NRG Report:
EU Dose Assessment and Discharge Database

River and Marine Discharges

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Summary

Periodically a survey of the radiological impact from routine releases by nuclear power stations and nuclear reprocessing plants in the European Union has to be made to visualise the environmental consequences, future prospects and policy. In these surveys the committed effective dose and the collective effective dose will represent this radiological impact on the adult population of the EU.

The last assessment covered the period 1977 to 1986. Hence, the aim of the current project, specified in tender document C1/SER/990066, was to calculate the individual doses and collective doses from 1987 to 1996. In this dose assessment, the calculations have been performed using the PC-CREAM package, while the site-specific discharges were taken from the Bilcom97 (compiled by the European Commission) via the EDDI program. NRG, as subcontractor, is responsible for the impact survey due to the routine radioactive effluent releases into surface waters. Accordingly, the present report deals only with the work approach and radiological consequences of releases into the aquatic environment.

Since the assessments were carried out using PC-CREAM, the nuclear sites with radioactive effluent releases were sorted into two groups: 'coastal' and 'inland' sites. The 'coastal' sites release their radioactive effluents directly into the marine environment. The 'inland' sites release their radioactive effluents into a river, which finally flows into the marine environment. The radioactive effluents from 28 'coastal sites' and 44 'inland sites' with one or more installations per site were assessed.

Coastal sites with releases resulting in relatively high individual doses received by the local population were the reprocessing facilities at Sellafield and Cap la Hague. In particular, the annual releases from Cap la Hague before 1991, have lead to individual doses larger than 1 mSv (the Euratom dose limit). The individual dose is calculated with rather conservative habit data. The major part of the high ingestion dose received by the local population stems from the consumption of locally caught molluscs. The radionuclide, which contributes mainly to this ingestion dose, is Ru-106 (half-life of about one year). As there was a reduction in the release of this radionuclide after 1990, the ingestion doses, as well as the total individual doses, were reduced to values below 0.5 mSv/year. Total individual doses for other coastal sites are less than 0.1 mSv.

The individual doses received by the local population of an 'inland' site, are relatively small in comparison to the doses received by the individual members of the population living at the 'coastal' site. Further, the total individual doses due to releases from 'inland' sites are much smaller than the doses due to releases from coastal sites. The individual dose as a consequence of the reprocessing site Marcoule (F) was, in 1996, roughly 0.31 mSv. Again the release of the radionuclide Ru-106, which accumulates in molluscs and crustaceans, is responsible for the relative high dose. The dose impact of other 'inland' sites is below 0.04 mSv. The accumulation of doses due to releases from several sites along the same river, were estimated for the 'real' Loire, Rhine and Rhone sites. The actual river dose for these three rivers is below 0.01 mSv.

1 Introduction

NRG, the Netherlands, is a subcontractor of the project *Assessment using PC-CREAM of the radiological impact on the population of the European Union of discharges from nuclear EU sites between 1987 and 1996*. The aim of the project is to calculate the collective and critical group doses to the adult population in EU-Member States resulting from routine radioactive liquid and gaseous releases during the period of 1987 to 1996 by nuclear power stations and nuclear fuel reprocessing plants in the EU [1]. A previous dose assessment study covered the period 1977 – 1986 [2].

The collective dose gives a reasonable representation of the total health detriment of a whole population; because this dose gives an indication of the exposure of a relatively large group of people with no special behaviour. Collective dose to populations due to routine discharges may occur over long time periods into the future and at such distances from the discharge point that radionuclide levels in environmental materials are below the limits of detection. Therefore, mathematical models have to be used to calculate collective dose [3]. In the current assessment this population is assumed to be all adults living in the EU who have the same intakes and metabolism. In the current assessment the collective dose was predicted after 500 years (approximately 10 generations). This integration time is somewhat arbitrary, but can be seen as an indication of the very long-term risk that might arise given the continued use of nuclear energy.

The critical group dose can be considered as a personal radiation risk, the so-called effective dose. The specific habits of such a critical group, for instance their food consumption, are therefore very important aspects. Critical group doses from routine discharges usually occur close to the release point. They are calculated from measured concentrations of radionuclides in environmental materials together with some knowledge of the habits of the most exposed group of people [3]. This group has to be small enough to be relatively homogenous with respect to age, diet and those aspects of behaviour that (could) affect the received doses [4]. However, to realise an average behaviour and homogeneity of high quality, this group must not be too small. Internal irradiation from radionuclides inhaled and / or ingested forms the most important part of the effective dose. This is because following the intake of radioactivity the internal exposure could continue, depending on the biological and radiological behaviour, for several tens of years. In contrast, external exposure stops when the radiation source is removed. As a consequence of this, the time period plays an important role in the individual doses calculations. Since, in this project, only the individual doses to adults were assessed an integration time of 50 years was chosen; this conforms to the committed equivalent dose as defined in ICRP* publication 60.

NRG's part of the work was the calculation of the annual collective dose and critical group doses for the EU adult population due to routine radioactive liquid releases into surface water from EU nuclear sites, and is reported in this report. This aquatic dose assessment was executed for all nuclear power stations and reprocessing plants that are entered in the Bilcom97 database [5]. The Bilcom97 database was set-up by the European Commission and covers the yearly discharge rates of all-existing nuclear sites within the EU. However, the nuclide breakdown for all years was missing, therefore, the database was completed during the project and finally the nuclide discharges were taken from the program EDDI.

The period of interest is restricted to the years 1987 and 1996. As already mentioned this project is a follow-up of a previous dose assessment study, done for the period 1977-1986 [2]. Hence, some results of these previous calculations have been used to check the assessment approach of the current study.

One of the boundary conditions of this assessment is that the radiological impact analyses must be carried out using the PC-CREAM suite [6]. This PC software package contains six applications to evaluate the individual and collective doses of routine discharges of radioactive effluents into the environment, based on a

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* International Commission on Radiological Protection

comprehensive methodology, CREAM*. The development of this tool was carried out under contract to the European Commission by several European institutions (co-ordinated by NRPB† in the UK).

2 Assessment Methodology

The individual doses and collective dose to the population of the European Union have been calculated based on routine discharges from nuclear sites into the aquatic environment. Only those nuclear sites that fulfil the following requirements have been included in this study [1]:

- nuclear power stations of capacity greater than 50 MW(e);
- nuclear fuel reprocessing plants;
- operational in the EU member states between 1987 and 1996.

Furthermore, the Bilcom97 database [5] acted as data bank to determine the nuclide spectrum of the discharge release for a site in this project. This database contains discharge rates for 97 nuclear sites operational in the (15) EU countries and is set-up by the European Commission. Thereafter the program EDDI generated the amount of discharge per nuclide for the years 1987, 1991 and 1996 (with the exception of Sellafield and Cap de La Hague where discharge data for the whole period 1987-1996 were used).

The assessment must be made using the PC-CREAM (version 98) software package [6]. This tool was developed, under contract to the European Commission Directorate-General Environment, to evaluate the radiological consequences of discharges of radioactive effluents during normal operations. The theoretical background of the system was based on the comprehensive CREAM methodology. This methodology, based on the most recent ICRP recommendations, consist of a series of models and data which assess the transfer of radionuclides through the environment, the pathways by which people may be exposed, and the resulting health detriment [7].

Within this study two PC-CREAM applications have been used to predict the impact due to releases into the aquatic environment, namely DORIS and ASSESSOR. A brief summary of these applications is given here, while a more extensive description can be found in the PC-CREAM user's guide [8]:

- DORIS estimates the dispersion of radionuclides in the coastal waters around Europe due to discharges into the (local) marine environment, and was used here to create data libraries for the so-called marine module of ASSESSOR.
- ASSESSOR was used for the radiological impact assessments in terms of individual and collective doses, using the marine and river modules.

The assessment was split-up into two parts depending on the origin of the nuclear sites. The first group contained nuclear sites that release their radioactive effluents directly into the marine environment (the 'coastal' sites). The other group covered all sites that release into a river, which eventually flows into a sea (the 'inland' sites).

To conform with the previous study [2] three major European rivers were defined for the so-called 'inland' sites, namely the Loire, the Rhine, and the Rhone. The characteristics of the actual river, in which the site discharges, and the geographical position of the actual river and site were criteria for the major river selection. With the three main rivers the radiological impact was calculated for river food consumption and occupancy along the river. In addition the river model was used to make predictions of the activity concentrations in the marine environment. These concentrations were used to assess the consequences of marine food consumption and exposure due to beach occupancy.

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* **C**onsequences of **R**eleases to the **E**nvironment: **A**ssessment **M**ethodology

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The (PC-CREAM) impact analyses of the so-called 'coastal' sites were performed in a relatively straightforward manner and therefore need no further description here.

All the existing PC-CREAM exposure pathways were taken into account to be certain that the highest critical group dose levels due to a specific habit were found. These pathways are: freshwater fish consumption; ingestion of drinking water; consumption of marine foods such as fish, crustaceans and molluscs; sea spray inhalation; and external exposure due to radiation from sediment and fishing gear.

The country-specific habit data of food consumption, inhalation rates and (beach) occupation times were incorporated in the assessment. Further it is assumed that these parameters, which define the habits of a population, are consistent over the period of interest: 1987 - 1996. The FAO* statistics form the base of most of the habit parameters, which are summarised in a NRPB note [9]. But in the case that extra information (not in this note) was needed the default PC-CREAM parameters, as described in RP72† [7], have been included in the analyses. All applied habit data parameters are listed in chapter 4.

For efficiency reasons, a flexible and amendment friendly approach was set up to perform this dose assessment study. One of the basic reasons for this approach was to perform the PC-CREAM calculations from unit releases. The site-specific discharge rates can then be scaled. In the case of any changes in the site-specific discharges it would be relatively easy to repeat the calculations. A new situation could arise because of another query for instance. Updates of discharge data or changing the period of interest are examples of a new situation.

The arrangement of this report is consequently in line with the above-mentioned approach. The PC-CREAM calculations, based on a unit discharge rate, will be outlined in chapter 4 in more detail. The adaptation of the PC-CREAM results in respect to the site-specific (yearly) release rates are elucidated in chapter 5. Excel worksheets [10] were created for that process.

The results in terms of the radiological impact to the European population are reported briefly in chapter 6. In Chapter 7, a reassessment is described for the sites with the highest dose impact on the EU population. Chapter 8 describes an evaluation of this assessment and in chapter 9 the conclusions are given.

3 Discharge Database

The European Commission (EC) has compiled the (Microsoft Access) database Bilcom97 [5], in which site-specific discharge data are obtained for the (civil) nuclear installations in Europe. The nuclear discharge rates in this database are specified in four categories, namely aerosol, gas, halogen and liquid. Since NRG was responsible for the radiological impact of routine releases into the aquatic environment to people inside the European Union, this report will only refer to the liquid category.

The data in the Bilcom97 database cannot be used directly in the PC-CREAM package. Therefore an interface program EDDI [11] was developed (by NRPB) to obtain the discharges for a specific site and a specific year. After designing, implementing and testing the interface program, associated NRPB staff compiled the discharge files that were used as input in this dose assessment study. The aquatic discharge data produced was sent to NRG and adopted into their radiological impact analyses of liquid discharges as described in the current report.

In the Bilcom97 database the discharge data is often given by type of activity, e.g. total gamma and/or total β, rather than by radionuclide, which is necessary for a PC-CREAM analysis. Therefore if this is the case, the type of activity has to be broken down for this dose assessment study. The NRPB has developed the interface program EDDI in which the total activities are broken down into individual radionuclides. Because the EDDI files were generated at the final stage of this assessment project, the spectrum of released radionuclides per site was taken from the Bilcom97 database. This means that from the EDDI data only the specific amount of releases per nuclide, which belongs to the 'Bilcom97' spectrum, is used as site-specific discharge data for the dose

* United Nations Food and Agriculture Organisation

† Radiation Protection 72

calculation. Each nuclear site has a different spectrum of released radionuclides. Hence the extra radionuclides which should be added when using the EDDI files, but were neglected in the present dose calculation, are also different per site.

From an evaluation of those radionuclides from each site that were not included, it was found that the most significant radionuclides were already present in the Bilcom97 database and consequently the contribution of these radionuclides to the total dose was small. To illustrate which extra radionuclides were neglected in the calculation, the annual releases from two sites are presented here as an example. Due to the fundamental design differences between a Boiling Water Reactor (BWR) and a Pressure Water Reactor (PWR), one of each type are shown. Both sites have two NPP's and a comparable total electrical output of about 1300 MWe. In Table 1 the annual release of the two BWR's at Gundremmingen in 1991 is presented. In Table 2 the annual release of the two PWR's at Bellevile in 1996 is presented.

In the case of Gundremmingen, shown in Table 1, a relatively large number of extra radionuclides were added with small releases. In principle, the contribution of short-lived radionuclides to the activity in the effluent release from a BWR would be relatively large when compared to a PWR. This is because of the direct flow of activity in the primary coolant to the condenser, from which this activity, in particular the soluble materials, is directly transferred, via the cleaning systems of the condensate, to the liquid waste processing facility. In a PWR the primary coolant is in a closed system and is continuously cleaned by filters and anion/cation resins also in the closed system. In general, the activity from these cleaning systems will only be transferred in batches to the liquid waste facility, for example during shutdowns. Due to this delay, the relative contribution of short-lived radionuclides to the total activity in the liquid waste stream will be reduced. Of course, the actual radioactive releases in the effluent will strongly depend on the quality of the liquid waste facility of the NPP.

The extra radionuclides in Table 1 namely, Se-75, Sr-isotopes, Ru-103, Te-123m, Sb-124 and Ce-isotopes contribute to the ingestion pathway. However, their dose per unit release is smaller when compared to radionuclides such as Co-60, Ag-110m and Cs-137. Also, because the absolute releases of these extra radionuclides are smaller than the latter ones, the doses from these extra radionuclides could be neglected. The extra radionuclides Zr-95 (via Nb-95), Ru-103, La-140 and Ce-144 are important sources of external radiation when considering exposure to sediments.. However, these are not important in comparison to sources such as the activity of Cs-137, Co-60 and Nb-95.

The second example, as shown in Table 2, has a relatively small number of extra radionuclides. The reasons for neglecting the dose contribution of these radionuclides are as follows:

- Cr-51, an activation product, which can be neglected for reason of a small dose per unit release when compared to the releases of Mn-54 and Co-60;
- The dose coefficient of fission product Sb-125 is a factor of 2 smaller than that of Sb-124. However, the lifetime of Sb-125 is 2.8 years, which is 17 times longer than that of Sb-124. Hence for accumulation effects Sb-125 may be more important than Sb-124. However, for individual doses, the contributions from Sb-124 and Sb-125 are comparable.
- The fission product Te-123m with a half-life 123 days has a relatively high transfer factor to seafoods. However, the ingestion dose per unit of release of Te-123m is small compared to a radionuclide such as Co-60.

From these comparisons it may be concluded that omission of the extra radionuclides in the dose calculation for these example sites will not lead to a large under estimation of the annual dose.

Basic information on the standard spectrum of radionuclides released in the liquid effluent from a BWR can be found in the report *Calculation of releases of radioactive materials in gaseous and liquid effluents from BWRs,* NUREG 0016, rev 1 of 1979 (USNRC). For a PWR information can be found in the report *Calculation of releases of radioactive materials in gaseous and liquid effluents from PWRs,* NUREG 0017, rev 1 of 1979 (USNRC).

It should be noted that for the Cap de La Hague site liquid discharges of C-14 are only included in the Bilcom97 database and the EDDI data for the year 1996. Therefore, radiation exposures from Cap de La Hague (F) as a consequences of liquid discharges have not been assessed. This should not be interpreted as “no C-14 discharges” from Cap de la Hague. Discharge data for C-14 from Sellafield are available for the whole period under consideration and were used for the dose assessment.

Finally, following discussions with the responsible Scientific Officer from the Commission, only the years 1987, 1991 and 1996 were taken into account. However, for the reprocessing plants Cap de la Hague in France and Sellafield in the UK every year from 1987 to 1996 were included in the dose assessment.

The approach outlined above resulted in discharge rates per nuclide into the aquatic environment for each nuclear site in Europe that is included in the Bilcom97 database for the period 1987 to 1996. The site-specific discharges into rivers and seas have been used from the interface program EDDI (for more information see the CD-ROM with all the calculations).

Table 1 ***Bilcom97 and EDDI data for Gundremmingen (D) in 1991***

Bilcom97 database	EDDI data	Discharge of Gundremmingen (D) in GBq/y	
Nuclide (spectrum)	Additional radionuclides	Bilcom97 database	EDDI data a)
Beta (excl H-3)		$5.00\ 10^{-01}$	
H-3		$3.00\ 10^{+03}$	$3.00\ 10^{+03}$
Cr-51			$3.32\ 10^{-02}$
Mn-54			$3.11\ 10^{-02}$
Fe-55			$9.81\ 10^{-02}$
Co-58			$1.07\ 10^{-02}$
Fe-59			$3.55\ 10^{-03}$
Co-60			$1.22\ 10^{-01}$
Ni-63			$1.71\ 10^{-02}$
Zn-65			$4.49\ 10^{-02}$
Nb-95			$1.85\ 10^{-03}$
Ag-110m			$4.60\ 10^{-03}$
Sb-125			$4.35\ 10^{-02}$
Cs-134			$7.15\ 10^{-03}$
Cs-137			$5.34\ 10^{-02}$
	Se-75		$3.00\ 10^{-04}$
	Sr-89		$1.85\ 10^{-03}$
	Sr-90		$1.90\ 10^{-03}$
	Zr-95		$1.60\ 10^{-03}$
	Ru-103		$7.00\ 10^{-04}$
	Sb-124		$1.60\ 10^{-03}$
	Te-123m		$1.50\ 10^{-04}$
	Ba-140		$5.50\ 10^{-04}$
	La-140		$3.05\ 10^{-03}$
	Ce-141		$6.70\ 10^{-03}$
	Ce-144		$1.03\ 10^{-02}$

Note

a) The EDDI data for the additional radionuclides are not used for the calculation of the annual dose.

Table 2 ***Bilcom97 and EDDI data for Belleville (F)-PWR in 1996***

Bilcom97 database	EDDI data	Discharge of Belleville (F) in GBq/y	
Nuclide (spectrum)	Additional radionuclides	Bilcom97 database	EDDI data a)
Beta (France)		$5.30\ 10^{+00}$	
Gamma (France)		$1.20\ 10^{+01}$	
Other activity			
Beta (excl H-3)		$6.13\ 10^{+00}$	
H-3		$3.57\ 10^{+04}$	$3.60\ 10^{+04}$
Mn-54			$1.10\ 10^{-01}$
Co-58			$1.00\ 10^{+00}$
Co-60			$1.80\ 10^{+00}$
Ag-110m			$2.30\ 10^{+00}$
Sb-124			$3.00\ 10^{-01}$
I-131		$3.00\ 10^{-02}$	$3.00\ 10^{-02}$
Cs-134			$1.10\ 10^{-01}$
Cs-137			$2.60\ 10^{-01}$
	Cr-51		$4.00\ 10^{-02}$
	Sb-125		$1.30\ 10^{-01}$
	Te-123m		$1.00\ 10^{-02}$

Note

(a) The EDDI data for the additional radionuclides are not used for the calculation of the annual dose.

4 Aquatic Releases

The dose assessment of the population of the European Union for releases into the aquatic environment of (civil) European nuclear sites is divided in two groups. The first group consists of the so-called ‘coastal’ sites, which means that the liquid radioactive effluents are directly discharged into the marine environment. The other group consists of ‘inland’ sites, which discharge the routine liquid releases via a river into a sea. Both kind of sites are included in this study and will be discussed separately in sections 4.2 and 4.3 following the PC-CREAM methodology.

Because the impact of all European nuclear sites on the population has to be taken into account, the individual doses and collective dose have been calculated for the both groups of nuclear sites mentioned above. However, to realise this goal a huge amount of calculations must be performed. Therefore a flexible and amendment friendly approach was used by combining the PC-CREAM package together with Excel worksheets. Consequently a unit release rate of 1TBq per year for all site-specific radionuclides was defined in the PC-CREAM calculations. In this way PC-CREAM computations could be performed without the need to know the site-specific discharges and updates to the Bilcom97 database could be carried out simultaneously.

Although in a radiological impact analysis the estimated doses and radioactive releases are strongly correlated, this report describes both aspects in two different chapters. The reason for this is the two step approach that was chosen. The unit doses were calculated using the PC-CREAM and the Excel worksheets were used to estimate the total impact to the people of the EU. In this chapter the PC-CREAM (pre-processing and calculation) phase will be outlined, and in chapter 5 the post-processing phase by means of Excel worksheets will be described in more detail.

4.1 Assessment boundary conditions

The assessment of the individual doses was based on critical groups. A critical group represents those individuals in a population who have received the highest exposure due to their specific habits in respect to food consumption (Table 3), inhalation rate (7600 m^3/y [9]), and beach occupancy (Table 4). Further, it should be mentioned that adults were the only age group of interest in this assessment study. An integration time of 50 years was chosen for the individual dose calculations.

With regard to the collective dose assessment, only the adult* population of the European Union was considered, for a time period of 500 years.

