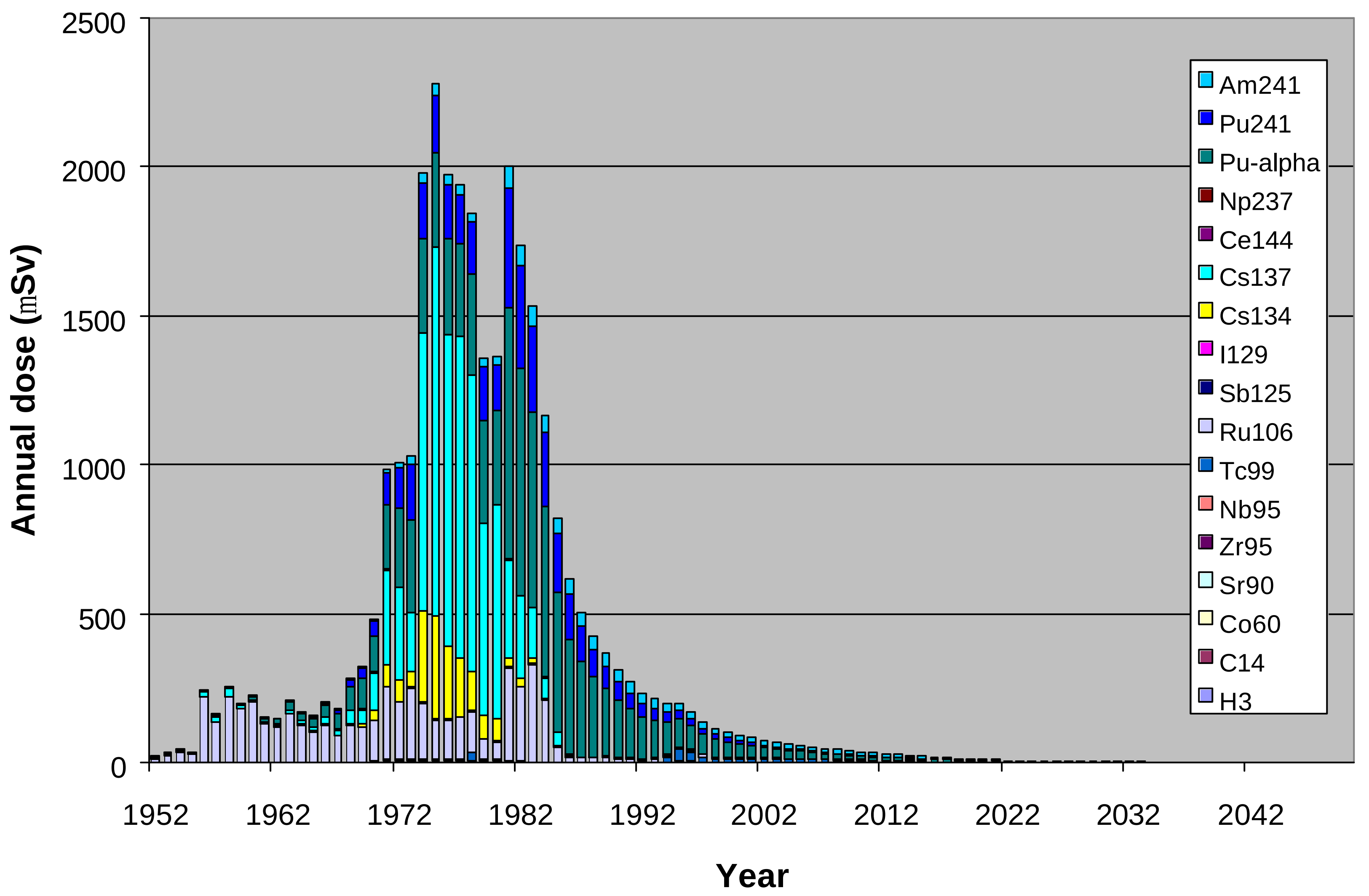


Figure 48: The annual dose to the critical group in West Cumbria broken down by radionuclide.