Table 3 ***Critical group ingestion rates (kg/y) of aquatic foods [9]***

	Marine Foods			
Country	**Fish**	**Crustaceans**	**Molluscs**	**Freshwater Fish**
Belgium*	68	28	28	22
Denmark	349	92	92	41
Finland	185	0.2	0.2	76
France*	67	60	60	33
Germany	47	10	10	22
Netherlands	99	57	57	25
Spain	125	35	35	18
Sweden	150	23	23	39
United Kingdom	91	20	20	23

* The crustacean ingestion rate for France in the table is set to the maximum allowable value in PC-CREAM. For completeness, the given statistical value was 61 [9].

The freshwater fish consumption for Belgians was not specified in [9]. But the Belgian intake rates for terrestrial foods in the current project were assumed to be similar to those of Germany. So, the ingestion rate of fresh water fish for Belgium is set to the German value also.

Table 4 ***Collective beach occupancy (man-hours year^{-1} metre^{-1}) (Table 4.14 in [7])***

European Region	**Occupancy**
Arctic regions	5
Scandinavia (Norway, Iceland, etc.)	10
Northern Europe	50
Mediterranean	75

4.2 Discharges of 'coastal' sites

The European nuclear 'coastal' sites that release liquid radioactive effluents directly into a sea, and taken into account for this dose assessment study, are given (in alphabetical order) in Table 5. The radiological impact due to liquid releases into the marine environment was estimated using the PC-CREAM suite in two steps, as described in the PC-CREAM user's guide [8]. First, a marine dispersion model (DORIS) was used to predict the activity concentrations in marine materials. DORIS creates (three) supplementary data libraries that were subsequently included in the so-called marine module of ASSESSOR to calculate the doses to individuals and EU-population.

* Currently there is no possibility to select an age group in the collective dose calculations. Only adults have been considered in these PC-CREAM computations.

Table 5 '*Coastal' nuclear sites in Europe*

Nuclear Site	Country	Marine Model	Regional Compartment
Barsebaeck	Sweden	Baltic sea	Belt sea
Bradwell	United Kingdom	North sea	North sea south west
Cap de la Hague	France	English channel	English channel south east
Capenhurst*	United Kingdom	Irish sea	Liverpool and Morecambe bays
Chapelcross	United Kingdom	Irish sea	Irish sea north east
Dounreay	United Kingdom	Scottish waters	Scottish waters east
Dungeness A	United Kingdom	English channel	English channel north east
Dungeness B	United Kingdom	English channel	English channel north east
Flammanville	France	English channel	English channel south east
Gravelines	France	North sea	North sea south east
Hartlepool	United Kingdom	North sea	North sea central
Heysham 1	United Kingdom	Irish sea	Liverpool and Morecambe bays
Heysham 2	United Kingdom	Irish sea	Liverpool and Morecambe bays
Hinkley Point A	United Kingdom	Bristol channel	Bristol channel
Hinkley Point B	United Kingdom	Bristol channel	Bristol channel
Hunterston B	United Kingdom	Scottish waters	Scottish waters west
Loviisa	Finland	Baltic sea	Gulf of Finland
Oldbury	United Kingdom	Bristol channel	Bristol channel
Olkiluoto*	Finland	Baltic sea	Bothnian sea
Oskarshamn	Sweden	Baltic sea	Baltic sea west
Paluel	France	English channel	English channel south east
Penly	France	English channel	English channel south east
Ringhals	Sweden	Baltic sea	Kattegat
Riso*	Denmark	Baltic sea	Kattegat
Sellafield	United Kingdom	Irish sea	Cumbrian waters
Sizewell A	United Kingdom	North sea	North sea south west
Sizewell B	United Kingdom	North sea	North sea south west
Springfields*	United Kingdom	Irish sea	Liverpool and Morecambe bays
Torness	United Kingdom	North sea	North sea central
Trawsfynydd*	United Kingdom	Irish sea	Irish sea north east
Vandellos*	Spain	Mediterranean sea	Gulf of lions
Wylfa	United Kingdom	Irish sea	Irish sea west

* Site-specific discharge data for Capenhurst, Riso and Springfields are currently not available in the Bilcom97 database and therefore these three 'coastal' sites have not been included in this dose assessment study. Also, the site name Olkiluoto can not be found in Bilcom97. But, it is assumed that in Bilcom97 discharge data for the TVO nuclear power plant was used for the Olkiluoto site.

Trawsfynydd and Vandellos are not predefined in the PC-CREAM site database. Accordingly, the user must give the local marine compartment parameters. The Chapelcross' local marine compartment parameters are used for the Trawsfynydd site, where as for Vandellos the local compartment details for the Mediterranean sea was defined (as summarised in Table 9).

An example of the typical work procedure for a 'coastal' site is given in Appendix A, on the basis of the Swedish Barsebaeck nuclear power plant.

Beside the already mentioned (country) specific habit data, as given in Table 3 and Table 4, the dose assessment also depends on the entered exposure pathways. As the basis of this study is to calculate the dose of the most exposed critical group; all exposure pathways in PC-CREAM (Table 6) were selected for the assessment, with an (PC-CREAM default) occupancy time of 2000 hours per year for inhalation and external irradiation. It is assumed that the entire occupancy time will be spent in the local marine compartment. Further it is supposed that all consumed marine food was caught in the local marine compartment.

Table 6 ***PC-CREAM marine discharges exposure pathways [8]***

Ingestion exposure pathways	Inhalation pathways	External irradiation
Consumption of marine foods as	Inhalation of seaspray	Gamma radiation in beach material
• Fish		Beta radiation in beach material
• Crustaceans		Gamma radiation in fishing gear
• Molluscs		Beta radiation in fishing gear

4.3 Discharges of 'inland' sites

The second group of European nuclear sites that was considered in this dose assessment study are plants that release their liquid radioactive effluents via a river into the marine environment. The radiological impact of such 'inland' sites was also estimated in terms of the individual doses to critical groups of adults and in collective dose for the population of the EU. The same approach was adopted as that used for nuclear sites which release 'directly' into the marine environment, as described in section 4.2. However, in respect to the 'coastal' sites a (small) distinction has to be made regarding the marine source term, which depends on activity concentrations in the river mouth instead of the site-specific discharge rate. Additionally the dose impact of the river exposure pathways should be taken into account.

In this study it is assumed that the rivers were characterised by three major European rivers: the Loire, the Rhone, and the Rhine. The specific features of these rivers are given in Appendix B where the river is divided into a number of compartments. For each river compartment (denoted by the river name followed by a number) the typical characteristics were summarised. In the PC-CREAM package two river models are (currently) implemented to assess the radiological impact of liquid radioactive releases into the river environment. The *screening model with complete mixing* was selected in this project. The choice for this river model could be argued by means of a scoping analysis, which is reproduced in Appendix C.

Before elucidating the typical work procedure for a so-called 'inland' site, one important aspect should be outlined first. The dose assessment of 'inland' sites was divided into two categories:

- Nuclear sites that discharge into a river and the river delta (where the river flows into the marine environment) belongs to the same country as that in which the site is located; denoted as category A.
- Nuclear sites that release into a river and the river delta does **not** belong to the same country as that in which the site is located; indicated as category B.

For both categories a different approach was assumed in respect of the marine exposure pathways for the critical group of adults. For sites that belongs to category A (e.g. the Dutch nuclear power plant Dodewaard) it is assumed that the inhabitants of the country where the site is located received all individual doses due to the selected marine exposure pathways. But, for the nuclear plants of category B (e.g. Almaraz, Spain) the individual doses were split-up into two kind of individuals, depending of their natural habitat. People who live in the site's 'home country' received the individual aquatic food doses (sea fish, crustaceans and molluscs), while the individual doses due to inhalation and external exposure (from sediment and fishing gear) were assigned to inhabitants of the country where the river flows into the sea.

In Table 7 the European nuclear 'inland' sites, taken into account in this dose assessment study, are given in alphabetical order and categorised using the scheme mentioned above. The radiological impact due to liquid releases into the river environment was estimated with the PC-CREAM suite in three steps:

1. Assessment with ASSESSOR's river module

2. Dispersion of radionuclides in the marine environment, with DORIS
3. Dose calculation with marine module of ASSESSOR

In the first step the individual doses* due to river pathways were calculated by ASSESSOR's river module. The actual river was 'transformed' into one of the three major model rivers as is indicated in Table 7. The river model parameters used in the analyses are described in Table 8.

Eventually, the radioactive effluents in the river flow into the sea. The individual doses and collective dose caused by the presence of radionuclides in the marine environment were estimated in the same manner as described in section 4.2, dose calculations of 'coastal' sites. Hence in step 2, a marine dispersion model (DORIS) base on unit discharges was used to predict the activity concentrations in marine materials. In fact the (water and suspended sediment) concentrations as predicted by the river module were used as a source term in the second step. But, this correction was carried out in the post-processing phase, described in more detail in section 5.2, together with the adaptation of the ASSESSOR results, which are also based on unit discharge rates.

Finally, ASSESSOR's marine module was used to calculate the doses to individuals and EU-population (step 3). The marine models and their accompanying compartments are given in Table 7.

Because the 'inland' sites are not predefined in DORIS the user must define the local marine compartment parameters. Except for those sites whose discharges flow into the Mediterranean sea, all local marine compartment parameters for 'inland' sites are taken from RP72 [7, Tables 4.5 and 4.7]. The local marine compartment parameters for the Mediterranean sea are given in Table 10.

* In the river module of ASSESSOR it is currently not possible to assess the collective dose. But, the impact of this will be very low due to the relatively short pass through times of the radioactive effluents in a river (just a few days) and in addition the consumption of freshwater fish and the intake of river water are not main exposure pathways.

Table 7 ***European nuclear sites that discharge into a river***

Nuclear Site	Country	River Data ←		→ Marine Module Data	
		Actual	Model	Marine Model	Regional Compartment
Category A					
Asco	Spain	Ebro	Rhone 7	Mediterranean sea	Gulf of lions
Belleville	France	Loire 1	Loire 1	Bay of Biscay	French continental self
Borssele	Netherlands	Scheldt	Rhine 10	North sea	North sea south east
Brokdorf	Germany	Elbe	Rhine 10	North sea	North sea east
Brunsbüttel	Germany	Elbe	Rhine 10	North sea	North sea east
Bugey	France	Rhone 1	Rhone 1	Mediterranean sea	Liguro provencal basin
Chinon A	France	Loire 3	Loire 3	Bay of Biscay	French continental self
Chinon B	France	Loire 3	Loire 3	Bay of Biscay	French continental self
Civaux*	France				
Cofrentes	Spain	Jucar	Rhone 7	Mediterranean sea	Gulf of lions
Creys-Malville	France	Rhone 1	Rhone 1	Mediterranean sea	Liguro provencal basin
Cruas Meysse	France	Rhone 5	Rhone 1	Mediterranean sea	Liguro provencal basin
Dampierre	France	Loire 1	Loire 1	Bay of Biscay	French continental self
Dodewaard	Netherlands	Rhine 10	Rhine 10	North sea	North sea south east
Forsmark	Sweden	Ekoln	Rhine 10	Baltic sea	Bothnian sea
Golfech	France	Gironde	Loire 3	Bay of Biscay	French continental self
Grohnde	Germany	Weser	Rhine 8	North sea	North sea east
Krümmel	Germany	Elbe	Rhine 10	North sea	North sea east
Le Blayais	France	Gironde	Loire 4	Bay of Biscay	French continental self
Marcoule	France	Rhone 7	Rhone 7	Mediterranean sea	Liguro provencal basin
Nogent	France	Seine	Loire 2	English channel	English channel south east
Phenix*	France	Rhone 8	Rhone 8	Mediterranean sea	Liguro provencal basin
Saint Alban	France	Rhone 4	Rhone 4	Mediterranean sea	Liguro provencal basin
Santa Maria de Garona	Spain	Ebro	Rhone 1	Mediterranean sea	Gulf of lions
St. Laurent A*	France	Loire 2	Loire 2	Bay of Biscay	French continental self
St. Laurent B	France	Loire 2	Loire 2	Bay of Biscay	French continental self
Stade	Germany	Elbe	Rhine 10	North sea	North sea east
Tricastin	France	Rhone 6	Rhone 6	Mediterranean sea	Liguro provencal basin
Unterweser	Germany	Weser	Rhine 10	North sea	North sea east
Würgassen*	Germany	Weser	Rhine 8	North sea	North sea east

Category B

Almaraz*	Spain	Tagus	Loire 3	Bay of Biscay	Portuguese continental self
Biblis A	Germany	Rhine 4	Rhine 4	North sea	North sea east
Biblis B	Germany	Rhine 4	Rhine 4	North sea	North sea east
Cattenom	France	Mosselle	Rhine 7	North sea	North sea south east
Chooz A	France	Meuse	Rhine 8	North sea	North sea south east
Chooz B	France	Meuse	Rhine 8	North sea	North sea south east
Doel	Belgium	Scheldt	Rhine 10	North sea	North sea south east
Emsland	Germany	Ems	Rhine 9	North sea	North sea south east
Fessenheim	France	Rhine 1	Rhine 1	North sea	North sea south east
Grafenrheinfeld	Germany	Main	Rhine 5	North sea	North sea south east
Gundremmingen B*	Germany	Danube	Rhine 1	Mediterranean sea	Aegean sea
Gundremmingen C*	Germany	Danube	Rhine 1	Mediterranean sea	Aegean sea
Isar 1*	Germany	Isar	Rhine 1	Mediterranean sea	Aegean sea
Isar 2*	Germany	Isar	Rhine 1	Mediterranean sea	Aegean sea
Jose Cabrera*	Spain	Tagus	Loire 1	Bay of Biscay	Portuguese continental self
Mülheim-Kärlich	Germany	Rhine 8	Rhine 8	North sea	North sea south east
Neckar 1	Germany	Neckar	Rhine 3	North sea	North sea south east
Neckar 2	Germany	Neckar	Rhine 3	North sea	North sea south east
Obrigheim	Germany	Neckar	Rhine 3	North sea	North sea south east
Philippsburg 1	Germany	Rhine 1	Rhine 1	North sea	North sea south east
Philippsburg 2	Germany	Rhine 1	Rhine 1	North sea	North sea south east
Tihange	Belgium	Muese	Rhine 8	North sea	North sea south east
Trillo	Spain	Tagus	Loire 1	Bay of Biscay	Portuguese continental self

* The radioactive effluent from the Spanish sites Almaraz, Jose Cabrera and Trillo finally flow into the Portuguese continental shelf, which is part of the Atlantic ocean. Currently, the marine model of the Atlantic ocean is included in the PC-CREAM module for the Bay of Biscay. Therefore the Bay of Biscay was chosen as the marine model for these three sites.

Site-specific discharge data for Phenix and St. Laurent A are currently not available in the Bilcom97 database and therefore these two 'inland' sites were not included in this dose assessment study. Furthermore, it should be noted that the nuclear power plant at Civaux started operation in 1997, which is beyond the interest time period (1987 - 1996) of this dose assessment study.

Except for those sites that finally flow into the Mediterranean sea, all local marine compartment parameters for 'inland' sites are taken from RP72 [7, Tables 4.5 and 4.7]. The local marine compartment parameters for the Mediterranean sea are given in Table 9.

Table 8 ***River characteristics of the three major European rivers***

River Model	Mean Flow [$m^3\ y^{-1}$]	SSL* [$t\ m^{-3}$]	Mean Depth [m]	Mean Width [m]
Loire				
Loire 4	$3.96\ 10^{10}$	$5.00\ 10^{-5}$	5.90	3.0510^{2}
Loire 3	$3.40\ 10^{10}$	$4.50\ 10^{-5}$	4.95	$2.94\ 10^{2}$
Loire 2	$2.83\ 10^{10}$	$4.00\ 10^{-5}$	3.93	$2.80\ 10^{2}$
Loire 1	$2.43\ 10^{10}$	$3.50\ 10^{-5}$	3.33	$2.61\ 10^{2}$
Rhine				
Rhine 10	$6.98\ 10^{10}$	$4.50\ 10^{-5}$	6.80	$3.25\ 10^{2}$
Rhine 9	$3.54\ 10^{10}$	$4.25\ 10^{-5}$	4.35	$1.77\ 10^{2}$
Rhine 8	$4.43\ 10^{10}$	$4.33\ 10^{-5}$	5.43	$2.51\ 10^{2}$
Rhine 7	$3.49\ 10^{10}$	$4.00\ 10^{-5}$	5.01	$2.13\ 10^{2}$
Rhine 6	$3.79\ 10^{10}$	$4.02\ 10^{-5}$	5.07	$2.10\ 10^{2}$
Rhine 5	$3.23\ 10^{10}$	$3.93\ 10^{-5}$	4.66	$1.85\ 10^{2}$
Rhine 4	$3.40\ 10^{10}$	$3.91\ 10^{-5}$	4.69	$1.83\ 10^{2}$
Rhine 3	$3.01\ 10^{10}$	$3.80\ 10^{-5}$	4.47	$1.68\ 10^{2}$
Rhine 2	$3.11\ 10^{10}$	$3.78\ 10^{-5}$	4.49	$1.67\ 10^{2}$
Rhine 1	$3.02\ 10^{10}$	$3.77\ 10^{-5}$	4.44	$1.60\ 10^{2}$
Rhone				
Rhone 9	$5.30\ 10^{11}$	$5.00\ 10^{-5}$	10.5	$2.29\ 10^{3}$
Rhone 8	$5.24\ 10^{11}$	$4.75\ 10^{-5}$	10.2	$2.24\ 10^{3}$
Rhone 7	$5.10\ 10^{11}$	$4.50\ 10^{-5}$	9.87	$2.20\ 10^{3}$
Rhone 6	$5.01\ 10^{11}$	$4.30\ 10^{-5}$	9.65	$2.15\ 10^{3}$
Rhone 5	$4.95\ 10^{11}$	$4.14\ 10^{-5}$	9.42	$2.12\ 10^{3}$
Rhone 4	$4.66\ 10^{11}$	$3.97\ 10^{-5}$	8.68	$2.14\ 10^{3}$
Rhone 3	$4.45\ 10^{11}$	$3.79\ 10^{-5}$	8.11	$2.15\ 10^{3}$
Rhone 2	$4.13\ 10^{11}$	$3.61\ 10^{-5}$	7.51	$2.10\ 10^{3}$
Rhone 1	$3.83\ 10^{11}$	$3.49\ 10^{-5}$	6.90	$2.10\ 10^{3}$

The value of the *Downstream Distance of Interest* is set to the maximum allowable value of 10,000m in all river models. River 'compartments' number 1 means the starting point of the river model, while the highest 'compartment' number stands for the river mouth.

* SSL = Suspended Sediment Load

Table 9 ***Local marine compartment parameters for Mediterranean sea***

Volume of local compartment [m^3]	2.4 10^8	Suspended sediment load [t m^{-3}]	2.0 10^{-4}
Depth of local compartment [m]	10	Sedimentation rate [t m^{-2} y^{-1}]	1.0 10^{-4}
Exchange rate [m^3 y^{-1}]	4.8 10^9		

The sediment model parameters *density*, *diffusion coefficient* and *bioturbation rate* were chosen to conform with the default values as described in RP72 [7, Table 4.7].

An example of the typical work procedure for an 'inland' site is given in Appendix D, for the Dutch nuclear power plant Dodewaard.

In conclusion, the habit data and exposure pathways must be mentioned for completeness. All PC-CREAM known river model exposure pathways, summarised in Table 10, were defined in this dose assessment study. The river occupancy time for the critical group adults was taken at 500 hours per year (the PC-CREAM default for a critical group) with respect to external exposure. The country-specific freshwater fish consumption rates are given in Table 3, while the drinking water ingestion rate is defined at 600 litres a year [9] (what is equal to the default value of PC-CREAM suite). For the habit data and exposure pathways, used in the dose assessment calculations for the marine environment, the parameters described in the previous section were used, and are given in Table 3, Table 4 and Table 6.

Table 10 ***PC-CREAM river discharges exposure pathways [8]***

Ingestion Exposure Pathways	External Exposure Pathways
Consumption of freshwater fish	External gamma radiation from deposit river sediment
Drinking water (no water treatment)*	External beta radiation from deposit river sediment

* In the screening river model it is (currently) not possible to select a drinking water treatment method.

5 Dose Assessment

As discussed in chapter 4, the PC-CREAM dose assessment is based on a unit discharge rate of all site-specific radionuclides. As a consequence of this approach the PC-CREAM calculated doses must be adjusted to the site-specific discharges. This adaptation was performed by means of Excel worksheets, and will be described in this chapter. As the work procedure differs for a 'coastal' site or an 'inland' site the explanation is set up in two separate sections.

5.1 Doses due to discharges of 'coastal' sites

As a result of the PC-CREAM computation, individual doses for all selected exposure pathways, as given in Table 6, as well as the collective dose related to the population of the European Union are written to (two) output files for that specific 'coastal' site. These estimated doses are based on unit marine discharges (of 10^{12} Bq/y) for each nuclide released, and refer to the critical age group of adults. Hence, for an indication of the radiological impact of the nuclear plant concerned, the PC-CREAM output must be up-dated with respect to the (actual) site-specific discharge rates, following:

$$D_{\mathrm{i}} = D_{\mathrm{i,\,cream}} \frac{B_{\mathrm{i}}}{B_{i,\mathrm{unit}}} \qquad (1)$$

Where:

- D_{i} is the radiological impact due to nuclide i of the specific site (in μSv);
- $D_{\mathrm{i,\,cream}}$ is the dose of nuclide i due to an unit release (calculated by PC-CREAM) in μSv;
- B_{i} is the site-specific release rate of nuclide i into the marine environment (in GBq/year);
- $B_{\mathrm{i,\,unit}}$ is the yearly unit marine discharge of nuclide i as defined in PC-CREAM (GBq/year).

The above equation was implemented in an Excel worksheet to predict the radiological impact for each nuclide discharged by the nuclear site concerned, and repeated for each year of interest. This method was adopted for both the individual and the EU collective dose.

5.1.1 Total individual marine doses

The individual dose impact is given for each selected nuclide and for each selected exposure pathway, in the PC-CREAM output. (All eight pathways, currently available in the marine module of ASSESSOR, have been included in the analyses.) With respect to the scope of this study and to prevent a huge amount of calculations the impact to a critical group of adults due to discharges into the marine environment will be restricted to the so-called *total individual doses* per nuclide. For each year of interest (in the period of 1987 to 1996) and for every nuclear site defined in the Bilcom97 database, the total individual marine doses were assessed in a manner as illustrated in this section.

As stated above, the impact due to a unit release was calculated by PC-CREAM for all eight-exposure pathways (as given in Table 6). In the 'individual doses' output file PC-CREAM gives, for each selected radionuclide, the dose contribution from each pathway and the total doses (a summation of all eight-dose contributions). Figure 1 is an example of this way of reporting.

Nuclide	**Individual Doses due to Exposure Pathway**				**Total Individual Doses**
	1	**2**	**………..**	**8**	
N_1	x_1	x_2	………..	x_8	$X = x_1 + x_2 + …….. + x_8$
N_2	y_1	y_2	………..	y_8	$Y = y_1 + y_2 + …….. + y_8$
.	.	.	.	.	.
.	.	.	.	.	.
N_m	z_1	z_2	………..	z_8	$Z = z_1 + z_2 + …….. + z_8$

Figure 1 ***PC-CREAM's reporting method of individual marine doses***

As already stated above only the total individual doses as written in the last column of Figure 1 were used to give an account of the radiological impact in this assessment study. Consequently, only the PC-CREAM results, denoted as X, Y, …, Z in Figure 1, were updated in respect of the actual release per nuclide using equation (1). This procedure is repeated for each year of interest.

5.1.2 Collective marine dose

For assessing the EU collective marine dose the same procedure was applied as described in the previous section (5.1.1). However, the (PC-CREAM) output is less complicated, because it consists of one result per selected nuclide.

For completeness it should be noted that the dose from global circulation was also assessed by PC-CREAM. For instance as a result of H-3 releases the collective dose was given for global circulation and excluding global circulation, as given in Figure 2.

Nuclide	Collective Dose
H-3	A
H-3 Global	B
H-3 Total	A + B

Figure 2 ***Collective dose of H-3 set up including global circulation***

As a consequence of this, both dose contributions, indicated as A and B in Figure 2, must be updated for the actual site discharge rates, taken from the Bilcom97 database, as discussed before.

5.2 Doses due to discharges of 'inland' sites

The dose assessment due to releases into a river by a so-called 'inland' nuclear site is a two step approach. As indicated in section 4.3, the radiological impact to individuals of the most exposed group along the river was calculated first. The second step is the exposure due to radioactive effluents in the marine environment that were discharged initially by an 'inland' site. The approach of this step 2 is very similar to that discussed in the previous section, which dealt with the dose assessment due to discharges of a 'coastal' site. Equation (1), which was used to calculate these marine doses, was adopted for the water and suspended sediment concentrations assessed by ASSESSOR's river module.

5.2.1 Total individual river doses

Based on equation (1) and the methodology as described in section 5.1.1, the total individual river doses were calculated for the most exposed group of adults. Two small differences should however be mentioned:

- only 4 (default) river exposure pathways have been considered (as mentioned in Table 10)
- individual doses (D_{i} and $D_{\mathrm{i,\,cream}}$) are defined in μSv per year (because no integration time is taken into account in the screening river model)

Beside this the output file, written by PC-CREAM, with activity concentrations in the river water and in the suspended sediment will be used in the source term for the marine dose assessment (due to discharges into the river environment).

5.2.2 Marine doses due to an 'inland' site

Since the river module and the marine module are not coupled in PC CREAM the results must be added to assess the impact to the marine environment from discharges into a river. To do so, as specified in Appendix E, it could be concluded:

$$D_{\mathrm{i}} = D_{\mathrm{i,\,cream}} \frac{B_{\mathrm{i}}}{B_{\mathrm{i,unit\ marine}}} * \frac{C_{\mathrm{i,\,cream}} \quad Q_{river}}{B_{\mathrm{i,unit\ river}}} \qquad (2)$$

Where:

D_{i}	is the marine dose due to nuclide i of the specific 'inland' site (in μSv);
$D_{\mathrm{i,\,cream}}$	is the PC-CREAM marine dose in μSv of nuclide i due to an unit marine release;
B_{i}	is the site-specific release rate of nuclide i (in GBq/year);
$B_{\mathrm{i,\,unit\ marine}}$	is the yearly unit marine discharge of nuclide i as defined in ASSESSOR's marine module (in GBq/year);

$C_{i,\ cream}$ summation of the river activity concentration in water (Bq/m^3) and in the suspended sediment (Bq/kg) per nuclide i (output of ASSESSOR's river module based on a unit discharge rate);

Q_{river} mean annual flow rate (in m^3/y) of the river (as defined in ASSESSOR's river module);

$B_{i,\ unit\ river}$ is the yearly unit river discharge of nuclide i as defined in the river module (in Bq/year).

It should be noted that the first part of the above formulae is identical to equation (1) that predicts the radiological impact due to discharges (directly) into the marine environment, by a 'coastal' site. The last term of equation (2) is a correction on the marine source term to update the radioactive effluents that flow into the sea in respect to the (actual) concentrations in the river materials.

Equation (2) was implemented in an Excel worksheet to predict the radiological marine impact for each nuclide discharged by the 'inland' site concerned, and repeated for each year of interest. This method was adopted for marine module results for both individual and EU collective dose, and the individual doses were categorised as outlined in section 4.3. This means that for 'inland' sites of the so-called category A (the discharge point and the river mouth are situated in the same country; e.g. the Dutch Dodewaard nuclear power plant) the *total individual marine doses* were assigned to the adults of the country where the site is located. Whereas for category B 'inland' sites (the nuclear plant and the river mouth are not part of the same country; as for instance Almaraz in Spain) a distinction has been made between the *aquatic foods doses* and the *doses due to inhalation and external exposure*. Thus, people who live in the site residence country will be exposed through the consumption of aquatic foods such as fish, molluscs and crustaceans. Further it is assumed that the people of the country in which the river finally flows into the marine environment were subject to external exposure and inhalation of seaspray.

6 Radiological Impact

6.1 Brief presentation of the impact of all 'coastal' sites

The radiological consequences from 1987 to 1996 for a critical group of adults within the European Union due to releases directly into the marine environment of European nuclear sites are shown graphically in Figure 3 and Figure 4.

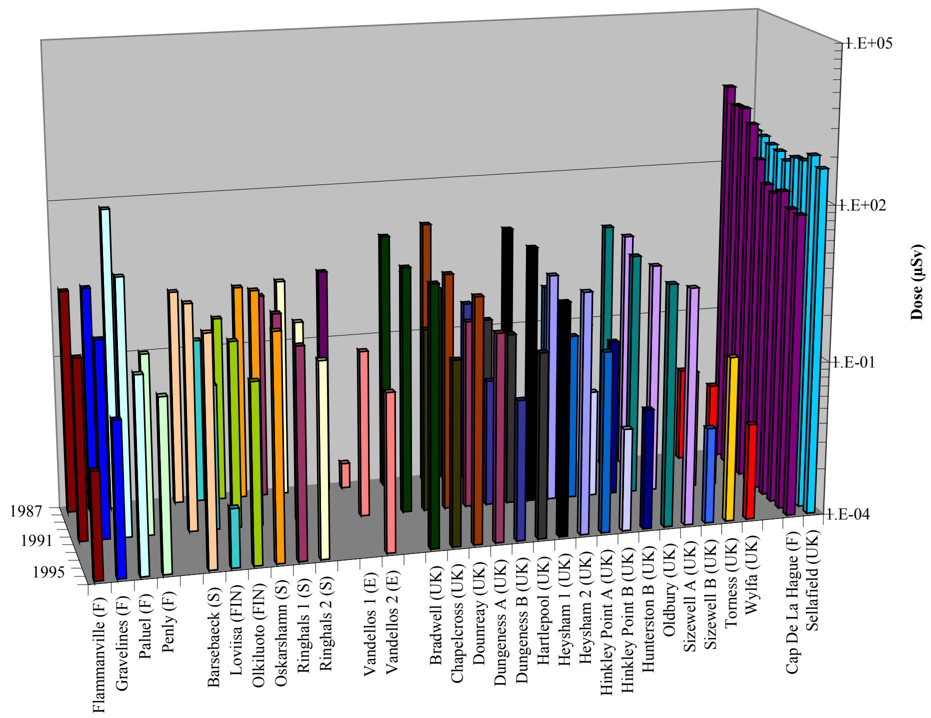


Figure 3 ***Total individual marine doses per 'coastal' site and year of interest***

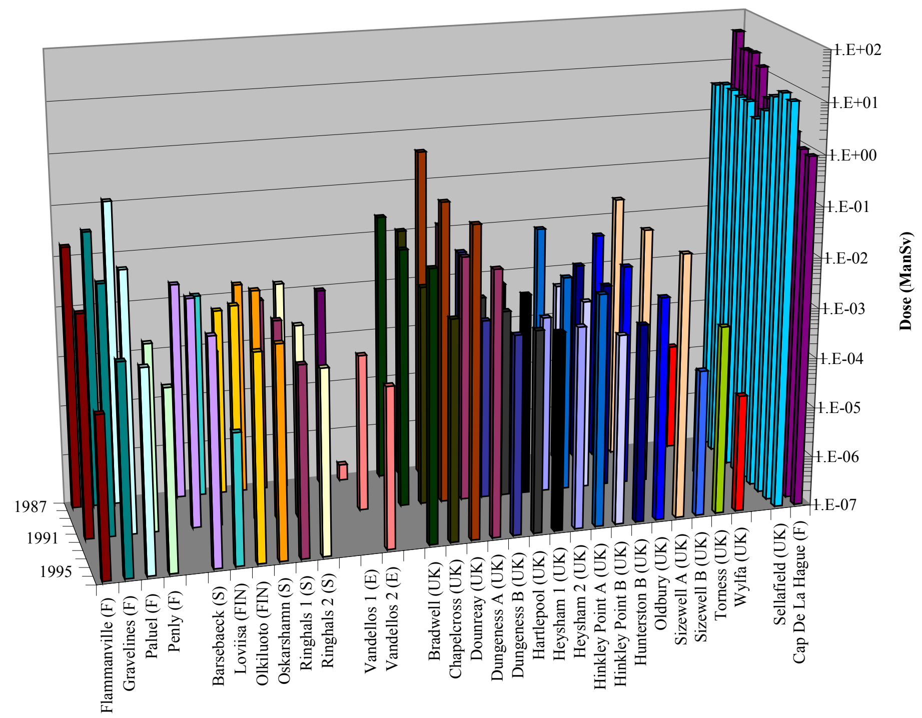


Figure 4 ***Collective marine dose per 'coastal site and year of interest***

The figures clearly show that for marine discharges the two reprocessing plants in Europe, Cap de la Hague and Sellafield, are responsible for the highest radiological impact to the European population, as well as the individual doses to the local inhabitants of France and England respectively.

Furthermore the ten highest levels of all ‘coastal’ nuclear power plants within the EU were summarised in terms of total individual doses and collective dose in Table 11 and Table 12. For these relatively high levels the main exposure pathway is given for completeness.

Table 11 ***Ten highest total individual marine dose levels due to ‘coastal’ sites***

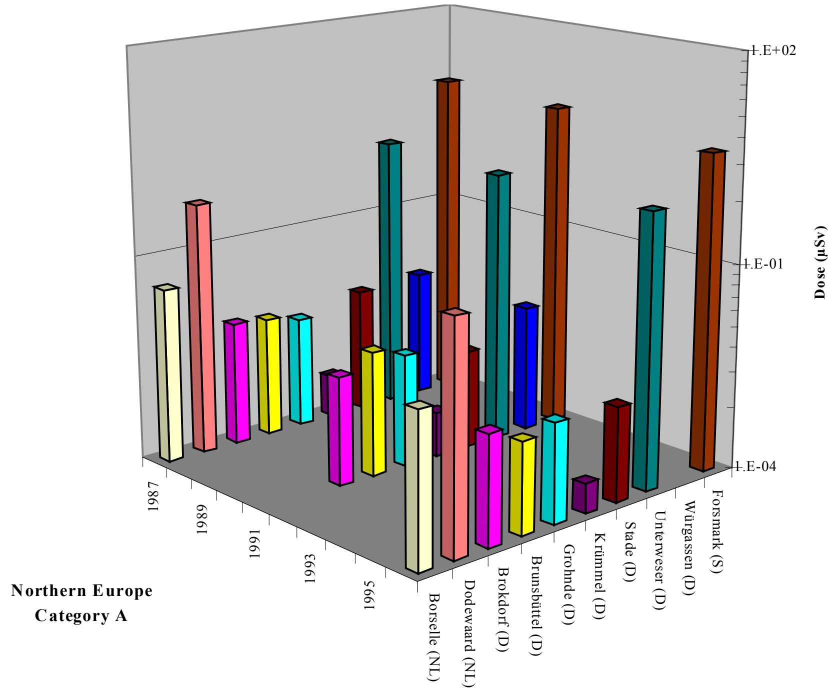
			Greatest contribution to Total Dose	
Site	**Total Doses [mSv]**	**year**	**Exposure Pathway**	**Dose level [mSv]**
Cap de la Hague (F)	3.4	1987	Molluscs	2.9
Cap de la Hague (F)	1.8	1989	Molluscs	1.6
Cap de la Hague (F)	1.8	1988	Molluscs	1.5
Cap de la Hague (F)	1.0	1990	Molluscs	0.92
Sellafield (UK)	0.69	1995	Gamma (sediment)	0.29
Sellafield (UK)	0.59	1987	Gamma (sediment)	0.37
Sellafield (UK)	0.53	1988	Gamma (sediment)	0.28
Sellafield (UK)	0.50	1989	Gamma (sediment)	0.24
Sellafield (UK)	0.47	1996	Consumption of fish	0.21
Sellafield (UK)	0.45	1994	Consumption of fish	0.18

Table 12 ***Highest EU collective marine dose levels due to ‘coastal’ sites***

Site	**Total Doses [man.Sv]**	**year**
Cap de la Hague (F)	41	1987
Cap de la Hague (F)	23	1989
Cap de la Hague (F)	22	1988
Cap de la Hague (F)	14	1990
Sellafield (UK)	13	1995
Sellafield (UK)	11	1996
Sellafield (UK)	8.9	1994
Sellafield (UK)	4.6	1988
Sellafield (UK)	4.3	1989
Cap de la Hague (F)	4.1	1991

6.2 Brief presentation of the impact of all ‘inland’ sites

The radiological impact due to the marine environment of European ‘inland’ nuclear sites for a critical group of adults within the European Union are given in Figure 5, Figure 6 and Figure 7. These figures represent the total individual marine doses for a critical group as well as the EU collective marine dose, respectively.



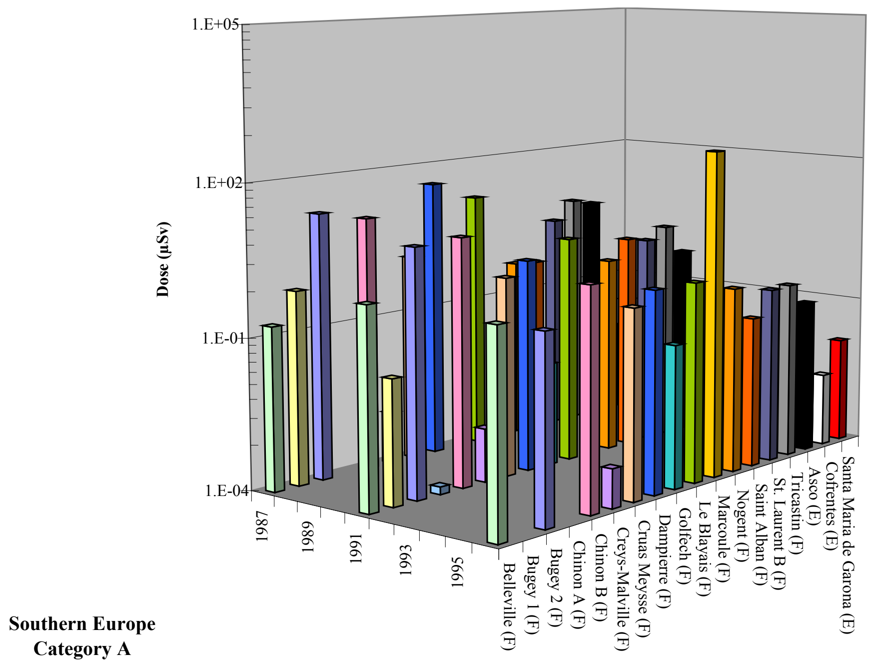
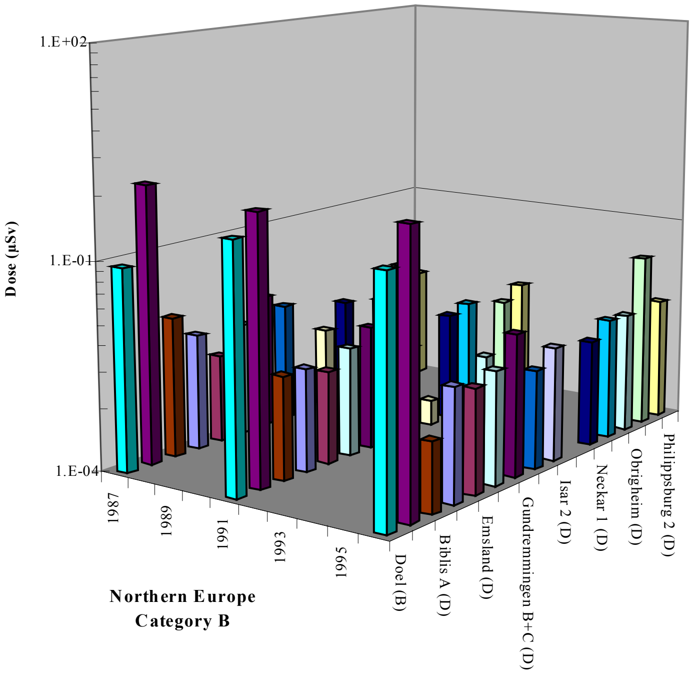


Figure 5 ***Total individual marine doses per 'inland' site of category A for every year of interest***



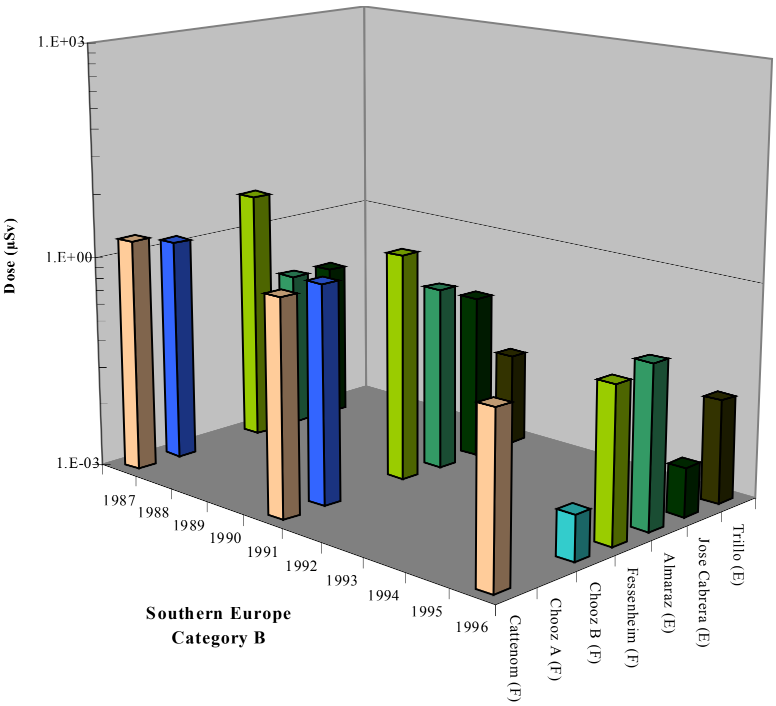
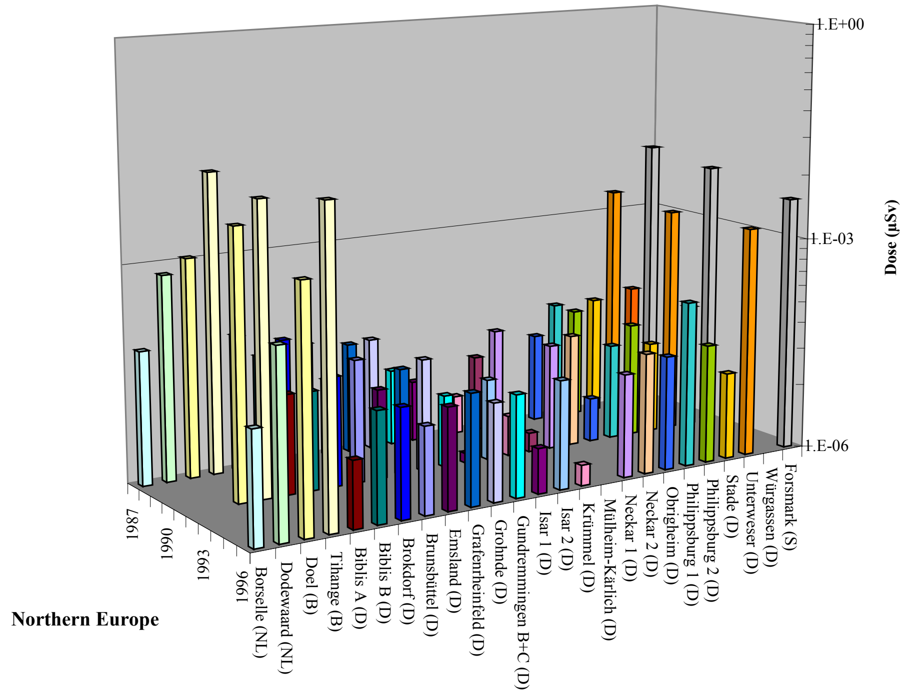