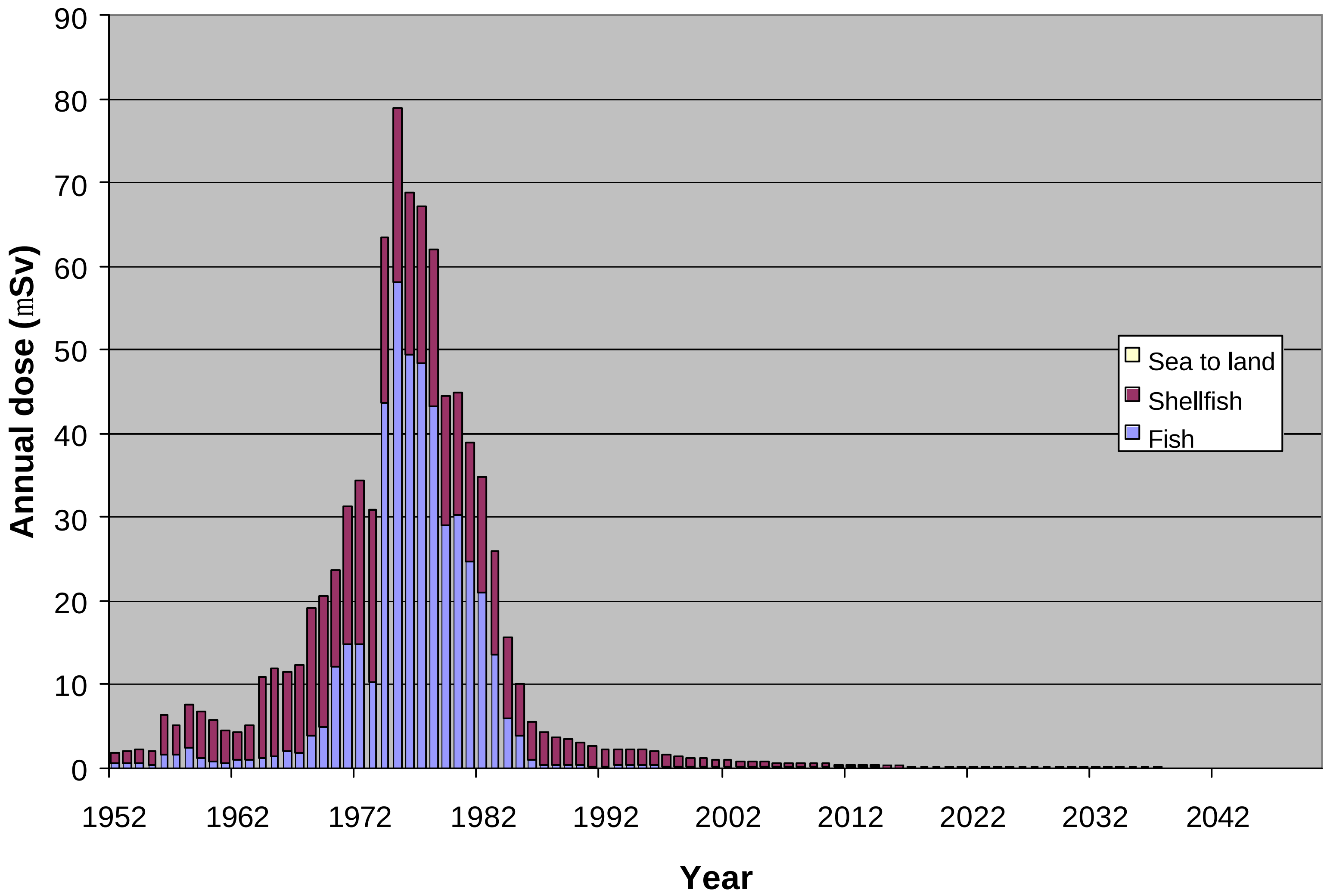


Figure 49: The annual dose to the typical group in Northwest England broken down by exposure pathway.