Figure 6 ***Total individual marine doses per 'inland' site of category B for every year of interest***



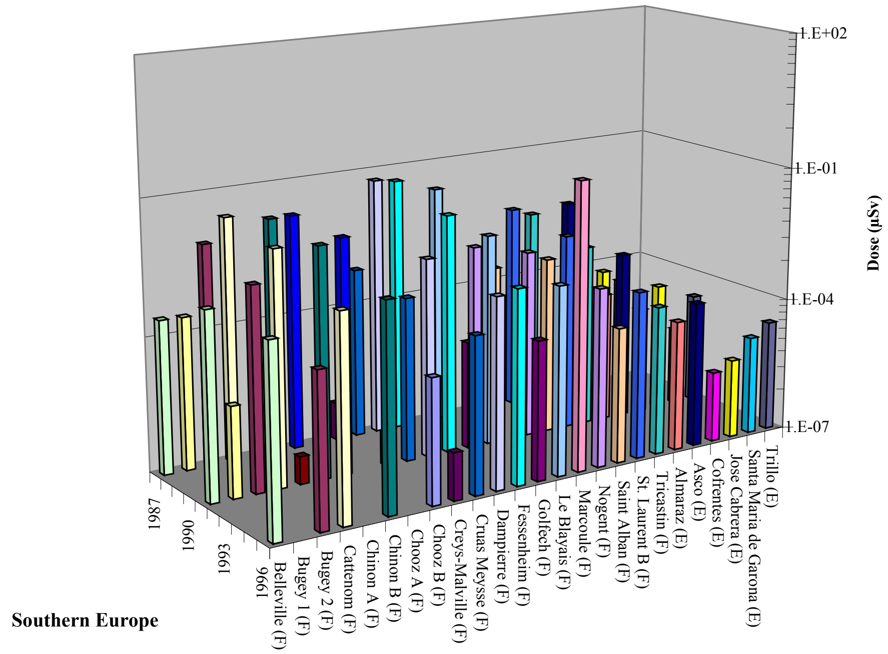


Figure 7 ***Collective marine dose per 'inland' site and year of interest***

The figures clearly show that for marine discharges the reprocessing plant Marcoule (F) is responsible for the highest radiological impact to the European population, as well as the individual doses to the local inhabitants of France. For the Marcoule site data were only available for 1996. Furthermore, the 'inland' sites of category A had more impact than the inland sites of category B.

The ten highest levels of all 'inland' nuclear power plants within the EU are summarised in terms of total individual doses and collective dose in Table 13 and Table 14.

Table 13 ***Five highest total individual marine dose levels due to 'inland' sites***

Site	Total Doses [mSv]	Year	Greatest contribution to Total Dose Exposure Pathway	Dose level [mSv]
Marcoule (F)	0.307	1996	Molluscs	0.27
Dampierre (F)	0.039	1987	Crustaceans & molluscs	0.018 & 0.017
Bugey 2 (F)	0.020	1987	Crustaceans & molluscs	0.089 & 0.086
Le Blayais (F)	0.016	1987	Crustaceans & molluscs	0.071 & 0.069
Chinon B (F)	0.012	1987	Crustaceans & molluscs	0.054 & 0.052

Table 14 ***Three highest collective (marine) dose levels due to 'inland' sites***

Site	Total Doses [man.Sv]	Year
Marcoule (F)	0.24	1996
Dampierre (F)	0.06	1987
Fessenheim (F)	0.05	1987

It should be noted that the total individual river doses are not reported in this section, because of their relatively small dose contribution. Here the actual river dose for the Rhine, Rhone and Loire is given in Figure 8, Figure 9 and Figure 10. The actual river dose comprises all the total individual river doses of the sites located near that river. Only groups located at the river mouth will be exposed to the actual river dose. In this project the results of the actual river dose are overestimated. Adding the total individual river dose from the PC-CREAM output for the sites together causes this overestimate. However in this project a river model is used that could only calculate the river dose at a maximum distance of 10 km from a site. For most sites the river length from discharge point to the sea is greater than 10 km.

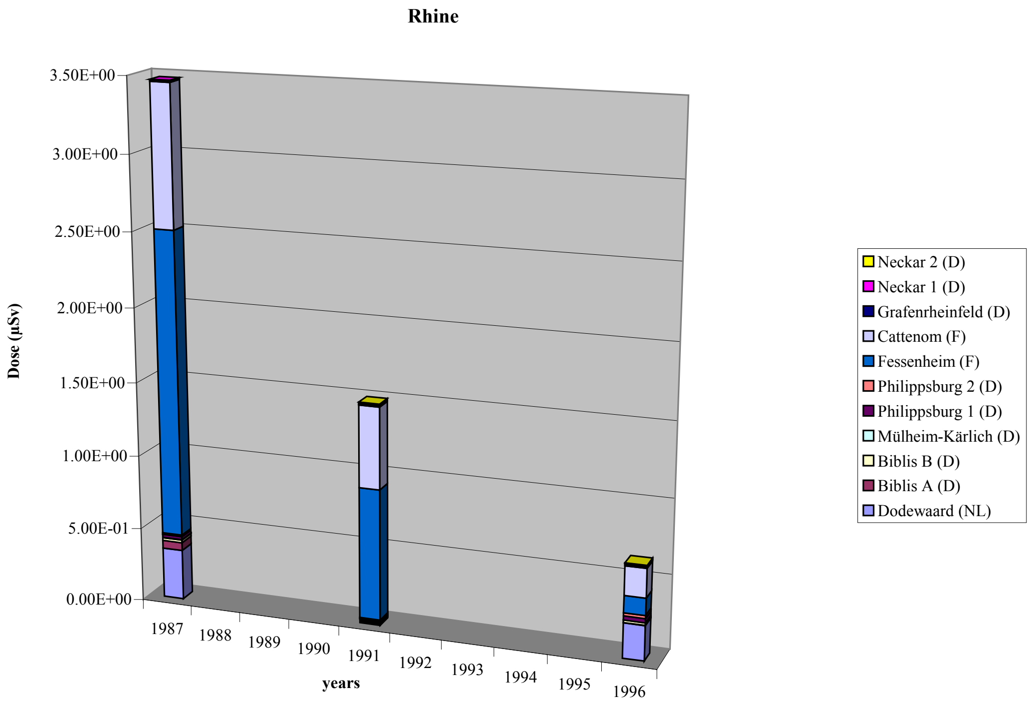


Figure 8 ***Actual river doses for all 'inland' sites that release radionuclides into the Rhine***

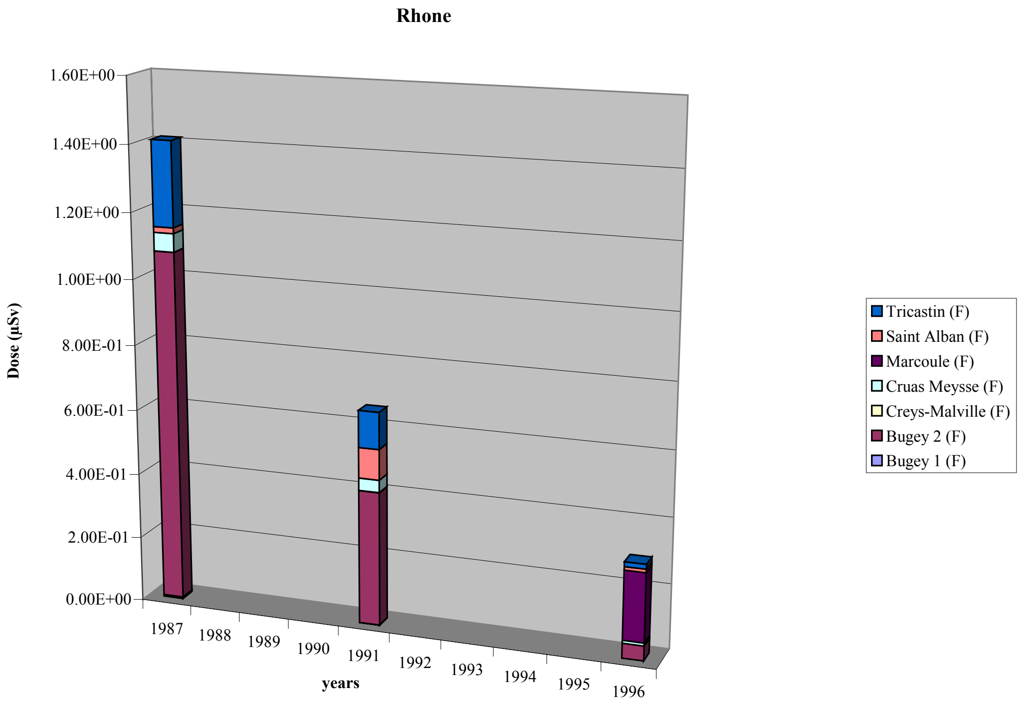


Figure 9 ***Actual river doses for all 'inland' sites that release radionuclides into the Rhone***

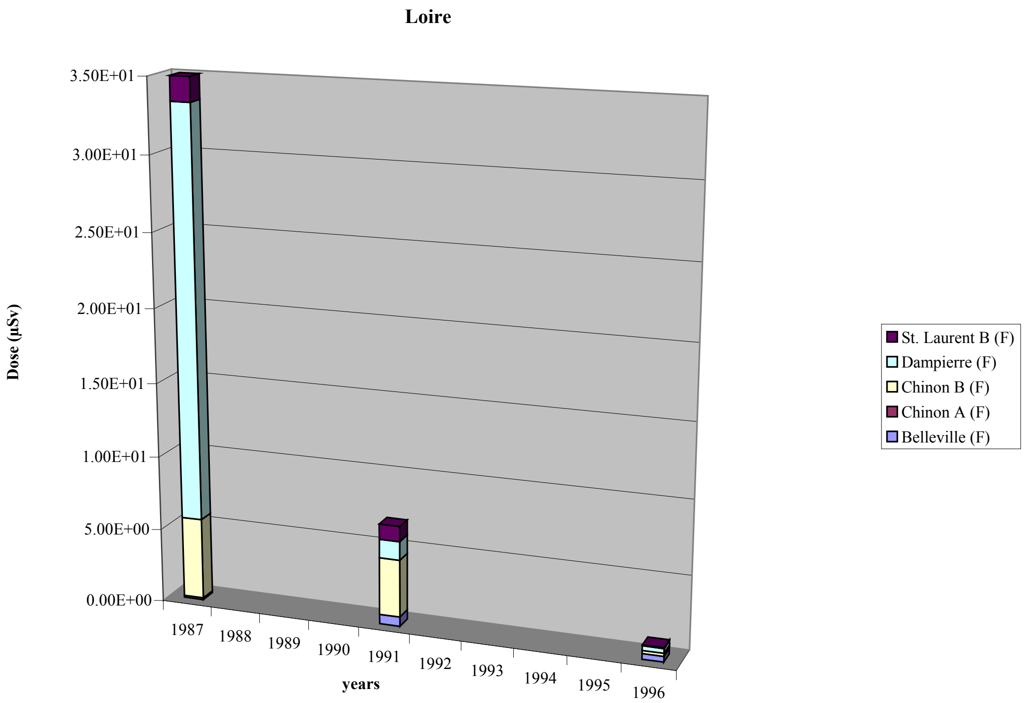


Figure 10 ***Actual river doses for all 'inland' sites that release radionuclides into the Loire***

6.3 Extensive presentation of all assessment results

In the two previous sections (6.1 and 6.2) only the main results of the assessment study, in terms of total individual doses and collective dose per European nuclear site, were reported for efficiency reasons. These selected results however only represent a small part of the enormous amount of data that was generated during this project. A complete set of PC-CREAM input files together with their accompanying output and Excel worksheets were collected on the enclosed CD-ROM. The data on this CD-ROM was arranged by site name, and can therefore be easily read by any interested party.

The Excel files have been made up of several so-called worksheets that can be activated simply by clicking on the relevant tab. Further background information can be found in the *information sheet*, which is located as the first worksheet in each Excel file.

7 Survey of Critical Dose Results

The radiological impact (for the period 1987 to 1996) of the EU adult population due to European nuclear sites was presented in Chapter 6. These results are, however, obtained from an assessment that is based on rough (conservative) estimates, as is usual in this kind of impact analyses. Therefore it is important to reassess some critical dose results with more specific input data; available from measurements and / or refined habit data for instance. In this chapter a dose reassessment is given for the reprocessing plants Sellafield (in the UK) and Cap de la Hague (in France), because of their large contribution to the total radiological impact.

7.1 Reassessment approach

It is common in an assessment of this size to begin with relatively conservative assumptions. The results of the analyses are then compared with (legal) limits. In this project where the results are within the required constraints, no reassessment was carried out and the (conservative) results are presented. However, where the results are higher than the limits a reassessment was performed based on more realistic (or extra) assumptions for that specific site. The adapted (less conservative) results were also compared to the limits. The above reassessment approach was repeated provided that any revised assumptions could be justified, the results considered reliable and no violation of (legal or Governmental) rules occurred.

In the current project first the relatively conservative approach was followed as discussed above. The assumptions for this assessment can be found in this document. The Government of the country to which the nuclear site(s) belong(s) prescribed the dose limits for the (national) population, normally based on the recommendations of the ICRP. For a reference group, as used in this assessment, the ICRP recommends an individual dose limit of 1 mSv per year. (But, the Government of the Netherlands however has reduced this recommended ICRP-limit to 0.1 mSv/year for example. This means that a person can be exposed to a maximum of 10 different sources in one year.)

As reported in Chapter 6, the reprocessing plants Sellafield and Cap de la Hague deliver a substantial part of the radiological impact to the European community,. Consequently, a reassessment was made for these two sites, by refining / tuning the steps:

- Discharge data
- Dispersion model assumptions
- Habit data refinement

Each of these is described in the next (three) paragraphs.

7.2 Discharge data

The site-specific discharges are taken from the Bilcom97 database and thereafter from the EDDI program as already described in Chapter 3. This data contains (some) uncertainties. The influence of these uncertainties however is not taken into account during this reassessment, but will be discussed in more detail in section 8.1.

7.3 Dispersion model assumptions

Three aquatic models have been used in the (PC-CREAM) assessment, namely: DORIS and ASSESSOR's river and marine models. Based on (user defined) discharge data, DORIS calculates the nuclide dispersion in the marine environment by dividing the sea into different compartments. Therefore (for each site) the parameter values of the marine compartments must be defined, such as suspended sediment concentrations, volume exchange rates, coastline length, volume and depth. For all these parameters the default values were selected.

Like every model, the marine dispersion model in DORIS is an approximation of reality and based on assumptions. But, for Cap de la Hague and Sellafield well-known measurement data of nuclide dispersion exist. Hence, these measurement data were compared with the DORIS model results. This resulted in correction factors that eliminated the differences between the model and measurement dispersion data, which depends on specific nuclide behaviour in seawater (expressed in parameters like the Kd value) and on exposure pathway.

The (NRPB) defined correction factors, that represent a significant contribution to the individual doses, are given in Table 15. The criteria for defining these correction factors were that a nuclide per pathway had a contribution of more than 5% to the total individual doses. The mentioned correction factors were included in the post-processing phase as outlined in Chapter 5.

The results of this reassessment with the correction factors are shown graphically in Figure 11 together with the (conservative) assessment for both reprocessing plants.

7.4 Habit data refinement

In the assessment conservative assumptions were made with respect to the habit data used for individual dose calculations for a critical group. During the reassessment, the habit data refinement focused on two major suppositions, namely the (yearly) beach occupancy time and the percentage of the fish consumption that would be caught in the local marine compartment.

From analysing the assessment results, it was found that external gamma irradiation by the sediment and marine foods are the most important exposure pathways for the critical group (see for instance Figure 11 and Figure 12). As no alternative food data were available, the reduction of the marine food consumption was not possible in the reassessment. However it is not plausible to assume that, even for the critical group, all consumed fish would be caught in the local marine compartment. Consequently, the percentage of the fish caught in the local marine compartment was revised in this reassessment.

Table 15 ***Dispersion correction factors based on measurement data***

Sellafield		Cap de la Hague		
	All years		Until 1990	Post 1990
Co-60 in Sediments (gamma dose)	1.61E-02	Co-60 in Crustaceans	4.03E-01	1.05E+00
Cs-137 in Sediments (gamma dose)	7.42E-03	Ru-106 in Crustaceans	4.08E-01	4.08E-01
Ru-106 in Crustaceans	4.53E-01	Ru-106 in Molluscs	1.63E-02	8.16E-02
Ru-106 in Molluscs	2.62E-01	C-14 in Fish	6.75E-02	6.75E-02
C-14 in Fish	1.13E-01	C-14 in Crustaceans	6.75E-02	6.75E-02
C-14 in Crustaceans	1.32E-01	C-14 in Molluscs	6.75E-02	6.75E-02
C-14 in Molluscs	8.60E-02	Cs-137 in Fish	2.19E-01	2.19E-01
Cs-137 in Fish	2.86E-01	Pu-239 in Crustaceans	8.87E-01	8.87E-01
Pu-239 in Molluscs	7.00E-01	Pu-239 in Molluscs	5.32E-01	5.32E-01
Tc-99 in Molluscs	4.63E-01	Pu-241 in Crustaceans	8.90E-01	8.90E-01
Tc-99 in Crustaceans	5.60E-01	Pu-241 in Molluscs	5.34E-01	5.34E-01
		Sb-125 in Fish	5.13E-02	5.13E-02

Sellafield		Cap de la Hague	
All years		Until 1990	Post 1990
	Sb-125 in crustaceans	9.44E-03	9.44E-03
	Sb-125 in molluscs	1.35E-02	1.35E-02

Due to the lack of measurement data there were no correction factors defined for the gamma dose from Nb-95 and Zr-95 for the Sellafield site and from Co-60 for Cap de La Hague reprocessing plant.

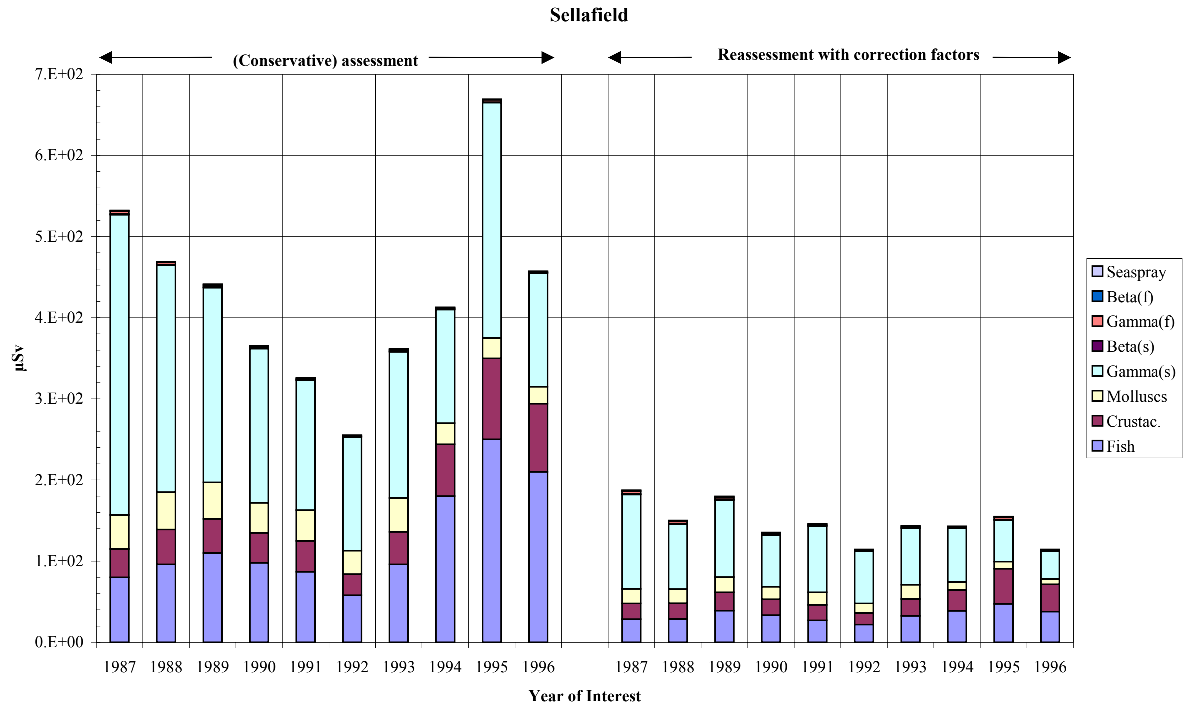


Figure 11 ***Individual doses without and with dispersion model correction factors for Sellafield plant***

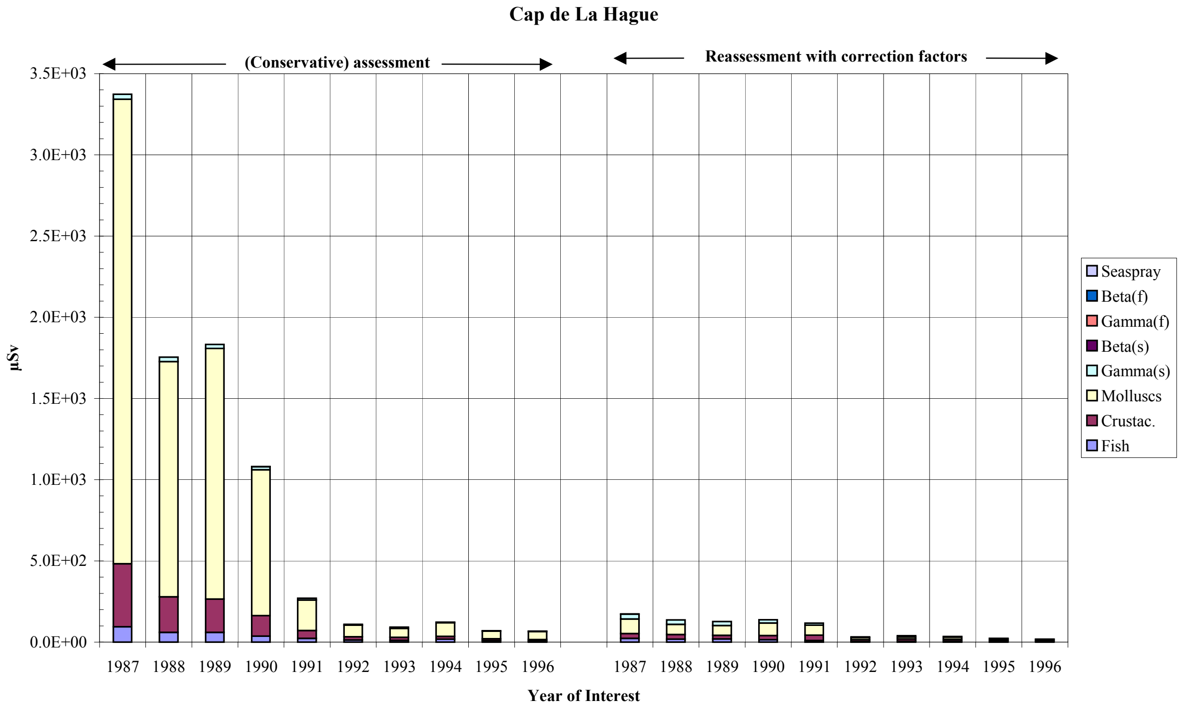


Figure 12 Individual doses without and with dispersion model correction factors due to Cap de la Hague

Regarding the exposure due to external radiation, the critical group consists of sport / fishing tourists, who spend almost the entire holiday period on the beach as well as live near the coastline.

Taking these considerations into account, the external irradiation exposure time was set to 30 days of 8 hours (i.e. 240 h/year), instead of 2000 hours per year as chosen in the first assessment. This approach meant that fishermen were not the most exposed group, because nearly all of them spend most of their time at sea and were accordingly protected for external irradiation by the seawater. Furthermore, the fishermen in general did not spent the remaining time on the beach but in a harbour working on their fishing gear for only a small part of the accommodated period (and certainly not for 50 weeks at 40 hours a year).

The above considerations gave new more realistic assumptions for the reassessment, as summarised in Table 16.

Table 16 ***Refinement of marine habit data parameters***

Marine habit data parameters	(Conservative) Assessment	Reassessment
Beach occupancy time	2000 hours/year	240 hours/year
External irradiation by fishing gear	2000 hours/year	2000 hours/year
Fish caught in local compartment	100 percent	10 percent
Crustaceans caught in local compartment	100 percent	100 percent
Molluscs caught in local compartment	100 percent	100 percent

Figure 13 and Figure 14 represent the results of the reassessment with the refined habit data parameters in terms of individual dose contribution per marine pathway for respectively Sellafield and Cap de la Hague.

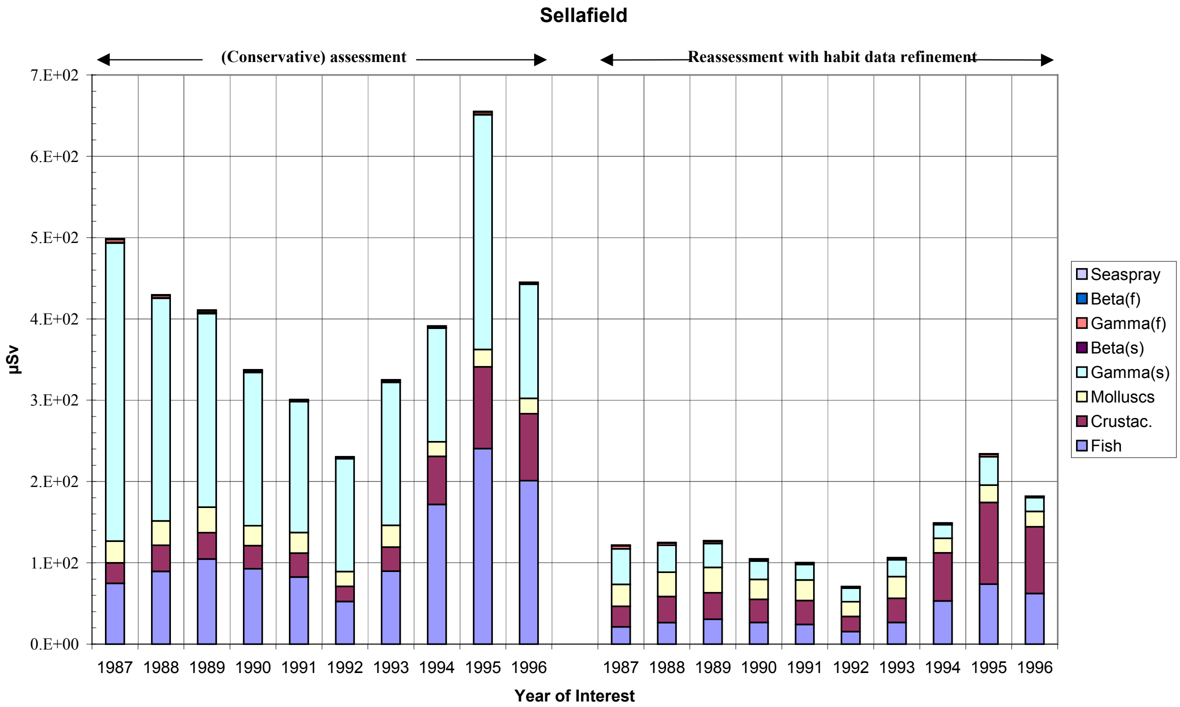


Figure 13 ***Sellafield results with and without habit data refinement***

7.5 Reassessment conclusions

For the Sellafield reprocessing plant the changes made within the reassessment, i.e. dispersion correction factors and habit data refinement, resulted in a significant decrease of radiological consequences with respect to the most exposed group.

For the Cap de la Hague site the adapted dispersion correction factors gave a major reduction to the individual doses. However, the reassessment with the habit data refinement shows only a small reduction to the radiological impact for the French reprocessing plant. The reason for this minor dose reduction is the fact that the significant pathway is the consumption of molluscs, which was not adapted within the reassessment. Analyses of the results showed that the majority of the individual dose contribution for mollusc consumption comes from Ru-106. This radionuclide accumulates in molluscs and crustaceans. As for Sellafield the discharge rate of Ru-106 and the consumption of molluscs is relatively high for the Cap de la Hague site.

The first four years of this assessment show that the radiological impact to individuals is higher than the ICRP limit of 1 mSv for Cap de la Hague. Hereafter the individual doses became lower than this limit, mainly due to a reduction in the discharge of Ru-106.

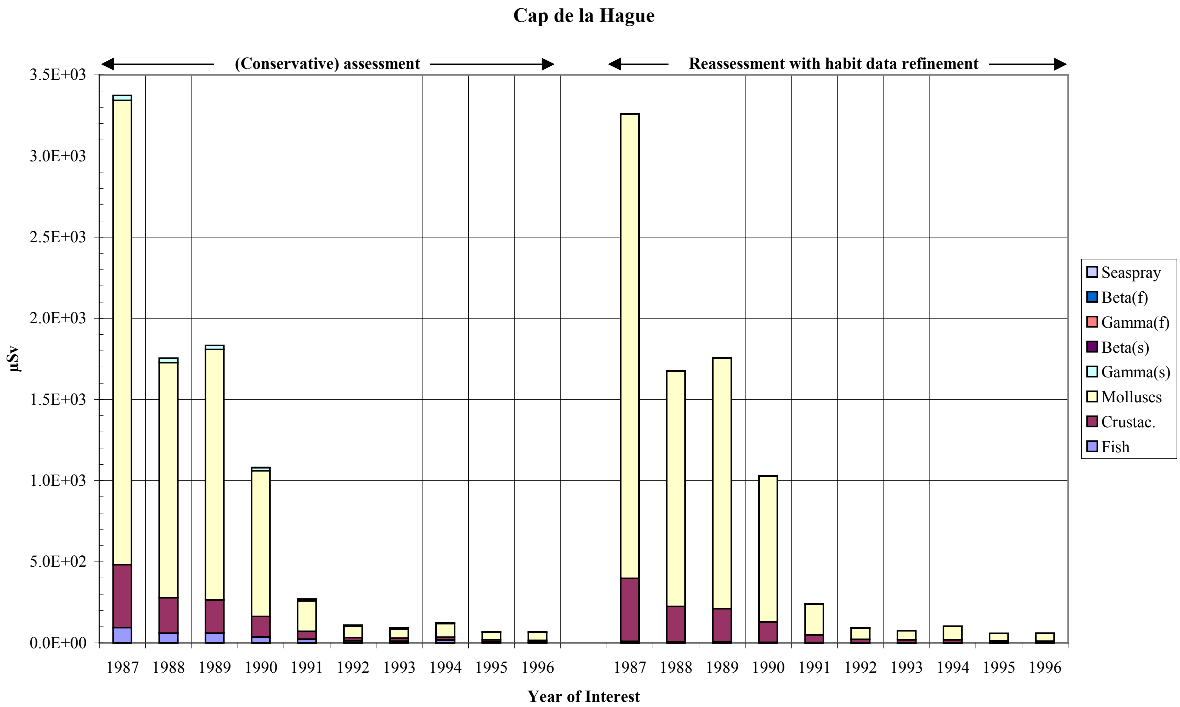


Figure 14 ***Results with and without habit data refinement of the Cap de la Hague site***

8 Assessment Evaluation

This chapter will discuss the conditions of the adopted approach, the PC-CREAM suite and the results of the radiological impact as described previously. The evaluation will follow the structure of the report. Hence, the discharge data (collection process) will be described first. Secondly, the PC-CREAM software package will be commented on (in addition to the more specific user's view as given in Appendix F). Finally there is a discussion regarding the dose assessment results.

8.1 Discharge database

The collection of data is always a time consuming and very complicated process. This was one of the reasons for limiting the dose assessment for all EU nuclear sites (except for the reprocessing plants Sellafield and Cap de la Hague) to the years 1987, 1991 and 1996 instead of every year within the time period of interest from 1987 to 1996.

Mostly the discharge data contain a lot of uncertainties. These uncertainties depend, among other things, on the analytical measurement method(s) for each radionuclide. Some radionuclides are relatively easy to measure while others are more difficult. For both types of radionuclides the uncertainty depends also on the method of monitoring. For example the sample volume, the preliminary treatment, the representative time and part of the water outflow are influential aspects. Other important points are the numbers of experiments that have been used to predict the yearly nuclide concentration and the discharge amount of a typical nuclide. In addition the detection of activity levels close to the detection limit of a measuring device for a typical nuclide is very difficult. Finally it should be mentioned that the adopted filter method and /or radioactive decay could restrict the presence of some radionuclides in the water sample taken from the liquid discharge. For instance short-lived radionuclides could hardly be found in the aquatic outflow of a nuclear site.

So the uncertainty in discharge data depends strongly on the way in which a specific nuclear site measure their routine releases. In spite of the existing measurement guidelines it is therefore difficult to speak about 'the error' in the given discharge rates for this dose assessment study. However, it could be concluded that in general the uncertainties in the discharge database are of the order of 20 to 50 percent for radionuclides that could be detected relatively easily and for radionuclides which are more difficult to measure, respectively.

Neglecting the inaccuracy of the dose conversion coefficients (DCC), the habit data, the (metabolic) models, etc. the uncertainty in the discharge data for a typical nuclide reflect directly in the same order of magnitude as the results of the dose impact assessment.

8.2 PC-CREAM

The evaluation of PC-CREAM is divided into two parts. The first part, given in this section, describes the functionality of the current PC-CREAM software for this project. The second part, given in Appendix F, elucidates some general recommendations to improve the PC-CREAM computer package. In talking about functionality for the current dose assessment it is not however the intention to rewrite the computer code or methodology, but must be seen in the broader scope of quality assurance. Consequently, the PC-CREAM aquatic models have been used as validated computer models that nevertheless could not be applied effectively to all EU sites evaluated in this project.

A model is an approximation of reality and is consequently built on assumptions that describe a chemical and / or physical phenomena to a certain (acceptable) accuracy. Mostly (and also in this case) some equations form the basis of a model, which will be solved by (numerical and /or analytical) mathematical methods and problem specific boundary conditions. In the dispersion query the basic idea is the mass conservation between two different points. Within the CREAM methodology and in the scope of this report this general law of mass conservation is translated to the more specific subject of dispersion of radionuclides in water. Therefore box models were defined that depict radionuclide dispersion into the marine and river environment. In such a box model several three dimensional compartments are created that each consist of a homogenous concentration for the different substances like (suspended) sediment, activity and hydrological characteristics. This approach results in a kind of 'pipeline construction' for the river models. The sea is modelled in this manner as a number of boxes where the dispersion is described by (different) velocity components between the compartments.

Currently no estuaries or lakes are modelled in PC-CREAM. Despite this limitation of the computer program some nuclear sites, involved in this dose assessment, discharge their liquid effluents directly, or indirectly, via a river into such water environments. For example a few German sites discharge in the Danube river, which flows finally into the Black Sea. The Black Sea is comparable to a (big) lake and will behave accordingly like a stock up facility. This is neglected in the current radiological impact analyses. The river mouth of the Scheldt is an example of an estuary. Into this estuary the Dutch nuclear power plant at Borssele discharges its liquid radioactive effluents. Following the approach used in PC-CREAM the Borssele site was modelled as a 'inland' site that consequently discharged into a river. (In respect of the site location ('inland' or 'coastal') it should be mentioned here that the defaults of the PC-CREAM program were chosen as far as possible within this project, despite the fact that it seems that the site location is not always consequently implemented within PC-CREAM.) Ignoring the complex aquatic environment of estuaries, such as the interaction between tides of the open sea and the (variable) freshwater flows, introduced an (minor) underestimation of dose to those individuals who's habits indicated (a great) exposure due to material arising from the estuary. In the scope of the EU dose assessment study this effect could be ignored.

The lack of an estuary model in the PC-CREAM code could explain the absence of a coupling between the river and the marine environment. This coupling was implemented in the current project by interweaving both uncoupled results from the river and the marine models as described in section 5.2.2.

Furthermore the uncertainties of the input parameters, like habit data and water characteristics, are discussed here. The parameters of the habit data are based on critical group behaviour for the specific country in which the site under consideration is located. The influence of the uncertainty in these data was shown by means of a simple error analysis with a substantial number of source terms. The Spanish nuclear site of Almaraz was used in this error analysis.

Point of departure for the error analysis form the input parameters as defined in chapter 4, such as the aquatic foods ingestion rates for Spain (Table 3), the beach occupancy time for the Mediterranean (as mentioned in Table 4), and the 'Loire 3' river characteristics (taken from Table 8). Both the individual river dose assessment and the individual marine dose assessment have been included in the error analysis. Furthermore it should be mentioned that all PC-CREAM exposure pathways, as indicated in Table 6 and Table 10, are taken into account. The discharge rate for every nuclide in the analysis was defined as 1 TBq/y.

During the error analysis a number of PC-CREAM runs were performed where for every calculation only one input parameter was changed from its initial value. In this way all the initial input parameters, with the exception of those that describe the exposure due to inhalation, were doubled or divided by two depending upon the permits of PC-CREAM. This multiplication factor is mentioned in the tables below that show the results of the error analysis for each input parameter. The presented results are based on the so-called total individual doses (as illustrated in Figure 1). The radiological consequences of increasing individual parameters, such as the freshwater fish consumption rate, by a factor 2 is shown. These consequences are given for every nuclide as a ratio with respect to the initial input parameters. A ratio higher then 1 stands accordingly for a proportional rise of the total individual doses.

The results of the error analysis on the habit data are evaluated first. Both aquatic situations, the river and marine environment, were considered in the analysis. Except for the radionuclides Zn-65 and Tc-99m, a variation in the crustacean ingestion rate (in this case half) had a small effect on the total individual doses. More or less the same can be said about the molluscs' consumption rate. In this case the greatest differences was found for the radionuclides Fe-59, Zr-95, Ce-141 and Ce-144. Last, but not least, varying the beach occupancy time influenced the dose impact for the radionuclides Nb-95 and La-140.

Table 17 shows that in the (screening) river model almost all radionuclides, with the exception of H-3, Sr-89, Sr-90, Nb-95 and Cs-137, are sensitive to a variation in the riverside occupancy time. With respect to the individual doses a variation of freshwater fish consumption was most relevant for the radionuclides Nb-95 and Cs-137, while no significant differences could be found for the drinking water pathway. Note that the radionuclides H-3, Sr-89 and Sr-90 dissolve easily in water and that the other two mentioned radionuclides Nb-95 and Cs-137 accumulate in fish.

The marine exposure pathways are similar to those for the river environment. The error analysis results are shown in Table 18. In this case the consumption of sea fish, crustaceans and molluscs as well as the beach occupancy time are considered. A doubling of the sea fish consumption shows, for nearly all radionuclides, a significant increase to the total individual doses. The most insensitive radionuclides, when varying the ingestion rate of sea fish are: Co-60, Zn-65, Zr-95, Nb-95, Tc99m, La-140, Ce-141 and Ce-144. Except for the radionuclides Zn-65 and Tc99m a variation of the crustacean ingestion rate (in this case half) had a small effect on the total individual doses. More or less the same can be said about the mollusc consumption rate. In this case the greatest differences was found for the radionuclides Fe-59, Zr-95, Ce-141 and Ce-144. Last, but not least, varying the beach occupancy time influenced the dose impact for the radionuclides Nb-95 and La-140.

Table 17 ***Dose impact effect ratios based on river environment related habits***

Nuclide	Freshwater Fish Consumption (Factor 2)	Ingestion of Drinking Water (Factor 0.5) *	River bank Occupancy (Factor 2)
H-3	1.0	0.7	1.0
Cr-51	1.0	1.0	2.0
Mn-54	1.0	1.0	2.0
Co-58	1.0	1.0	2.0
Fe-59	1.0	1.0	2.0
Co-60	1.0	1.0	2.0

Zn-65	1.5	1.0	1.5
Sr-89	1.6	0.9	1.0
Sr-90	1.6	0.9	1.0
Zr-95	1.0	1.0	2.0
Nb-95	2.0	1.0	1.0
Ag-110m	1.0	1.0	2.0
Sb-125	1.0	1.0	2.0
I-131	1.2	0.9	1.4
I-132	1.0	1.0	2.0
I-133	1.1	1.0	1.8
Cs-134	1.6	1.0	1.4
I-134	1.0	1.0	2.0
I-135	1.0	1.0	2.0
Cs-136	1.2	1.0	1.8
Cs-137	1.8	1.0	1.2
Ce-144	1.0	1.0	2.0

The initial drinking water consumption parameter (of 600 litres a year) could not be doubled in PC-CREAM. Therefore this ingestion rate was divided by 2 in the error analysis.