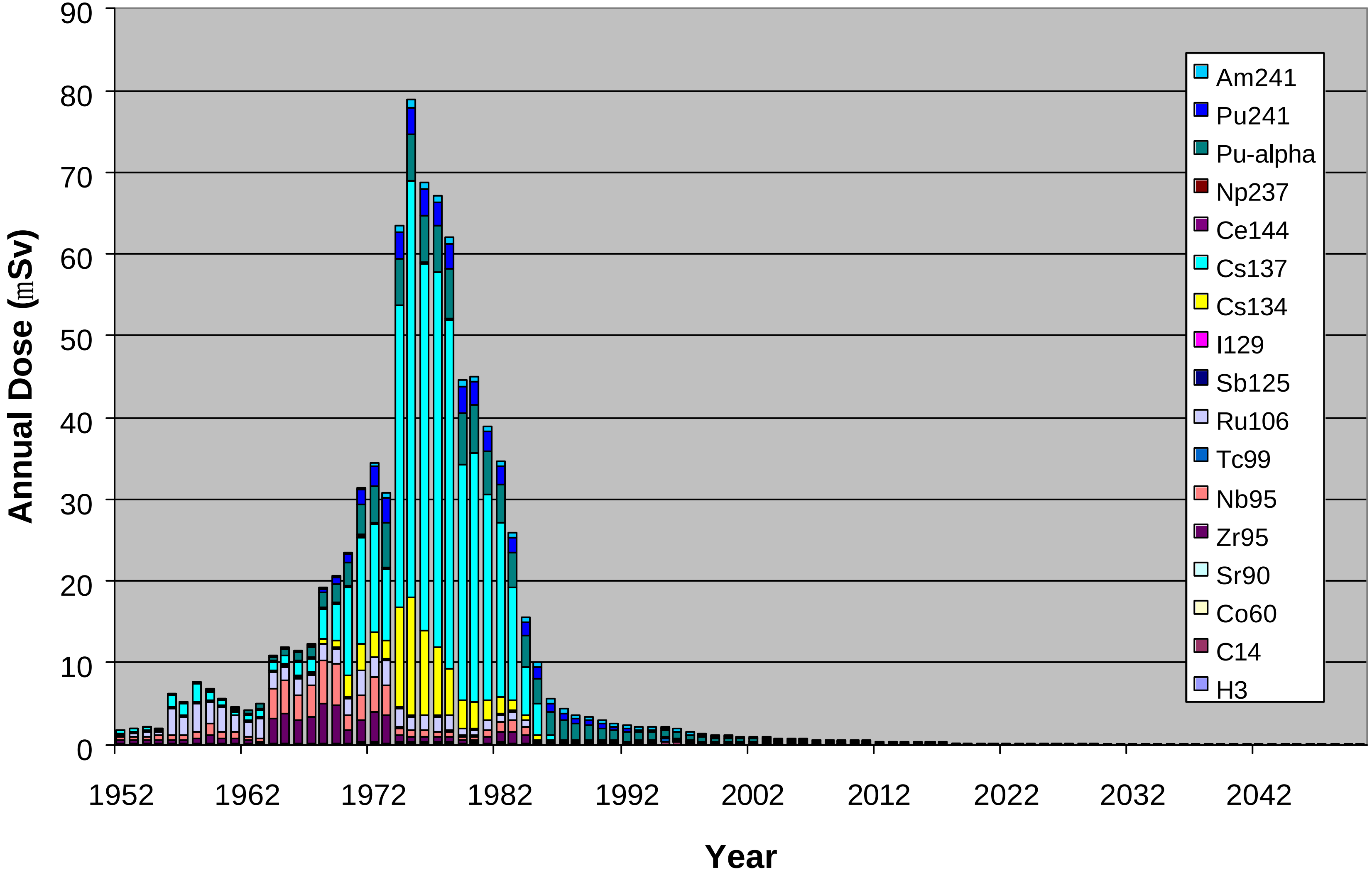


Figure 50: The annual dose to the typical group in Northwest England broken down by radionuclide.