Table 18 ***Impact ratios on the individual dose through variation of the marine environment habits***

Nuclide	Sea Fish (Factor 2)	Crustaceans (Factor 0.5) *	Molluscs (Factor 2)	Beach Occupancy (Factor 2)
H-3	1.7	0.9	1.1	1.0
Na-24	1.4	0.9	1.1	1.3
Cr-51	1.4	0.8	1.2	1.0
Mn-54	1.3	1.0	1.3	1.4
Co-58	1.3	0.7	1.1	1.0
Fe-59	1.4	0.9	1.4	1.0
Co-60	1.2	0.8	1.1	1.4
Zn-65	1.1	0.6	1.2	1.0
Sr-89	1.8	0.9	1.1	1.0
Sr-90	1.8	0.9	1.1	1.0
Zr-95	1.0	1.0	1.5	1.5
Nb-95	1.1	1.0	1.2	1.8
Tc-99m	1.1	0.6	1.2	1.0
Ag-110m	1.2	0.8	1.3	1.0
Sb-124	1.7	0.9	1.0	1.0
Sb-125	1.7	0.9	1.1	1.0
I-131	1.7	0.9	1.1	1.0
I-133	1.7	0.9	1.1	1.0
Cs-134	1.9	1.0	1.0	1.0
Cs-136	1.9	1.0	1.0	1.0
Cs-137	1.8	1.0	1.0	1.0
Ba-140	1.8	1.0	1.2	1.0
La-140	1.0	1.0	1.0	1.9
Ce-141	1.1	0.8	1.5	1.1
Ce-144	1.1	0.8	1.6	1.1

The marine food consumption parameter for crustaceans could not be doubled in PC-CREAM. Therefore this ingestion rate was divided by 2 in the error analysis.

Finally the effect of a variation in the (screening) river model input parameters was studied and the results are listed in Table 19. A doubling of the river flow rate generally resulted in a decrease of the total individual doses by a factor 2, except for H-3, I-132, I-134 and I-135. The impact of variations in the suspended sediment load parameter depends strongly however on the typical nuclide behaviour. For some radionuclides, like Cr-51, Mn-54, Co-58, Co-60, Zr-95 and Ce-144, the total individual doses will fall by a factor of 10 or more. For others, as for example Sr-89, Sr-90, Cs-134, Cs-136 and Cs-137, the impact decreases in the same order of magnitude as the growth of the flow rate. A change in the river depth or river width was comparable, because usually only the cross section was taken into account in the calculations. This cross section will be simply seen as a multiplication of depth and width in most (river) models. An increase of the river cross section (by a factor 2) results accordingly in the same lowering of the activity concentration and therefore in the total individual doses contributions of almost all radionuclides with some exceptions being Cr-51, Mn-54, Co-58, Fe-59, Co-60, Zr-95, I-132, I-134 and Ce-144.

Increasing the water flow, the depth or the width of a river will increase the dilution of the radioactive material in the water. Raising the suspended sediment load may increase the adsorption of radionuclides to (small) particles abounded in the river water, which means that the suspended sediment concentration grows for radionuclides that do not easy dissolve in water. Regarding the (PC-CREAM) exposure pathways no major radiological impact differences were found by varying the river characterisation parameters in the error analysis. Only the contamination due to drinking water was a little lower if one of the river characteristics was increased.

Table 19 ***Individual dose impact divisors based on variations in the river characteristics***

Nuclide	Flow Rate (Factor 2)	Suspended Sediment Load (Factor 2)	Mean Depth (Factor 2)	Mean Width (Factor 2)
H-3	1.5	0.8	0.8	0.8
Cr-51	2.0	10.0	5.3	5.3
Mn-54	2.0	14.1	7.2	7.2
Co-58	2.0	10.0	5.3	5.3
Fe-59	2.0	6.9	3.8	3.8
Co-60	2.0	10.0	5.3	5.3
Zn-65	2.0	1.8	1.4	1.4
Sr-89	1.8	2.3	1.6	1.6
Sr-90	1.8	2.3	1.6	1.6
Zr-95	2.0	14.9	7.6	7.6
Nb-95	2.0	1.1	1.0	1.0
Ag-110m	2.0	1.2	1.1	1.1
Sb-125	2.0	1.4	1.2	1.2
I-131	1.8	1.1	1.0	1.0
I-132	1.1	1.3	3.5	3.6
I-133	1.8	1.2	1.2	1.2
Cs-134	2.0	2.6	1.7	1.7
I-134	0.5	1.3	23.1	24.6
I-135	1.6	1.2	1.7	1.7
Cs-136	2.0	2.6	1.8	1.8
Cs-137	2.0	2.6	1.7	1.7
Ce-144	2.0	11.8	6.1	6.1

Note: By doubling (in relation to the initial values) the river input parameters the activity concentrations will decrease. As a consequence of this effect the total individual doses will become smaller too. The results in this table should therefore read as a divisor. This means that for instance the total individual doses due to H-3 will be 1.5 times less if the flow rate of the river doubled.

Within the error analysis no evaluation was made of the radiological effects due to variations of the characteristic input parameters for the marine environment. In the current project all (PC-CREAM) default parameters were used and in that context a sensitivity evaluation for the marine model was not as relevant as for the river model.

8.3 Critical groups

A critical group is a number of people, who would have the highest dose impact from nuclear sites. The exposure pathways and the habit data define the characteristics of a critical group.

The habit data in this project was known to be conservative (Table 3 and Table 4). For example, it is assumed that members of the Danish critical group eat almost 1kg fish per day, but in reality this should be much lower. Another point, the difference between the countries with respect to the consumption of marine food is quite large. It is assumed that members of the French critical group consume 60 kg/y molluscs and 60 kg/y crustaceans, but in the United Kingdom only 20 kg/y molluscs and 20 kg/y crustaceans are consumed. Finally from an economical point of view, the marine food, which is caught in regional or local compartments of a specific site, are sold in a larger part of Europe. So finally, in reality a critical group for a specific site consumes less marine food in a year, which may have been caught in completely different parts of Europe.

In this assessment all exposure pathways defined in PC-CREAM, are taken into account (Table 6 and Table 10). The behaviour of a radionuclide (expressed by different parameters like Kd) determines the relevancy of an exposure pathway for that radionuclide. Since the total individual river dose can be neglected compared to the total individual marine dose, only the marine exposure pathways are considered. The most important radionuclide accumulations for the marine exposure pathways were determined for Cap de La Hague, as the total individual marine dose for Cap de La Hague is relatively high (in this assessment). Table 20 shows the important radionuclides for the consumption of marine food and for external gamma radiation from sediment. These pathways are responsible for the largest part of the total individual marine dose. The table shows that the radionuclide Ru-106 is important especially for the consumption of crustaceans and molluscs. Ruthenium-106 is only released by reprocessing plants like Cap de La Hague, Sellafield and Marcoule. For Cap de La Hague (F) and Marcoule (F) the discharge of Ru-106 is responsible for the large total individual marine dose. For Sellafield (UK) the most important pathways are the consumption of (marine) fish and external gamma radiation from sediment. The reason is that the consumption of crustaceans and molluscs and the discharge of Ru-106 are both lower.

Table 20 ***Most relevant radionuclides for the four most important marine pathways***

Marine exposure pathway	Radionuclide
Consumption of fish	Sb-125, Cs-137
Consumption of crustaceans	Ru-106, Pu-241, Sb-125, Co-60
Consumption of molluscs	Ru-106, Pu-239, Pu-241
Gamma (Sediment)	Co-60, Cs-137

In this project each specific site is related to its own critical group. In the assessment no cross combinations of release sites and critical groups were considered, although this does occur in reality. It could even be that the release site and the critical group are not from the same country. An example of this situation occurs in Denmark. Seawater flows near the North-European seaboard of France, Belgium and the Netherlands to Denmark. All the radionuclides, which are released by the sites in these countries, would flow to Denmark where the marine food consumption is high (especially fish) The total individual dose for the Danish people would be higher compared to the dose for the critical group of the nuclear sites. In two cases the assumptions were not needed. The first case is an inland site discharging into a river, which flows through other countries in a sea. Here only the consumption of marine food was taken into account for the calculation of the total individual marine dose. Secondly, the total dose for a river (Rhine, Rhone and Loire) is the addition of all the site-specific doses located near the river. Here a critical group is formed that would be exposed to more than one site.

8.4 Dose Assessment Approach

The PC-CREAM outcomes were based on unit discharge rates, as mentioned. This approach therefore needed a so-called post-processing phase to up-date the predicted unit results to the specified liquid discharges, which is extensively elucidated in chapter 5. The equations, that were adopted to 'translate' the PC-CREAM results to a radiological dose impact, have no uncertainty and accordingly no discussion should be held here about this procedure.

8.5 Results of radiological impact analyses

The results of this dose assessment study are summarised in chapter 6. The total individual river and marine doses (Figure 3, Figure 5, Figure 6, Figure 8, Figure 9 and Figure 10) for all sites could be compared to each other. The ICRP (International Commission on Radiological Protection) has defined a limit of 1 mSv/year for an individual adult. In chapter 7 a reassessment was given for the Cap de La Hague and Sellafield sites because their dose impact to individual adults is more than the ICRP limit. Furthermore, it was concluded that the total individual marine dose is the most important dose for a critical group that are exposed to marine and river pathways. This conclusion can be drawn despite the overestimation of the actual river dose.

9 Conclusions

The aim of this project is to determine the radiological impact from routine releases by nuclear power stations and nuclear reprocessing plants in the European Union in the period of 1987 to 1996. The individual doses and collective doses were calculated using the PC-CREAM package. NRG's part of the work was the calculation of the annual collective dose and critical group doses for the EU adult population due to routine radioactive liquid releases into surface waters from nuclear sites. The nuclide discharge is taken from the Bilcom97 database and the program EDDI.

The nuclear sites with radioactive effluent releases are divided into two groups: 'coastal' and 'inland' sites. The radioactive effluents of the 'coastal' sites are released directly into the marine environment. The 'inland' sites have their radioactive effluents released into a river, which finally flows into the marine environment.

The main (marine) exposure pathway for the 'coastal sites' and the 'inland sites' is the consumption of marine food. It was conservatively assumed that all this marine food was caught in the local marine compartment. Another important marine pathway was the exposure of the local population to external irradiation when visiting the local beach. The consumption of marine food and the beach occupancy time was rather high. The marine exposure pathways of inhalation of seaspray and external irradiation from contaminated fishing gear are less important for the local population.

In this assessment the reprocessing facilities at Sellafield and Cap de la Hague gave the largest dose impact to the EU population. In particular, the annual releases from Cap de la Hague before 1991, led to individual doses greater than 1 mSv (Euratom population limit). The individual doses received from an 'inland' site, were relatively small compared to the doses received from a 'coastal' site. The total individual doses for a 'coastal' site was less than 0.1 mSv except for the reprocessing plants Sellafield and Cap de La Hague. The dose impact of 'inland' sites was below 0.04 mSv except for the reprocessing plant Marcoule (F). The individual dose as a consequence of Marcoule (F) in 1996 was roughly 0.3 mSv. Finally, the dose impact on a population living near the local marine compartment of a river outlet was below 0.01 mSv for the sites located near the 'real' Loire (4 sites), Rhine (10 sites) and Rhone (9 sites).

The major part of the high individual dose received by the local population from the reprocessing plants Marcoule and Cap de La Hague originate from the consumption of locally caught molluscs. The radionuclide which contributes mainly to this ingestion dose, is Ru-106 (half-life of about one year). Since the discharge of this radionuclide was reduced from Cap de La Hague after 1990, the ingestion doses together with the total individual doses were reduced to values of below 0.5 mSv/year.

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[5] Reference to Bilcom97 database (to be Published)

[6] NRPB, *PC-CREAM software suite version 98*, Environmental Assessments Department, November 1998.

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[9] C. Walsh, *Establishment of a guide for the realistic assessment of radiation doses to members of the public due to operation of nuclear installations under normal conditions; Note on ingestion rates of terrestrial and aquatic foods and note on habit data*, NRPB notes B986/115.

[10] Microsoft Excel software package 97

[11] Reference to Interface program EDDI (to be published)

Appendices

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Appendix A PC-CREAM Assessment Example of a 'Coastal' Site

In this appendix an example for a PC-CREAM assessment, based on the Barsebaeck nuclear power plant in Sweden, is briefly illustrated for a 'coastal' site. Background information is given of input data, specific details and assessment options that were defined for the PC-CREAM calculations. The dose assessment for a 'coastal' site was build-up in two steps. First, a marine dispersion model (DORIS) was used d to predict the activity concentration in the marine environment. The DORIS output files were subsequently used in the marine module of ASSESSOR to calculate the doses to individuals and EU population.

A.1 Step 1: DORIS application

In the program DORIS, **D**ispersion **O**f **R**adionuclides **I**n the **S**ea, the easy set-up facility was chosen to define the input data (Figure A.1), after starting a new run.

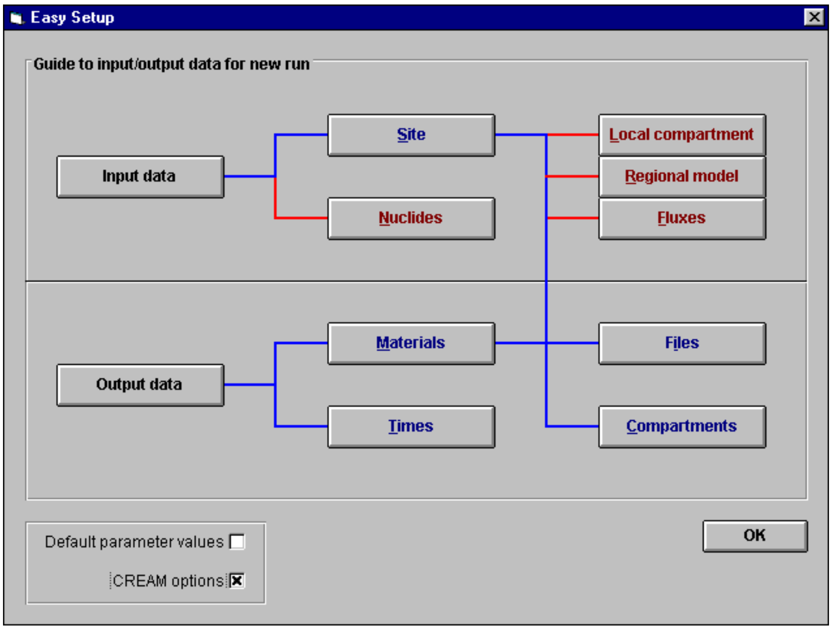

Figure A.1 ***Easy set-up in DORIS***

After opening the easy set-up window the site details were entered by clicking the *site* button. This form enables the user to enter the name of the site, the marine model module (or local compartment) and the regional compartment (that is adjacent to the local compartment). By choosing a site name from the DORIS list, which includes all major nuclear sites in the European Union and therefore used in this assessment study, the default compartments, as mentioned in Table 4 in section 4.2, were automatically set up by the program. This means that all default marine parameters related to the local and regional compartment, for instance volume, depth, coastline length, and fluxes, were used in the DORIS runs.

The *CREAM options* parameter, in the lower left corner of the easy set-up window (Figure A.1), were checked to create ASSESSOR compatible output libraries. Consequently, no output data, as given in the middle part of the easy set-up window in Figure A.1, need to be given by the user.

However, before running DORIS the input data box needs to be completed and controlled. All radionuclides discharged by the specific site, as specified in the Bilcom97 database, were defined as well as data for the local compartment and the regional marine model. The available radionuclides in DORIS are listed in Table A.1. Since the *CREAM options* parameter was checked, as mentioned above, the discharge rate for each defined radionuclide was automatically set to a default value of 10^{12} Bq/y by DORIS. Finally, the *local* *compartment*, the *regional model*, and *fluxes* were given by selecting the appropriate button. All default values were used, because the PC-CREAM data forms the background of this assessment study.

Table A1. R*adionuclides available in DORIS*

H-3	Sr-90	I-125	Eu-154	U-236
C-14	Y-88	I-129	Eu-155	U-238
Na-22	Y-90	I-131	Ta-182	Np-237
Na-24	Y-91	I-133	Pb-210	Pu-238
P-32	Zr-95	Cs-131	Po-210	Pu-239
S-35	Nb-95	Cs-134	Ra-226	Pu-240
Ca-45	Tc-99	Cs-136	Ra-228	Pu-241
Cr-51	Tc-99m	Cs-137	Ac-227	Am-241
Mn-54	Ru-103	Ba-131	Th-228	Am-242m
Fe-55	Ru-106	Ba-133	Th-229	Am-243
Fe-59	Ag-110m	Ba-140	Th-230	Am-244
Co-57	Sn-113	La-140	Th-232	Cm-242
Co-58	Sb-122	Ce-141	Th-234	Cm-243
Co-60	Sb-124	Ce-144	Pa-231	Cm-244
Ni-63	Sb-125	Pr-143	Pa-234	
Zn-65	Te-123	Pr-144	U-233	
Se-75	Te-123m	Pm-147	U-234	
Sr-89	Te-125m	Eu-152	U-235	

A.2 Step 2: ASSESSOR's marine module

The DORIS output files created, as described in section A.1, were used in the marine module of ASSESSOR to calculate the doses due to releases into the marine environment. Setting up a run option file (ROF) for ASSESSOR's marine module for the current assessment study will be described in this section. The *assessment details* window (Figure A.2) opens up after the input of the site details information box followed by choosing the marine mode assessment type. In the site details information box the name of the nuclear site can be chosen from the default list, which contains all major nuclear sites of the European Union. In doing this ASSESSOR automatically filled in the *country* and *site location* entry, in the current context of a 'coastal' site.

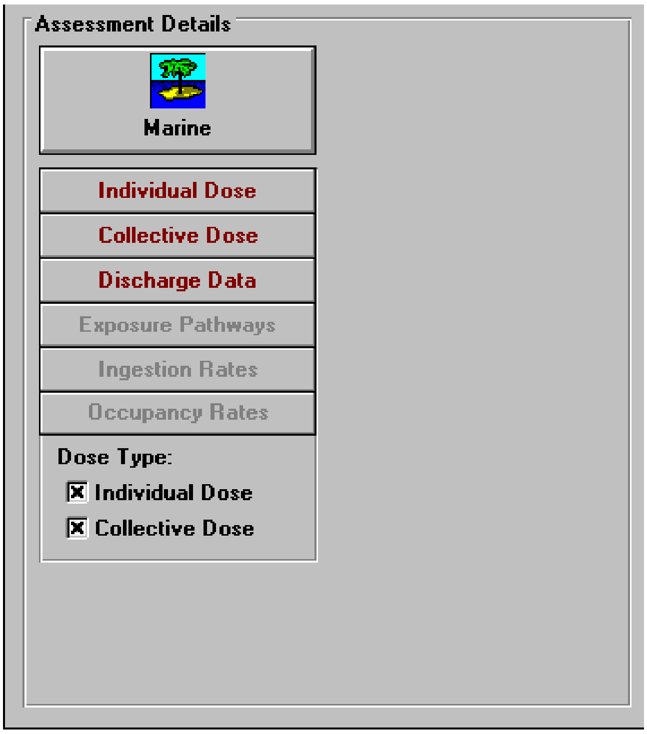

Figure A.2 ***Assessment details definition box of marine module in ASSESSOR***

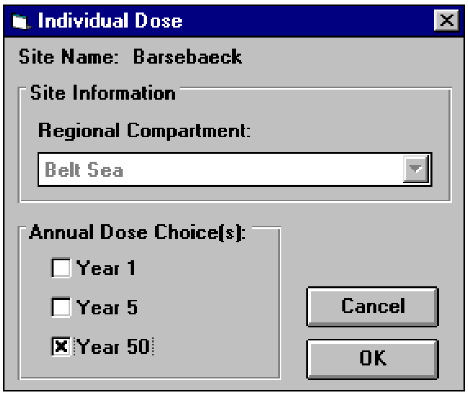

Figure A.3 ***Individual dose definition in ASSESSOR***

As both individual dose for a critical age group and the collective doses of the EU population are required both these boxes were checked in the assessment details definition box as indicated in Figure A.2.

Hereafter the buttons *individual doses* and *collective dose* becomes active, and by clicking on the respective button the user can include the required data. The choices for this dose assessment study are given in Figure A.2 and Figure A.4 respectively.

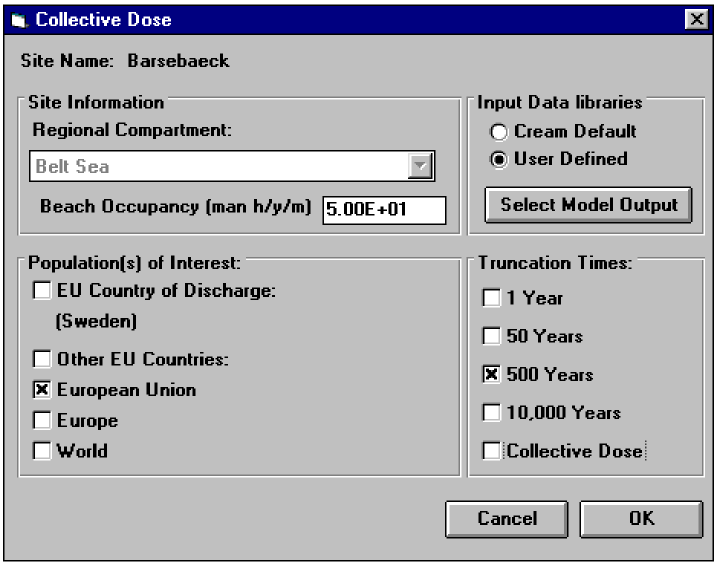

Figure A.4 ***ASSESSOR's collective dose window***

The dispersion data created by DORIS must be used for the calculation of the collective dose. Therefore the *user-defined* option must be checked in the input data libraries entry in the upper right corner of ASSESSOR's collective dose window. The relevant DORIS output files were selected by choosing the button *select model output*.

By clicking the *ok* button after defining all data the collective dose window will be closed and the user returns to the assessment details box of Figure A.2. In this box the *discharge data* will be selected as next step in creating a ROF. (As pointed-out in the PC-CREAM manual the best approach to fill-in all assessment details is a top-down process. As a consequence of this recommendation this example will describe all buttons of Figure A.2 in this order.) When the discharge data box is active the site-specific releases can be defined by selecting the nuclide from the list and filling-in the discharge rate. Due to efficiency reasons a unit discharge (of 10^{12} Bq/y) was given here for all selected radionuclides. It should be noted that the list of known radionuclides contains only those radionuclides that had been defined in the referring DORIS run, because the DORIS files were coupled to ASSESSOR by the option *input data libraries*.

Finally, the exposure pathways and the habit data for the critical group must be included before the impact analyses due to marine releases can be performed. Adults, who are most exposure, form the interest of this study and therefore all exposure pathways defined in PC-CREAM have been selected as indicated in Figure A.5. For all these selected pathways the specific habit data, as given in Table 3 and Table 4 of section 4.2, will be entered and are given, as an example for the Barsebaeck nuclear power plant, in Figure A.6 and Figure A.7.

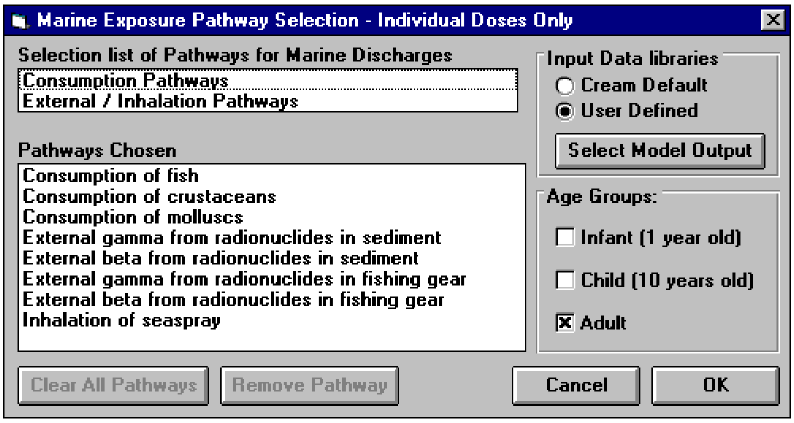

Figure A.5: ***Marine exposure pathways definition box***

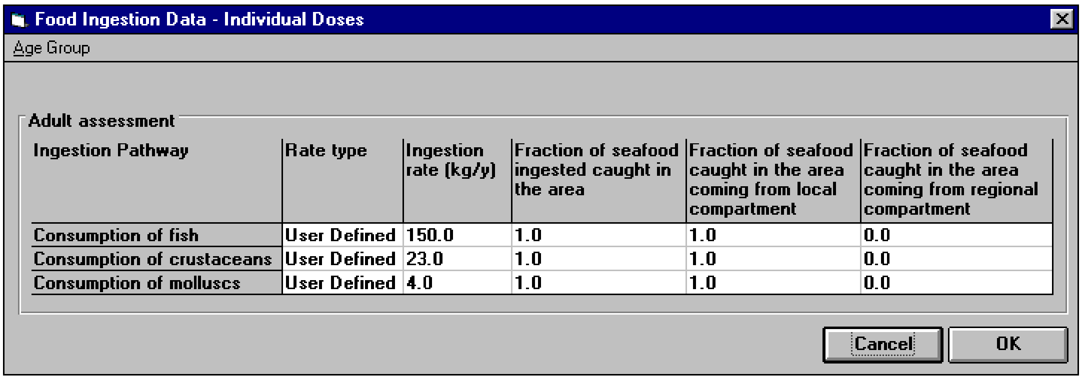

Figure A.6: ***Marine food ingestion data for critical group; see Table in section 4.2***

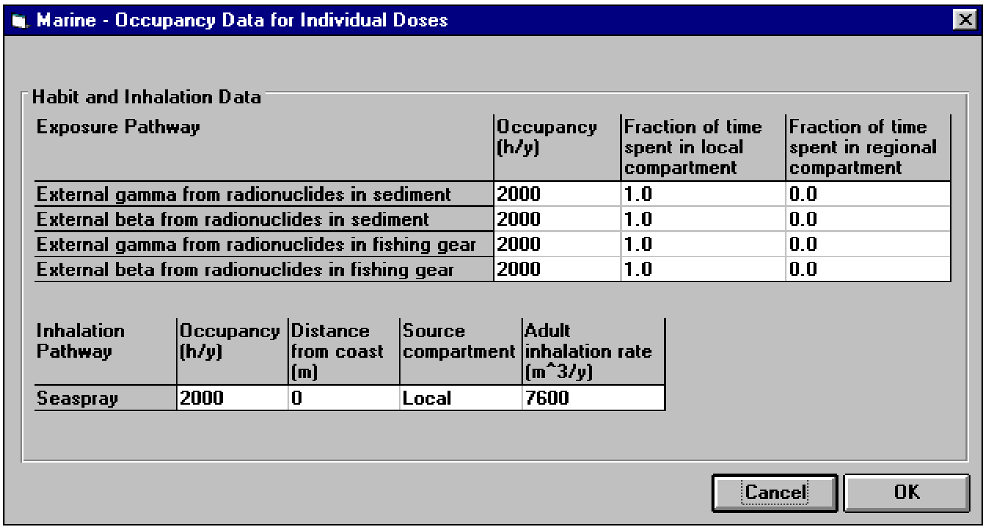

Figure A.7 ***Occupancy rate for an individual adult***

The assumption that all marine food consumed would come from the local compartment and that the adults spend their total beach occupancy time in the local compartment too, forms the basis of finding the most exposed individual. This (conservative) approach is clearly shown in the figures above.

Appendix B Characteristics of the Three Major European Rivers

To conform with the previous EU dose assessment study RP77[B.*], the characteristics of all actual European rivers into which nuclear sites release their radioactive effluents are translated into three major ones, namely: Loire, Rhine and Rhone. In this appendix the properties of these rivers, which were used to define the input for the river-screening model with complete mixing used in the assessment from river discharges, are summarised. In order to do this, the river was subdivided into compartments (1 to x) as shown in the tables below. Compartment 1 defines the starting point and the last compartment refers to the river mouth.

Table B.1: *Characteristics of the River Loire*

Compartment	Length (m)	Water velocity (m/s)	Water volume (m3)	Water depth (m)	Susp. Sediment load (t/m3)
1	$1.70\ 10^{5}$	$4.10\ 10^{7}$	$5.20\ 10^{7}$	1.50	$2.00\ 10^{-5}$
2	$1.10\ 10^{5}$	$3.47\ 10^{7}$	$5.30\ 10^{7}$	1.90	$3.00\ 10^{-5}$
3	$1.15\ 10^{5}$	$2.52\ 10^{7}$	$1.30\ 10^{8}$	4.00	$4.00\ 10^{-5}$
4	$1.00\ 10^{5}$	$2.20\ 10^{7}$	$1.80\ 10^{8}$	5.90	$5.00\ 10^{-5}$

Table B.2: *Characteristics of the River Rhine*

Compartment	Length (m)	Water velocity (m/s)	Water volume (m3)	Water depth (m)	Susp. Sediment load (t/m3)
1	$1.20\ 10^{5}$	$5.36\ 10^{7}$	$4.90\ 10^{7}$	3.90	$3.70\ 10^{-5}$
2	$1.25\ 10^{5}$	$5.36\ 10^{7}$	$9.10\ 10^{7}$	4.70	$3.60\ 10^{-5}$
3	$1.65\ 10^{5}$	$1.77\ 10^{7}$	$2.90\ 10^{7}$	2.90	$3.00\ 10^{-5}$
4	$7.50\ 10^{4}$	$5.05\ 10^{7}$	$6.50\ 10^{7}$	4.90	$3.80\ 10^{-5}$
5	$3.80\ 10^{5}$	$3.16\ 10^{7}$	$5.50\ 10^{7}$	2.60	$3.50\ 10^{-5}$
6	$9.50\ 10^{4}$	$4.73\ 10^{7}$	$1.00\ 10^{8}$	5.30	$4.10\ 10^{-5}$
7	$2.50\ 10^{5}$	$1.77\ 10^{7}$	$9.40\ 10^{7}$	3.75	$3.00\ 10^{-5}$
8	$1.75\ 10^{5}$	$2.05\ 10^{7}$	$5.30\ 10^{8}$	7.60	$4.50\ 10^{-5}$
9	$1.50\ 10^{5}$	$1.89\ 10^{7}$	$8.50\ 10^{6}$	1.90	$4.00\ 10^{-5}$
10	$2.40\ 10^{5}$	$3.16\ 10^{7}$	$5.30\ 10^{8}$	6.80	$4.50\ 10^{-5}$

Table B.3: *Characteristics of the River Rhone*

Compartment	Length (m)	Water velocity (m/s)	Water volume (m3)	Water depth (m)	Susp. Sediment load (t/m3)
1	$1.45\ 10^{5}$	$3.47\ 10^{7}$	$5.87\ 10^{8}$	2.00	$2.50\ 10^{-5}$
2	$2.00\ 10^{4}$	$3.16\ 10^{7}$	$1.19\ 10^{8}$	3.30	$2.40\ 10^{-5}$
3	$4.00\ 10^{4}$	$3.09\ 10^{7}$	$4.16\ 10^{8}$	4.70	$2.70\ 10^{-5}$
4	$6.00\ 10^{4}$	$2.90\ 10^{7}$	$6.65\ 10^{8}$	5.00	$3.10\ 10^{-5}$
5	$4.50\ 10^{4}$	$2.78\ 10^{7}$	$7.64\ 10^{8}$	8.50	$3.50\ 10^{-5}$
6	$4.00\ 10^{4}$	$2.62\ 10^{7}$	$7.20\ 10^{8}$	9.00	$3.70\ 10^{-5}$
7	$5.50\ 10^{4}$	$2.49\ 10^{7}$	$1.07\ 10^{9}$	9.20	$4.00\ 10^{-5}$
8	$3.50\ 10^{4}$	$2.37\ 10^{7}$	$7.63\ 10^{8}$	9.90	$4.50\ 10^{-5}$
9	$5.00\ 10^{4}$	$2.21\ 10^{7}$	$1.20\ 10^{9}$	10.5	$5.00\ 10^{-5}$

[B.*] Mayall A et al. Radioactive effluents from nuclear power stations and nuclear fuel reprocessing plants in the European Community 1977-1986, Radiation Protection 77 Part 2: Radiological aspects, European Commission Report EUR 15928 EN (1995).

Appendix C PC-CREAM River Model Selection

The impact due to routine releases into a river is calculated using the PC-CREAM suite, version 98. The river module contains two main models namely the dynamic model and the screening models. In this dose assessment study the *screening model with complete mixing* was used to predict the impact due to discharges into the river environment. The selection of this river model will be illustrated in this appendix.

The dynamic model divides the river into sections with homogeneous hydrological characteristics. A maximum of eight compartments can be defined over a total river length of 800 km. For each compartment the advection-diffusion equation is solved for different substances. In this case the different substances are radionuclides on bed sediment, on suspended sediment and dissolved in water. The only limiting condition to solve this equation is that the in- and output concentrations of the mentioned substances are equal at the borders of adjacent compartments.

Three screening models are currently included in ASSESSOR's river module, viz. *simple screening model*, *extended screening model with complete mixing* and *extended screening model with incomplete mixing*. The *extended screening model with complete mixing* was selected to calculate the impact of releases into a river in this dose assessment study. In this model the three major European rivers were modelled accurately in respect of the known input parameters and their statistical deviations. In the remaining part of the text the selected *extended screening model with complete mixing* will be called screening model.

Beside the annual effective doses the screening model calculates the activity concentration in suspended sediment and in filtered water. Further the distance of interest is limited from 0.1 to 10 km with respect to the release point.

For the Spanish site Almaraz a comparison was made between the dynamic and the screening river model. This run supports the following comments:

- The individual doses have roughly a value of some μSv. For comparison the ICRP defines the upper limit for the individual doses as 1 mSv[C*].
- With respect to the dynamic model the screening model overestimates the individual doses by a factor of 2 to 3, and this is radionuclide dependent. The difference between both river models is relatively large for metals like magnesium, but the dose difference between, for example, tritium is rather small. An important parameter is the sediment distribution coefficient (Kd). The Kd-value for metals is large and the Kd for tritium is small, so tritium dissolves more easily compared to metals.
- The effort required to perform the dose calculations using the screening model is much less when compared to the time necessary to run the dynamic model.

The three statements above form the main arguments for using the screening model in the dose calculations due to radioactive effluents in the river environment. Furthermore, the overestimation is a compensation for the lack of some radionuclides in the PC-CREAM river database.

[C*]: International Commission on Radiological Protection publication 60

Appendix D PC-CREAM Assessment Example of an 'Inland' Site

In this appendix an example for a PC-CREAM assessment, based on the Dodewaard nuclear power plant in the Netherlands, will be briefly elucidated for an 'inland' site. Background information is given of input data, specific details and assessment options that were used for the PC-CREAM calculations. The dose assessment for an 'inland' site was split up into three steps.

1. Dose assessment using the river module in ASSESSOR due to the site-specific radionuclides released into the river;
2. A marine dispersion model (DORIS) was defined to predict the activity concentration in the marine environment;
3. Dose assessment due to radioactive effluents in the marine environment by ASSESSOR's marine module.

D.1 Step 1: ASSESSOR's river module

Using the river module in ASSESSOR the individual doses were calculated for releases into the river environment. As stated in Appendix C the *screening river model with complete mixing* was selected for this dose assessment study. After starting-up ASSESSOR and defining the site details data the river assessment type was chosen (Figure D.1).

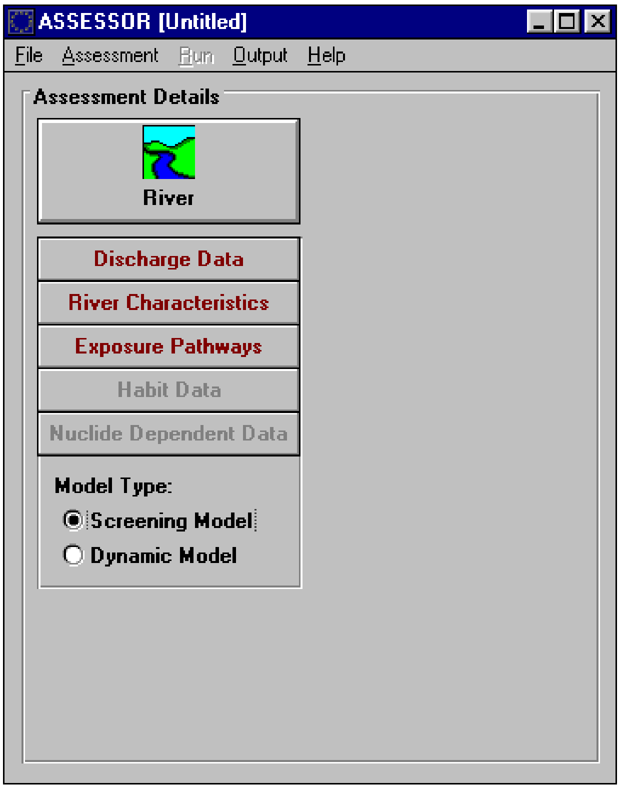

Figure D.1 ***Selecting river mode type***

In the *Assessment Details* box the screening river model was selected, as illustrated in Figure D.1. Thereafter the three upper buttons become active and were selected in order to define *Discharge Data*, *River Characteristics* and *Exposure Pathways*.

All radionuclides released by the nuclear site, as specified in the Bilcom97 database, were incorporated by the user in the river discharge data box. Since the actual discharges were taken into account in the post-processing's phase (as described in section 5.2), all discharge rates for each defined radionuclide were set to a unit release of 10^{12} Bq per year.

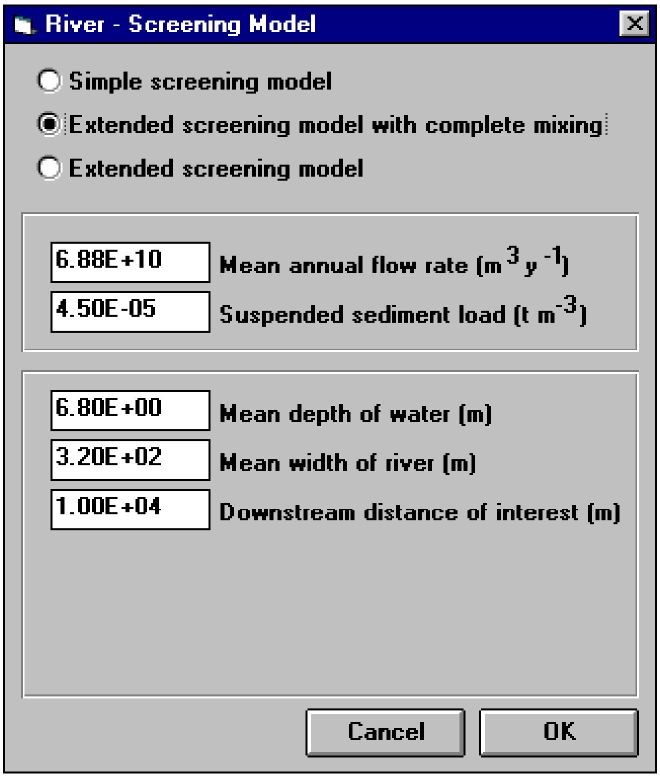

Figure D.2 ***Definition of the river characteristics for the screening model***

Following definition of all discharge rates for the nuclear site, the river characteristics were included. In Figure D.2 the river properties of the major river model 'Rhine 10' are given as an example, as given in Table 7 and of section 4.3 for the Dutch power plant Dodewaard.

In the next phase of ASSESSOR's river module input process the exposure pathways, which must be taken into account during the individual doses calculations, were defined. An example of this input phase is represented in Figure D.3. The river consumption ingestion rates belonging to the specified pathways were filled-in, see Figure D.4.

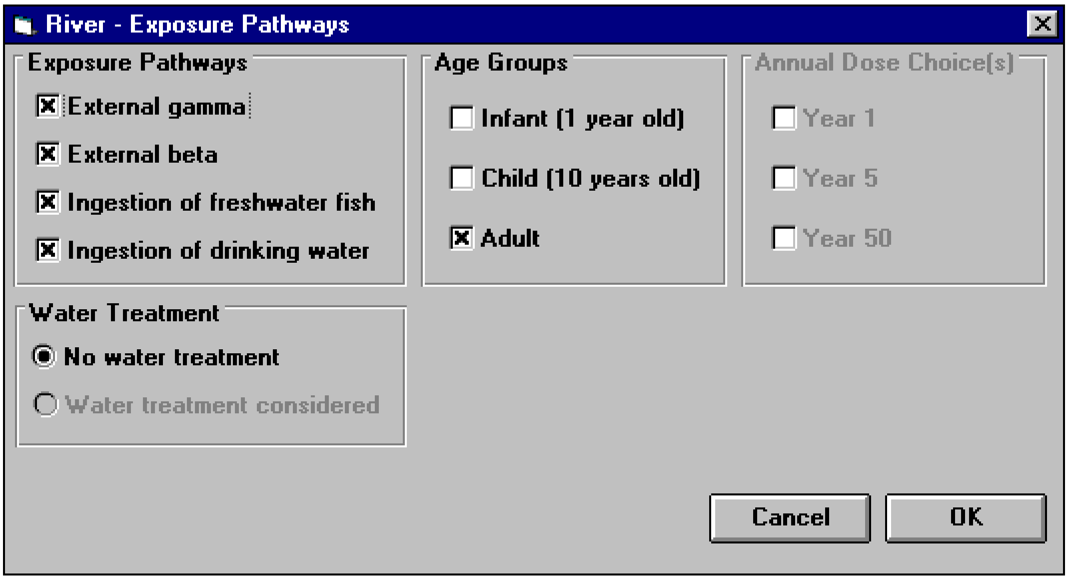

Figure D.3 ***River exposure pathways box***

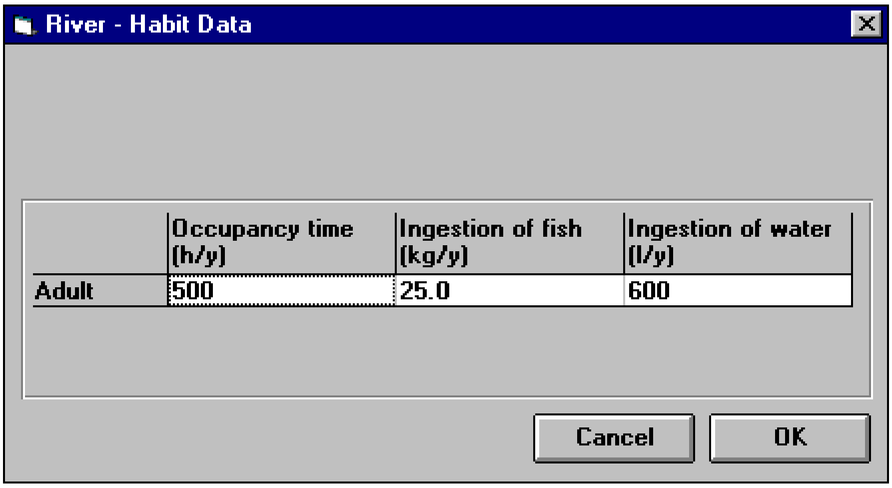

Figure D.4 ***River ingestion and habit data for an individual adult from the critical group***

Finally, the nuclide dependent data, such as sediment distribution coefficients and fish concentration factors, were given by selecting the last button in the *Assessment Det*ails box (Figure D.1). As PC-CREAM forms the background of this assessment study and no extra data is available all default values were used in the *nuclide dependent data* box. An example of the radionuclide dependent data for the Dodewaard site in the Netherlands is given in Figure D.5, whilst Table D.1 lists all currently available radionuclides in the river module.

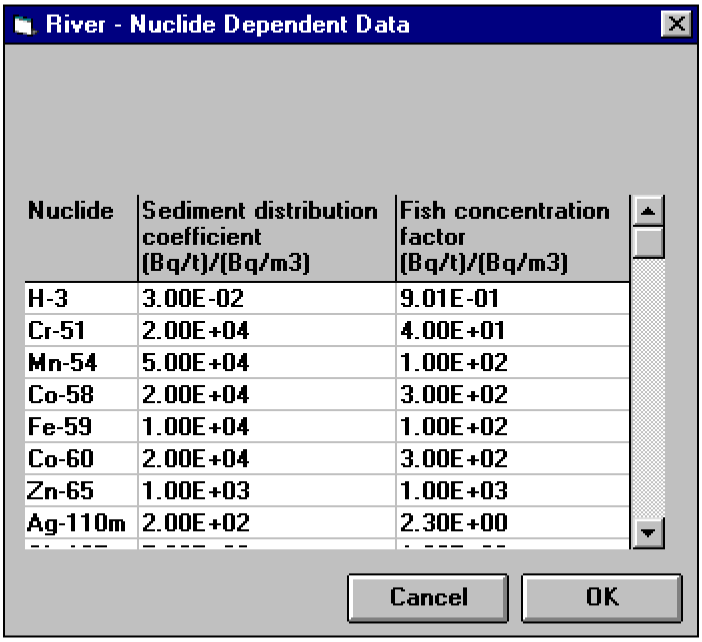

Figure D.5 ***Nuclide dependent data box in ASSESSOR's river module***

Table D.1 ***Radionuclides available in the river module of ASSESSOR***

H-3	Zn-65	Ag-110m	Cs-136	Pu-239
C-14	Sr-89	Sb-125	Cs-137	Pu-240
P-32	Sr-90	I-125	Ce-144	Pu-241
S-35	Y-90	I-129	Eu-154	Pu-242
Cr-51	Y-91	I-131	Eu-155	Am-241
Mn-54	Zr-95	I-132	Ra-226	Am-242
Fe-55	Nb-95	I-133	U-234	Am-243
Fe-59	Tc-99	I-134	U-235	Cm-242
Co-58	Ru-103	I-135	U-238	Cm-243
Co-60	Ru-106	Cs-134	Pu-238	Cm-244

Before starting the second step of the dose assessment of an 'inland' site, one important issue should be noted here. In the river module of the PC-CREAM suite it is not possible to assess the collective dose. The reason is probably due to the relative short pass through times of the radioactive effluents in the river, just a few days.

D.2 Step 2: DORIS application

The radioactive materials released into a river will eventually flow into a sea, therefore, before the dose assessment due to the radionuclides in the marine environment can be performed the activity concentration must be predicted for all site-specific discharged effluents. Hence, the PC-CREAM application DORIS, **D**ispersion **O**f **R**adionuclides **I**n the **S**ea, was used to define the site specific data and the marine model parameters.

The work procedure for this process is identical to that one as already mentioned in step 1 of Appendix A. However, the definition of the site details (by selecting the *site* button as illustrated in Figure A.1), as name of the site, the marine model module and regional compartments, is an important difference in relation to that of a ‘coastal’ site. The user must specify all the three items of the *Site Details* box, because the ‘inland’ sites are not predefined in DORIS. In our example of the Dodewaard power plant this user-defined box is given in Figure D.6.

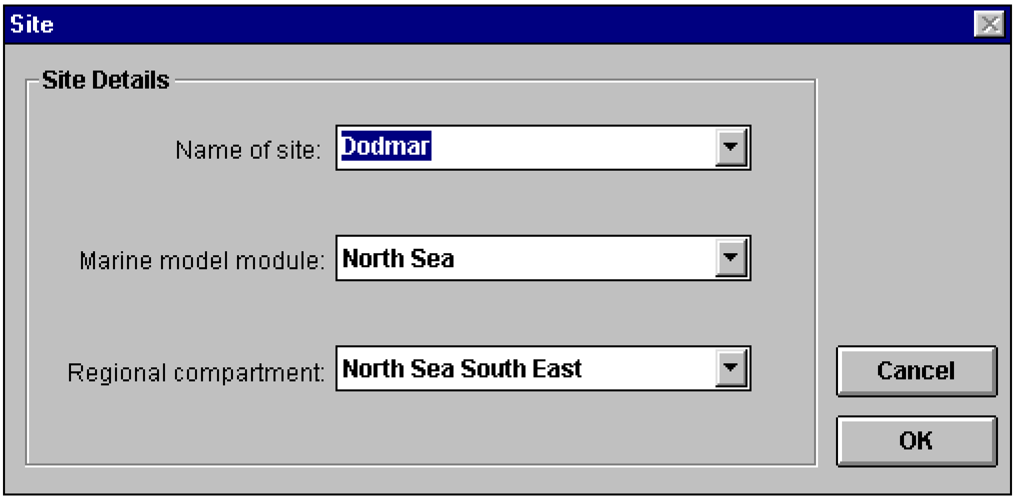

Figure D.6 ***Example of a DORIS site details box for an ‘inland’ plant***

As a consequence of this approach the user must also define the local marine compartment parameters, which are taken from the RP72[D.*] for this project. This means that for the above example the properties of the North Sea south-east local marine compartment are defined as specified in Table 4.5 of RP72, whilst the marine sediment model parameters are taken from Table 4.7 of RP72.

D.3 Step 3: ASSESSOR’s marine module

After running DORIS, the result files created were included in the marine dose assessment calculation. This (third) step in the dose analysis of an ‘inland’ site is very similar to the work procedure for a ‘coastal’ site outlined in step 2 of Appendix A. The only difference in respect to the previously mentioned approach concerning a ‘coastal’ site is again the site data box. The user must make sure that the site name defined in the marine module of ASSESSOR is identical to that used in the DORIS run. For our example this name of the site is Dodmar, as shown in Figure D.7 for completeness.

As a closing remark of this section, a reference to Appendix A was made for finalising the input of a dose assessment due to radioactive effluents into the marine environment for a so-called ‘inland’ nuclear site.

Figure D.7 ***Example of site details for a marine assessment for a ‘inland’ site***

[D.*] Radiation Protection 72, EC Directorate-General Environment, EUR 15760, 1995

Appendix E Marine Source Term for 'Inland' Nuclear Sites

In the PC-CREAM package it is currently not possible to carry out in one run a marine dose assessment from a discharge into a river. Therefore the river and marine modules of PC-CREAM have to be used successively to predict the marine impact from releases into the river environment. Hence, the independent / uncoupled results of both modules must be linked together by the user, which is discussed in this appendix. Since only one marine model is available in the PC-CREAM suite, the *screening model with complete mixing* is selected in the river model for this dose assessment study, as discussed in Appendix C. This implies that tributaries are not fully included in the river model. On the other hand these tributaries could be included easily in the dynamic river model by defining different characteristics for each defined compartment. However, as indicated in Appendix C the dynamic river model was not selected, because in the context of this project, the above mentioned screening model is sufficiently accurate.)

E.1 Theoretical background

The method for determining a correct source term for the marine compartments is interesting. The source term for the river model is very straightforward, because the amount of release from a nuclear site is simply included in the river module by the user. Apart from the annual effective dose to individuals[E.*] the river module predicts activity concentrations in several materials, such as river water, and bed sediment. Out of these materials the law of mass conservation makes the source suspended sediment term for the (local) marine compartment. In this project the river could be seen as a pipeline within which three processes occur, namely radionuclides on suspended sediment, on bed sediment or dissolved in (river) water.

The basis of interweaving the river module output results and the marine module source term forms the equilibrium of radionuclide concentrations on suspended sediment, bed sediment and in filtered water. This assumption can be justified by the fact that the pass through time of a particular radionuclide is very short compared to the time that radionuclides will be discharged into the river environment. But this statement does not exclude the transfer of radionuclides between the three processes that occur in the river. The aspect of radioactive decay however could be neglected in defining the marine source term. The very short-lived radionuclides do not contribute to the source term after all when the particular river particle flows into the sea. For the other radionuclides the lifetimes are relatively long compared to the river pass through time (which is roughly speaking 5 days for a river of 800-km length and with an average water velocity of 1 m/s). As a consequence of this relatively short pass through time the doses via the river exposure pathways are very low. Nevertheless the activity concentrations of the river materials are important, because of the determination of the source term for the (local) marine compartment.

It is expected that the source term contribution from the bed sediment activity concentration could be neglected, because the bed sediment velocity is relatively low compared to water velocity. The activity concentration of the suspended sediment is taken into account in the marine source term due to discharges into a river. The suspended sediment velocity is somewhere in the range between the bed sediment velocity and the flow rate of the river water. But, the suspended sediment velocity was unfortunately not given in the major river data derived by NRPB (Appendix E). Since most of the suspended sediment will, however, flow together with the river water into the sea, the speed of the suspended sediment is assumed to be equal to that of the water.

As explained above, the source term for the (local) marine compartment was set up from two components in this dose assessment study, namely the river activity concentrations in (filtered) water and in the suspended sediment. The river module of PC-CREAM calculates these concentrations at the end of the river. (In the screening model, used in the current project, the maximum downstream distance of interest of 10 km was selected to represent the end of the river. Scoping analyses, discussed in Appendix C, show that this downstream

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[E.*] The collective dose can (currently) not be calculated by the river module.

point of interest could be interpreted as the fictitious end of the river within the accuracy bounds of this assessment study.)

First, the source term due to the activity concentration in water is defined. The river water concentration that flows finally into the sea is given in equation (E1).

$$\left[T_s^n\right] = Q \cdot \left[T_r^n\right] \tag{E1}$$

Where:

- $[T^n_s]$: the activity concentration due to nuclide *n* of filtered water in the sea [Bq/year];
- Q: the flow rate of the river [m^3/year];
- $[T^n_r]$: nuclide *n* activity concentration of filtered water at the end of the river [Bq/m^3].

The activity concentration in (filtered) water at the end of the river for each nuclide selected in the river module, $[T^n_r]$ in equation (E1), could be simply taken from the output. While the river flow rate *Q* is identical to the value that must be defined by the user within PC-CREAM's input process of the river characteristics. (The water velocities of the major rivers in this study are given in Appendix B.)

The suspended sediment activity concentration forms the second part of the marine source term due to releases into a river environment, and can be calculated in two steps. In the first step (see equation E2) the suspended sediment activity concentration per unit of volume has to be defined based on the PC-CREAM calculated concentration per kg suspended sediment. Secondly, as in equation (E1) the suspended sediment activity concentration that will flow each year into the marine environment is calculated; described by equation (E3).

$$\left[S_v^n\right] = SSL \cdot \left[S_m^n\right] \tag{E2}$$

$$\left[S_r^n\right] = Q \cdot \left[S_v^n\right] \tag{E3}$$

Where:

- $[S^n_v]$ is the suspended sediment activity concentration for nuclide *n* per volume [Bq/m^3];
- *SSL* is the suspended sediment load factor [kg/m^3], as given in the input of the river module;
- $[S^n_m]$ suspended sediment activity concentration per nuclide *n* as given in PC-CREAM's output file [Bq/kg];
- Q: the annual river flow rate [m^3/year];
- $[S^n_r]$ is the suspended sediment activity concentration for nuclide *n* that flows into the sea [Bq/year].

Finally, the total marine source term is given by the summation of the activity concentrations in water (equation E1) and in the suspended sediment (equation E3):

$$\left[C^n\right] = \left[T_s^n\right] + \left[S_r^n\right] \tag{E4}$$

Where C^n forms the total river activity concentration per radionuclide *n* (in Bq/year) that run into the (local) marine compartment.

It is clear that the fraction between the two sea-source term components depends on the specific radionuclide behaviour. The characteristic parameter in this case is the Kd value, which represents the ratio between the (maximum) activity concentration in suspended sediment and the activity concentration in (filtered) river water. This sediment partition coefficient, Kd, could be relatively high, as for instance for metallic substances like Mn (Kd = 50000), while the value for tritium is extremely low (Kd ≈ 0.03). As a consequence the activity concentration of H-3 in the suspended sediment might be neglected in equation (E4), because H-3 does not adsorb strongly onto the sediment. But, in this project a generic approach was performed, in order to proceed an identical (source term) methodology for all radionuclides. In doing so the reduction of errors and human effort will be minimised, whilst the standardisation and automation of the process could be maximised.

E.2 Implementation in the dose assessment

The theoretical background of the marine source term due to discharges into a river, as outlined in section E.1, was implemented in the dose assessment calculations for 'inland' sites. These calculations consist of two separate uncoupled PC-CREAM analyses as already mentioned. The results of both analyses have been used to predict the marine dose assessment due to the release into the river environment through the equation:

$$D_{\text{i, marine}} = D_{\text{i, cream marine}} \frac{B_{\text{i, actual river}}}{B_{\text{i,unit marine}}} * \frac{C_{\text{i, river}} \; Q_{river}}{B_{\text{i,unit river}}} \qquad \text{(E5)}$$

Where:

$D_{\text{i, marine}}$	is the marine dose due to nuclide i of the specific 'inland' site (in μSv);
$D_{\text{i, cream marine}}$	is the PC-CREAM marine dose in μSv of nuclide i due to an unit marine release;
$B_{\text{i, actual river}}$	is the site-specific release rate into the river environment of nuclide i (in GBq/year);
$B_{\text{i, unit marine}}$	is the yearly unit marine discharge of nuclide i as defined in ASSESSOR's marine module (in GBq/year);
$C_{\text{i, river}}$	summation of the river activity concentration in water and in the suspended sediment per nuclide i conform equation (E4);
Q_{river}	mean annual flow rate (in m^3/y) of the river (as defined in ASSESSOR's river module);
$B_{\text{i, unit river}}$	is the yearly unit river discharge of nuclide i as defined in the river module (in Bq/year).

As unit discharge rates (of 10^{12} Bq/y) were used in both PC-CREAM analyses, subsequently the river and marine module, these results must be updated in respect to the actual site-specific discharge. Together with the marine source term this correction was also included in above equation (E5). Finally it should be noted that this post processing activity, which can be seen as the finishing touch of the dose assessment, was implemented in Excel worksheets.

Appendix F PC-CREAM Improvements

During the European dose assessment study, which covered the period 1987 to 1996, many PC-CREAM calculations were performed to analyse the radiological impact to the European population due to routine releases of the (97) EU nuclear sites. Because of this the PC-CREAM suite is frequently used and applied in its entirety. Features of the system include the databases with nuclear site details and radionuclide data, definitions of marine compartments and parameters, exposure pathways, habit data, etc. Version 98 of the PC-CREAM software package is used for this project.

Throughout the project users have identified a number of enhancements. These are briefly mentioned in this appendix for completeness. Since the current report discussed (only) the liquid discharges into the aquatic environment, only improvements to the DORIS application and ASSESSOR's marine and river modules are described here.

F.1 DORIS enhancements

A. After selecting the marine model *Mediterranean Sea* in DORIS the *volume exchange rate* can only be set by using the *default parameters option* in the easy set-up window. The fluxes cannot be activated by pushing the *fluxes* button in the easy set-up mode nor via the menu *input data*.

B. The default bioturbation rate for the *Mediterranean Sea* is set to 0.00158 m^2/y when selecting the marine module *Bay of Biscay*. However this value is too large and will result in a load operation failure if the *dof* file is reloaded in DORIS again, despite the fact that DORIS has written this file itself. Replacing the bioturbation value manually to the more common rate of 0.000036 prevents this fatal loading failure. (During the current assessment the above procedure must be performed, for instance, for the Almaraz nuclear site.)

C. Although the Spanish 'coastal' site Vandellos is listed in the PC-CREAM user's guide [F.*] (Table 2: *PC-CREAM site database*) the name of this nuclear power plant is unknown in DORIS. It should also be mentioned here that the (in DORIS selectable) Riso site (Denmark) is not listed in the user's guide.

D. Some Spanish 'inland' sites, e.g. Almaraz, release their radioactive effluents via a river into the marine environment of the so-called Portuguese continental shelf, which is part of the Atlantic Ocean. The model of the Atlantic Ocean is currently included in the Bay of Biscay module in DORIS. Adding a more detailed marine model of the Atlantic should be considered.

E. The marine compartment names of the *Mediterranean Sea* are not given in RP72 [F.†] (Figure 4.10: *Compartments of European marine model*). The local marine compartment parameters for the *Mediterranean Sea* are not given in (Table 4.5: *Site and local marine compartment parameters*).

F.2 ASSESSOR's marine module enhancements

F. Although the Spanish 'coastal' site Vandellos is listed in the PC-CREAM user's guide (Table 2: *PC-CREAM site database*) the name of this nuclear power plant is unknown in the site name database of ASSESSOR. Furthermore, it should be mentioned here that the Riso site (Denmark) is not available in ASSESSOR's site name database neither is it listed in the user's guide.

G. The original *catches.dat* file delivered with the PC-CREAM 98 software produced a run time-error due to an error in the file while running the collective dose for the Swedish Oskarshamn site. But, during the dose assessment study the file was updated (by NRPB) to add the Swedish coastline length to the Baltic Sea West (surface waters) compartment.

F.* User's guide PC-CREAM 97, publication no. EUR 17791 (NRPB-SR296) of the European Commission

F.† Radiation Protection 72, CREAM methodology EC document EUR 15760

H. As the regional compartment of the *Portuguese continental shelf* is mistyped in the marine module of ASSESSOR, the user defined data libraries (in DORIS) cannot be selected. Hence, the compartment name in these libraries must be changed manually before including the files in ASSESSOR.

I. The ingestion of crustaceans for France was limited in the marine module to 60 kg/y. As mentioned in section 4.3 of this report, this sea food consumption rate is 61 kg/y.

J. It should be recommended to include in ASSESSOR a button or option that enables the user to define a default (unit) discharge rate for all selected radionuclides. This feature is found in the DORIS application.

F.3 ASSESSORS's river module enhancements

K. The effort needed to model the river data (in the river module of ASSESSOR) could be significantly reduced by defining (major) river sections in a manner such as is found in the predefined marine compartments of the European coastal waters, which are included in DORIS. The characteristics of the rivers in Europe, for example dimensions and velocity, could than be selected from the 'river database'. In accordance with the approach of the DORIS application the site name and the (default) river sections could be linked together.

L. Rivers finally flow into a sea (or lake). The calculation of the radiological marine impact due to the river activity concentrations could be simplified by coupling the river module and the (existing) marine compartment models. This 'connection' could be made in two ways. One possibility is to read in the river activity concentration as a source term into the marine model. The second way is based on the 'river database' as mentioned in point K, so that the river Rhine is automatically linked to the marine compartment *North Sea south east*.

M. It should be recommended to include in ASSESSOR a button or option that enables the user to define a default (unit) discharge rate to all selected radionuclides. An example of this feature can be found in the DORIS application. Such an approach would also be very useful in the river module regarding the definition of the *nuclide dependent data*. In doing so, the (default) sediment distribution coefficients and fish concentration factors could be set in a more convenient way.

N. Adding models for estuaries (and lakes) in ASSESSOR's river module. In the current study for instance a number of German sites (e.g. Isar and Gundremmingen) release their liquid radionuclides into the Danube river. This river runs into the Black Sea, which is connected to the Mediterranean Sea. (For this assessment it is assumed that the Danube river flows directly into the Aegean Sea.)

F.4 General enhancements

O. At the moment the PC-CREAM applications have at their disposal different nuclide libraries. As a consequence of this variety in available radionuclides the interweaving of the river and marine module results, as described in chapter 5 of this report, can not always be done in a straightforward manner. Therefore it would be advisable to define one nuclide database for all PC-CREAM applications. (To a large extent source terms for 'inland' sites could not be defined in the river module of ASSESSOR in the current project.)

P. Inclusion of Windows features such as *cut*, *copy* and *paste* to enable the user to copy or move the contents from one field to another.